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

K.P. Marley[1], C.R. Hart[1], and D.A. Kuchma[2]

ABSTRACT

A series of large-scale experimental tests on reinforced concrete (RC) structural walls is being conducted in the University of Illinois NEES MUST-SIM testing facility as part of the project "NEESR-SG: Seismic Behavior, Analysis and Design of Complex Wall Systems." The work is a collaborative effort between researchers and staff at the University of Washington, the University of Illinois, and UCLA. In previous research on RC structural walls, the value of the collected experimental data and finding were limited by one or more of the use of: simplified load applications, simplified boundary conditions, smaller-scale test specimens, and the sole use of traditional measurement systems such as strain gages and displacement transducers.

This NEESR project strives to conduct more realistic and informative tests on RC walls through the use of the new testing capabilities that are available at the Illinois facility. Fully realistic loading was applied to the bottom three storeys of ten storey RC walls using the Illinois NEES Loading and Boundary Condition Boxes (LBCBs). These LBCBs are able to control all six degrees-of-freedom at a specimen connection point in any combination of load or displacement control. Loading histories were cyclically increasing, with repetitions at various key stages of structural response such as pre-cracking, cracking, yielding, and higher drift ratios so that the overall behavior and cyclical strength degradation could both be studied. In addition to improving the quality of the tests themselves, the quality and quantity of data collected was also improved upon prior testing efforts by the use non-traditional non-contact measurement systems. These non-contact measurement systems include a coordinate measurement machine that was used to measure the coordinates of nearly 200 surface mounted targets in 3-dimensional space to an accuracy of approximately 0.001 inches (0.025 mm) and a set of more than 10 high-resolution cameras that were used to record the development of cracking, other forms of surface damage, and specimen geometry at more than one thousand points over the loading history of each wall.

This paper presents a discussion of how the testing capabilities of the Illinois facility are being used for conducting very realistic tests on reinforced concrete walls. It emphasizes the importance and challenge of defining loading protocols when using loading devices that can apply forces and displacement in any of six degrees-of-freedom.

[1]PhD Candidate, Dept. of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, IL 61801
[2]Associate Professor, Dept. of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, IL 61801

Introduction

The Multi-Axial Full-Scale Sub-Structured Testing and Simulations Facility (MUST-SIM), part of the University of Illinois Network for Earthquake Simulation (NEES), has the capability of conducting large-scale testing of specimens under complex loading conditions. A series of tests on large-scale reinforced concrete wall systems is currently in progress in the facility under the "NEESR-SG: Seismic Behavior, Analysis, and Design of Complex Wall Systems" project led by Drs. Lowes and Lehman from the University of Washington, Dr. Kuchma from the University of Illinois, and Dr. Zhang from UCLA.

All tests conducted rely on the use of two MUST-SIM Loading and Boundary Condition Boxes (LBCBs), which are capable of applying load and displacement combinations in all six degrees of freedom (DOFs). Thus far, four planar reinforced concrete walls have been tested at the facility. In these tests, the bottom three storeys of a ten-storey prototype structure were constructed at 1/3-scale, with the LBCBs applying loads and displacement about a common control point. Upcoming tests include coupled and C-shaped wall systems, also at 1/3-scale. In-depth information on the LBCBs, specimen instrumentation, and loading protocol of the planar walls will be presented first to contrast against the work required to develop loading protocol for the coupled wall system. This work involved the creation of finite element models of the ten-storey prototype and three-storey test specimen, applying the proposed loading protocol to the specimen model, comparing the results against the prototype model, and updating the protocol until the two model responses matched. Advanced instrumentation on the physical test specimen will provide feedback for load protocol verification and will be a source of dense data for post-processing model validations.

NEES MUST-SIM Facility

The MUST-SIM facility exists within the floor space of the Newmark Structural Engineering Laboratory at the University of Illinois, occupying an area of 25 meters by 15 meters. The facility has an L-shaped concrete reaction wall (9 m tall, 1.5 m thick) post-tensioned to a 5 meter deep concrete box girder reaction floor, as shown in Figure 1. This configuration allows for specimens to be post-tensioned to the reaction floor, with loading units mounted to the strong wall to push against the specimens. Although uniaxial actuators are sometimes used in a supplementary manner, the primary loading units have always been LBCBs.

