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EFFECT OF SHEAR WALL REDUCTION IN RENOVATED RC BUILDINGS DESIGNED BY NEW CODE ON SEISMIC PERFORMANCE

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Abstract

The Japanese seismic design code was revised and strengthened in 1981 (hereinafter called "new seismic code"). Many existing buildings designed according to the new seismic code and constructed shortly after 1981 will be renovated in the near future owing to aging. It is widely believed that such buildings do not suffer significant damage even during severe earthquakes, judging from past cases such as the 1995 Kobe earthquake. However, the seismic performance of such buildings could deteriorate owing to the design changes during renovation. An example is the removal of shear walls, often used in Japanese seismic design to increase both the lateral load-carrying capacity and story stiffness in reinforced concrete (RC) buildings. When renovating such RC buildings, the shear walls might be removed to grant additional openings requested for architectural and equipment planning. Such renovations are often carried out to improve openness and create comfortable rooms. As a result, however, the structural performance of the renovated buildings may deteriorate, which may be hazardous in the event of future earthquakes. The seismic performance of such renovated buildings is obscure. Moreover, there is no evaluation method for such a structural deterioration of buildings in the new seismic code. This study aims to examine, by conducting static and dynamic analysis, the structural deterioration after the renovation of RC buildings designed according to the new seismic code.

As an example, an existing five-story RC school building, designed according to the new seismic code and constructed in 1982, was analyzed. It had three spans in both the longitudinal and the transverse direction. The structural type was an RC rigid-frame structure with shear walls in both directions. In this study, the seismic resistance of the longitudinal direction was considered. The building was represented by a plane-frame analytical model. The post-renovation model was represented by removing the shear walls between rooms and corridors in the longitudinal direction. The pre-renovation and post-renovation models were compared.

Static analyses were performed on the building models. Lateral load-carrying capacities regulated in Japanese seismic code were calculated to consider the difference between the pre- and post-renovation models. Notably, the lateral load-carrying capacity was calculated for two horizontal directions and each story. Each lateral load-carrying capacity needed to be confirmed to be greater than or equal to the required lateral load-carrying capacity. The lateral load-carrying capacity was calculated as the sum of the shear forces of the columns and shear walls. In addition, the effect of different degrees of shear wall reduction was assessed.

Inelastic dynamic response analysis was performed on the building models using various ground motions. The relationship between the ground motion level and the maximum story drift was discussed. In addition, for strong ground motions, the differences in the type of damage caused to the pre- and post-renovation building models were investigated.

The results revealed that the lateral load-carrying capacity decreased, and the maximum story drift increased when removing the shear walls. These results indicate that the strength of the buildings decreased, and their deformability increased after the renovation with the removal of the shear walls.

Keywords: Reinforced concrete building, New seismic code, Shear wall reduction, Lateral load-carrying capacity, Dynamic response analysis

1. Introduction

The Japanese seismic design code was revised and strengthened in 1981 (hereinafter called "new seismic code"). Many existing buildings designed according to this new seismic code and constructed shortly after 1981 will be renovated in the near future owing to aging. It is widely believed that such buildings should not suffer significant damage, even during severe earthquakes such as the 1995 Kobe earthquake. However, the seismic performance of such buildings could deteriorate owing to the design changes made during renovation. An example is the removal of shear walls, which are often used in Japanese seismic design to increase the lateral load-carrying capacity and story stiffness in reinforced concrete (RC) buildings. In the renovation of such buildings, the shear walls might be removed to create additional openings requested for architectural and equipment planning. Such renovations are often performed to improve openness and build comfortable rooms. As a result, the structural performance of these renovated buildings may deteriorate, which may be hazardous in the event of earthquakes. However, the seismic performance of such renovated buildings has not been studied sufficiently, and there is no evaluation method for the structural deterioration of these buildings. Therefore, this study aims to examine through static and dynamic analyses, the structural deterioration occurring after the renovation of RC buildings designed according to the new seismic code.

