Interlocking Compressed Earth Block Walls: Out-Of-Plane Structural Response

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SUMMARY:

Interlocking compressed earth blocks (ICEBs) are cement stabilized soil blocks that allow for dry stacked construction. The incomplete understanding of the inelastic performance of ICEB building systems limits wide spread acceptance of this structural form in earthquake prone areas. This paper presents results from an experimental program designed to explore the behaviour of ICEB walls built according to current design practice in Indonesia and Thailand, and subjected to out-of-plane loading. A total of five reinforced and grouted walls were constructed and tested. Results from experimentation show that the current masonry design code in the U.S. can adequately predict the yield strength of these walls. However, the masonry code grossly over-predicts the actual wall stiffness. Furthermore, a brittle failure was observed in one wall before reaching the predicted flexural strength. The testing results provide useful data for developing analytical models that predicts the seismic behaviour of ICEB walls under out-of-plane loading.

Keywords: Compressed Earth Block Wall, Out-of-Plane Loading, Interlocking Masonry, Dry Stack

1. INTRODUCTION

Interlocking compressed earth block (ICEB) masonry is a cost effective and sustainable construction material. ICEB construction has the potential to bring durable and affordable homes to developing countries around the world. Today, ICEB construction is becoming increasingly popular in developing countries. Compressed earth blocks are energy efficient; they require anywhere from 1/5 to 1/15 of the energy to make when compared to fired bricks and concrete masonry units (Maini 2010). Since indigenous soil is the main ingredient in ICEBs construction, there is a large reduction in purchased materials (Maini 2010). Traditional masonry relies heavily on skilled labor and expensive materials. The interlocking nature of ICEBs allows for dry stacked, mortar-less construction, which reduces the need for skilled labor and shortens construction time. These reductions lower the cost of labor by as much as 80% (Anand and Ramamurthy 2005). These advantages make ICEBs a practical and preferred construction form.

Presently, the understanding of the behaviour of ICEB walls is incomplete. While research and testing results have been presented on material properties (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), little effort has been made to quantify and analyze strength and performance of ICEB walls. From previous experiments with ICEB walls, it is clear that using the current U.S. masonry code (ACI 530) to calculate shear strength and displacement response is inaccurate (Bland *et al.* 2011; Stirling 2011). In regions with seismic activity, it is imperative that these design inaccuracies be addressed through experimentation

It is the goal of this paper to present preliminary results from testing of ICEB walls under out-of-plane loading. Experimental values of strength and stiffness are compared to ACI 530 calculations to provide a better perspective of performance for ICEB walls. In-plane seismic performance of ICEB shear walls was investigated concurrently and presented elsewhere (Qu *et al.* 2012; Bland *et al.* 2011).





Figure 2.1: Variations of Rhino Blocks (Source: Wheeler, 2005)

2. MATERIAL PROPERTIES

The ICEB used for this experimental program was the Rhino Block. The block and press were developed by the Centre for Vocational Building Technology (CVBT). These blocks allow for drystacking and have holes for grout and reinforcement. A total of nine different varieties of these blocks can be made on the same press by removing or adding inserts. Varieties include channel blocks for horizontal reinforcement, pillar blocks with no grout cores at the ends, and half blocks of each type. Some varieties (dimensions in centimetres) are shown in Fig. 2.1.

The mixture used in the making of the blocks was chosen to balance economy and strength. The soil, free of organic matter, consisted of 18% clay (particles finer than 0.002 mm) and was dried and pulverized into a fine consistency. A mixture of 74.3% soil, 10% sand, 6.2% portland cement and 9.5% water by weight was used (Proto *et al.* 2010). Water was added to the dry components slowly, until a specific consistency was achieved. Blocks were pressed manually with each type of block containing set amounts of the mixture. Blocks were then allowed to cure for a minimum of 7 days in humid conditions before wall construction began. Individual blocks were tested for compressive strength in order to guarantee the blocks were formed with consistency (Table 2.1).

Grouted ICEB prisms were tested for compressive strength for each wall built, see Fig. 2.2. Stacks of three blocks were used with a 2:1 height to thickness ratio. Prisms and test units were grouted simultaneously as construction progressed to ensure accurate values for masonry strength (f_m). Table 2.1 shows average prism strength of 2.81 MPa, a value considerably lower than 10.3 MPa used for low strength concrete masonry units. The coefficient of variation (COV) was high compared to current masonry standards, indicative of the variation in mixture batches and curing conditions.



