TESTING OF RC WALLS USING ADVANCED LOAD-CONTROL AND INSTRUMENTATION METHODS

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ABSTRACT :
A series of experimental tests on large reinforced concrete structural walls are being conducted at the University of Illinois NEES facility as part of the project "NEESR-SG: Seismic Behavior, Analysis and Design of Complex Wall Systems" which is led by Drs. Laura Lowes and Dawn Lehman from the University of Washington. The types of walls being tested include planar, coupled, and C-shaped walls. Each of the test structures is one third scale, approximately 4 m high, and represents the bottom three stories of a high-rise building. Two versatile six degree-of-freedom loading units are being used at the top of the walls to apply the axial compression, shear, and an overturning moment that would be expected at the third story level of the 10 story building. These loading units are capable of applying a total downward force of 9000 kN, a lateral force of 5500 kN, and an overturning moment of 4500 kN-m. They will be operated in mixed mode control such that some degrees-of-freedom are in force control and others are in displacement control. An additionally unique feature of the research program is that advanced non-contact measurement systems will be used to make dense and accurate measurements of displacement fields. These systems measure the movement at hundreds of points to an accuracy of approximately 0.01 mm and thereby provide an unprecedented level of detailed test data. This dense information is being used to advance our understanding of complex structural behavior and enables the development and validation of more reliable and comprehensive non-linear finite element analysis methods.

KEYWORDS:
Reinforced concrete, structural walls, experimentation

1. INTRODUCTION

A series of experimental reinforced concrete wall tests are being conducted at the University of Illinois Multi-Axial Full-Scale Sub-Structured Testing and Simulations Facility (MUST-SIM), which is part of the University of Illinois Network for Earthquake Simulation (NEES). The project funding this research is titled "NEESR-SG: Seismic Behavior, Analysis, and Design of Complex Wall Systems" which is led by Drs. Laura Lowes and Dawn Lehman from the University of Washington. A series of planar, coupled, and C-shape walls are planned to be tested to investigate wall shape, reinforcement ratios, and loading protocol to better understand the behavior, response, and performance of these structural systems.

The MUST-SIM facility is built around three large versatile six degree-of-freedom loading units called, load-and-boundary-condition boxes (LBCB), which can be mounted in several orientations on a massive strong wall and floor. The NEESR wall project utilizes two LBCBs to impose realistic loads on the test specimen.

The two units are capable of testing the specimen about a common point located at the top of the wall, or each box can control six degrees-of-freedom about different points such as the top of two wall piers connected by a series of coupled link beams. The MUST-SIM facility is capable of conducting hybrid simulation tests, whereby displacement demands are computed by analytical tools and are updated with feedback from experimental data. Hybird simulation coupled with six degree-of-freedom loading units allows the facility to conduct versatile component testing where the structural component of interest is tested experimentally and the remainder of the structure is modeled analytically.

2. OBJECTIVE AND SCOPE

Structural walls are widely used in practice to resist lateral loads imposed by wind or earthquake loads. The design of these walls is highly empirical and is based on previous experimental research in which it was not possible to impose realistic loading patterns. Specifically, many experiments on structural walls maintain axial load while imposing a single or series of lateral loads that are applied at each story level, whereby the accumulating overturning moment in the lower story levels is rarely accounted for. Additionally, many typical wall shapes, reinforcement details and boundary conditions found in the field have not been used in structural wall tests.

The series of experimental tests that are currently being conducted at the University of Illinois at Urbana-Champaign attempt to overcome most of these deficiencies. To simulate the demand originating from the upper stories of a multi-story structure, the specialized load-and-boundary-condition boxes (LBCBs) are used. Additionally, special attention has been given to the reinforcement details, in particular to the longitudinal splice used at the base of a structural wall.

The test data is being developed specifically to improve the tools and technologies for performance-based design of structural wall buildings and will include information from planar walls, coupled walls, C-shaped walls, and possibly a core wall system. Within the complete test program, the planar wall test series was developed to evaluate the influence of the shear-force distribution and longitudinal reinforcement configuration on walls that represent current engineering and construction practices. The damage and gathered measured data will be presented and compared with test results and current practice expectations.

