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Development of residual seismic capacity evaluation system –Shaking table test with rocking behavior-

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ABSTRACT: Authors have been developing a new residual seismic capacity evaluation system with few inexpensive accelerometers. Inertia force at each floor is calculated from the assumed mass and measured absolute acceleration. Response displacement is calculated by double integral with measured acceleration. The wavelet transform technique is applied for the integral to reduce the effect of the error contained in the measured acceleration. The residual seismic capacity of a building is evaluated with the capacity spectrum method with measured inertia force and derived displacements. Before the 2011 off the pacific coast of Tohoku Earthquake, two buildings in Yokohama National University were instrumented, and its performance curve during the earthquake was successfully measured. Moreover, rocking behavior was measured and it can affect the performance curve of the buildings. Therefore, 3-story plane steel frame specimen with mechanical rocking system was prepared and tested on the shaking table of the Urban Renaissance Agency to investigate how to subtract the effect of rocking behavior from the calculated performance curve.

1 INTRODUCTION

Authors have been developing a new residual seismic capacity evaluation system with few inexpensive accelerometers. Inertia force at each floor is calculated from the assumed mass and measured absolute acceleration. Response displacement is calculated by double integral with measured acceleration. The wavelet transform technique is applied for the integral to reduce the effect of the error contained in the measured acceleration. The residual seismic capacity of a building is evaluated with the capacity spectrum method with measured inertia force and derived displacements.

The monitoring system is instrumented to two buildings of Yokohama National University in the beginning of year of 2008. The building for the department of architecture, which is one of the two buildings, is SRC structure that has 8 floors and 1 basement floor. The responses during the 2011 Off the Pacific Coast of Tohoku earthquake were successfully measured. The performance curve during the main shock calculated from the measured accelerations is shown in Figure 1.

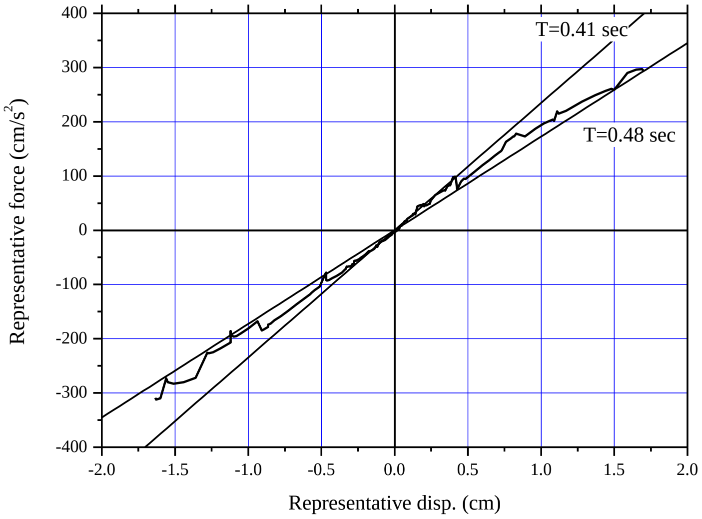

Figure 1. The measured performance during the 2011 Off the Pacific Coast of Tohoku Earthquake (EW direction)

During the main shock, rocking behavior at the bottom of the building due to the deformation of soil and piles, was also measured as shown in Figure 2. If the response of the ground beneath the building becomes nonlinear, the performance of the building may show a nonlinear response,too, even if the building itself is elastic. It is needed to subtract the effect of the rocking behavior from the performance curve calculated from measured accelerations in order to evaluate the damage of the building. Therefore, 3-story plain steel frame specimen with mechanical rocking system was prepared and tested on the shaking table of the Urban Renaissance Agency to investigate how to subtract the effect of rocking behavior from the calculated performance curve.

