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EFFECTS OF SECONDARY WALLS ON DAMAGE TO A CONCRETE BUILDING ATTACKED BY THE 2011 TOHOKU, JAPAN EARTHQUAKE

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ABSTRACT

Exterior/partition flat walls in concrete buildings were severely damaged by the 2011 earthquake off the Pacific coast of Tohoku. It is revealed that concrete buildings lose their function due to failure of non-structural walls nevertheless structural components are not damaged significantly. This paper describes several specific problems on restoring ductile concrete buildings with damage to flat walls, and discusses through numerical analyses focusing on a typical earthquake-damaged building which formed a strong column/weak beam mechanism. Consequently, it is clarified that typical flat walls are brittle and do not significantly affect earthquake response/seismic performance of the ductile building. Threshold of structural and non-structural walls is presented for this type of building.

INTRODUCTION

Exterior/partition flat walls in concrete buildings were severely damaged by the 2011 earthquake off the Pacific coast of Tohoku (AIJ, 2012). It is revealed that concrete buildings lose their function due to failure of non-structural walls nevertheless structural components are not damaged significantly. Earthquake-damaged buildings are generally judged to be restored/demolished according to the guideline for post-earthquake damage evaluation (Nakano et al., 2004) in Japan. After the 2011 Tohoku earthquake, however, several specific problems have been clarified when applying it to ductile concrete buildings with damage to flat walls as follows:

1) Structural performance of flat walls is not clear.
2) Damage to flat walls causes a loss of serviceability even though they are regarded as non-structural components.
3) Structural damage grade seems to be overestimated when damage to flat walls is considered for the damage evaluation according to the Japanese guideline.

Therefore, this paper summarizes such specific problems focusing on an example of earthquake-damaged ductile concrete buildings with typical damage to flat walls, and discusses a threshold of structural and non-structural walls through numerical analyses.

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SPECIFIC PROBLEMS IN POST-EARTHQUAKE DAMAGE EVALUATION

This study focuses on an 11-story steel reinforced concrete residential building in Sendai which was damaged by the 2011 Tohoku earthquake. Figure 1 and Photo 1 show the location and the northwest face of the building. Dimensions of the building are 30.9 m, 71 m, and 27 m in height, longitudinal length, and transverse length, respectively. The building has a symmetric plan along the principal axes, as shown in Figure 2. Figure 3 gives damage to the Y4 frame which was observed by the authors' post-earthquake on-site investigation. Exterior/partition flat walls were constructed in the longitudinal direction and suffered severe damage, as shown in Photo 2. On the other hand, minor damage was observed to structural components which formed a strong column/weak beam mechanism. Damage grade of the building was classified into "heavy"/"moderate", when considering with/without damage to flat walls, according to the Japanese guideline (Nakano et al., 2004), where the residual capacity index, R by Eq. 1 represents damage grade of earthquake-damaged buildings. Table 1 summarizes the damage grade of each story evaluated based on damage classification of building components including/excluding flat walls. It indicates the specific problems caused by damage to flat walls:

1) Structural damage grade of ductile buildings seems to more appropriate when damage to flat walls is not considered, because it has been originally defined based on the residual ultimate capacity of R. However, effects of flat walls on the ultimate seismic capacity of buildings have not been clarified.
2) Damage grade significantly depends on damage to flat walls, as shown in Table 1. However, the seismic capacity of flat walls itself has not been clarified.

Therefore, this study investigates the effects of flat walls on earthquake response/seismic performance of the investigated building.

$$R = \frac{\sum_{j=0}^{5} \eta_j A_j}{A'_{org}} \tag{1}$$

where, A_j : total number of columns having damage class 0 through V, A_{org} : total number of investigated columns, η_j : seismic capacity reduction factor from Table 2.

