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EXPERIMENTAL TESTING OF RC WALLS USING EXTENSIVE INSTRUMENTATION TO INVESTIGATE CYCLICAL NONLINEAR WALL BEHAVIOR

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ABSTRACT

A series of experiments on large reinforced concrete structural walls are being conducted in the University of Illinois Network for Earthquake Engineering Simulation (NEES) facility. The types of walls being tested include planar, coupled, and C-shaped walls. Most of these walls are approximately one-third scale, 4 m high, and model the bottom three stories of a high-rise building. Two versatile six degree-of-freedom loading units are being used at the top of each tested wall segment to apply the axial compression, shear, and overturning moment that would be expected at the third story level of a 10 story prototype building. An additional special feature of this research program is that advanced non-contact measurement systems are being used to make dense and accurate measurements of displacement fields and developing damage. A set of high-resolution pre-calibrated cameras are used to record damage on the surface of the test structure over the entire loading history.

The overall objective of this project is the development of improved performance-based design methods for structural walls. This presentation will focus on two important aspects of the measured response of already tested wall structures, those being the compressive response of boundary regions and the tensile response of cracked structural concrete. In both of these cases, the extensive data collected by the coordinate measurement machine and high-resolution cameras provided what is considered to be an unprecedented level of information for understanding the response of these walls. For the compressive response, these measurements were used to assess the influence of amount of longitudinal and confinement reinforcement, stress level, and cycle number on the limit states of localized crushing, full engagement of confinement reinforcement, wall bulging, bar buckling, distributed crushing, and structural instability. For the tensile response, these measurements were used to similarly assess the influence of structural reinforcement detailing on the development of cracking (spacings and widths), bond degradation, tension stiffening, dimensions of yielding zone, and rupture of bars in pure tension. In both the examination of the compressive and tension responses, a detailed comparison was made between the measured responses of the test specimens and the responses that were predicted by non-linear finite element analysis. These comparisons were used to examine the limitations of existing models for strength degradation and how best to apply these models and revisions to these models to make reliable predictions of the response of structural concrete walls. Due to limitations in length, this paper presents only selected results.

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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) facility. The project funding this research is titled "NEESR-SG: Seismic Behavior, Analysis, and Design of Complex Wall Systems" which is led by Drs. Lowes and Lehman from the University of Washington, Dr. Kuchma from the University of Illinois, and Dr. Zhang from the University of California Los Angeles. A series of planar, coupled, and C-shape walls are being tested to investigate the influence of wall shape, levels and configuration of reinforcement in boundary and web regions, and loading protocols on the performance of these structural systems over their entire loading history.

The Illinois MUST-SIM facility is a large-scale static-rate component testing facility. The primary loading devices are three large and versatile six degree-of-freedom (dof) loading units, named load-and-boundary-condition boxes (LBCBs). These units have a self-weight of 35 tons and can be connected in several orientations on a massive strong wall and floor. They can be use to control displacements, forces, or any combination thereof for all 6 dofs; the maximum force and displacement that can be applied in any one direction is 5000 kN and 0.5 m The NEESR wall project utilizes two LBCBs to impose realistic patterns of loads on the test specimen; in the case of the tested planar walls this consisted of a constant axial compression loading (F_z = constant), a increasing lateral displacement history (Δx = cyclic pattern), and a fixed moment to shear ratio at the three storey level ($M_y = K \bullet F_x$) to represent a fixed effective height ratio on the 10 storey prototype structure. The MUST-SIM facility is capable of conducting hybrid simulation tests, in which an entire system is divided into experimental and analytical components. One of the upcoming C-Shaped walls is expected to be tested using the hybrid simulation methodology.

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 collected test data is needed to improve the tools and technologies for performance-based design of structural wall buildings. 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 collected information will be used to calibrate improved continuum and performance models and design practices.

Experimental Testing and Instrumentation Overview

Each wall test structure is the lower three stories of a ten story tall building. Side mounted actuators have been used in some instances to simulate the shear forces induced at the second and third floor levels. Each wall is approximately 4 m tall, 3.2 m wide, and 0.15 m thick. A picture of the test setup is presented in Figure 1.