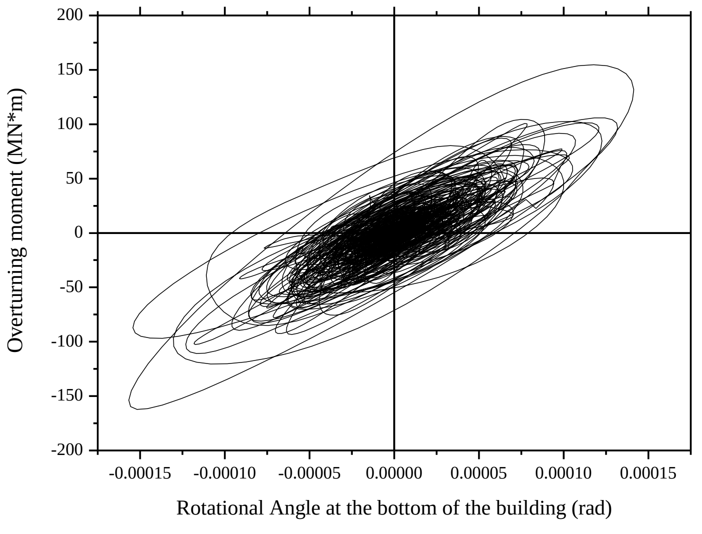

Figure 2. The relationship between overturning moment and rotational angle at the bottom of the building (EW direction)

2 PERFORMANCE CURVE FROM MEASURED ACCELERATION

The performance curve is the relationship between the representative deformation Δ and the representative restoring force, which shows the predominant response of a structure. Non-linear response of multi-degree-of-freedom system is simplified down to a single-degree-of-freedom system with restoring force and deformation of Δ. The restoring force $\ddot{\Delta}$ is the base shear divided by the total mass of the building to change the unit to acceleration.

The configuration of the monitored building is shown in Figure 3. Each floor basically has one accelerometer. If torsional response is expected, more than one accelerometer can be placed on a floor. In order to calculate inertia force, which is calculated as the mass multiplied by absolute acceleration, the mass of which response is represented by each accelerometer, m_i is needed. The summation of m_i is equal to the total mass of the building.

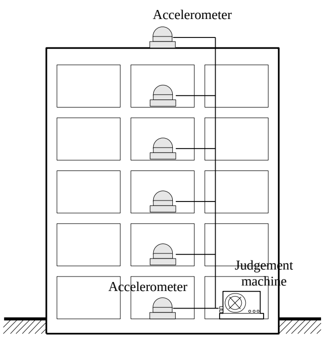

Figure 3. Configuration of the monitoring

The representative restoring force $\ddot{\Delta}$ and representative deformation Δ are calculated as Equation (1) and Equation. (2), respectively [Kusunoki et al, 2008].

$$\ddot{\Delta} = \frac{\sum m_i \cdot \left({}_M\ddot{x}_i + \ddot{x}_0 \right)}{\sum m_i} \tag{1}$$

$$\Delta = \frac{\sum m_i \cdot {}_M x_i}{\sum m_i} \tag{2}$$

Where ${}_M\ddot{x}_i$ is i-th measured relative acceleration to the basement, $\ddot{x}_0$ is the ground acceleration measured at the basement, and ${}_M x_i$ is i-th relative displacement to the basement derived from the measured relative acceleration.

From Equation (1) and Equation (2), it can be said that m_i is not necessarily the absolute value but the relative to the total mass, which can be represented by the floor area governed by each accelerometer.

In order to decompose the acceleration and displacement into several components that have different Nyquist frequencies, the wavelet transform method (WTM) is applied as Equation (3) and Equation (4).

$$\left\{ {}_{M}\ddot{x} + \ddot{x}_{0} \right\} = \left\{ \sum_{i=1}^{N} g_{Accel,i} + f_{Accel,n} \right\} \tag{3}$$

$$\left\{ {}_{M}x \right\} = \left\{ \sum_{i=1}^{N} g_{Disp,i} + f_{Disp,n} \right\} \tag{4}$$

Where $g_{Accel,i}$ and $g_{Disp,i}$ are the i-th rank components of the absolute acceleration and relative displacement to the basement, and $f_{Accel,n}$ and $f_{Disp,n}$ are constant error values contained in the acceleration and relative displacement, respectively. The representative restoring force for the r-th rank $\ddot{\Delta}_r$ and the representative displacement for the r-th rank Δ_r are calculated as Equation (5) and Equation (6), respectively.

$$\ddot{\Delta}_r = \frac{\sum m_i \cdot_i g_{Accel,r}}{\sum m_i} \tag{5}$$

$$\Delta_r = \frac{\sum m_i \cdot_i g_{disp,r}}{\sum m_i} \tag{6}$$

If the i-th rank is not predominant, the performance curve of i-th rank shows meaningless relationship.

