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SEISMIC BEHAVIOR OF DOUBLE WALLS WITH CONTINUITY REINFORCEMENT

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ABSTRACT: The conventional precast construction has deficiencies especially related to its connections between structural elements. Hence, its use in earthquake zones has been limited. However, the seismic performance of these systems can be improved by a semi-precast system, namely the double wall system. In this structural system, both precast and cast-in-situ concrete elements are utilized during the construction period, i.e. precast concrete shells are benefitted as a formwork to place cast-in-situ concrete. In this way, monolithic building elements, which finally show the same effectiveness as cast-in-situ concrete walls and slabs can be constructed. In this study, reversed cyclic test results for the double walls are reported. The main objective of the experimental program is to compare the seismic response of two double walls, one cast monolithically, the other one composed of two walls constructed side-by-side and having monolithically cast concrete at the central region along with the continuity reinforcement between the two separate wall elements. Test results demonstrate that the use of continuity reinforcement between adjacent double walls ensure monolithic response with increased stiffness and energy dissipation characteristics.

1. Introduction

A double wall is a semi-finished product and consists of two thin precast concrete shells connected to each other by special reinforcements, i.e. the lattice girder or the wave (Fig. 1a and 1b). After the installation of these precast concrete elements, cast-in-situ concrete is placed inside the void between the shells. The inside faces of precast concrete shells are intentionally roughened to obtain a monolithic behavior of double wall section, i.e. to generate proper shear transfer. Through the use of double wall elements, extensive moulding works and major part of the reinforcement works are done in the factory, which significantly reduces the construction time. There is also the possibility to product double walls with inside thermal insulation (Fig. 1c). The insulation thickness is usually around 5 to 20 cm depending on the respective structural-physical requirements of the thermal protection calculation. The insulation is well protected inside the shell against environmental effects and fire. The insulation is also prepared in the factory, thereby removing the need of any insulation needs on site. This property enables the double walls system to be a complete structural system with only in the need of window/door installation and minor finishing.

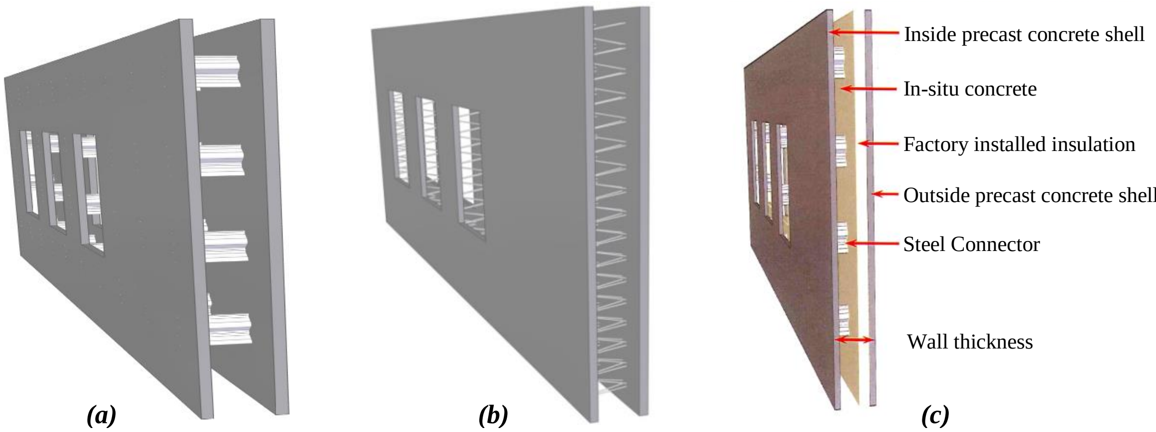


Fig. 1 – Double walls with (a) steel waves, (b) lattice girders and (c) sketch of insulated double walls

