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RESPONSE EVALUATION OF A BASE-ISOLATED BUILDING WITH MEASURED ACCELERATIONS DURING TOHOKU EARTHQUAKE

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Abstract

After a catastrophic earthquake happens, buildings need to be evaluated its damage level in order to prevent human loss caused by damage or collapse due to an aftershock. Kobe earthquake revealed that most people evacuated from their own houses in fear of their damage even though the damage level was not severe. “Quick inspection of the damaged building” can be an option to evaluate the damage level and mitigate their fear. Shelter buildings such as school buildings need to be evaluated their damage level quickly to evaluate if they can be used or not. It needs, however, time to inspect buildings visually one by one. Tohoku earthquake revealed that high-rise buildings need to be evaluated their safety to re-open. The visual inspection needs much time to check whole members of high-rise building, then down-time elongated. Development of a quick damage evaluation system with sensors is indispensable to overcome these problems.

The author has been conducting research to develop a residual seismic capacity evaluation system. According to the proposed method, the absolute acceleration at each story is measured by an instrumented accelerometer, and the displacement is derived from the measured acceleration with double integral technique. In order to eliminate the effect of the error component contained in the measured acceleration, the Wavelet transform technique is applied to decompose the measured acceleration into several components with certain frequency band in temporal domain. The components that has low frequency band are then eliminated as error components. Then the response of building, which is multi-degree-of-freedom system, is simplified down to the single-degree-of-freedom system by using the capacity spectrum method. The damage level is evaluated with the simplified force-displacement relationship of SDoF.

The proposed method has been confirming its validity with instrumented existing buildings and shaking table tests. Any base-isolated building, however, has not been discussed yet. Since the base-isolation story can show non-linear response during relatively small earthquake, the validity of the proposed system for non-linear response can be discussed with the response of a base-isolated building. A building of Earthquake Research Institute, the University of Tokyo was instrumented in 2006 when it was constructed, and the dynamic behavior during Tohoku earthquake was successfully recorded. In this paper, the damage level of the building was evaluated by the proposed method and discuss its validity. The accuracy of the derived displacement from measured acceleration with Wavelet transform technique was also confirmed by comparing it with mechanical measurement result. The damage level of each story was evaluated linear from the calculated relationship between the story shear and the inter-story drift.

Keywords: Structural health monitoring, Base-isolated building, Tohoku Earthquake, Damage evaluation

1. Introduction

After a catastrophic earthquake happens, buildings need to be evaluated their damage levels in order to prevent human loss caused by damage or collapse due to an aftershock. Kobe earthquake revealed that most people evacuated from their own houses in fear of their damage even though the damage level was not severe. “Quick inspection of the damaged building” can be an option to evaluate the damage level and mitigate their fear. The quick inspection method is based on the visual inspection done by engineers. Shelter buildings such as school buildings, hospitals, and governmental buildings need to be evaluated their damage levels quickly if they can be used or not. It needs, however, time to inspect buildings one by one visually. Tohoku earthquake revealed that high-rise buildings need to be evaluated its safety to re-open even though the damage does not look severe. The visual inspection needs much time to check whole members of high-rise building, then down-time elongated. Development of a quick damage evaluation system with sensors is indispensable to surmount these problems.

The author has been conducting research to develop a residual seismic capacity evaluation system [1, 2, 3, 4]. According to the proposed method, the absolute acceleration at each floor is measured by an instrumented accelerometer, and the displacement is derived from the measured acceleration with double integral technique. In order to eliminate the effect of the error component contained in the measured acceleration, the Wavelet transform technique [5] is applied to decompose the measured acceleration into several components with certain frequency bands in temporal domain. The components that has low frequency band are then eliminated as error components. The residual displacement is, however, also eliminated by the Wavelet transform, since it is a low frequency component, which is a disadvantage of the Wavelet transform. Then the response of building, which is multi-degree-of-freedom system, is simplified down to the single-degree-of-freedom system by using the capacity spectrum method. The damage level is evaluated with the simplified force-displacement relationship of single-degree-of-freedom system.

The proposed method has been confirmed its validity by instrumented existing buildings and shaking table tests. Any base-isolated building, however, has not been discussed yet. Since the base-isolation story can show nonlinear response during relatively small earthquake level, the validity of the proposed system for nonlinear response can be discussed with the response of a base-isolated building. A building of Earthquake Research Institute, the University of Tokyo, which is a base-isolated building, was instrumented in 2006 when it was constructed, and the dynamic behavior during 2011 Tohoku earthquake was successfully recorded. The damage evaluations of the base-isolated buildings have been conducted with recorded data by many researchers [for example, 6, 7]. The main objective of these research was to evaluate damage, but that of our research is to develop an automatic damage evaluation system by suing only accelerometers. Thus, the objectives of this paper are to confirm the validity of the proposed damage evaluation method for the base-isolated building, the accuracy of the displacement derived with the Wavelet transform with using the recorded data.

