DAMAGE DETECTION OF REINFORCED CONCRETE STRUCTURE BASED ON LIMITED STRONG MOTION RECORDS

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ABSTRACT

The author presents one simplified technique and methodology for structural parameter identification and global damage detection from limited number of strong motion records. The time-invariant and time-varying parameters of structure are identified by using the off-line system identification method ARX and the on-line system identification method RARX respectively. The presence of damage is detected primarily by checking the changes of parameters during the earthquakes. Then, one procedure is introduced to convert MDOF structural system to equivalent SDOF system. The integral damage level of the equivalent SDOF system is detected by using the ductility factor and damage index. The damage index of the equivalent SDOF system can be considered as the integral damage level indicator of the MDOF system. The method is applied to Hachinohe City Hall building which was lightly damage in the Sanriku-oki Earthquake on Dec. 28, 1994. The parameters of the building are identified and the damage level is detected from the strong motion records. The results show that the method has with high efficiency, validity, applicability and practicability. The method can be implemented to assess the structural damage level and to judge if the damage is repairable or not after a big earthquake. Furthermore, the method can be used to predict the failure of a whole structure and to evaluate the performance in earthquake. The presented technique and method can be considered as a significant aid for making structural retrofitting decision after devastating earthquake.

Keywords: Strong motion record, Damage detection, System identification.

INTRODUCTION

The structural damage detection aims to detect, localize and classify damage of structures and also to predict and assess the safety and remaining service life of structures. Many kinds of techniques and methods have been developed and applied for the purpose in the past decades (Doebling, 1996; Sohn, 2003; Farrar, 2007). In fact, the damage is not meaningful without comparison between undamaged state and damaged state. That means the structural parameters before and after damage are critical information for damage detection. Determining the dynamic properties of a structural system from the response data is well known as system identification, and many kinds of methods have also been developed. Generally speaking, the damage detection is related to or based on the structural parameter identification at a certain extent. To monitor the structural response and performance during earthquakes, strong motion seismographs are installed in many buildings. The response data recorded by the strong motion observation system during earthquakes can be used to determine the structural parameters and damage state (Loh, et al, 1996, 2000). It is very important to judge damage level after earthquake especially for the buildings slightly or moderately damaged, but sometimes it is difficult to check the damage by visual inspection since the structural members are covered with finishing materials. In such case, it has remarkable meaning to detect the damage and determine the damage level by using the strong motion records. Such kind of post-earthquake damage assessment and

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damage detection has significant life-safety implication, because it helps to determine whether the building is safe enough for reoccupation. Furthermore, it has great meaning to judge if the building can be repaired and reoccupied from the economy issues. According to the analysis stated above, the author presents simplified methods to identify the parameters and diagnose the damage level after huge earthquake from the limited strong motion records.

METHODOLOGY

System Identification

Two system identification methods are used to obtain the structural parameters. One is the off-line ARX (Auto-Regression with eXogenous) method for time-invariant parameters, the other is RARX (Recursive ARX) method for the time-varying parameters. The ARX model can be denoted as:

$$y(t)=\varphi^{\mathrm{T}}(t)\theta+e(t) \tag{1}$$

where θ is the vector including unknown system parameters; $\varphi(t)$ is the vector including input and output samples. The solution of Eq. (1) can be estimated by the following Eq. (2) (Ljung, 1999):

$$\hat{\theta}_N=\left[\sum_{t=1}^{N}\varphi(t)\varphi^{\mathrm{T}}(t)\right]^{-1}\sum_{t=1}^{N}\varphi(t)y(t) \tag{2}$$

The modal parameters can be calculated once the system parameters are obtained as shown below:

$$\omega_r=\frac{1}{\Delta t}\sqrt{\ln Z_r\ln Z_r^*}\ ,\quad \xi_r=\frac{-\ln(Z_rZ_r^*)}{2\sqrt{\ln Z_r\ln Z_r^*}} \tag{3}$$

where (Z_r,Z_r^*) is the r-th discrete complex conjugate eigenvalue pair and Δt is the sampling period. ω_r and ξ_r are the r-order modal frequency and damping ratio respectively.

