A Study on the Response Characteristics of a High-Rise Building Built on the Reclaimed Land along the Osaka Bay

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SUMMARY:
An earthquake known as the Off the Pacific Coast of Tohoku earthquake hit Japan on 11 March 2011. It was a CMT magnitude 9.0 event and one of the most devastating earthquakes in Japan. A skyscraper with 53 stories built on the reclaimed land along the Osaka Bay, labeled as "S" Building here, was also encountered to pretty large shaking, despite of the long distance of 769 km away from the epicenter. The maximum displacement reached over 1.3 m at the top of the building and we have several non-structural damages.

We construct a single-degree-of-freedom model to know the transition of 1st natural period and the damping ratio. Next, we construct multi-degrees-of-freedom (shear and bending) model and simulate the building responses to see the maximum floor deformation angle. Moreover, we perform the response prediction for the Nankai earthquake, which will occur within 30 to 50 years, using our multi-degrees-of-freedom model.

Keywords: Response Characteristics, Skyscraper, Tohoku-Oki earthquake, Natural operiod

1. THE BACKGROUND AND PURPOSE OF THIS STUDY

The 2011 Off the Pacific Coast of Tohoku Earthquake (hereinafter, the Tohoku-Oki Earthquake) struck Japan on March 11, 2011 and caused great damage primarily by tsunami in the Tohoku region. This magnitude 9.0 earthquake was the most powerful known earthquake ever to have occurred in or near Japan since modern seismic observation began. According to information released from the Japan Meteorological Agency, the epicenter was approximately 70 km east of the Oshika Peninsula of Tohoku and the hypocenter was approximately 24 km deep. The focal region of this earthquake was approximately 500 km in length, 200 km in width, and 67500 km^2 in area.

The Building S, which is the subject of this research, is a super high-rise building that was built on reclaimed land in the northern Osaka Bay area and is located 769 km from the epicenter. Despite this distance, Building S swayed on a grand scale and the peak displacement reached more than 1.3 m at the top floor. In addition, while no significant damage to the structural members was found, the nonstructural members sustained extensive damage. This building has 55 stories above ground (two stories are placed as a penthouse) and 3 below. Its height is 256 m, making it the third tallest building in Japan at present. The reason for the extensive damage is believed to be the resonance between the natural period of the building and the long-period wave of the earthquake at the site.

This means that the Osaka region, where Building S is located, would receive massive earthquake-induced vibrations from the predicted Tonankai or Nankai megathrust earthquake if one of them strikes in 30 to 50 years as Japanese seismologists expect. To prepare for such an earthquake, the reason why the peak displacement exceeded 1.3 m on the top floor of Building S during the Tohoku-Oki Earthquake needs to be investigated thoroughly so that necessary measures can be implemented to mitigate the risk.

2. RESPONSE ANALYSIS OF 1-DOF DAMPER SYSTEM

First a 1-DOF system model was created. The first natural period and damping constant of the earthquake response of the one-mass spring-damper system were identified in order to minimize the residual error with respect to the acceleration observed on the 52nd floor.

The legends on the figure denote the clockwise angle from the north: 229 refers to the short-side direction and 319 refers to the long-side direction. Hereafter, the short side direction is referred as the 229 component, and the long-side direction is referred as the 319 component.

Of the observation records on the 52nd floor, 52FN (north side observation point) will be the main subject of the analysis here.

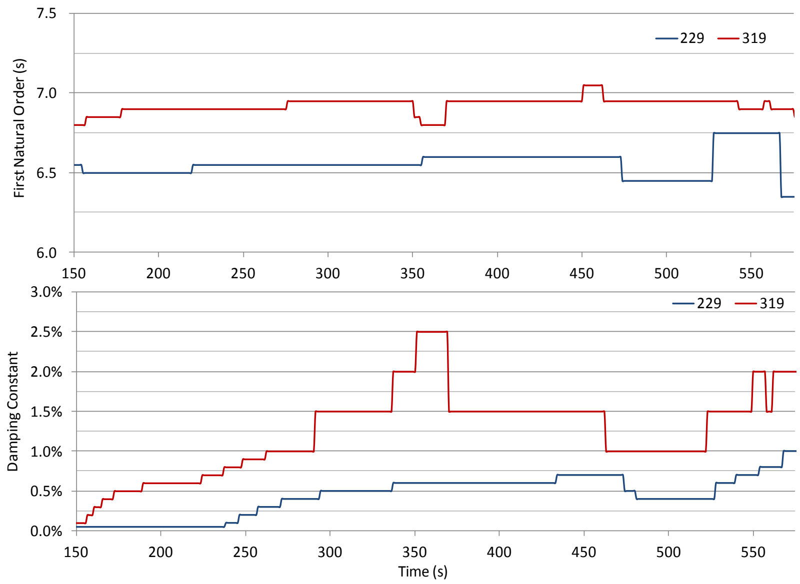


Figure 1. Time History of First Natural Orders and Damping Constant

With respect to this time history, the mean first natural period and damping constant at every 50 s duration are obtained, and the validity of the one-mass spring-damper system was accordingly analyzed in increments of 50 s. The acceleration time history obtained from this analysis was taken as the acceleration time history of the one-mass spring-damper system model. Then, the velocity and displacement that are obtained by integrating this acceleration time history are considered as the velocity time history and displacement time history of the one-mass spring-damper system.

