

## Proposing a method of seismic load for aftershocks of a huge earthquake

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**Abstract:** After the 2011 off the Pacific coast of Tohoku Earthquake, M5-M6 class aftershocks occurred frequently, and M7 class aftershocks occurred several times. Based on this experience, it was clarified that countermeasures against not only the main shock but also its aftershocks are important issues for M8 class and larger earthquakes. Therefore, this paper proposes a seismic performance evaluation method based on aftershock hazard evaluation. Specifically, aftershock hazard assessment for the assumed Nankai Trough Earthquake is performed based on statistical characteristics of the huge earthquake's aftershock evaluated in previous studies. Probability or number of aftershocks' ground motion exceeding the design seismic load is evaluated from the aftershock hazard.

**Keywords:** Aftershock Hazard Assessment, Business Continuity Plan (BCP)

### 1. Backgrounds

The 2011 off the Pacific coast of Tohoku Earthquake was a magnitude Mw9.1 undersea megathrust earthquake off the coast of Japan that occurred at 14:46 JST on Friday 11 March 2011. Its epicenter is approximately 70 kilometers east of the Oshika Peninsula of Tohoku and the hypocenter at an underwater depth of approximately 29 km. After the huge Earthquake, many M5-M6 class aftershocks occurred and four aftershocks which Mw over 7.0 were occurred at the same day. About one month later, Mw7 class aftershocks occurred in April 7 and 12 and the buildings were damaged by aftershocks which ground motions were same or greater than the main shock in some areas. In the case of the Nankai Trough Earthquake which magnitude is same class as the huge earthquake, it is assumed that structural damage by aftershocks. However, re-damage by many aftershocks is ignored in existing seismic load evaluation. Against this background, a method of evaluating seismic load about aftershocks for buildings continual usability is proposed in this paper.

### 2. Purpose and Outline of Proposed Method

#### 2.1 Purpose of Proposed Method

The purpose of this study is to verify the safety of the building regarding aftershocks that repeatedly occur after the main shock. The main shock will reduce the usability and seismic performance of the building. If no measures are taken, recovery from the main shock will take a long period of time, and during that period the aftershock will cause re-damage. Therefore, it is necessary to shorten the restoration period due to the main shock and to prevent re-damage due to the aftershocks by designing the building using earthquake load that takes into account not only the main shock but also the aftershocks. Conceptual diagram of preventing re-damage due to the aftershocks which is expected effects of proposed method in this paper is shown Fig. 1.

#### 2.2 Outline of Proposed Method

In proposed method, seismic load about aftershocks will be evaluated as design ground motion which contains multiple ground motion such as Fig. 2. At first, it is

necessary that a main shock occurrence is assumed. Then, number and occurrence area of aftershock is evaluated based on main shock magnitude, and aftershock hazard assessment is done. Furthermore, design ground motion which contains multiple ground motion is evaluated based on main shock and aftershocks hazard.

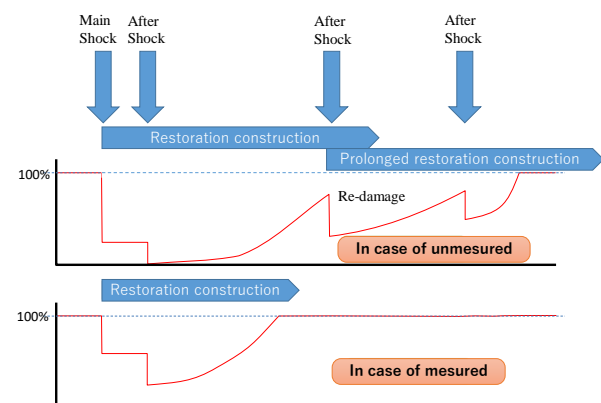


Figure 1. Expected effects of proposed method (conceptual diagram)

