INVESTIGATION OF THE SEISMIC BEHAVIOR AND ANALYSIS OF REINFORCED CONCRETE STRUCTURAL WALLS

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ABSTRACT:
Reinforced concrete structural walls are commonly used as the primary lateral-load resisting system in buildings. The research presented herein represents the first-phase of a multi-year research effort aimed at developing tools to enable performance-based earthquake engineering (PBEE) of structural walls. The first-phase of the research effort focused on the seismic behavior and analysis of slender planar walls. To design the experimental investigation, including a prototype specimen and test matrix, the following steps were taken: 1) drawings for 18 walls from 10 buildings designed for construction on the west coast since 1991 were reviewed to determine representative design details, 2) practicing engineers were consulted to establish the wall design process for the test specimens, 3) the results of previous experimental studies were reviewed to determine the parameters that control response, and 4) elastic, effective-stiffness analyses of a representative 10-story building were conducted to determine representative load patterns. These results are used to support experimental testing of wall sub-assemblages which will be conducted using the NEES MUST-SIM facility. The results of previous studies and data from numerical simulation were used to design an instrumentation layout that would fully utilize the advanced instrumentation available at the NEES facility. The experimental investigation is being complemented by an analytical investigation. Data generated from testing and analysis will provide for an improved understanding of wall behavior, provide a basis for advancing simulation and design of walls, and be used to support the subsequent phases of the research effort, and address different wall configurations.

KEYWORDS:
Reinforced concrete, walls, buildings, experimental testing, damage, performance, performance-based design

1. INTRODUCTION

Reinforced concrete structural walls are used commonly as the primary lateral-load resisting system for new and retrofit construction. However, despite the heavy reliance on wall systems by practicing engineers, recent efforts to develop performance-based earthquake engineering (PBEE) methods have not yet begun to address structural walls. Today engineers have few resources to consult regarding the simulation of wall response using practical linear and nonlinear numerical models or the prediction of wall damage (e.g., concrete crack width and concrete spalling) as a function of engineering demands (e.g., inter-story drift).

A number of issues make the development of performance-based seismic design tools a difficult problem. First, structural walls in modern buildings typically have complex configurations that induce three-dimensional seismic load effects and could be expected to produce significant variation in local damage patterns and ductility demands. Second, walls are rarely fully restrained at the base, as earthquake loading induces deformation in the foundation and soil; thus, design procedures must account for nonlinear three-dimensional simulation tools that account for soil-structure interaction. Third, few previous experimental investigations provide data that characterize the earthquake response of walls with representative configurations, reinforcement layouts, base conditions and load patterns. Fourth, few previous experimental investigations provide the high-fidelity response and damage data that are required to support the development modern performance-based design tools.

The research presented here represents the first-phase of a multi-year research effort to develop tools to enable performance-based design of structural walls with complex configurations. This multi-year effort includes (i) experimental testing of planar, coupled, and c-shaped wall components as well as a three-dimensional wall system to generate high-resolution response and damage data, (ii) development of model and modeling recommendations to enable simulation of earthquake response of wall structures and prediction of demands, and (iii) development of damage-prediction models for PBEE. The first phase of this effort focuses on behavior, analysis and design of planar walls and includes a series of laboratory tests of planar wall sub-assemblages with design details representative of modern construction and load histories representative of those that develop in mid-rise buildings.

To ensure that high-quality experimental data are generated, the NEES "Multi-Axial Full-Scale Sub-Structured Testing and Simulation" (MUST-SIM) facility at the University of Illinois, Urbana-Champaign is being used. The MUST-SIM facility includes non-contact measurement systems that enable reliable high-resolution measurement of deformation and damage. To ensure that wall response is representative, it is necessary that wall sub-assemblages tested in the laboratory be relatively large scale with boundary conditions and reinforcement layouts that are representative of those that develop in the bottom stories of a mid-height building. Specifically, laboratory specimens were 1/3-scale models of the bottom three stories of a representative 10-story building. The application of loads is achieved through using traditional ancillary actuators at each "floor" and load-and-boundary-condition (LBC) boxes to apply shear, moment, and axial load at the top of the specimen. In total, the test matrix will include planar, coupled, C-shaped walls. These categories of structural walls represent both individual walls found in seismic-resisting buildings as well as components of core-wall (typically elevator core) buildings.