2. Building for examination

2.1 Pre-renovation model

A five-story RC school building located in Niigata City was considered. The building was designed in accordance with the new seismic code in Japan and constructed in December 1982. The building was originally an RC rigid-frame structure with shear walls in both directions. Fig.1 shows the beam plan of the first story of the pre-renovation building (hereinafter called the pre-renovation model). It had three spans in both the longitudinal (X) direction and the transverse (Y) direction. In Fig.1, Y3 and Y4 denote the structural frames. Both the X and Y directions had RC shear walls (W12, W15, and W20 in Fig.1; numerals denote wall thicknesses, in cm). The shear walls were placed from the first story to the fourth story. There was an open ceiling from the first floor to the second floor. The building had a pile foundation.

The seismic capacity index, I_S, was computed for each story of the building using the second-level procedure from the Standard for Seismic Evaluation [1, 2, 3]. In Japan, the I_S value is commonly used to evaluate the seismic performance of existing RC buildings; it is widely accepted that, when I_S is 0.6 or greater, a building will not suffer severe damage or collapse, even during severe earthquakes. The I_S values for the studied building were gleater than 0.6.

2.2 Post-renovation model

In this study, the seismic resistance of the longitudinal (X) direction was considered. The post-renovation model was represented by removing the shear walls between the rooms and corridors in the longitudinal direction. In addition, the effect of different degrees of shear wall reduction was assessed. Fig.2 (a) to (d) show the beam plans of the first story of the post-renovation building. For example, for the renovation 1 in Fig.2(a), a shear wall in the Y4 frame of all stories was removed to create additional openings requested for architectural and equipment planning. During renovations 2, 3, and 4, structural walls were removed by two, three, and four, respectively. The numerals after "renovation" denote the number of reduced shear walls. The other structural elements were not changed.

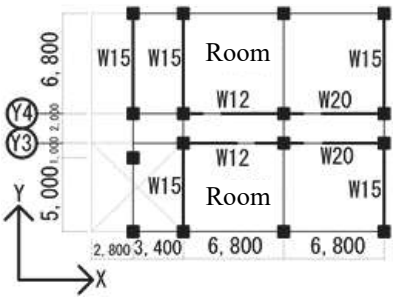
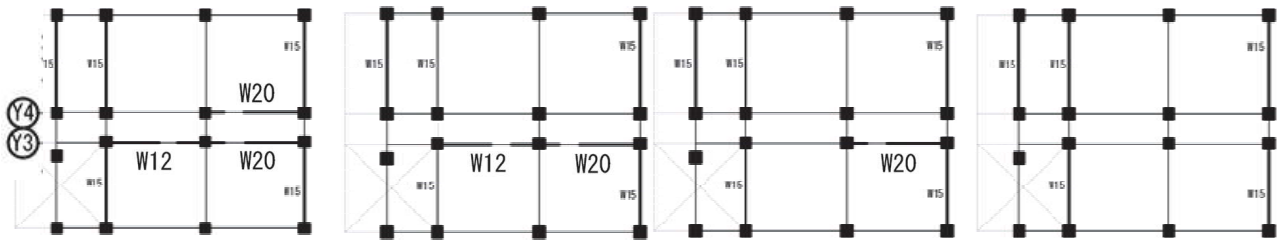


Fig. 1 – Beam plan of first story (pre-renovation)



(a) Renovation 1 (b) Renovation 2 (c) Renovation 3 (d) Renovation 4

Fig. 2 – Beam plan of first story (post-renovation)

3. Stastical analysis

The buildings were represented by plane-frame analytical models. The pre-renovation and post-renovation models were compared.

The lateral load-carrying capacities mandated in the Japanese seismic code were calculated to consider the difference between the pre- and post-renovation models. The lateral load-carrying capacity was calculated for both horizontal directions and for each story as the sum of the shear forces of the columns and shear walls. Each lateral load-carrying capacity needed to be confirmed to be greater than or equal to the required lateral load-carrying capacity.

Static incremental analyses were performed on the building models to calculate the lateral load-carrying capacity using the software Super Build/SS7 for consistent structural calculation [4]. Fig.3 shows the lateral load versus inter-story drift of the first story of the pre- and post-renovation buildings. The circles indicate the points where the collapse mechanisms were achieved. The lateral loads at the collapse mechanism points were equal to the lateral load-carrying capacities. The lateral load-carrying capacities for the pre-renovation and renovations 1 to 4 were 5660 kN, 5040 kN, 4650 kN, 3950 kN, and 4430 kN. The inter-story drifts at the collapse mechanism point for the pre-renovation and renovations 1 to 4 were 0.088%, 0.086%, 0.13%, 0.12%, and 0.37%. As the number of shear walls decreased, the lateral load-carrying capacity decreased, and the inter-story drift at the collapse mechanism point increased.