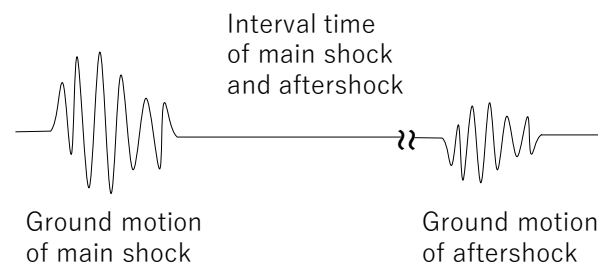


Figure 2. Concept of design ground motion evaluated by proposed method

### 3. Method for Evaluating Design Ground Motion Considered Aftershocks

#### 3.1 Method of Evaluating Aftershock Hazard

Herein a certain main shock is assumed for simplicity although specifying main shock with de-aggregation of

main shock hazard is necessary essentially. Assumed building location is in Osaka city and source of main shock is Nankai Trough Earthquake which magnitude is Mw 9.0 shown in Fig. 3. The source is same as a certain case of “Second Report of Nankai Trough Study Group on Large Earthquake Model -Strong Earthquake Fault Model-.” (The Cabinet Office 2012).

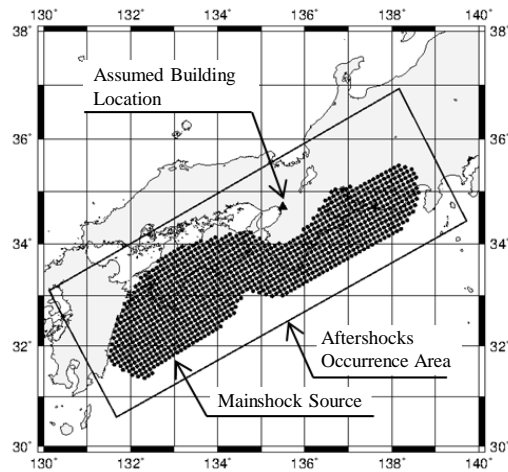


Figure 3. Assumed main shock, aftershock and building site

However, aftershocks are not assumed in the report, so aftershocks occurrence area is assumed as rectangle which depth is constant in Fig. 3. Aftershock hazard will be evaluated with the size and number of aftershocks evaluated stochastically based on statistics of past data included the 2011 off the Pacific coast of Tohoku Earthquake (Choi and Takada 2013). In aftershock hazard assessment, aftershocks of M4 and above are considered and maximum predicted aftershock size is assumed as Mw7.8. For reference, the largest aftershock of the 2011 off the Pacific coast of Tohoku Earthquake was M7.6. Average of predicted total number of aftershocks is 2,818 which probability of larger earthquake smaller as the Gutenberg–Richter law and which probability gets small with time after main shock as Fig. 4 which shows average of predicted daily number of aftershocks.

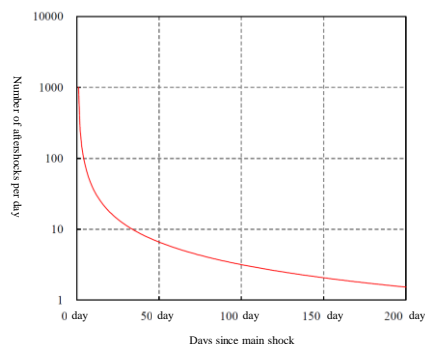


Figure 4. Predicted number of aftershocks per day

### 3.2 Results of Evaluating Aftershock hazard

Since it is assumed that the emergency recovery about damage by main shock was completed within one month and the building's strength was expected to recover, the

