3-D Seismic Response Analysis of a High-Rise Building in Tokyo, Japan, for the 2011 Tohoku Earthquake

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LISBOA 2012

SUMMARY:
We report seismic response and numerical simulations of a high-rise building for the 2011 Tohoku Earthquake (Mw 9.0). The building is the Shinjuku campus of Kogakuin University of the 29-story steel structure of 143 m height, and is located in the downtown of Tokyo, Japan. Since the previous 3-D moment frame model (Hoshi *et. al.*, 2010) showed shorter natural periods than observation records during the 2011 Tohoku earthquake, we constructed a new model by considering the shear deformation at the joint panels between beams and columns. The new model's natural periods became close to the observed results. In addition, the new model shows close seismic response to the observations. In particular, it is important that the new model show the smaller plasticity rates of the structural elements and the maximum drift. This is probably caused by the relaxation of the stress at the beam edge, because of the elastic deformation.

Keywords: 3-D Seismic response analysis, High-rise building, The 2011 Tohoku Earthquake

1. INTRODUCTION

In the Tokyo metropolitan area, there are more than 320 high rise buildings taller than 100 m, which have to be prepared for the hypothetical large earthquakes, such as the Tokai-Tonankai earthquake of M8 and the Tokyo Metropolitan Earthquake of M7. To predict reliable building response, it is important to obtain accurate building models. The 2011 Tohoku earthquake provided the opportunity to know the accurate vibration characteristics of the high-rise building of the Shinjuku campus. As for the building model (Hoshi *et al.*, 2010) constructed a 3-D moment frame model, and estimated the response and damage for the hypothetical large earthquakes (Nakano *et al.*, 2010). However, we found that the model needed improvements, after comparing the simulation and observation for the 2011 Tohoku earthquake (Arata *et al.*, 2011). In this study, we propose a new 3-D moment frame model by considering the shear deformation at the joint panels between beams and columns

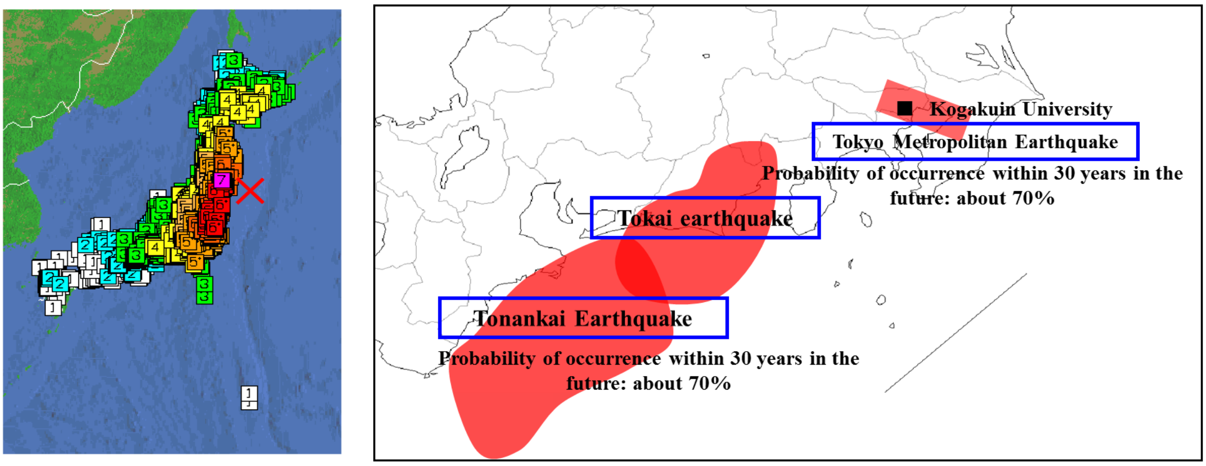


Figure 1.1. Distribution of seismic intensities of Tohoku Earthquake (Japan Meteorological Agency) and distribution of scenario earthquakes (The Headquarters for Earthquake Research Promotion)

2. HIGH-RISE BUILDING OF KOGAKUIN UNIVERSITY

Table 2.1. shows the outline of the structure of Kogakuin University. Figures 2.1.to 2.4. show the typical floor plan, the standard flaming plan, the elevation and the flaming elevation. The building has 29 stories above ground and 6 stories below. It has the double cores at the east and west sides, and the cores are connected by the long span beams of about 26 m. The super-frames of the truss structures are located on the 16th and 21st floors in the EW direction. Tables 2.2. to 2.4. show examples of the structural elements at a representative floor.
The building has acceleration sensors, which are located at the G.L.-100 m borehole, the 6th basement, the 1st, 8th, 16th, 22th, and 29th floors. The building emergency manager can always monitor and record the building response for strong seismic and wind response.

