IN-PLANE SHEAR STRENGTH OF MASONRY WALLS – A CLASS EXPERIMENT

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ABSTRACT

Many engineering classes have an extensive theoretical basis, but have little instruction on construction methods, particularly in courses on masonry and concrete. This paper presents experimental results of two reinforced masonry shear walls subjected to in-plane lateral loads and evaluates the ultimate strength compared to the US masonry code. A graduate student constructed, planned and tested the first wall, while the second wall was constructed, grouted, and tested during four masonry laboratory sessions with planning accomplished by the course instructor. While the cost to benefit ratio is high, the authors believe that hands-on experience of laying concrete masonry units (CMUs), grouting, and constructing material test specimens are invaluable to the education of civil, architectural or structural engineers.

KEYWORDS: in-plane, shear strength, experimental, CMU wall, educational

INTRODUCTION

Accurately predicting failure of partially and fully grouted shear walls is an important design task for today's engineers. Furthermore, shear walls are a common structural element which must resist lateral in-plane loads from earthquakes or wind. Two main failure modes for masonry shear walls are flexure and shear failure. Flexural failure happens when the reinforcing steel yields and ultimately ruptures. This ductile failure mode is preferable because yielding of the longitudinal reinforcement is an effective energy dissipation mechanism. In general, masonry walls are designed to fail in flexure. However, walls with a low aspect ratio (squat walls) tend to fail in shear. Shear failure occurs when the web of the wall undergoes shear cracking and then fails. This failure mode can occur in squat walls or walls with excessive flexural reinforcement. This is a brittle failure mode, and therefore is not preferred.

The primary goal of this project was to involve students in the strength testing of two reinforced masonry walls subjected to in-plane lateral loads. Both specimens were used as educational tools for students to observe the behaviour of masonry walls designed to fail in flexure. A secondary function of this testing was to examine the feasibility and educational value of this project as a requirement for an undergraduate masonry laboratory course. Specific goals were to:

- Encourage students to visualize in-plane versus out-of-plane behavior;
- Demonstrate the importance of reinforcement in masonry walls; and
- Quantify values of ductility that can be achieved by lightly reinforcing shear walls.

MATERIALS AND METHODS

Each wall was constructed of 200 mm (8 in.) nominal concrete masonry units. Specimen 1 was 7 courses tall with end cells grouted, while Specimen 2 was 6 courses tall and was fully grouted. Each course consisted of one full and one half CMU block laid in running bond. Both specimens were reinforced by 10-mm diameter (#3) reinforcing bars on both ends of the wall. Speed poles were bolted to the cast foundation to ensure the wall was plumb. A concrete cap was constructed to attach loading equipment. Figure 1 shows individual components of the specimens, instrumentation and a final constructed wall without the concrete cap.

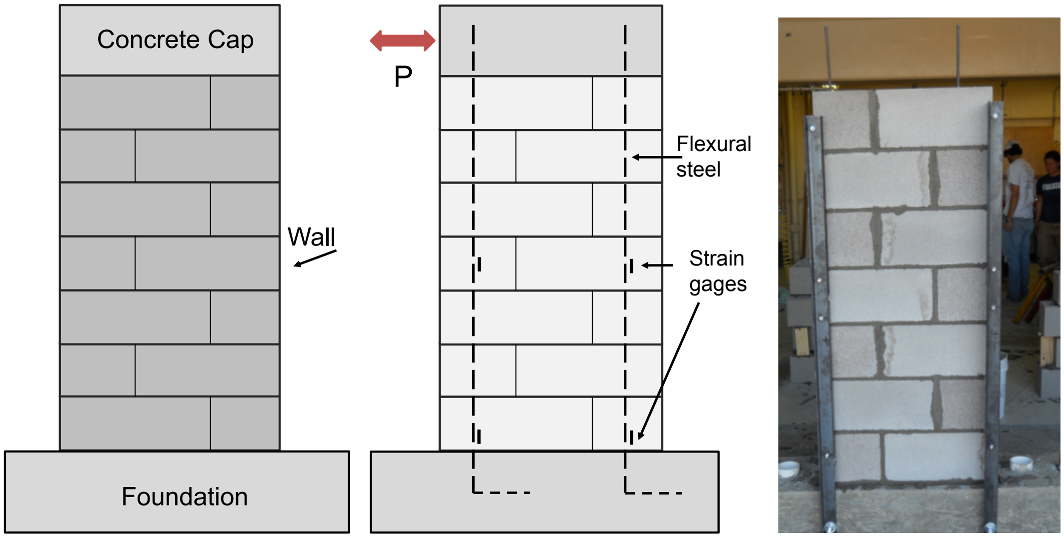

Figure 1: a) Specimen 2 illustration b) steel and strain gage placement and c) constructed wall