2. Target building

Earthquake Research Institute (referred to as ERI, hereafter) of the University of Tokyo is located at north end of main campus (Hongo campus). ERI consists of three buildings, No.1, No.2, and No.3 as shown in Fig. 1. The target building of this paper is No.1.

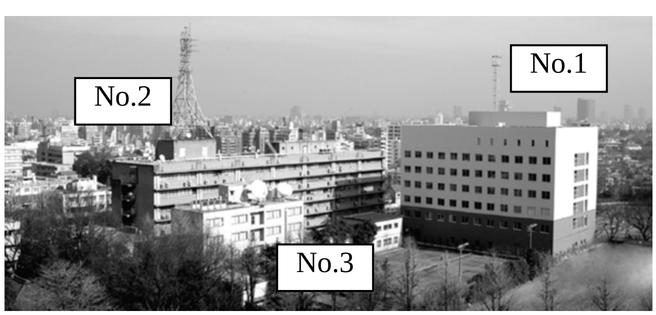


Fig. 1 – Earthquake Research Institute of the University of Tokyo

The plan view of the building is shown in Fig. 2. The plan is rectangular of which longitudinal direction (north-south) is 43.2m and transverse direction (east-west direction) is 28.2m. Fig. 3 shows Y2 and X2 frames. The building has 7 stories, of which story height is 5.7m for the first story and about 4m for other stories. The building also has single story penthouse on top and telecommunication steel tower (h=20.8m). The weight of each story considered at structural calculation is listed in Table 1. The building has 22 lead rubber bearings and 6 linear sliders.

As shown in Fig. 2, one accelerometer is placed under the base-isolator at near the X6-Y1 column, two accelerometers are placed on the first floor at the X6-Y1 and X2-Y4 columns, and one accelerometer is on the 7th floor at the X4-Y1 column. A mechanical measurement recorder is placed at near the X4-Y2 column to record inter-story drift of base-isolation story [8].

The accelerometers are JEP-4B3(Mitsutoyo Co. ltd.) and JEP-4A3(Mitsutoyo Co. ltd.), of which measurable acceleration range is ±2,097 cm/sec^2, sensibility is 3V/9.8m/sec^2±3%, and measureable frequency band is from DC to 400Hz. All sensors are connected with special cables to the data acquisition system (AJE-8200). A/D converter has 24bit, and sampling frequency is 100Hz. The structural monitoring started from April 27, 2007.

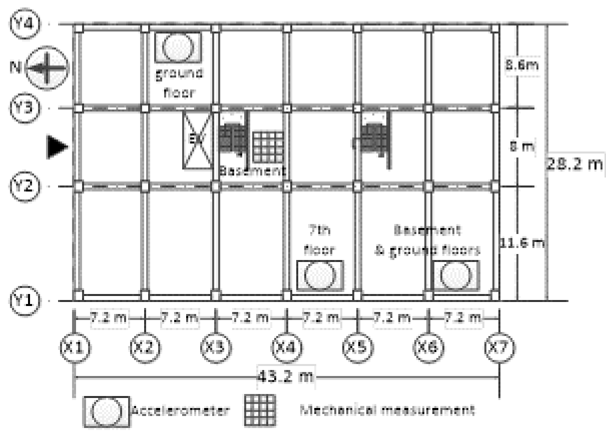
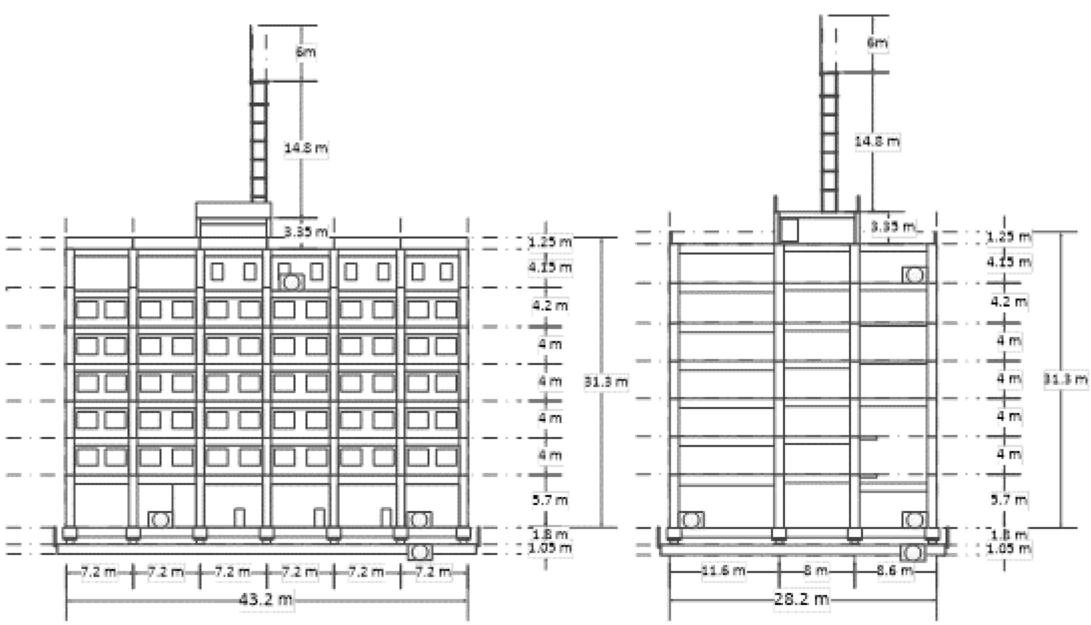


