THE DEVELOPMENT OF AN EVALUATION SYSTEM FOR STRUCTURAL DAMAGE

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Abstract

In order to reduce additional damage due to an aftershock, a quick inspection on the damaged buildings must be carried out. However, the buildings have to be entirely investigated by engineers or researchers under existing situation. The judgement made can vary accordingly to the engineers’ experiences and usually takes a long time to investigate all damaged buildings. Furthermore, it is very difficult to conduct visual inspection on tall buildings. This research aims to develop a new automatic and quick inspection system that requires only several accelerometers. This system makes it possible to obtain the information of safety level against an aftershock to professionals immediately.

Keywords: Quick Inspection, Performance-based, Capacity Spectrum Method, Double Integral, Monitoring

1. Introduction

In a big earthquake, many buildings are usually damaged, giving rise to many homeless. The level of damage could deteriorate due to an aftershock, in some cases thus harmful to the buildings occupants. Some people would even flee from buildings that suffer physical damage from building that might still have enough residual seismic capacity from the engineering point of view. Hence, the number of homeless could increase drastically. In order to reduce further damage due to an aftershock and to reduce the number of homeless, a quick inspection on the damaged buildings should be carried out immediately after a main shock. However, in the conventional process, buildings have to be investigated one by one by engineers or researchers. For example, 5,068 engineers and 19 days were needed to investigate 46,000 buildings on a damaged area at the Kobe earthquake [JBDP, 1995]. Apart from time consuming the number of investigation intended were not entity covered. Buildings judged as “Caution”, require detailed investigation by engineers. On the other hand, a quick investigation system presents a dilemma as buildings are investigated through visual inspection only and such judgement varies accordingly with the engineers’ experiences.

Alternatively, a comparison between the performance and demand curve could also be used to estimate the residual seismic capacity in solving the problem above. The absolute response accelerations and relative response displacement on each floor are needed in order to draw the performance curve. Some features are generally needed to measure the inter-story drift or the relative response displacement to the basement. However these present some inconvenience for usage. On the contrary, it is easy to measure accelerations with accelerometers. If displacements can be derived from the accelerations with double integral, the performance curve of structures can be easily measured.

It is well-known that measured acceleration can contain noise disturbance due to the non-linearity of the accelerometers used and the noise in the measuring equipments [Iwan et al., 1985, Boore et al., 2001]. The noise level is usually small, but upon integrating twice, the noise effect will be magnified, as much as twice [Iwan et al., 1985]. The proposed integration method by authors [Kusunoki and Teshigawara, 2002] was applied in this paper.

In this paper, a new real-time residual seismic capacity evaluation system was proposed. Furthermore, the proposed integral method and the evaluation system were applied to the existing shaking table test results, and the validity of the method is confirmed.
2. Configuration of the System and Outline of Evaluation

This system has basically two accelerometers and one evaluation machine as shown in Fig. 1. The evaluation method is based on the performance design concept as shown in Fig. 2. The residual seismic capacity will be evaluated by comparing the measured performance curve of a structure and the measured demand curve.

![Fig. 1 Configuration of the system](image1)

![Fig. 2 Outline of the evaluation based on the Performance design concept](image2)

The performance curve is the relationship between the representative deformation $\Delta$ and the representative restoring force $S$, which shows the predominant response of a structure. The method to evaluate these representative values is outlined below.

The calculated relative displacement vector to the basement $\{Mx\}$ from measured accelerations can be derived as Eq. 1 with the modal participation factor $M\beta$, mode vector $\{Mu\}$, and the assumption that the $\{Mx\}$ is the unique vibration mode.

$$\{Mx\} = M\beta \cdot \{Mu\} \cdot \Delta \quad \text{Eq. 1}$$

The story shear (inertia force) of the first story $M Q_B$ can be calculated using Eq. 2 with the measured absolute acceleration $\{M \overset{\cdot}{\mathbf{A}}\}$ and mass $m_i$ of each floor.

$$M Q_B = \sum m_i \cdot (M \overset{\cdot}{\mathbf{A}} + \mathbf{g}) \quad \text{Eq. 2}$$