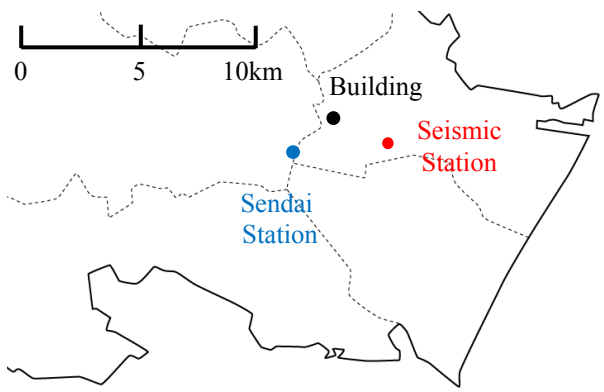


Figure 1. Location of building and seismic station

Photo 1. Northwest view of building

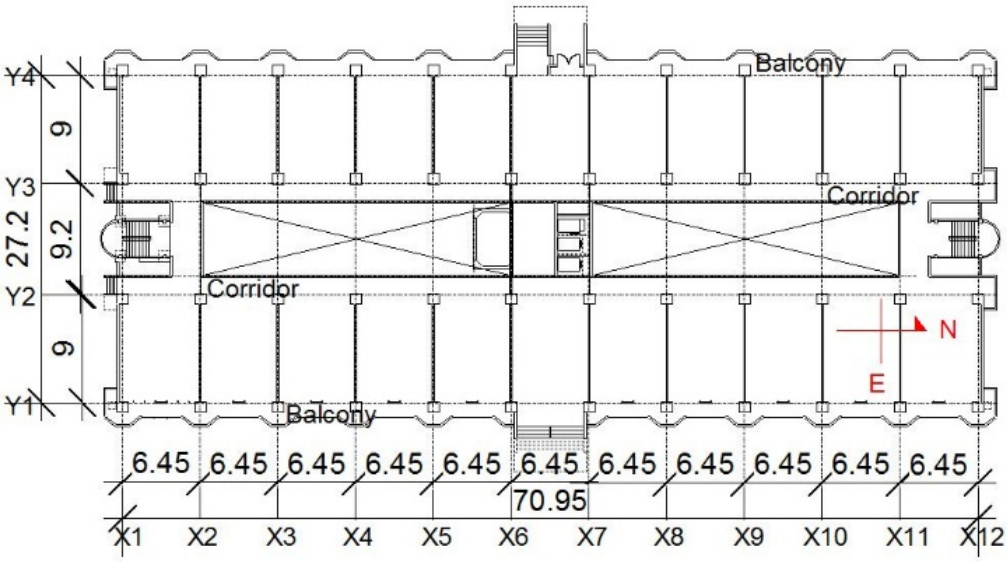


Figure 2. Ground floor plan

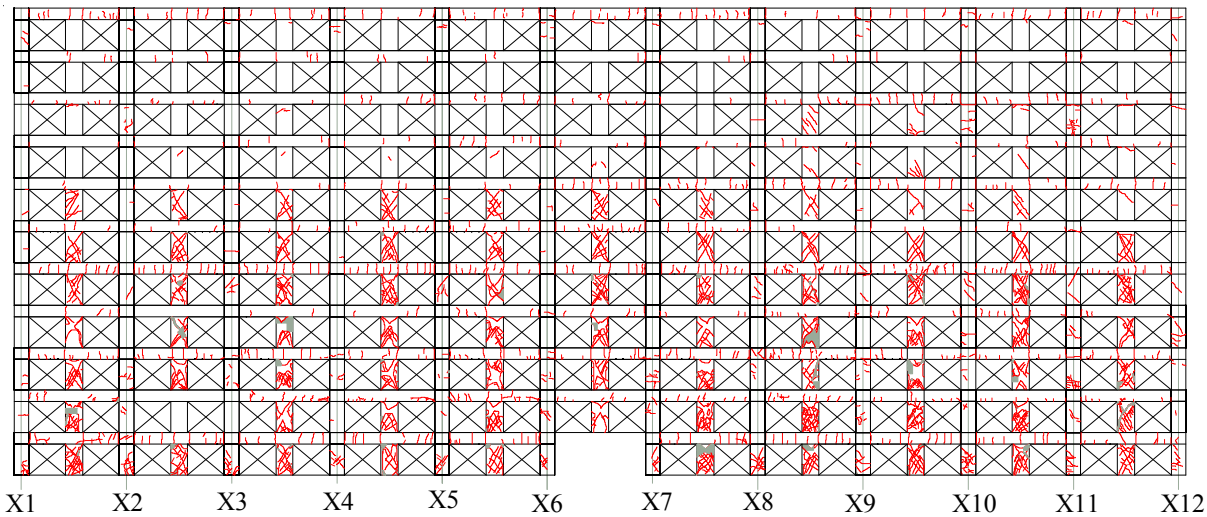


Figure 3. Damage to Y4 frame

Photo 2. Damage to flat walls

Table 1. Damage evaluation results of the west tower in the longitudinal direction

Story	*R* index (damage grade*)	
	Including flat walls	Excluding flat walls
11	86.9% (light)	81.7% (light)
10	95.4% (slight)	93.3% (light)
9	94.6% (light)	93.3% (light)
8	93.1% (light)	95.0% (slight)
7	74.9% (moderate)	91.7% (light)
6	70.6% (moderate)	89.2% (light)
5	57.1% (heavy)	78.3% (moderate)
4	56.3% (heavy)	82.0% (light)
3	50.0% (heavy)	72.9% (moderate)
2	47.1% (heavy)	68.8% (moderate)
1	58.8% (heavy)	76.7% (moderate)

* Damage grade of a building is defined according to the following classification based on *R* index.