3. DESCRIPTION OF EXPERIMENTAL PLAN

The experimental plan is composed of several large structural walls that are one third scale. Each wall to be tested is the lower three stories of a ten story tall building. Additional side mounted actuators are attached at the 1.3 and 2.6 m height locations to simulate the shear forces induced at the second and third floor levels. Each wall will be approximately 4 m tall, 3.2 m wide, and 0.15 m thick. A picture of the test setup is presented Figure 1.

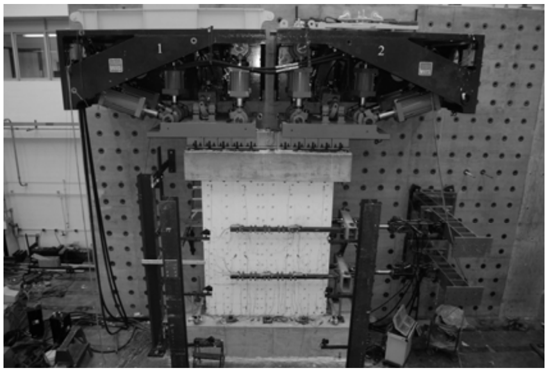


Figure 1 Planar wall test with two LBCBs

Four planar walls have been tested thus far, and coupled and C-Shaped wall tests are planned. Table 3.1 depicts the total testing plan, not all of which may be possible due to budget limitations. The main variables within the experimental plan are the longitudinal reinforcement ratios, effective height ratio, and shape of the wall. The influence of longitudinal reinforcement ratio is being investigated by altering the boundary element region. Three of the planar wall tests are built with heavily reinforced boundary elements; one planar wall contains the same overall reinforcement ratio as the other three planar walls, but the reinforcement is smeared evenly across the entire cross section. The effective height ratio is the fraction of the 10 story building height for the center position of the lateral loading. A high effective height ratio will then lead to higher flexural demand whereas a lower effective height ratio will lead to higher shear demand. In the test program, the effective height is controlled by the Moment to Shear (M/V) ratio that is imposed at the top of the wall.

Table 3.1 Experimental Testing Plan

	Moment – Shear Ratio	Long. Reinf. Ratio	Load History	SSI Boundary Conditions
Unidirectional Loading	Planar (2) Flanged Coupled			
Bidirectional Loading	Core-Wall System			

4. PLANAR WALL SPECIMEN DESIGN

Each wall was fabricated in the Newmark laboratory at the University of Illinois by students and lab technicians. One wall was built at a time due to formwork and lab space constraints. Each wall was built in three separate concrete lifts: the foundation, wall specimen, and cap beam. The generic details for one of the planar wall specimens is presented in Figure 2. A target concrete strength of 5000 psi (34.5 MPa) was used in all four planar walls. The selected concrete mix was a highly fluid self consolidating concrete (SCC) because the reinforcement cage was extremely tight due to the one third scale. Standard grade 60 reinforcing bars were used. Special deformed #2 bars (6 mm diameter) had to be specially purchased and heat treated in order to adequately represent bond characteristics in this one-third scale model.

