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Seismic Behavior of Multi-story Structural Walls under Cyclic Lateral Loading: Experimental Study

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Abstract: The objective of this study was to investigate the seismic force resisting mechanisms of structural walls considering the interaction with the foundation beam, ground floor slabs and piles that supported the walls. Experimental tests were conducted on two 15% scale sub-assemblage specimens of the bottom three stories of a twenty-story structural wall. The structural walls were of monolithic construction for one specimen and of precast shear wall construction for the other. Cyclic lateral loads were applied with proportionally varying vertical loads to simulate loading conditions for the twenty-story prototype building. Conclusions were drawn concerning the deformation capacity and the strength deterioration after maximum strength shown by the walls. Contrary to the design, the yielding of the shear wall preceded the yielding of the foundation beam. Flexure-shear cracks of the shear wall penetrated the slabs transversely and developed to the foundation beam. At the ultimate state, the shear wall separated along these cracks involving the parts of the foundation beam, the pile, the transverse foundation beam and the slabs. These experimental phenomena clarified the monolithic action between the foundation beam and peripheral members.

Keywords: Cyclic loading, reinforced concrete, seismic behavior, structural wall

INTRODUCTION

Earthquake-resistant structural systems generally used in Reinforced Concrete (RC) buildings may be one of the following: moment-resisting space frames, shear walls, or a combination of both. The shear wall systems have shown better performance than the space frame systems, as noted many years ago by Fintel (1974) and evidenced by the behavior of RC buildings during 1995 Hanshin-Awaji earthquake of Japan (Architecture Institute of Japan, 1998). Therefore, in seismic zones, building resistance to earthquakes is often ensured by adopting structural systems where seismic actions are assigned to structural walls, designed for horizontal forces and gravity loads, while columns and beams are designed only for gravity loads (Paulay and Priestley, 1992). However, experience during the 1995 Hanshin-Awaji earthquake of Japan and the 2008 Wen-chuan earthquake of China (China Academy of Building Research, 2009; Yin *et al.*, 2008) has shown that the economic losses can be significant in buildings that satisfied the life-safety design criteria in current design codes. Typical mid-rise and high-rise buildings have multiple bay RC frames in the longitudinal direction and single bay shear wall system in the transverse direction. Extensive studies have been made of the seismic behavior of each member in such frames, such as the shear walls, the foundation beams and the piles that support those frames and walls (Hirata *et al.*, 2001; Eberhard and Meigs, 1995). Further, design procedures for these structural members are well established (Architecture Institute of Japan, 1999). However, the seismic behavior of a multi-story structural wall, considering its interaction with peripheral members such as foundation beams, ground floor slabs and piles, has not been studied well. In current design code, cantilever structural walls are generally assumed to stand on a solid foundation and the foundation beams, slabs and piles that support those walls are designed separately without considering interaction effects. Moreover, neglected in practical design is the fact that the shear transfer mechanism along the wall base varies with the crack patterns and the degree of inelastic deformation at the wall base. Designers choose appropriate design procedures based on their engineering experience. As a result, the ultimate failure mechanism may not be correctly identified and the seismic force resisting mechanisms between the shear wall and the peripheral members incorrectly evaluated, leading to irrational designs of each member of the system.

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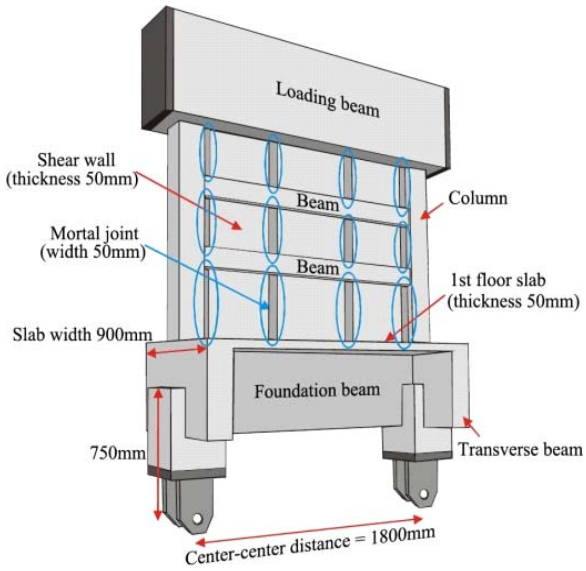