Fig.4(a) and (b) show the framing elevations of the Y4 frame with hinges when the collapse mechanisms were achieved for the pre-renovation and renovation 4, respectively. The circles indicate the yield hinges of the girders and columns. The triangles in Fig.4(a) indicate the shear failure of the shear walls. As shown in Fig.4(a), the shear walls of the pre-renovation model failed in shear in the second story. Therefore, the shear walls with high strength worked at maximum capacity, and the pre-renovation model had a large lateral load-carrying capacity (see Fig.3). Moreover, for renovation 4 (see Fig.4(b)), the collapse mechanism was decided by the yield hinges, and shear failure did not occur due to the removal of the shear walls. Thus, the renovation 4 model had a small lateral load-carrying capacity and high deformability (see Fig.3).

Fig.3 indicates that the lateral load-carrying capacity decreased as the shear wall reduction increased except for renovations 3 and 4. The reason was that the inter-story drift at the collapse mechanism point for renovation 4 was the greatest among the five models (because the structural frame of renovation 4 changed to a pure frame structure as a result of the removal of all shear walls in the longitudinal direction). Thus, the lateral load-carrying capacity of renovation 4 was greater than that of renovation 3.

Fig.5 shows the lateral load-carrying capacities of each story for the pre- and post-renovation buildings. The lateral load-carrying capacity of each story decreased as the shear wall reduction increased except for renovations 3 and 4. The reason was the same as that stated before.

The calculated lateral load-carrying capacities were lower than the required lateral load-carrying capacity for all cases because the pre-renovation model was designed as a high-strength building. In the Japanese design code, a lateral load-carrying capacity lower than the required level is acceptable if the building is of the strength-resistance type.

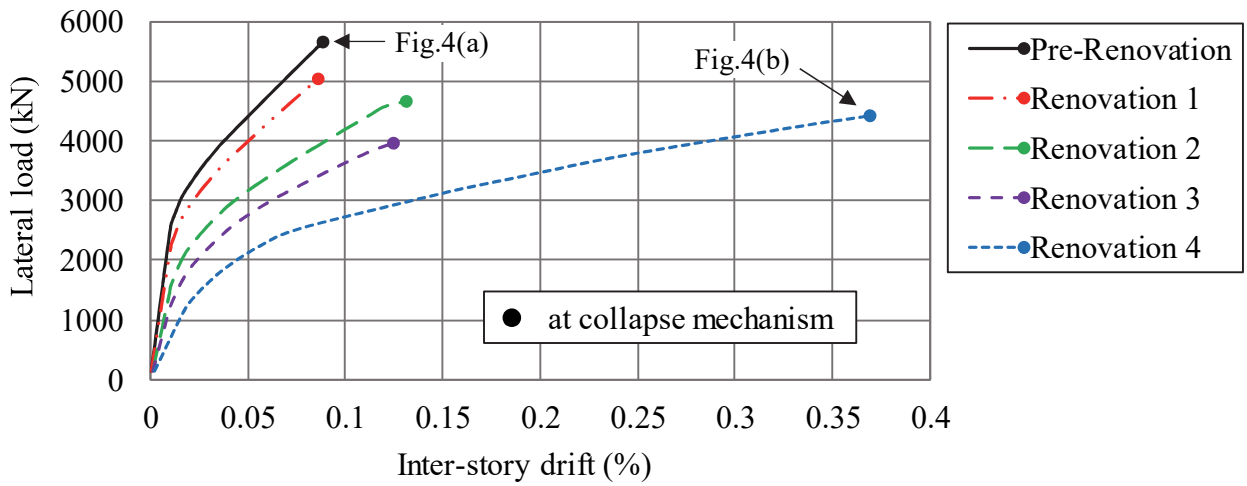
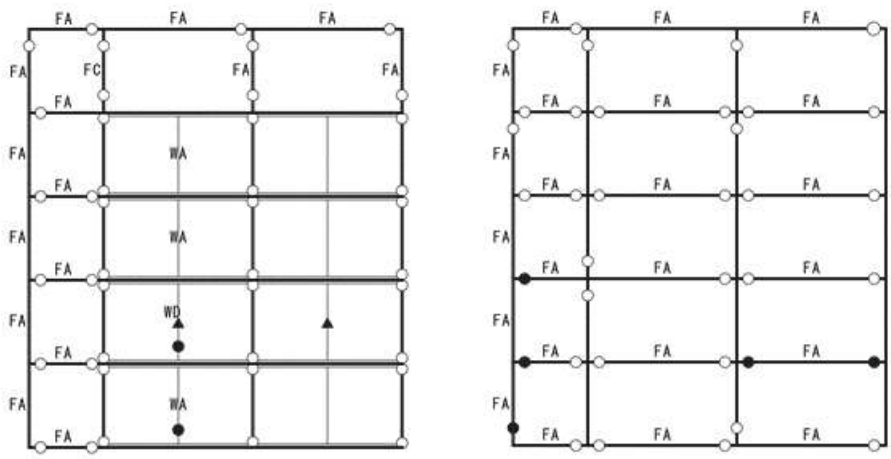