Specimens were tested in-plane under reversed cyclic load to illustrate the ductile behavior of walls with a large aspect ratio. Testing was videotaped to be used as an educational tool in future masonry classes. Design and construction were integral to the project. Construction cost, materials, and labor were evaluated to determine the feasibility of using a similar wall as a laboratory project. In the construction process, reuse of parts helped reduce the time and expense of building future specimens.

Table 1: Specimen details

	Height m (in.)	Thickness mm (in.)	Grouted cells
Specimen 1	1.5 (60)	190 (7.63)	Exterior two only
Specimen 2	1.3 (52)	190 (7.63)	All three cells grouted

The foundation was a 0.30 by 0.30 by 1.52 m (12x12x60 in.) concrete prism with an internally reinforced steel cage. Vertical PVC pipes served as post-tensioning ducts to clamp the specimen to the strong floor. Two large-diameter threaded rods were bolted to the strong floor to provide a fixed base. The average compressive strength of the foundation was 42 MPa (6 ksi).

The tested strength, f_m, of a block filled with grout was 22 MPa (3.2 ksi). Each wall had three strain gauges on each bar of reinforcing steel, with two at the base and one at mid-height of the specimen. The reinforcing steel yield strength was approximately 54 ksi (345 MPa) and a representative stress-strain diagram is shown in Figure 2. An additional three bars showed the same behavior because all of the bars were cast in the same heat.

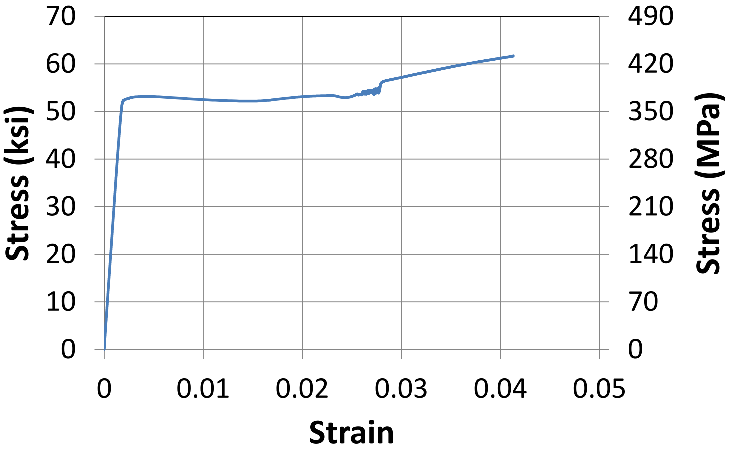

Figure 2: Stress-strain behavior of tested bar

The average tested compressive strength of the concrete cap was 31 MPa (4.5 ksi). Two channels were bolted to the sides of the concrete cap. A plate was welded to the front end of each channel and served to connect the ram to the specimen.

Figure **3**a) and b) show the ram connected to the specimen. The ram was mounted on a temporary strong wall. The ram has a 22 kN (5 kip) capacity and applied forced is measured by an internal load cell. Load was applied in a sinusoidal manner with a repetition of three cycles for every predetermined force or displacement. Initially the wall was loaded by programming predetermined levels of load. After yielding, target displacements were selected and three cycles were repeated at each level.

Axial load was limited to the self-weight of the wall. Because of the low axial load, sliding was prevented by placing steel plates between the wall and the vertical post-tensioning rods of the foundation, Figure 4. Future test specimens could use axial load to prevent sliding.

