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DAMAGE DETECTION AND ESTIMATION OF BUILDINGS THROUGH MEASUREMENTS

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SUMMARY

In this paper, results of shaking table test using a three-story large-scale steel structure with cementitious devices are shown. Two types of identification are tried. One is identification using data under excitation and the other is identification using data of before and after the excitation. From identified results, natural frequency decreases, damping ratio increases and story stiffness decreases as experienced amplitude increases or input amplitude increases. A model using stick-slip elements is proposed. Natural frequency, damping ratio and story stiffness described by this model are consistent with experimental results. Damage estimation method using test results and stick-slip model is proposed.

INTRODUCTION

If we have to reduce life cycle costs of a building from construction to maintenance, it is very effective to monitor structural health of a building. Most buildings built during 1970's construction rush in Japan seem to rapidly deteriorate, and it is necessary to establish structural health estimation of these buildings. In 2002, performance certification mark system of existing housings is started in Japan, and structural performance will be displayed by visual inspection and structural design data, etc. However, in this performance evaluation, measurement such as acceleration is not carried out because of technical difficulties. The decisions from the inspection by experts according to manuals tend to be judged to safe side. It is important to carry out measurement to evaluate damages objectively and quantitatively. Damage detection and health monitoring method are classified into two methods. First one is based on vibration measurement, and the other is based on phenomena like cracking or fever. Each method has strong points and weak points. System identification based on vibration measurements is strong for damage detection of whole or story level and is weak for damage detection of specific portion such as structural members. On the other hand, damage detection based on phenomena is strong for damage of specific portion such as devices. By combining these two methods, it becomes possible to monitor structural health exactly, but system identification based on vibration measurement is suitable to estimate whole structural performance such as performance certification mark system. We had a damage detection test on shaking table of five-story steel frame with simulated damages sing accelerometers and smart sensors, as fiber optics, Morita [1]. Damage identification was carried out by the comparison between vibration characteristics before

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damage and vibration characteristics after damage, and it was confirmed that damage detection was possible in a whole building or story level. In this experiment, damage detection has been carried out by comparing sound test specimen and specimen with simulated damages (i) Removing studs from only one story, ii) Exchanging sound beam for damaged beam, iii) Extracting braces from only one story, iv) Cutting of part of column etc.), the process which damages actually occur was not included. In this paper, we show results of shaking table test using a three-story large-scale steel structure with cementitious devices. Cementitious devices are installed in the center frame of tested structure and devices are actually damaged during the shaking. We carry out more realistic damage detection test by damaging devices and we measure the process of damaging devices. We apply damage identification methods to these phenomena and try to identify the damaging.

OUTLINE OF TEST FRAME

The test frame is a three-story steel structure shown as Figure 1, Fukuda [2]. Dimension of test structure is shown as Table 1. Floor height is 1.8m, total height is 5.4m, floor plan is 4mx3m and there are two spans in excitation orthogonal direction. Cementitious system devices are installed in the center frame of tested structure at each story. We carry out excitation test, before cementitious devices are installed. First natural frequency is 1.83Hz, second natural frequency is 5.30Hz and third natural frequency is 7.89Hz.