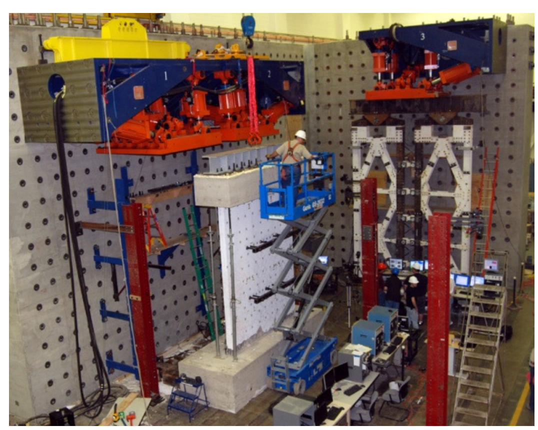

Figure 1. MUST-SIM reaction wall, LBCBs, and test specimens.

Loading and Boundary Condition Boxes

The LBCBs are able to impose forces and displacements in all six degrees of freedom. Their general construction consists of six servo-hydraulic actuators connected between the loading platform and reaction box. Each actuator has a tension/compression force capacity of 960/1460 kN, and it is through the simultaneous execution of motions in all six actuators that Cartesian translations and rotations can be executed. The LBCBs can be positioned either horizontally or vertically on the strong wall and post-tensioned into place. A total of three large-scale LBCBs are operated in the MUST-SIM facility.

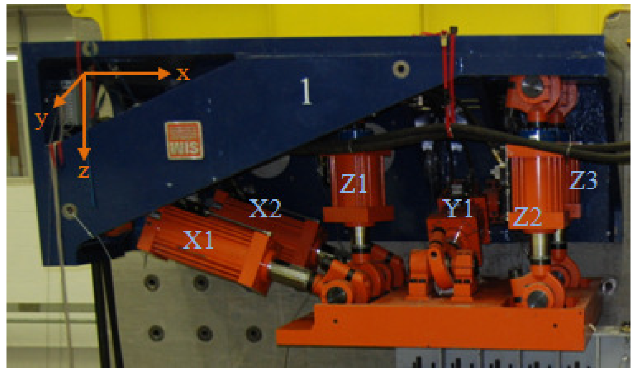

Figure 2. Typical LBCB with Cartesian axis and actuator names.

Figure 2 shows one LBCB mounted on the strong wall, with the Cartesian-space directional convention displayed in the corner. Two actuators are roughly aligned in the x-axis, one actuator along the y-axis, and three along the z-axis. Acting alone, an LBCB is capable of applying the forces, moments, translations, and rotations listed in Table 1. If higher load levels are required, then additional LBCBs can be used in combination to applied the needed actions. The four NEESR-SG planar walls, for example, required the combined action of two LBCBs to apply the required top moment.

Table 1. Capabilities of an individual LBCB.

Loading DOF	**Force Capacity**	**Stroke**
X-Translation	1920/2920 kN (T/C)	± 250 mm
Y-Translation	960/1460 kN (T/C)	± 125 mm
Z-Translation	2880/4380 kN (T/C)	± 125 mm
X-Rotation	860 kN-m	± 16°
Y-Rotation	1150 kN-m	± 11.8°
Z-Rotation	860 kN-m	± 16°

LBCB Control Software

Executing commands in Cartesian space requires that all actuators displace in the correct proportions. Additionally, it is often desirable to apply mixed-mode conditions—displacement control in some DOFs and load control in the remainder—on a specimen to achieve realistic loading. Both of these functionalities are addressed by the LBCB control software, the Operation Manager (OM), as well as incorporating load and displacement limits for all DOFs and individual actuators.

Coordinating Cartesian displacements and rotations is the most basic capability of the Operation Manager. An internal LVDT from each actuator provides the displacement of each actuator, and the relative positions of all actuators in their initial positions are known from construction documents and high-precision machining work. Knowing the initial positions, initial actuator lengths, and current actuator lengths, current displacement and rotation of the LBCB loading platform can be calculated for a defined Cartesian system (Nakata et al., 2007). The displacements required of each actuator for a given Cartesian command must be constantly calculated depending on the specific position of the loading platform, and several such calculations and movements must be executed at about 50 Hz to allow for smooth movement from one set of Cartesian coordinates to another. Accepting Cartesian commands from the user and producing corresponding actuator commands is handled by the OM.