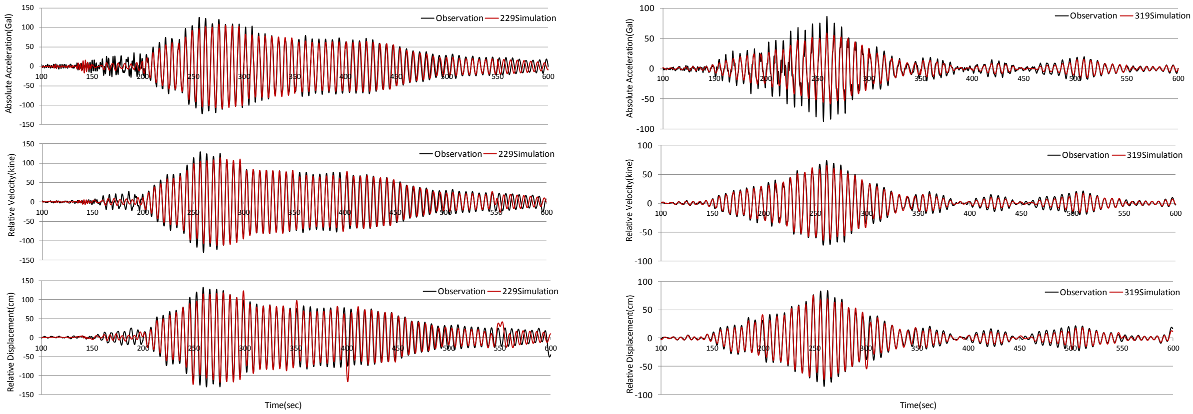


Figure 2. Comparison between Simulation Results from 1-DOF and Observation Records from Tohoku-Oki Earthquake
(From Top, absolute acceleration, relative velocity, and relative displacement)

The simulation results roughly matched with the observation records, which confirmed that this 1-DOF damper system model is valid. These results indicate that the influence of the first mode is predominant and that the higher modes do not have a strong influence.

3. RESPONSE ANALYSIS OF 53-DOF DAMPER SYSTEM

Using nonlinear restoring force characteristics and the mass of each story, which were provided by the "N" architectural design firm in Japan, a multi-DOF response analysis was performed. In this analysis, the first natural frequency agreed with the observation records; however, the second natural frequency did not match; therefore, to account for this, stiffness was adjusted.

The stiffness was adjusted as shown in the following figure, where α times the stiffness was applied uniformly to the 35th floor and above, β times the stiffness was applied to the 25th floor and below, and stiffness between the 35th and 25th floors was left linearly interpolated. Here, to minimize the residual error with respect to the observed waves, the damping is set as 0.5% in the short-side direction and at 2.0% in the long-side direction based on the 1-DOF analysis.

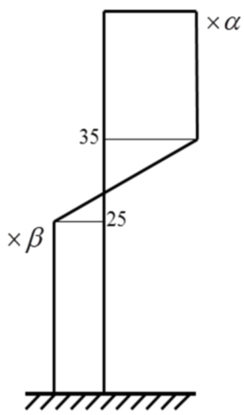


Figure 3. Stiffness Adjustment

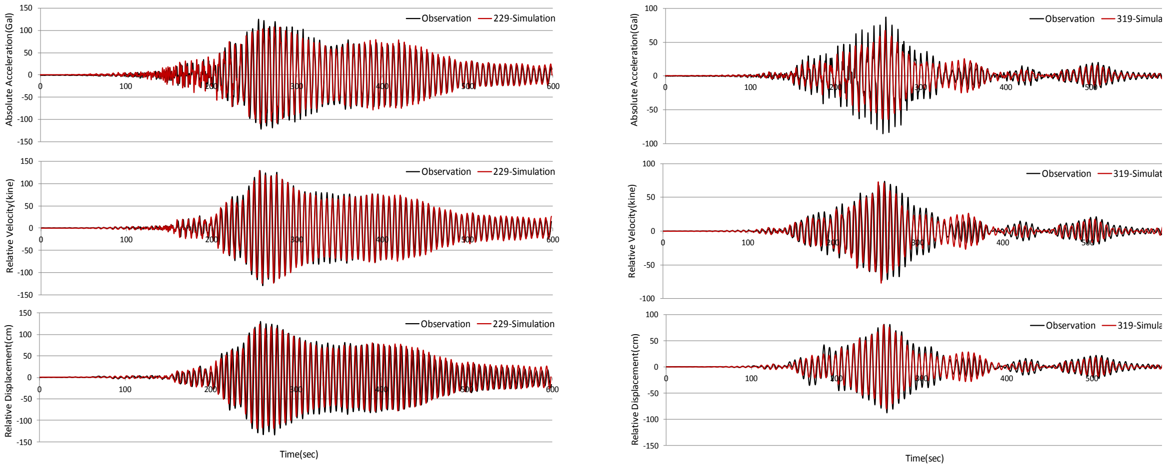


Figure 4. Comparison between Simulation Results from 53-DOF and Observation Records from the Tohoku-Oki Earthquake
(From top, absolute acceleration, relative velocity, and relative displacement)

