

# Interlocking Compressed Earth Block Walls: In-plane Structural Response of Flexure-dominated Walls



## **B. Qu**

*Assistant Professor, Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, USA.*

## **B.J. Stirling**

*Junior Structural Engineer, AMEC Americas Ltd. Calgary, AB Canada.*

## **P.T. Laursen**

*Assistant Professor, Dept. of Architectural Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, USA.*

## **D.C. Jansen**

*Professor, Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, USA.*

## **D.W. Bland**

*Associate Welding Planner, Pacific Gas & Electric, Avila Beach, CA 93424, USA.*

## **SUMMARY:**

Interlocking Compressed Earth Blocks (ICEBs) are a form of dry stack masonry units, which can be manufactured by inexperienced labourers using predominantly low cost materials. This paper presents results from a testing program investigating flexure-dominated ICEB walls. Four 1.8-m high ICEB walls were constructed and tested under in-plane cyclic loading. The specimens were varied to identify the effects of height-to-width aspect ratio, presence of a flange at one end of the wall, and presence of an opening in the wall on performance of the system. Testing results show that flexure-dominated ICEB walls can exhibit stable hysteretic behaviour until a ductile failure occurs. Furthermore, the strength of the wall can be enhanced due to the presence of a flange at one end and will be reduced due to the presence of an opening. Ordinary plastic analysis procedure is shown to provide reasonable predictions for in-plane resistance of flexure-dominated ICEB walls.

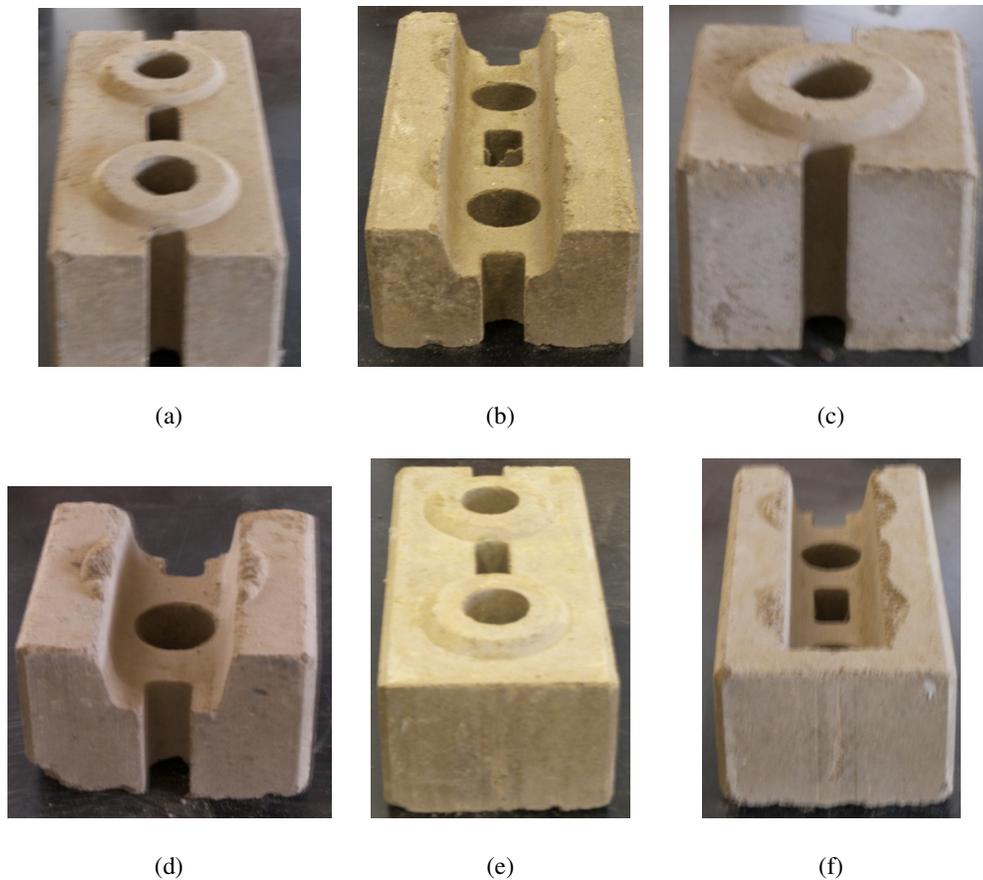
*Keywords: Interlocking compressed earth block, flexure-dominated, cyclic loading, seismic performance.*