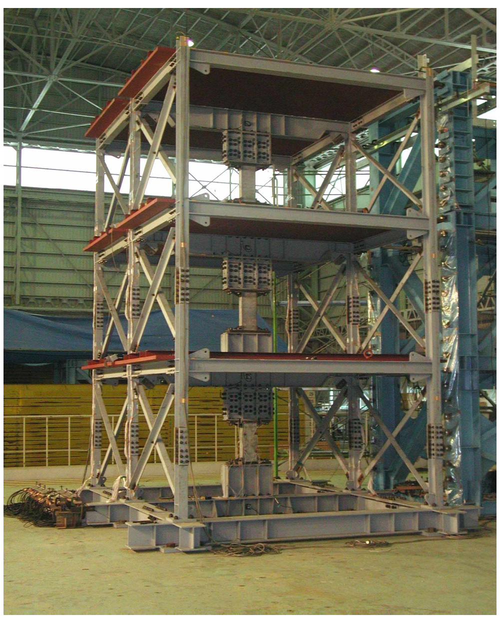

Figure 1. Exterior of test frame

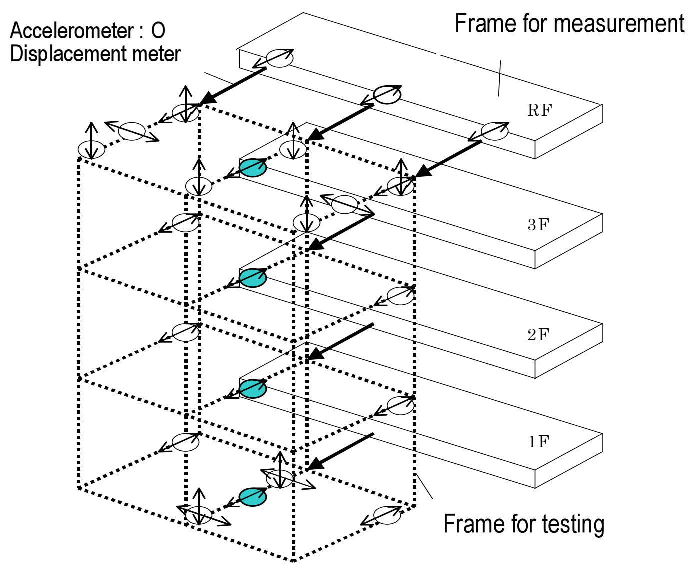

Figure 2. Installed accelerometers and displacement meters

Table1 : outline of test frame

floor height	1.8m
total height	5.4m
floor plan	3mx4m
column	H148x100x6/9
Beam(cross direction of shaking)	H148x100x6/9
Beam(edge beam of shaking d.)	H150x150x7/10
Beam(center beam of shaking d.)	H300x150x6.5/9
weight of floor	4000kg

Shaking table test is carried out at large-scale earthquake simulator facility of the National Research Institute for Earth Science and Disaster Prevention. The dimension of the shaking table is shown as Table2, excitation schedule is shown as Table3. Input waves of shaking are El Centro 1940 NS and BCJ-L 1(simulation wave Level 1 of Building Center of Japan), and input level in order to the maximum velocity is gradually raised to 60 cm/sec. Free vibration test using manpower, white noise excitation and microtremor observation are carried out before and after of damage in order to obtain vibration characteristics of before and after damage. Installed sensors are accelerometers, strain gauges and displacement meters. Sampling frequency is carried out at 2000Hz. RFID tag sensors, AE sensors and temperature sensors are also installed in order to detect the local damage of cracks or fever absorption directly. Accelerometers are installed at each story center in order to obtain vibration characteristics of the excitation direction. Strain gauges are installed at columns and beams of each story and displacement meters are installed at each story. Load-displacement relationships are estimated from these data. Installation schematic diagram of accelerometer and displacement meters is shown as Figure 2. When microtremor observation and free vibration test are carried out, hydraulic pressure source of shaking table is stopped.

Table2 : specifications of shaking table

table	15.0×14.5m
power output	3528kN (882kN×4)
max. load weight	500,000kg
max. displacement	±23cm
max velocity	90cm/sec
max. acceleration	490cm/sec^2(500,000kg) 921cm/sec^2(200,000kg)

Table3 : schedule of shaking

No.	Input wave	Target Level
1	BCJ wave	2.5cm/sec
2	El Centro 1940 NS	5cm/sec
3	El Centro 1940 NS	10cm/sec
4	El Centro 1940 NS	15cm/sec
5	BCJ wave	20cm/sec
6	El Centro 1940 NS	30cm/sec
7	El Centro 1940 NS	40cm/sec
8	El Centro 1940 NS	50cm/sec
9	El Centro 1940 NS	60cm/sec

LOAD-DISPLACEMENT RELATIONSHIPS

Load-displacement hysteresises of first layer are shown at Figure 3. In this figure, the red line is Q (story-shearing force)-δ(relative story displacement) curve of the whole(frame + device) which calculated from mass and acceleration, the black line is Q - δ curve of the frame and the blue line is Q-δ curve of the device. The value, which deducted the story-shearing force of the frame from the whole, was estimated as that of the device. Cracks in devices are observed during El Centro 10cm/sec and main reinforcements yield during El Centro 30cm/sec. Strength of device rises after main reinforcement yielding by axial force rising.

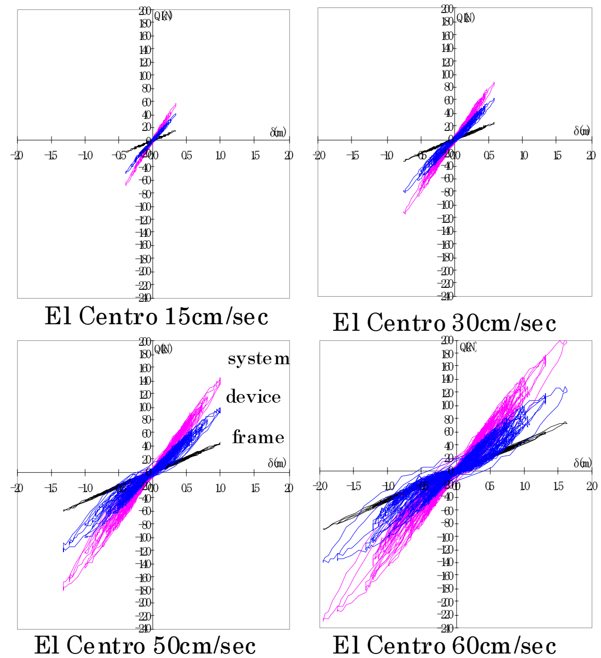

Figure 3. Displacement vs. load of 1st floor

DATA SETS AND IDENTIFICATION METHOD FOR DAMAGE IDENTIFICATION

Using the record of center accelerometers in excitation direction of each story, damage identification is carried out by use of the system identification technique. Only the accelerometers of halftone dot meshing in Figure 2 are used. Two types of identification are tried. One is a) identification using the data under excitation and the other is b) identification using the data of before and after of the excitation. In case a), we assume that earthquake measurements are carried out. In case b), we assume that microtremor observations of a building before and after disaster are carried out. In both cases, we use identification method by ARX model, Los Alamos National Laboratory [3]