Table 2.1. Outline for Kogakuin University

The site	Shinjuku, Tokyo, Japan
Completed year	1989
Area of typical floor	$1170m^2$
Number of floors	Ground floors:29 stories Basement floors:6 below
Aspect ratio	NS:5.59 EW:3.73
Structure classification	Ground floors: steel construction
	From B1 to B2 floors : steel-framed reinforced concrete construction
	From B3 to B6 floors : reinforced concrete construction

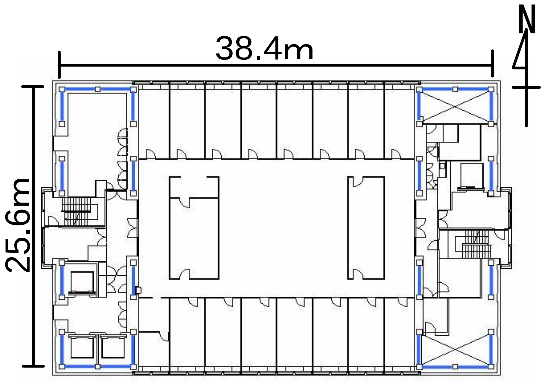


Figure 2.1. University typical plan

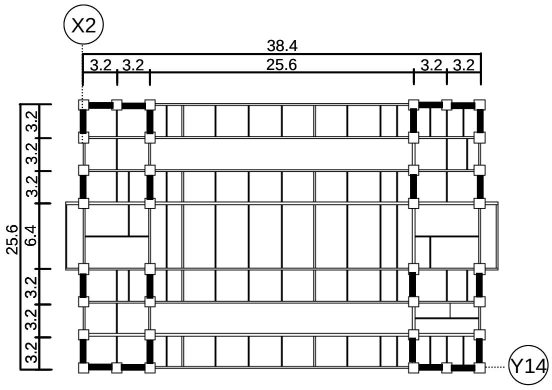


Figure 2.2. Universiy standard flaming plan

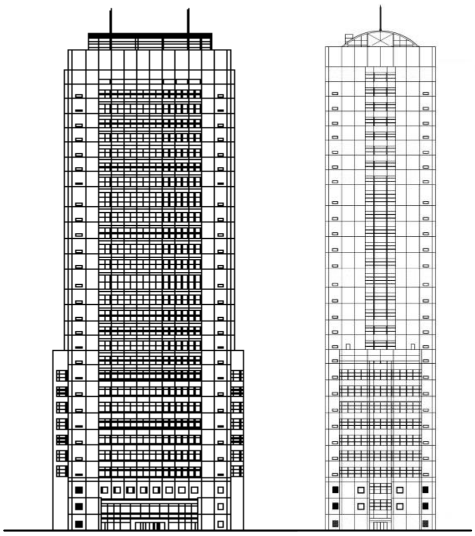


Figure 2.3. University elevation
Left: North side Right: East side

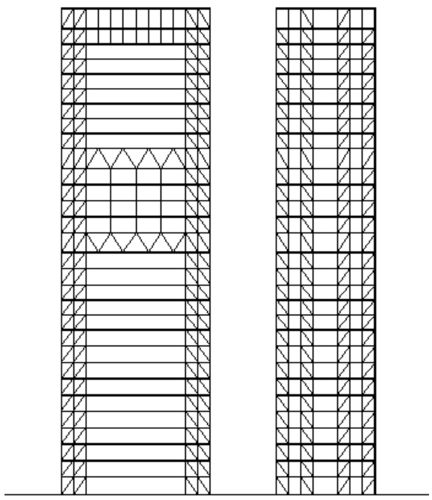


Figure 2.4. University framing elevation
Left: Y14 line Right: X2 line

Table 2.2. Pillar size

Floor	Pillar Size
30	□-488-19
20	□-500-25
10	□-530-40
1	□-550-50

Table 2.3. Brace size

site	Brace size
X14	H-250×250×9×14
Y2	H-250×250×9×14
Super frame	H-300×300×12×22

Table 2.4. Long span beam size and Girder size

Floor	Long span beam size	Girder size
30	H-600×300×12×25	H-100×320×19×25
20	H-600×350×12×32	H-100×300×19×28
10	H-600×400×12×32	H-100×350×19×28
2	H-600×350×12×32	H-100×320×19×28

3. SEISMIC RESPONSE ANALISYS

3.1. Analytical software

We construct 3-D moment frame models of Kogakuin University for the seismic response, by using the software, SNAP (Structure Non-linear Analysis Program) ver.4, which is the dynamic finite element method including elasto-plasticity analysis.

3.2. Outline of 3-D moment frame model

3.2.1. Assumptions of the model

Figure 3.2.1. shows an axonometry of 3-D moment frame model of the building. Since the basement is a very rigid structure of the steel-framed reinforced concrete, we model the structures above the ground level only. The other assumptions are shown below.

- All the floors are rigid for lateral forces
- All the columns are elastic
- The beams have hysteretic characteristics of bilinear
- The braces have hysteretic characteristics of buckling (the Shibata and Wakabayashi model (Shibata et al. 1982)
- Panel zones between columns and beams show elastic deformations
- The attenuation model is the Rayleigh-type damping of 1% for the 1st and 2nd modes

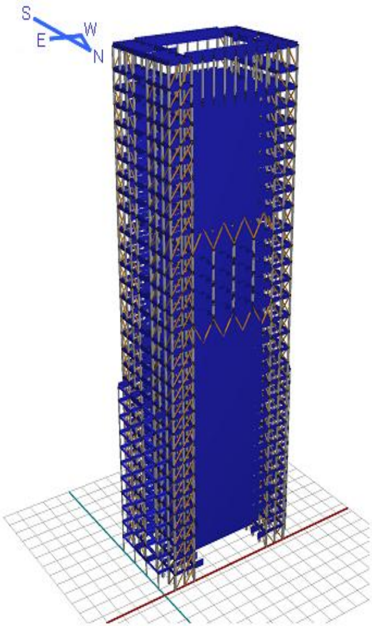


Figure 3.2.1. Axonometry of 3-D moment frame model

3.2.2. Model of Panel Zones

In the previous model (Hoshi et. al., 2010), we did not consider the deformation of the panel zones, whereas we include it in our new model in this study. The rigidities of the panel zones are given by the following equation (Kozo System Corporation).

$$\begin{pmatrix} m_{xp} \\ m_{yp} \end{pmatrix} = \begin{bmatrix} K_{yp} & 0 \\ 0 & K_{xp} \end{bmatrix} \begin{pmatrix} \gamma'_x \\ \gamma'_y \end{pmatrix} \quad (3.2.1)$$

$$K_{xp} = GV_{xp} \quad K_{yp} = GV_{yp} \quad (3.2.2)$$

where, m_{xp} and m_{yp} are the shearing moment, γ_x and γ_y are shearing deformation angle, K_{xp} and K_{yp} are the joint panel rrigidities, G is the shearing elasticity coefficient, and V_{xp} and V_{yp} are the panel volumes.

Table 3.2.1. shows the natural periods of the previous model, the new model, microtremor measurements, and the observations from the Tohoku earthquake. The natural periods of the new model are closer to those of the observations of the Tohoku Earthquake.