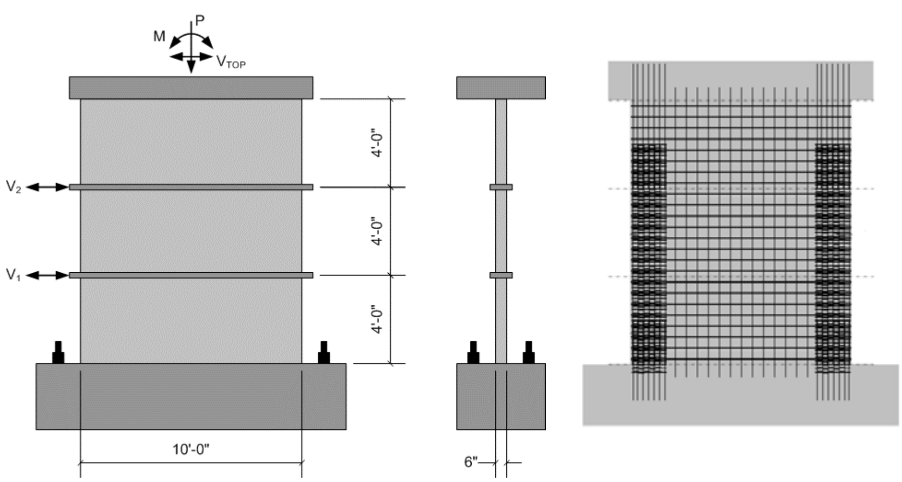


Figure 2 Planar wall specimen design

Each planar wall was designed to have a minimum nominal shear strength according to the ACI 318-05 code. All four planar walls contain a minimum horizontal reinforcement ratio with two #2 bars spaced every 0.15 m along the entire height of the wall.

Longitudinal reinforcement bars used to date have been principally #4 bars (12.5 mm diameter). In specimens where heavily reinforced boundary elements are used, #2 bars are used as the vertical web longitudinal reinforcement. The #2 bars are also used for the horizontal reinforcement, boundary element hoops or stirrups, and boundary element hooks.

Lateral shear force is introduced at the second and third story levels by two force controlled actuators that are each connected to the wall with ten 38 mm diameter threaded rods that are evenly distributed throughout the width of the wall to simulate an evenly distributed shear force which would be introduced by rigid diaphragms.

A lap splice was used at the base of the wall in the first three planar wall specimens. The splice was used to mimic construction practices in which bars are normally spliced at the foundation-wall interface. It was hypothesized that this splice detail, would have a significant impact on the damage and overall behavior of the specimen. For this splice, all vertical reinforcing bars were fully anchored in the foundation portion of a specimen in which the bars extended into the wall approximately 0.6 m for #4 bars and 0.15 m for #2 bars. The bars that extend the height of the wall into the cap beam were bent slightly to remain at the same flexural depth after the splice zone.

5. LOAD CONTROL

Utilizing two six degree-of-freedom loading units in combination to impose actions about a single common point was a difficult task for the research group to accomplish as it required very precise and coordinated movement of the loading unit platforms. Operating the loading units in mixed mode control also presented difficult challenges as well as did accounting for the elastic deformations of the loading units in the test control architecture. All of these problems had to be overcome before testing could get underway.

5.1. Description of Load-and-Boundary-Condition Boxes (LBCB) Loading Units

Load was applied to the top of each wall specimen with two versatile six degree-of-freedom load-and-boundary-condition boxes (LBCB). Each loading unit is composed of six 1500/1000 (compression/tension) kN actuators: three actuators are oriented in the vertical direction (z-axis), two in the lateral direction (x-axis), and one in the out of plane direction (y-axis). Therefore, each unit has a downward vertical loading capacity of 4500 kN, a bi-direction lateral capacity of 2000 kN, and a bi-directional out of plane loading capacity of 1000 kN. Each of the vertical and out-of-plane actuators has a +/- 0.12 m stroke capacity, while the two parallel horizontal actuators have a +/- 0.24 m stroke capacity.

5.2 Test Control

The test is controlled using an in-house load-control and data-acquisition architecture that enables for hybrid simulation testing. The overall program that controls the testing is called SIM-COR, which controls the communications between all of the load-control and data acquisition computers. A National Instruments LabView based program was developed by the Illinois NEES site to provide for the coordinated Cartesian-based control of the LBCBs. This software allows the user to control each unit in mixed mode control, where some degrees-of-freedom are operated in force control and others can be operated in displacement control. Further development was needed for the reinforced concrete wall testing to align and control both LBCBs simultaneously.

5.3 Loading Protocol

Each wall tested to date was loaded over the course of three to five days in which upwards of 40 hours of testing were logged for each wall. The loading was not continuous, rather the loading was stopped at the completion of each day and resumed the following day. A constant axial load of approximately 10% of the axial capacity of each wall was maintained in force control throughout the duration of the test. An example of the loading protocol is presented in Table 5.1. The lateral displacement at the top of each wall was controlled in displacement control. The lateral force that was measured at the top of the wall at each load step was used to compute an overturning moment with a fixed ratio of 3.5 m. For example, if the specimen was at a lateral displacement of 12.5 mm, which a corresponding lateral force of 670 kN kips, then a moment of 670 x 3.5 = 2345 kN-m would be applied at the top of the wall, while maintaining the constant axial compression. This axial force and overturning moment to shear ratio were maintained throughout the lateral displacement cycles.