RESULTS OF DAMAGE IDENTIFICATION

Estimation of characteristics during excitation

ARX model structure is the simple linear difference equation as,

$$y(t) + a_1 y(t-1) + \ldots + a_{na} y(t-na) = b_1 u(t-nk) + \ldots + b_{nb} u(t-nk-nb+1) \qquad \ldots(1)$$

which relates the current output y(t) to a finite number of past outputs y(t-k) and inputs u(t-k). The structure is thus entirely defined by the three integers na, nb, and nk. na is equal to the number of poles and nb-1 is the number of zeros, while nk is the pure time-delay (the dead-time) in the system. From this model structure, the coefficients *aj* and *bj* are estimated.

If A and B are expressed as,

$$A(q) = 1 + \sum_{j=1}^{n_a} a_j q^{-j} \qquad \ldots(2)$$

$$B(q) = \sum_{j=1}^{n_b} b_j q^{-j+1-n_k} \qquad \ldots(3)$$

${}_z p_j$ is root of A(z)=0 and ${}_z r_j$ is residue of a partial fraction expansion of *B(z)/A(z)*.

Natural frequency f_j damping ratio h_j and participation function βu_j are expressed as following:

$$f_j = \frac{\sqrt{(\log|{}_z p_j|)^2 + (\arg{}_z p_j)^2}}{2\pi\Delta t} \qquad \ldots(4)$$

$$h_j = \frac{-\log|{}_z p_j|}{2\pi f_j \Delta t} \qquad \ldots(5)$$

$$\beta u_j = \Re\left[\frac{2\,{}_z r_j\sqrt{1-h_j^2}}{T(2\pi f_j h_j - i\,sign[\Im[{}_z p_j]]2\pi f_j(1-2h_j^2))}\right] \qquad \ldots(6)$$

Stiffness coefficient will be estimated by these coefficients and mass.

The measured Stiffness matrix [K] is estimated from the mass-normalized measured mode shapes $[\Phi]$ ($[\Phi]^T[M][\Phi]=[I]$) and frequencies $[\Lambda]$ as :

$$[K] \cong ([\Phi][\Lambda]^{-1}[\Phi]^T)^{-1} \qquad \ldots(7)$$

Story stiffness will be estimated from [K] multiplying a displacement vector, in which each relative story displacement is 1, from right.

Natural frequency, damping ratio, participation function and story stiffness identified by these method are shown as Figure 4. When model numbers change as na=10 to 64(even number),nb=na+1, nk=0, we select the numbers in which AIC is estimated as minimum. Recorded data for identification are divided for 5-second length waves in applying ARX method.

Shown as Figure 4, first natural frequency is constant during shaking and first natural frequency will increase after shaking. It is because maximum input acceleration appears at about 4 second and first-step-identified frequency is already small. Damping ratio also decreases after shaking. Identified story stiffness is not stable during shaking, but stiffness is stable after shaking. Identified stiffness is 20 –30 % larger than that calculated by Q-δ curve.

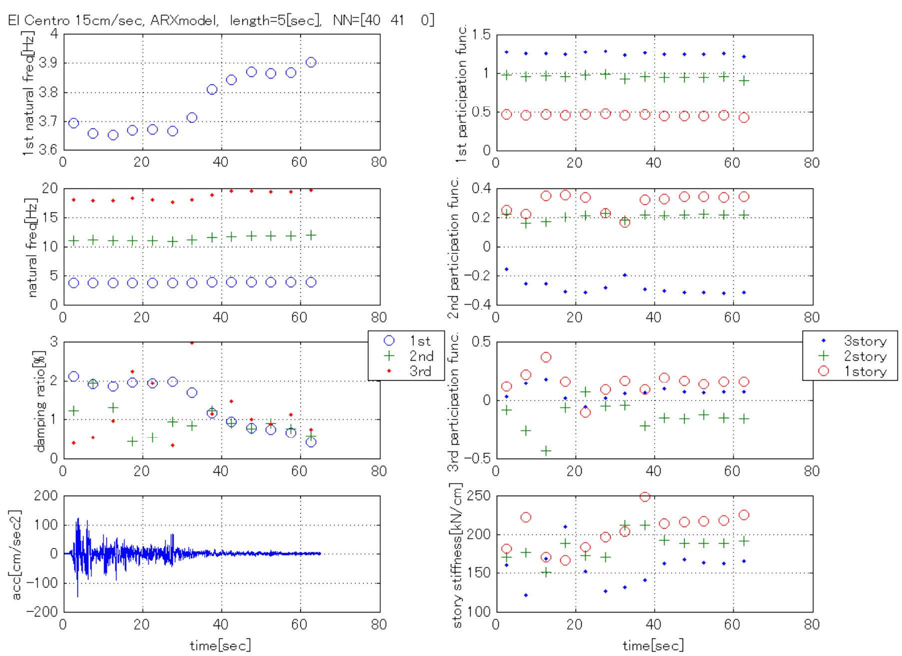

Figure 4. Change of identified characteristics of structure during El Centro 15cm/sec

Estimation of characteristics before and after excitation

Between shakings scheduled as Table 3, we carry out both white noise shaking test and microtremor observation. Using white noise shaking and microtremor data, same method as previous section is applied. We apply identification by ARX model and model numbers are same as previous section. The duration of microtrimor observation is 30 min. with the sampling interval at 0.005 sec, and the duration of white noise shaking is 65 sec with the sampling interval at 0.005 sec.