In addition to an LVDT, each actuator has a load cell attached in line to provide force readings to the OM. Knowing the positions of all actuators and their internal forces, Cartesian forces and moments about a defined control point are calculated within the OM. Having all this information available, the OM is also capable of enforcing force-control in any number of DOFs. After executing all displacement-control Cartesian commands, deviations from measured and desired Cartesian forces are calculated. Based on constantly-updated stiffness characteristics, target displacements for the force-controlled DOFs are executed, and the new force deviations are measured. Further iterations are executed in this manner until all force-controlled DOFs are within their user-defined tolerances. Further features of the OM are the ability to enter a holding state upon exceeding force and displacement limits, continuous force and displacement data archiving, and capabilities for passing data or receiving commands over a network connection.

NEESR-SG Planar Wall Testing

The four planar walls tested within the NEESR-SG project all had the same external dimensions, measuring 3 meters wide, 3.7 meters tall, and 150 mm thick. Again, this size corresponds to the bottom three floors of a structure at 1/3-scale. Parameters varied within the specimens include loading condition (high or moderate effective heights), longitudinal steel placement (distributed or edge-concentrated), and construction detailing (spliced or continuous longitudinal steel). Since this paper focuses on development of loading protocol for the coupled wall test, more detail on the planar wall loading is given below.

Loading Protocol

One of the earliest issues facing the NEESR-SG project was selecting the general loading protocol to be used. Hybrid-simulation testing was considered, but ultimately rejected since the structural response would correspond to only a single earthquake record. Instead, a series of earthquake analyses were conducted on a model of the ten-storey prototype structure, and the moment-to-shear (M/V) ratios at peak loading at the base of all results were compared. After choosing a representative M/V, a distributed loading along the height of the prototype was established. Finally, the loading to be applied to the test specimen was calculated by performing free-body diagram calculations of the statically determinate system at the top of the third storey, as shown in Figure 3. Moment, shear, and axial load at the top of the specimen were provided by two LBCBs, and shear loads at the top of the first and second storeys were applied with uniaxial actuators. Figure 4 illustrates this test setup.

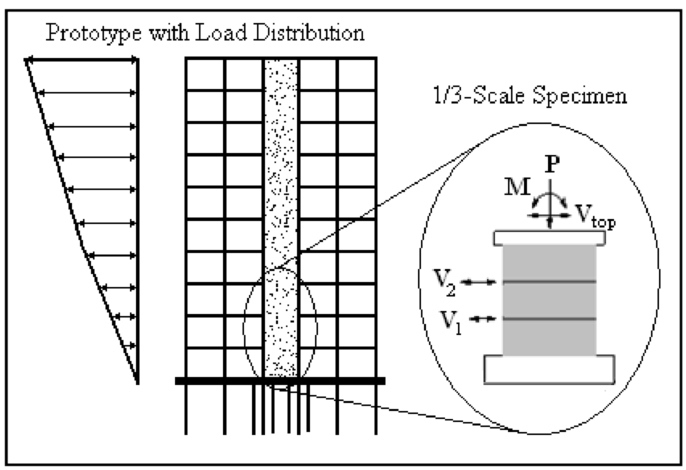

Figure 3. Extraction of test specimen loading from prototype structure loading.

Having established the M/V ratio to be maintained throughout the duration of the test, additional loading details needed to be set. A reverse-cyclic protocol with displacement states at pre-cracking, cracking, yielding, and higher drift ratios was selected to investigate strength and stiffness degradation at various stages in the specimen response.