Fig. 1: Specimen PCW (MNW has no slits)

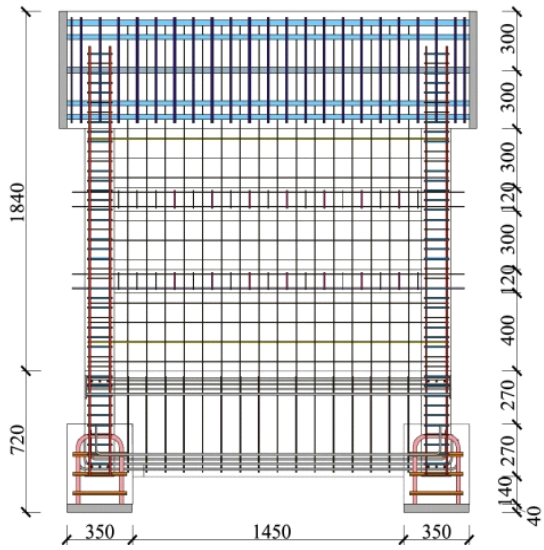


Fig. 2: Dimension and reinforcement

Therefore, in this study two specimens were tested to clarify the variations in the seismic force resisting mechanisms of structural walls considering the interaction with foundation beams, ground floor slabs and piles. Moreover, the purpose of experimental tests described herein was to not only increase the knowledge of how shear critical such RC structural walls behave, but also to provide much needed experimental data for further theoretical and analytical development in this area.

METHODOLOGY

Structural wall description: Two specimens of multi-story RC structural walls (MNW and PCW) were constructed and tested at Kyoto University to investigate the seismic behavior of structural walls considering their interaction with foundation beams, ground floor slabs and piles.

Specimens: As shown in Fig. 1, 2 15% scale structural wall specimens consisting of three-storied shear walls with a foundation beam, first floor slab and piles beneath each of the side columns were constructed, which were designed according to design code of AIJ.

Two specimens were identical except that the shear wall of PCW had four vertical slits that extended the height of each story and were filled with joint mortar to simulate a precast wall system. The horizontal joints of

Table 1: Material properties

	Concrete		
Location	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (Gpa)
Foundation beam, pile	36.9	3.84	25.3
Wall, column, beam	41.3	3.77	27.6
Joint mortar	52.7	3.04	23.5
Reinforcement			
Type	Compressive strength (MPa)	Tensile strength (MPa)	Young modulus (Gpa)
D4	499	587	226
D6(S)	375	534	182
D6(K)	1084	1183	176
D10	377	524	188
D22	324	514	172
D25	319	491	183

Table 2: Reinforcing bars in MNW and PCW

Member	Bar type		Steel ratio (%)
Column (160*160 mm)	longitudinal	4-D10	1.11
	transverse	2-D6(K)@50	0.79
Beam (100*120 mm)	upper long	4-D6(S)	0.65
	lower long	4-D6(S)	0.65
	transverse	2-D4@100	0.25
Shear wall (50 mm)	vertical	D4@100	0.25
	horizontal	D4@100	0.25
Pile (350*350 mm)	longitudinal	8-D22	2.53
	transverse	4-D10@100	0.82
Foundation beam (100*540 mm)	upper long	8-D10	1.23
	lower long	8-D10	1.23
	shear rebar	2-D6(S)@100	0.63
Transverse foundation beam (100*540 mm)	upper long	3-D10	0.25
	lower long	3-D10	0.25
	shear rebar	2-D6(S)@100	0.40
Slab (50 mm)	both direction	D4@100	0.25
Loading beam (400*600 mm)	upper long	8-D25	1.80
	lower long	8-D25	1.80
	shear rebar	2-D10@100	0.36

*D6(S) and D6(K) had different mechanical properties as shown in Table 1

the precast wall were not modeled to simplify specimen construction. While, specimen MNW was cast monolithically. For both specimens, the shear walls were designed to fail in flexure and the point of contra flexure for the piles was fixed at 750 mm from their top, even though the depth of the contra flexure point in practice varies with soil conditions and the intensity of the axial and lateral forces acting on the piles. The square piles were designed to remain elastic throughout the test because that the lateral load could be increased until the shear wall failed. The piles extended to mid-height of the foundation beam and were without caps for simplicity even though piles in practice are circular and have solid pile caps. The first floor slab extended 450 mm on each side of the centerline of the wall. The shear wall and the slab had the same thickness of 50 mm. Material properties and the type of reinforcement are listed in Table 1 and 2, respectively.