Maximum acceleration of input of mirotremor observation is much less than 1.0[cm/sec^2] and maxi-mum acceleration of white noise is about 20.0[cm/sec^2]. Natural frequency, damping ratio and story stiffness identified by ARX model are shown as Figure 5.

Damping ratio will increase as experienced maximum velocity increases. In other words, damping ratio will increase as damages occur. First and second damping ratio by white noise are about 5 times larger than those by white noise because of amplitude dependence. White noise amplitude is over 20 times larger than microtremor amplitude. First and second story stiffness by microtremor have same tendency as those by white noise. Third story stiffness by microtremor is 20 – 30 % larger than that by white noise. Almost all characteristics by microtremor can be estimated to be same as those by white noise.

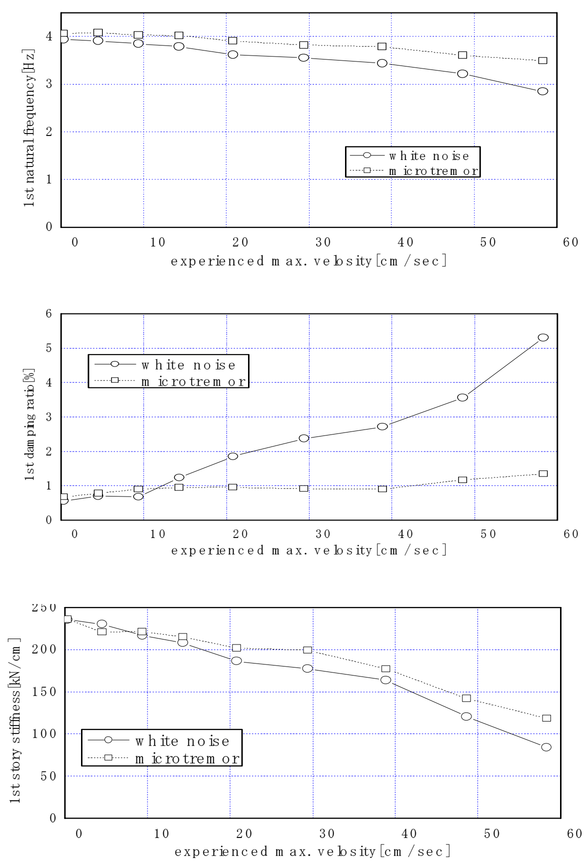

Figure 5. Parameters change according to experienced max. velocity

MODELLING OF CHARACTERISTICS

From Figure 4, natural frequency increases as input amplitude decreases. Damping ratio decreases as input amplitude decreases. Story stiffness decreases as input amplitude decreases. From Figure 5, natural frequency decreases, damping ratio increases and story stiffness decreases as experienced amplitude increases. Examples of fitting of test results are shown as Figure 6. Test results can be expressed by regression curve using power function. The ‘stick-slip’ model proposed by A. G. Davemport et al. (1986)[4][5], which can explain the tendency of damping, can be expanded to a model applicable to these results.

In 'stick-slip' model shown as Figure 7, the energy loss per cycle ΔE is

$$\Delta E = 4f(X - X_0) \quad \text{...(8)}$$

where *f* is the friction force and $X_0 (= f / k)$ is the amplitude at which slipping starts.

If there are a large number of such 'stick-slip' elements, as Figure 8, the hysteresis energy depends on the number density of stick-slip elements given as $n_{f,X_0}(f, X_0, X_{e\max})$. The total energy loss ΔE is then expressed as

$$\Delta E = \int_0^X \int_0^\infty 4 n_{f,X_0}(f, X_0, X_{e\max}) f (X - X_0) df dX_0 \quad \text{...(9)}$$

where $X_{e\max}$ is experienced maximum amplitude. Since X_0 and *f* are independent, the number density of elements can be written $n_{X_0}(X_0, X) p_f(f)$, where $p_f(f)$ is probability density of the friction force *f*. Then

$$\Delta E = 4\int_0^X (X - X_0) n_{X_0}(X_0, X_{e\max}) dX_0 \int_0^\infty p_f(f) f df = 4\bar{f} \int_0^X N_X(X, X_{e\max}) dX \quad \text{...(10)}$$

where $\bar{f}$ is the mean value of maximum friction force of each element and

$$N_X(X, X_{e\max}) = \int_0^X n_X(X, X_{e\max}) dX \quad \text{...(11)}$$

is the number of 'stick-slip' elements which are slipping when experienced maximum amplitude is $X_{e\max}$ and amplitude is X.