Figure 2.2: Standard Prism Test

Material Type	Number of Samples	Compressive Strength, MPa	Coefficient of Variation
Individual ICEB	22	7.76	13.5 %
Grouted ICEB Prisms	12	2.81	10.7 %
Grout Cylinders (Cured in ICEB)	19	9.19	16.4 %
Soil-Cement Plaster Cylinders	3	0.85	13.3 %

Table 2.1: Compressive Test Results

Based on stress and strain measurements during the prism tests, an average modulus of elasticity of 350 MPa was calculated. This modulus equals 125 f'_m , which is much lower than the ACI 530 values of 700 f'_m for clay masonry and 900 f'_m for concrete masonry. The relatively high flexibility of the prisms is particularly caused by the gaps inherent in dry stacked masonry.

2.1 Grout

Grout mixtures for ICEB construction must be workable enough to pour into the small holes of the ICEB block. Therefore, a grout mixture with fine sands and a very high slump was used. An effort was also made to create a grout that would closely match the compressive strength of the ICEBs. Previous testing had shown that brittle failure occurs in prisms where the grout has a significantly higher compressive strength than the ICEBs (Bales et al., 2009). The grout mixture chosen consisted of approximately 1:0.4:2.6:4.2 parts of Portland cement to lime to water to sand; all measured by dry volume. Preparation of the grout consisted of dry mixing the ingredients in 15 liter batches. The dry mixture was then added slowly to a portion of the water and mixed until a homogeneous mixture was obtained. Water was then slowly added until a highly workable grout was achieved.

Grout samples were tested for each batch of grout poured. Due to the ICEB's inherent water absorbing properties, it was decided to test grout samples that had been poured into the blocks. Grout cylinders were carefully extracted from the blocks before testing. Compressive test results in Table 2.1 show the grout strength to be comparable to the ICEB block strength and about three times as high as the masonry prism strength.

2.2 Soil-Cement Plaster

A plaster was to be applied to one wall for testing. A sustainable and cost effective mixture using materials that would already be on site during construction was preferred. A suitable mixture of soil, sand, and cement was deemed to be the best option for this experiment. Iterations of different plasters were made in order to find a mixture that would not crack once dried, and had a compressive strength that would be compatible with the stiffness of the ICEB wall. The final mixture consisted of 1:6:0.25 parts of soil to sand to Portland cement.

For compressive tests, the soil-cement mixture was formed in 76 mm diameter plastic cylinders. Once the mixture had surface hardened, it was removed from the form in order to allow the mixture to air dry. The compressive strength of the plaster was low, see Table 2.1, partially attributed to initial curing under conditions not representing the actual porosity of the ICEB.

3. TEST SETUPS AND PROCEDURES

A total of five walls were built for this testing program. Three 1100 mm tall cantilever walls were built to explore general flexural response, lap splicing and plaster surface coating. These cantilever walls were used to provide a basis for testing the larger walls. Two full scale walls were built to study the ICEB out-of-plane behaviour with and without a stiffening element in the wall. All walls used

Grade 40 (276 MPa) D10 (9.53 mm diameter) steel reinforcement with measured average yield strength of 338 MPa.

3.1 Cantilever Walls

All cantilever walls had identical block layouts. One D10 rebar was inserted into a concrete footing using an anchoring adhesive. The concrete footing was clamped to the testing facility strong floor. The first layer of ICEBs was laid level on a 20 mm thick cement mortar base. Each wall was 1.5 blocks (450 mm) wide and 11 blocks (1100 mm) tall. At the first, fifth, ninth, and eleventh layer, channel blocks allowed for one D10 steel rebar to be laid horizontally. After every channel block layer was placed, grout was poured into all holes and allowed to cure.

The first wall was the reference wall. The second wall contained a 460 mm lap splice at the base of the wall in accordance with ACI 530. The third wall was constructed exactly like the first wall. However, once finished, a 20 mm thick soil-cement plaster finish was applied to both sides of the wall. The plaster was applied in two coats and allowed to cure. During the application, the wet plaster was forced into the cracks between layers of the dry-stacked blocks, ensuring that none of the inherent gaps were left unfilled.

The cantilever walls were loaded cyclically using a hydraulic jack as suggested in Fig. 3.1. A loading sequence was selected to best observe the cracking and yielding behaviour, as well as the performance past yield. Each target load or displacement was achieved twice in both the push and pull direction.