## **1. INTRODUCTION**

Recent rapid population growth has created significant demands for housing in many countries, in particular in those developing countries. The high cost of materials and experienced labor has prevented many people from buildings with appropriate and safe construction methods. Developing an affordable, safe, and sustainable building system has become an imperative task for civil engineers and researchers around the globe. Earth construction, as one of the oldest building materials, with documented use as far back as 2500 BC (Maini 2010), has been used extensively around the world due to the sustainable and economical use of indigenous soils as well as the significant reduction in manufactured materials required. Interlocking Compressed Earth Blocks (ICEBs) discussed in this paper are a special form of dry stack earth construction units made with indigenous soil typically stabilized with cement. ICEB construction combines the benefits of compressed earth technology and dry stack interlocking masonry. A typical stabilized ICEB consists of less than 10% Portland cement by weight (Walker 1999), which significantly reduces the amount of cement necessary to build a structure. Therefore, from an environmental perspective, ICEB construction allows for a large reduction in embodied energy when compared to a building with concrete or kiln fired clay masonry. Moreover, ICEBs can be manufactured by inexperienced laborers and construction of ICEB buildings requires no special skills, making ICEB constructions a viable building option throughout the globe.

To date, extensive research and testing have been conducted for ICEBs aiming at understanding specific compressed earth material properties such as compressive strength, and bond characteristics

based on soil and stabilization properties, optimum earth block mix with consideration of different soil types, cement content, and water content, and durability and compaction of ICEBs (Bales *et al.* 2009; Perera and Jayasinghe 2003; Bei and Papayianni 2003; Bryan 1988; Heathcote 1991; Reddy *et al.* 2007; Burroughs 2006; Jayasinghe and Mallawaarachchi 2009). While these efforts have improved the performance of ICEBs at the material level, there are remaining issues regarding the structural performance of ICEB structures, particularly performance of ICEB walls in the regions with moderate and high seismicity, limiting the wide spread acceptance of this system. This paper presents results from a testing program investigating the seismic performance of flexure-dominated ICEB walls. A total of four large scale specimens (designated as W1, W2, W3, and W4, respectively) were constructed and tested. The specimens were varied to identify the effects of the following factors on performance of ICEB walls: height-to-width aspect ratio, presence of a flange at one end of the wall, and presence of an opening in the wall. The following sections describe ICEB material properties, specimen design and construction, test setup, loading program, observations and results from testing. Incidentally, seismic performance of the shear-dominated ICEB walls and out-of-plane performance of ICEB walls were also investigated by the authors and the corresponding results are presented elsewhere (Bland *et al.* 2011; Herskedal *et al.* 2012).



**Figure 2.1.** Types of blocks used in wall construction (a) full block; (b)full channel block; (c) half block; (d) half channel block; (e) end block; (f) end channel block (f).

## 2. ICEB PROPERTIES

The ICEBs used in construction of the wall specimens in this investigation were manufactured using the Soeng Thai Model BP6 press developed by the Centre for Vocational Building Technology (CVBT), a non-governmental organization in Thailand (Wheeler 2005). The Soeng Thai Model BP6

press is capable of producing different types of block by adding or removing various inserts. The standard masonry unit is a 100 x 150 x 300 mm (4" x 6" x 12") block commonly called the "Rhino Block" as shown Fig. 2.1(a). The "Rhino Block" is composed of two reinforcement holes used for vertical grouted reinforcement, three "grout key channels" commonly filled with a fluid grout to provide wall stability and load transfer, and two interlocking dowels aligning adjacent blocks. For the specimens constructed in this investigation, five variations of the standard full block shown in Fig. 2.1 (b) to (f) were used. A mixture identified to provide the best durability, desired constructability, and most stable compressive strength from past testing work (Proto *et al.* 2010), which consists of soil, sand, cement, and water with weight percentages of 74.3%, 10.0%, 6.2% and 9.5%, respectively, was adopted in manufacture of ICEBs.