In literature, there are many alternatives to construct double walls, two of which are the usage of lattice girder and steel wave. Lattice girder has been the classical method of constructing double walls in Europe in the last five decades (FIB Bulletin 2003). These elements should be placed at most 40 cm away from the ends of concrete shells in order to prevent cracks and/or undesired deformations of concrete shells during the placement of in-situ concrete (Fig. 2). Thus, this requirement limits the length of continuity reinforcement utilized between adjacent walls. Most of the time, the available length for the continuity reinforcement is less than the required development length for these reinforcement cages. Consequently, the adjacent walls do not behave monolithically and it is impossible to benefit from the advantages of increased stiffness and strength. Furthermore, the continuous vertical reinforcement application (lattice case) deprives the design and site engineers of easily placing the reinforcements required between the two concrete shells for seismic detailing. From the beginning of the 21st century, the usage of steel waves (Fig. 1a) to connect the two concrete shells become more popular. Steel waves are discrete connection elements and resolves many problems like 1- more space for transfer reinforcements, 2- allowing the application of any type of extra reinforcements between the two concrete shells, 3- reduction of steel amount for the connection of two shells.

There are a number of experimental studies conducted to understand the seismic behavior of various precast walls and their connections. The experimental programs mainly concentrate on the determination of different shear connectors' performances to generate full-composite action (Bush and Stine 1994, PCI Committee 1997, Salmon *et al.* 1997, Naito *et al.* 2012 and Gara and Ragni 2012). The performance of precast walls under cyclic loading is also investigated to determine the stiffness and strength degradation characteristics of precast RC walls although these efforts are very limited compared to the cast-in-place concrete counterparts (Demeter *et al.* 2010 and Pavese and Bournas 2011). In addition to the precast RC wall members, the performance of different types of connections is also tested in numerous studies (Cheok and Lew 1993, Loo and Yao 1997 and Zenunovic and Folic 2012). Recently, the seismic behavior of concrete filled double steel plate walls is investigated (Ji *et al.* 2013 and Nie *et al.* 2013). In addition, the behavior of GFRP connectors to tie precast walls with insulation material in the middle is studied (Woltman *et al.* 2013). None of the aforementioned studies addresses the seismic behavior of the reinforced concrete double walls produced with steel waves.

In this study, reversed cyclic test results for the double walls are reported. The main objective of the experimental program is to compare the seismic response of two double walls, one cast monolithically, the other one composed of two walls constructed side-by-side and having monolithically cast concrete at the central region.

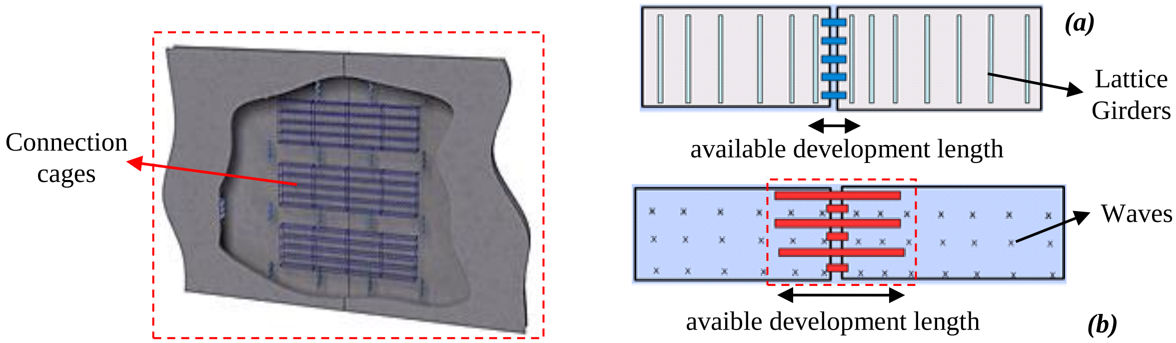


Fig. 2 – Continuity reinforcement application in (a) lattice girders and (b) steel waves

2. Experimental Research

2.1. Test specimens and instrumentation

As described in the previous section, double wall systems are constructed by placing double walls side-by-side, placing continuity reinforcement cages and casting concrete monolithically at the central hollow regions. Therefore, it is important to examine whether such walls act as single walls or not. For this purpose, two test specimens are tested to compare the seismic response of two double walls, one cast monolithically (Specimen 1), the other one composed of two walls constructed side-by-side and having monolithically cast concrete at the central region (Specimen 2). Continuity reinforcements (cages) are placed at the intersection of the two double walls in order to ensure proper shear transfer for Specimen 2.