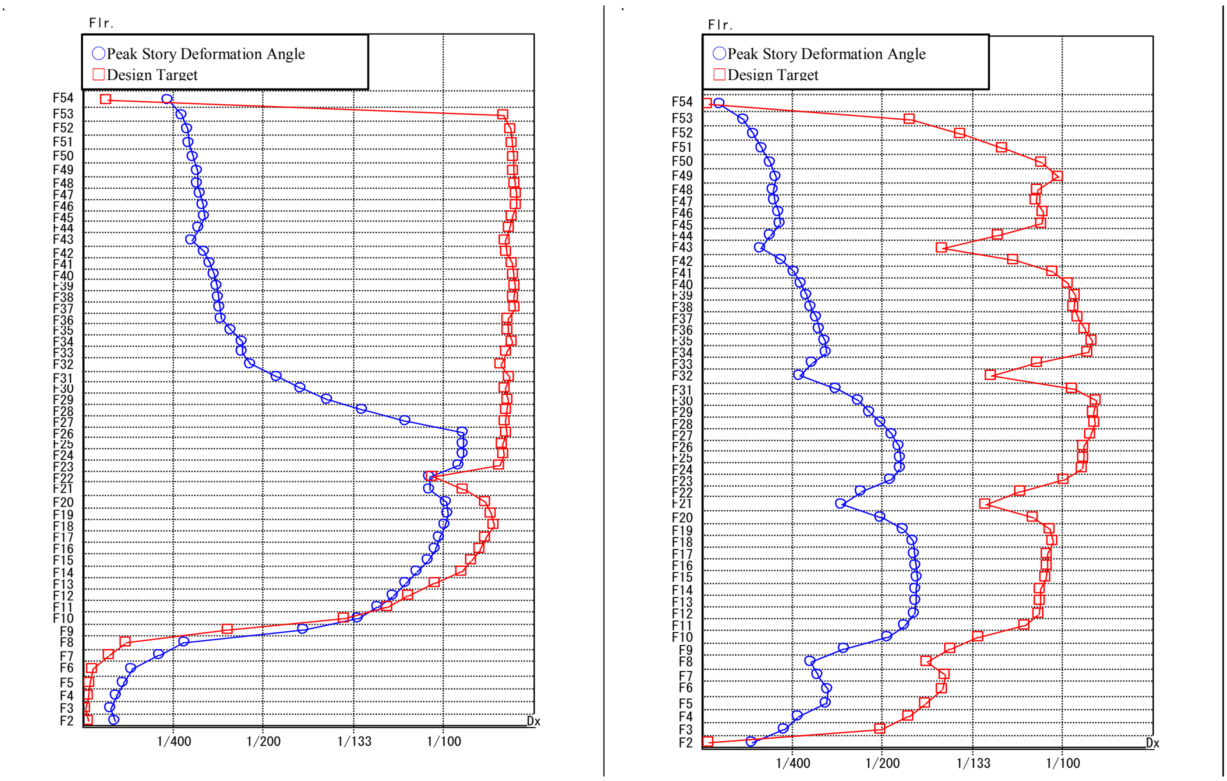


Figure 5. Peak Story Deformation Angle of Each Story (Left:229 Right:319)

(The design target in red refers to the elastic limit based on the data provided by N architectural design firm)

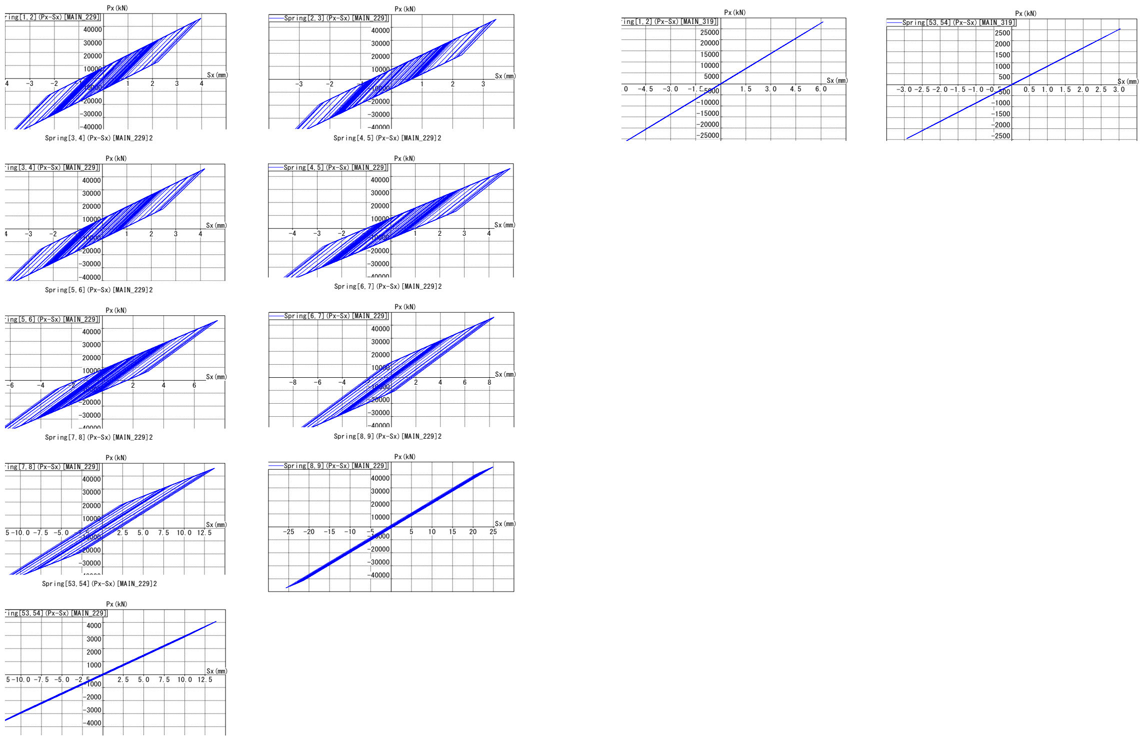


Figure 6. Story Shear Force versus Story Deformation Charts

The following presents the analytical results where the damping was increased by adding a damper as earthquake-resistant reinforcement. The damping constant here is 5.0% with the addition of the damper.