The displacement $g_{Disp,i}$ is calculated by the double integral of the acceleration $g_{Accel,i}$ with the conventional trapezoidal integral method. It is well-known that the double integral can give too large displacement because of the error component contained in the measured acceleration. Since the error component of the displacement has very long period, WTM can separate the error component from the predominant component [Kusunoki, et Al, 2008].

3 SHAKING TABLE TEST

3.1 Outline of the specimens

The specimen is plane steel frame with 3 stories as shown in Figure 4. The specimen has steel mass (about 18.5 kg) at the beam column joints. The size of the steel plate (SS400) for beams columns is the width of 100mm and the thickness of 6mm. Two different steels were used for the specimen, of which characteristics are shown in Table 1.

Table 1. Characteristics of the steel plates

Steel type	Type	Young's modulous E N/mm2	Yield Strength σ_y N/mm2	Tensile Strength σ_u N/mm2
Type A	SS400	205000	326	430
Type B			341	460

Second and third stories have steel bracing so that they will not yield but remain elastic. The bracing in the first story was detached for the specimens to fail in the first story. Rocking behavior is reproduced by using steel springs at the bottom of the specimen. The stiffness of the spring is designed so that the horizontal displacements of the building due to rocking and due to the deformation become almost the same. Three different support conditions were applied; fixed, rocking, and rocking with bracing in the first story as shown in Figure 5.

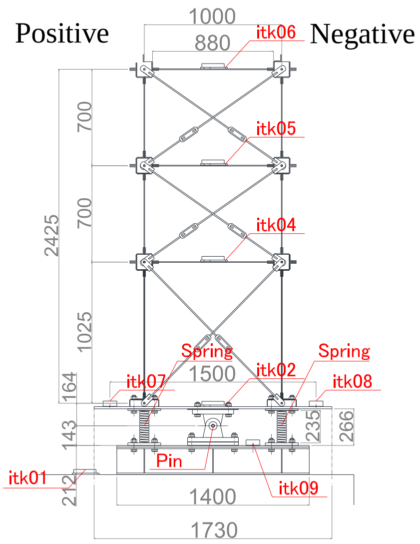

Figure 4. Specimen (S-BN) unit: mm

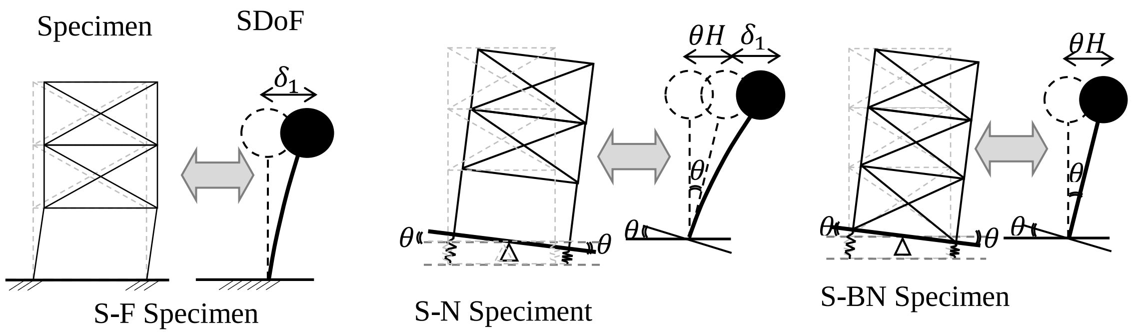

Figure 5. Specimens

Initial compression force with the deformation of 5.5mm and 24.5mm were applied for the steel springs. Linear rocking behavior is expected with 24.5mm and nonlinear behavior is expected with 5.5mm by separating the spring and basement of the specimen in the tensile direction.

3.2 Input motions

One artificial wave (referred to as wg60, hereafter), NS component of the KOBE earthquake recorded at JMA Kobe (referred to as Kobe, hereafter), and the NS component of the K-Net MYG013 site recorded during the 2011 Off the Pacific Coast Earthquake (referred to as MYG013, hereafter) were used for the input motions.