The equation of motion of a multi-degree-of-freedom system can be abbreviated to a single-degree-of-freedom system as given in Eq. 3.

$$M \cdot \overset{\cdot}{\mathbf{A}}_M + \bar{C} \cdot \overset{\cdot}{\mathbf{A}}_M + \bar{K} \cdot \Delta = -M \cdot \mathbf{g} \quad \text{Eq. 3}$$

where, $M$ is the total mass of a structure, $M\bar{C}$ is the equivalent damping, $M\bar{K}$ is the equivalent stiffness, and $\mathbf{g}$ is the ground acceleration, respectively.

The $M Q_B$ can be calculated with Eq. 4. If the first mode is predominant enough, the calculated angular frequency, $\omega_1 = \sqrt{M\bar{K} / M}$, can be the natural angular frequency of the first mode.

$$S = M Q_B = M \cdot \mathbf{g} \quad \text{Eq. 4}$$

Eq. 5 can be derived from Eq. 1 by dividing both sides by $\Delta$. The inertia force acting on each floor $M P_i$ can be derived as Eq. 6 by using Eq. 1 and Eq. 5.
$$M \beta \cdot M \; u_i = \frac{M \; x_i}{\Delta} \quad \text{Eq. 5}$$

$$M \; p_i = m_i \cdot M \; \beta \cdot M \; u_i \cdot \frac{\mathcal{W}}{\Delta} = m_i \cdot M \; \frac{M \; x_i}{\Delta} \quad \text{Eq. 6}$$

The total mass $M$ can also be derived from Eq. 4 and Eq. 6 since the total mass $M$ is the sum of each floor mass, i.e.;

$$M = \sum m_i \cdot M \; \frac{M \; x_i}{\Delta} = \sum m_i \cdot M \; x_i = \sum m_i \quad \text{Eq. 7}$$

Therefore, the representative displacement $\Delta$ can be derived as Eq. 8.

$$\Delta = \frac{\sum m_i \cdot M \; x_i}{\sum m_i} \quad \text{Eq. 8}$$

The representative acceleration, $\mathcal{W}$ is applied to the representative restoring force, $S$ ($S = M \; Q_S / \sum m_i = \mathcal{W}$). If a system is elastic, the representative displacement, $\Delta$ and the representative acceleration, $\mathcal{W}$ can be calculated with Eq. 8, i.e.;

$$\mathcal{W} + 2 \cdot M \; h \cdot M \; \omega \cdot \Delta + M \; \omega^2 \cdot \Delta = -\mathcal{W} \quad \text{Eq. 9}$$

where, $M \; h$ is the damping coefficient, and $M \; \omega$ is the angular frequency, respectively.

As a result, the maximum representative displacement $\Delta_{\text{max}}$, and the absolute acceleration $(\mathcal{W}_{\text{max}})$ correspond to the value from the response displacement and acceleration spectrum with a damping coefficient of $M \; h$.

The demand curve is the relationship between the response acceleration (Sa) and displacement (Sd) spectrum. The intersection point of the demand and performance curve indicates the value of maximum elastic response. Since, the damage of a structure can dissipate some amount of input energy, thus the damping effect can be increased. Therefore to reduce this effect, the demand curve can be reduced accordingly to the magnitude of damage (Fig. 2). The intersection point of the reduced demand and performance curves indicates the value of maximum inelastic response.

Additionally, the following four assumptions were applied for the evaluation of the residual seismic capacity. These assumptions need further studies.

a) The mechanism of an aftershock is the same as the main shock, and the aftershock is always smaller than the main shock. With this assumption, the demand curve of the aftershock corresponds to the main shock.

b) The damping coefficient for the demand curve of an aftershock is assumed at 5%.