As an important design parameter, compressive strength of ICEBs,  $f_{mo}'$ , was determined from testing of masonry prisms. Each prism was constructed from three fully grouted, vertically stacked ICEBs which were built at the same time and cured under the similar conditions as the wall specimens. The grout includes sand, cement, and lime with volume percentages of 75%, 18% and 7%, respectively. Six ICEB prisms (including two for each of W1 and W4, and one for each of W2 and W3) were tested. The prism compressive strengths from specimens W1, W2, W3, and W4 were determined to be 3.04 MPa, 2.77 MPa, 3.16 MPa, and 2.25 MPa, respectively. All prisms experienced a similar failure mode, that is, diagonal compression cracking followed by conical spalling on the unconfined sides as well as vertical crushing of the prism.

### 3. SPECIMEN DESIGN

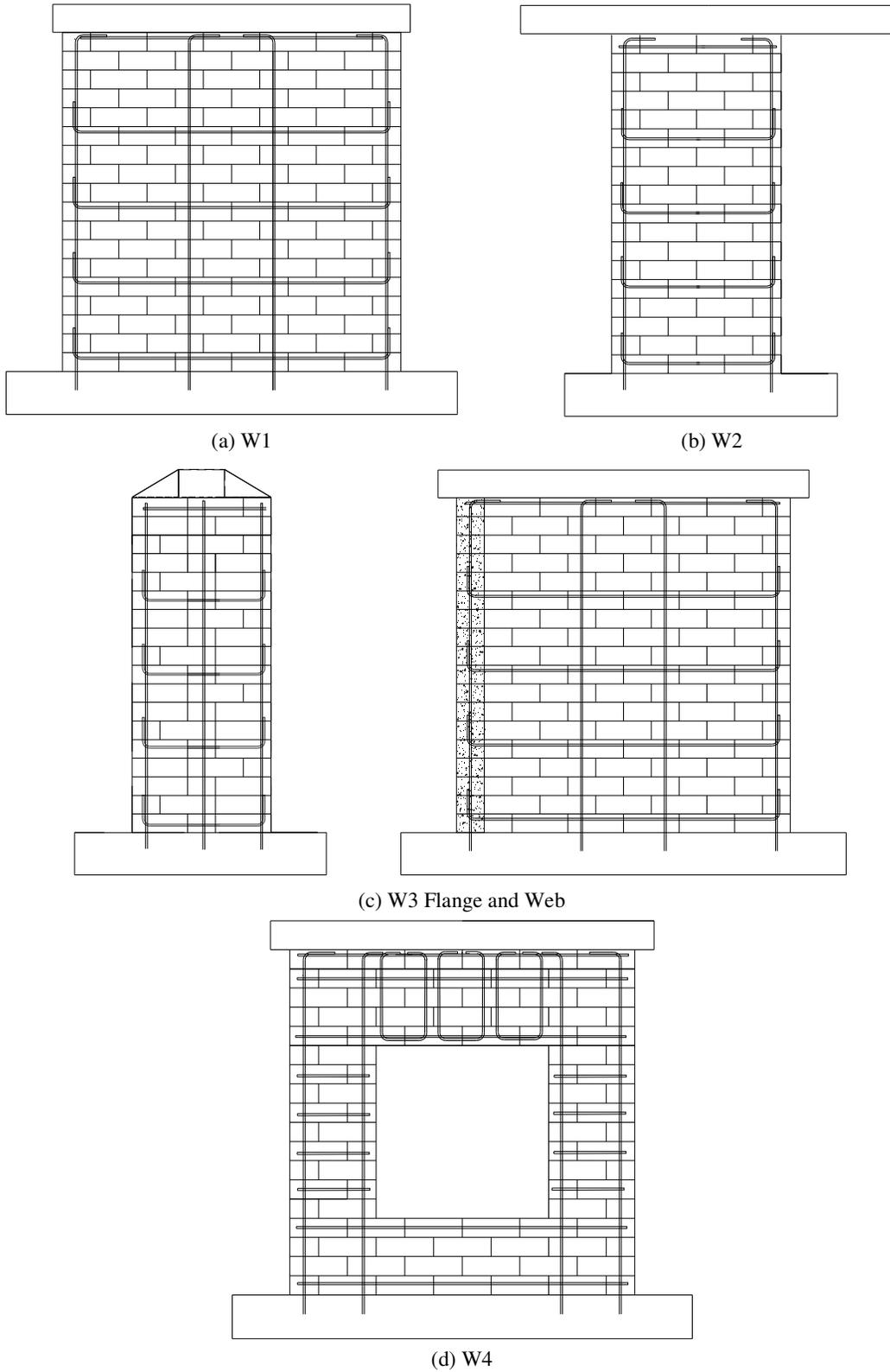
The specimens, W1, W2, W3, and W4, were constructed using the ICEBs and grout material described in the previous section. In order to focus on behavior of the flexure-dominated ICEB walls, shear strength and flexural strength of each specimen were estimated using the procedure provided in (Stirling 2011) and each wall was reinforced with the #3 steel bars with a nominal area of 71 mm<sup>2</sup> longitudinally and transversely to ensure the wall can reach its flexural strength without experiencing a shear failure. Reinforcing patterns of the specimens are shown in Fig. 3.1. The following describes the detailed information of each specimen.