If

$$n_X(X, X_{e\max}) = n_0 X^\alpha X_{e\max}^{\alpha'} \quad \text{...(12)}$$

then

$$\Delta E = \frac{4\bar{f} n_0 X^{\alpha+2}}{(\alpha+1)(\alpha+2)} X_{e\max}^{\alpha'} \quad \text{...(13)}$$

So

$$h(X, X_{e\max}) = \frac{2}{\pi} \frac{\bar{f} n_0}{K(\alpha+1)(\alpha+2)} X^\alpha X_{e\max}^{\alpha'} = A X^\alpha X_{e\max}^{\alpha'} \quad \text{...(14)}$$

This equation is consistent with results of experiments.

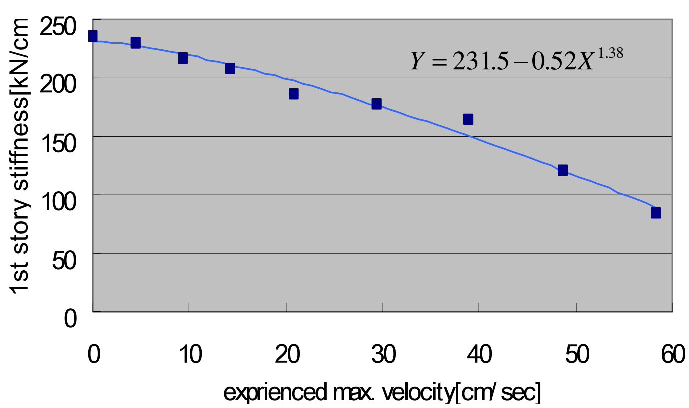

Figure 6. Fitting of changing story stiffness according to experienced max. velocity

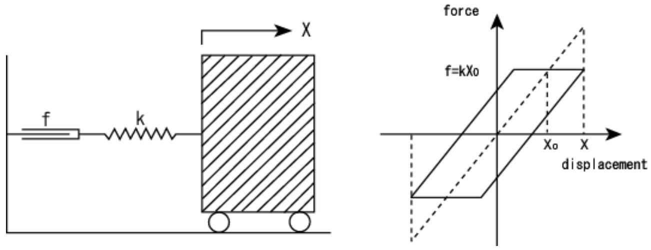

Figure 7. Stick-slip element

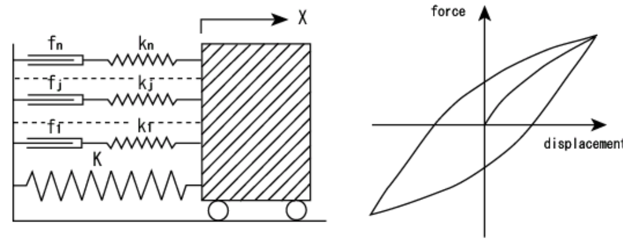

Figure 8. Multi stick-slip elements

From relationship of stiffness and shear force $K(X, X_{e\max}) = Q / X$, if initial stiffness is expressed as K_0

$$Q(X,X_{e\max}) = K_0 X - X\int_0^\infty p_f(f)kdf\int_0^X N_X(X,X_{e\max})dX + \int_0^\infty p_f(f)fdf\int_0^X N_X(X,X_{e\max})dX \quad \ldots(15)$$

Substituting equation (11) and (12) to equation (15)

$$Q(X,X_{e\max}) = K_0 X - \bar{k}\frac{n_0}{(\alpha+1)(\alpha+2)}X^{\alpha+3}X_{e\max}^{\alpha'} + \bar{f}\frac{n_0}{(\alpha+1)(\alpha+2)}X^{\alpha+2}X_{e\max}^{\alpha'} \quad \ldots(16)$$

where $\bar{k}$ is mean value of stiffness of each element . So

$$K(X, X_{e\max}) = K_0 - (\bar{k}X - \bar{f})\frac{n_0}{(\alpha+1)(\alpha+2)}X^{\alpha+1}X_{e\max}^{\alpha'} \quad \ldots(17)$$

Because of the relationship $\bar{k}X - \bar{f} > 0$, $K(X, X_{e\max})$ decreases with larger X and $X_{e\max}$. Then natural frequency $f_n(X, X_{e\max})$ is also increased with larger X and $X_{e\max}$. So these tendencies are also consistent with experimental results. Regression surface of 1st damping ratio can be calculated as Figure 9 using equation (14). White squares in the figure are experimental results and mesh is regression surface. Idetified damping values have some dispersion, but general tendency can be expressed by equattion (14). If we use the equation as:

$$K(X, X_{e\max}) = K_0 - BX^{\alpha+1}X_{e\max}^{\alpha'} \quad \ldots(18)$$

regression surface of 1st story stiffness can be calculated as Figure 10.

