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Strengthening methods for existing wall type structures by installing additional shear walls

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Abstract. Before incorporating the earthquake-resistance design in design standard (1988) in South Korea, most of existing residential buildings were built without having lateral resistance capacity in addition to their structural peculiarity, such as exterior stair ways, exterior elevator room. For these reasons, the demands on retrofitting research for existing buildings arise recently and many retrofitting methods are proposed. These tasks are important to reduce the enormous economic loss and environmental issues. As the main purpose, this study was intended to examine the performance improvement in terms of ductility and strength in the wake of retrofitting and to suggest retrofitting details.

Keywords: earthquake-resistance design; existing building; strengthen methods; seismic design; CSM

1. Introduction

The Sendai earthquake in March, 2011 has brought an increasing attention to seismic preparedness of buildings. Importance of seismic design is well described in the report by the Architectural Institute of Japan (Japan 1996) on damages by the earthquake that struck Hyogo Prefecture, the southern part of Japan. According to the assessment of the damage extent depending on application of seismic design, it was reported that the buildings designed as seismic design standards were significantly suffered less than the non-seismic designed buildings. This emphasizes the importance of seismic design. Generally speaking, in the region of earthquake belt, seismic design has been reflected in building design standards because such region has experienced earthquakes continuously. In this region, seismic codes have been suggested for buildings where seismic design was not taken into consideration. On the contrary, in the region located within the earthquake region, seismic codes have been only applied to newly constructed buildings without any consideration in seismic design for existing buildings. This is because such region was considered as relatively safe from earthquake. According to the example from an

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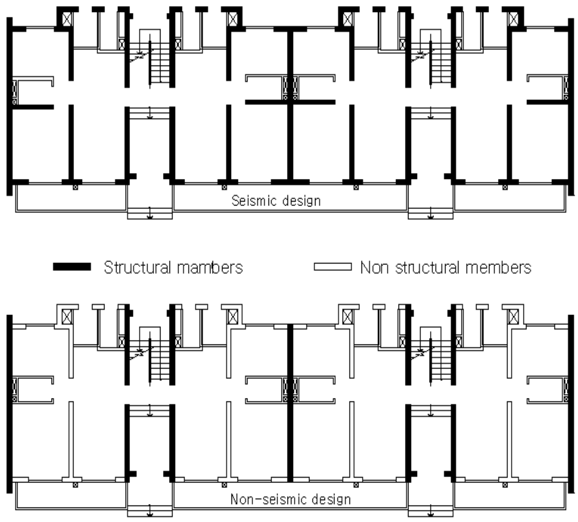


Fig. 1 Seismic and non seismic designed on wall-type apartment building

earthquake stroked Tangshan in China located in the Euro-Asia plate (year: 1976, magnitude: 8.2, and casualties: approximately 300,000 people) was believed that any region within plate cannot be said to be safe from earthquake. This led to the fact that South Korea is not an exceptional region. South Korea has also made it obligatory to take the seismic design into consideration for buildings, which exceed a certain height, since 1988. However, such obligation considering seismic design has not been imposed on the buildings which were constructed before year of 1988 nor buildings whose height was smaller than the requirements for seismic design. These buildings are exposed to risk of earthquake even though the scale of earthquake is relatively small. As an example, there are an enormous number of dwelling houses built in Korea that had the bearing wall-type structure with reinforced concrete, which was a unique design style during the industrialization and urbanization in the 1960s. Such design style and method allow a rapid construction that requires tunnel-form type to maintain its short period. For this reason, no shear walls were placed in the longitudinal direction as described in Fig. 1. As a result, plastic hinge was placed in a joint to prevent from earthquake strikes, which might have caused total collapse of building. Therefore, it is necessary to establish a certain criterion against such possibility.

In general, apartment-type buildings were required for remodeling or reconstruction due to deterioration of equipment and facilities in 20 years from the initial construction. Remodeling is highly recommended because reconstruction causes an economic loss and also environmental problems. However, the structures, required remodeling without seismic design, are actually predicted to take huge damages in case of earthquake outbreak. Despite the prediction, there are still many apartment complexes which have not been renovated that urgently requires development of technology to solve these problems. In this study, the structural verification of the method was conducted to install additional shear wall, this could provide seismic performance to high-rise and time-worn apartment buildings without seismic design considered after remodeling of such apartment buildings. As the main purpose, this study was intended to examine the performance improvement in terms of ductility and strength in the wake of retrofitting and to suggest retrofitting details.