If further damage occurred in a structure during an aftershock, additional damping can be applied so that the demand curve can be lowered. However, at present it is difficult to estimate accurately the damping effect due to aftershock. In this case, the damping effect due to inelastic behaviour during an aftershock is neglected and instead 5% viscous damping is taken into account for a safe evaluation. The residual seismic capacity can be calculated by the comprising the demand curve of 5% damping with the performance curve. If the ratio of the $\text{Sa}(=S_{a_{5}})$ at the ultimate displacement on the performance curve to the $\text{Sa}(=S_{a_{5}})$ on the demand curve is greater than 1.0, then the structure will be regarded as SAFE, and if the values is less than 1.0, it will be regarded as UNSAFE.

c) The restoring force and the vibration mode are assumed constant after the maximum response is reached and is considered less than the ultimate.
If the maximum response is less than the ultimate displacement, the performance curve to the ultimate displacement must be extrapolated. The restoring force and the vibration mode are assumed constant after the maximum response reached the ultimate displacement.

![Graph showing the relationship between acceleration and displacement](image)

**Fig. 3 Elastic-inelastic judgement**

1. Measure \( \text{acceleration} \)
2. Measure relative disp. \( \delta_x \)
3. Vibration mode of building
4. Calculate Inter-story drift \( c \Delta x_i \)
5. Calculate Abs. Acc. on each floor \( \ddot{x}_i \)
6. Mass ratio \( \bar{m}_i \)
7. Representative Disp. \( S_c \)
8. Representative Acc. \( S_a \)
9. Generate Performance Curve
10. Draw envelope curve of 9
11. Ultimate Disp. \( R \)
13. From measured acc.
   - Calculate Resp. Acc. Spectra Ra
   - Calculate Resp. Disp. Spectra Rd
14. Calculate Demand curve(Ra-Rd Curve)
15. Judgement
   - Elastic
   - Safe
   - Danger
16. Indicate judgement

**Fig. 4 Evaluation flow chart**
(d) How to evaluate a structure as elastic

If a structure is elastic during a main shock, the performance curve calculated using assumption c) can be considerably underestimated since the restoring force at the ultimate displacement can be less than the yielding strength. Therefore, it must be evaluated separately if a structure is elastic. The elastic-plastic evaluation method is shown in Fig. 3. Firstly, the approximate stiffness of the envelope curve for the performance curve is calculated. Secondly, the error between the envelope curve and the approximated line, \( \Delta S_d_{ij} \), is calculated. If the ratio of the maximum value of, \( \Delta S_d_{ij} \), to the maximum response, \( S_d_{max} \), is less than a given tolerance, then it is judged as elastic. In this study, a 5% tolerance is applied.

The evaluation flowchart is shown in

Fig.4. The response of a building and an input earthquake motion are measured by accelerometers, and the residual seismic capacity, i.e. the magnitude of aftershock that can be sustained by the building, is calculated from these measured accelerations. The safety level against an aftershock can be obtained just soon after a main shock. This system has a computer application, which can perform the following:

(a) A double integration of the measured accelerations to calculate the response displacements.
(b) Calculation of the base-shear coefficient and the representative displacement of the building with an assumed mode shape. (items 7 & 8 in
(c) Fig.4)
(d) Drawing of the performance curve of the structure. (item 9 in
(e) Fig.4)
(f) Drawing of the envelope curve of the performance curve. (item 10 in
(g) Fig.4)
(h) Calculation of the response spectrum of the measured acceleration on the basement, and hence calculate the demand curve. (item 14 in
(i) Fig.4)
(j) Evaluation of the residual seismic capacity of the building by means of the performance and demand curves.

Items 3, 6, and 11 in

Fig.4 must be defined prior to any evaluation. Item 3 (vibration mode shape) is used to calculate the response accelerations on the floors where there are no accelerometers. For example, a linear or a constant distribution shape between measured floors can be applied. The item 6 (mass ratio) can be calculated from floor area ratio between each floor. At present, item 11, (ultimate displacement), can be defined from the corresponding adopted building code. However, in the future the ultimate displacement measurement can be carried out by placing a health-monitoring system.

3. The Shaking Table Test Result

The results of the evaluation system and the integral method were compared with the shaking table tests carried out by Dr. Kumasawa to confirm their validities. The integrated displacements were compared with the proposed method whilst the calculated performance curve and the integrated displacements compared with the test results.