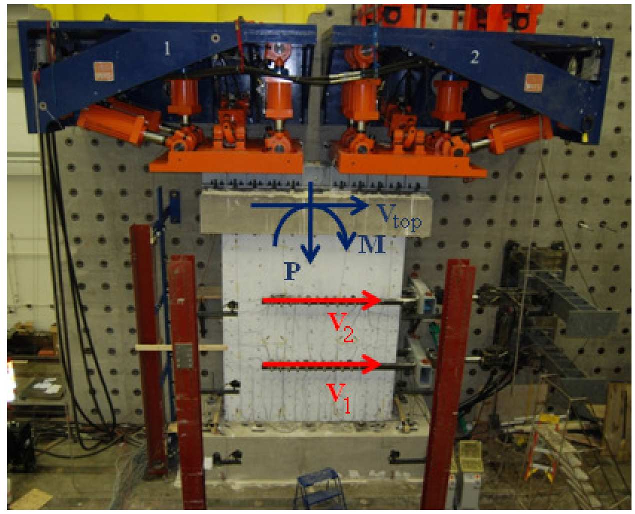

Figure 4. Representative test specimen with loading methods indicated.

Many steps must be taken to ensure all aspects of the loading protocol are satisfied. First, a constant axial load must be maintained at all times. Next, depending on the specimen damage state, a horizontal displacement of 0.1-0.75 mm is executed, and the top shear force is measured. This value is used to calculate the top moment and floor shears to be applied to satisfy the M/V constraint. Once the correct forces are imposed, a final check on the displacement is conducted with an external set of instruments since the reaction boxes of the LBCBs can deform, thus altering their readings. For the planar wall, a single horizontal string pot with a long gauge length was sufficient since x-translation was the only displacement-controlled DOF of importance. The three out of plane displacements (inactive DOFs) were kept at zero throughout that duration of the tests. Despite the multitude of steps required, the loading protocol for the planar wall tests remained fairly simple since the wall system was statically determinate and all DOFs had specific requirements at all times.

NEESR-SG Coupled Wall Testing

The next NEESR-SG specimen to be tested is a coupled wall system—two wall piers joined by coupling beams at the top of each storey. Also at 1/3-scale, the wall piers are 1.2 meters wide, 150 mm thick, and have a clear spacing of 0.6 meters between them. The coupling beams span this space, have a depth of 0.3 meters, and have diagonal reinforcement running through them and into the wall piers. The test specimen is shown in Figure 5.

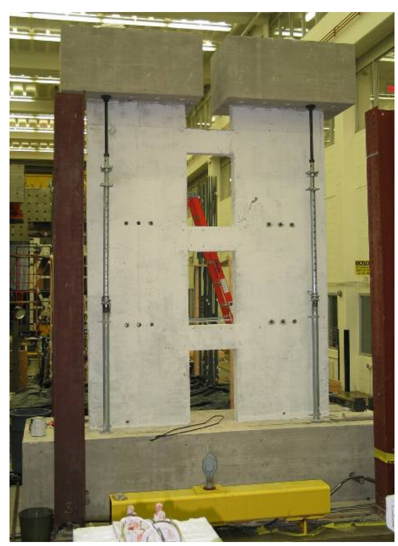

Figure 5. Coupled wall specimen.

Unlike the planar wall specimens, the coupled wall specimen by necessity must be controlled by two LBCBs acting independently on top of each wall pier. Neglecting out of plane motions, vertical (axial) displacement, horizontal (shear) displacement, and rotation (moment) commands must be determined for both LBCBs for a total of six active DOFs. The free-body diagram from the load distribution, however, only provides constraints on three global DOFs: total axial load, total shear force, and total moment. Therefore, three additional constraints are required to fully define a viable loading protocol.

Coupled Wall Loading Protocol Development

In order to develop the coupled wall loading protocol, first investigations into the ten-storey prototype coupled wall were conducted. Analyses were run with VecTor2, a nonlinear finite element program based on the Modified Compression Field Theory for reinforced concrete developed at the University of Toronto (Wong and Vecchio, 2002).

The model for the prototype wall is mostly composed of four-node quadrilateral elements with smeared reinforcement corresponding to the specimen's design, typically measuring about 100 mm on a side. Discrete truss bars are also included to account for the diagonal reinforcement through the coupling beams. Material properties were set based on the actual materials used in the physical specimen. The analysis was run in force control so as to maintain a constant moment-to-shear ratio. Axial loading is spread uniformly at floor levels such that stress at the bottom is 0.10(f'_c). Horizontal loads were applied such that their resultant location matched the effective height to be used in the physical test. Boundary conditions included fixing all nodes at the base against vertical and horizontal translations.