2. Seismic performance evaluation of building structures

For Seismic performance improvement, of structures with shear wall improves strength and lateral stiffness of the structures against seismic force. Therefore, installation of shear wall plays an effective role in seismic performance improvement of non-seismic design buildings. A common method to improve seismic performance is to conduct retrofitting after selecting a proper construction method based on use of each structure, economic factors and judgment by engineers. Among various methods, installation of additional shear wall is widely used for structures that require strength reinforcement. Even though the method has the weakness that it requires wet-condition construction (e.g., for curing concrete), it is believed that the method can be used without difficulties for remodeling that requires sweeping renovation (Bozdogan and Kanat 2013). Shear wall such as masonry wall or concrete walls are reported to have a significant influence on lateral force resistance (Priestley and Seible 1995). Many studies have been conducted on effects and method of installing additional shear wall for seismic performance improvement of existing buildings (Binici *et al*. 2007, Marini and Meda 2009, Rahai and Hatami 2009, Carpinteri *et al*. 2012).

However, they have focused on experimental and analytical studies for seismic performance improvement of moment frame that has a certain level of lateral force resistance. Unfortunately, there have been insufficient confirmed studies on installation of shear wall for bearing wall-type structures that have the narrow and long shape in one direction. In particular, the buildings considered in this study have the walls placed only in the long-side direction for convenience of construction without any wall placed in the short-side direction. Such buildings are believed to be very vulnerable to tremor in one direction at the outbreak of earthquake (Park *et al*. 2011), which is considered to urgently require study on resolution of such problem (Alam and Kim 2012).

This study is expected to give reasons for seismic performance improvement construction for structures with low seismic performance, to promote execution of the construction, and to secure seismic performance of buildings with generally low construction cost, which will be eventually an economical way to ensure social stability.

3. Case study

3.1 Description of building model

Case study building is built for residence in 1982, and thus seismic loads were not considered in the structural design. This structure can be classified to very important building because a certain number of people constantly stay in the building when an earthquake possibly happens. However, the structure was not designed with seismic consideration, it has not appropriate details for seismic resistance. The 30-year-old residential building (15-story with 2.6 m story height) was selected as a structure model, details are shown in Fig. 2 and Table 1. This building was built without seismic design. This apartment-type building is designed as a wall type structure that stair ways and elevators are located at the end of corridor. Two different cases are shown in Fig. 3 which is differentiated by the wall thickness. Fig. 3(a) shows the wall thickness of 200 mm provided from (Japan 1996) and Fig. 3(b) shows the 170 mm wall thickness (Priestley and Seible 1995).

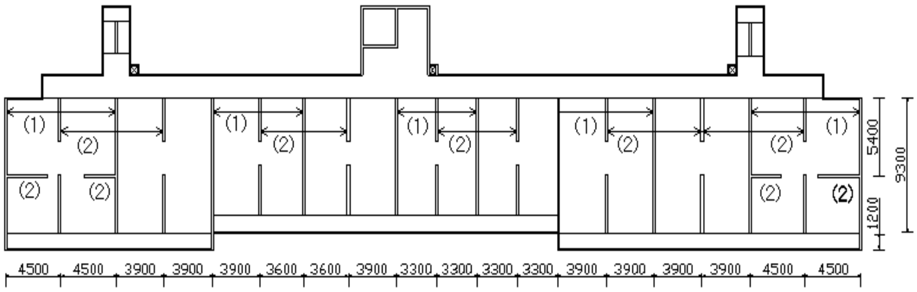
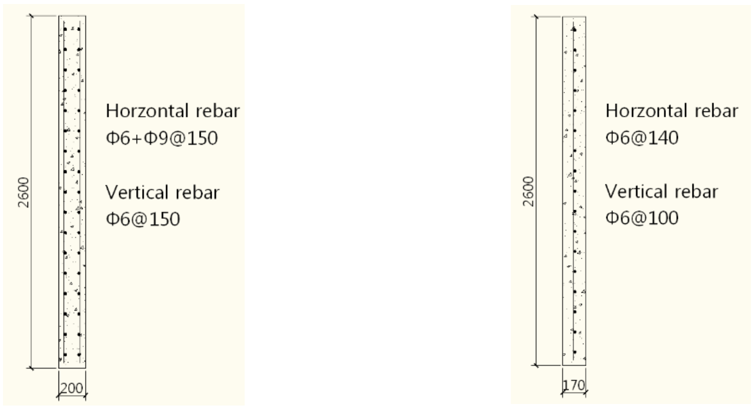