To track changes of structural parameters during the vibration, RARX method is used to identify the time-varying parameters. RARX is a system algorithm to estimate recursively parameters of ARX model in Eq. (1) by using RLS method. The solution can be estimated as following (Ljung, 1999):

$$\hat{\theta}(t)=\hat{\theta}(t-1)+P(t)\varphi(t)\varepsilon(t) \tag{4}$$

$$\varepsilon(t)=y(t)-\varphi^{\mathrm{T}}(t)\hat{\theta}(t-1) \tag{5}$$

$$P(t)=\frac{1}{\lambda}\left(P(t-1)-\frac{P(t-1)\varphi(t)\varphi^{T}(t)P(t-1)}{\lambda+\varphi^{T}(t)P(t-1)\varphi(t)}\right) \tag{6}$$

Then the equivalent stiffness K_{eq} can be calculated by using the following Eq. (7):

$$K_{eq}=\frac{4\pi^2M}{T^2} \tag{7}$$

where, M is the total mass of the structure or system; T is the fundamental period of the structure.

MDOF System to Equivalent SDOF System

To estimate global damage index of structures under the excitation of earthquake based on the limited strong motion response records, the MDOF system is converted to equivalent SDOF system. The total mass M is assumed as the equivalent mass M_{e} of the SDOF system as shown in Eq. (8):

$$M_e=\sum_{i=1}^{N}m_i \tag{8}$$

where m_{i} is the mass of the i-th story of MDOF system. Then the distribution of the earthquake shear force of the MDOF system is assumed as the following Eq. (9) (AIJ code):

$$A_i=1+\left(\frac{1}{\sqrt{\alpha_i}}-\alpha_i\right)\frac{2T}{1+3T} \tag{9}$$

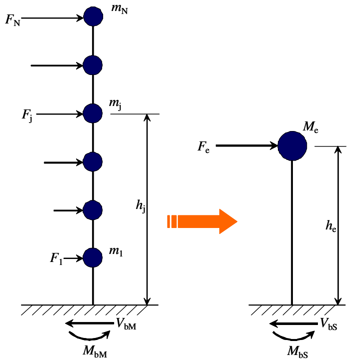


Figure 1. Equivalent SDOF system of MDOF system

where the α_i is the normalized weight of the i-th story, which is calculated as the weight above i-th story divided by the weight above ground. T is the natural period. If the response data on roof is recorded, the earthquake force on the i-th story can be estimated by the following Eq. (10):

$$F_N = m_N a_{N\max}\,,\ \ F_i = \frac{A_i}{A_N} F_N \qquad i = 1,2\cdots N \tag{10}$$

where m_N is the mass of top story and $a_{N\max}$ is the maximum acceleration on the top. From $V_{\mathrm{bS}} = V_{\mathrm{bM}}$, the a_{Smax} of the SDOF system under the same excitation can be estimated by Eq. (11):

$$a_{\mathrm{Smax}} = F_{\mathrm{e}} / M_{\mathrm{e}} = \sum_{i=1}^{N} F_i / M_e \tag{11}$$

Ductility Factor and Damage Index Calculation

The structural damage can be described by the ductility factor and hysteretic energy dispersed by the building in earthquake. Herein, the ductility factor is estimated from the nonlinear response spectra for damage detection purpose. The concept is if we have the properties of the SDOF system, such as period, damping and ductility factor, we can find out the maximum response from the response spectra. On the contrary, the ductility factor can be determined from the constant ductility nonlinear response spectra if the maximum response of the SDOF is known.