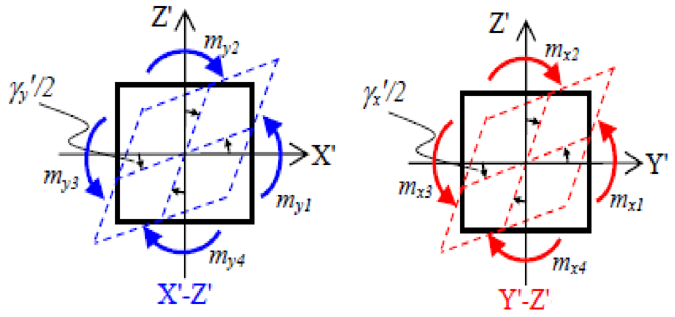


Figure 3.2.2. Shearing moment and shearing deformation angle (Kozo System Corporation)

Table 3.2.1. Comparisons of the natural period

	Natural period (s)			
	EW		NS	
	First mode	Second mode	First mode	Second mode
Microtremor measurements	2.63	0.87	2.75	0.89
Observation from The Tohoku Earthquake	3.01	1.00	3.11	0.93
Previous 3-D model	2.83	0.99	2.91	0.93
New 3-D model	2.95	1.04	3.09	0.99

3.3. Input earthquake motion

Figures 3.2.1. and 3.2.2. show the input accelerations, which are the records at the 1st floor during the Tohoku earthquake, and their velocity response spectra. They show very long durations (more than 10 minutes) and broad frequency contents. We use the three components (EW, NS, and UD) for the simulations.

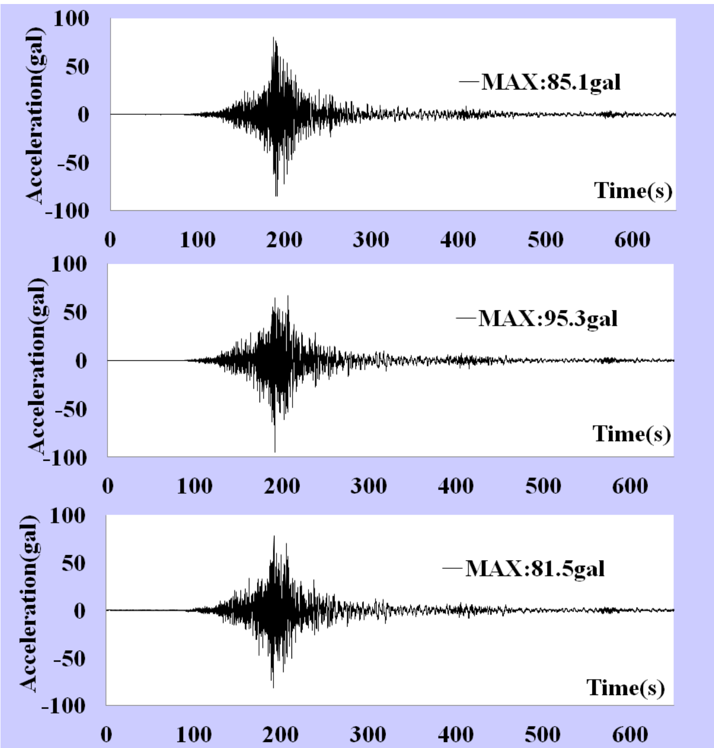


Figure 3.2.1. Input acceleration wave (Top: EW, Center: NS, Under: UD)

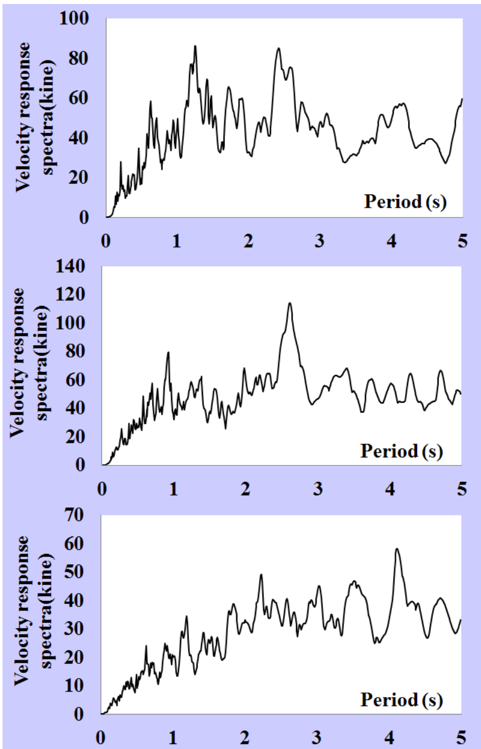


Figure 3.2.2. Velocity response spectra (Top: EW, Center: NS, Under: UD)

4. SIMULATION RESULTS

Figure 4.1. shows the comparison of accelerations of the EW components among the two simulation models and observation at the 29th floor, and Figure 4.2. shows the maximum response values. The new model generally show better results. However, it should be noted that the maximum responses of the new model underestimate the observations in velocities and displacements.