Fig. 2 Plan view of case-study building (unit in mm)



(a) W1 (b) W3

Fig. 3 Reinforcement of case study building (unit in mm)

Table 1 Dimension and properties of the prototype and the scaled model

Site	Seoul, Korea			
Structural type	RC wall type			
Uses	housing			
Structural	15 stories, story height 2.6m			
Material	concrete	21MPa	steel	240MPa
Wall type of each story				
Floor	(1)	(2)	Wall thickness	
10 ~ 15	W4	W4	W1 : 200mm W3 : 170mm W4 : 140mm	
8 ~ 9	W4	W3		
5 ~ 7	W3	W3		
1 ~ 4	W3	W1		

3.2 Seismic performance evaluation for mode structure

Seismic performance evaluation of case study building was achieved via capacity spectrum method as outlined in ATC-40 (ATC-40). Pushover analysis on case study building was conducted

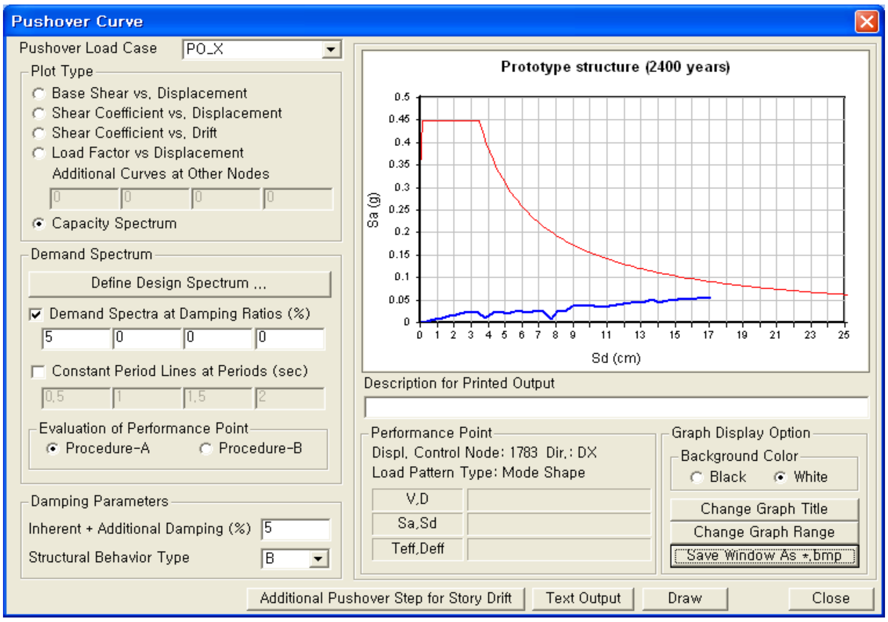


Fig. 4 Performance point of structure applied 5% elastic spectrum

to compute its capacity curve. The building were loaded first with gravity loads (KBC-2009), then pushed with the incrementally increased lateral load distribution until the specified level of roof drifts was reached. The capacity spectrum method (CSM) was then utilized to identify the performance level of the building according to ATC-40. The CSM is assumed to uniquely define the structural capacity irrespective of the earthquake ground motion. In order to reach a comparable conclusion about the expected demand of the structure under the design earthquake level, the capacity curve should be plotted on the same format with the specified demand spectrum. The demand curve is represented by earthquake response spectra, and 5% damped response spectrum is used to represent the elastic demand. The capacity curves were converted into the acceleration displacement response spectrum (ADRS) format for comparison with demand curves.

To evaluate the 3-dimensional nonlinear seismic response of case study building, commercial finite element program MIDAS Gen (MIDAS-IT 2006) was used. As shown in Fig. 4, it is noted that the structure doesn't have enough strength level required to resist the code-specified seismic load corresponding to the Contingency Level Earthquake (CLE), while the structure has the strength level to resist the seismic load corresponding to the Operating Level Earthquake (OLE).

4. Experimental study

4.1 Manufacture of test specimens

The specimens were manufactured as the model structure in 70% of the real size as shown in Fig. 5 in consideration of transport of experiment specimens and conditions of the laboratory.