Fig. 2 – Plan view



(a) Y2 frame (b) X2 frame

Fig. 3 – Framing elevation

Table 1 – Story weight

Story	Weight(kN)
Steel tower	26.6
Penthouse	1,233
RF	14,810
7F	16,988
6F	16,977
5F	16,994
4F	15,449
3F	14,925
2F	19,911
1F	26,904

3. Record during 2011 Tohoku Earthquake

The NS components of measured accelerations during 2011 Tohoku Earthquake are shown in Fig. 4. The Japanese seismic intensity at Hongo was announced as 5-. The maximum and minimum accelerations in NS direction are shown in Fig. 5. It was observed that the response of upper structure was reduced due to base-isolator. Fig. 6 shows the transfer function with accelerometers on the ground and 7th floors. Spectral window with band width of 0.20Hz was applied for smoothing. The Nyquist frequency of each rank of the Wavelet transform technique is also shown in the figure. The predominant frequencies for the first mode and second mode are 0.72Hz (1.38sec) and 4.24Hz (0.24sec), respectively. The predicted predominant period at structural calculation with deformation of the base-isolator of 2cm was 1.504 sec, which agreed well with the observed value.

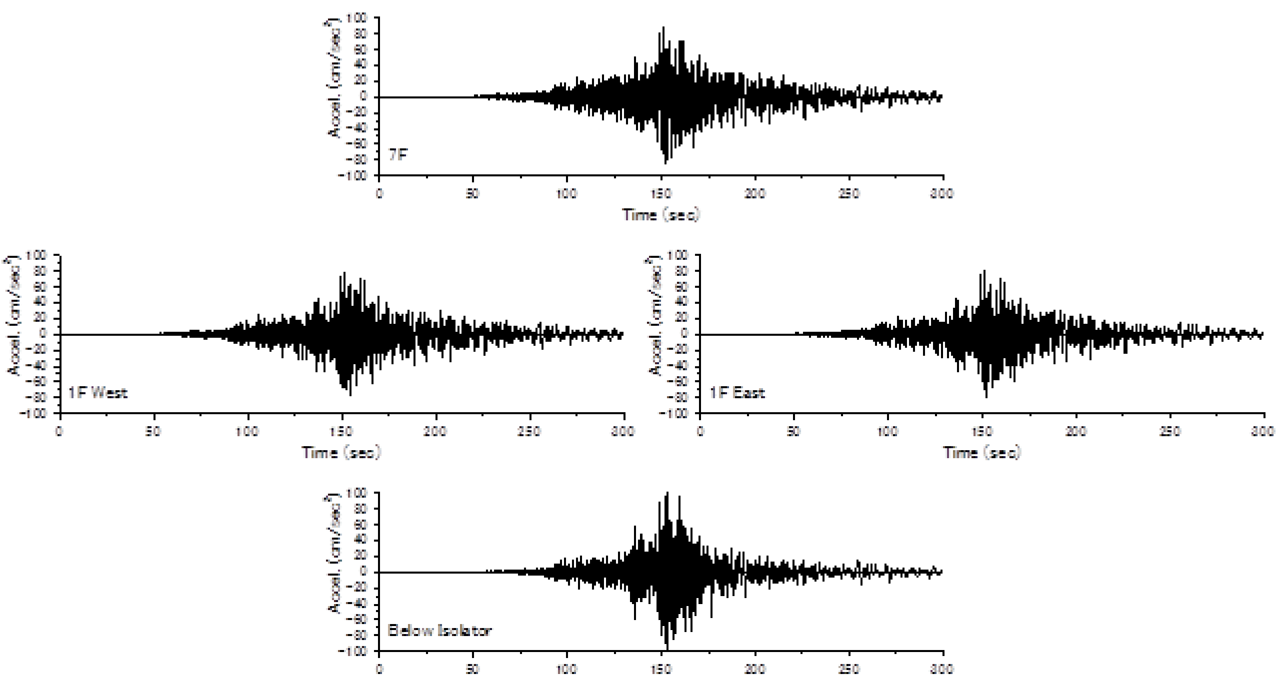


Fig. 4 – Recorded accelerations during 2011 Tohoku Earthquake (NS component)