Loading system: As shown in Fig. 3, the lateral load, Q, was applied statically to the loading beam on the top of the wall using a 1MN hydraulic jack. Two vertical jacks in the plane of the wall created appropriate column axial forces, N_1 and N_2, which were liner functions of Q to simulate the loading conditions on the prototype twenty-story shear wall system during earthquakes:

$$N_1 \text{ and } N_2 = 133 \pm 3.10Q \ (Kn) \quad (1)$$

For the roller supported pile, a horizontal force was applied to the pile by a 500 kN jack so that the pile on the tension side carried 30% of Q and the pile on the compression side carried the rest. Thus, the south pile carried 30% of Q for positive loading and 70% of Q for negative loading. Two cycles of load were applied at each preselected increasing value of lateral drift until crushing occurred in the core concrete of the columns.

TEST RESULTS

Observed damage: Figure 4 shows the cracks and other damage observed in the specimens at the ultimate state.

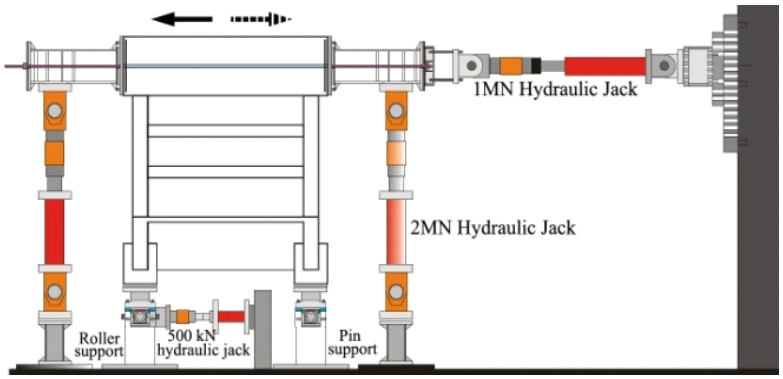
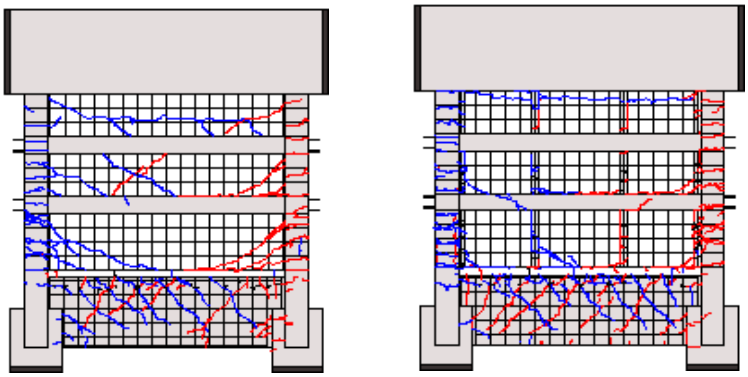
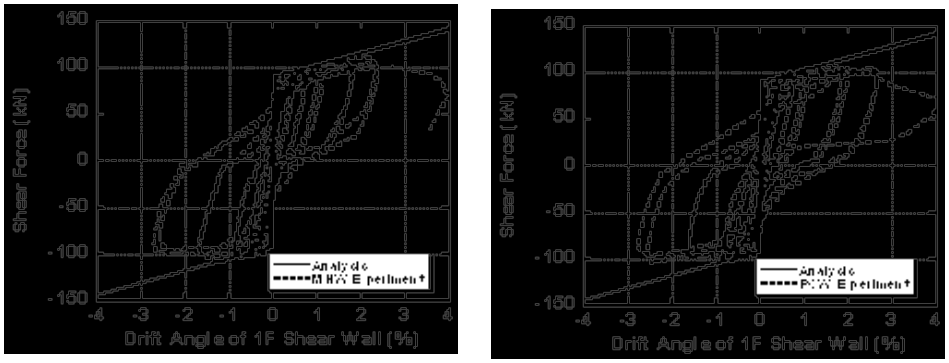