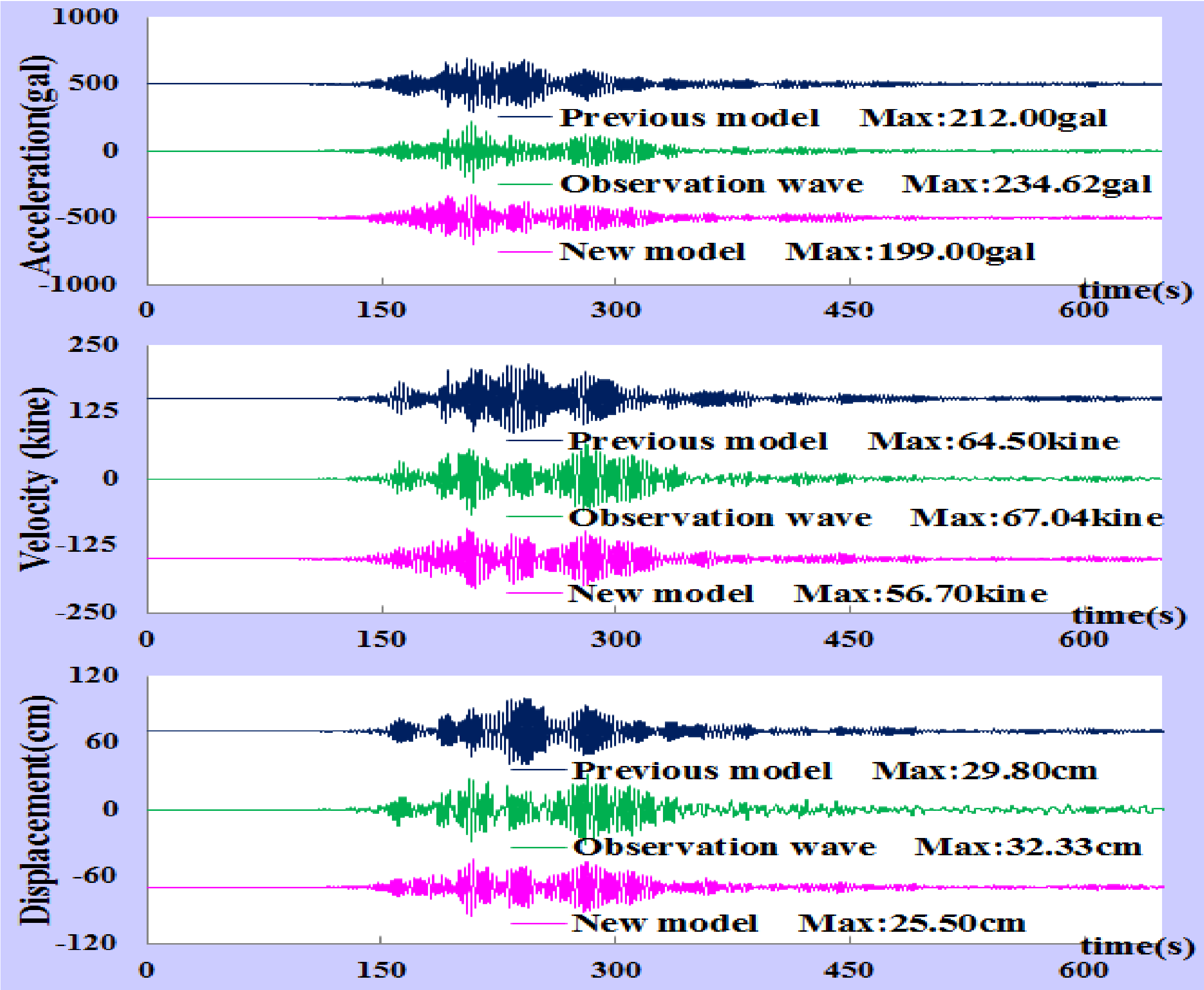


Figure 4.1.
The simulated results and the observation at the 29th floor (EW)
Top: Acceleration, Center: Velocity, Under: Displacement