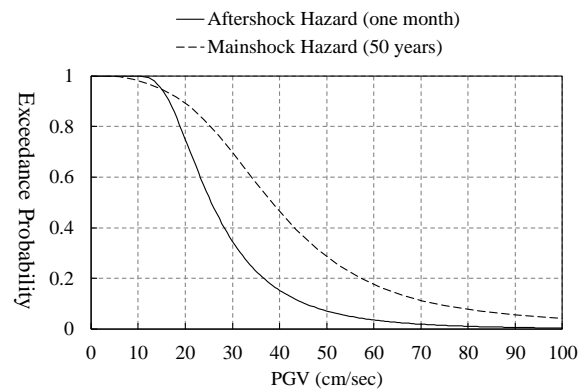
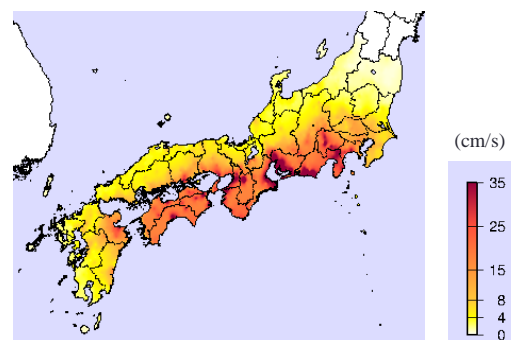
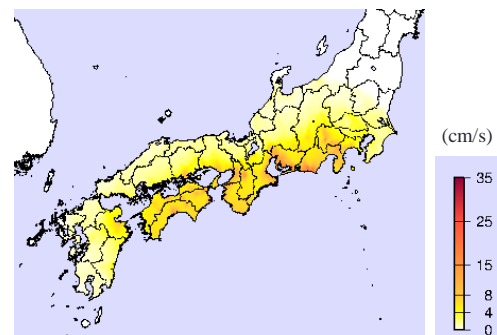


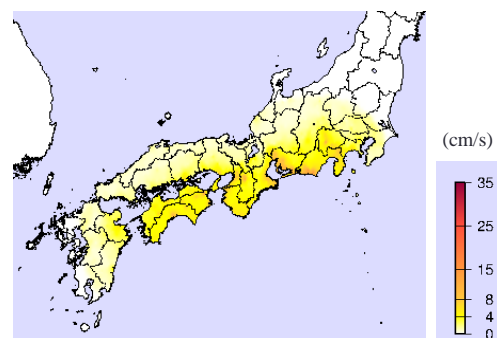
Figure 5. Result of aftershock hazard



PGV as 10% exceedance probability from 1st day to 30th day after main shock



PGV as 10% exceedance probability from 30th day to 60th day after main shock



PGV as 10% exceedance probability from 60th day to 90th day after main shock

Figure 6. Example of aftershock hazard map

evaluation period for the aftershock hazard was set to one month (30 days). The results of the aftershock hazard evaluation calculated by considering the ground motion prediction equation in addition to the conditions for the main shock and aftershock activities described above are shown in Fig. 5 and Fig. 6. Main shock hazard evaluated by J-SHIS (NIED, 2014) are also shown in Fig. 5. Contribution rate of Nankai Trough Earthquake against main shock hazard is so high in Osaka city assumed as building location that the huge earthquake is assumed without de-aggregation of seismic hazard.

Although magnitude of the main shock is much larger than the aftershocks, the median PGV is about 35 to 40(cm/s) in Fig. 5 because hypocenter distance of the construction site (Osaka City) about 70 km. On the other hand, the median PGV of aftershocks is about 25 (cm/s) in Fig. 5 because an aftershock may occur near the construction site.

Fig. 6 shows PGV corresponding to 10% exceedance probability and those are confirmed that decreasing of aftershock hazard for time after the main shock and that aftershock hazard is high for 30 days after the main shock. Since it is considered that damages from the main shock has not been recovered hardly in this period, it can be determined that it is important to consider aftershock hazard in this period for design.

### 3.3 Evaluating Design Ground Motion Considering Aftershock Hazard

In Japanese Building Design Code, there are two level ground motions. Level 1 used for elastic design for usability of building and Level 2 used for elastic design for safety of human life protection. Design ground motion as seismic load is decided by deterministic method in Japanese Building Design Code, so return period is not considered explicitly. However, it is said that level 2 design ground motion is corresponding to 10% in 50 year (475 year mean return period) at main shock hazard and evaluation period of aftershocks hazard is 1 month which is not same that of main shock. Herein, aftershock hazard is assumed main shock occurrence which is corresponding to 10% in 50 year. So, it is conceivable that evaluation period of main shock hazard has been considered indirectly when aftershocks hazard used. According to this thought, exceedance probability used for aftershocks can be set as 10% which is same value of main shock hazard although evaluation period isn't same.

Based on results shown in Fig. 5, 10%-in-50-year PGV value of main shock hazard is 72.9(cm/sec) and 10%-in-1-month PGV value of main shock hazard is 45.3(cm/sec) as shown in Table 1.