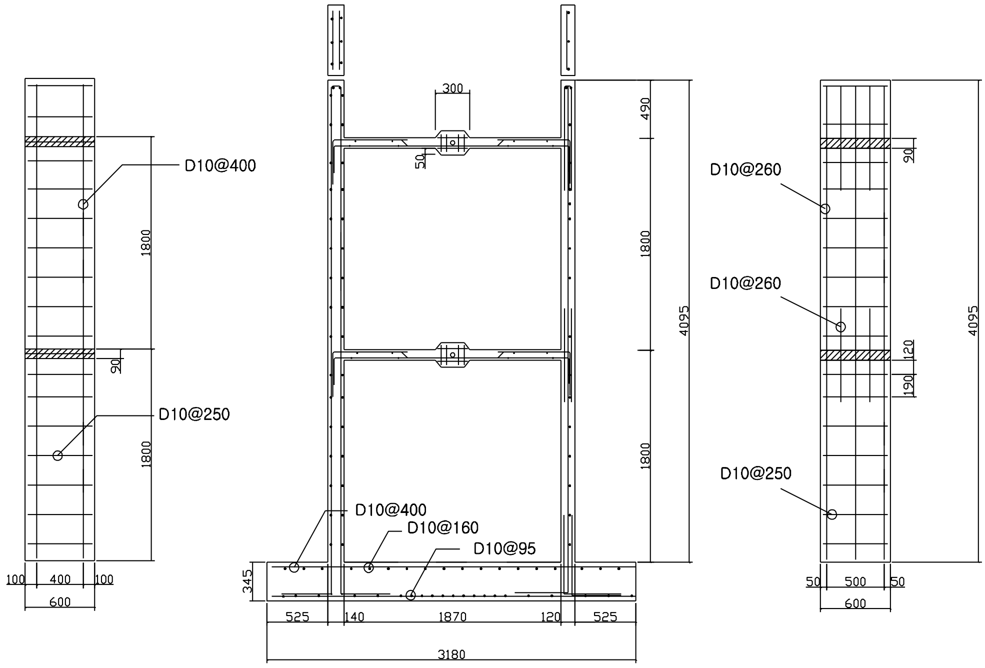
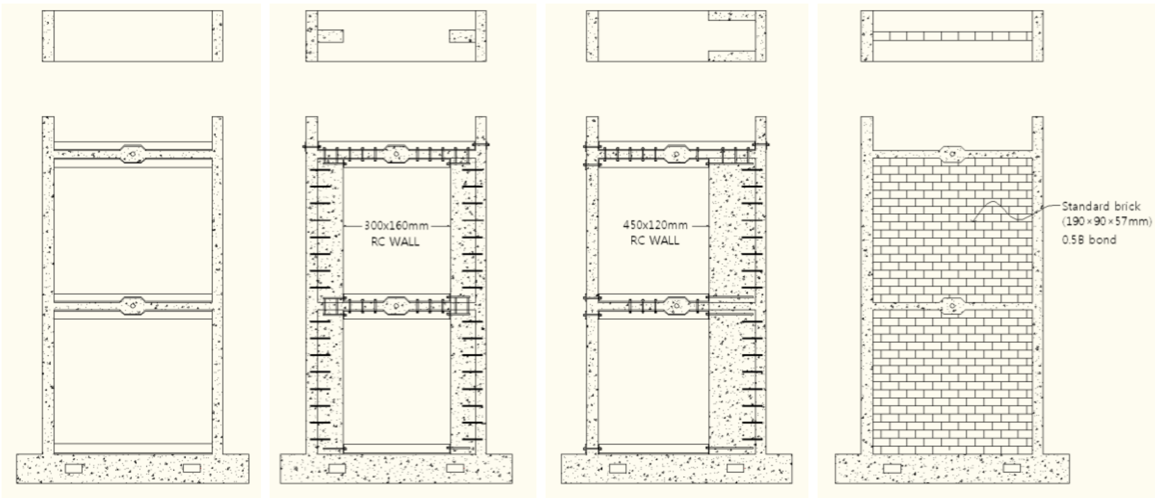


Fig. 5 Reinforced arrangement of test-specimen (unit in mm)



(a) W-N (b) W-SW-A (c) W-SW-B (d) W-BW

Fig. 6 Retrofitting model for experimental study

To this end, the law of similarity (Lee *et al*. 1999) was applied to manufacturing reinforcing bars and concrete members in the reduced size. The compressive strength of concrete ranged from 22.05 MPa to 26.75 MPa for each experiment specimen. As for reinforcing bar, we used D10 that was commonly used in construction site. The yielding strength was 395.33 MPa, the tensile strength 564.87 MPa and the ratio of ductility 30.84%. In order to improve seismic performance of