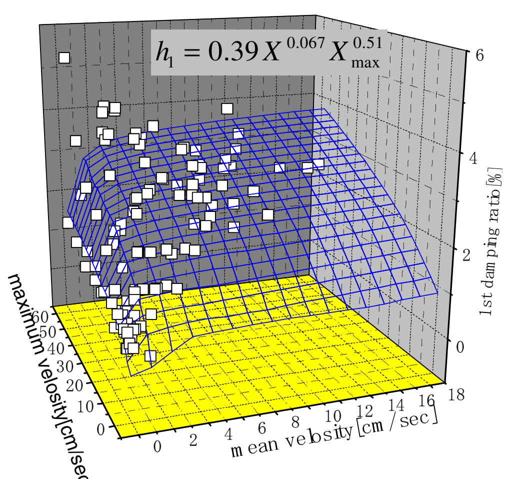

Figure 9. Fitting of 1st damping ratio

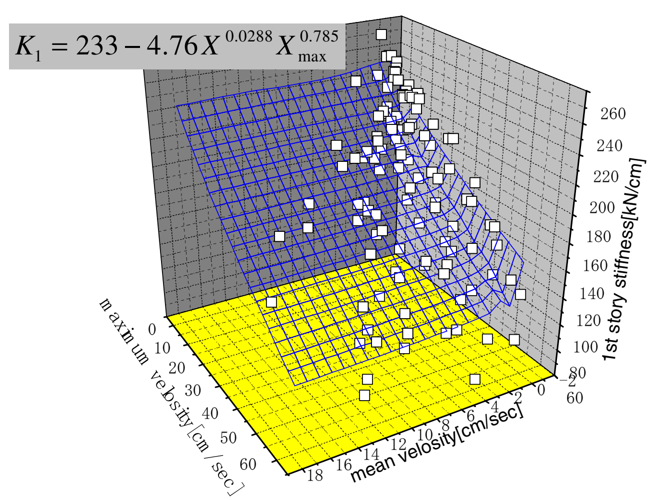

Figure 10. Fitting of 1st story stiffness

Small dispersion can be observed and it is well expressed by equation (18). The power coefficient α' of maximum amplitude X_{emax} is much larger than that α of amplitude X, that is, it depends on the value of the maximum amplitude. Response analysis, in which amplitude dependence are considered, will be possible, if coefficients in equation (14) and (18) are evaluated.

EVALUATION OF DAMAGES

By using the experimental results and regression equation, damage evaluation is tried here. Damage evaluation method using equation (18) is respectively shown on 1) case with seismic observation and microtremor observation just after earthquake and 2) case with microtremor observation before and after earthquake.

Evaluation using seismic observation and microtremor observation just after earthquake

In the case of the seismic observation, information about amplitudes such as maximum velocity can be obtained, so it is possible to obtain the regression equation shown as equation (18). Earthquakes are repeatedly observed after building completion, and from these data stiffness can be identified, and the regression equation shown in equation (18) is obtained. In equation (18), α +1 is very small, so it can be also expressed by

$$K(X, X_{e\max}) \fallingdotseq K_0 - BX_{e\max}^{\alpha'} \quad \ldots(19)$$

Almost same regression equation in equation (19) can be obtained in the case using all data (up to 60cm/s) and in the case using data up to 10cm/s shown as figure 11. These equations also tend to comparatively agree with the result of the microtremor measurement. From these results, regression equation in case of large earthquake can be estimated from regression equation in case of middle earthquake. As shown figure 12, maximum velocity can be expressed by the equation of maximum displacement as:

$$X_{e\max} = C\delta \quad \ldots(20)$$

where $X_{e\max}$ is maximum velocity and δ is maximum displacement. By using (eq.8.2), (eq.8.1) can be transformed as:

$$K = K_0 - BC^{\alpha'}\delta^{\alpha'} \quad \ldots(21)$$

By multiplying δ in both side, equation (21) is expressed as:

$$Q = K_0\delta - BC^{\alpha'}\delta^{\alpha'+1} = \frac{K_0}{C}(C\delta) - \frac{B}{C}(C\delta)^{\alpha'+1} \quad \ldots(22)$$

By multiplying $X_{e\max}$ in both side, equation (19) is expressed as:

$$KX_{e\max} = K_0 X_{e\max} - BX_{e\max}^{\alpha'+1} \quad \ldots(23)$$

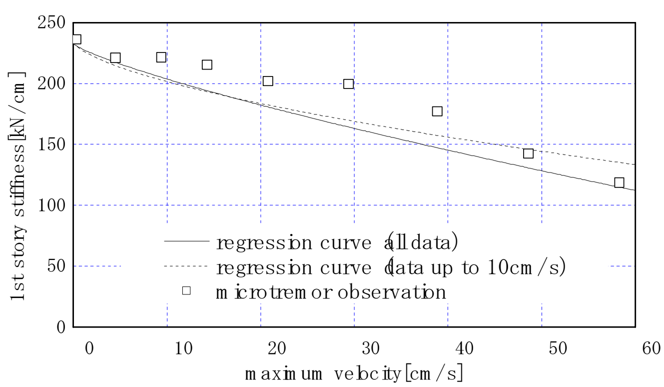

Figure 11. comparison of regression curves

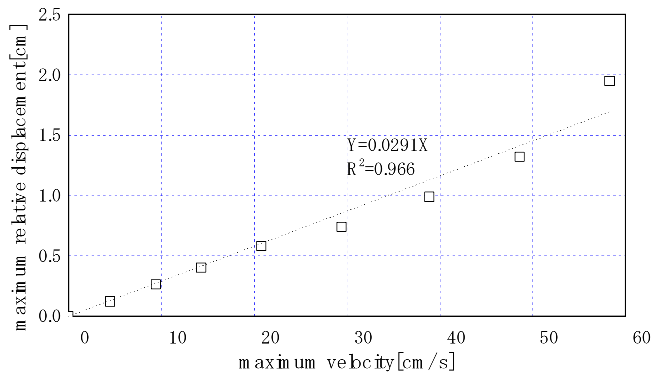

Figure 12. relationship between maximum velocity and maximum relative displacement