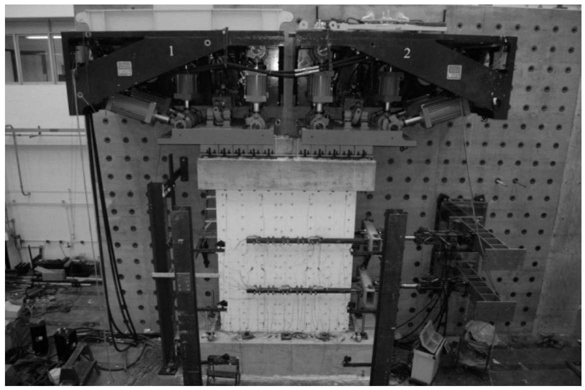

Figure 1. Planar wall test with two LBCBs and two side-mounted actuators

The main variables within the experimental plan are the longitudinal reinforcement ratios, effective height ratio, and shape of the wall. Four planar wall tests were conducted in the first phase of the research program. The influence of longitudinal reinforcement ratio is being investigated by altering the boundary element regions. Three of the planar wall tests were built with heavily reinforced boundary elements; one planar wall contained the same overall reinforcement ratio as the other three planar walls, but the reinforcement was smeared evenly across the entire cross section.

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. A target concrete strength of 5000 psi (34.5 MPa) was used in all four planar walls. A self consolidating concrete (SCC) mix was used since the reinforcement cage was extremely tight in some regions due to the one third scale. Standard grade 60 reinforcing bars were used. Deformed #2 bars (6 mm diameter) had to be specially purchased and heat treated.

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 6 inches (150 mm) along the entire height of the wall. Longitudinal reinforcement bars used to date have been principally #4 bars (12.7 mm diameter). In specimens with heavily reinforced boundary elements, #2 bars were used as the vertical web longitudinal reinforcement. The #2 bars were also used for the horizontal reinforcement, boundary element hoops or stirrups, and boundary element hooks.

A lap splice was used at the base of the wall in the first three planar wall specimens to represent typical construction practices. 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 extended over the height of the wall were bent to remain at the same flexural depth after the splice zone.

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 first step in the loading was the application of a constant axial load (F_z) of approximately 10% of the axial capacity of each wall. A cyclically increasing lateral displacement (Δ_x) history was then imposed at the top of each wall, and a fixed moment to top measured lateral force ($M_y = K \bullet F_x$) was maintained. For example, if the specimen was at a lateral displacement of 12.5 mm with 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.

Advanced Instrumentation

A special 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 in-plane accuracy of approximately 0.02 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 coordinate measurement markers (LEDs), 10 high resolution cameras, and actuator load cell and LVDT readings. All instruments were connected to two National Instruments (NI) SCXI-1001 chasses. Offsite researchers can monitor the experiment in progress using a Remote Data Viewer (RDV) program.

Metris/Krypton K600

The Metris/Krypton K600 coordinate measurement system was used to measure the 3-dimensional locations of a grid of approximately 150 LEDs. The LED grid covered the lower two stories of the test specimen. Additionally, this system was used extensively to align the two LBCBs as wells as align the LBCBs with the wall specimen. The accuracy and ease of use of the K600 made it possible to accurately fine tune the LBCBs for precise and accurate load control.

High resolutions cameras

One component of the advanced instrumentation plan is the use of automated high resolution digital cameras. Pictures were taken using 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, a transaction message is sent 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 2. Additionally, oriented crack maps composed from several photographs can be utilized to determine crack spacings, crack patterns, and crack orientations. PhotoModeler 6.0 is the close-range photogrammetry software that was used.

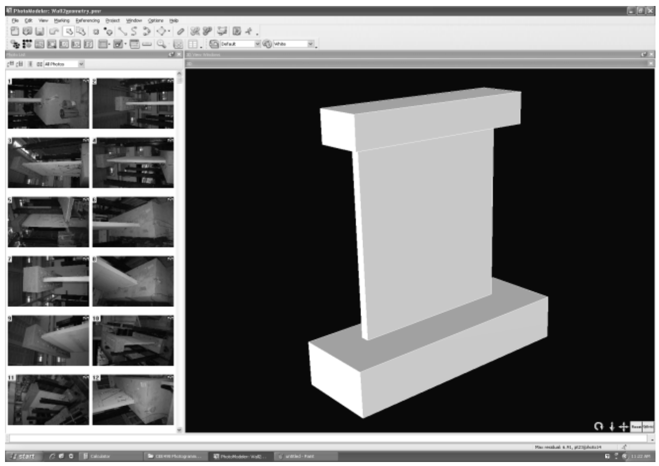

Figure 2. As built 3D rendering of wall specimen constructed with close-range photogrammetry

Measured Response of Structural Wall

The primary focus of this research is to better understand the behavior or reinforced concrete walls under reverse cyclic loading. Current analytical models and finite element analysis packages have been calibrated from over simplified test experiments that do not necessarily capture true behavior and damage states. In this paper that presents some of the initial comparisons between measured behavior and analytical predictions, the measured behavior of planar wall #2 and the predictions of the following two programs are used.