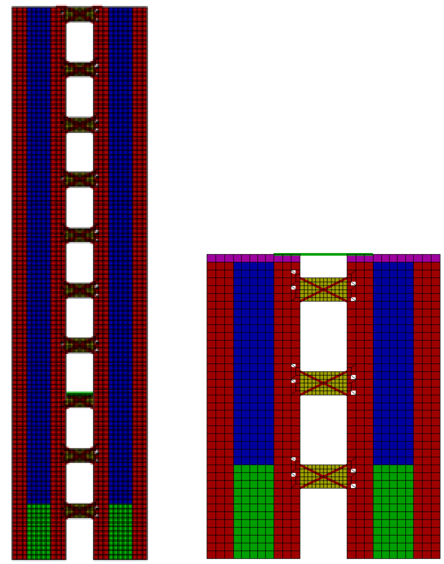

Figure 6. Prototype and specimen models (at variable scale).

The geometry of the test specimen model is very similar to the prototype model, with two exceptions. First, its height is reduced so as to match the height of the physical specimen. Second, a layer of highly-reinforced quadrilateral elements is added to the top of both wall piers to accommodate simulated LBCB loading. Loading for the test specimen model was withheld until after inspecting the response of the prototype model. Both FE models are illustrated in Figure 6, with colors indicating differing material property assignments.

Response of Wall Models and Loading Protocol Determination

The initial analysis on the prototype model involved a simple one-direction pushover of the system, with reaction forces at the base and displacements at the top of the third storey being of primary interest. The results of plotting total base shear against floor drift for both piers is provided in Figure 7, and the similarity of the displacements suggested that it might be acceptable to keep the displacements of both piers the same during testing.

To further investigate this possibility, this displacement constraint was imposed on the test specimen model by tying the two wall piers together with sufficiently large discrete truss bar element which can also be seen in Figure 6. Axial loading was introduced at the pier caps and the two lower storey levels. Shear load was uniformly distributed across the pier caps, with appropriate loading fractions present at the lower levels. Bending moment was applied via a linearly varying axial load applied to the pier caps with net tension on the left pier and net compression on the right pier.

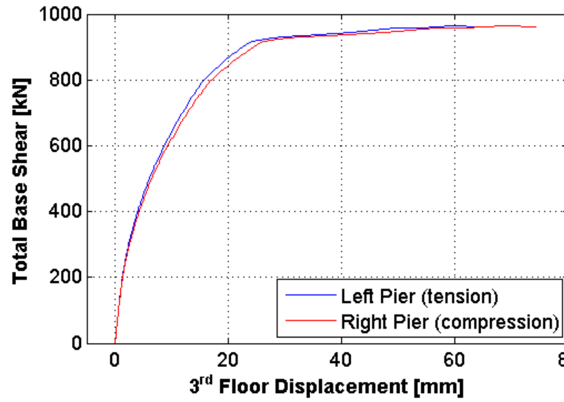

Figure 7. Load-displacement results for prototype pushover analysis.

After running the analysis, overall behavior of the two models was compared. At peak loading, many similarities existed between the models. Maximum shear loads were 965 kN and 959 kN for the prototype and test specimen models, respectively, and full yield for both models occurred at 3rd storey displacement of about 25 mm. Further system-wide similarities exist between the two models. Figure 8 depicts the exaggerated deformed shape and cracking pattern of the bottom three storeys of the prototype and the entirety of the test specimen model. Note the relatively high level of cracking on the tension corners of the coupling beams at the top of the second and third storeys compared against the first storey coupling beam. Figure 9 shows the principal compression stress trajectories for the two models at peak loading. In both models, the transfer of load from the left pier to the right pier through the coupling beams occurs in a similar manner, with stress concentration arising in the corners. The general flow of forces within the two piers are also very much in agreement between the two models.

Due to the high level of agreement between the two models, a fourth constraint setting the displacements of both piers to be equal is established, leaving two more to be set. Realizing the physical test would differ from these pushover analyses due to damage accumulation, subsequent analyses employed reverse-cyclic loading conditions. When looking at the displacement and rotation above the third storey in the prototype analysis, a rather strong link between the two emerge. For most of the response, pier rotation can be predicted by multiplying a constant factor to the displacement, and only near the failure of the prototype model does a deviation from this trend occur. Figure 10 shows both the displacement-rotation trend and the overall load-displacement plot to illustrate when the relationship breaks down. Since the trend does persist for most of the response, top rotation will be set as the computationally-obtained function of the third storey rotation, n.