Fig. 3: Loading system



MNW PCW

Fig. 4: Observed damage after testing



(A) MNW (b) PCW

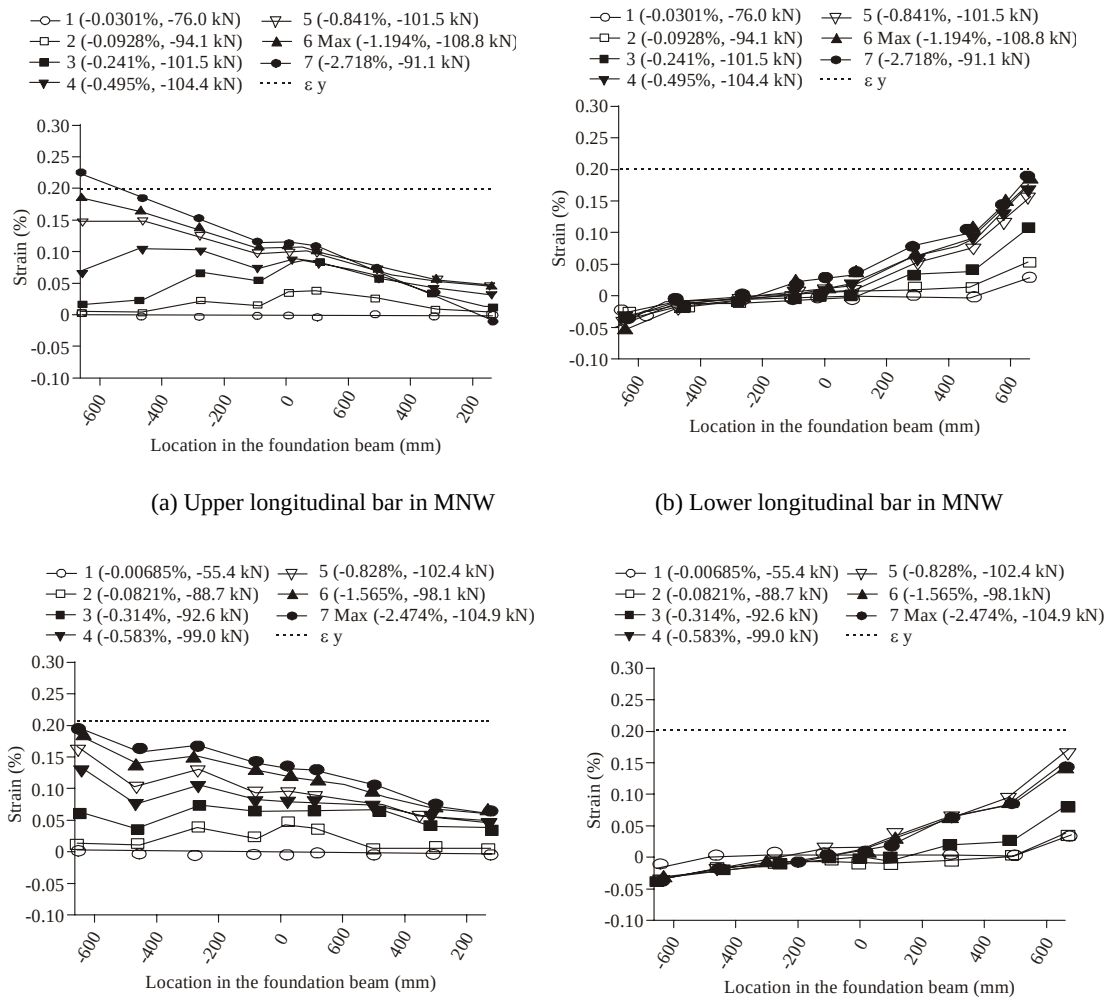
Fig. 5: Lateral load-drift angle relations

As designed the cracks in the walls of both specimens were dominated by flexure. PCW had some diagonal cracks running down the vertical slit to the bottom of each story after those cracks reached the slits. Due to this crack pattern, the wall cracks in PCW were concentrated more along the slits and the beam interfaces as compared with the cracks in MNW. The foundation beams of both specimens showed similarly large amounts of shear cracking after the crack at the wall base opened due to the rotation of the shear wall. In addition, large gaps due to flexural actions were found at the interface between the foundation beam and the piles.