Fig. 3.1 shows the cantilever wall test setup. At three heights, vertical displacements were measured on both sides of the walls in order to determine the curvature along the wall. A strain gauge was also applied to each bar 40 mm above the concrete footing. For the lap splice, an additional strain gauge was added to the midpoint of the splice.

3.2 Full Scale Walls

Layouts for the full scale walls were determined to best represent a typical ICEB structure in Thailand. Fig. 3.2 shows the wall cross sections and D10 reinforcement layout of each wall. The difference in width of each wall was to provide symmetry to each wall.



Figure 3.1: Cantilever Wall Test Setup



Figure 3.2: Full Scale Walls, Cross Section Layout



Figure 3.3: Full Scale Wall Test Setup

Each wall was 22 blocks tall, with a pin to pin height of 2.4 meters (Fig. 3.3). The first course was made from channel blocks and placed on a mortar base. Every fourth layer was made from channel blocks and included a horizontal D10 rebar. A concrete beam was cast in place at the top of each wall in order to transfer the load from the pinned connection to the wall. The top pin connection was achieved using two steel pipes that transferred the load back into the reaction frame.

ICEB structures in Thailand and Indonesia contain shear reinforcement in pilasters and columns. For this experiment, ties were installed at every four blocks with the channel block layers. Smooth 6 mm diameter Gr. 60 (414 MPa) pencil rod bars with measured average yield strength of 435 MPa were used. A masonry saw was used to cut openings to fit the ties and a layer of grout, see Fig. 3.4.

Both full scale walls were loaded cyclically (push only) using a hydraulic jack and a load spreader simulating seismic loading with four equal and equally spaced loads. A loading sequence was determined for each wall to best observe the cracking, yielding, and post yield performance. Two cycles of each target load or displacement was achieved. The pilaster wall was loaded on the flat side.



Figure 3.4: Pilaster Tie Placement

A single load cell attached to the hydraulic jack measured the total load applied to each wall. A total of ten displacement transducers were used for each wall as shown in Fig. 3.3. Strain gauges were placed in each wall at mid-height. The flat wall had one strain gauge on each vertical rebar, while the pilaster wall had one on a tension rebar and another on a compression rebar.

4. RESULTS

4.1 Cantilever Walls

All tests were carried out successfully. However, the maximum stroke of the hydraulic jack hindered the test from continuing cyclically. Once the jack could not be extended any further, the jack was repositioned closer to the wall, but subsequently could only load the wall in the push direction.

The hysteretic behaviour of the cantilever walls is presented in Fig. 4.1. V_n corresponds to the predicted nominal flexural strength per ACI 530. It can be seen that each wall exhibited stable hysteretic behaviour, large displacement capacities and show large amounts of pinching throughout the tests. These results show flexure-dominated behaviour for ICEB walls under out-of-plane loading. On each hysteresis loop there are also distinct points of initial stiffness loss due to cracking and significant stiffness loss due to yielding. These points were used to create piecewise linear approximations to be used for comparing the walls (Envelope Comparison in Fig. 4.1).

The comparison shows a slight increase of initial stiffness in the lap splice wall compared to the reference wall. Despite the difference in stiffness, the flexural strength was similar to the reference wall. Compared to the reference wall, the plastered wall results showed a significant increase in stiffness, due to the plaster filling the cracks between the dry stacked blocks, and flexural capacity, due to the increased wall thickness. The plaster wall also showed a drop in flexural strength past being pushed 50 mm that coincided with the plaster spalling from the ICEB wall.



Figure 4.1: Hysteretic Curves of Cantilever Walls

Figure 4.2: Common Flexural Cracking

Wall Type	Nominal Flexural Strength		Initial Wall Stiffness	
	ACI	Actual	ACI	Actual
1: Basic	1528 N	1720 N	96.1 N/mm	19.3 N/mm
2: Lap Splice	1528 N	1660 N	96.1 N/mm	16.7 N/mm
3: Plastered	2013 N	2215 N	216.5 N/mm	87.2 N/mm

Table 4.1: Cantilever Wall Summary of T	est Result
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Horizontal cracking in the grout cores initiated under low force levels at dry-stacked joints, see Fig. 4.2. The cracks were observed starting above the base layer of ICEBs and slowly progressing up the wall above each layer of blocks. On the plastered wall, cracks appeared in the plaster on each face of the wall in various locations, and not always at the dry-stack joints. The plastered wall had significantly more rotation at the base than the other cantilever walls.