Slight damage: $95\% \leq R$
Light damage: $80\% \leq R \leq 95\%$
Moderate damage: $60\% \leq R \leq 80\%$
Heavy damage: $0\% \leq R \leq 60\%$
Collapse: $R \approx 0\%$

Table 2. Damage class definition of seismic capacity reduction factor, η of RC columns

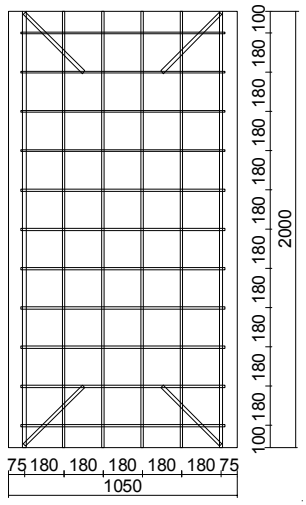
Damage class	Description of damage	η for brittle column*	η for ductile column*
I	- Visible narrow cracks on concrete surface (crack width of less than 0.2 mm)	0.95	0.95
II	- Visible clear cracks on concrete surface (crack width of about 0.2-1.0 mm)	0.60	0.75
III	- Local crushing of concrete cover - Remarkably wide cracks (crack width of about 1.0-2.0 mm)	0.30	0.50
IV	- Remarkable crushing of concrete with exposed reinforcing bars - Spalling off concrete cover (crack width of more than 2.0 mm)	0	0.10
V	- Buckling of reinforcing bars - Cracks in core concrete - Visible vertical and/or lateral deformation in columns and/or walls - Visible settlement and/or leaning of building	0	0

* Brittle column: $h_0/D \leq 3$, Ductile column: $h_0/D > 3$, where h_0: column clear height, D: column depth.

PERFORMANCE EVALUATION OF FLAT WALLS BY FEM ANALYSES

A typical flat wall, whose reinforcement arrangements are shown in Figure 4, was replaced by a numerical model for FEM analyses to evaluate the structural performance, as shown in Figure 5. Compressive/tensile stress-strain relationships of concrete presented by Naganuma (1995)/Izumo et al. (1989) were applied to the analyses and shown in Figure 6. Restraint to the axial elongation of flat wall by beams was also considered in the modelling, as illustrated in Figure 7. Thirteen analytical cases were prepared representing the 1st to 11th-story walls and two imaginary walls with no/complete restraint, as shown in Table 3.

As a result of the analyses, the 1st to 9th-story walls failed in shear, while the 10th to 11th-story ones exhibited ductile flexural yielding, as shown in Figures 8 and 9. The analytical results were approximately consistent to the actual damage observed in the 1st to 7th stories where the flat walls suffered severe shear damage, as shown in Figure 3.



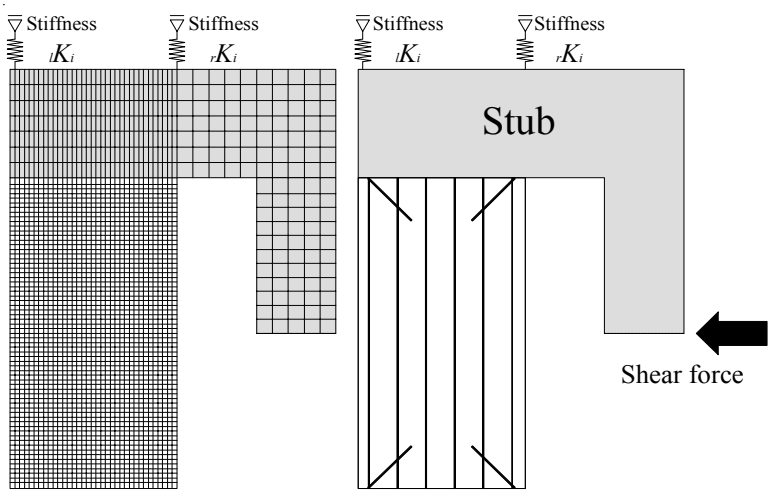


Figure 4. Rebar arrangements of flat wall Figure 5. FEM modelling of flat wall (top: concrete, bottom: rebars)