Response 2000

Response 2000 (Bentz 2000) is a sectional analysis program in which the cross section is divided into discrete layers or fibers. Contrary to typical sectional analysis programs, this program does include effects of shear, making it suitable to compare to the walls tested in this study due to the combination of axial load, shear, and overturning moment. While the program Response 2000 assumes that plane sections remain plane and this was not the expectation for the behavior of these walls, it is useful to examine the predictive capacity of such an approach.

VecTor2

VecTor2 (Vecchio, VecTor Analysis Group) is a reinforced concrete finite element analysis package developed by Frank Vecchio at the University of Toronto. The program employs the Modified Compression Field Theory (MCFT, Vecchio and Collins 1986). It is a 2D membrane modeling package that enables a wide range of material and constitutive properties for both steel and concrete to be used. Additionally, it has the ability to model the damage from cyclic loading. The VecTor2 model of wall #2 and the deformed shape at failure of the model can be found in Figure 3.

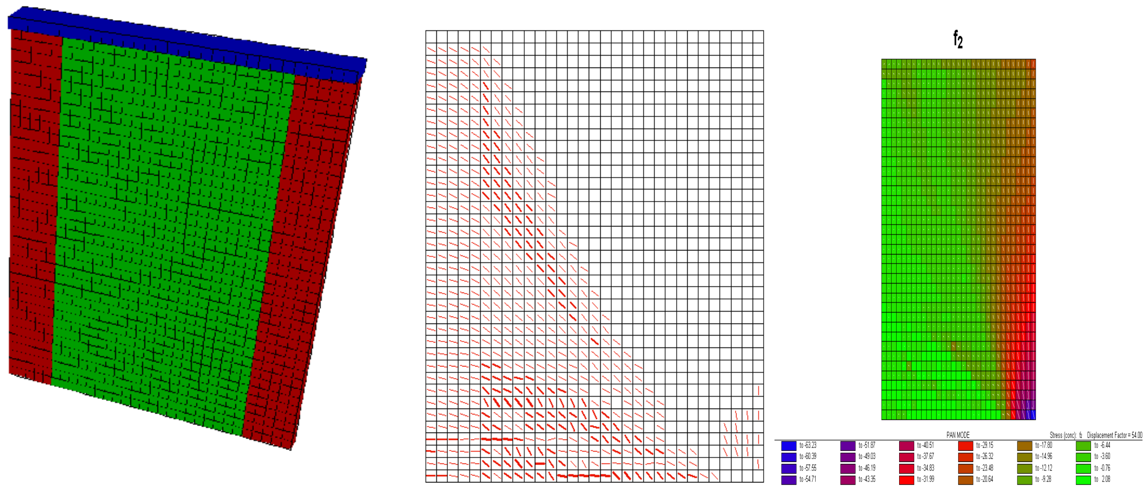

Figure 3. VecTor2 FEM model of planar RC wall. Cracked pattern at failure. Principal compression contour map.

Compressive Response

Both Response 2000 and VecTor2 provided reasonable predictions of the overall response of the planar walls that have been tested. The observed ultimate strength of planar wall #2 was 1228 kN of base shear, associated moment of 7919 kN-m. Response 2000 predicted a shear failure at a base shear of 952 kN, associated moment of 6085 kN-m. VecTor2 predicted a failure at a base shear of 1268 kN, associated moment of 8300 kN-m. The VecTor2 model accurately predicted the capacity of the wall to within 3.3%. VecTor2 predicted a flexural failure by crushing of the toe of the wall, while Response 2000 predicted a shear failure. This may be attributed to the shear-moment interaction at the base of the wall due to the actual boundary conditions that are present in the test structure which can be modeled with VecTor2, but not captured in Response 2000. Regardless, neither model was able to predict that the test specimen would fail just above the spliced region as now discussed.

A lap splice was used at the base of the wall to replicate typical construction practice. This test specimen failed just above the spliced region and at a fairly low drift. In Figure 4 it can be seen that crushing is initiating just above the splice and not at the base of the wall where the moment was the largest. In comparison to the same distressed region in the VecTor2 model, it is predicted that failure is occurring at the very base of the wall, where the contours of the stresses is a light green color signifying crushing of the concrete.