ACI 530 does require minimum properties for proper use of the design methods, some of which were not met with these ICEBs. These include a minimum compressive strength of 10.34 MPa, a minimum vertical reinforcing ratio of 0.002, and although it is not ever explicitly stated in the ACI code, design options do not include dry-stacked masonry. Nevertheless, the cracking and nominal flexural strength and stiffness values were calculated with this code.

Table 4.1 shows a comparison between the experimental values and the code estimations. Initial stiffness was defined for both the ACI code predictions and the experiments by the slope of the line from zero to the displacement at flexural strength. Note how the ACI values for nominal flexural strength were achieved and slightly surpassed by each test, but also that all stiffness estimations were significantly higher than actual. This indicates that the strength design methods translate well to ICEB design, but that the inherent gaps between the ICEB courses creates a behaviour that allows for more rotation and therefore less stiffness than traditional masonry.

4.2 Full Scale Walls

The hysteretic behaviours of the two full scale walls are shown in Fig. 4.3. Dramatic differences in stiffness and strength are evident. As predicted from the outcome of the cantilever wall tests, the flat wall was found to be very flexible. The pilaster wall was observed to have an overall stiffness, calculated from zero load until significant strength degradation was observed, that was about 17 times greater than that of the flat wall. Table 4.2 shows a comparison of actual values versus ACI 530 expected values for nominal strength and stiffness. These values for stiffness were determined in

Figure 4.3: Hysteretic Curves for Full Scale Walls

similar fashion to the cantilever walls. For these two walls, the predicted flexural strengths were not achieved. Uneven load distribution from the load spreader could have contributed to this.

The flat wall proved to be flexure controlled, similar to the cantilever walls. The wall had cracking that was similar to the cantilever walls. Horizontal cracks began at the wall mid-height and continued both above and below mid-height at the dry-stacked joints. After yielding in the steel reinforcement had occurred, a large crack started to form four courses of blocks from the base. Further push cycles made this crack grow to the point where the wall was able to slide away from the base layers of blocks and create instability. The two strain gauges showed steel yielding prior to this instability.

The pilaster wall exhibited signs of shear dominated behaviour before any significant yielding could be observed by the strain gauges. The shear cracking started to form at a shear force of 8.7 kN, at a displacement of 10.9 mm. Fig. 4.4 shows cracks forming in the bottom few layers of the pilaster. The cracks were predominantly vertical along the lines of the reinforcement holes. These cracks are most likely caused by inadequate tie spacing. More ties, spaced closer together, would likely mitigate this issue.

Wall Type	Nominal Strength		Initial Wall Stiffness				
	ACI	Actual	ACI	Actual			
Flat	8720 N	8166 N	352 N/mm	75.6 N/mm			
Pilaster: Flexure	29100 N	-	3307 N/mm	1265 N/mm			
Pilaster: Shear	31038 N	26940 N	-	-			

Table 4.2: Full Scale Wall Summary of Test Results

Figure 4.4: Shear Induced Cracking in Pilaster

Along with the shear cracks, uplift began between the first and second block layers. The vertical reinforcement and surrounding grout began to separate from the first layer of ICEBs. This uplift shows that the construction technique used at the base could have been improved by restraining the rebar from lifting away from the base. A detail of the base as built, with a bent D10 U-bar connecting two vertical D10 bars, is included in Fig. 3.3. Note that the reinforcement ends at the first course of blocks.

Had a displacement limit of 2% been imposed on these walls, only a fraction of the flexural strength could have been developed for the flat wall (see Fig. 4.3). Conversely, a large amount of the pilaster wall strength would be developed with the drift limit. The 2% limit was quasi-arbitrarily chosen to limit the P-delta effects and to reduce the non-structural damage. Fig. 4.3 includes lines to illustrate where this 2% limit would fall on the hysteresis curves.

5. CONCLUSIONS

Three cantilever walls and two full scale walls were constructed and tested to explore the performance of ICEB walls under out-of-plane loading. The testing results provide useful data for developing analytical models that can predict the seismic performance of ICEB walls under out-of-plane loading. All tests showed that current ACI 530 analysis techniques work reasonably well in determining the nominal flexural strength of ICEB walls. However, the code proved to be unsatisfactory at predicting stiffness for ICEB walls.

A lap splice was found to have virtually no effect in the overall flexural strength of the wall, but did affect the initial stiffness. The comparison of the lap splice wall to the reference wall suggests that using the ACI 530 to determine the necessary splice length is acceptable. The plaster coating increased the flexural strength, and was still accurately predicted by code. Deflections measured in the plaster wall also showed more concentrated rotation at the base. This can be attributed to the application of the plaster into the gaps between the dry-stacked blocks, showing the plaster's ability to control the rotations inherent in ICEB dry-stack joints.