Several measurements are taken in order to record the response of specimens during tests. Load cells are utilized to measure the applied lateral and vertical loads. Linear variable differential transducers (LVDTs) are installed to record the lateral displacement of the specimens and the relative displacements of the walls between two points. The instrumentation employed for each test specimen are shown in Fig. 3.

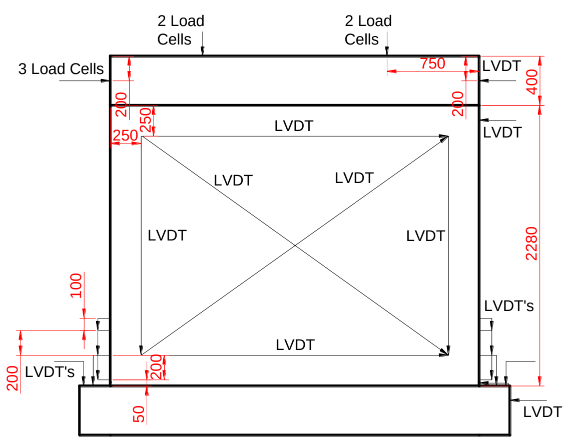


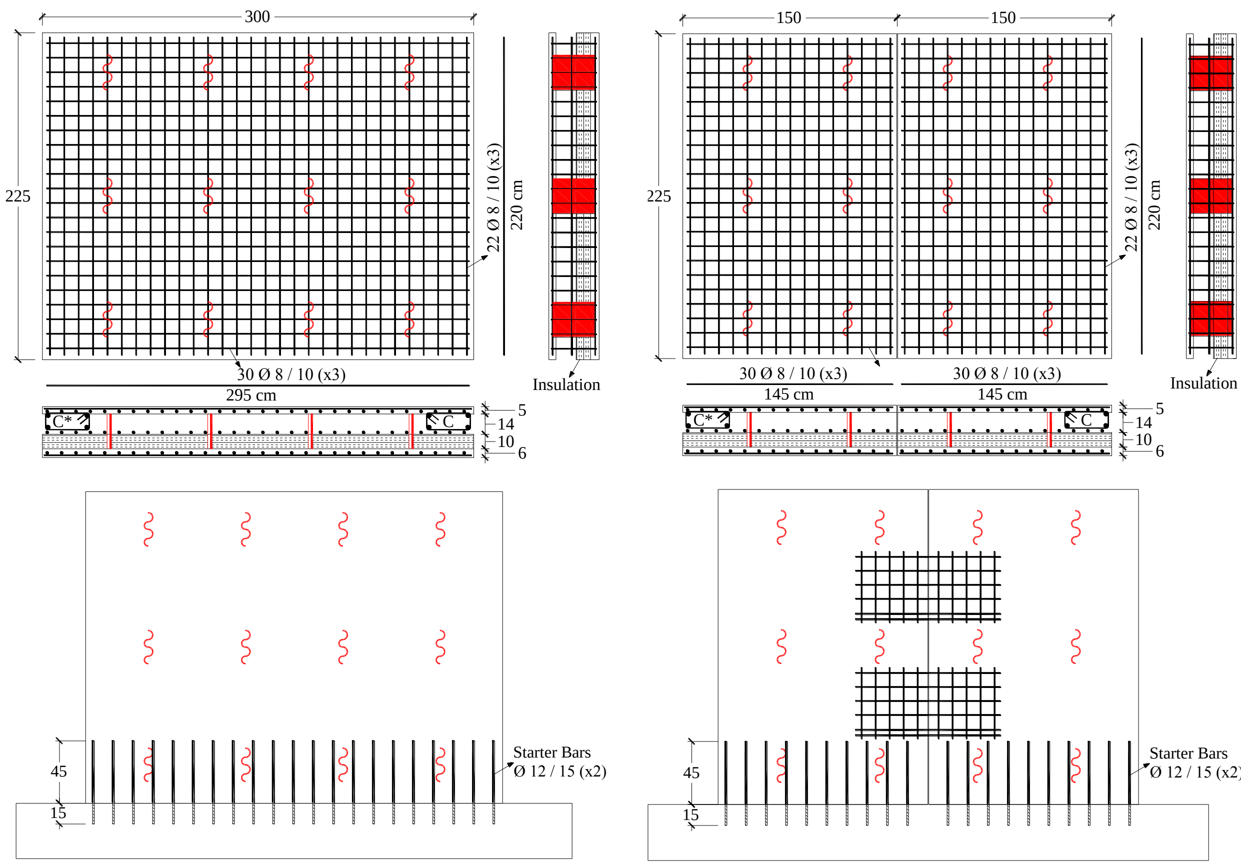
Fig. 3 – Instrumentation installed on both Specimen 1 and Specimen 2 *(All dimensions are in mm.)*