The foundation beam was expected to act monolithically with the shear wall, piles and slabs,

Table 3: Load-drift angle at cracking and yielding

		MNW		PCW	
Type damage		positive	negative	positive	negative
Flexural cracking	load Q_{cr} (kN)	78.9000	-76.0000	84.8000	-83.8000
	drift (%)	0.0093	-0.0201	-0.0517	-0.0053
Flexural yielding	load Q_y (kN)	84.3000	-94.1000	86.3000	-88.7000
	drift (%)	0.0514	-0.0751	0.0936	-0.0419



(a) Upper longitudinal bar in MNW

(b) Lower longitudinal bar in MNW

(c) Upper longitudinal bar in PCW

(d) Lower longitudinal bar in PCW

Fig. 6: Strain distributions of longitudinal reinforcement in foundation beams

because the vertical reinforcement of the shear wall was well anchored into the foundation beam and the longitudinal reinforcement of the foundation beam was well anchored into the pile as specified in the design codes (Architecture Institute of Japan, 1997). Therefore, damage in the foundation beam was expected to be minimal. However, the observed damage indicated that the foundation beam did not act monolithically with the peripheral members to resist the external loads once the rotation of the shear wall became significant and the gap between the wall and the foundation beam opened.

Lateral load-drift angle relations: Figure 5 shows lateral load-first story drift angle relations. Both specimens showed ductile behavior up to a drift angle of 2%. After drift angle R = 2%, the lateral load carrying capacity degraded because the concrete at the base of the compressive column started to crush. Load and drift angle at cracking and yielding of the walls are listed in Table 3. Flexural cracking loads, Q_{cr}, were close to the flexural yield loads, Q_y, for both specimens. Drift angle at Q_{cr} and Q_y varied widely and this shows the difficulty of measuring the deformations of this stiff system. Main

differences with regard to the lateral load-drift angle relations were not observed since the damage to the two specimens was similar except for the crack patterns as explained in the above section.

Strain distributions: Figure 6 shows the strain distributions of the longitudinal bars in the foundation beams of specimen MNW and PCW. Strains in the upper longitudinal reinforcement near mid-span tended to be larger than strains at the beam ends up to stage 4. After stage 5 where the cracks between the shear wall and the foundation beam became large, the strains on the tensile side increased to similar values to those at mid-span. Strain distributions in the lower longitudinal reinforcement were nearly linear for any loading stage as shown in Fig. 6b and 6d.

CONCLUSION

Two 15% scale structural walls were tested to failure to clarify the lateral force resisting mechanisms considering interaction between the shear wall, foundation beam, first floor slab and piles. Conclusions were summarized as follows.

- Monolithic action between the foundation beam and peripheral members, such as the shear wall and piles, was much less than expected and unexpected shear cracking spread extensively over the length of the foundation beam at the ultimate stage when the width of the crack between the shear wall base and the foundation beam became large.
- Flexure-shear cracks of the shear wall penetrated the slabs transversely and developed to the foundation beam. At the ultimate state, the shear wall separated along these cracks involving the parts of the foundation beam, the pile, the transverse foundation beam and the slabs.
- Contrary to the design, the yielding of the shear wall preceded the yielding of the foundation beam. These clarified monolithic action between a foundation beam and peripheral members.
- Strain distributions of longitudinal reinforcement in foundation beams show the shear transfer mechanism clearly. It could be validated that the foundation beam is subjected to moment from the piles, moment and axial force due to lateral force acting on the upper edge of the foundation beam and moment due to vertical longitudinal bars in the shear wall.
- Finally, taking into account all the involved uncertainties, the scale effects and the inadequate number of samples for each specimen, it has to be emphasized that the experimental results of the presented study and the aforementioned conclusions are mainly limited to the study cases and must be used and extrapolated carefully and cautiously.

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