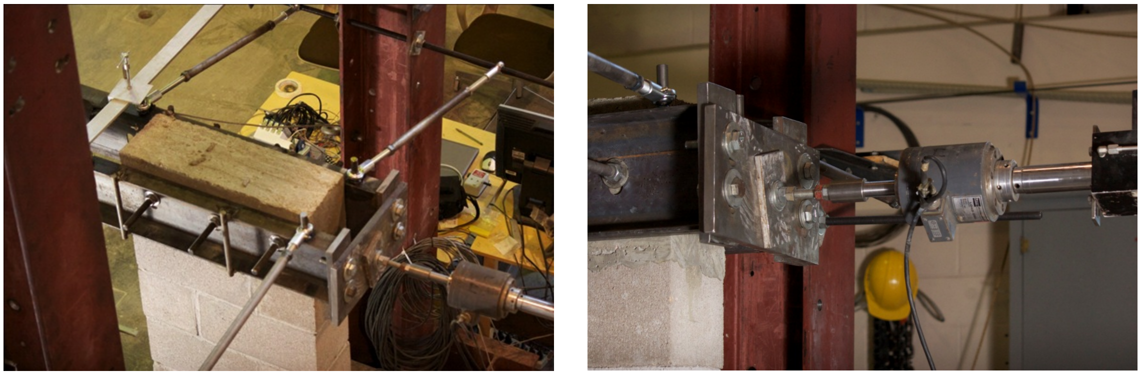

Figure 3: a) Loading channels and out-of-plane braces (view from top) b) ram connected to specimen

Figure 4: Plates to prevent sliding at base

Four measuring devices were used: a linear potentiometer (displacement); a load cell connected to the ram (force); an internal displacement sensor located within the ram; and six strain gauges applied to the reinforcing bars. The displacement potentiometer was clamped to a reaction frame and connected to an angle adhered to the concrete cap. This device measured the horizontal displacement at the top of the wall.

TEST RESULTS

Specimen 1 test results are shown in Figure 5. The force-displacement behavior has stable loops and is typical of a flexure dominated wall. Strain recording based on time indicate yielding after roughly 80 seconds of loading with increasing permanent strain beyond this point. Stable cycles of increasing displacement were applied until reaching roughly 25 mm (1 in.) in each direction. The experiment was halted when a diagonal crack formed at the base of the wall. Permanent vertical displacement at the base of the wall confirmed the inelastic behavior of the reinforcing bars.

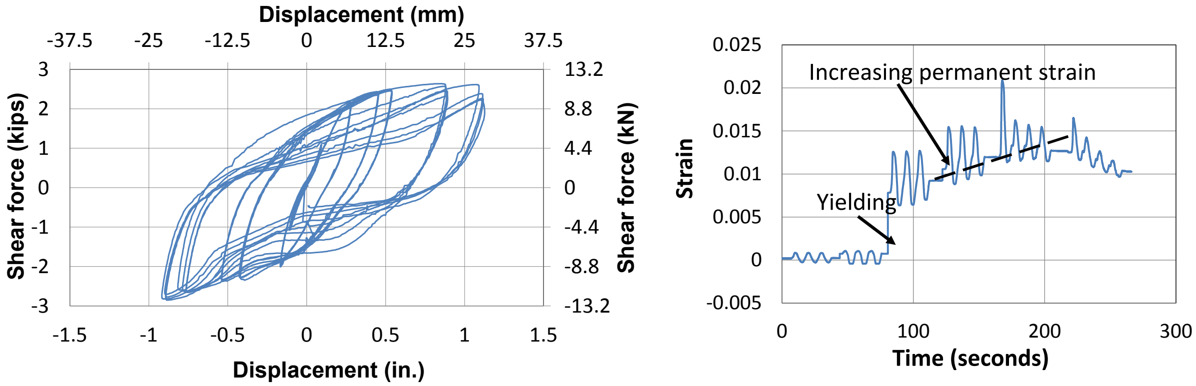

Figure 5: Specimen 1 test results a) force-displacement behavior b) recorded strain for positive force and displacement