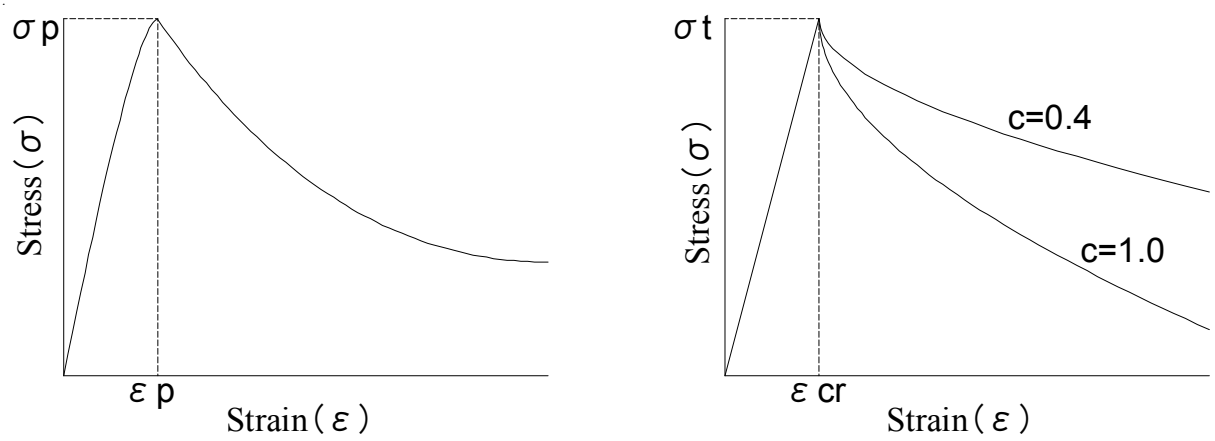
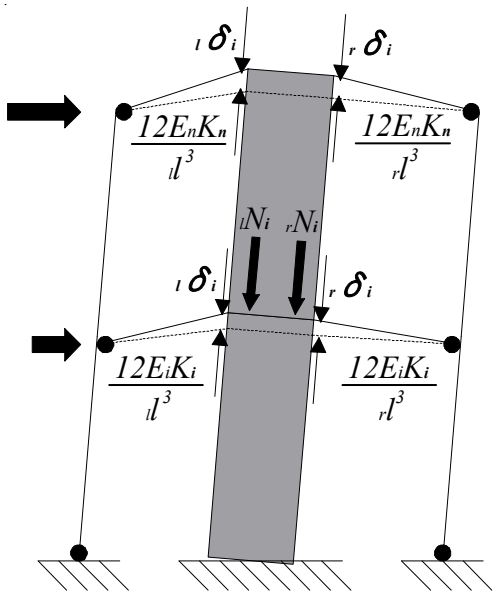


Figure 6. Modelling of stress-strain relationships for concrete (right: compression, left: tension)



$_{l/r}\delta_i$: Vertical displacement at the top left/top right of i-th story secondary wall

$_{l/r}K_i$: Restraint stiffness of the left/right beam connected to the top of i-th story secondary wall

Axial force in i-th story secondary wall, $_{l/r}N_i$ caused by the left/right beam

$$_{l/r}N_i = {}_{l/r}K_i \cdot {}_{l/r}\delta_i$$

Figure 7. Restraint stiffness to axial elongation of flat wall by beams

Table 3. Analytical cases and results

Analytical case			Analytical result				
Name	Assumed story	Restraint stiffness (kN/mm)	Mechanism	Max. strength (kN)	Deformation capacity (% rad.)	Max. axial force ratio	Deterioration stiffness ratio
Case 1	1	5682	Shear	329.7	0.127	0.106	-0.61
Case 2	2	5088	Shear	331.3	0.127	0.107	-0.56
Case 3	3	4495	Shear	329.2	0.129	0.106	-0.54
Case 4	4	3901	Shear	330.5	0.129	0.106	-0.56
Case 5	5	3307	Shear	333.3	0.124	0.107	-0.57
Case 6	6	2806	Shear	333.1	0.125	0.107	-0.57
Case 7	7	2305	Shear	327.9	0.131	0.105	-0.57
Case 8	8	1792	Shear	327.7	0.129	0.105	-0.54
Case 9	9	1279	Shear	319.8	0.132	0.102	-0.43
Case 10	10	852	Flexure	297.1	0.158	0.094	-
Case 11	11	426	Flexure	258.8	0.237	0.081	-
Case 0	-	0	Flexure	204.7	0.289	0.000	-
Case ∞	-	∞	Shear	329.6	0.122	0.106	-0.67