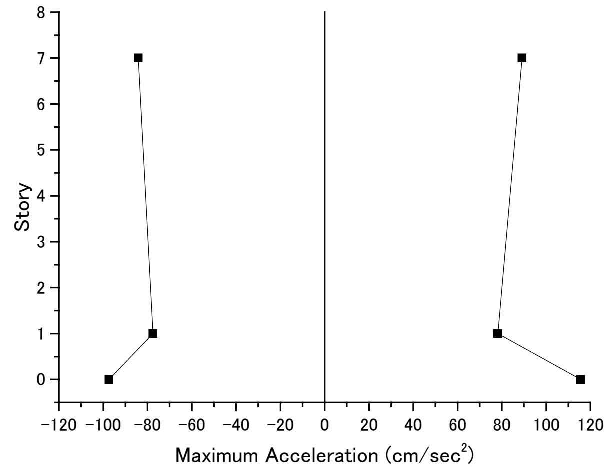


Fig5. Maximum and minimum accelerations

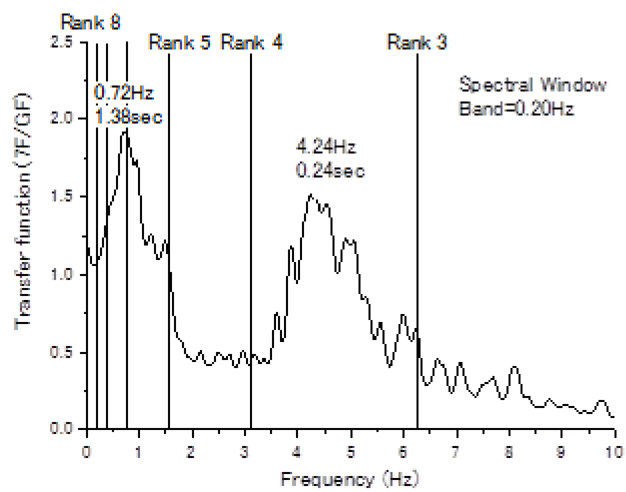


Fig. 6 – Transfer function (NS)

4. Dynamic behavior

4.1 Assumption of the acceleration of the floor without accelerometer

As mentioned in section 2, accelerometers are placed on only the ground floor, first floor and 7th floor. Therefore, the accelerations of the floors without accelerometer were interpolated as shown in Fig. 7.

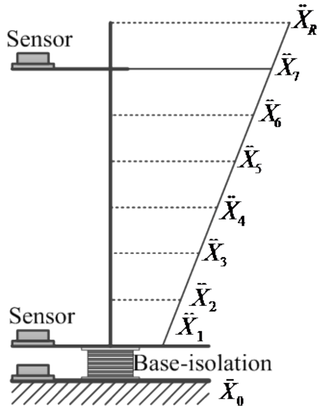


Fig. 7 – Interpolation to calculate accelerations of the floors without accelerometers

4.2 Performance curve derived from measured acceleration

The performance curve, which is the simplified base shear – deformation relationship of the single-degree-of-freedom system, was derived based on the method shown in [4]. The tentative representative displacement ${}_1\Delta'$ and the tentative representative acceleration (force) $\left({}_1\ddot{\Delta}' + {}_1\ddot{x}_0\right)$ are calculated with Eq. (1) and Eq. (2), respectively. Where; m_i is the mass of i-th story, ${}_1x_i$ and ${}_1\ddot{x}_i$ are the relative displacement and acceleration of the 1st mode at i-th floor to the basement, and ${}_1\ddot{x}_0$ is the component of the ground acceleration with 1st mode predominant period.

$$ {}_1\Delta' = \frac{\sum m_i \cdot {}_1x_i}{\sum m_i} \tag{1}$$

$$ \left({}_1\ddot{\Delta}' + {}_1\ddot{x}_0\right) = \frac{\sum m_i \cdot {}_1\ddot{x}_i}{\sum m_i} + {}_1\ddot{x}_0 \tag{2}$$

The tentative performance curve is derived as the backbone curve of the relationship between $\left({}_1\ddot{\Delta}' + {}_1\ddot{x}_0\right)$ and ${}_1\Delta'$. The equivalent mass ratio is calculated at each step of the backbone curve, then the tentative representative displacement and accelerations are divided by the calculated equivalent mass ratio to get performance curve as shown in Eq. (3) and Eq. (4).

$$ {}_1\Delta = \frac{\sum m_i \cdot {}_1x_i^{\,2}}{\sum m_i \cdot {}_1x_i} \tag{3}$$

$$ \left({}_1\ddot{\Delta} + {}_1\ddot{x}_0\right) = \frac{\sum m_i \cdot {}_1x_i^{\,2}}{\left(\sum m_i \cdot {}_1x_i\right)^2} \sum_{i=1}^{N} m_i \cdot {}_1\ddot{x}_i + {}_1\ddot{x}_0 \tag{4}$$

Since the weights of steel tower and penthouse are relatively light as shown in Table 1, they were not modeled but only the weights were considered as the part of the top story. Displacements were calculated with double integral from the components of the measured accelerations as rank 4 to 7 by Wavelet transform technique, because these ranks were major responses as shown in Fig. 6. Fig. 8 shows the tentative and derived performance curves of the NS direction. The total building behavior showed nonlinear response. The design equivalent period at the deformation of the base-isolator of 2cm is also superimposed. As mentioned later, the recorded maximum deformation of the base-isolator was about 2.5 to 3.0 cm. The design equivalent period agreed very well with the measured value.