The following describes the preliminary findings on planar walls. Initially, reviews of previous research results and current inventory of buildings in high-seismic zones analysis were conducted. The prior research results were used to develop performance-oriented engineering methods, which were evaluated using the seismic response of shake-table tests on structural walls. Although analysis of the prior test data resulted in provisional performance tool, comparison of the prior test data and results of inventory study indicate that the prior test data do not simulate current wall designs for boundary conditions found in practice. The NEES experimental research was aimed at filling this important gap. The NEES experimental research results are presented including used to develop the test matrix and specimen geometry and reinforcement as well as the experimental results. Differences of the structural performance of the NEES wall test results with the prior results are considered.

2. EXPERIMENTAL STUDY

2.1 Infrastructure Review

A priority in the testing program was to develop and evaluate specimens that simulated modern construction. Prior to designing the experimental test specimens, the research team worked with the advisory-panel members to gather information on modern buildings for which walls were the primary lateral load resisting elements. A data set comprising 12 buildings, designed after 1991 by four firms for construction on the West Coast, and including 47 walls with various configurations was assembled. The data collected from the drawings included geometry, reinforcement ratios, and material properties. The data for planar walls (Table 1) were used to identify appropriate ranges for wall geometries characteristics for use in designing the planar wall test specimens. In addition to the geometric, reinforcement and material data, the loading conditions, or effective height of the lateral load, were needed to determine appropriate values of the shear demand-capacity ratios at the base of the wall. The results of previous experimental research (Brown et al. 2006) indicate that failure mode is largely determined by the shear-demand capacity ratio. To determine the possible range of effective heights for mid-rise systems, a series of linear analyses were conducted using one of the buildings from the infrastructure review and effective stiffness reduction factors. The results of this study indicate that effective heights ranging from 0.7 (ASCE-7 (2005) load distribution) to 0.5 are possible (Brown et al. 2006).

Table 1: Planar wall design characteristic generated from building inventory review

Wall Design Characteristic	**Min. Value**	**Avg. Value**	**Max. Value**	**Coeff. of Var.**	**Prototype Design Value**
Thickness	12 in (305 mm)	21.9 in (556 mm)	30 in (762 mm)	0.27	18 in. (457.2 mm)
Length	4.3 ft (1.31 m)	24.3 ft. (7.4 m)	44.5 ft (13.6 m)	0.46	30 ft. (9.1 m)
Boundary-element longitudinal reinforcement ratio	1.54%	3.22%	4.70%	0.31	3.5%
Mid-span vertical reinforcement ratio	0.21%	0.50%	0.99%	0.58	0.25%
Gross vertical reinforcement ratio	0.31%	0.98%	1.81%	0.54	1.4%
Mid-span horizontal reinforcement ratio	0.24%	0.46%	1.38%	0.69	0.27%

2.2 Test Matrix

The objectives of the planar wall test program are to improve understanding of the seismic behavior of planar wall sub-assemblages and to generate high-resolution experimental data characterizing the performance of these sub-assemblages. Based on the inventory review, previous research review, and the following gaps in the research on planar walls were identified:

1. The response and performance characteristics of mid-rise walls (most tests have focused on 1- to 3-story walls),
2. The effect of the moment gradient and shear demand on the response of mid to high-rise structural walls,
3. The influence of the longitudinal reinforcement distribution, and
4. The influence of the splice region on the performance and behavior of modern planar walls.

Table 2 presents the test matrix. On the basis of the results of the inventory review, the test matrix was developed to include the range of effective heights, vertical reinforcement distributions, and whether or not the longitudinal reinforcement was spliced at the base. (Practicing engineers report that most walls are spliced yet this condition has rarely been tested.) The target shear demand-capacity ratios resulted from the prior analyses and studies, and were approximately 0.85 and 1.4, corresponding to shear stress demand ratios of approximately 3.5 and $5.5\sqrt{f'_c}$, respectively. The resulting test matrix consists of four specimens. The first specimen is the reference, and is aimed at evaluating an “idealized” wall specimen subjected to the ASCE-7 load distribution, and is detailed with boundary elements and splices. The next specimen is nominally identical, with a lower effective height and therefore higher shear ratio and shear stress demand, thus representing the other end of the range of possible effective height. The third specimen evaluated the effect of longitudinal reinforcement layout in that a uniformly distributed reinforcement layout and one-bar size were used. The splices at the base of the wall were eliminated for PW4.