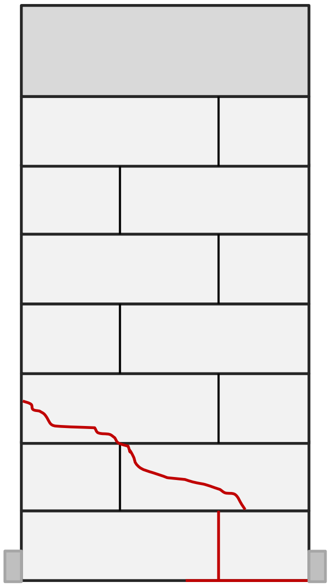

Figure 6: Cracking pattern of Specimen1 at end of the test

Predictions of the wall behavior based on the TMS 402 or masonry design code were evaluated for both flexure and shear. An interaction diagram for Specimen 1 is shown in **Figure 7**. As expected, the capacity as governed by flexure was slightly greater than the tested strength. Diagonal cracking occurred at the maximum load of 11.6 kN (2.6 kips). Although this load is well below the predicted shear capacity (V_{nm}=55kN=12.3 kips) of TMS 402, the crack was likely influenced by the steel plates used to restrain sliding. In hindsight, testing should have continued to determine the maximum drift and observe the cracking capacity while loading in the other direction. The drift of this wall was 0.02 or 2%.

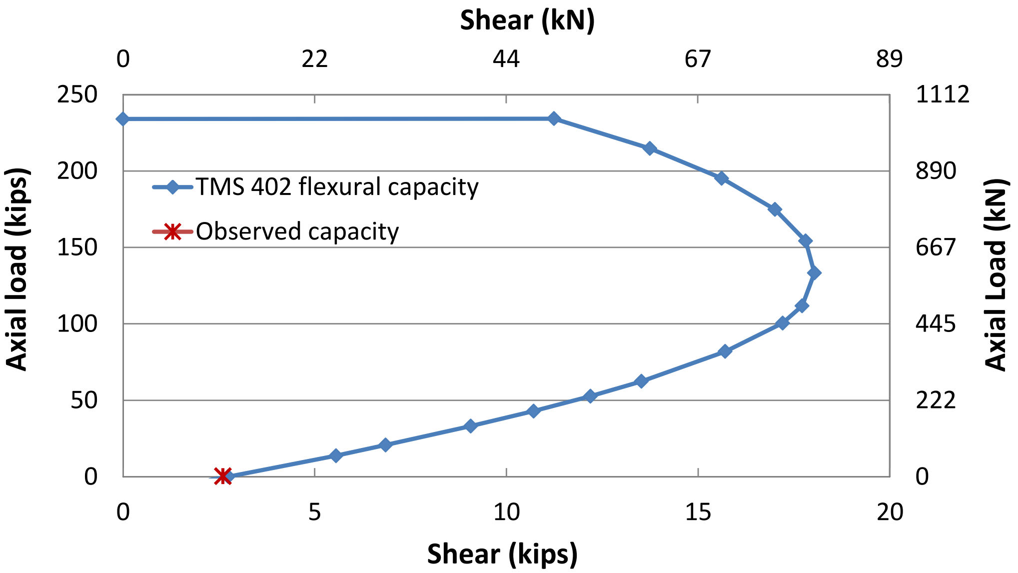

Figure 7: Interaction diagram of shear wall based on TMS 402 design provisions

Results from Specimen 2 are shown in Figure 8. Force-displacement results are primarily positive, or limited to the first quadrant of the graph. This is due to early yielding in the tensile steel to yield at the base of the wall at approximately 150 seconds. The flexural capacity determined in accordance with TMS 402 is shown by dashed red lines. Capacity above this limit is due to inadvertent slipping of the lateral braces. Despite those incidents, the wall reached a drift ratio of 4%. Measured strains at the base (purple) and mid-height (orange) of the wall. Between 150 and 200 seconds, strains at the base are roughly twice those at mid-height. As testing progressed strains at the mid-height of the wall reached yield at 200 seconds. Shortly thereafter, the base and mid-height strains were nearly equal, indicating a loss of bond between the grout and reinforcing bar. Although these observations are not intuitive to senior level students, many students understand the behavior when trends are pointed out during class. The test was halted when the linear potentiometer reached the end of its stroke at 2 inches.