Table 5.1 Cyclical Loading Protocol

Peak Drift Level	Peak Displacement	Number of Cycles
Pre-crack ($\Delta_{cr}/2$) = 0.014%	0.02 in.	3
Crack (Δ_{cr}) = 0.028%	0.04 in.	3
Δ_y / 2 = 0.139%	0.20 in.	3
Δ_y *3/4 = 0.208%	0.30 in.	3
Δ_y *5/4 = 0.347%	0.50 in.	3
0.50%	0.72 in.	3
0.75%	1.08 in.	3
1.00%	1.44 in.	2
1.50%	2.16 in.	2
2.00%	2.88 in.	2
3.00%	4.32 in.	2

6. ADVANCED INSTRUMENTATION

An additionally unique feature of the research program is that advanced non-contact measurement systems are being used to make dense and accurate measurements of displacement fields. These systems will measure the movement at hundreds of points to an accuracy of approximately 0.01 mm and thereby provide a new level of detailed test data. This dense data is being used to advance our understanding of complex structural behavior and enables the development and validation of more reliable and comprehensive non-linear finite element analysis methods. Each of the completed wall tests have been instrumented with 24 concrete surface strain gauges, over 110 reinforcing bar strain gauges, 59 linear potentiometers, 23 string potentiometers, 6 LVDTs, 150 Krypton LEDs, 10 high resolution cameras, and actuator load cell and LVDT readings. All instruments were connected to two National Instruments (NI) SCXI-1001 chasses. A comprehensive NI LabView program was developed to monitor all data acquisition channels throughout the test. Additionally, offsite researchers can monitor the experiment with a program developed and supported by NEESit called Remote Data Viewer (RDV). Offsite researchers are capable of viewing all instrumentation channels and video cameras, and have the capability to “rewind” the test to further investigate behavior.

6.1. Krypton K600

The Krypton K600 camera system was used to measure the 3-dimensional locations of a grid of 150 LEDs. This system is a non-contact measuring device that utilizes three linear charged coupling devices (CCD). The LED grid covers the lower two stories of the test specimen. Additionally, this system is used extensively to align the two LBCBs as wells as align the LBCBs with the wall specimen. The system has an accuracy of 0.01 mm for in-plane measurements and 0.06 mm for out-of-plane measurements. This accuracy and ease of use made it possible to accurately fine tune the LBCBs for precise and accurate load control.

6.2. High resolutions cameras

One component of the advanced instrumentation plan is the use of automated high resolution digital cameras. Pictures are recorded with several 10 megapixal Nikon D80 cameras. The cameras are controlled with a MatLab based program called the UIUC Camera Plugin that was developed at the University of Illinois. At the completion of each load step, SIM-COR sends a transaction message to each computer with the UIUC Camera Plugin running and triggers each camera to take a picture. This technology has allowed the research group to make high resolution videos from a series of still pictures, which would otherwise be unfeasible with standard video equipment over an extremely long testing duration.

High resolution cameras have also made it possible to utilize close-range photogrammetry. Close-range photogrammetry has been used to measure 3D global locations of all instrumentation as well as overall specimen shape. Several high resolution photographs are needed to construct an actual 3D image of the test specimen. 3D renderings of the reinforcing layout prior to casting and instrumentation layouts can be superimposed on top of the actual as built test specimen to accurately measure absolute and relative locations of instruments. An example of this can be seen in Figure 3. PhotoModeler 6.0 is the close-range photogrammetry software that was used.