Specimen W1 is a 1.8 m high and 1.8 m wide solid wall with a 1:1 height-to-width aspect ratio.

Compared with W1, W2 is a relatively slim wall with height and width respectively equal to 1.8m and 0.9m, allowing the wall with a 2:1 height-to-width aspect ratio. To focus on the impact of wall aspect ratio on its seismic behavior, the only variable changed from W1 to W2 is the aspect ratio, done by essentially building half of W1. To ensure the flexure-dominated behavior and have a direct comparison between W1 and W2, the transverse rebar arrangement used in W1 was adopted in W2.

Specimen W3 is a 1.8m high wall with an intersecting flange at one end. The web width of W3 is 1.8m, allowing the web with a 1:1 height-to-width aspect ratio which is the same as W1. Moreover, the longitudinal and transverse rebar arrangements in the web of W3 are similar to those in W1. Therefore, a direct comparison can be made between W1 and W3, allowing for investigation of the contribution of a flange at one end of a wall to strength, ductility, and overall performance of the system. The flange width of W3 was determined to be 750 mm. The reinforcement arrangement in the flange is shown in Fig. 3.1.

Specimen W4 is a 1.8 m high and 1.8 m wide wall with a 0.9 m x 0.9 m square window opening at its centre. W4 was developed to create a direct comparison between a solid wall and one with an opening, i.e., comparison between W1 and W4.



**Figure 3.1.** Reinforcement arrangements in tested specimens (a) W1; (b) W2; (c) W3 flange and web; (d) W4 (height of each block = 100mm)

#### 4. TEST SETUP AND LOADING PROGRAM

A similar test setup was used for all the specimens in this investigation. Fig 4.1 illustrates the test setup for W2. The in-plane cyclic loads were provided by a 350 kN MTS hydraulic actuator with stroke of +/- 250 mm. One end of the actuator was connected to the top of each specimen and the other end was connected to strong wall. The reinforced concrete footing on which the ICEB wall specimens were built was bolted to strong floor to prevent movement during the tests. Along the out-of-plane direction, the top of each specimen was restrained by steel rollers attached to a steel reaction frame, preventing the specimens from deflecting in the out-of-plane direction.