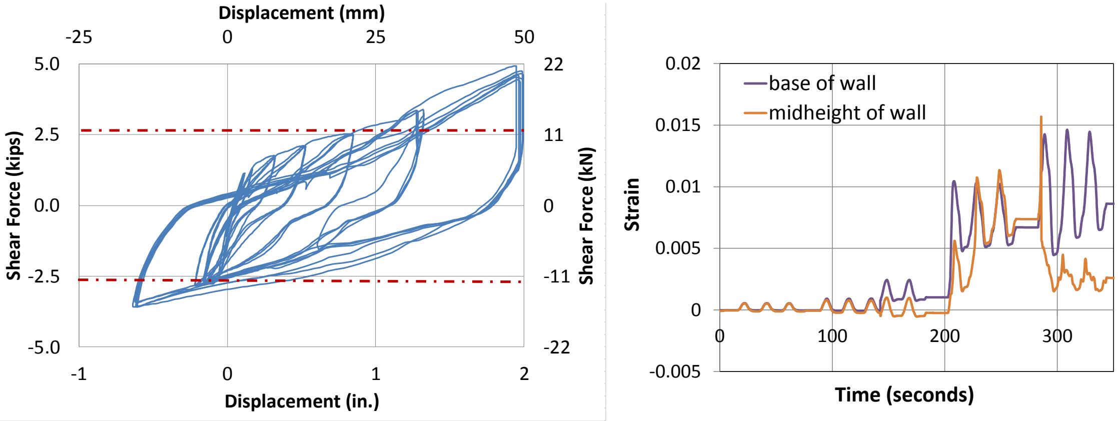

Figure 8: Specimen 2 test results a) force-displacement behavior b) recorded strain for positive force and displacement

Both walls exhibited an elastic initial phase followed by yielding of the reinforcement. As additional load cycles were applied, the wall continued to rock. The force-displacement behavior for both walls indicates stable loops. Permanent vertical displacement was observed in both walls. It was measured to be 8 mm (5/16 in.) at the end of Specimen 2.

FINITE ELEMENT ANALYSIS (FEA) MODEL

An analysis was done using ABAQUS to simulate the behaviour of the walls. Finite element modeling based on continuum mechanics generally follows two different methods: (1) smeared crack modeling and (2) damage plasticity modeling. In the smeared property modeling an average material properties are used to represent CMUs and mortar so that the masonry is treated as a homogeneous material. Vertical steel was modeled by smearing the appropriate tensile strength over the entire exterior grouted cell and material properties were based on experimental testing. Two main constitutive relationships are specified in damage plasticity modeling methods: an elastic stress-strain relationship until cracking and a gradually softening compressive stress-strain relationship until crushing. These two constitutive relationships have successfully been used in stimulating masonry wall behaviour [2], [3].

Material properties for the foundation and concrete cap were based on tested cylinder strengths. Specimen 1 is partially grouted and fully grouted prisms were constructed and tested. Figure 6a) shows fully grouted cells in red and ungrouted cells in blue. Compressive strengths in this FEA model 80% of the tested values. Un-grouted cells were modeled using a net thickness of 75mm (3 in) to account for the fact that the cells are hollow. Figure 9b) shows the principal tensile stresses in the wall as lateral loading pushes the wall to the right. A flexural crack formed on the tension side of the wall as shown in Figure 9c). Stresses in the reinforcing steel increased with increasing displacement.

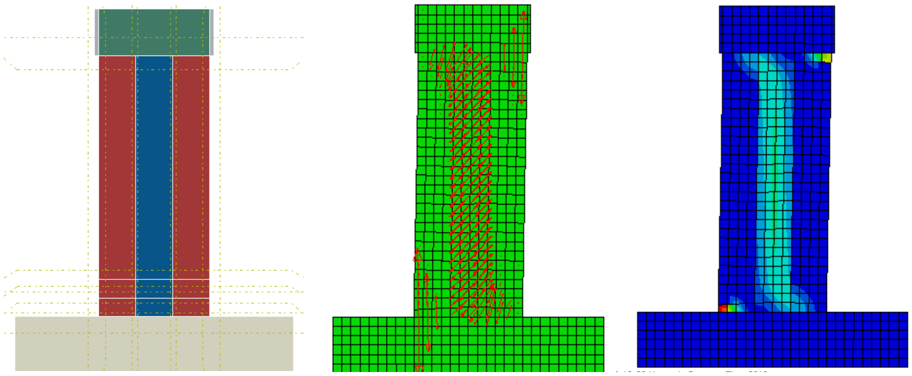

Figure 9: a) Smeared elements representing concrete cap, fully grouted cells and ungrouted cells b) tensile stresses in specimen c) stresses observed at flexural cracking

Figure 10 shows the force-displacement envelope resulting from the analytical model (dashed black) superimposed over the test data (blue). The finite element model agrees with experimental data in the elastic region of the graph. Although the FEA model did not capture the exact diagonal cracking pattern, the inelastic envelope is slightly higher than the experimental data and results generally agree. Future analytical work will consider including strain hardening in the steel, modeling reversed cyclic loading, and using a more discretized modeling approach.