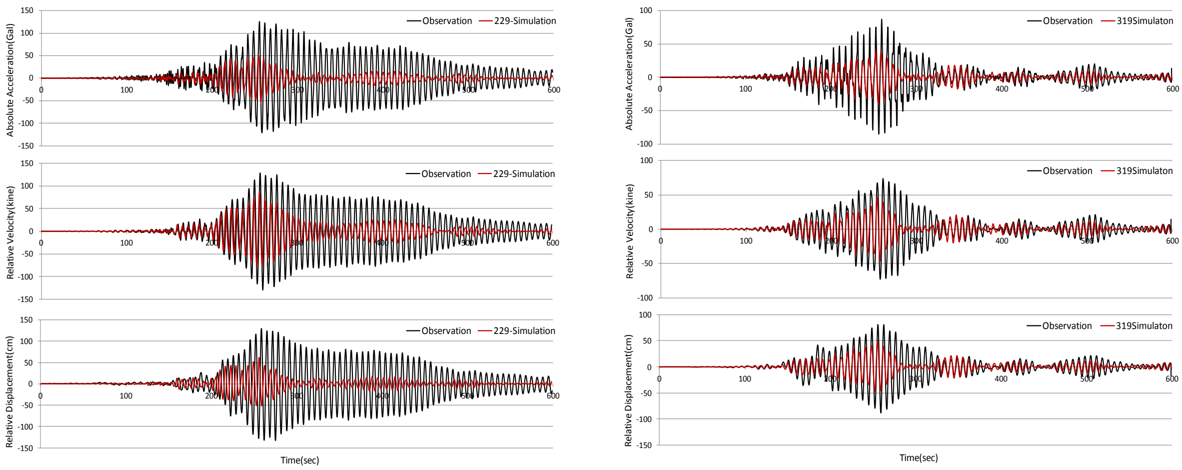


Figure 7. Comparison between Simulation Results and Observation Records from the Tohoku-Oki Earthquake with Damping Constant of 5.0%

(From top, absolute acceleration, relative velocity, and relative displacement)

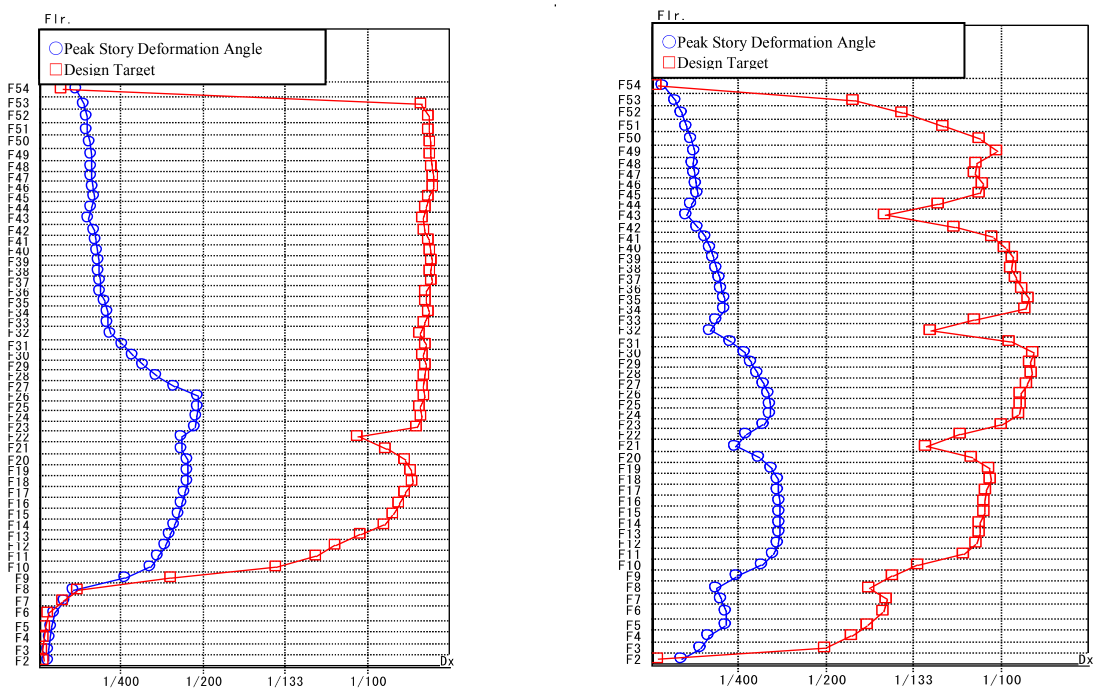


Figure 8. Peak Story Deformation Angle of Each Story with Damping Constant 5.0%

(Left:229 Right:319)

(The design target in red refers to the elastic limit based on the data provided by N architectural design firm)