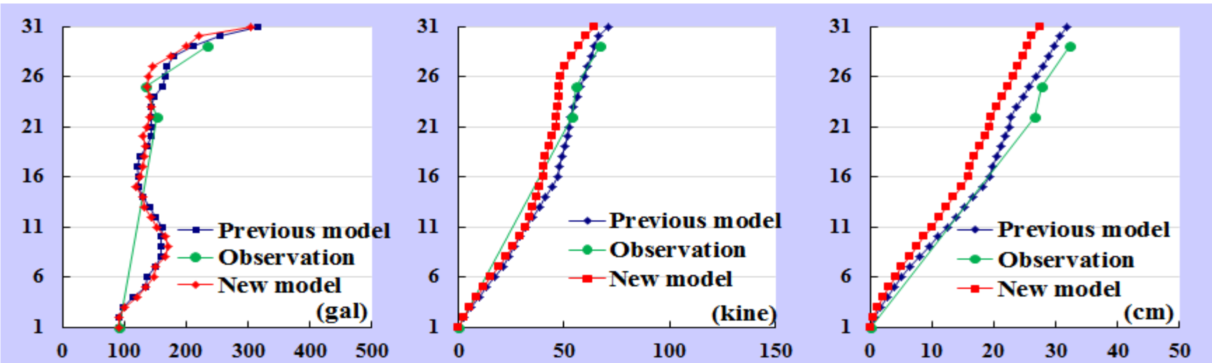


Figure 4.2.
The maximum response values (EW)
Left: Acceleration, Center: Velocity, Right: Displacement

Similarly, Figure 4.2. shows the comparison of accelerations of the NS components at the 29th floor, and Figure 4.2. shows the maximum response values. Again, the new model show better results than the previous model.