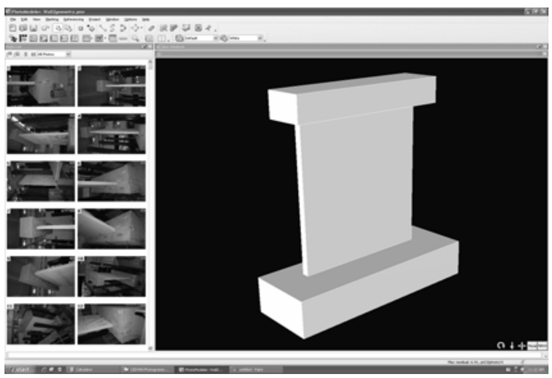


Figure 3 As built 3D rendering of wall specimen constructed with close-range photogrammetry

7. RESULTS

To date, four planar walls have been successfully tested and the failure mechanisms will be summarized here. Extensive data analysis has not been completed at this time. Table 7.1 summarizes the variables that were altered for the first four planar wall tests.

Table 7.1 Testing Variables

Speciment ID	Reinforcement Layout		Loading History	
	Boundary Element Utilized	Lap Splice Provided	Effective Shear Height (ft.)	Moment to Shear Ratio (in)
Planar Wall #1	Yes	Yes	28	-196.8
Planar Wall #2	Yes	Yes	20	-138.0
Planar Wall #3	No	Yes	20	-138.0
Planar Wall #4	Yes	No	20	-138.0

7.1 Planar wall failure mechanisms

Planar wall #1 began to fail in compression immediately above the splice in the boundary element at a drift of 1.5%, but eventually gave up due to longitudinal reinforcing bars rupturing at the base of the wall. Approximately 7 bars out of the 21 bars in the boundary element that were anchored in the foundation portion of the specimen ruptured at the interface between the foundation and wall before loading was suspended. Planar wall #2 failed in compression above the splice in the boundary element. There was extensive bar buckling occurring at the location of failure and it is believed that the dramatic cycling between bar buckling and bar straightening out accelerated cover spalling and crushing in this zone. Planar wall #3 failed in compression as well, but the damaged region was not localized above the end boundary element regions because this specimen had uniformly distributed longitudinal reinforcement. Instead, an approximate 0.6 m tall band of concrete crushed along the entire width of the wall immediately above the spliced region. Longitudinal bar buckling was noted throughout the entire width of the wall as well. Figure 4 summarizes the overall response of the first four walls.