3.1 Outline of the Shaking Table Test

A half scale structure was used in the shaking table test. Rigid slabs made of reinforced concrete provided the inertia forces on the shaking table. The floor mass was 76.9kN for the first floor and 78.0kN for the second floor. The variable factor of this experimental test was eccentricity. Accordingly, two of the four columns were located closer to the centre of the slab than the others to provide mass eccentricity as shown in Fig. 5. The test results of the specimen without eccentricity were studied in this paper.
H-Shaped steel was used for the columns (\( H = 125 \times 125 \times 6.5 \times 9 \) for the first floor and \( H = 100 \times 10 \times 6 \times 8 \) for the second floor). The length of the column between top and bottom base plates was 1,500 mm. Story shear coefficient for the first story is 1.43 and 1.85 for the second story. The natural period of the structure was 0.26 sec.

North-South component of JMA (Japan Meteorological agency) KOBEnorth recorded at the Hyogo-Ken-Nambu earthquake in 1995 was used as the input motion. As mentioned above, the time axis was scaled to 1/2. The input wave and its response acceleration spectrum are shown in Fig. 6. Five different PGA values of 200, 450, 900, 1640 and 2400 gal were used as input in order of sequence representing actual size of 100, 225, 400, 820 and 1200 gal respectively. The result for an input 2400 gal input was reported in this paper.

The locations of sensors for measuring the accelerations and displacements were illustrated in Fig. 5. The displacements of each floor and basement were measured from outside of the shaking table. The response accelerations on each floor and the table were measured with accelerometers. The accelerometer has a rated flow of 5V and a measurable frequency characteristic of 100 Hz. The time increment for measurement was 0.005 sec.

![Fig. 5 Setup and measuring equipment](image)

![Fig. 6 Input motion](image)

### 3.2 Residual Seismic Capacity Evaluation

The residual seismic capacity evaluation of the proposed method was undertaken using the shaking table test results. The measured acceleration of the basement, 2nd floor, and roof floor were used. The ultimate deformation angle of each floor was assumed as 1/50. The ultimate displacement was calculated as 31.4 mm, since the height of each column was 1,570 mm.

The comparison of measured and integrated displacements of the top floor is shown in Fig. 7. It can be seen from these figures that the integrated displacements on the roof floor correlates well with the measured displacements. The calculated residual displacements using the proposed integral method also agreed well with the measured residual values. Generally, it is very difficult to calculate an accurate residual displacement from measured acceleration. However, the difference of the two residual displacements can have no effect on the evaluation result, since the latter is carried out with the performance envelope curve.
The envelope of each performance curve calculated using the integrated and measured displacements is shown in Fig. 8. The envelope curve can be identified by selecting the Sd maximum steps of the performance curve. The envelope of the performance curve calculated with the integrated displacements agreed very well with the measured envelope curve.

The demand curve with the damping coefficient of 5% was superimposed on Fig. 8. As the ultimate performance was less than the required demand capacity, this structure was regarded as UNSAFE. The safety ratio, which can be defined as the ratio of the representative restoring force (Sap) to that of the demand curve (Ssd) for the same equivalent natural period, was only 0.32. The safety ratio of 0.32 implies that the structure can resist an aftershock of PGA equivalent to 2400gal×0.32=768gal. Since the inter-story drift in the 2nd story at 4.2 sec was greater than the assumed ultimate displacement, therefore, the UNSAFE evaluation can be regarded reasonable.

![Fig. 7 Comparison of the response displacements (Roof floor)](image1)

![Fig. 8 Envelopes of the performance curves and the demand curve](image2)

**Concluding Remarks**

In order to develop the real-time residual seismic capacity evaluation system for improving safety against an aftershock, the problem and the solution of the integral method, and the evaluation results with existing shaking table results, were proposed. The investigation provides an alternative method of evaluating aftershock damages using simple techniques. Existing methods which were used to validate the results indicate some correlations thus illustrating the validity of the method, in giving a better understanding of the aftershock performance.

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