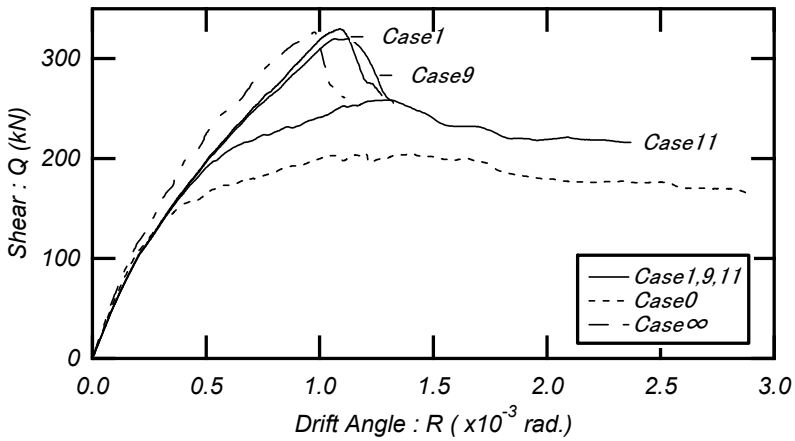


Figure 8. Comparisons among shear force-drift ratio relationships

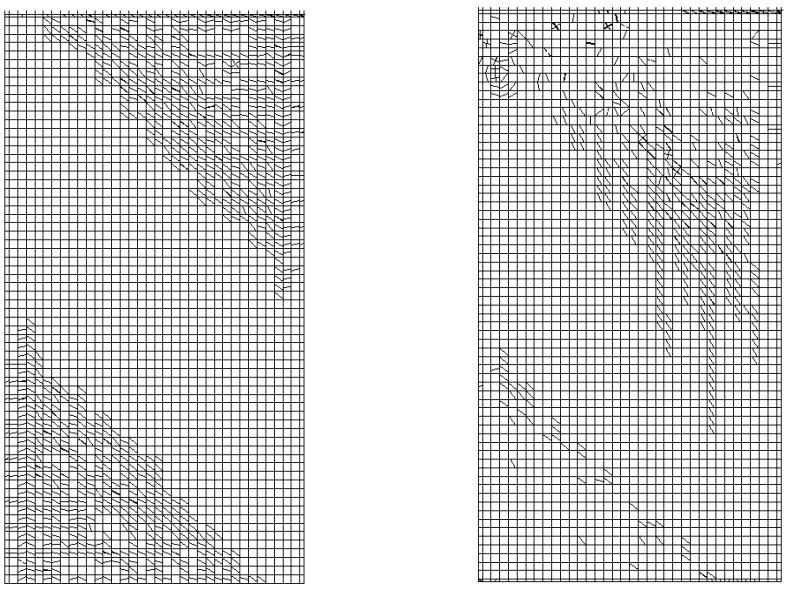


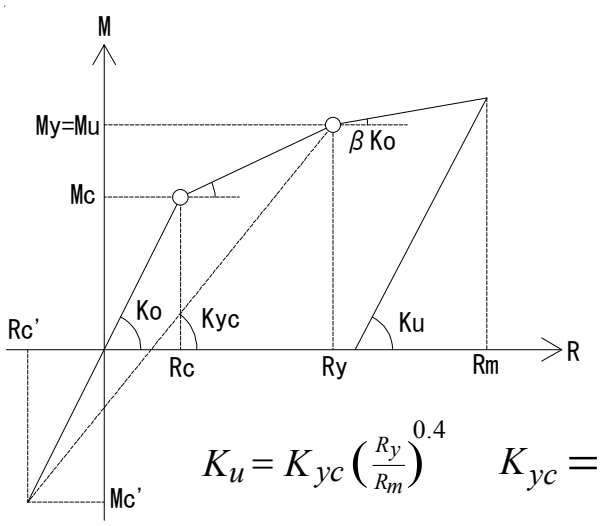
Figure 9. Comparison between crack patterns (left: Case 1, right: Case 11)

EFFECTS OF FLAT WALLS ON EARTHQUAKE RESPONSE/SEISMIC PERFORMANCE OF THE INVESTIGATED BUILDING

Two-dimensional frame analyses were conducted to clarify the effects of flat walls on the earthquake response and seismic performance of the investigated building in the longitudinal direction. The building was replaced by two analytical models, Case A/B considering without/with flat walls.