Fig. 3 – Lateral load vs. inter-story drift (first story)

○, ●: Yield hinge, ▲: Shear failure
FA: Ductile girder and ductile column, WA: Ductile shear wall, WD: Brittle shear wall



(a) Pre-renovation (b) Renovation 4

Fig. 4 – Collapse mechanism (framing elevation of Y4 frame)

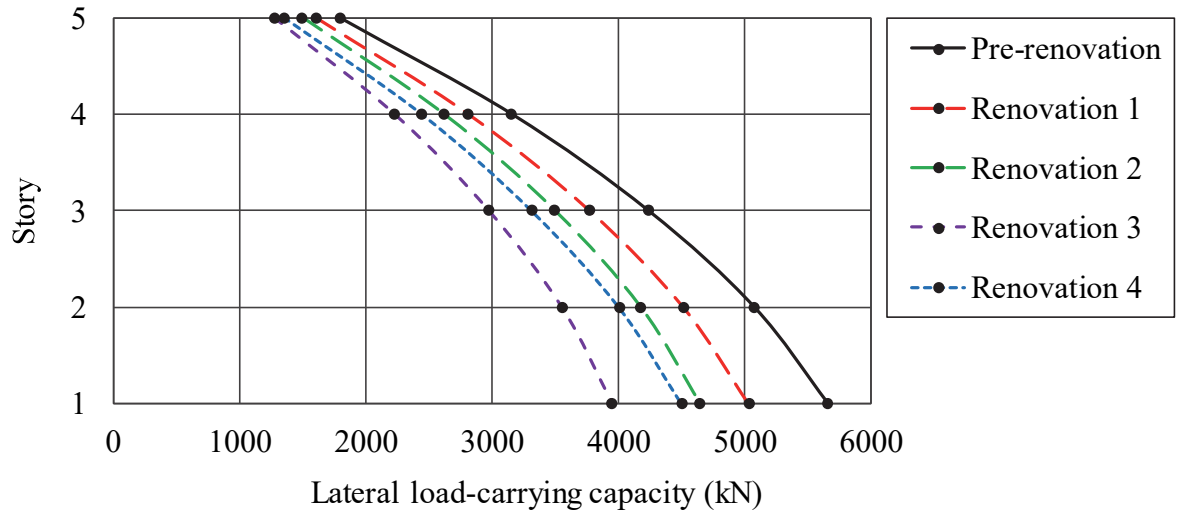


Fig. 5 – Lateral load-carrying capacity

4. Dynamic analysis

4.1 Outline of analysis and ground motion

Inelastic dynamic response analysis was performed on the building models using the software 3D DynamicPRO [4]. The hysteresis framework of the flexural members was based on the Takeda model [5]. The viscous damping was assumed proportional to the instantaneous stiffness. The damping ratio was set to 3%.