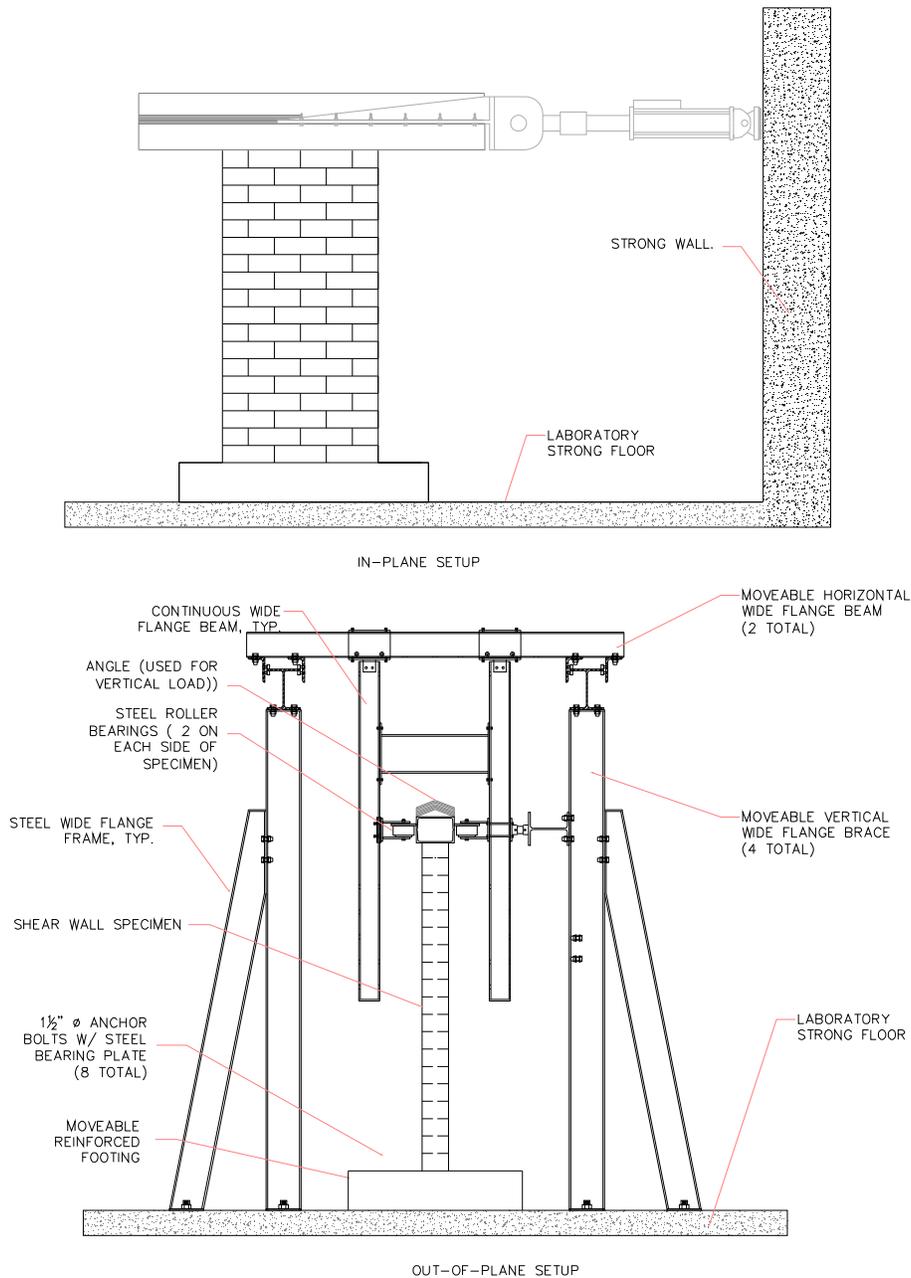


Figure 4.1. Test setup of W2

Vertical loading was applied by adding a series steel angles stacked on top of the steel loading beam installed at the top of each specimen to simulate the weight of the lightweight roofing system. In addition, a portion of the vertical loading was provided by the self-weight of the actuator head, which was weighted before being mounted to the top of the wall. The resulting vertical load imposed on each specimen remained at a constant of 2.5 kN/m.

A displacement controlled loading protocol presented in Table 4.1 was used for testing all specimens, which allows a direct comparison of the wall behaviors obtained from different specimens. It is noted that the cyclic loads applied on the top of the specimens can be differentiated into two categories, the push and pull cycles, which respectively cause tension and compression in the blocks on the actuator side. For the loading protocol presented in Table 4.1, the displacements corresponding to the pull and push cycles were respectively assigned positive and negative signs. Also note from Table 4.1 that such a loading protocol consists of two push and pull cycles at each displacement level. The loading protocol was continued until more than 50 percent of the specimen strength has degraded, or the wall became unstable during the test.