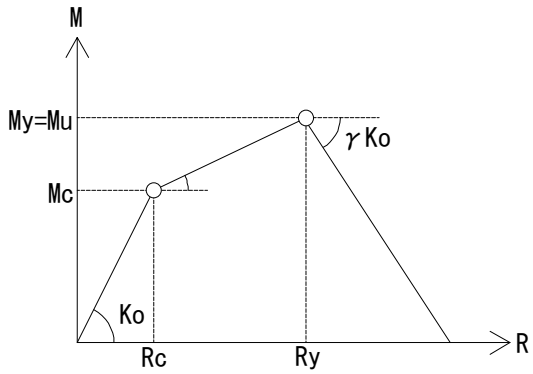
Columns and beams were replaced by line elements considering nonlinear flexural and linear shear and axial behaviour. Nonlinear behaviour in flexure was represented by Takeda model, as shown in Figure 10. Flat walls for Case B were also replaced by line elements with a nonlinear shear spring. Figure 11 illustrates the nonlinear behaviour for shear spring where K_0: elastic stiffness, M_c: cracking shear force, M_y and R_y: maximum shear force and corresponding drift, and γ: deterioration stiffness to K_0, which is given in Table 3, from the FEM analyses.

Earthquake responses of both models were evaluated using the NS component of ground motion, which was recorded about 2.7 km far from the building, as shown in Figure 1, during the 2011 Tohoku earthquake. Figure 12 gives the spectral acceleration of ground motion with the fundamental periods of both analytical models.



$$K_u = K_{yc}\left(\frac{R_y}{R_m}\right)^{0.4}$$

Figure 10. Hysteresis model for column and beam



$$K_{yc} = \frac{M_y - M_c'}{R_y - R_c'}$$

Figure 11. Modelling of strength degradation for flat wall

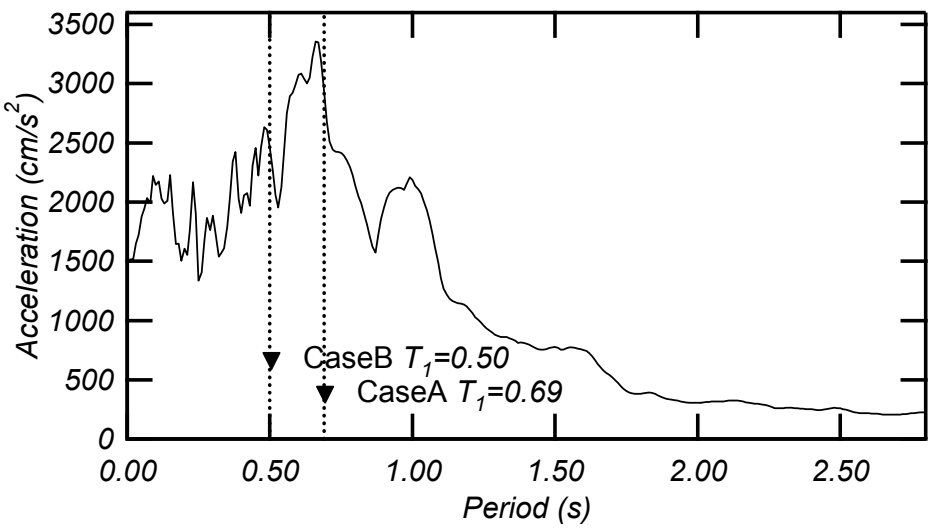


Figure 12. Spectral acceleration of ground motion

As a result of the analyses, both models behaved in a similar manner, as shown in Figure 13 which compares the first mode responses from both analyses (Kuramoto, 2006). This was caused by a similar seismic performance particularly after yielding of both models, as shown in Figure 14 where the capacity spectra (Kuramoto and Matsumoto, 2004) are compared to the demand spectra considering hysteretic damping. Consequently, the flat walls did not affect the building responses by the earthquake. The analyses also simulated the actual damage along building height well, as shown in Figure 15.