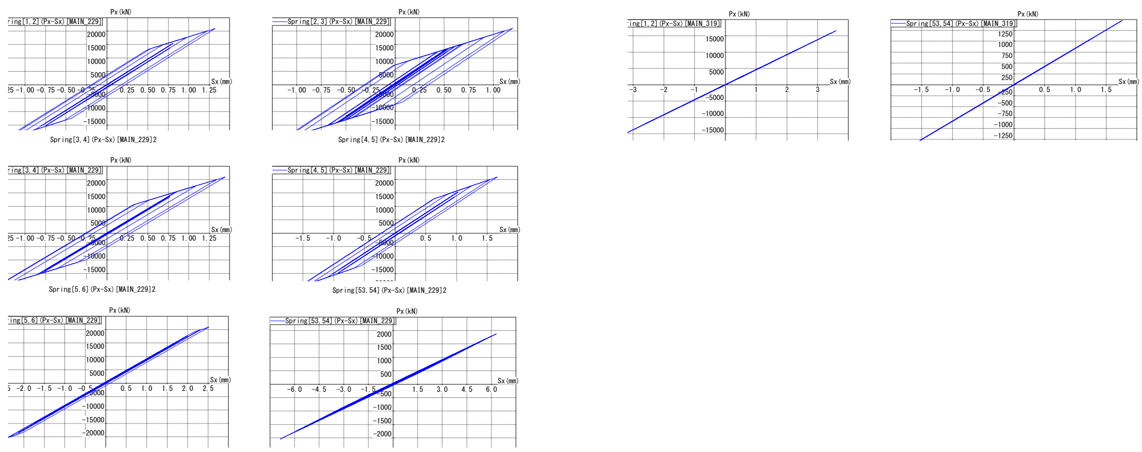
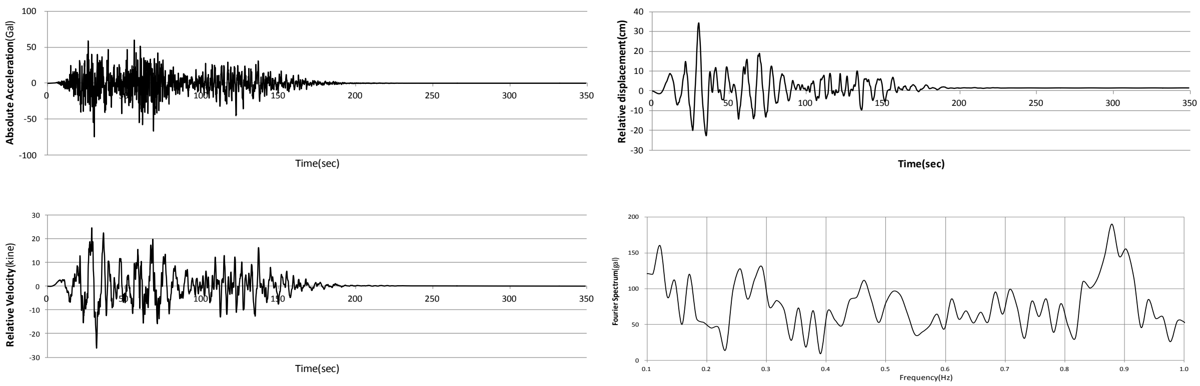


Figure 9. Story Shear Force: Story Deformation Charts with Damping Constant 5.0%

4. SEISMIC RESPONSE PREDICTION FOR THE NANKAI EARTHQUAKE

The strong earthquake ground motion from the possible Nankai Earthquake was estimated by using a stochastic Green's function that effectively covers long-period ground motions. The variation of the heterogeneous distribution on the asperities was factored into this seismic response prediction along with the heterogeneous characteristics of the asperity on the earthquake source fault and the saturation characteristics of seismic motion near the earthquake source fault.

There is a model that consists of three major asperities and background regions, which was developed based on the Kamae model and a publication from the Headquarters for Earthquake Research Promotion, but it differs from the Kamae model for the possible Nankai Earthquake. That model factored in the assumptions that 22% of the asperity portion slips 1.5 times more than the mean slipping amount and that the rest (78%) slips less than the mean amount because the asperities of this earthquake source would slip far more heterogeneously in order to account for the natural fractal characteristics of the seismic sources.



Time History Waveforms and Spectrum of the Possible Earthquake Ground Motion (OSKH02)

Figure 10. Seismic wave and spectrum of predicted ground motion

Then the seismic response of the S building for the possible Nankai Earthquake was predicted by using the above-mentioned 53-DOF system model. The following figures show the prediction results.