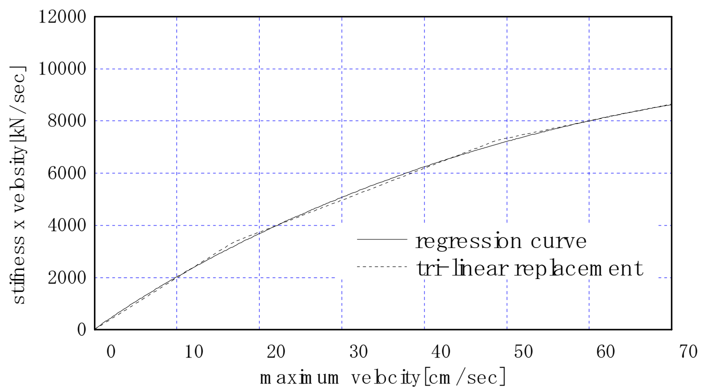

Figure 13. regression equation (23) and tri-linear replacement

Equation (22) has same figure as equation (23). Equation (22) can be considered as Q-δ relationship, so it is possible to replace tri-linear by using the curve equation (23). An example of tri-linear replacement is shown as figure 13.

Stiffness values (here, 199[kN/cm] and 149[kN/cm]) which correspond to break point in the tri-linear replacement are considered as thresholds. Story stiffness identified from microtremor observation just after earthquake can be compared with these thresholds, and the damage level is grasped.

Evaluation using microtremor observation before and after earthquake

In this evaluation, equation (19) is used. By carrying out microtremor observation just after building construction, initial story stiffness(K_{mic}) can be estimated. To determine B and α' in equation (19) , results of structural design can be applied. Fukuda A. et al.[2] shows the skeleton curve of this test frame with devises. Skeleton curve of 1st layer of this test structure are shown as Figure 14. Shear forces in Figure 14 can be transformed to story stiffness. Story stiffness from Figure 14 and story stiffness identified from microtremor observation are plotted in Figure 15 for comparison. From this figure, the value by push over analysis and the value identified from mirotremor are almost same. Regression curve obtained using results of push over analysis and initial stiffness identified from microtremor observation is shown as figure 16. From push over analysis, relative displacement where cracks occur or main reinforcements yield can be calculated, and corresponding stiffness (here, 218[kN/cm] and 166[kN/cm]) is considered as threshold. Story stiffness identified from microtremor observation just after earthquake can be compared with these thresholds, and the damage level is grasped.

Damage evaluation method are shown by the flow as figure 17.

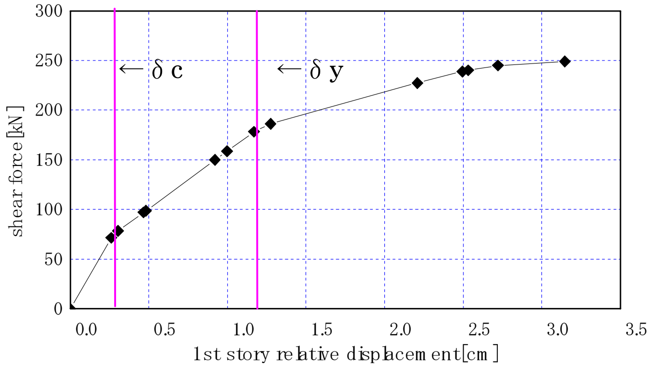

Figure 14. Skeleton curve of 1st story

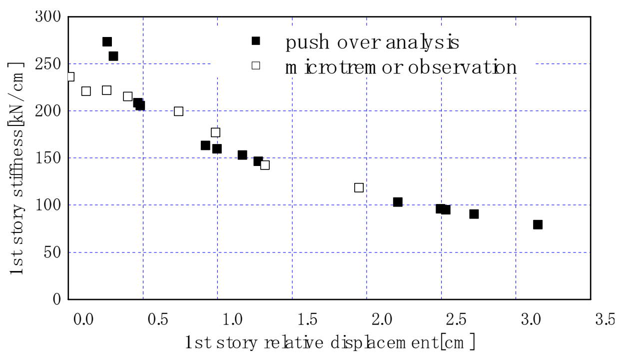

Figure 15. comparison of stiffness between push over analysis and microtremor observation