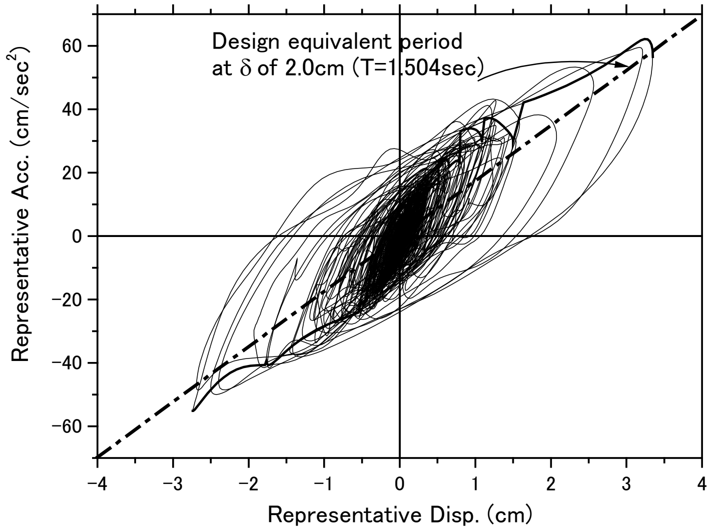


Fig. 8 – Derived performance curve (NS direction)

Fig.9 shows the performance curve and demand curve that is the relationship between response acceleration spectrum and response displacement spectrum. The theoretical equivalent damping ratio, h_d of the bi-linear model with initial stiffness of K and stiffness after the yielding of Ky, can be calculated as Eq. (5), where α is the ratio of the stiffness, Ky/K. The stiffness of K and Ky were defined as shown in Fig. 9. Since the theoretical equivalent damping is for steady-state response and earthquake response is not steady-state, 80% of h_d is applied for the equivalent damping ratio, h'_d according to the Japanese Building Code. The demand curve was reduced according to the equivalent damping ratio, h'_d with response reduction factor of F_h as shown in Eq. (6), which is defined in the Japanese Building Code. The intersection of the performance curve and demand curve with considering h'_d is the predicted maximum response point. Fig. 9 shows that they coincide to each other very well.

Fig. 10 shows the calculated equivalent mass ratio at each point of the performance curve shown in Fig. 9. Although the ratio was calculated very small for small deformation range due to error component contained in the derived displacement, the ratio became constant as 1.0 for deformation of greater than 0.3mm. It meant that the first mode was predominant and higher mode was not effective.

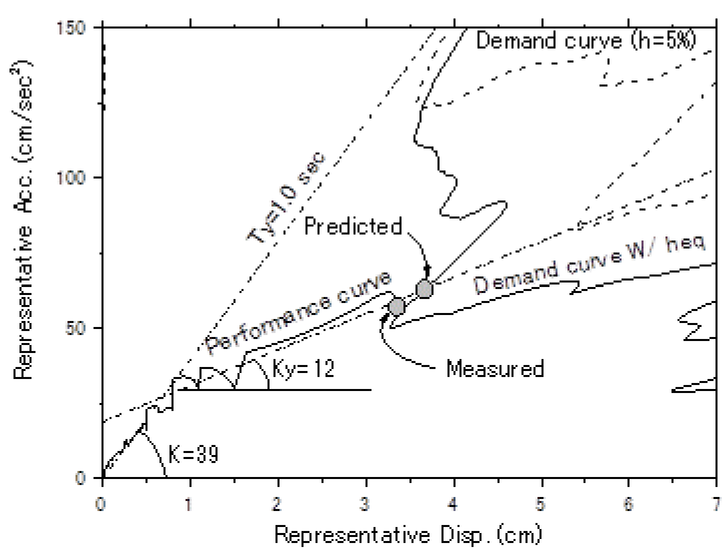


Fig. 9 – Tentative and derived performance curves and demand curves (NS direction)

$$h_d = \frac{1.6}{\pi}\left(1 - \frac{1}{\mu}\right)\frac{1-\alpha}{1+\alpha(\mu-1)} \tag{5}$$

$$F_h = \frac{1.5}{1+10h'_d} \tag{6}$$

4.3 Performance curve of the upper structure

Fig. 11 shows the performance curve of the upper structure, where the measured acceleration on the first floor was applied as the input motion for the upper structure. Since the performance curve does not show any nonlinear behavior, the upper structure can be evaluated as elastic. It will be discussed in details later, but this conclusion agrees with the result that each story was also evaluated as elastic from the measured relationship between story shear and story deformation as shown in Fig. 13.