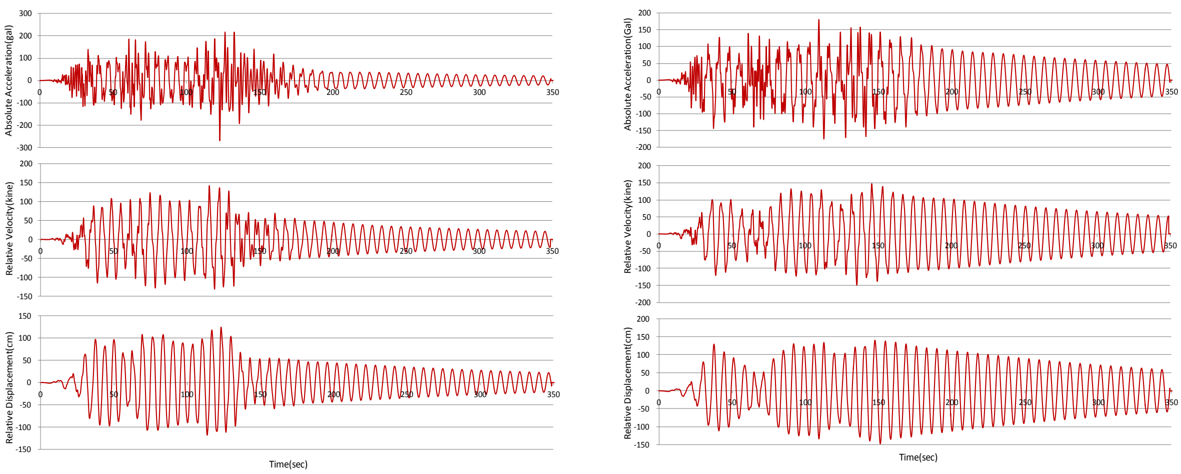


Figure 11. Seismic Response Prediction for the predicted Nankai Earthquake

(From Top, absolute acceleration, relative velocity, and relative displacement)

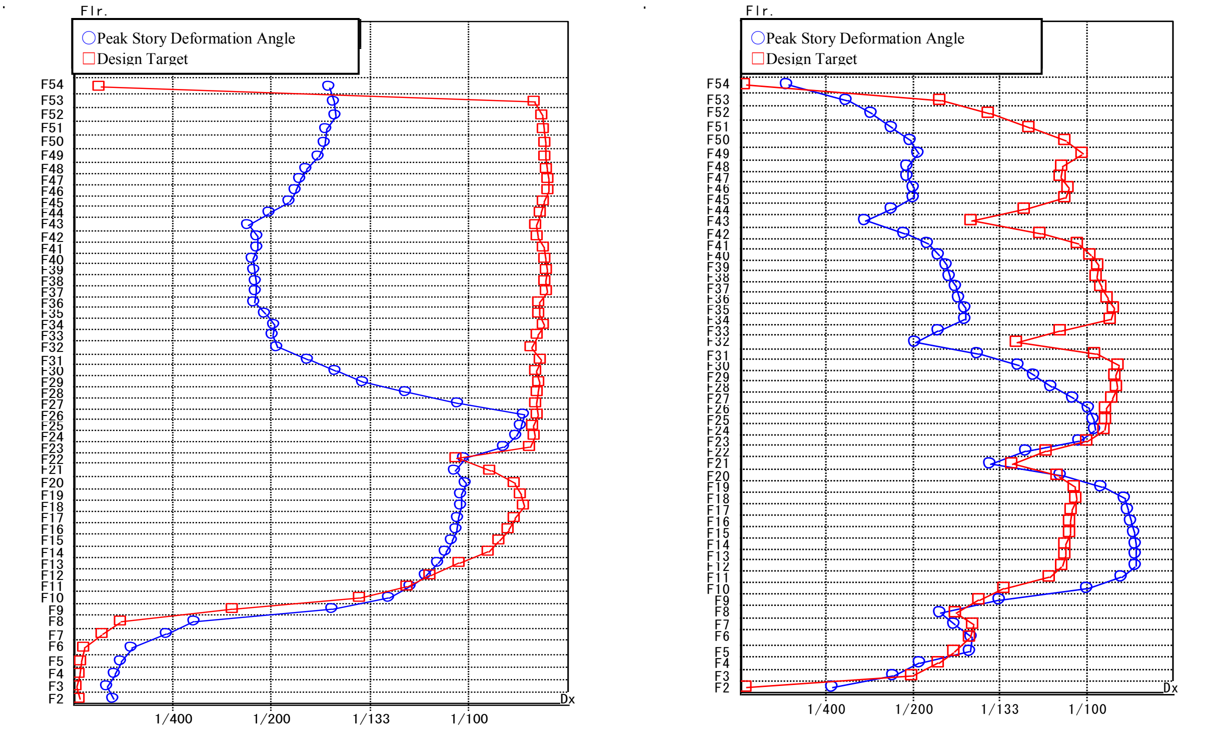


Figure 12. Peak Story Deformation Angle of Each Story for the Nankai Earthquake(Left:229 Right:319)

(The design target refers to the elastic limit based on the data provided by N architectural design firm.)