Table 1. Main indicators of seismic hazard.

Type of Earthquake	Evaluation Period	Exceedance Probability	PGV value for Design Load
Main shock	50 year	10%	72.9 cm/s
Aftershocks	1 month	10%	45.3 cm/s

Design ground motion of main shock which PGV is 72.9cm/sec is corresponding to 10%-in-50-year and to level 2 design ground motion. On the other hand, design

ground motion of aftershocks is thought to be corresponding to level 1 design ground motion because which PGV is smaller than that of main shock. Then, BCL-L2 with corrected its amplitude 72.9cm/sec ground motion is used as design ground motion of main shock and BCL-L1 with corrected its amplitude 45.3cm/sec ground motion is used as that of aftershocks. Herein, BCL-L2 and BCL-L1 ground motions are evaluated and have been published by Building Center of Japan (BCL). A design ground motion is created by connecting above ground motions as shown in Fig. 7, with 80 seconds interval for attenuating buildings response.

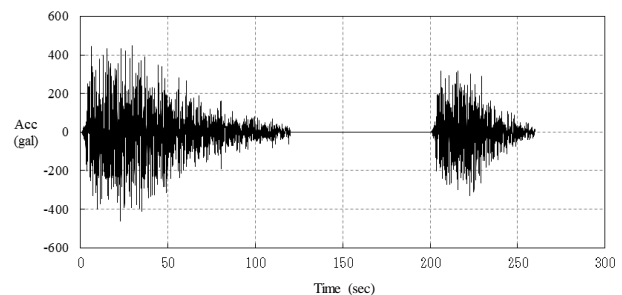


Figure 7. Sample of design ground motion evaluated by proposed method

## 4. Application Example of Design Ground Motion Considered Aftershocks

### 4.1 Outline of Target Building

Target building is a 5-story steel structure which plane shape is 96m with 8m x 12 span in X direction and 30m with 7.5m x 4 span in Y direction. The floor height is 6.1m on the first floor, 5.9m on the second floor, and 4.8m on the third to fifth floors. Plan view is shown in Fig. 8. Cross section of the building is shown in Fig. 9. The columns are rectangular steel pipes, H-beams are used for the girders, and the beam-column joints are through diaphragms. The foundation type is pile foundation, but pile damage is not considered here.

Girder  
3rd, 4th, 5th floor : BH-582x300x12x18 (SM490)  
1st, 2nd : BH-800x350x16x26 (SM490)

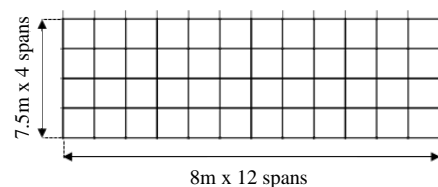


Figure 8. Plan view of the target building model

Column  
3rd, 4th, 5th floor : □-600x600x28 (BCP235)  
1st, 2nd : □-700x700x28 (BCP235)

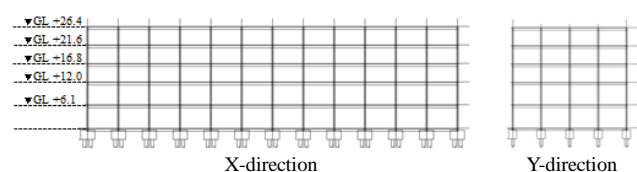


Figure 9. Cross section of the target building model

The building is designed according to Japanese building standards which assume 2 levels of seismic load. Level 1 seismic load is assumed with parameter  $C_0$  which is 0.2, and level 2 seismic load is assumed as BCJ-L2 design ground motion. Maximum story deformation angle at the required horizontal strength was 1/232 rad against level 1 seismic load. Maximum story deformation angle by the BCJ-L2 is 1/100 rad in the X direction and 1/113 rad in the Y direction.

#### 4.2 Modeling of Target Building Structure

3D frame model of the target building which columns and girders are modeled with bar elements as shown in Fig. 10 is used for analysis. As boundary condition, lower end of columns at ground level are supported by pin models.