To summarize the loading protocol, both wall piers will be displacement-controlled in the x-direction by the same magnitude (Eq. 1), with pier rotations set as a constant multiple, n, of displacement (Eq. 2). Total axial load will be maintained as 10% nominal capacity (Eq. 3), and the overall moment applied at the top shall satisfy the moment-to-shear requirement, k, determined from the assumed distributed load on the prototype structure (Eq. 4).

$$\Delta_{x1} = \Delta_{x2} = \Delta_x \quad (1)$$
$$\theta_{y1} = \theta_{y2} = n*\Delta_x \quad (2)$$
$$F_{z1} + F_{z2} = 0.10*A_g*f'_c \quad (3)$$
$$M_{y,total} = k*(F_{x1} + F_{x2}) \quad (4)$$

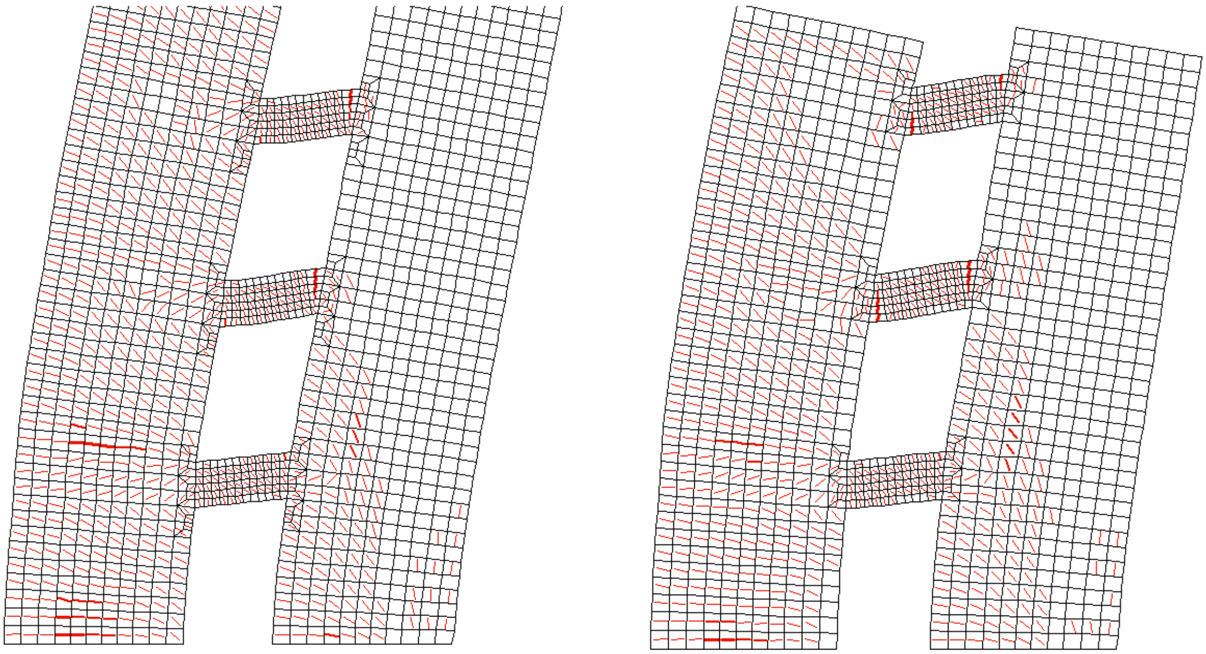

Figure 8. Crack maps for prototype (left) and test specimen (right) finite element analyses at peak load level. Note that thicker lines indicate larger cracks and that these regions of large deformation are common to both analyses.