Table 2: Planar Wall Test Program

Specimen Description	Effective Height	Shear Ratio: V_{max}/V_n	Boundary Elements?	Splice?
PW1 ASCE-7 Load Dist.	**0.71**	**0.85 (3.5√f'$_c$) [psi] 0.85 (0.29√f'$_c$) [MPa]**	**Yes**	**Yes**
PW2 Low Effective Height	**0.5**	**1.4 (5.5√f'$_c$) [psi] 1.4 (0.46√f'$_c$) [MPa]**	Yes	Yes
PW3 Uniform Reinforcement	0.5	1.4 (5.5√f'$_c$) [psi] 1.4 (0.46√f'$_c$) [MPa]	**No**	Yes
PW 4 No Splice	0.5	1.4 (5.5√f'$_c$) [psi] 1.4 (0.46√f'$_c$) [MPa]	No	**No**

2.3 Test Specimen and Setup

Figure 1 shows the layout of the reference specimen. On the basis of the data generated from this study and discussions with the advisory panel members, it was decided that the prototype wall would have a full-scale thickness of 18 in. (457 mm), a full-scale length of 30 ft. (9.14 m) and a horizontal reinforcement ratio at mid-span of 0.25%. The sub-assemblage is representative of the bottom three stories of a 10-story building and will be tested at 1/3-scale in the laboratory. Earthquake loading of the sub-assemblage will be simulated through application of a moment and shear at the top of the wall as well as shear loads at intermediate stories. Figure 2 shows a photograph of the wall test setup. The moment-to-shear ratio will remain constant during the test with loading varied to generate a prescribed cyclic displacement history at the top of the wall.

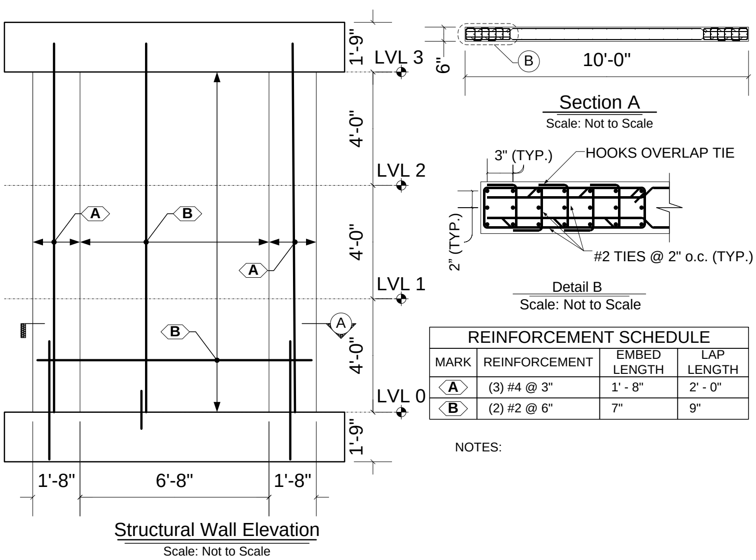

Figure 1: Wall Specimen PW1
(1' = 12" = 305 mm)

Figure 2: PW3 in NEES UIUC MUST-SIM Facility

3. EXPERIMENTAL RESULTS

3.1 PW1 (h_{eff}=0.71h_{10} and BE)

Specimen PW1 was designed to represent a modern planar wall meeting ACI Code (ACI Com. 318 2005) requirements, detailed with heavily reinforced boundary elements, and subjected to shear and moment demands that would result from a standard ASCE-7 load distribution. Figure 3 indicates the measured response of the wall in terms of the base shear and third-story drift (top of the experimental specimen).