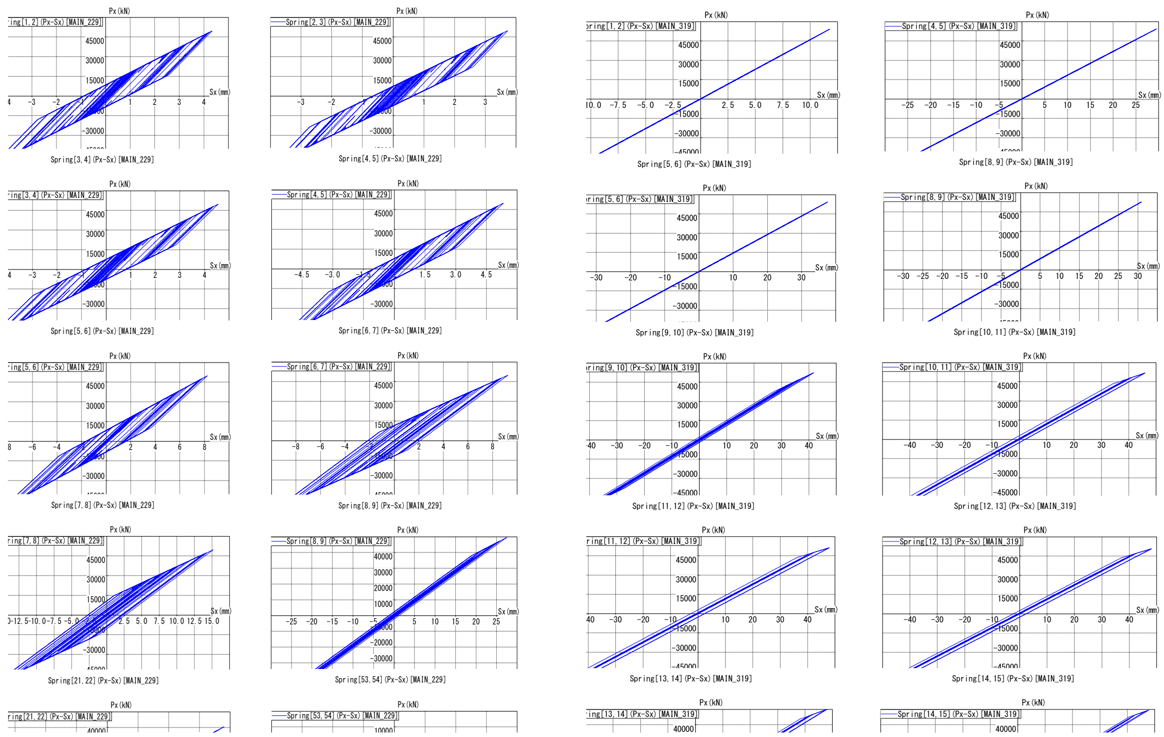


Figure 13. Story Shear Force of Stores Exceeded Elastic Limit versus Story Deformation Charts

These results indicated that the peak acceleration response exceeded 200 gal on the 52nd floor, and the peak displacement exceeded 1.0 m as well. In addition, the 229 component (short-side direction) indicated that approximately lower 10 stories as well as the top floor deform into the nonlinear regime as indicated in the analytical results for the Tohoku Earthquake, and the 319 component (long-side direction) indicated that approximately lower 20 stories would deform into the same level.

The damping applied here was 0.5% in the short-side direction and 2.0% in the long-side direction, which are the same values that are used for the 53-DOF system model.

Then the analytical results where the damping was assumed to be 5.0% are presented below.

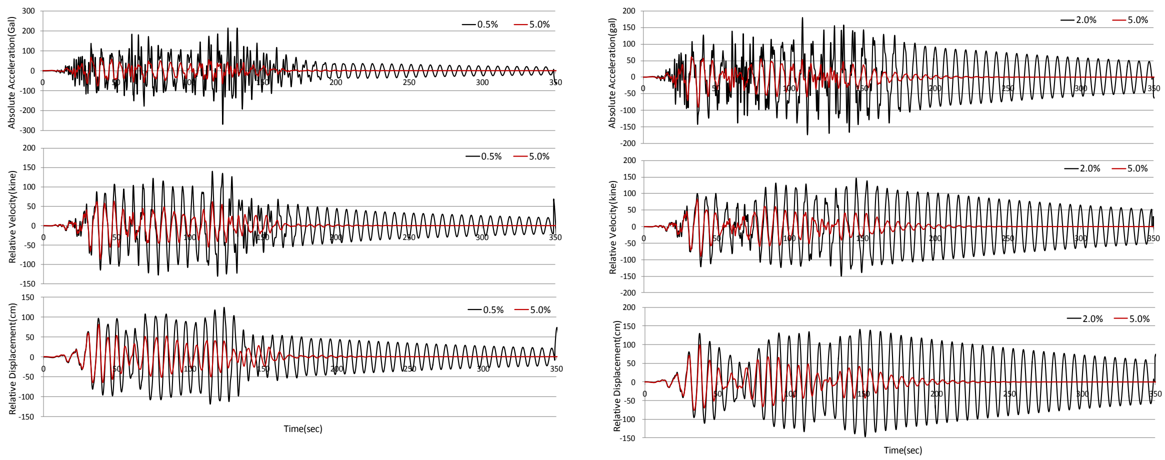


Figure 14. Response Prediction for Nankai Earthquake: Comparison before/after Additional Damping

(From top, absolute acceleration, relative velocity, and relative displacement)