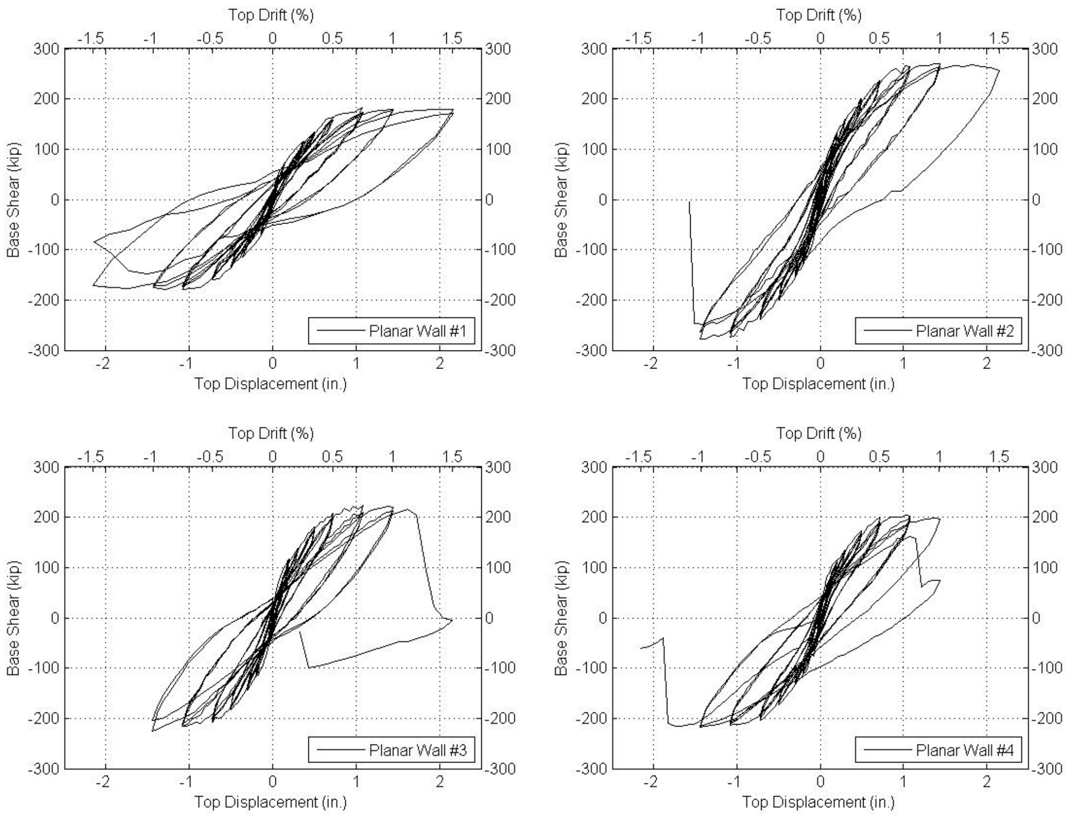
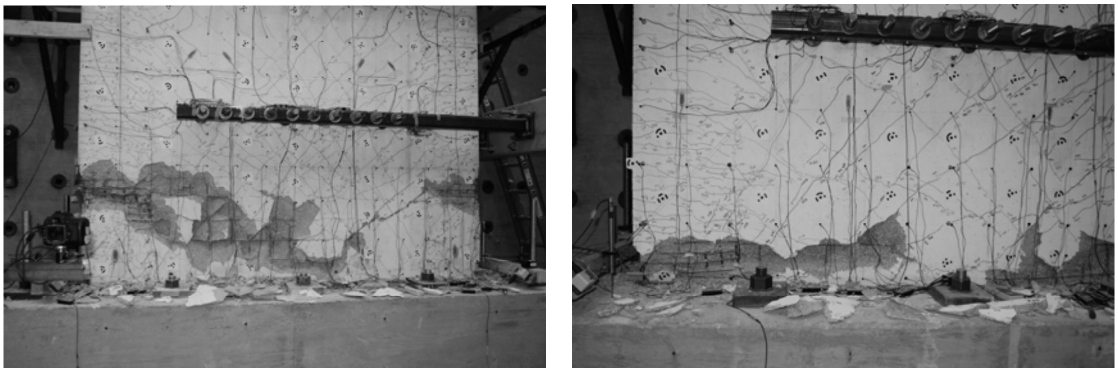


Figure 4 Load displacement plots of first four planar wall tests
(1 kip = 4.4482 kN; 1 inch = 25.4 mm)

8. PRELIMINARY CONCLUSIONS

The first three planar wall specimens began to fail by a similar concrete crushing mechanism immediately above the splice of the boundary element. This observation led researchers to test a fourth planar wall without a spliced region. Figure 5 depicts the crushing zones for planar wall #2 and planar wall #4. It can be seen in Figure 5a that both the left and right hand side of planar wall #2 began to fail in crushing approximately 0.6 m up from the base of the wall which is just above the boundary element splice. Figure 5b depicts the crushing zone of planar wall #4 which is located at the base of the wall. It is believed that the additional steel located at the base of the wall adds considerable compressive strength to the boundary element and introduces a stress concentration just above the spliced zone. Additionally, the longitudinal bars are bent just above the splice which initiates damage in this region.



(a) Planar Wall #2 (b) Planar Wall #4 (No Splice)

Figure 5 Depicts influence of longitudinal spliced boundary element region on damage at failure

9. FUTURE WORK

There is much work to be done as outlined in the experimental testing plan. There are still up to six wall specimens that remain to be built and tested including two coupled walls, three C-shaped walls, and possibly a full core wall system. The loading protocol for the coupled wall specimens will be different from the planar wall specimens, because each wall pier will be controlled by a single LBCB, which is different from coupling two LBCBs to control one common point at the top of the specimen. Conversely, for the C-shaped walls in-plane and out-of-plane motions will have to be controlled while maintaining force controlled shear to moment ratios in two directions. The C-shape walls are still being designed. An in-depth data analysis tool called ExViz (Experimental Visualization) is being developed to help visualize and analyze the large dense quantity of data that is being collected with each test.

10. ACKNOWLEDGEMENTS

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