In addition, a summary of the specimens tested in this study is summarized in Table 1. The reinforcement drawings of all the walls are presented in Fig. 4. All of the specimens are tested with fixed boundary at the specimen base and free boundary condition at the tip of the specimen. Then, the lateral forces are applied at the tip of the each specimen. Interstory drift ratio is selected as the control variable throughout the tests. Each displacement target is attained twice before moving to the next stage. The target drift ratios (DR) utilized during experiment are shown in Fig. 5.

Table 1. Properties of test specimens

Specimen	Section	Height (m)	Depth (m)	Axial Load (kN)	f_{cks}* (MPa)	f_{ckc}** (MPa)	ϕ6 f_y, f_u (MPa)	ϕ8 f_y, f_u (MPa)
1	R***	2500	3000	602	45	28	340, 470	380, 540
2	R	2500	3000	610	43	27	340, 470	380, 540

*: f_{ck} for concrete shell, **: f_{ck} for concrete core, ***: rectangular section



a) Specimen 1

b) Specimen 2

Fig. 4 – Reinforcement drawings of (a) Specimen 1 and (b) Specimen 2
(*: Cage C is formed by 4Φ14 longitudinal bars and Φ6/100 mm stirrups.)

2.2. Test results

Measured response of the test specimens along with the observed damage patterns are presented in this part. A summary of the test results for the each specimen is provided in Table 2. In this table, measured response parameters important for the seismic performance are summarized. First cracking load and deformation values are obtained from the visual observations. The yield and ultimate displacement are found from an idealized elastic perfectly plastic response as shown on each Load-displacement curves as red lines (Fig. 6). First yield point is defined by connecting the origin with a line passing through 70% of the ultimate load on the initial loading curve. The extension of this line to the 85% of the ultimate load is assumed to give the yield displacement. The ultimate deformation at 15% capacity drop is taken as the ultimate displacement level. Displacement ductility is calculated by dividing the ultimate displacement with the yield displacement.

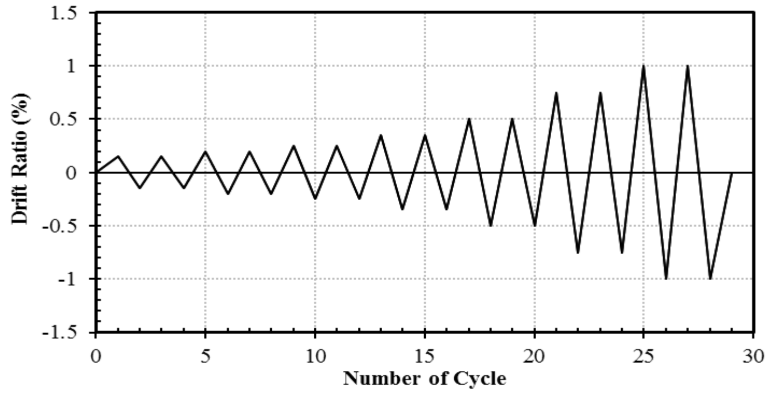


Fig. 5 – Displacement history during all tests

Table 2. Summary of Test Results

Response Parameters	Specimen 1	Specimen 2
First Cracking Load (kN)	450	495
First Cracking DR (%)	0.06	0.05
DR at First Yielding (%)	0.13 (0.12)*	0.10 (0.11)
Ultimate Load (kN)	1057 (895)	1052 (1011)
DR at Ultimate Load (%)	0.20	0.20
DR at Ultimate Displacement (%)	0.85 (0.8)	0.75 (0.5)
Displacement Ductility	6.5 (6.7)	7.5 (4.5)
Failure Mode	Flexure-Shear	Flexure-Shear

*: Numbers in parenthesis denote negative direction values.