Several different levels of the waves were inputted, elastic level and inelastic level derived from the calculated strength of the specimen. The waves were inputted twice at the level to represent main shock and aftershock when the specimen showed nonlinear response. Between the inputs, the specimen was shook with white noise (RMS of 40gal and frequency band between 0.5 and 20Hz) to measure its predominant frequency. The response acceleration spectra of input motions (which is measure on the table) with viscous damping ratio of 5% are shown in Figure 6.

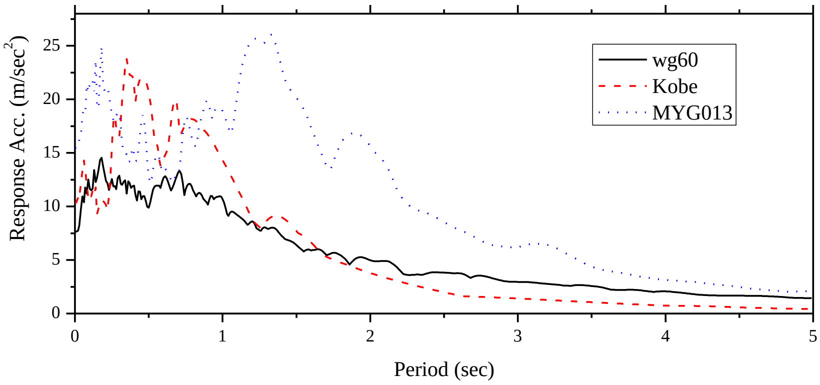

Figure 6. Response acceleration spectra of input motions

3.3 *Measurement*

Horizontal absolute displacements at the beam end of each floor, at the top and bottom of the pin were measured by transducers from outside of the table. Vertical deformations of springs were measured by laser transducers. Absolute accelerations were measured by ITK accelerometers at the middle of beam of each floor, at the top of bottom of the pin, above the springs and on the shaking table as shown in Figure 4. ITK accelerometer has the accuracy of about 0.2 cm/s^2. Sampling rate was 100Hz.

4 TEST RESULTS

Test cases are summarized in Table 2.

Table 2. Test cases

Specimen	Condition	Spring N/mm	Input	amplification factor for each input						Steel Type
				1	2	3	4	5	6	
S-F01	Fixed	-	Wg60	15%	60%	60%				A
S-F02			Kobe	10%	15%	45%	45%			
S-F03			MYG013	5%	10%	25%	25%	30%	30%	
S-BN01	Rocking (nonlinear) Initial deformation of springs:5.5mm	110.5	Wg60	15%	25%					
S-N01				15%	25%	60%	50%			
S-BN02			Kobe	10%	15%					
S-N02				10%	15%	45%	50%	50%		
S-BN03			MYG013	5%	10%					
S-N03				5%	10%	30%	40%	50%	50%	
S-BN04	Rocking (linear) Initial deformation of springs:24.5mm	110.5	Wg60	15%	25%					B
S-N04				15%	25%	50%	50%	60%	60%	
S-BN05			Kobe	15%						
S-N05				15%	50%	50%				
S-BN06			MYG013	10%						
S-N06				10%	50%	50%				

4.1 *Rotation angles due to rocking behavior*

For the monitoring, the rotation angle at the bottom of the building needs to be calculated from vertical displacements at the bottom of the building. Measured vertical acceleration is conducted double integral with wavelet transform method to get vertical displacements. Figure 7 shows the comparison of the maximum rotational angle at the bottom of the specimen S-BN and S-N for all input motions derived from the laser transducers and accelerometers (double integral). It can be seen that the rotational angle by accelerometers agree well with the angle by laser transducers, and the error ratio is approximately less than 5%.

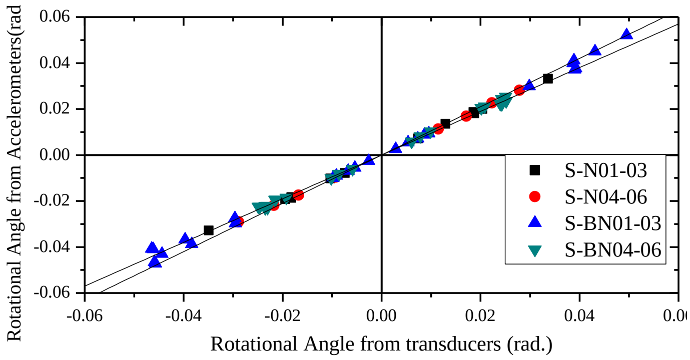

Figure 7. Comparison of rotational angle derived from laser transducers and accelerometers

4.2 Performance curve

Figure 8 shows the relationship between overturning moment and rotational angle of S-N01 with the input motion of 60% of wg60, of which spring had the initial deformation of 5.5mm so that nonlinear rocking behavior could occur. It can be found that nonlinear elastic behavior was observed because the spring separated from the bottom of the specimen in the tensile direction when the vertical response displacement was more than 5.5mm.