Table 2 Attachment of additional mass to meet similarity law

Name	Retrofitting methods	Shape
W-N	Reference	-
W-SW-A	Addition wall with concrete	Two–side
W-SW-B	Addition wall with concrete	One-side
W-BW	Addition wall with Cement brick	Stuffing

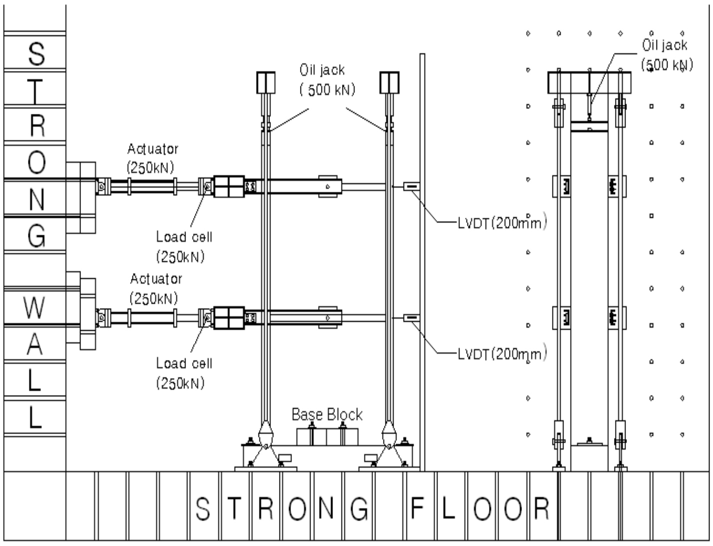


Fig. 7 Test set-up

structures, we used the retrofitting method to improve the capability of lateral load resistance by installing additional wall to the reference specimen (Al-Nimry *et al*. 2002, Hitakis *et al*. 1999, Moehle 1999). We used the W-SW-A experiment specimen where walls in the size of 30 cm×16 cm were added and placed to the walls on the both sides of the experiment specimen as shown in Fig. 6(b), the W-SW-B experiment specimen where the two walls in the size of 45cm×12cm were added and placed to one side as a way to improve efficiency of using plane as shown in Fig. 6(c), and the W-BW experiment specimen where frame plane was filled with masonry walls as shown in Fig. 6(d). The retrofitting details of the experiment specimens are shown in Table 2.

4.2 Test Method

For the experiment method, in order to apply load of structure to the experimental specimens in a similar way to the case with a real structure, we used the loads on the first floor and the second floor of the experiment specimens along with the compressive load as shown in Fig. 7 to apply load and simultaneously put moment and shear force under control. The ratio of load on the first floor to load on the second floor used in the experiment specimens was $P_1/P_2 = -86\%$. The load was applied in the displacement control method for the second floor. And for the first floor, the feedback on the second floor data was received before load was applied for control at 86% of the load on the second floor. The increment of displacement for applying load was 2.5 mm which is a

Table 3 Comparison of 1st floor maximum resistance force of all specimens

Specimen	Force (kN)		Retrofit effective ratio (%)	
	Yield	Max.	Yield	Max
W-N	14.5	15.89	-	-
W-SW-A	90.15	96.24	520	506
W-SW-B	120.47	131.55	771	763
W-BW	89.66	100.84	518	534

half of the initial yielding displacement (Δy) in 5 mm up to the stage 4 and $2\Delta y$ in 10 mm from the stage 5. In regard to applying load, the compressive load was applied in consideration of gravity load in the upper part of the experiment specimen. Then, the lateral load was applied after making a hole in the center of upper slab of the floor and manufacturing additional hardware that connects the hole with the actuator. In this case, we conducted retrofitting for the surrounding of the hole to prevent the load from being concentrated on the point where load was applied so that destruction may occur. The end point of the experiment was planned to be the case where the experiment specimen showed the displacement of 10 mm or higher, or the case where the load of the experiment specimen was reached 70% of the maximum load.

5. Test results and discussion

We made comparison of yielding load and maximum load between each experiment specimen and the reference specimen. As shown in Table 3, the results showed the excellent effects of load improvement compared to all of the reinforcement experiment specimens, which proved that each retrofitting method was the appropriate reinforcement method with strength enhancement. In addition, the excellence of each retrofitting method can be described as below in detailed comparison between each experiment specimen and the reference specimen.