Data from the vertical displacement measurements (see Fig. 3.1) can used to calculate the rotations and curvatures along the height of the cantilever walls. It is a goal of this research program to develop a moment-curvature relationship that will allow for accurate prediction of displacements.

The full scale walls were designed to investigate the strength and stiffness with and without stiffening elements (pilasters). The pilaster increased the out-of-plane wall stiffness significantly and confirms the beneficial effect of using pilasters to control out-of-plane displacement. The testing showed that the pilaster decreased the ductility of the walls, leading to a non-ductile failure. Because the pilaster wall failed in shear, the experiment also gave insight into the shear strength of ICEB pilasters and columns. Comparing the experimental and ACI 530 shear strengths, the ACI code appears to over predict the shear strength. A smaller tie spacing and/or increased shear reinforcement area than used in the pilaster wall appears warranted, to minimize the risk of a brittle failure.

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REFERENCES

- ACI 530 (2008). Building Code Requirements & Specification for Masonry Structures. American Concrete Institute, Farmington Hills, MI 48331 U.S.A
- Anand, K.B., and Ramamurthy, K. (2005). Development and Evaluation of Hollow Concrete Interlocking Block Masonry System. *The Masonry Society Journal*. 23:1, 11-19.
- Bales, C., Donahue, C., Fisher, M., Mellbom, A., and Pearson, T. (2009). Interlocking Compressed Earth Blocks: From Soil to Structure. *Senior Project*, California Polytechnic State University, San Luis Obispo, California.
- Bland, D.W., Jansen, D.C., Stirling, B.J., Qu, B., and Laursen, P.T. (2011). In-Plane Cyclic Performance of Interlocking Compressed Earth Block Shear Walls. *The 11th North American Masonry Conference*. Minneapolis, Minnesota. June 5-8, 2011.
- Bei, G., and Papayianni, I. (2003). Compressive Strength of Compressed Earth Block Masonry. *Structural Studies, Repairs and Maintenance of Heritage Architecture*. **VIII**:367-75.
- Bryan, A.J. (1988). Criteria for the Suitability of Soil for Cement Stabilization. *Building and Environment*. **23**:309-19.
- Burroughs, S. (2006). Strength of Compacted Earth: Linking Soil Properties to Stabilizers. *Building and Research & Information.* **34**:55-65.
- Heathcote, K. (1991). Compressive Strength of Cement Stabilized Pressed Earth Blocks. *Building Research and Information*. **19**:101-5.
- Jayasinghe, C., Mallawarachchi, R.S. (2009). Flexural Strength of Compressed Stabilized Earth Masonry Materials. *Materials and Design*. 3859-68.
- Maini, S. (2010). Earthen Architecture in the World. *Auroville Earth Institute*. Retrieved from http://www.earthaurovillecom/?nav=menu&pg=earthworld&id1=26&lang_code=en (Accessed September, 2011).
- Perera, A., Jayasinghe, C. (2003). Strength Characteristics and Structural Design Methods for Compressed Earth Block Walls. *Masonry International*. **16**:34-8.
- Proto, C., Sanchez, D., Rowley, K., and Thompson, R. (2010). ICEB: Design and Construction Manual. *Senior Project*, California Polytechnic State University, San Luis Obispo, California.
- Qu, B., Stirling, B.J., Laursen, P.T., Jansen, D.C., and Bland, D.W. (2012). Interlocking Compressed Earth Block Walls: In-plane Structural Response of Flexure-dominated Walls. 15th World Conference on Earthquake Engineering. Lisbon, Portugal.
- Reddy, B.V., Lal, R., and Rao, K.S. (2007). Optimum Soil Grading for the Soil-Cement Blocks. *ASCE Journal of Materials in Civil Engineering*. **19**:139-48.
- Stirling, B.J. (2011). Flexural Behavior of Interlocking Compressed Earth Block Shear Walls Subjected to In-Plane Loading, *M.S. Thesis*. California Polytechnic State University, San Luis Obispo.
- The Center for Vocational Building Technology (CVBT). Accessed from: <www.cvbt-web.org> (Accessed September, 2011).
- Wheeler, G. (2005). Manual of Construction Interlocking Compressed Earth Blocks. Center for Vocational Building Technology. Isarn, Thailand. Volume II.