The design equivalent period of the upper structure at structural design of 0.499 sec, and the predominant period derived from the measured performance curve by using least square method of 0.387 sec are shown in the figure. The reason why the measured period was a little shorter than the design period is that the actual mass is less than the design value.

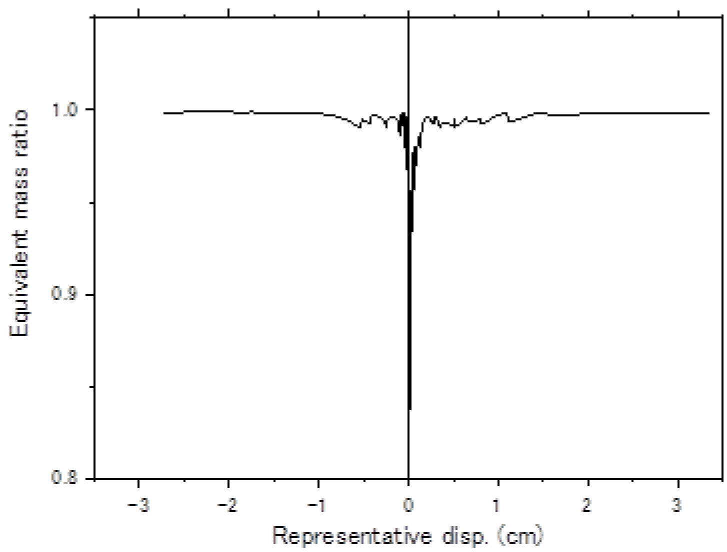


Fig. 10 – Equivalent mass ratio

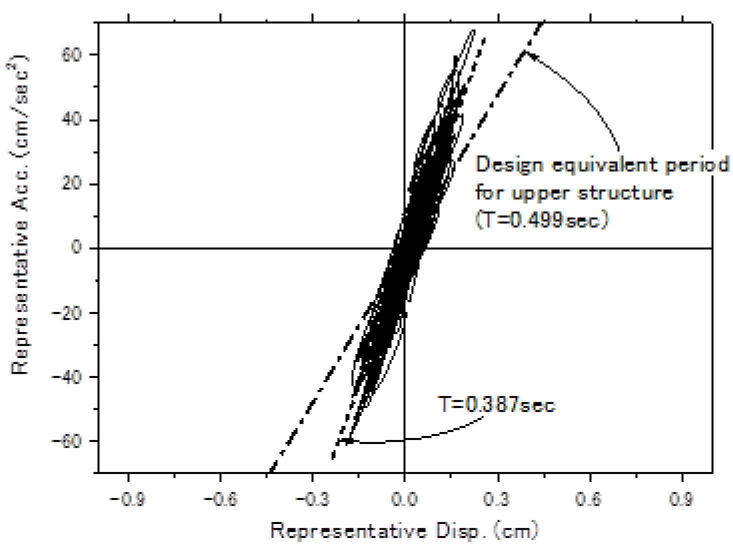


Fig. 11 – Performance curve of the upper structure (NS direction)

4.4 Relationship between story shear and story drift of each story

In order to investigate the reason of the nonlinearity shown in Fig. 8, the relationship between story shear and story drift of each story was calculated. The story shear was calculated from the inertia force as the mass multiplied by the measured acceleration at each floor. The story drift was calculated from the derived displacement at each floor from the ranks of 4 to 8 components of the measured acceleration with double integral.

Fig. 12 shows the relationship between the story shear and story drift of the base-isolation story. The figure shows the backbone curve and linear model at the maximum response, and the applied bi-linear model at structural calculation. The figure shows clearly that the base-isolation story showed nonlinear response. The first corner of the bi-linear model agreed well with the measured backbone curve. The measured stiffness after the first corner was, however, larger than the applied model, of which tendency was often reported in other research papers.

Fig. 13 shows the relationships between the story shear and story drift of the 1st to 7th story. The backbone curve and linear model calculated with the least square method are also shown in the figure. The relationship scattered a little, but it can be said that the upper stories remained elastic. The reasons of the scattered relationship were that the story drifts of upper structure were much smaller than that of the base-isolation story and the response accelerations of the 2nd to 6th floor were calculated with the interpolation as shown in Fig. 7.

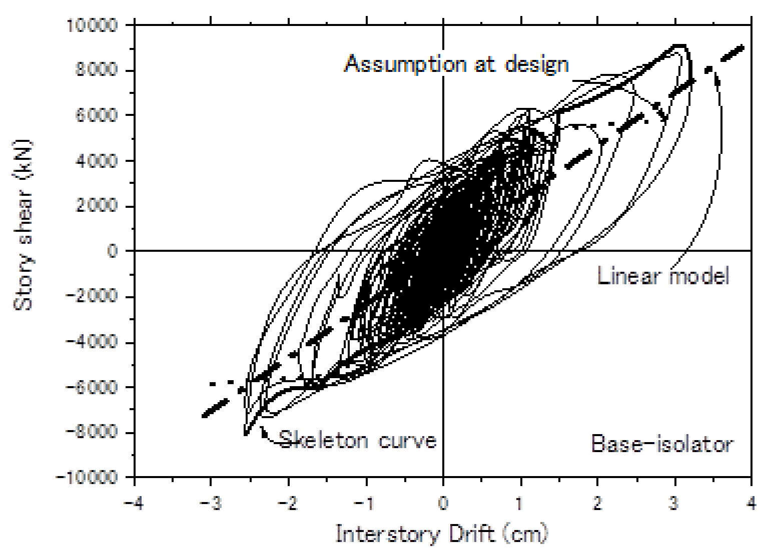


Fig. 12 – The relationship of story shear and story drift (base-isolation story)