5.1 Load-displacement envelope curve

In the W-N experiment specimen, cracks appeared first on the slab in the slab-wall joint part in the stage 4. As the experiment went on in the stages, the cracks in the joint part expanded and at the same time, the transverse cracks also appeared in large numbers on the wall. In the stage 6, the slab on the first floor also showed cracks, which proved that the experiment specimen reached the yielding point. The lateral load on the first floor that was loaded in case of yielding was −14.5 kN while the maximum load was −15.89 kN. These values are around 41% of 26.67 kN that is the required strength of structure that was obtained based on calculation of the base side shear force, which demonstrated the need for strength enhancement in the lateral direction.

In the W-SW-A experiment specimen, the yielding load was 90.15kN while the maximum load was +96.24 kN. As a result, the maximum load was increased by around 520% comparing to the case with the W-N experiment specimen. Because the experiment was finished as the load was on the increasing trend, it is believed that the experiment specimen has the higher strength and ductility.

In the W-SW-B experiment specimen, the yielding load was 120.47 kN while the maximum load was −131.55 kN. As a result, the maximum load was increased by around 771% in the (+)

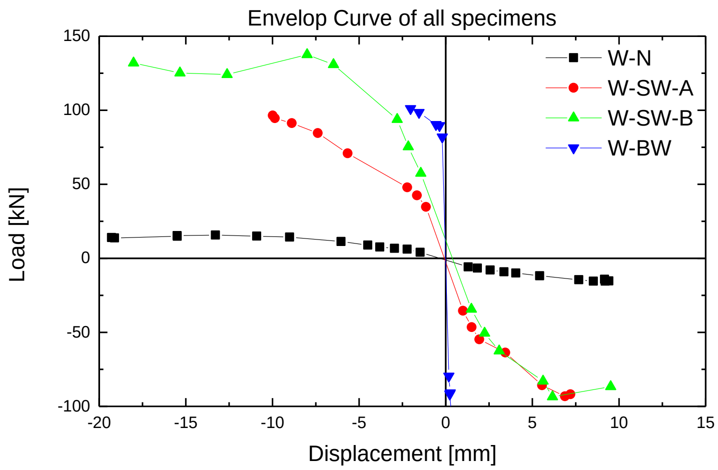


Fig. 8 Envelope curve of all specimens

direction comparing to the case with the reference specimen, which demonstrated that the reinforcement effect was very good in terms of load enhancement.

In the W-BW experiment specimen, the yielding load was 89.66 kN while the maximum load was 100.84 kN. As a result, the maximum load was increased by 534% in the (−) direction. However, unlike the case with other experiment specimens, the internal retrofitting materials of cement bricks showed that their load dramatically plummeted due to brittle failure. According to the result above, it was found that the specimen had no ductility after finishing the experiments. Therefore, it is necessary to avoid using only cement bricks for retrofitting.

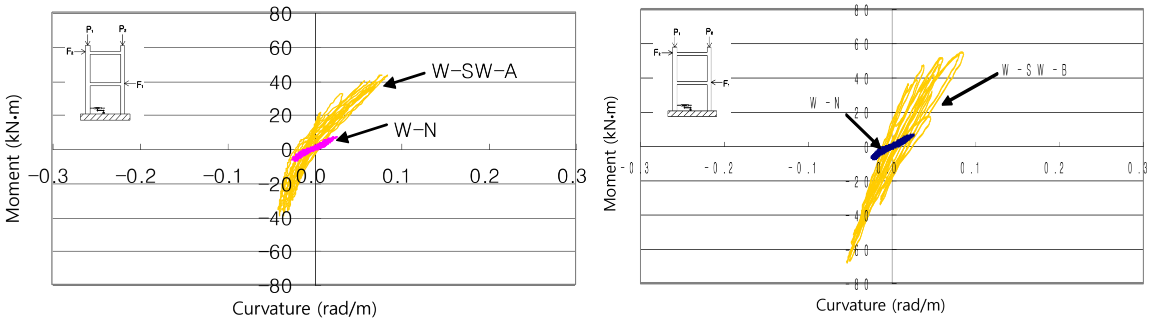
For holistic comparison of each experiment specimen, we examined the envelope curve in Fig. 8 that connected vertexes of load-displacement curves for each stage in the load-displacement curve of each experiment specimen. According to the examination, all of the experiment specimens including W-SW-A, W-SW-B and W-BW showed the excellent capability of resistance against lateral force, compared to that of the W-N experiment specimen. However, the W-BW experiment specimen reinforced with cement blocks showed the much lower ductility than the reference specimen.