However, a clear difference was observed on the seismic performance at a small drift level between both models in Figure 14. Therefore, Figure 16 compares the relationships between the maximum drift response and amplification of ground motion. It indicates that larger differences were obtained between both analytical cases when lower ground motions were applied to the analyses. On the other hand, a little difference was observed under the ground motions with amplifications of more than 75%, which indicates a threshold of structural and non-structural walls.

Finally, the seismic performance of both models was represented by a performance index, which was adopted in the Japanese standard for seismic evaluation of existing buildings (JBDPA, 2005), and drift relationship, as shown in Figure 17. The basic seismic index of structure, E_0 is defined by Eq. (2) considering the ductility as well as strength.

$$E_0 = C \cdot F \tag{2}$$

where, C: strength index which is equivalent to the vertical value in Figures 13 and 14, however, standardized by the gravity acceleration, F: ductility index defined by JBDPA (2005).

It is found that the E_0 indexes are similar to each other beyond a drift of 0.009 rad. (F=1.5) while they have a larger difference by the drift, which corresponds to the threshold on drift obtained in Figure 16.

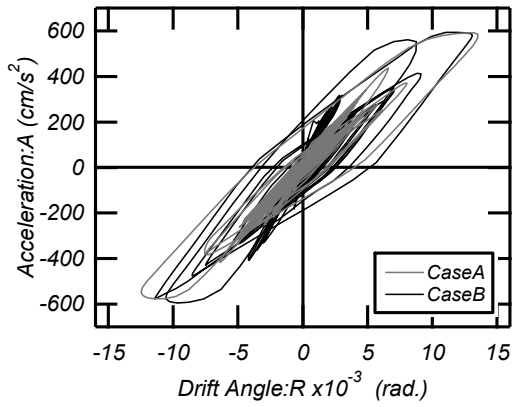