**Table 4.1.** Cyclic Displacement Histories

Displacement Step	Number of Cycles	Cumulative Number of Cycles	Deflection (mm)	Drift (%)
1	2	2	0.5	0.03
2	2	4	1	0.06
3	2	6	2	0.11
4	2	8	4	0.22
5	2	10	6	0.33
6	2	12	8	0.44
7	2	14	10	0.56
8	2	16	12	0.67
9	2	18	14	0.78
10	2	20	16	0.89
11	2	22	20	1.11
12	2	24	24	1.33
13	2	26	28	1.56
14	2	28	32	1.78
15	2	30	36	2.00
16	2	32	40	2.22

## 5. TESTING RESULTS

Tests were smoothly conducted for W2 and W4. However, during the preparation of test setup for W1 and W3, actuator failures occurred while zeroing the data acquisition system, resulting in sudden movements of the actuator. When the actor was stopped, damages including crack and permanent deformation were observed in W1 and W3. However, further inspections on W1 and W3 revealed that the damages caused by the unexpected mechanical problems were limited to the top several courses of the specimens and the rest portions of the specimens were deemed to be in satisfactory condition for further tests. As such, it was determined to salvage the specimens by replacing the damaged courses with reinforced concrete. The top four courses of W1, the top four courses of W3 web, and the top three courses of W3 flange were carefully removed. The vertical bars bent during the accidents were returned to vertical and the horizontal bars in the original specimens were replaced with new ones at each course level. The concrete for repair was a high strength, fast curing, fluid mix, which would provide load transfer from the actuator to the remaining courses of the specimens. Specimens W1 and W3 after repair are shown in Fig. 5.1.



(a)



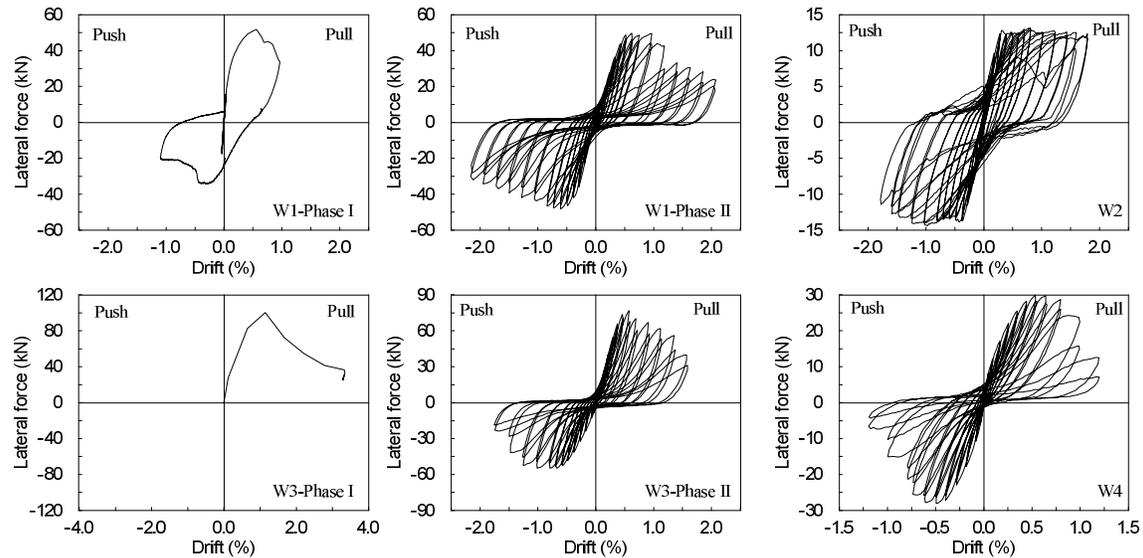
(b)

**Figure 5.1.** Repaired specimens (a) W1; (b) W3.

The hysteretic curves of all specimens are summarized in the Fig 5.2. For differentiation purpose, the testing data associated with W1 and W3 were classified as Phases I and II for the testing accident and re-test, respectively. As shown in Fig. 5.2, while strength degradations are seen at the large drift levels, all specimens exhibited stable force-displacement behavior and stable hysteretic energy dissipation capacity. Compared with the hysteretic curves from the shear-dominated walls in which brittle shear failures occurred (Bland *et al.* 2011), the hysteretic curves obtained from this investigation are more stable, reach higher drift levels, and exhibit less strength and stiff degradations, indicating that the flexure-dominated ICEB walls are more desirable from the seismic design perspective. Compared with W2 and W4, the hysteretic curves of W1 and W3 exhibit slightly pinching at the low drift levels. This was caused by pre-test damage, i.e., W1 and W3 experienced loading accidents in which the flexural bars had been elongated into inelastic range and minor cracks also developed in the walls. However, the hysteretic loops of W1 and W3 became full as the magnitude of drift increased.