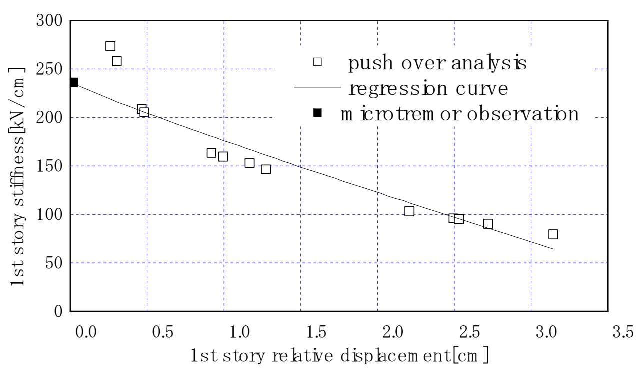

Figure 16. Design value and value by microtremor with regression curve

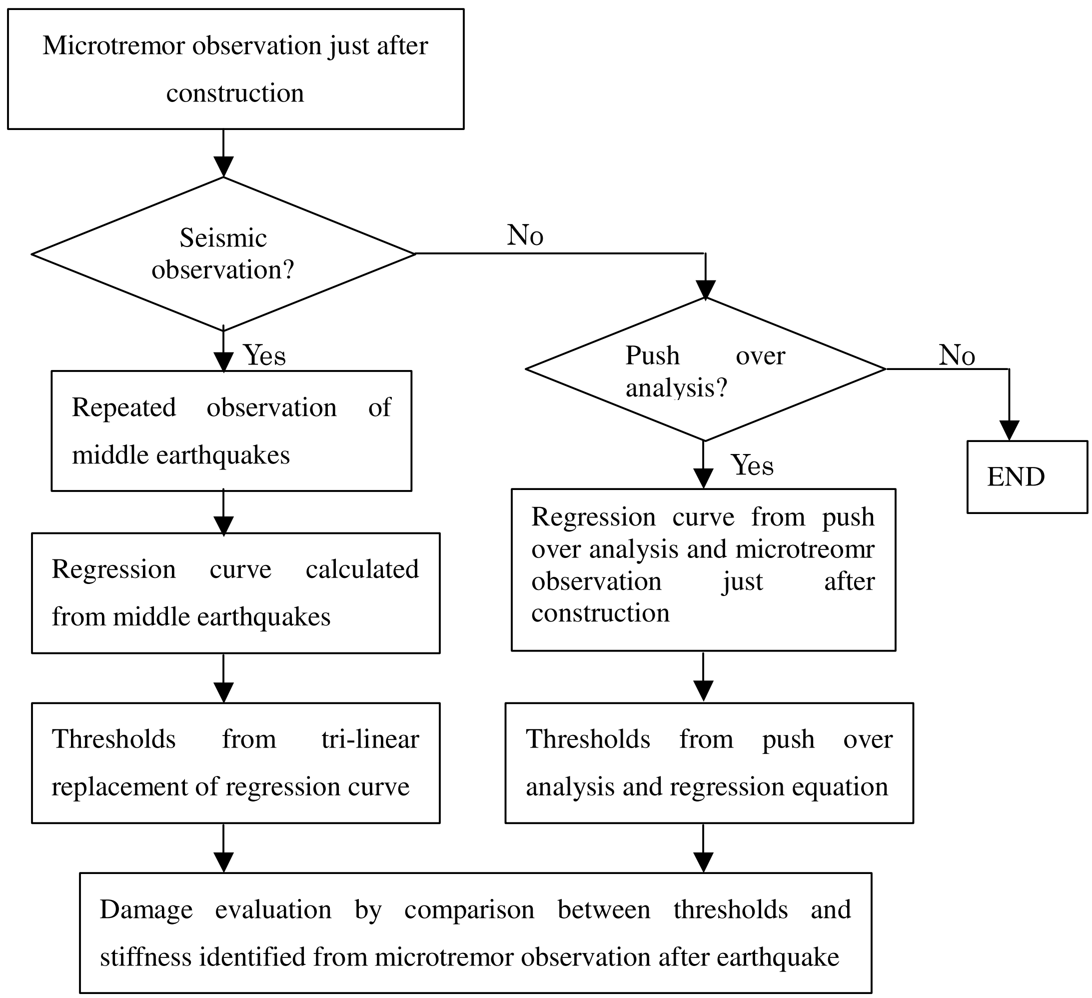

Figure 17. Flowchart of damage evaluation

CONCLUDING REMARKS

The outlined results of damage detection test using large scale test frame with cementitious devices are shown here. We identified characteristics of structure in which devices are actually damaged during the shaking. Results obtained from this experiment can be summarized as follow;

1) Natural frequency, damping ratio, participation function and story stiffness are identified by Recursive Parameter Estimation using ARX model. Natural frequency increases, damping ratio decreases, story stiffness decreases as input amplitude decreases.

2) Natural frequency, damping ratio, participation function and story stiffness are identified by estimation of characteristics before and after excitation using ARX model. Natural frequency decreases, damping ratio increases and story stiffness decreases as experienced amplitude increases.

3) Almost all characteristics by microtremor can be estimated to be same as those by white noise.

4) From these results, a model using stick-slip elements is proposed. Natural frequency, damping ratio and story stiffness described by this model are consistent with experimental results.
5) Procedures of damage evaluation which use microtremor observation and skeleton curve obtained by structural design are proposed.

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