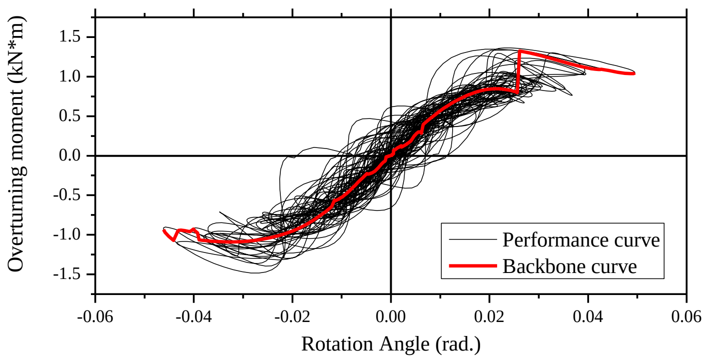

Figure 8. Relationship between overturning moment and rotational angle (S-N01, wg60 60%)

The calculated backbone curve of the performance curve with rocking behavior is shown in Figure 9.The first story of S-N01 showed nonlinear response during the input motion of 60% of wg60, too as shown in Figure 9. In the figure, the slope of the predominant period of S-N01 (1.11 sec) is also superimposed, which is calculated from the transfer function with small input level. The initial slope of the performance curve of S-N01 coincides very well with the predominant period.

The representative displacement due to rocking, Δ_R can be calculated as $\theta_R \cdot H_e$, where θ_R is the rocking angle and H_e is the equivalent height of the specimen, which is calculated from measured accelerations and height of the specimen. The rocking behavior can be neglected by subtracting Δ_R from the representative displacement, Δ at each step. The performance curve of which rocking behavior is neglected is shown in Figure 9 (W/O rocking). The performance curve of S-F01 (Fixed) with the same input, and the slope of the predominant period of S-F01 (0.92sec) are also superimposed. The performance curve without rocking behavior agrees very well with that of S-F01, which means that the rocking behavior can be subtracted with measured accelerations successfully.

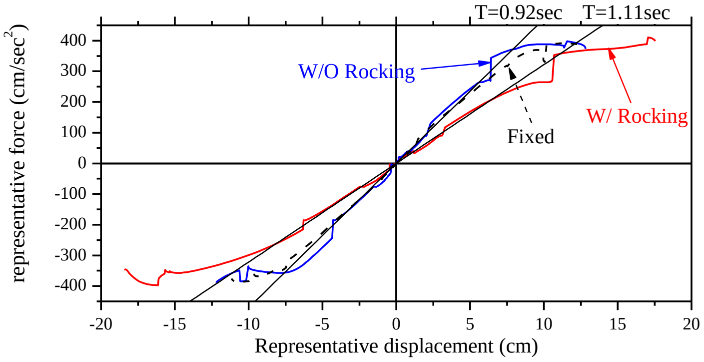

Figure 9. Comparison of performance curves W/ and W/O rocking (S-N01, wg60)

5 CONCLUSIONS

In order to study the effect of the rocking behavior on the performance curve derived from the measured accelerations and to verify the method to subtract the effect from the performance curve, a series of shaking table tests with 3-story plane steel frame with rocking behavior was conducted. Results from the studies are as follows;

1. It is confirmed that the rocking rotational angle at the base of the specimen can be derived from the measured vertical accelerations at the base.
2. The relationship between overturning moment and rotational angle at the base of the specimen can be derived from the accelerometers even if the rocking behavior is not linear.
3. Rocking behavior can be successfully subtracted from the performance curve no matter if the responses of the rocking or building are inelastic. The performance curve, of which rocking behavior was subtracted, coincides with the performance curve of the specimen of which bottom was fixed to the table.

6 ACKNOWLEDGEMENT

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