Another interesting observation that has been made is with respect to the length of the region under high straining. When the compression edge of the wall is under significant loading approaching crushing, the results from the VecTor2 model differ greatly from the observed measurements. Figure 5 compares the vertical strain between the VecTor2 model and data collected from the Krypton non-contact measurement system. Note that the strain profile in the VecTor2 model in continuing to increase down the height of the wall, which is what one would expect as a wall is commonly modeled as a cantilever beam. Therefore, failure would occur at the very base of the wall either as a rebar tension failure or compression failure at the wall toe. Clearly, this is what VecTor2 is predicting to be the failure mechanism seen in Figure 4. However, the measured strain values do not follow this pattern. Rather, the strain seems to increase but then drastically increases to a strain of almost 8 mm/m approximately 0.6 meters above the base of the wall which is the location just above the splice and where local damage has initiated. While FEM packages typically utilize nice plastic materials that can distribute deformation smoothly across the structure and which fosters convergent solutions, damage in most reinforced concrete structures is inherent a local phenomenon as illustrated in Figure 5.

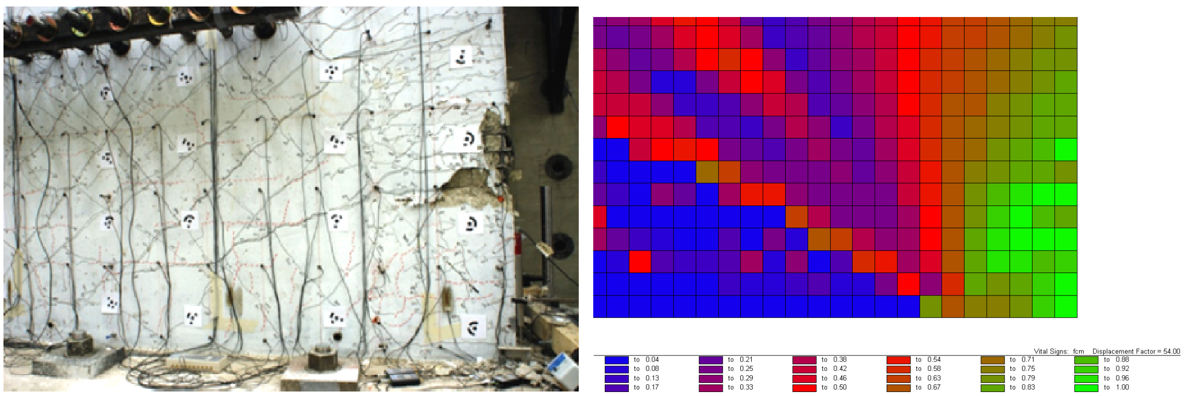

Figure 4. Comparison of distressed regions at failure.

Tensile Response

This paper also provides some initial comparisons of the measured and predicted tensile response of the wall test structures. In particular, the influence of structural reinforcement detailing on the development of cracking (spacings and widths), bond degradation, tension stiffening, dimensions of yielding zone, and rupture of bars in pure tension are all of interest.

Similar to the compression edge of the wall, the vertical straining along the tension edge of the wall has been plotted in Figure 5. Similar to the compression face, there is a large discrete jump in the strain at the location just above the splice. This is due to a large discrete crack that initiated just above the splice. Here again, VecTor2 does not capture this behavior because a smeared crack model is utilized.