Two ground motions were used for the analysis (see Table 1; JMA was from the 1995 Southern Hyogo Prefecture earthquake, and ELC was recorded from the 1940 Imperial Valley earthquake). In the analyses, the level of ground motion was adjusted on the basis of the maximum ground velocity V_{max}, which was set to 25 cm/s (moderate earthquake) and 50 cm/s (strong earthquake). V_{max} was calculated as the maximum response velocity for an elastic single-degree-of-freedom system with a natural period of 10 s and a damping ratio of 0.707% [6]. In Japan, such normalization based on V_{max} is commonly used to evaluate the seismic intensity of earthquake motions in buildings. Fig.6 shows the spectrum of acceleration for earthquakes with V_{max} = 50 cm/s. In the figure, the damping ratio is 5%. According to Fig.6, the response acceleration rose sharply around the natural period of 0.5 s for both ground motions.

Table 1 – Ground motions (original level)

Name	Site, Direction	Year, Earthquake	Maximum ground velocity V_{max} (cm/s)
JMA	Japan Meteorological Agency Kobe, NS	1995, Southern Hyogo Prefecture	82.6
ELC	El Centro, NS	1940, Imperial Valley	33.6

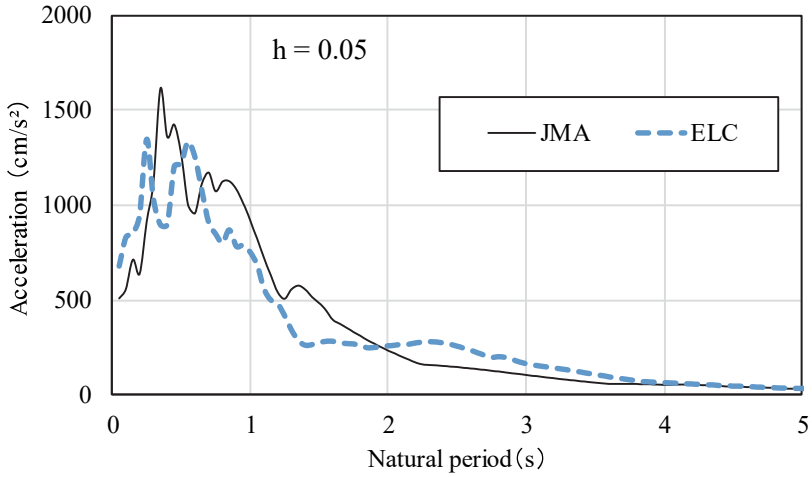
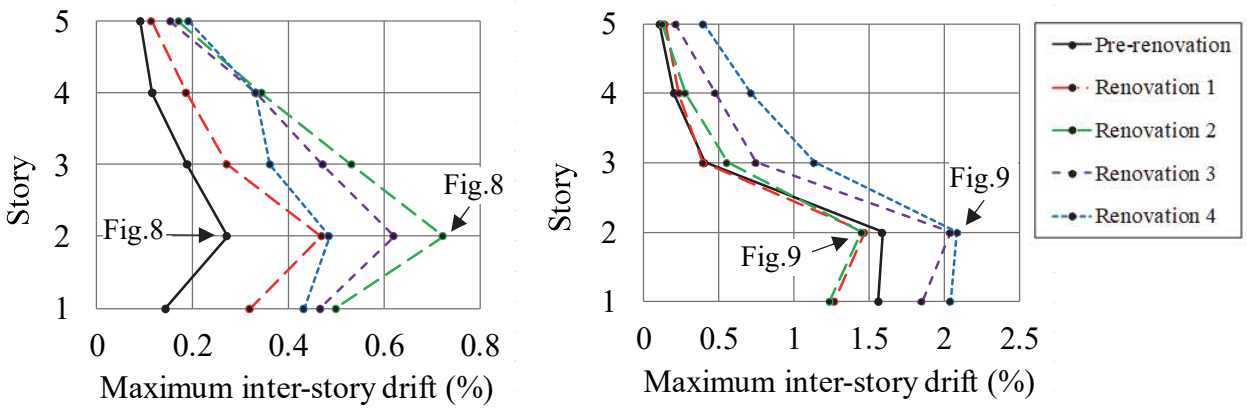


Fig. 6 – Acceleration spectrum (V_{max} = 50 cm/s)

4.2 Effect of shear wall reduction

Fig.7(a) and (b) show the maximum inter-story drift of each story for all models and the input motion of JMA (V_{max} = 25 cm/s and 50 cm/s). The maximum inter-story drift generally increased as the shear wall reduction increased. The second story was suffered the largest inter-story drift in all cases. The analytical results for the second story are as follows.