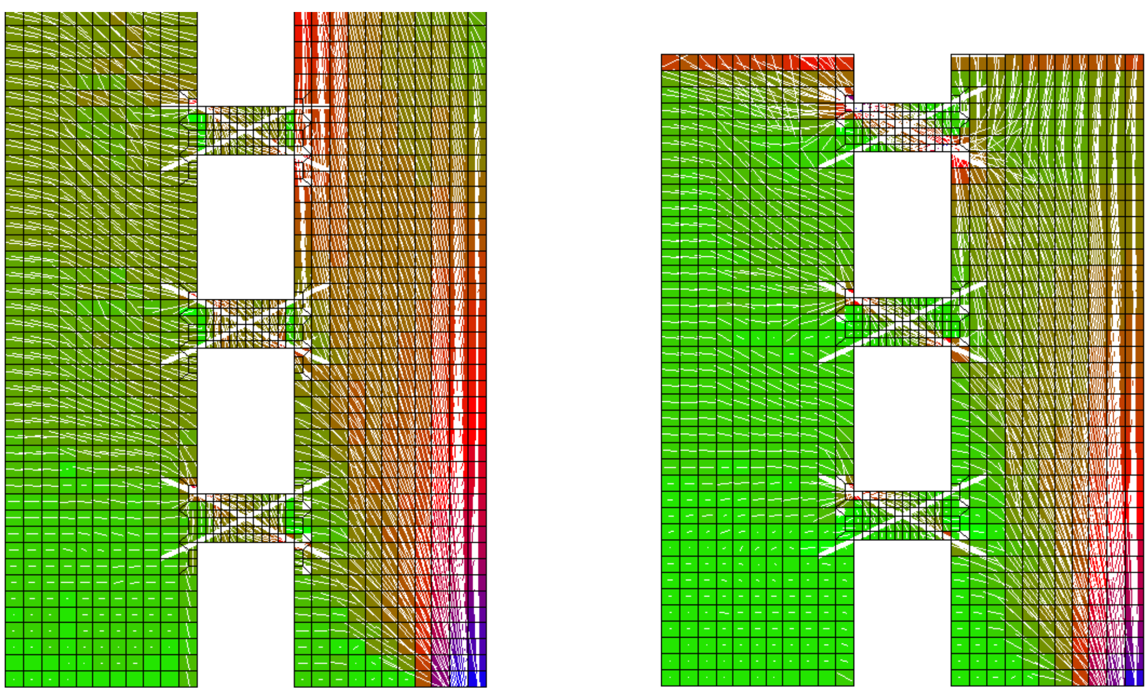

Figure 9. Principal compression stress trajectories for the prototype (left) and test specimen (right) finite element analyses at peak load level. Color gradients are not the same between models.

Role of Instrumentation in Coupled Wall Testing

With the loading protocol outlined above, the methods for enforcing the protocol during the actual specimen testing must next be devised. Whereas the planar wall tests were conducted with a single external displacement check, three string pots must be employed for each pier in the coupled wall system: one primarily aligned with the x-direction, and two offset from one another primarily aligned in the z-direction to measure rotation.

Due to space limitations, relatively short gauge lengths must be used for all string pots, with the consequence that motions in all DOFs result in changes in displacement readings. To work around this issue, Cartesian displacements must be obtained in a very similar manner as done in the Operation Manager. Knowing anchorage points, original gauge lengths, and current gauge lengths of all string pots, translations in the x- and z-directions and rotation about the y-axis can be calculated for each wall pier.

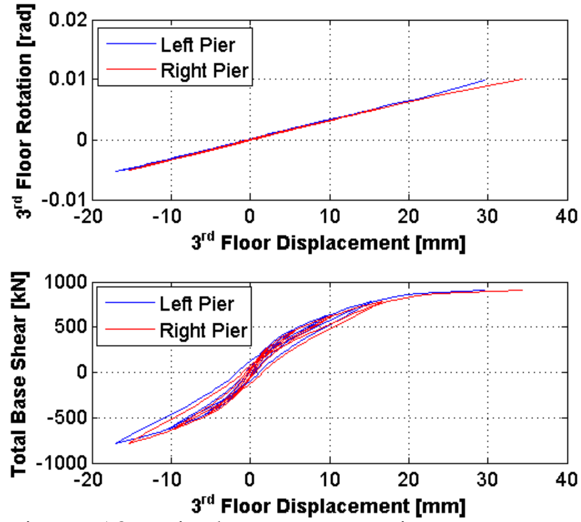

Figure 10. Displacement-rotation agreement and overall structural response.