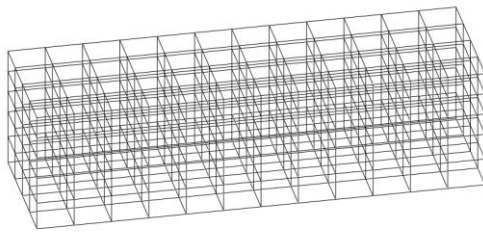


Figure 10. 3D-Frame model diagram of the target building

Slip-bilinear model is used as shear non-linear property without considering strength reduction. Strength reduction is only considered in bending non-linear property which hysteresis is modeled as shown in Fig. 11. Skeleton curve of the non-linear property is modeled as four lines which 1st and 2nd stiffness are positive, which 3rd and 4th stiffness are negative. The hysteresis is Modified-Ramberg-Osgood model during unloading and reloading. In Fig. 11,  $M_y$  means yield bending moment and  $M_c$  means ultimate bending moment at break limit.  $\theta_c$  is the breaking limit rotation angle. In the range exceeding  $\theta_c$ , the proof stress decreases due to the fracture of the member. The building is designed as when ground motion more than 1.1 times that of BCJ-L2 is input the model, response of some members are more than  $\theta_c$  and their strength reduce.

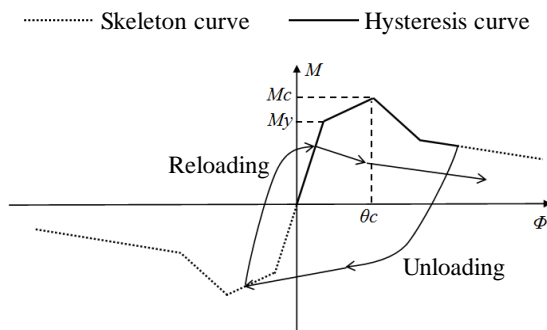


Figure 11. Bending non-linear property

### 5. Response Analysis and Damage Evaluation

#### 5.1 Result of Dynamic Seismic Response Analysis

Herein, 2 cases of dynamic response analysis are done for comparison. Case-1 is considering only aftershocks

and Case-2 is considering both main shock and aftershocks. In the Case-1, only BCL-L1 with corrected its amplitude 45.3 cm/sec is used. In the Case-2, both BCL-L2 with corrected its amplitude 72.9 cm/sec ground motion and BCL-L1 with corrected its amplitude 45.3 cm/sec is used continuously such as Fig. 7.

For comparing result of Case-1 and Case-2, only result against aftershock of Case-2 is taken as Case-2', i.e. result of later than 200 second in Fig. 7 is shown as Case-2'. Maximum response acceleration are shown in Fig. 12, maximum story deformation angle are shown in Fig. 13 and time histories of  $Q-\gamma$  are shown in Fig. 14.

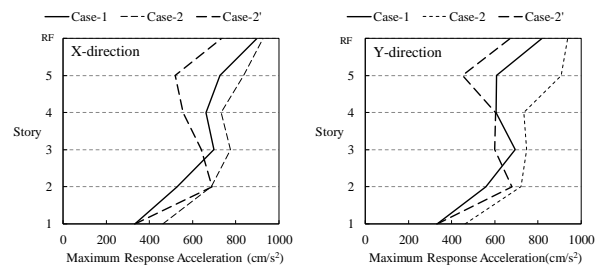


Figure 12. Maximum response acceleration

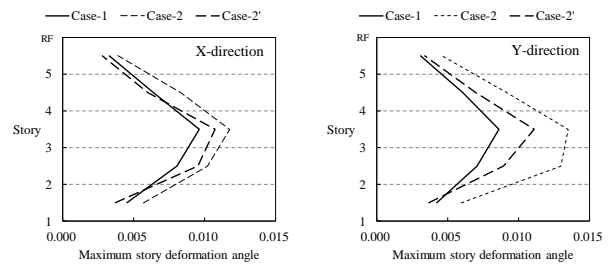


Figure 13. Maximum story deformation angle

It's aware that maximum story deformation angle of Case-2' are larger than Case-1 from Fig. 13. It shows that the building had become easy to displace caused by damage of main shock. Effect of aftershocks is discussed basically, but story deformation angle by the main shock which has become large is shown here for reference. About X-direction, story deformation angle of 2nd floor is 1/98 and that of 3rd floor is 1/85. About Y-direction, that of 2nd floor is 1/77 and that of 3rd floor is 1/74. From hysteresis of story response shown in Fig. 14, it's aware that story rigidities are reduced from 2nd to 4th floor and structure period of aftershock response in Case-2 become longer and easy to displace due to main shock.