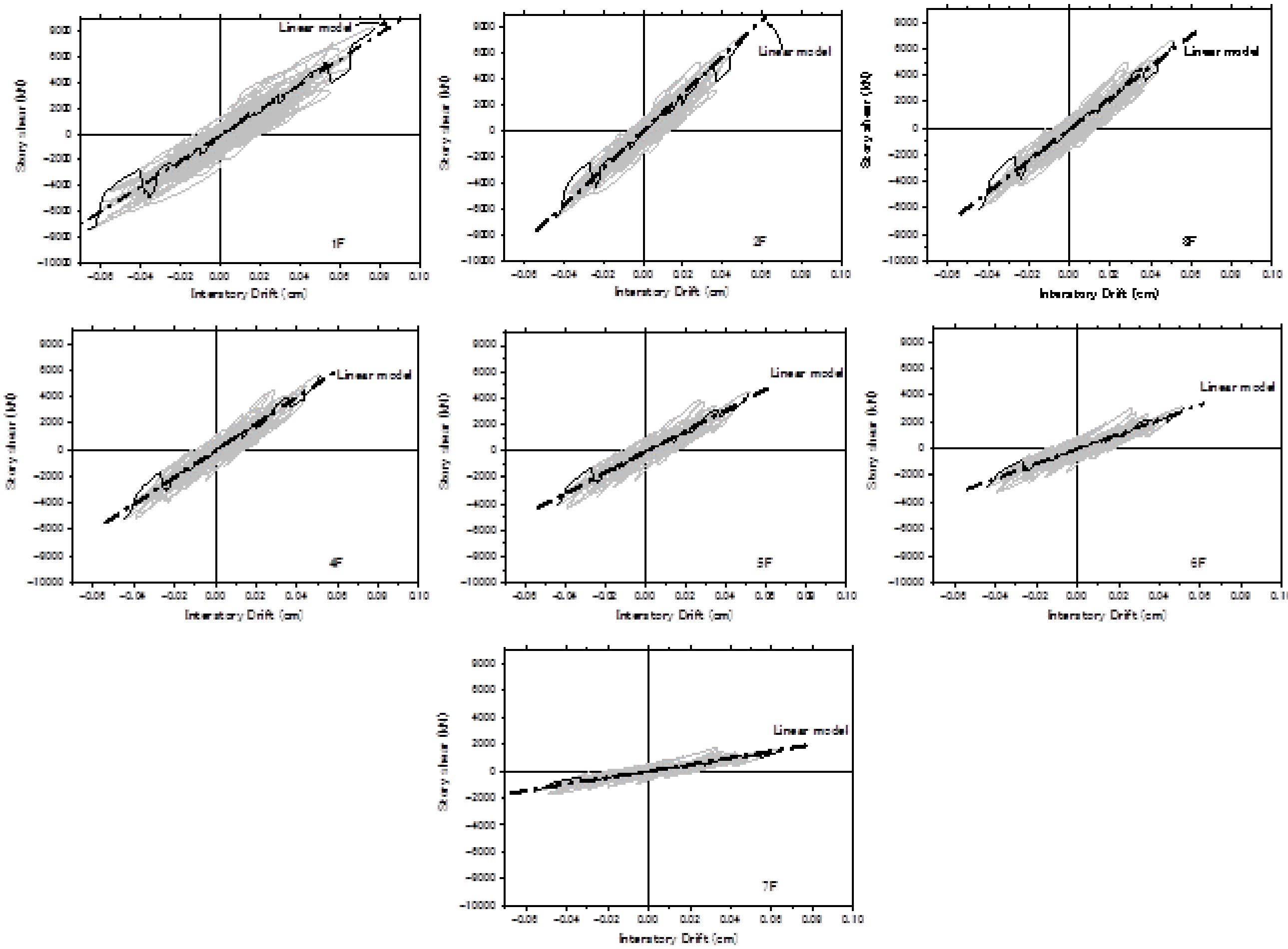


Fig. 13 – Relationships of story shear and story drift of upper structure (NS direction)

4.5 Mode shape

The eigenvalue analysis was conducted with the slope of the linear models showed in Fig. 12 and Fig. 13. The calculated predominant periods were 1.61 sec for the first mode and 0.25 sec for the second mode, respectively. Compared with the measured periods shown in Fig. 6, the period of the first mode was longer than the measured period. This is because the linear model at the maximum drift had smaller stiffness than that of the linear model at the maximum story shear as shown in Fig. 12. The equivalent mass ratios of the first and second modes were 0.99 and 0.01, which showed that the first mode was predominant and higher modes were not effective. This result agreed well with Fig. 9.