(a) V_{max} = 25 cm/s (b) V_{max} = 50 cm/s

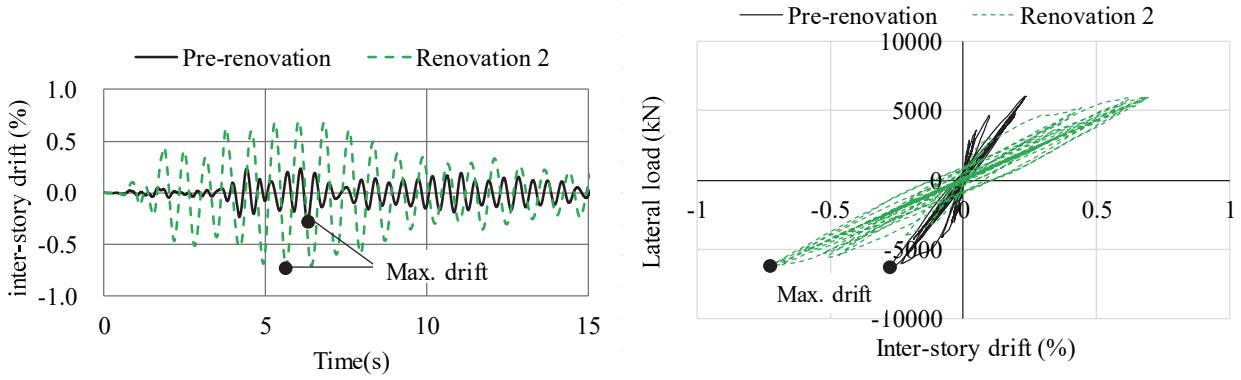
Fig. 7 – Maximum inter-story drift of each story for JMA

Fig.8(a) and (b) show the time histories of the inter-story drift and lateral load versus inter-story drift relations of the second story for the pre-renovation and renovation 2, respectively. The input motion was JMA (V_{max} = 25 cm/s). As shown in Fig.8(a), the maximum inter-story drifts of the pre-renovation and renovation 2 were 0.27% and 0.72%, respectively. The deformation of the latter, which involved shear wall removal, was 2.7 times less than that of the former. The maximum inter-story drift exceeded the drift at the collapse mechanism.

Fig.9(a) and (b) show the time histories of the inter-story drift and lateral load versus inter-story drift relations of the second story for renovations 2 and 4, respectively. The input motion was JMA (V_{max} = 50

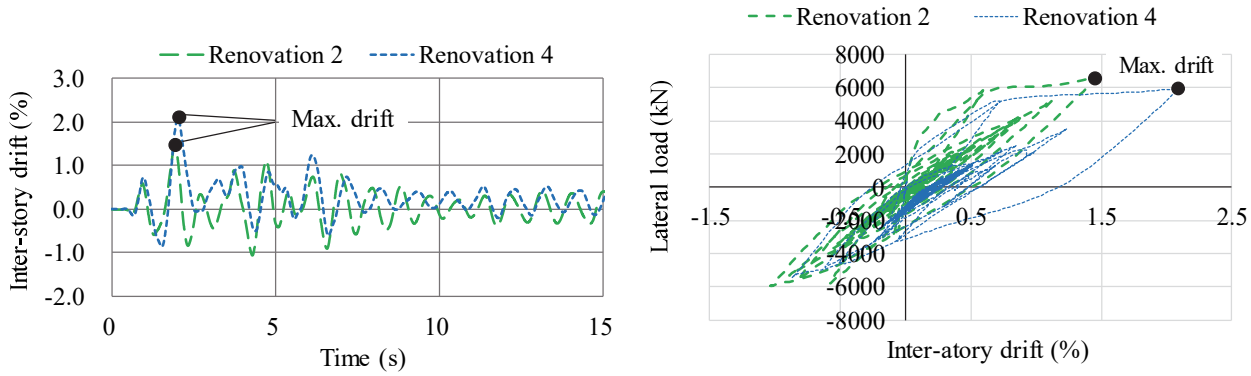
cm/s). As shown in Fig.9(a), the maximum inter-story drifts of renovations 2 and 4 were 1.45% and 2.08%, respectively (the latter was 1.4 times the former). The maximum inter-story drift exceeded the drift at the collapse mechanism, and the inelastic deformation increased.