The maximum resisting force and the corresponding displacement, and the maximum displacement and the corresponding resisting force identified from the hysteretic curves are summarized for all specimens in Table 5.1. Comparing the ultimate lateral load resistance of W1(48.1 kN and 49.9 kN in push and pull cycles respectively) with those of W2 (14.5 kN and 13.2 kN in push and pull cycles respectively), it is found that if the rebar arrangement remains the same, reducing the height-to-width

aspect ratio of a flexure-dominant wall by 50% will cause a lateral force resistance reduction in more than 50%. Comparing the results of W1 and W3, it is found that the ICEB walls with and without flange at one end have a similar lateral load resistance when the flange is in compression; however, when the flange is in tension, strength of the flanged wall is higher than the wall without flange (about 40% increase in strength is observed in this case). Results from W1 and W4 indicate that the presence of window opening significantly reduces the strength of the wall, (in this case, about 50% reduction in strength is observed).



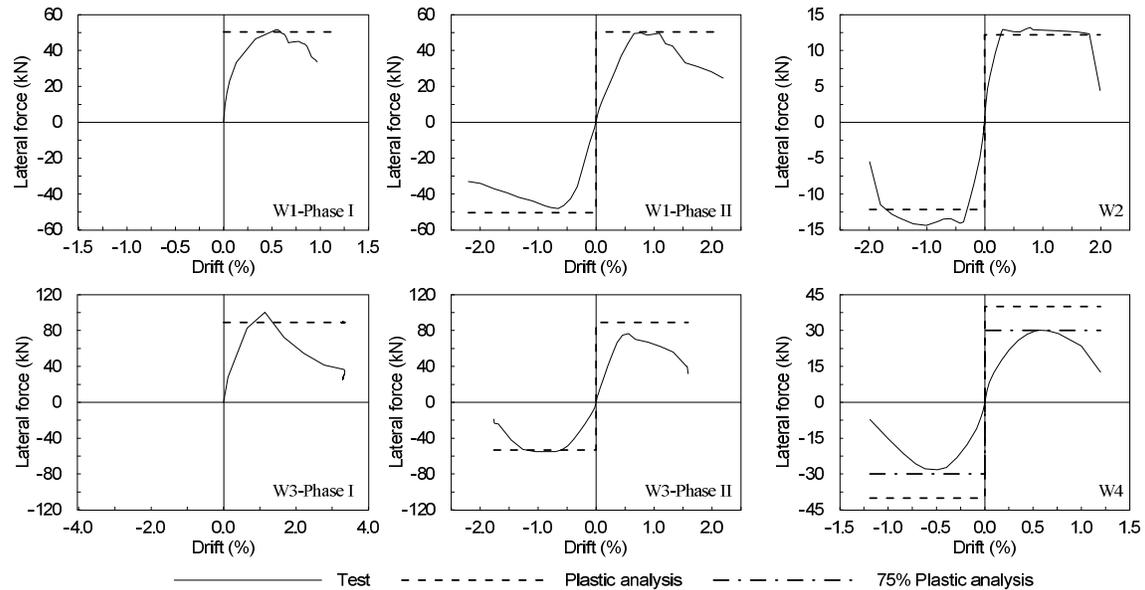
**Figure 5.2** Hysteretic curves of tested specimens.