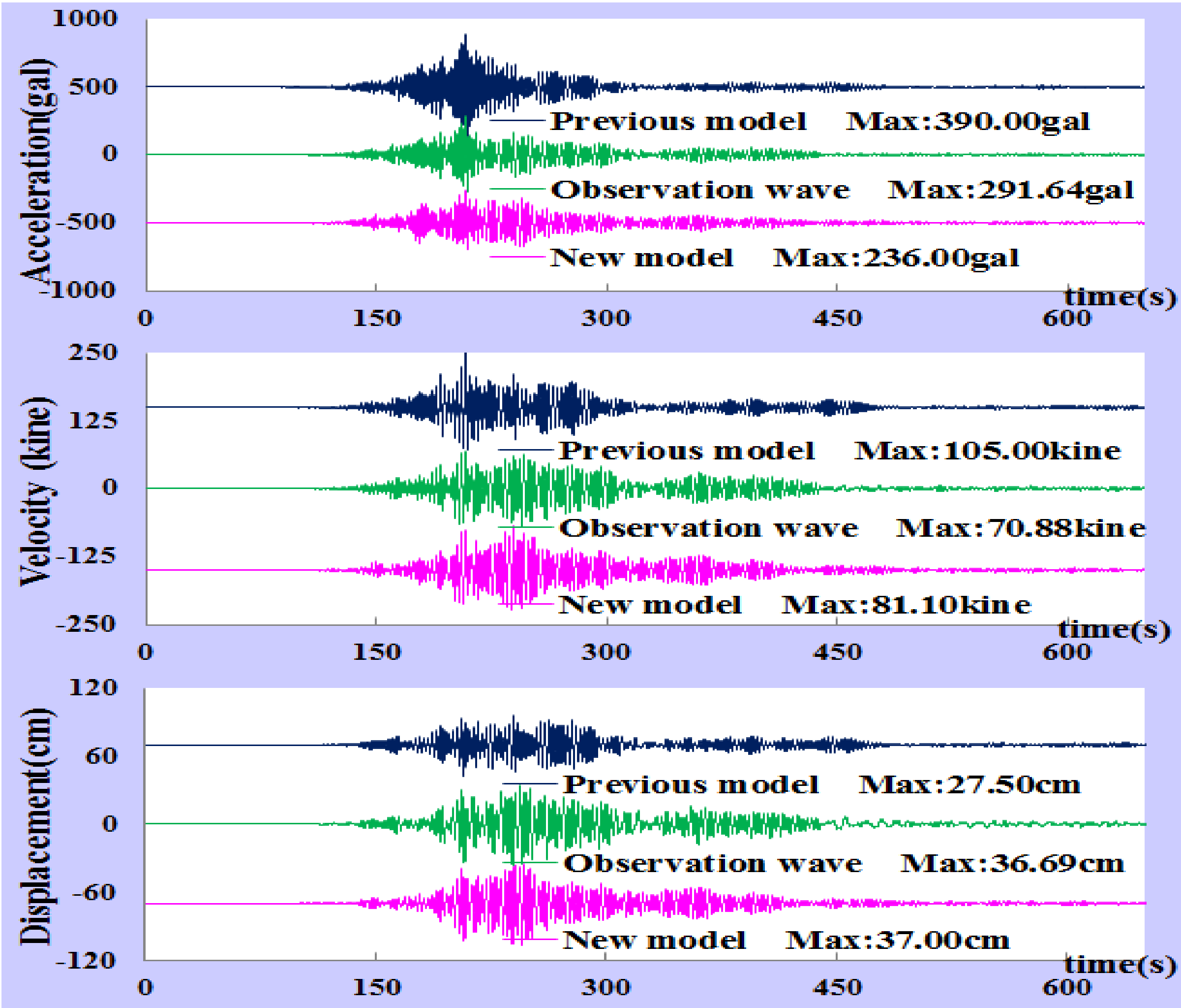


Figure 4.3.
The simulated results and the observation at the 29th floor (NS)