Therefore, the shear wall reduction corresponded to a larger inter-story drift.



(a) Time history of inter-story drift (b) Lateral load vs. inter-story drift

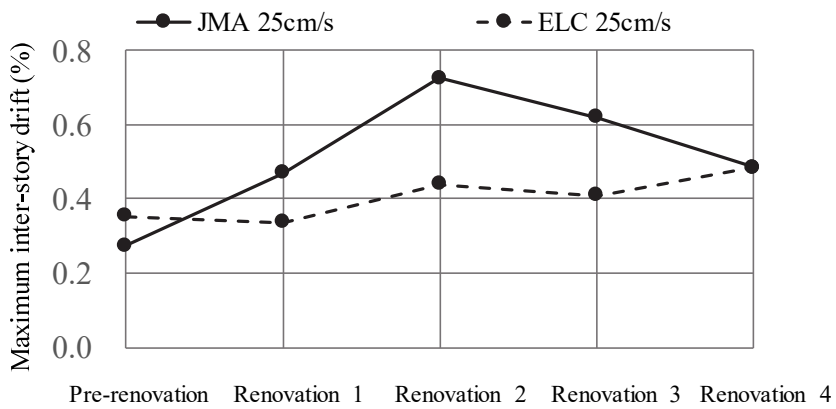
Fig. 8 – Response results for JMA (V_{max} = 25 cm/s; second story)



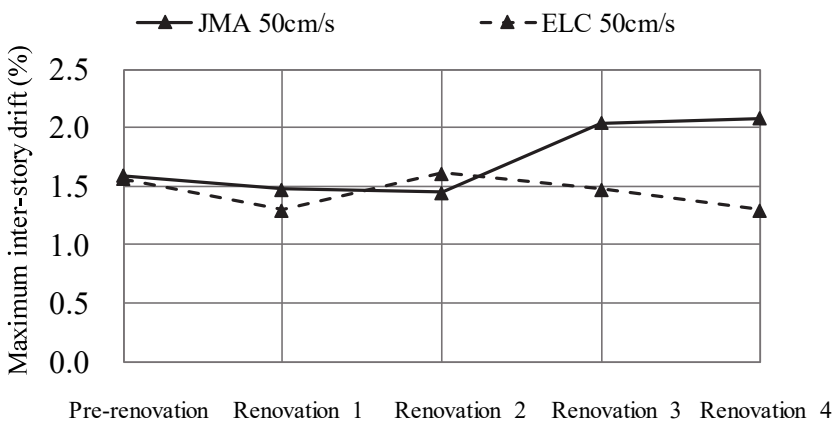
(a) Time history of inter-story drift (b) Lateral load vs. inter-story drift

Fig. 9 – Response results for JMA (V_{max} = 50 cm/s; second story)

Fig. 10 shows the maximum inter-story drift of the second story for all models and all input motions. As shown in Fig.10(a), for ground motions of V_{max} = 25 cm/s for JMA, the maximum inter-story drift increased as the shear wall reduction increased except for renovations 3 and 4. It was unclear a reason of the exception. As shown in Fig.10(b), for ground motions of V_{max} = 50 cm/s, the maximum inter-story drift of JMA increased as the shear wall reduction increased, whereas that of ELC was almost constant. Generally, the maximum inter-story drift increased with the shear wall reduction. The deformability of the building increased as the shear wall reduction increased. Thus, the shear wall reduction did not necessarily reduce the seismic performance of the renovated buildings with shear wall removal.



(a) V_{max} = 25 cm/s



(b) V_{max} = 50 cm/s

Fig. 10 – Maximum inter-story drift for all models (second story)

5. Conclusions

In this study, an existing five-story RC building designed in accordance with the new seismic code in Japan was considered. The differences in the structural performance of the pre- and post-renovation buildings were investigated via models. The post-renovation model was represented by removing the shear walls in the longitudinal direction. The results revealed that, upon removal of the shear walls, the lateral load-carrying capacity decreased, and the maximum story drift increased. Thus, the strength of the buildings decreased, and their deformability increased after the renovation involving the removal of the shear walls. This tendency increased as the degree of shear wall removal increased. Thus, shear wall reduction did not necessarily reduce the seismic performance of the renovated buildings without shear walls.

6. References

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