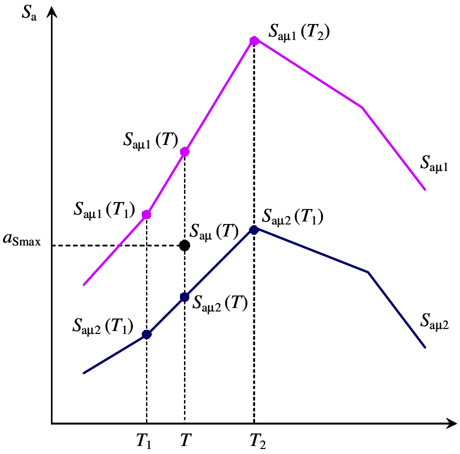


Figure 2. Interpolation relationship

The relationship between the equal ductility response spectra and maximum response of the SDOF system can be expatiated by Figure 2 from which the ductility factor can be obtained if the response spectra $S_{\mathrm{a\mu1}}$ and $S_{\mathrm{a\mu2}}$ of the strong motion record at base are known. From Figure 2, we can have the following calculations:

$$S_{\mathrm{a\mu1}}(T) = S_{\mathrm{a\mu1}}(T_1) + \frac{T - T_1}{T_2 - T_1}\left(S_{\mathrm{a\mu1}}(T_2) - S_{\mathrm{a\mu1}}(T_1)\right) \tag{12}$$

$$S_{\mathrm{a\mu2}}(T) = S_{\mathrm{a\mu2}}(T_1) + \frac{T - T_1}{T_2 - T_1}\left(S_{\mathrm{a\mu2}}(T_2) - S_{\mathrm{a\mu2}}(T_1)\right) \tag{13}$$

The ductility factor of the SDOF system can be approximately estimated by Eq. (14) from a_{Smax}.

$$\mu = \mu_1 + \frac{S_{\mathrm{a\mu1}}(T) - S_{\mathrm{a\mu}}(T)}{S_{\mathrm{a\mu1}}(T) - S_{\mathrm{a\mu2}}(T)}(\mu_2 - \mu_1) = \mu_1 + \frac{S_{\mathrm{a\mu1}}(T) - a_{\mathrm{Smax}}}{S_{\mathrm{a\mu1}}(T) - S_{\mathrm{a\mu2}}(T)}(\mu_2 - \mu_1) \tag{14}$$

A hybrid damage index of combination of ductility and hysteretic energy is adopted to predict integral damage level and the damage index is calculated by using the Bispec software (Hachem, 2002, 2008).

PARAMETER IDENTIFICATION AND DAMAGE DETECTION

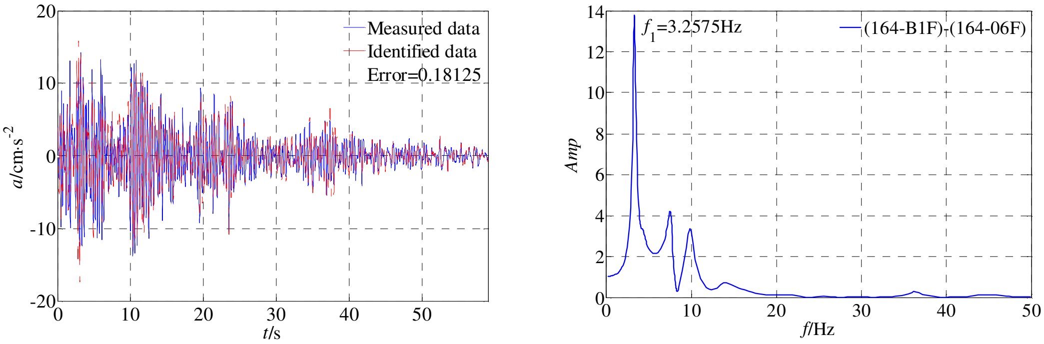
Hachinohe City Hall Building

The Hachinohe City Hall building (Figure 3) is used as the example to determine the parameters and damage level from the strong motion records. The building is a 5-story with one story basement, and RC type structure is adopted for bearing system. The building was damaged by Sanriku-oki Earthquake on Dec. 28, 1994 (denoted by EQ2). The response data were obtained in the earthquake and its aftershock (denote by EQ3). Before EQ2, the response data was recorded in one small earthquake (denoted by EQ1) on Oct. 9, 1994.