The progression of damage for PW1 was as follows: Horizontal cracking was initiated in the wall during the 0.1% drift cycle in the boundary element. Diagonal cracking was initiated during the 0.15% cycle at the interior edge of the boundary element. Yielding of the longitudinal reinforcement was measured at 0.3% drift. Damage to the concrete was initiated at 0.45% drift, in the form of spalling of the concrete cover at the top of the spliced region. Additional cycling resulted in an increase in the spalled region at the two edges of the walls, with the cover along the spliced region off at the 0.9%-drift level. Larger drift demands and cycling of the specimen resulted in buckling of the longitudinal bars at the top of the spliced region at the 1% drift level. Initiation of loss of lateral capacity occurred during cycling to 1.5% drift due to fracture of the longitudinal reinforcement at the base of the wall. The buckled bars at the top of the spliced region did not fracture; conversely, the bars at the bars of the wall (above the footing) did not buckle. Figure 7 shows PW1 after testing was completed.

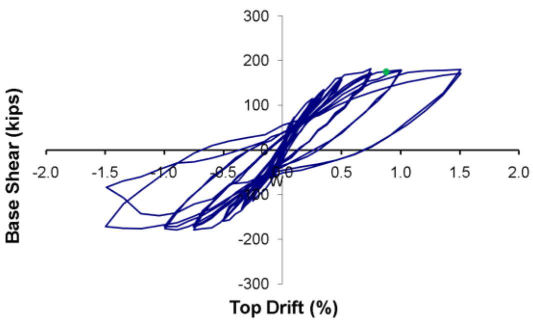

Figure 3: PW1 – Base Shear vs. Drift
(1 kip = 4.45 kN)

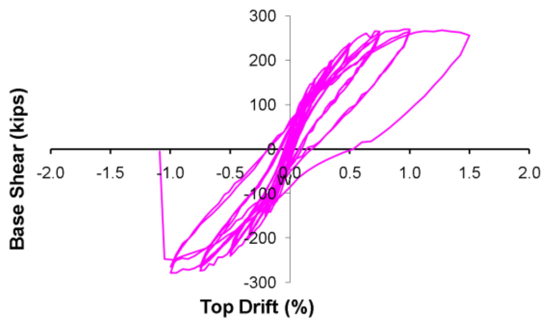

Figure 4: PW2 - Base Shear vs. Drift
(1 kip = 4.45 kN)

3.2 PW2 (h_{eff}=0.5h and BE)

Specimen PW2 was designed to represent a modern planar wall meeting ACI Code requirements, detailed with heavily reinforced boundary elements, and subjected to shear and moment demands that corresponds to an effective height of $0.5h_{10}$, where h_{10} is the total height of the prototype 10-story wall. Figure 4 indicates the measured response of the wall in terms of the base shear and third-story drift (top of the experimental specimen).

Progression of damage for PW2 was as follows: Diagonal and horizontal cracking initiated at 0.1% drift. Yielding of the reinforcement was measured at 0.45% drift. Concrete spalling at the top of the spliced region at initiated at 0.53% drift; spalling initiated at the base of the wall at 0.75% drift. Buckling of the reinforcement occurred at the top of the spliced region at 1% drift. Initiation of core concrete damage in boundary element occurred at 1.5% drift. Lateral capacity was lost during cycling to 1.5% drift due to an apparent compressive failure of the boundary element and web region adjacent to the boundary zone. The final state of PW2 is shown in Figure 8.

3.3 PW3 (h_{eff}=0.5h and Uniform)

Specimen PW3 was designed to represent a modern planar wall meeting ACI code requirements, detailed with uniformly distributed longitudinal reinforcement, heavy transverse reinforcement in the ACI-defined boundary elements, and subjected to shear and moment demands that corresponds to an effective height of $0.5h_{10}$, where h_{10} is the total height of the prototype 10-story wall. The specimen was reinforced with No. 4 bars along its length, in contrast to Specimens PW1 and PW2, which had No. 2 bars in the interior of the wall. As a result, the height of the spliced bars was at a single plane in Specimen PW3.