Specimen 1 experiences base cracking at a drift ratio of about 0.06%. Beyond this drift ratio level, a number of flexure cracks occur starting from the base level towards the upper portions of the wall. Cracks occur on the tension side of the wall depending on the direction of the wall that is subjected to tension. At about 0.20% drift ratio, wall base shear capacity is reached. Inclined cracking is observed to occur starting at about 0.25% drift ratio. The longest shear cracking spanning from both sides of the wall is observed at about 0.35% drift ratio. Lateral load carrying capacity of the wall slightly decreases while displacing the wall from 0.20% to 0.25% drift ratio, however it picks up beyond 0.25% without evidencing any significant failure event. Beyond 0.35% drift ratio, the width of the base cracks significantly increases (up to a few millimeters). At a drift ratio of about 0.75%, the lateral capacity of the wall does not drop significantly. This shows that the wall behaves in a ductile manner in both directions of loading. The lateral load carrying capacity of the wall is about 1050 kN in the positive direction, whereas it is about 900 kN in the negative direction of loading. An elastic perfectly plastic envelope is drawn on the lateral load-displacement figure as shown in Fig. 6a. Based on this idealized response, it can be stated that the wall has a displacement ductility of at least 6.5 in both directions. Despite relatively squat dimensions of the test specimen (H/L ≈ 0.85), the double wall system is able to behave in a very ductile manner. This proves the success of the designed reinforcement in shear and flexure. It should be noted that the concrete shell with insulation material does not sustain any deformations or damage. The central part and the adjacent concrete shell carried all of the lateral forces. Observed cracks are shown in Fig. 7.

Similar to Specimen 1, Specimen 2 has experienced base cracking at a drift ratio of about 0.05%. Afterwards, flexure cracks occur at a spacing of about the stirrup size from the bottom of the wall. Cracks occur on both sides of the wall depending on the direction of the loading. At about 0.20% drift ratio, wall base shear capacity has reached. Inclined cracking is observed starting at about 0.20% drift ratio in the form of flexural shear cracking. The longest shear cracking spanning from both sides of the wall is observed at about 0.35% drift ratio. Lateral load carrying capacity of the wall slightly decreases while displacing the wall from 0.20% to 0.25% drift ratio, however it picked up beyond 0.25% without evidencing any significant failure event. Even at a drift ratio of about 0.75%, the lateral capacity of the wall does not drop significantly. This shows that the wall has behaved in a ductile manner in both directions of loading. The lateral load carrying capacity of the wall is about 1050 kN in the positive direction, whereas it is approximately 1000 kN in the negative direction of loading. An elastic perfectly plastic envelope is drawn on the lateral load-displacement figure as shown in Fig. 6b. Based on this idealized response, it can be stated that the wall has a displacement ductility of at 7.5 and 4.5 in the positive and negative directions, respectively. Just like Specimen 1, this test specimen is also able to behave in a very ductile manner. It should be noted that the concrete shell with insulation material did not sustain any deformations or damage similar to Specimen 1. The central part and the adjacent concrete shell have carried all of the lateral forces. Final crack map of Specimen 2 is shown in Fig. 8. It is interesting to note that the cracks are well distributed for this specimen and their widths remain limited throughout testing. Another important issue for this specimen is the behavior of the two double wall interface. No cracking or differential displacement is observed at the interface of the two adjacent double walls (Fig 8). This proves that Specimen 2 behaves no differently than the monolithic version of it (Specimen 1).