Top: Acceleration, Center: Velocity, Under: Displacement

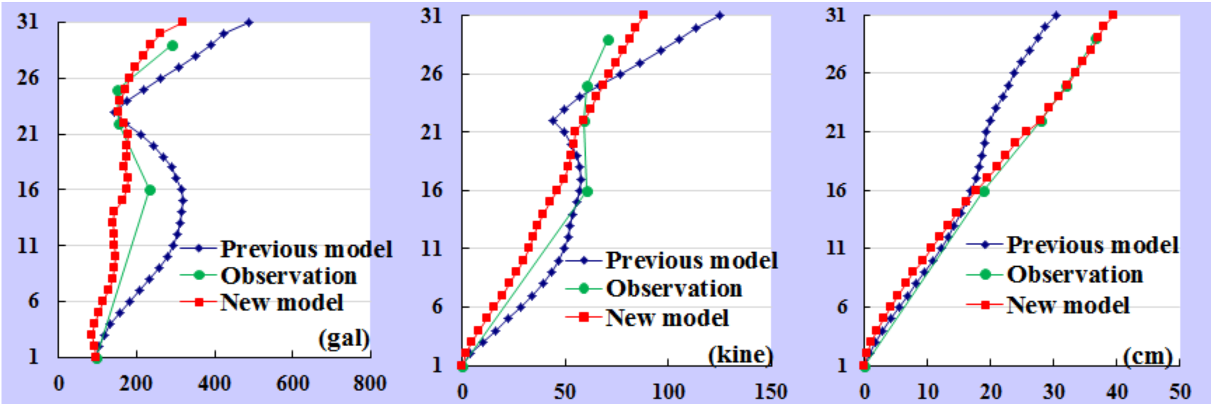
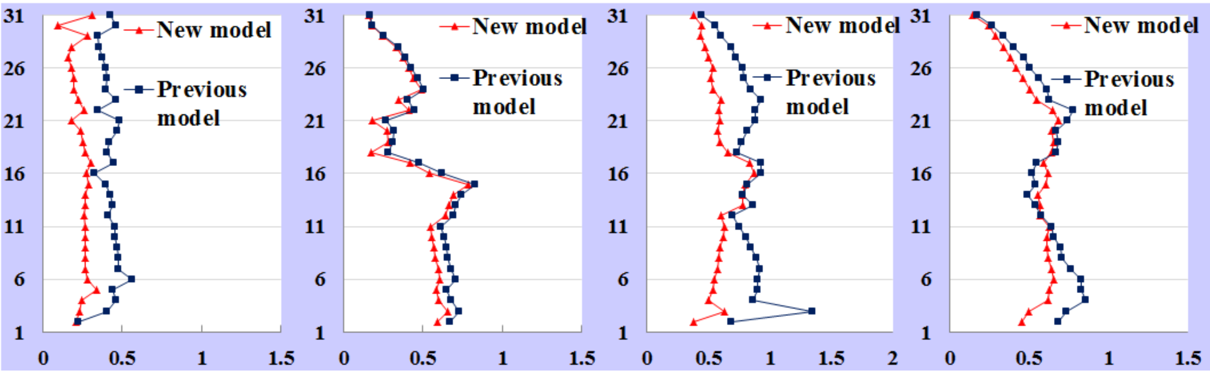