Figure 5 indicates the measured response of the wall in terms of the base shear and third-story drift (top of the experimental specimen). Progression of damage for PW3 began with diagonal and horizontal cracking initiated at 0.06% drift. Yielding of longitudinal reinforcement was measured at 0.31% drift. Concrete spalling occurred at the top of the splice region at 0.35% drift. No spalling occurred at the wall base. At 0.75% drift, buckling of the reinforcement occurred at the top of the spliced region and damage to the wall web was initiated. Lateral capacity was lost during the cycle to 1.25% drift due to an apparent compressive failure of the entire web region adjacent to the boundary zone. Figure 9 shows PW3 at the end of testing.

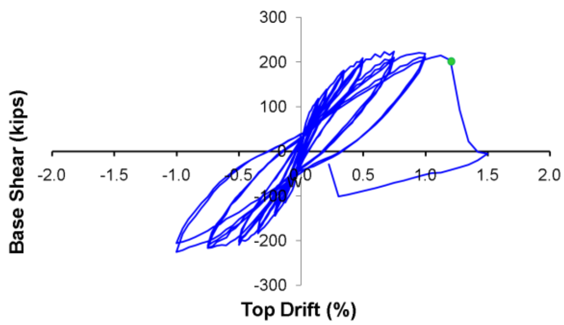

Figure 5: PW3 –Base Shear vs. Drift Response
(1 kip = 4.45 kN)

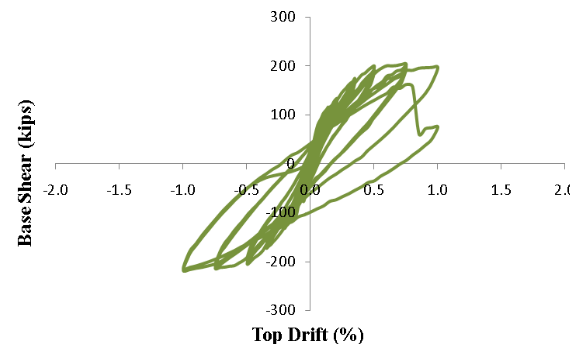

Figure 6: PW4 –Base Shear vs. Drift Response
(1 kip = 4.45 kN)

3.4 PW4 (h_{eff}=0.5h and BE, No Splice)

Specimen PW4 had a design similar to that of PW1 and PW2 with heavily reinforced boundary elements; however, for PW4 longitudinal reinforcement was continuous and was not spliced at the base of the wall, as was the case for the previous specimens. Shear and moment demands for the wall were identical to PW2 and PW3, corresponding to an effective height of $0.5h_{10}$, where h_{10} is the total height of the prototype 10-story wall.

Figure 6 shows the measured response of the wall in terms of base shear and third-story drift (top of the experimental specimen). Damage to PW4 initiated with horizontal cracking at 0.06% drift and diagonal cracking at 0.07% drift. Longitudinal reinforcement yielded at 0.31% drift. Concrete spalling was first observed at 0.5% drift. The 0.75% drift cycles saw buckling of reinforcement and core concrete damage at the base in the East boundary element. This damage became progressively worse until initiation of loss of lateral capacity at 1.0% drift level in an apparent compressive failure. At loss of strength, the West boundary element had only minimal core crushing. Figure 10 shows the final state of PW4.

3.5 *Comparison of Four Walls*

The test results indicate that the effect of the wall study parameters on the seismic performance is significant. Using PW2 as the reference, the impact of i) the effect of the load distribution (PW1 in comparison to PW2), ii) the effect of the distribution of the longitudinal reinforcement (PW2 in comparison to PW3), and iii) the effect of the splice of wall longitudinal reinforcement above the foundation (PW2 in comparison to PW4) on the performance can be assessed.

In all cases, initial damage to the walls included horizontal and diagonal cracking followed by yielding. Damage to the cover concrete always initiated at the top of the spliced region for the first three specimens, whereas cover concrete damage occurred at the base of the wall in the continually reinforced PW4. The next damage state and progression of damage depended on the moment-to-shear (or effective height) of the wall and the distribution of the longitudinal reinforcement, as discussed below.

