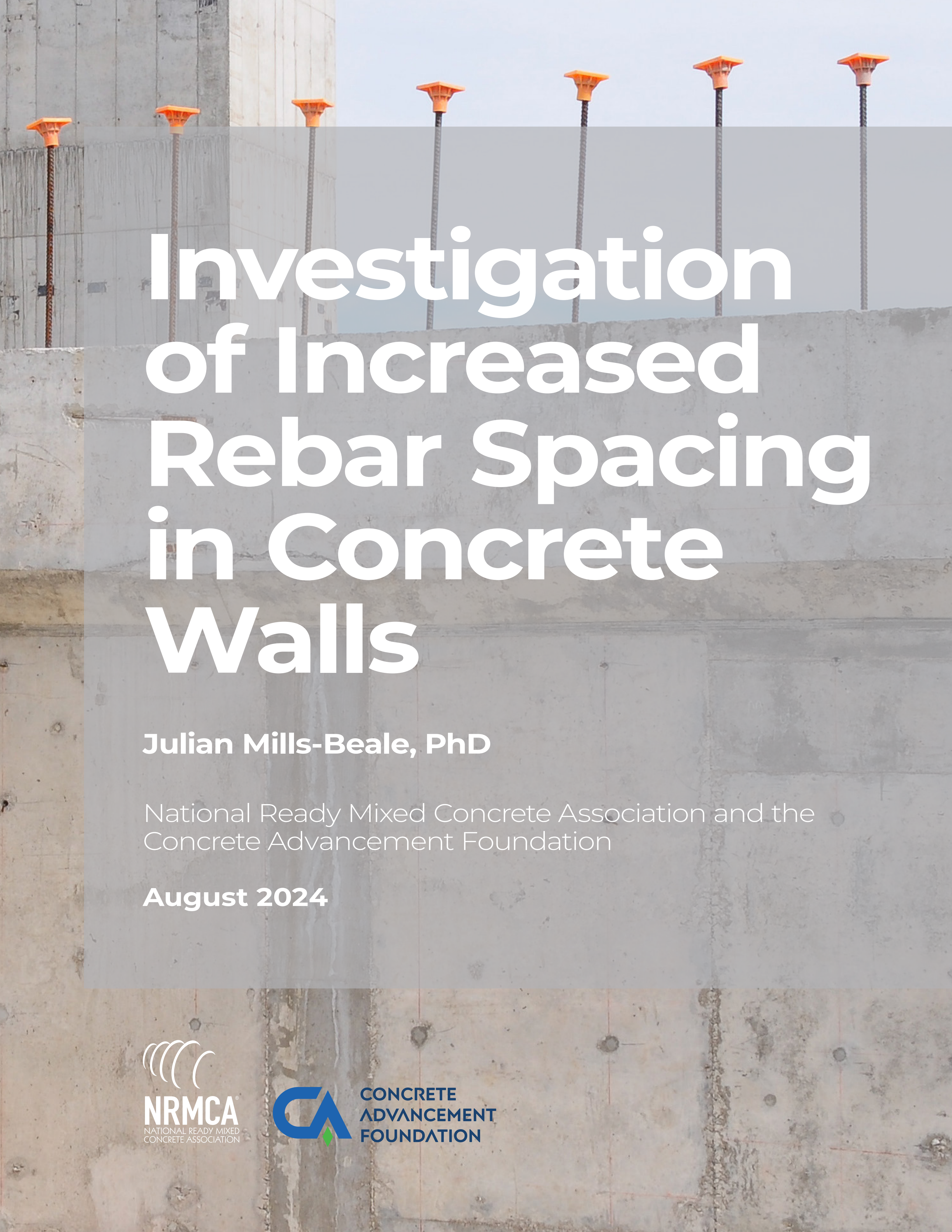

Investigation of Increased Rebar Spacing in Concrete Walls

Julian Mills-Beale, PhD

National Ready Mixed Concrete Association and the
Concrete Advancement Foundation

August 2024

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Acknowledgment

This research study was spearheaded and jointly funded by the National Ready Mixed Concrete Association (NRMCA). Founded in 1930, the National Ready Mixed Concrete Association is the leading industry advocate. Our mission is to provide exceptional value for our members by responsibly representing and serving the entire ready mixed concrete industry through leadership, promotion, education and partnering to ensure ready mixed concrete is the building material of choice.

Co-funding for the project was provided by the Concrete Advancement Foundation. The Concrete Advancement Foundation is a 501(c)3 non-profit organization dedicated to decarbonization of the concrete industry, as well as advancing resilient, affordable communities and sustainable infrastructure.

NRMCA posthumously acknowledges the contributions of Dr. Scott Campbell, under whose dedication and expertise this project was initiated.

Limitations

Proper application of this study requires recognition and understanding of the limitations of both the scope and methodology of the entire study. The analyses, discussions and conclusions about this study are based on the limited laboratory testing and the accompanying results. Therefore, while results may be presented in precise terms, precision does not imply accuracy beyond the limitations and uncertainties inherent in the assumptions and analysis methodologies. Results should not be considered a guarantee of relative performance between the walls and their associated reinforcement configurations considered.