Figure 3. Hachinohe City Hall (Photograph by T. Kashima)

Time-invariant Parameters

Just for example, the time-invariant parameters in 164° direction identified from the data in EQ1 are shown in Figure 4. All the identification results are shown in Table 1 in which the parameters in both directions are also compared. From Table 1 we can see, the structural natural frequency and equivalent stiffness decreased but the damping ratios increased after the EQ2. The reduction degree of the parameters is shown in Figure 5. It can be concluded that the building was damaged by the EQ2.



(a) Comparison of measured and identified data (b) Transfer function between base and roof

Figure 4. ARX Identification results from EQ1 data

Time-varying Parameters

The presence of damage can be detected by comparison of the parameters in 2 small events before and after the big earthquake. However, we don't know when the damage occurred and how is the damage level. Even we don't know damage occurred during the big earthquake if we don't have small earthquake response data before the big earthquake for comparison. For damage detection by only using strong motion records from one earthquake, the on-line RARX method is used to detect the accurate damage time and the decline trend during the earthquake. The time-varying parameters of 254° direction in EQ2 are shown in Figure 6. From which we can see the natural frequency decreased gradually until arrived at the lowest level, then, it was a little bit recovered at the tail part of the strong motion records but not reach the original value. That means the building was definitely damaged by the earthquake. The decrease of the frequency indicates the damage process during the big earthquake.

Table 1. Identified parameters from data in the 3 earthquakes

Earthquake	f (Hz)		ξ (%)		K_{eq}(10^9N/m)	
	254°	164°	254°	164°	254°	164°
(a) EQ1	3.25	3.26	2.72	4.87	4.11	4.14
(b) EQ2	2.64	2.78	3.83	6.26	2.71	3.01
(c) EQ3	2.66	2.78	2.96	4.88	2.75	3.01
(b-a)/a(%)	-18.77	-14.72	+40.81	+28.54	-34.06	-27.29
(c-a)/a(%)	-18.15	-14.72	+8.82	+0.21	-33.09	-27.29

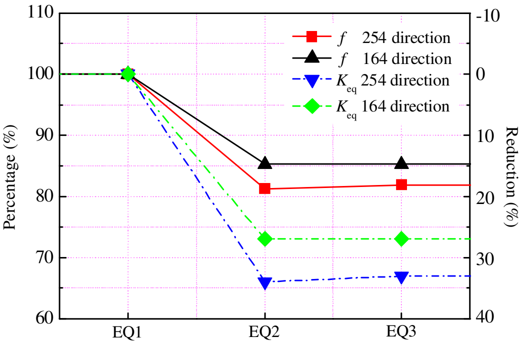
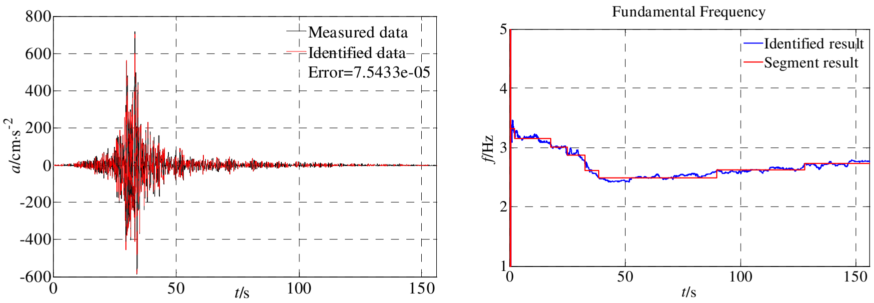


Figure 5. Variation of f and K_{eq}

Furthermore, it can be concluded that the building started to be damaged at around 20s and stopped at around 38s from the variation of the parameters. From the above analysis, we can know that by using on-line RARX method, the damage can be detected by only using strong motion



(a) Comparison (b) Time-varying frequency

Figure 6. RARX Identification results from EQ2 data (254°)

records from one earthquake. The RARX method has good qualities to detect the changes of the parameters in big earthquakes, and the parameters of the original state (undamaged) of the structure can also be determined for comparison purpose. It can be concluded the presence of damage can also be detected primarily by only using strong motion data from one earthquake.