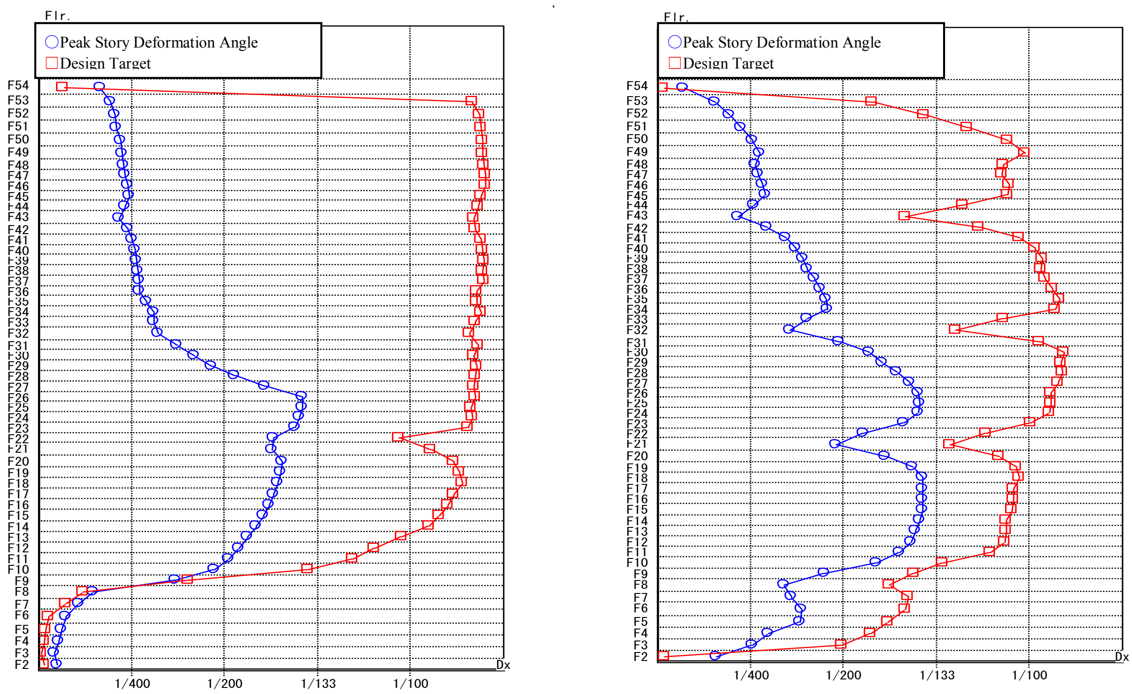


Figure 15. Peak Story Deformation Angle of Each Story with Damping Constant 5.0%.

for the predicted Nankai Earthquake (Left:229 Right:319)

(The design target refers to the elastic limit based on the data provided by N architectural design firm.)

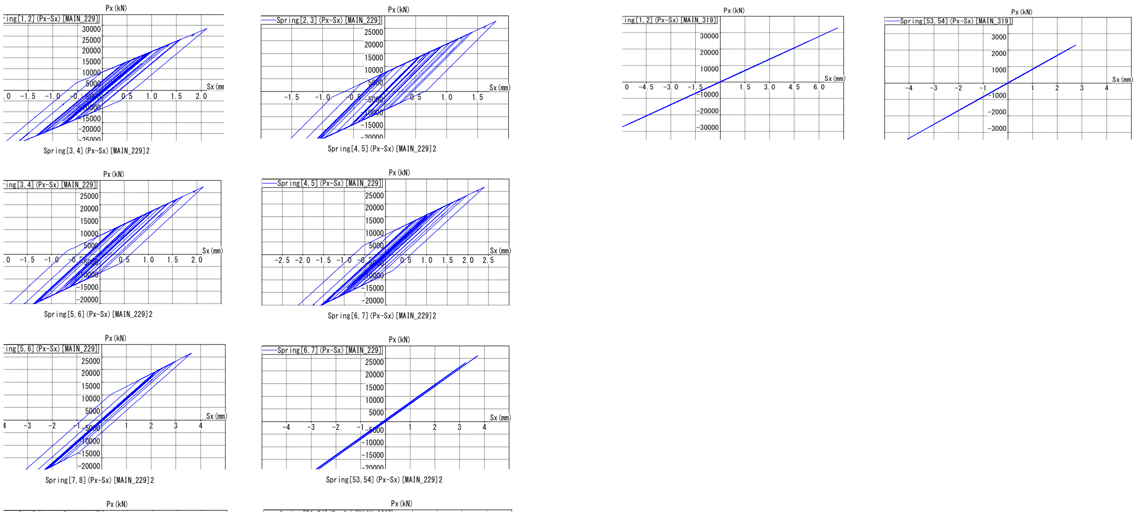


Figure 16. Story Shear Force: Story Deformation Charts with Damping Constant 5.0% for the predicted Nankai Earthquake

These response calculations mean that the reaction will be smaller if the damping ratio is 5.0%. But the stories which will be plastic are still there.

5. SUMMARY

The simulation using a 1-DOF damper system model, which was prospectively validated as a roughly effective method, identified that the influence of the first-order mode is predominant and that the higher-order modes did not influence the target Building S in the Tohoku Earthquake to the same extent. This simulation also revealed that the nonlinearity is not particularly significant since the period and damping constant are not drastically altered during the main shock. The obtained damping was 0.1% to 1.5% (short-side direction) and 0.5% to 2.0% (long-side direction), smaller than the assumption that was factored in when the building was designed.

The 53-DOF system model allowed more detailed analysis, and by making the first-order mode and second-order mode correspond to each other, a model that roughly agrees with the observation records was developed. The analysis with that model found that approximately 10 stories on the bottom as well as the top floor may have exceeded the pure elastic limit. In addition, according to the response predicted from this analysis, in which a damper was added to increase damping as earthquake-resistant reinforcement, the damper controlled the resonance and reduced the motion in the later response; however, the peak response values in time did not significantly change.

In this research, by using the 53-DOF system model, response analysis was performed with respect to the possible earthquake ground motion from the predicted Nankai Earthquake. Even for the stronger input ground motion for the predicted Nankai earthquake, the building would behave quite similar way as we observed during the Tohoku-Oki earthquake.

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