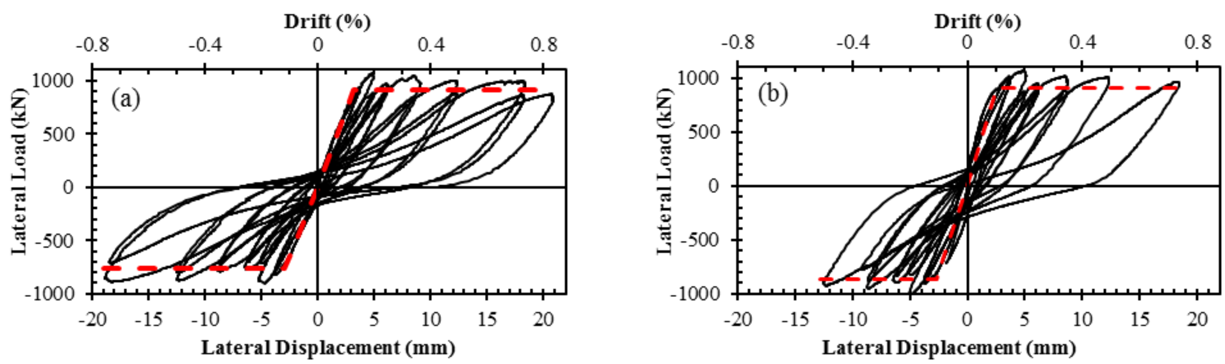
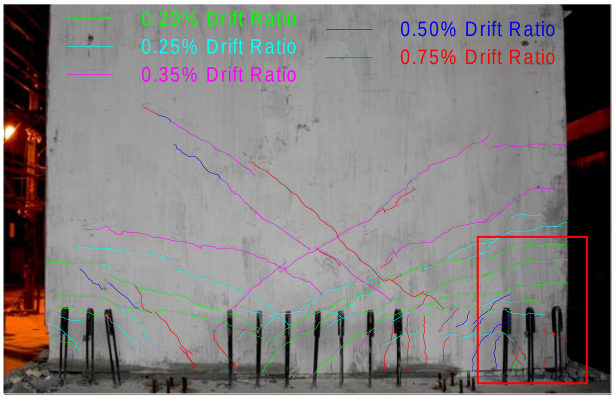


Fig. 6 – Load-displacement responses of test specimens: (a) Specimen 1 and (b) Specimen 2

3. Discussions

The objective of testing of Specimens 1 and 2 is to observe the difference of behavior when the same wall length is constructed monolithically and with an interface between shells. The comparisons of the load-deformation responses of Specimens 1 and 2 are shown in Fig. 9. It can be observed that the two measured curves perfectly follow each other. This proves that casting monolithic central region and providing continuity reinforcement cages to connect the two shells (as in Specimen 2) ensures monolithic response of the doubles built with adjacent panels.

The moment-curvature responses of all test specimens are computed during the preparation of the test setup in order to estimate the lateral strength. The computed moment-curvature versus measured moment-curvature responses for Specimen 1 and Specimen 2 are presented in Fig. 10. Standard section analysis procedures are used along with Mander *et al.* (1988) stress-strain model for both confined and unconfined concrete and elasto-plastic hardening model for steel reinforcement. It can be observed that the lateral strength and ultimate curvature estimations are in reasonable agreement with the measured quantities except for the ultimate curvature values. Such estimations enable to comfortably state that standard reinforced concrete section calculations can be performed to compute the capacity of structural elements built with double walls for design and performance estimation objectives.