Ductility Factor Estimation and Damage Detection

The strong motion data in 164° direction is used as the example to show the ductility factor estimation and damage detection. The building is converted to equivalent SDOF system as shown in Table 2 from which we can see the natural period is 0.3067s which is from the identification results and the peak value of the acceleration of the SDOF system is 586.44cm/s^2 which is used to calculate the ductility factor from the nonlinear equal ductility response spectra, and the equivalent height is 13.5m.

Table 2. Parameters of the equivalent SDOF system for Hachinohe City Hall (164°)

story	M_i(t)	$\sum_{j=i}^{N} M_j$ (t)	α_i	T(s)	A_i	PA(cm/s^2)	F_i(kN)	h_i(m)
1	2141	9862	1.00	0.3067	1.000	/	8.78E+03	4.50
2	2488	7721	0.78	0.3067	1.111	/	9.76E+03	3.95
3	2070	5233	0.53	0.3067	1.269	/	1.11E+04	3.95
4	1572	3163	0.32	0.3067	1.462	/	1.28E+04	3.95
5	1591	1591	0.16	0.3067	1.744	962.60	1.53E+04	3.95
SDOF	**9862**	**/**	**/**	**0.3067**	**/**	**586.44**	**5.78E+04**	**13.5**

The nonlinear response spectra of the record at the base of the building with different ductility factors and with 5% damping ratio are shown in the Figure 7. The damping factor is adopted from the identification results from EQ1 in Table 1. According to the T=0.3067s and the maximum acceleration PA=586.44cm/s^2 of the SDOF system, the ductility factor can be calculated from the equal ductility spectra by using the interpolation method as shown in Table 3 from which we can know the ductility factor of the equivalent SDOF system of Hachinohe City Hall is 1.85. The ductility factor can be considered as the average ductility level of the building in Sanriku-oki Earthquake on Dec. 28, 1994.

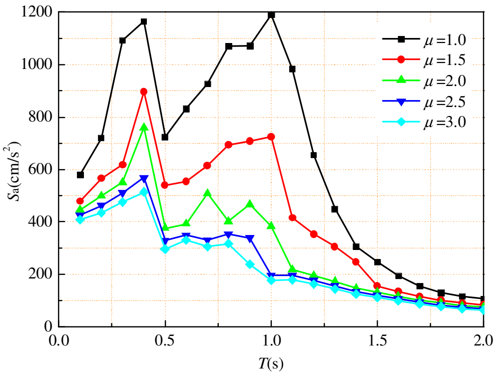


Figure 7. Equal ductility response spectra of base record 164° ($\xi = 5\%$)

Table 3. Ductility factor estimation in 164° direction

	T_1	T_2	T	μ
T	0.30	0.40	0.3067	/
$S_{a\mu 1}$	617.57	896.76	636.41	1.50
$S_{a\mu 2}$	550.17	759.24	564.28	2.00
$S_{a\mu}$	/	/	586.44	**1.85**

Table 4. Damage index in 164° direction

	T_1	T_2	T	μ
T	0.30	0.40	0.3067	/
$DI_{\mu 1}$	0.0962	0.0555	0.093	1.50
$DI_{\mu 2}$	0.1588	0.111	0.156	2.00
DI_{μ}	/	/	***0.137***	**1.85**