**Table 5.1.** Summary of test results

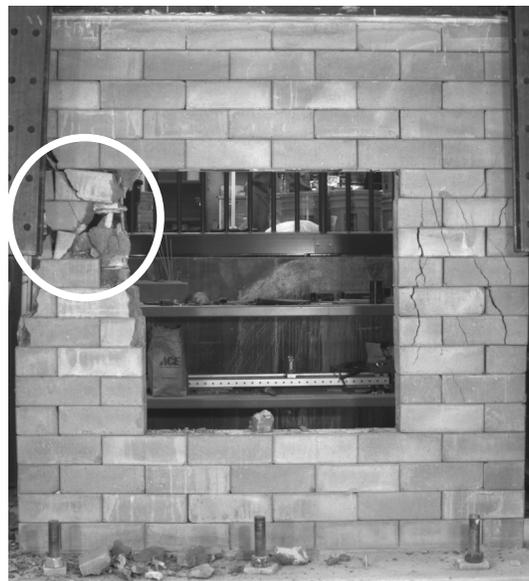
Specimen	Maximum Lateral Resistance (kN)		Displacement corresponding to Maximum Resistance (mm)		Maximum Recorded Lateral Displacement (mm)		Force corresponding to Maximum Displacement (kN)	
	Pull	Push	Pull	Push	Pull	Push	Pull	Push
W1- Phase I	51.7	--	9.8	--	17.4	--	33.6	--
W1-Phase II	49.9	48.1	13.9	11.8	37.3	39.0	27.1	30.0
W2	13.2	14.5	14.1	22.2	35.9	35.8	4.4	5.6
W3- Phase I	100.5	--	20.7	--	60.2	--	33.6	--
W3-Phase II	72.7	55.1	10.2	18.2	28.6	31.8	31.9	18.9
W4	30.2	28.2	8.8	9.83	21.6	21.4	12.6	7.2

Lateral force resistance of a flexure-dominated ICEB wall can be estimated based on its cross-sectional flexural resistance and classic plastic mechanism analysis. The flexural resistance of the wall cross-sections can be determined following the ACI recommendations on conventional masonry walls (ACI 2008) and the plastic analysis procedure can be found in typical structural analysis literature (Bruneau *et al.* 2011). Fig. 5.3 illustrates the envelopes of the hysteretic curves of the specimens, known as backbone curves, together with the lateral force resistances of these walls predicted from the plastic analysis model. It is recognized that specimens W1 and W3 experienced loading accidents during the tests and they were repaired before re-test. Therefore, the testing data associated with W1 and W3 were classified as Phases I and II for the testing accident and re-test, respectively. As shown, the plastic analysis model provides reasonable results for all specimens, except the W4, in which an

overestimate is observed. Revisiting on this specimen reveals that a localized shear failure occurred at the top end of one pier due to the stress concentration effect at the window corner (see Fig. 5.4), resulting in a reduced plastic flexural strength at that location. Excluding the strength contribution of the cross-section with shear failure to the lateral strength of W4, i.e., reducing the system strength to 75% of its expected strength, an improved estimate, is obtained. Throughout all cases, predictions from the plastic analysis model, which can be achieved conveniently from hand calculations, are accurate enough for practical applications.



**Figure 5.3.** Hysteretic curves of tested specimens.



**Figure 5.4.** W4 after test.

## 5. CONCLUSIONS

Four large scale flexure-dominated ICEB walls were constructed and subjected to in-plane cyclic

loading to experimentally address their seismic performance. Variations in the tested specimens allowed investigation of the effects of the wall height-to-width aspect ratio, presence of a flange at one end of the wall, and presence of an opening at the centre of the wall on seismic performance of the system. Testing results show that flexure-dominated ICEB walls can exhibit ductile behaviour and stable hysteretic energy dissipation capacities under in-plane cyclic loads. A larger height-to-width aspect ratio causes strength reduction in a wall; however, it tends to increase ductility of the system if other design parameters remain the same. Adding a flange to one end of a flexure-dominated wall enhances its strength only when the flange is in tension. The lateral load resistance of a flexure-dominated ICEB wall will be reduced due to the presence of a window opening at its centre; the opening may also cause stress concentration at the opening corners, resulting in localized shear failures in the wall piers. The testing results developed from this investigation provide useful data for developing and calibrating the analytical models that can replicate the flexure-dominated ICEB wall behaviour and further evaluate the seismic performance of ICEB constructions.

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