The calculated mode shapes, ${}_s\beta\{{}_su\}$, of the first and second modes are shown in Fig. 14. The drift of the first story was much more than the others, and the mode shape of the upper structure was linear for the first mode. It can be said that the assumed accelerations of the 2nd to 6th floors with the interpolation are reasonable.

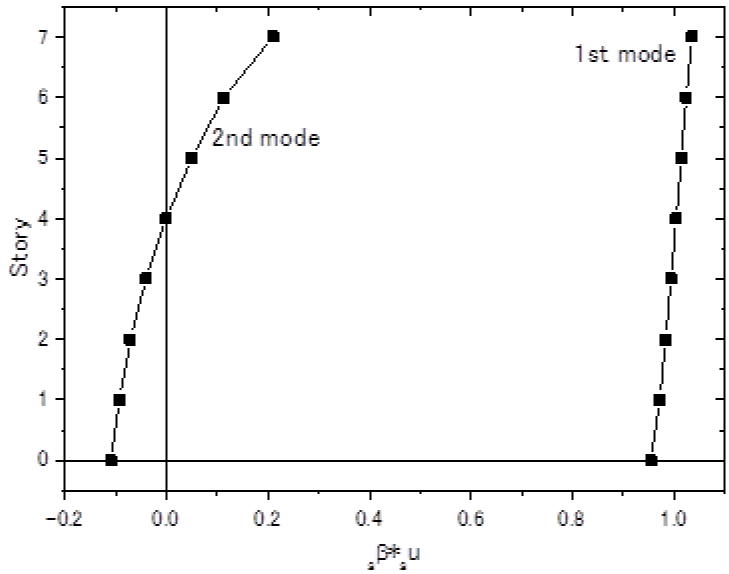


Fig. 14 – Calculated and measured orbit of base-isolation story

4.6 Orbit of the base-isolation story

The orbit of the base-isolation story drift was calculated from the measured accelerations on the basement and first floor. The calculated orbit is shown as dotted line in Fig. 15. The figure also shows the envelope of the mechanically recorded orbit by the mechanical measurement recorder shown in Fig. 2. They coincide with each other very well. Observed slight difference is probably caused by the difference of the location of the recorder and accelerometers. The mechanically recorded orbit also showed that there was no large residual displacement. It is the characteristics of the isolator. Since residual displacement can be eliminated and difficult to be estimated by the Wavelet transform technique, this characteristic of the isolator is an advantage to the Wavelet transform technique to estimate the base-isolation story drift by the proposed method.

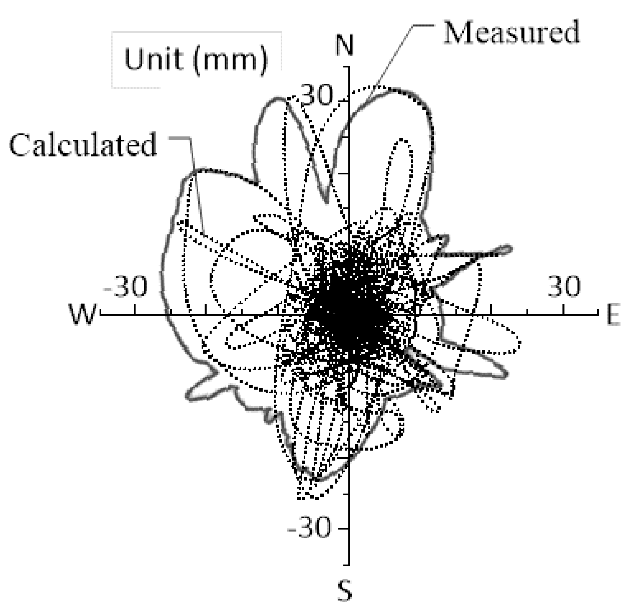


Fig. 15 – Calculated and measured orbit of base-isolation story

5. Concluding remarks

The dynamic response and damage evaluation of an instrumented existing base-isolated building during 2011 Tohoku Earthquake was investigated. Results from the studies are summerized as follows;

- The maximum response of the structure was predicted based on the proposed capacity spectrum method. The predicted and measured responses coincide each other very well. It can be said that the response of the base-isolated buildings can be predicted with the capacity spectrum method.
- The design equivalent period and measured equivalent period also coincide very well.
- The accuracy of the displacement derived from measured acceleration by double integral with Wavelet transform technique is high. The calculated orbit of the base-isolation story agreed very well with the mecanically recorded orbit.
- The damage of the upper structure can be evaluated by using the proposed method only for the upper structure.

6. References

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