5.2 Sectional properties of wall

Based on comparison of moment generated on unit member at the 10 cm point from the end of the wall in each experiment specimen with rotational accuracies of members, we made comparison of the maximum moments that the unit members were able to take up. The comparison showed that all of the members of each retrofitting experiment specimen maintained the higher maximum moment than the members of the reference specimen. According to the analysis results, the section effect for each experiment specimen was found to be superior in the order of W-SW-B, W-BW, W-SW-A, and W-N, which demonstrated the similar results to the ones from the retrofitting effect that was shown on the load-displacement curve. However, it was impossible to obtain measurement values in the W-BW experiment specimen because of the failure to measure the values of transformation content due to poor contact in strain gauge. Consequently, we excluded the W-BW experiment specimen from the moment-curvature comparison curve.

Table 4 Section effect by maximum moment of each specimen on unit member

Specimen	Maximum moment (kN . m)	Section effect (%)
W-N	7.36	-
W-SW-A	42.87	482
W-SW-B	58.66	697
W-BW	-	-



(a) Comparison of W-SW-A and W-N (b) Comparison of W-SW-B and W-N

Fig. 9 Moment-curvature relation

According to the experiment results, the W-N experiment specimen showed the maximum moment in −7.36 kN·m, which was similar to the expected value of −7.75 kN·m. As shown in Table 4, the maximum moment of reinforcement experiment specimen was 42.87 kN·m for the W-SW-A experiment specimen and 58.66 kN·m for the W-SW-B experiment specimen, showing the retrofitting effect of 482% and 697%. The moment-curvature curves for each experiment specimen are shown in Fig. 9.

5.3 Comparison of stiffness for each experimental specimen

Stiffness of each experiment specimen was deteriorated as the experiment went on to a higher stage. The initial stiffness of W-BW experiment specimen was very high, which was around 61 times higher than that of the reference specimen, depending on the retrofitting method for experiment specimen. In addition, the stiffness decreased dramatically after the stage 4 of applying load and was around 25 times higher until the end of the experiment. The stiffness of the W-SW-A experiment specimen or the W-SW-B experiment specimen increased by around 7 times compared to the reference specimen. And the stiffness remained at the high value up to the stage 4 before decreasing slightly after the stage 5. And after the stage 7, the W-SW-A experiment specimen showed the higher stiffness than the W-SW-B experiment specimen. Until the end of the experiment, all of the experiment specimens maintained the higher stiffness than the W-N experiment specimen. According to the overall comparison, the stiffness was high in the order of W-BW, W-SW-B, W-SW-A, and W-N. Therefore, it is believed that all of the retrofitting methods are the appropriate reinforcement method with strength enhancement. Fig. 10 shows comparison of stiffness for all of the experiment specimen.

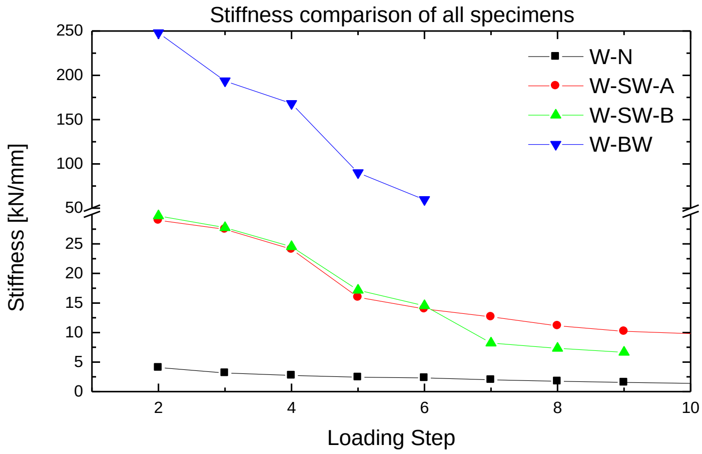


Fig. 10 Stiffness degradation for each specimen

Table 5 Maximum rotation value according to shear wall shape

Shape ratio	δy	0.3 δm	0.6 δm	0.8 δm
1	0.003	0.0055	0.008	0.010
2	0.004	0.008	0.012	0.015
3	0.01	0.019	0.028	0.035

5.4 Comparison of seismic-resistance capability of reinforcement structures

5.4.1 Limited wall displacement on code

To review the basic ductility ratio required for walls in wall-type structures to behave in a ductile manner and to evaluate the minimum requirements for total amount of walls, from a design code perspective, limited displacements were summarized and comparatively analyzed with the test results.