The final role of instrumentation in the coupled wall testing will involve post-processing the data and checking that specimen deformations match with the anticipated deformations. To perform these checks, two sources of data will be particularly useful. First, high-resolution digital cameras record information about global deformation and cracking. The second tool, a non-contact coordinate measurement machine, allows for precise tracking of a uniform grid of targets on the lower two storeys of the structure. The data collected can be processed similarly to data obtained from FEA to show strain patterns within the wall system. The black dots in the left photo of Figure 11 are the measurement targets, and the right image depicts the state of axial strain at each Gauss point within quadrilateral elements.

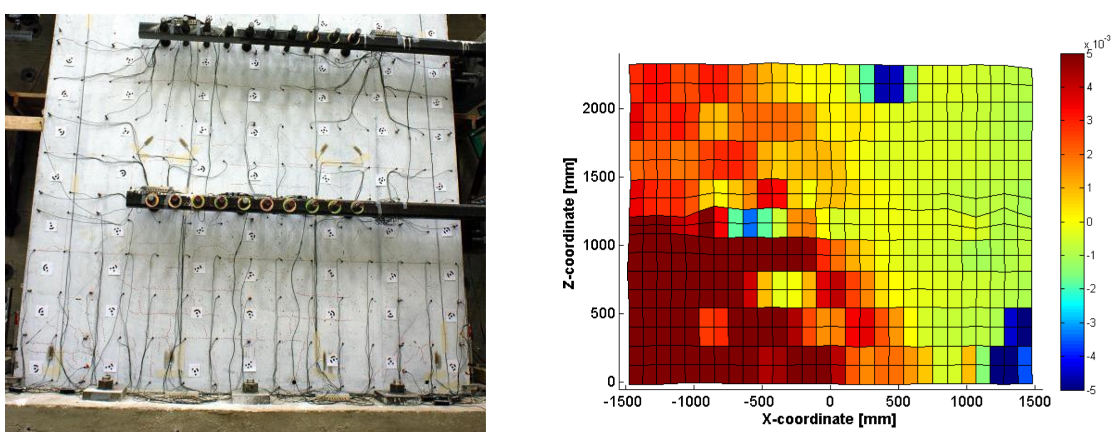

Figure 11. Arrangement of non-contact measurement targets on a wall specimen (left) and post-processed axial strain data at an advance load level for planar wall 4 (right).

Future Work

While the loading protocol is set for the coupled wall specimen, a complete system check-out must be performed before conducting the test, requiring use of the small-scale MUST-SIM facility. In the 1/5-scale facility, the Operation Manager, external Cartesian measurement system, and dedicated data acquisition unit will be coordinated with each other to load a rubber coupled wall system in a manner consistent with the large-scale test. Only after the small-scale test is conducted successfully can the researchers confidently test the concrete test specimen. After the coupled wall test, development of loading protocol for three C-shaped walls must next be completed. Finally, data from all wall tests will be used to either validate current concrete models or propose modifications to existing models.

Conclusions

The ability to conduct tests with multiple active degrees of freedom provides researchers with the means to apply more complex and realistic loads on test specimens. In order to perform such tests, though, one must be prepared to conduct detailed analyses ahead of time to fully develop a realistic loading protocol. Through the use of multiple finite element models, the ramifications of applying simplified loading constraints to a coupled reinforced concrete wall specimen were investigated. In the end, the loading decisions were deemed to provide simplicity in execution while strongly maintaining the character of the overall system behavior.

The quantity and quality of data obtained from the NEESR-SG wall tests will provide sufficient material for performing in-depth analyses on several aspects of structural response. This includes, but is not limited to, development of cracking and damage, strength degradation of reinforced concrete under cyclic loading, and the validity of the Modified Compression Field Theory and various constitutive concrete models on a realistically loaded system.

Acknowledgments

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References

Nakata, N., Spencer, B.F., and Elnashai, A.S., 2007. Multi-dimensional Mixed-mode Hybrid Simulation Control and Applications, *Report No. NSEL-005*, University of Illinois, Urbana-Champaign.

Wong, P.S. and Vecchio, F.J., 2002. *VecTor2 and FormWorks User's Manual*, University of Toronto, Toronto, Ontario.