#### 5.2 Evaluating Seismic Damage

Herein, for focusing on the continuous use of the building against aftershocks, the damage probability beyond the moderate that causes the building to stop working is used as a damage index. Mean value of story deformation angle corresponding to the moderate damage is 1/75 (Kitamura et al. 2006), and its logarithmic standard deviation is assumed as 0.45 in natural logarithm.

The damage probability beyond the moderate damage which shown as  $P_f$  is calculated by Eq. 1. Where  $R$  is stochastic variable of structural strength;  $S$  is stochastic

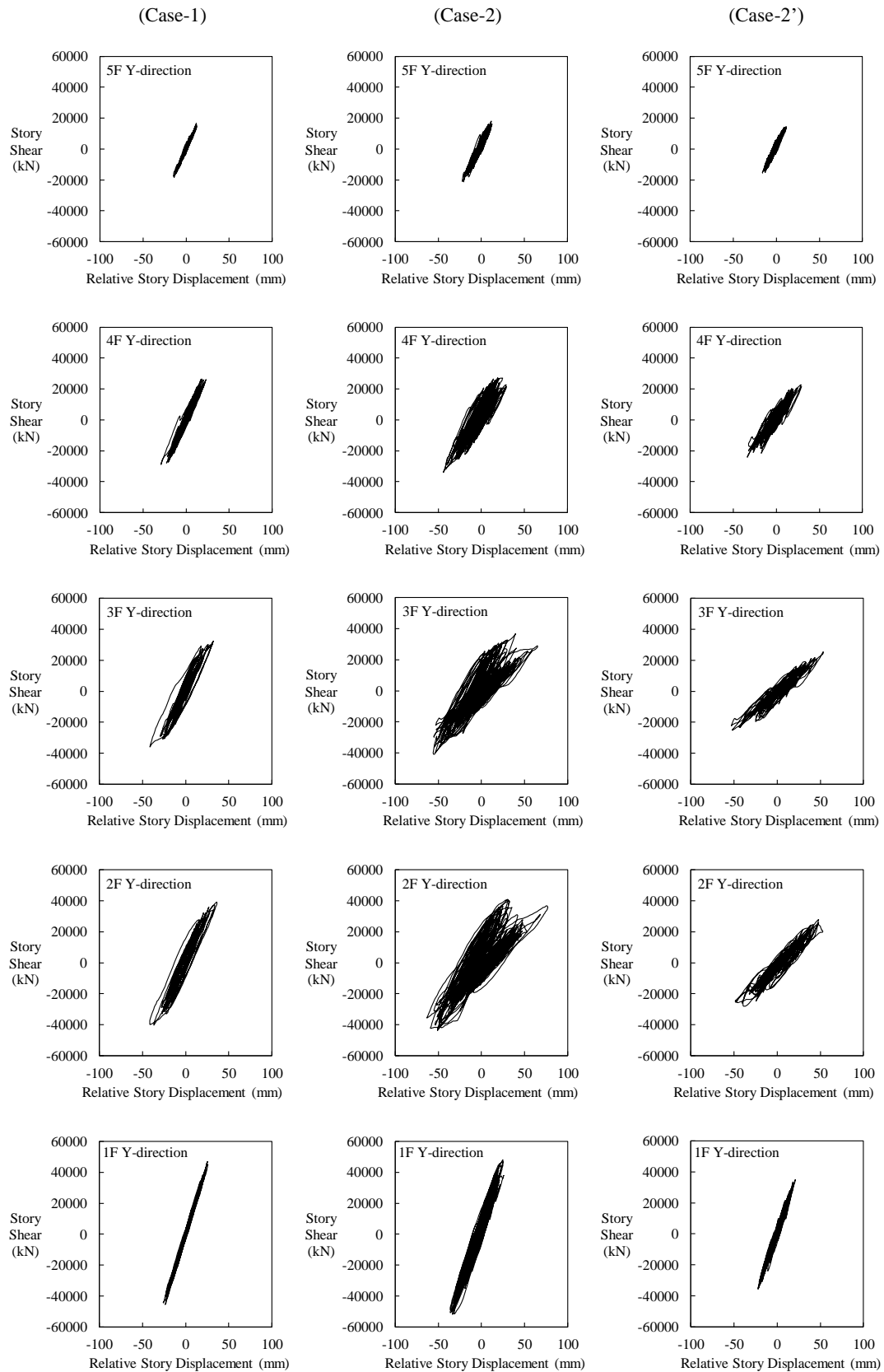


Figure 14. Hysteresis of story response (only Y-direction)



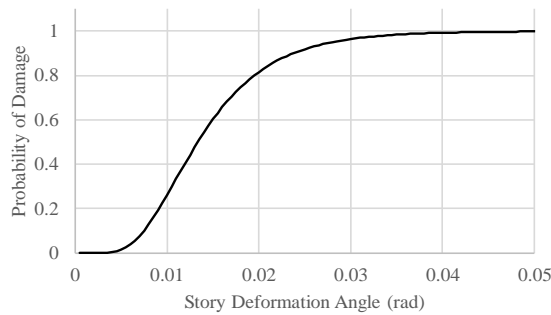


Figure 15. Fragility Curve of Moderate Damage

$$\begin{aligned}
 Pf(R, S = s_0) &= \text{Prob}[R - s_0 < 0] \\
 &= \int_0^{s_0} f(R) dR \\
 &= F(R = s_0)
 \end{aligned} \quad (1)$$

Table 2. Evaluation results of damage caused aftershock.

Case	Direction	Maximum Story Deformation Angle	Probability of Damage Beyond Moderate
Case-1	X	1/104	23%
	Y	1/116	17%
Case-2'	X	1/93	32%
	Y	1/90	34%

variable of building response by seismic load;  $s_0$  is sample value, i.e. results of dynamic response analysis;  $f(R)$  is probable distribution and  $F(R)$  is a cumulative probability. Fragility curve which is calculated by Eq. 1 is shown as Fig. 15 and result of the damage probability is shown as Table 2.

It should be noted here that  $Pf$  is a conditional probability assuming the occurrence of a main shock. To estimate the damage probability more accurately, it is necessary to multiply  $Pf$  by the probability of occurrence of the main shock, but it is omitted here. From the damage probability beyond the moderate damage which shown in Table 2, it's aware that the damage probability caused by aftershocks become large due to strength of the building was reduced by the main