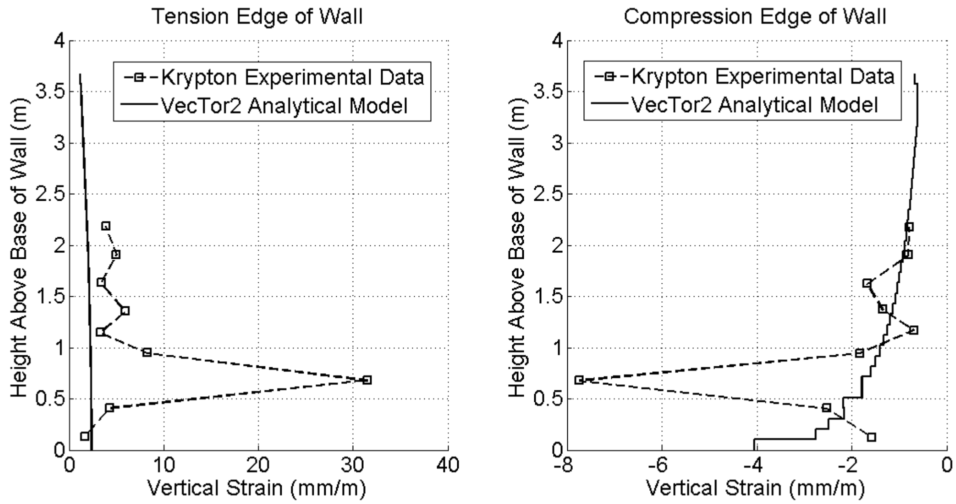

Figure 5. Comparison of region under high straining on compression and tension edge of wall (V = 1180 kN)

The influence of the splice can also be seen when comparing the vertical strain distributions across the width of the wall. Figure 6 depicts several strain distributions at different load levels (230 kN, 700 kN, and 1200 kN respectively) and at two locations along the height of the wall (at the splice level and in the middle of the second story level). First, it should be noted that the VecTor2 model predicts a linear strain distribution at the lower load levels and the measured response of the wall seems to fit well within this prediction. Second, at the base of the wall at the large lateral load of 1200 kN, there is a large spike in the strain which is located just within the web of the wall. It is at this location where the discrete crack that was described above dives down into the base of the wall, and crosses the strain distribution that is plotted in Figure 6. Finally, it seems that the VecTor2 model accurately predicts the strain distribution at the middle of the second story location better than at the base of the wall. The middle of the second story can be assumed to a B-region in which plane sections remain plane and are easier to model. On the other hand, the base of the wall is clearly a D-region and can be much more difficult to model accurately considering what was discussed earlier with respect to the splice region, local damage effects, and boundary conditions.

Another aspect of the tensile response of reinforced concrete structures that is being investigated is the predicted crack spacing. A most common model for predicting crack spacing is the CEB-FIP model Eq. 1.

$$s_{ave} = 2\left(c + \frac{s}{10}\right) + k_1 k_2 \frac{d_b}{\rho_{eff}} \tag{1}$$

There are principally two regions in the planar wall specimens, the boundary element and web region. It can be assumed that the crack spacings in the boundary element will be perpendicular to the longitudinal reinforcement, but the cracks within the web will be inclined. Eq. 1. estimates that the spacing of the cracks within the boundary element will be 90 mm and 144 mm in the web. The observed sustained crack spacing in the boundary element was approximately 50 mm or about half of the prediction. This is most likely a result of the presence of the confinement hoops or transverse reinforcement (Rizkalla 1983). From close-range photogrammetry, crack spacings in the web were observed to vary between 50 to 250 mm. This range differs from the CEB-FIP prediction because the model merely estimates the spacing given an amount a reinforcement, and does not correspond to loading, a transition between different levels of reinforcement, or the presence of transverse reinforcement. The observed crack pattern on planar wall #2 is most likely the result of the compression fan funneling toward the wall toe and the transition from a heavily reinforcement boundary element, to a lightly reinforced web.