SEAOC (1999)

A target lateral displacement for preliminary design and the displacement of shear wall is shown in Table 5. The optimal ratio in accordance with the inelastic displacement; the function of aspect ratio up to 80% maximum and it regulates limited displacement; the target lateral displacement can be calculated from the mode effects in accordance with each limited displacement, story, ductility ratio.

IBC-2003

In the IBC 2003 design code, the allowed story displacement is calculated as the maximum non-elastic displacement response, and that calculation is regulated to be 0.025 when the period is less than 0.7 second and 0.02 when the period is more than 0.7 second. And, the maximum non-elastic displacement is regulated to be calculated according to the following (Eq. (4.6))

$$\delta_x = C_d \delta_{xe} \prec \Delta_a \tag{4.6}$$

Table 6 Comparison of ductility ratio between codes and test-results

Specimen / Code	Allowed ductility ratio	W-N	W-SW-A	W-SW-B	W-BW
Experiment	-	1.20	2.33	3.86	5.74
SEAOC	3.75	N.G	N.G	O.K	N.G
IBC-2003	3.15	N.G	N.G	O.K	N.G
FEMA-273	1.5% of Story height	N.G	N.G	O.K	N.G

Here, Δa represents the allowed story displacement, δ_{xe} is displacement by elastic analysis, and C_d is displacement amplification factor.

In other words, the ductility ratio required in materials is 0.7 R, and the ductility ratio required in shear wall type structure is 3.15.

FEMA-273

Depending on the target behavior for earthquake, the limit for lateral displacement is regulated, and the maximum displacement, which is for preventing collapse, is regulated as follows. In the cases of rectangular wall with $h\omega/l\omega \leq 2.5$ and wall structure with flange with $h\omega/l\omega \leq 3.5$, the sheer displacement is evaluated as important and allowed, and the limit value is regulated to 1.17%. If it's above that, then it is considered that the bending behavior is dominant, and based on the sheer stress, acting compressive stress and compressive strength of concrete, the allowed value varies and is regulated to maximum of 1.5%.

5.4.2 Application for this study

The minimum displacement limit for structures presented in each design code requires the displacement ductility ratio to have, per the design code, a value greater than 3-times. The recently-modified structural design code for buildings in Korea is comprised to be the same as the IBC2003, and it regulates the limit value so that the displacement ductility ratio is greater than approximately 3.15. Comparing the limit values for the 4 models applied in this test Table 6, in the case of design code test structure, ended up with a trend of decreasing load and the ductility ratio was 1.20, thereby being deemed as not satisfying the displacement limit value.

In addition, in the case of the test structure with expanded sheer walls on either side, the displacement ductility ratio was 2.33, thereby, it did not show as satisfying all the design code values; however, its structural property showed a trend of increasing load when the test ended, hence, it is expected to have greater ductility. In the case of the test structure with expanded sheer wall on one side, it showed displacement ductility ratio of 3.86, although it doesn't fairly meet the NEHRP design code, it is above the values required in other design codes, and its structural property showed a trend of increasing load when the test ended, hence, it is expected to satisfy all the design code values. Additionally, the test structure reinforced with steel columns showed ductile ratio of 5.74, thereby sufficiently satisfying all design code values. In each of the reinforced test structure case, considering that the test ended due to the test equipment limit, it is deemed that, although the structure had more ductility, it did not show; therefore, it is expected that all the reinforced test structures to satisfy the displacement limit value.

6. Conclusions

As shown above, the experiment on the construction method of installing additional reinforced concrete wall was conducted to examine the retrofitting method for seismic performance improvement by enhancing strength of time-worn apartment buildings with bearing wall-type structure. The experiment brought us to the conclusions as follows.

• The reference specimen showed the strength that was 41% less than the required strength. But all of the reinforcement experiment specimens were found to satisfy the required strength.

• According to the comparison of stiffness between the reference specimen and the reinforcement experiment specimens, the initial stiffness showed the conspicuous retrofitting effect. Even after the experiment specimen reached the yielding point, all of the reinforcement experiment specimens were found to maintain the higher stiffness than the reference specimen.

• Based on examination of the sectional properties of the pillar member, it was found that all of the reinforcement experiment specimens had the section effect of 450% or higher, compared to the reference specimen.

• According to analysis of the experiment results and the calculation results, it is believed that the calculated values can be applied to a real structure because the error rate was less than 10% for all of the experiment specimens.

• All of the methods to improve seismic performance of the existing building structures without considering seismic design are evaluated as the appropriate construction method, which provides a sufficient strength enhancement for retrofitted buildings.

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