shock. Therefore, it is necessary to consider of effect of main shock in evaluating structural reliability and designing against aftershocks. Although not examined in this paper, proposed method make it possible that designing buildings which has usability performance, i.e. the damage probability of moderate damage is lower than target probability. A concrete countermeasure for reducing the probability is designing a structure as higher seismic performance: increasing the cross section of columns and beams; using steel members with higher strength or ductility. If a structure is designed as higher seismic performance, it is possible to prevent the bearing capacity from being reduced due to the main shock and to reduce the damage probability for aftershocks.

## 6. Conclusions

After The 2011 off the Pacific coast of Tohoku Earthquake which magnitude was Mw9.1, many aftershocks occurred. Therefore, a method of evaluating seismic load about aftershocks for buildings continual usability is proposed in this paper. In proposed method, seismic load about aftershocks is evaluated as design ground motion which contains multiple ground motion by aftershock hazard curve; dynamic response analysis with 3D-frame model which strength reduction considered are done; the probability of damage beyond the moderate damage is evaluated as damage index. In result of an example shown in this paper, probability of damage beyond the moderate damage with considering main shock and aftershock are larger than that with considering only aftershock. The results confirmed the followings. Due to the damage during the main shock, the layer stiffness decreases at the beginning of the aftershock, which increases the maximum story deformation angle, but the maximum story shear force decreases. It is also possible that the horizontal bearing capacity of the layer may decrease.

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