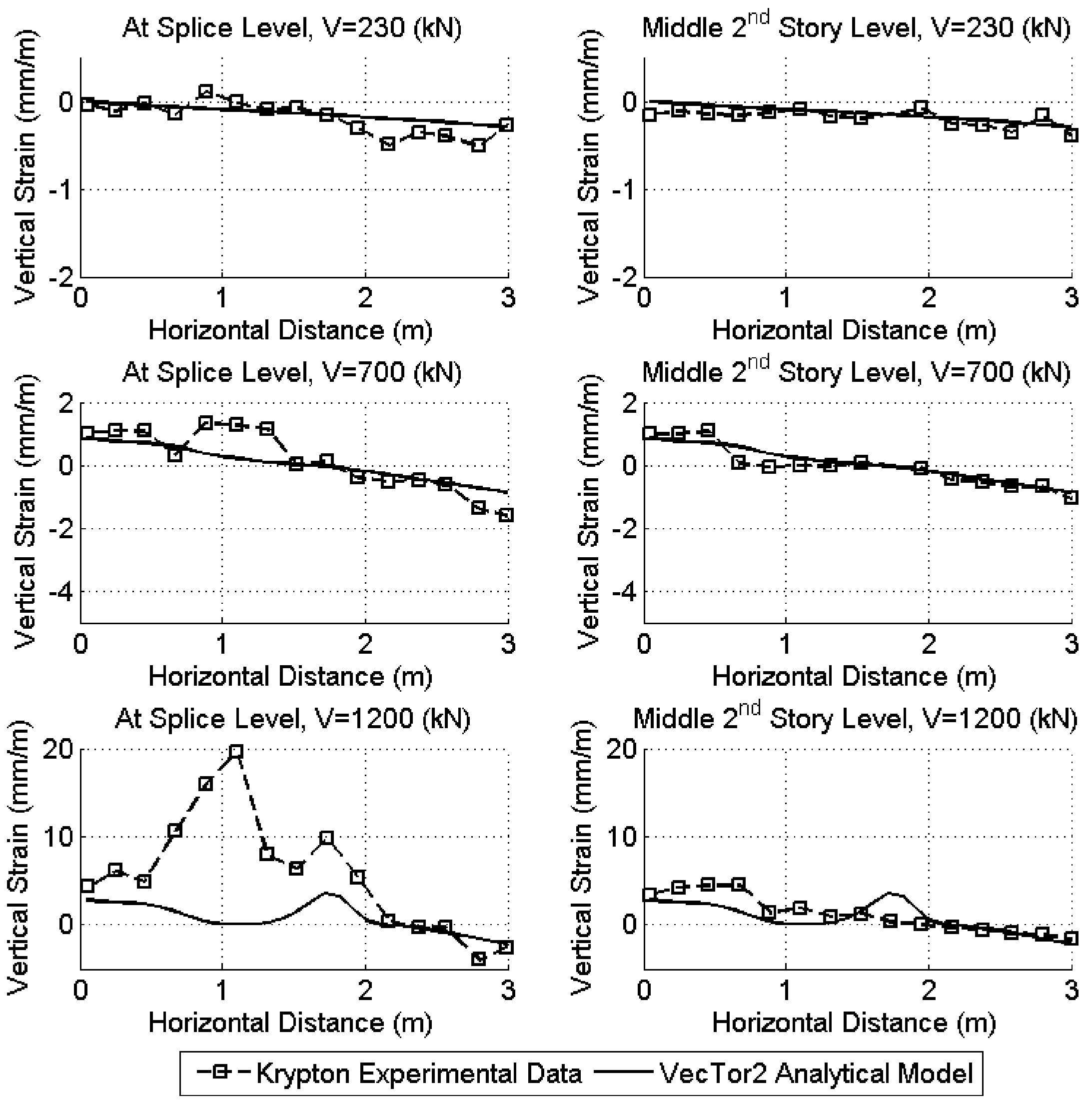

Figure 6. Vertical strain distribution comparison across the width of the wall.

Ongoing and Future Work

The comparisons given in this paper provide a sampling of the investigation being conducted into the compressive and tensile region response of these structures. The very large amount of information being collected by the advanced measurement systems, and their similarity to the detailed predictions from finite-element methods are enabling for an in-depth investigation of smeared and local behavior. This investigation is ongoing and the associated presentation to this paper will present additional findings. In addition, and prior to the conference, the results from one coupled wall and one C-shaped wall expected to be available.

With respect to the compressive response of the test structures, the effectiveness of current confinement models are being evaluated and suggested changes will be made, as needed, to better predict the behavior of heavily reinforced boundary elements and for potential incorporation into numerical tools. This includes accounting for the effect of splices.

With respect to the tensile response of reinforced concrete, it is clear from the data collected from this and other studies, that improved models for crack spacing are needed. Close-range photogrammetric techniques are being used to develop comprehensive and accurate crack maps from which to calibrate improved crack-spacing models. In addition to crack spacings, the crack maps will be utilized to understand crack patterns throughout the entire loading history of each specimen, including angles of development and changes in direction of principal straining. As part of this work, methods are being created to smoothly merge high resolution images from different regions of the wall into one uniform oriented surface of the wall. Similarly, methods are being developed to study tension stiffening and bond degradation effects and how the phenomenon relates to stiffness degradation over reverse cyclic loading.

Conclusions

A series of fully realistic tests on reinforced concrete walls are being conducted at the University of Illinois in which the loading on the bottom three stories of 10-storey prototype structures are being simulated. Comprehensive full field displacements and the development of damage are being recorded over the loading history. This information is being used in conjunction with the predictions from numerical programs to better understand the compressive and tensile response of reinforced concrete walls, and to suggest improvements for numerical models and for design.

Acknowledgments

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