Figure 13. Comparsion between earthquake responses from Case A and B

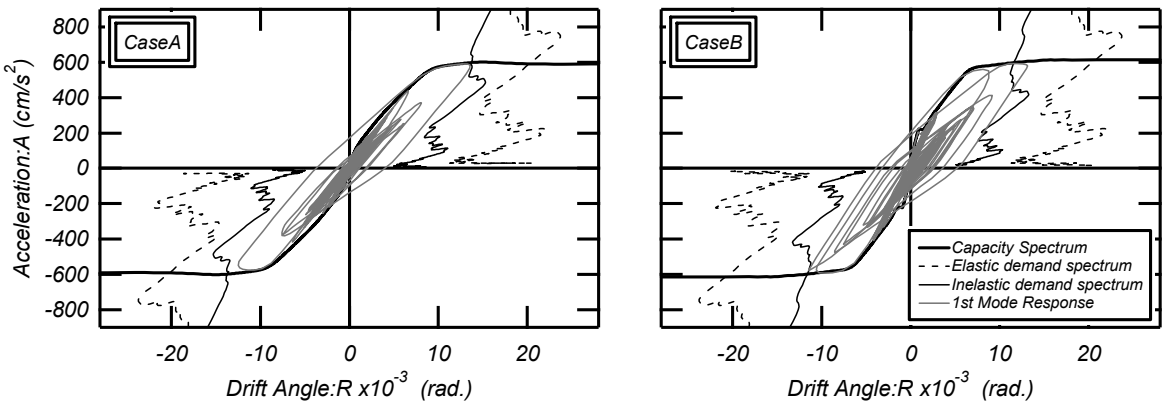


Figure 14. Capacity and demand spectra

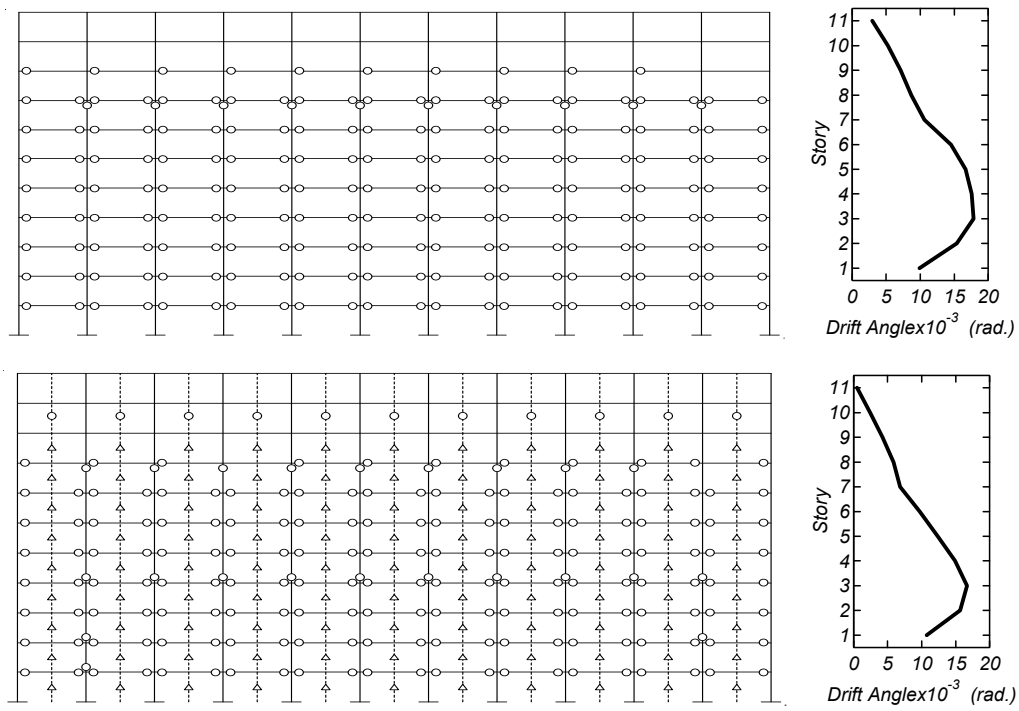


Figure 15. Hinge locations and interstory drifts at the maximum drift responses (top: Case A, bottom: Case B)

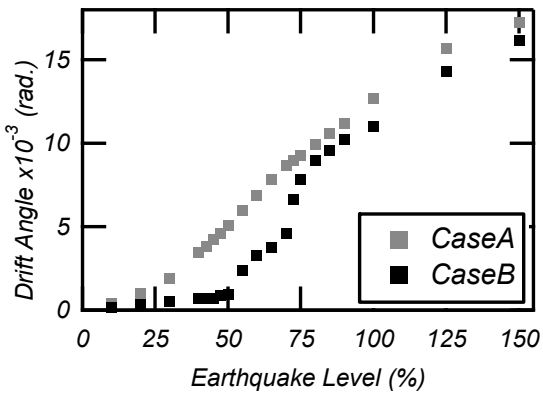


Figure 16. Maximum drift vs. amplification of ground motion relationship

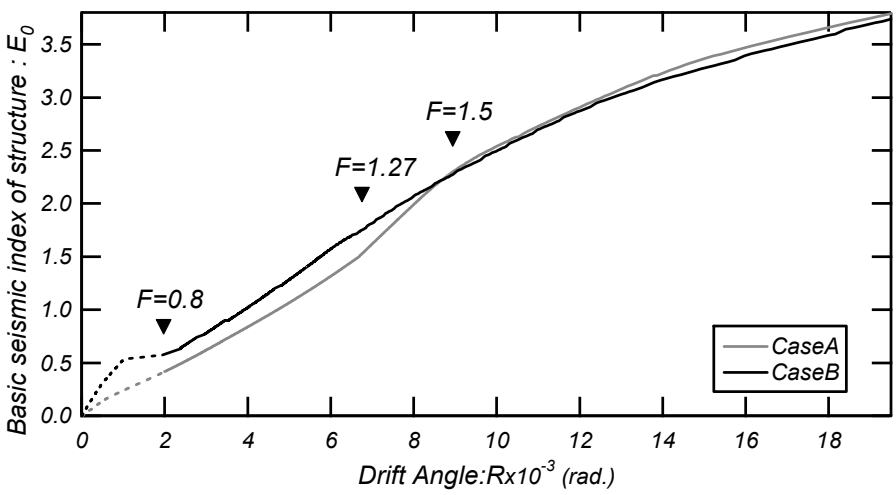


Figure 17. Seismic performance index E_0 vs. drift ratio relationship

CONCLUSIONS

This paper summarizes and discusses specific problems for post-earthquake damage evaluation caused by damage to flat walls in ductile concrete buildings, exemplifying an earthquake-damaged residence by the 2011 earthquake off the Pacific coast of Tohoku. Several numerical analyses were conducted to investigate contributions of flat walls to the earthquake response and seismic performance of the investigated building. Brittle flat walls did not significantly affect the seismic behaviour and performance of the ductile building. In particular, a threshold of structural and non-structural walls is presented based on the analytical results. The basis seismic index adopted in the Japanese standard is effective to clarify the threshold.

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