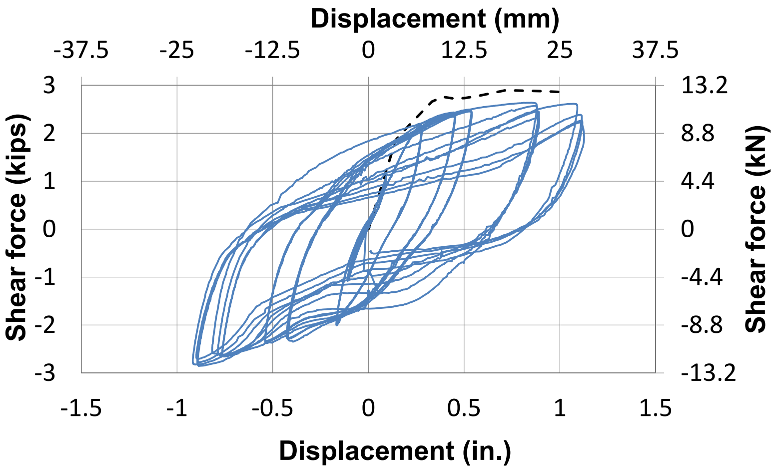

Figure 10: Specimen 1 force-displacement behavior including finite element model results

PROJECT COST AND EDUCATIONAL VALUE

Approximately $1500 in supplies and loading equipment was used to construct Specimen 1; an additional $3500 covered a graduate student summer stipend. Specimen 2 was constructed by the fall 2012 masonry class. After construction, the instructor and laboratory personnel spent another 12 hours, setting up the instrumentation, data acquisition system and performing validation testing. Specimen testing was conducted within a one hour laboratory period. If labor costs and technical support were included the cost of each experiment would be around $5000. The first time an experiment is completed the learning curve and cost are steep; repeating experiments becomes easier and more cost-effective. When deciding if physical experiments should be part of a class project, an instructor needs to consider all required resources such as supplies, construction expertise, laboratory space, equipment, safety and technical support. The authors believe that research and teaching exercises should remain separate. One reason is that working within constraints of laboratory time frames can cause inadvertent errors that would be difficult to justify and explain in a research report.

On the other hand, there are many rewards, tangible and intangible [4]. For this project, student learning was gauged by results of a three question survey. Overall, results were complimentary and selected student quotes are listed below:

- I enjoyed seeing the deformations and cracking as the load was being applied. It was a good visual for what we have been learning in class.
- I learned about the process of constructing a masonry wall as well as how to set up and test the wall.
- I learned how different components of masonry work together.

Student suggestions included the following comments:

- Have us build a lintel also, or a corner connection of two walls.
- Have us complete a report or homework analyzing the deflection data.
- Have us work in smaller groups so we can help with every part of construction and testing.

Despite the positive comments, a significant amount of time and technical support were required. Even with a small class size (11) students asked to participate more fully. Every course instructor should carefully evaluate how much effort one should spend on teaching versus research efforts. In future classes, the instructor will reduce the cost and effort by having students watch the test video and analyze the data. While this saves valuable departmental resources, future students will have a different educational experience than the fall 2012 class. A relevant homework assignment would be to calculate the interaction diagram of either shear wall specimen. Undoubtedly the partially grouted wall will be a more difficult assignment. An additional class project or demonstration could include modeling the wall using commercial software such as SAP 2000 or other finite element software. Such work would fit well within the scope of a graduate level masonry or earthquake engineering course. When more detailed analyses become a regular part of structural design, students capable of performing such analyses will have a competitive edge over their colleagues.

CONCLUSIONS AND FUTURE WORK

Participating in laboratory experiments and other hands-on learning projects naturally affords student opportunities beyond the traditional lecture setting. Efforts to test both walls were weighed against student learning and the authors believe the experience was valuable to the fall 2012 masonry class. In future classes, the author will use data and well synthesized video to convey the behavior of flexure dominated walls. Future modeling should include reversed cyclic loading as opposed to monotonic behavior, as well as a more exact approach to modeling the wall behavior.

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