Specimen PW1 was tested to determine the behavior of a modern wall subjected to the code-specified load distribution. As indicated by the prior discussion, the wall responded in a ductile mode, with loss of lateral capacity resulting from fracture of the longitudinal reinforcement at the base of the wall. In contrast, Specimen PW2, which was nominally identical to PW1, was subjected to a lower base moment-to-shear ratio, which in practical terms would result from a change in the effective height resulting from the dynamic response of the system. The resulting damage progression changed from one of flexure to a mixed flexure-shear response, in that concrete damage concentrated at the top of the spliced region and spread into the interior of the wall. This change resulted in a reduction in the lateral drift capacity and a sudden loss in lateral strength.

Specimens PW2 and PW3 were subjected to the same moment-to-shear ratios, but had different longitudinal reinforcement distributions. In comparison with PW2, the peak shear strength of PW3 was lower, damage initiated at lower drifts and drift capacity were reduced. Where significant damage in Specimen PW2 initiated at 1.5% drift, for PW3, significant damage in the interior of wall initiated at 0.75% drift and loss of lateral capacity occurred at 1.25% drift. In addition, the damage pattern was altered. Specimen PW2 sustained damage primarily in the boundary element and the adjacent interior portion of the wall. In contrast, Specimen PW3 sustained damage along the entire plane of the wall at the top of the spliced region.

Specimens PW2 and PW4 were subjected to the same moment-shear ratios and had identical longitudinal reinforcement distributions; however, while longitudinal reinforcement was spliced in PW2, it was continuous in PW4. Similar to PW2, damage for PW4 was concentrated in the boundary elements and adjacent portion of the web. While for PW2, damage concentrated at the top of the splice, for PW4 damage occurred lower down at the base of the wall. The order of damage progression in PW4 was the same as PW2, but key damage states were reached earlier in PW4 than in PW2, with base concrete spalling at 0.5% drift (0.75% PW2), bar buckling at 0.75% (1.0% PW2), and core concrete damage occurring at 0.75% (1.5% PW2). Additionally, the lateral drift capacity of PW4 (1.0%) was lower than for PW2 (1.5%), as was the peak shear capacity.

Figure 7: PW1 at End of Test (1.5% Drift)

Figure 8: PW2 at End of Test (1.5% Drift)

Figure 9: PW3 at End of Test (1.25% Drift)

Figure 10: PW4 at End Test (1.0% Drift)

4. CONCLUSIONS

A NSF-sponsored research program is underway to develop tools and technologies to enable performance-based design of structural reinforced concrete walls. As part of this project, a series of large-scale planar wall subassemblages were tested using the advanced experimental capabilities of the NEES UIUC Must-Sim Laboratory facility. The walls were constructed using modern wall details and designed to simulate the lower three stories of a ten-story prototype building. The capabilities of the load-and-boundary-condition boxes (LBCLs) permitted the application of moment, shear and axial load to the top of the wall, thereby permitting the top of the experimental wall to be subjected to the demands resulting from the upper stories of the prototype structure. In addition, changing the moment-to-shear ratio permitted different load distributions to the wall, to better simulate the effect on seismic performance of both dynamic loading and changes in the wall stiffness. Preliminary results and observations of these laboratory tests are as follows:

1. Damage always initiated at the top of the splice, suggesting that the splice impacts seismic performance.
2. Even for a wall with ductile detailing, altering the moment-to-shear (or effective height) of the wall can significantly impact the response mode that causes loss of lateral capacity. In the walls tested, this difference changed the determining response mode from flexure to compression-shear in the boundary zone.
3. A reduction in the effective height had a significant impact on the drift capacity. The lower effective height resulted in a reduction of the cyclic response capacity as well as a more sudden loss of strength.
4. The uniformly reinforced wall (Specimen PW3) was detailed with the same reinforcement along it length and therefore a single level of the spliced region. In this wall, damage initiated in the interior and progressed to the sides where as for Specimen PW2 damage initiated at the boundary elements. In addition, damage in the uniformly reinforced wall occurred at a single plane, located at the top of the spliced region. This damage mode resulted in earlier initiation of damage as well as a reduction in the wall drift capacity.

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