Figure 4.4.
The maximum response value (NS)
Left: Acceleration, Center: Velocity, Right: Displacement

Figure 4.5. shows the comparisons of the maximum plasticity rates between the two models. The previous model show larger plasticity rates than those of the new model, especially in the beams. This is probably caused by the relaxation of the stress at the beam edge, because of the elastic deformations in the new model. Consequently, the maximum drift angles are smaller in the new model, as shown in Figure 4.6.



Beam (EW) Brace (EW) Beam (NS) Brace (NS)

Figure 4.5. The maximum plasticity rate

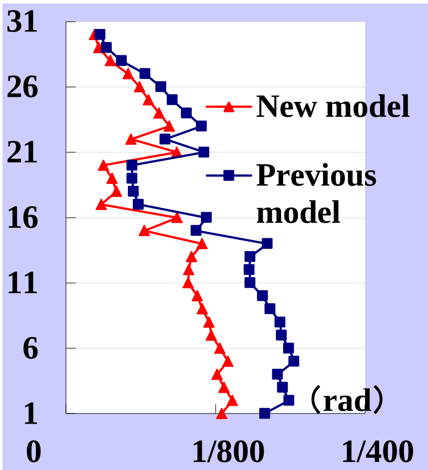


Figure 4.6. The maximum story drift angle (EW)

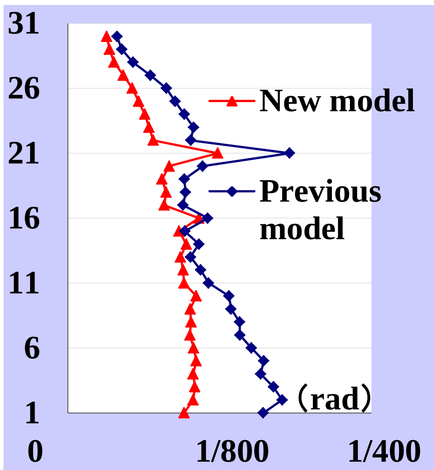


Figure 4.7. The maximum story drift angle (NS)

5. CONCLUSION

We proposed a 3-D moment frame model of the steal high-rise building of Kogakuin Univeristy, by considering the shear deformation of the panel zones. As compared with the previous model, which neglects the shear deformation, the new model shows close results to those of the observation during the 2011 Tohoku earthquake. In particular, it is important that the new model show the smaller plasticity rates of the structural elements and the maximum drift. This is probably caused by the relaxation of the stress at the beam edge, because of the elastic deformation.

AKCNWLEDGEMENT

We thank Mr. Hoshi (Hazama Corporation) and Mr. Shimamura (Fujita Corporation) for providing the 3-D moment-frame model of Kogakuin University. This work was supported by "MEXT (Japan Ministry of Education, Culture, Sports, Science and Technology)-Supported Program for the Strategic Research Foundation at Private Universities for establishing Research Center of Urban Disaster Mitigation (UDM) in Kogakuin University.

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