a) Observed Cracks at different drift ratio levels

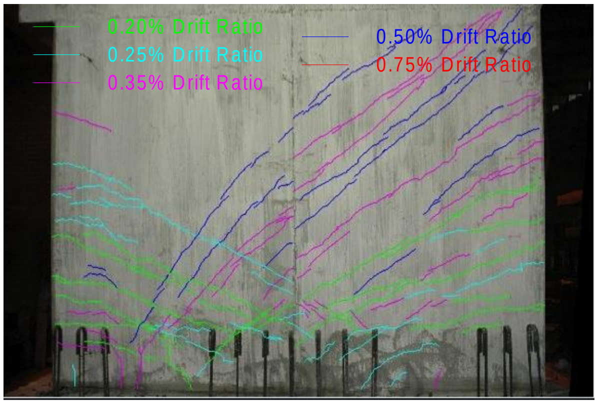
b) Flexural cracks at the base

c) Observed base cracks at drift ratio of 0.1%

d) Observed base cracks at drift ratio of 0.5%

e) Observed base cracks at drift ratio of 0.75%

Fig. 7 – Observed cracks of Specimen 1



a) Observed Cracks at different drift ratio levels

b) View of interface at drift ratio of 0.20%

c) Observed base cracks at drift ratio of 0.15%

d) Observed base cracks at drift ratio of 0.35%

Fig. 8 – Observed cracks of Specimen 2

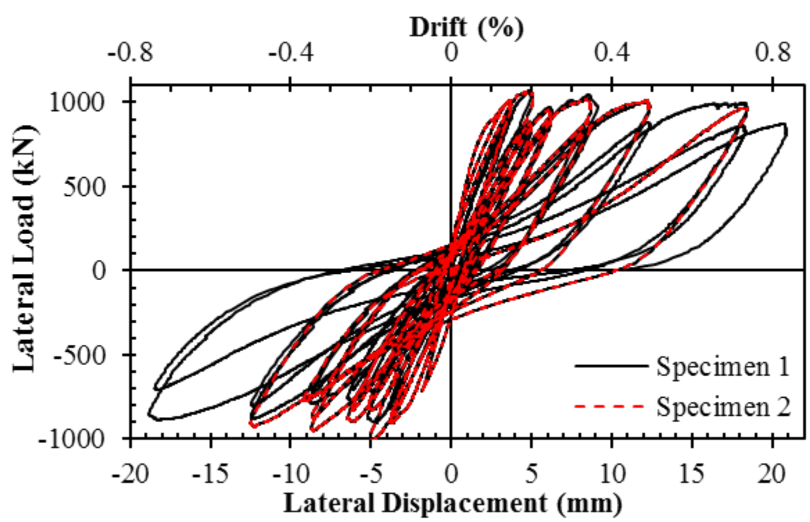


Fig. 9 – Comparison of Load-deformation Responses of Specimens 1 and 2

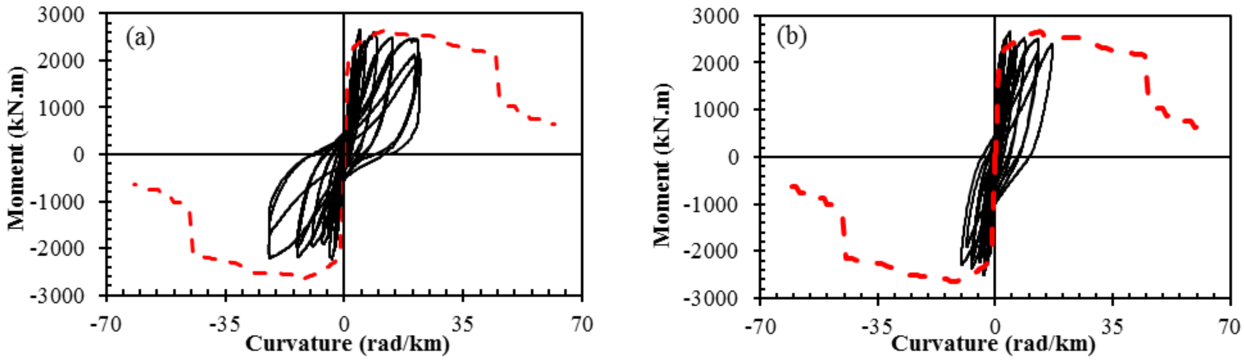


Fig. 10 – Moment-curvature response of specimens at wall bases: (a) Specimen 1 and (b) Specimen 2 (*Dashed lines show the analytical estimations.*)

4. Conclusions

This study investigated experimentally the behavior of two double wall specimens tested under simulated earthquake loading with reversed cyclic testing method. The following conclusions can be drawn on the basis of the observed response of the test specimens:

- Specimen 1 (monolithic double wall) and Specimen 2 (built from two double walls) have behaved practically in the similar manner. In other words, the lateral load carrying capacity, deformation capacity and ductility of the two specimens are alike for these two specimens. This result proves that walls built by placing adjacent double walls connected to each other with continuity reinforcement cages can be thought to behave as monolithic walls.
- Moment-curvature results for the test specimens reveal that the capacity of double walls can be estimated by utilizing standard RC section analysis procedures. This fact supports the use of existing analysis tools for structural design when double wall systems are employed.
- The tested specimens have performed in a ductile manner resulting in ductilities of 6.5 and 4.5 for Specimen 1 and Specimen 2, respectively. This result enables the use of double walls in buildings located in earthquake prone regions provided that correct detailing are performed at the design stage. As the double walls can be designed with any desired reinforcement detailing, one can easily follow the rules of earthquake codes during their production.

5. Acknowledgements

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