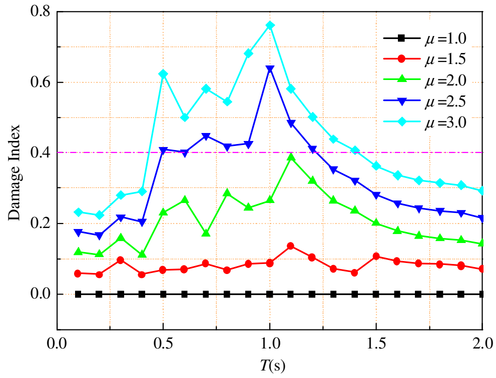


Figure 8. Damage index of base record 164° ($\xi = 5\%$)

The damage index spectra calculated from the base record (164°) are shown in Figure 8 from which the damage index of the system can be estimated according to the fundamental period T, damping ratio ξ and the ductility factor μ obtained in Table 3. The calculation result is shown in Table 4 from which we can see the damage index of equivalent SDOF system is 0.137. By using the same procedure, the damaged index in 254° direction is 0.083. Considering the real circumstance, for the same building, the maximum damage index in both directions should be adopted to describe the damage level. From this concept, the damage index of the building is 0.137. According to study of Valles, et al (1996), the damage index 0.137 means the damage of the building is slight and the damage is repairable for reoccupation after the earthquake.

By using same procedure and methodology, the damage of one 9-story RC building, Department of the Architecture and Building Science of Tohoku University which was damaged in Miyagi-ken Earthquake (Sep. 15, 1998), is detected. It is found that the damage index is 0.282 in the earthquake, which means the building is moderately damaged by the earthquake and the damage is repairable.

From the example, it can be concluded that the structural damage caused by the earthquake can be detected and assessed only by using the strong motion records on the roof and at the bottom of the structure through implementing the procedure and methodology presented in the study.

CONCLUSIONS

The author presented one method to identify parameters and detect damage level of RC buildings by using strong motion records at the top and the bottom. The parameters of Hachinohe City Hall building are identified and damage level is detected. Some conclusions are summarized as follows:

1) The time-invariant and time-varying structural parameters including modal frequency, damping ratio and equivalent stiffness can be determined from the strong motion records by using the off-line ARX and on-line RARX system identification models. The changes of the parameters, such as decreasing of the frequency and reduction of the equivalent stiffness, can be used to find out the presence of damage with the structure.

2) The MDOF structural system can be converted to equivalent SDOF system for damage detection purpose. The ductility factor and damage index can be obtained by using the interpolation method from the constant ductility nonlinear response spectra and damage index spectra.

3) The ductility factor of the equivalent SDOF system can be considered as the average ductility level of structure, and damage index of the equivalent SDOF system can be considered as integral damage level indicator of the building.

4) The damage index of structure in the study is defined as the global damage indicator and can be used to predict damage state or the failure of a whole structure after earthquake.

5) The method presented in the study can be implemented for structural performance evaluation and for decision making of repair and continuous use of the instrumented buildings after devastating earthquakes.

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REFERENCES

Doebling, S. W., et al, 1996, Los Alamos National Laboratory report, LA-13070-MS.
Farrar, C. R., and Lieven, N. A. J., 2007, Phil. Trans. R. Soc. A 365, 623-632.
Hachem, M. M., 2002, Doctoral Thesis, University of California, Berkeley, USA.
Hachem, M. M., 2008, http://www. ce.berkeley.edu/~hachem /bispec/index.html.
Ljung, L., 1999, PTR Prentice Hall, Upper Saddle River, N.J.
Loh, C. H., and Lin, H. M., 1996, Earthquake Engineering and Structural Dynamics, 25, 269-290.
Loh, C. H., Lin, C. Y., and Huang, C. C., 2000, Journal of Engineering Mechanics, 126(7), 693-703.
Sohn, H., et al., 2003, Los Alamos National Laboratory Report, LA-13976-MS.
Valles, R. E., Reinhorn, A. M., Kunnath, S. K., et al., 1996, NCEER-96-0010.