Disclaimer

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Executive Summary

The objective of this study was to investigate optimization of rebar area and spacing in reinforced concrete walls, including ICF walls commonly used in low- and mid-rise construction. Formed using modular insulating units that are left in place after the concrete cures, ICFs provide substantially higher insulation and energy efficiency. When designing in regions of low and moderate seismicity, the out-of-plane loading case controls the design instead of the in-plane loading scenario. ACI 318-19 provides the requirements for minimum reinforcement ratio or maximum allowable bar spacing. For cast-in-place walls, the spacing, *s,* of both longitudinal and transverse reinforcement is required not to exceed the lesser of $3h$ and 18 in. In design cases where shear reinforcement is needed for in-plane strength, spacing of longitudinal and transverse bars shall not exceed $l_w/3$ and $l_w/5$, respectively, where l_w is the length of the entire wall segment.

In many scenarios, concrete walls in low- to mid-rise structures are designed and constructed using only the minimum specified reinforcement ratio. The use of such minimum specified reinforcement ratio (increased bar spacing) could lead to more sustainable and economic designs. However, any proposed change to the standard will require engineering justification to show that the change is not detrimental to the performance of the walls.

ACI 318 does permit designing walls as unreinforced walls per chapter 11 which would permit the use of reinforcing steel below the required minimum area and spacing of reinforced concrete walls. Specifically, ACI 318-19 Section 11.6.1 states that “the limits (ratios of area of distributed longitudinal or transverse reinforcement to gross concrete area) need not be satisfied if adequate strength and stability can be demonstrated by structural analysis. Furthermore, there are limitations including maximum height of wall and limited to one story.

It is believed that it is possible for walls to meet performance expectations if larger steel bars are used at greater spacing in lieu of smaller steel bars at lower spacing. In other words, maintaining the minimum area but increasing spacing. For example, could a minimum requirement of #4 @ 18 be substituted with #5 @ 24 or 30? Or could the same minimum requirement of #4 @ 18 be substituted with #6 at 36 or 48?

Prior to this project, collaborative research between the National Ready Mixed Concrete Association (NRMCA) and the University of Washington in Seattle was conducted on the influence of reinforcement spacing and fiber reinforcement on the out-of-plane response of concrete walls using nonlinear finite element modelling. Significant among the outcomes was the fact that for lightly reinforced concrete walls subjected to out-of-plane loading, strength is controlled by concrete cracking and is not dependent on reinforcement ratio or spacing. Furthermore, the results provided the basis for defining the project methodology, scope, detailed schedule, and anticipated deliverables for this laboratory research program.

This project seeks to investigate the possibility of utilizing longitudinal or transverse reinforcement spacing exceeding the ACI 318 maximum requirement of 18 inches and using area lower than the minimum reinforcing ratio as required by ACI 318 for reinforced concrete walls. Specifically, the reinforcement spacing was extended through to a maximum of 48 inches while holding the bar size the same meaning the area of steel is below the minimum. Some unique wall specimens were also designed with either only longitudinal reinforcement or only transverse reinforcement.

Smith-Emery Laboratories, an independent commercial testing laboratory based in Los Angeles, California, was subsequently consulted to conduct the laboratory research investigations which focused on the physical testing and microstructural analysis of concrete specimen walls. Their research plan was categorized into two distinct subtasks: 1) design, fabrication, compressive load testing and analysis of four (4) concrete wall specimens; 2) design, fabrication, flexural load testing and analysis of four (4) concrete wall specimens.

The final experimental testing program involved the application of a horizontal load at the rate of 0.5 in. per minute until it reaches 6 in. of displacement from the initial loading point. Loading to failure conditions also considered the safety situation and behavior of the specimen. The compressive specimens were 12.5 ft long, 10.0 ft high and 0.5 ft thick while the flexural specimens were 10.0 ft long, 6 ft or 8.5 ft high, and 0.5 ft thick. Testing was performed on each specimen once the compressive strength of the concrete reached 4,000 psi or more. As expected, the failure generally occurred inside the middle third of the span for all the flexural specimens.

Based on the results from this research, the use of greater steel sizes (to replace relatively smaller steel sizes) combined with increased bar spacing such that the minimum area of steel remains unchanged or below the minimum, cannot be concluded or validated. Thus, further experimental research is necessary to investigate if increasing spacing while still meeting the minimum steel requirement or otherwise is justified.

Introduction

Reinforced concrete walls are often utilized for low- to mid-rise construction due to their strength, stiffness, and durability properties. The objective of this research is to investigate optimized levels of reinforcement in reinforced concrete walls, including ICF walls commonly used in low- and mid-rise construction.

ICFs are a type of reinforced concrete walls that combine reinforced concrete for strength and durability and expanded polystyrene (EPS) insulation for energy efficiency. ICF walls are composed of two layers of rigid insulation materials held together with plastic ties to form ICF units with a cavity in the center. These units are stacked in the shape of the wall, reinforcing steel is added into the form cavity, and then concrete is placed into the form. The result is a reinforced concrete wall with a layer of insulation on each side. ICFs differ from traditional concrete construction in that the forms remain in place after the concrete is cured to provide thermal insulation. The combination of reinforced concrete and insulation provides an ideal loadbearing wall, thermal envelope, fire barrier, and sound barrier.

Modern building construction demands that innovative techniques, codes and standards be pursued towards sustainability and economical optimization. One such optimization is the reduction of reinforcement requirement for concrete walls.

ACI defines plain concrete as structural concrete without any reinforcement or with less than the minimum amount required by ACI 318 for reinforced concrete. Contrarily, reinforced concrete encompasses a combination of adequate reinforcement (usually steel bars with raised lugs called deformations) and concrete designed to work together to resist applied loads.

For concrete walls in locations of low and moderate seismicity, out-of-plane rather than in-plane loading dictates the load case, and reinforcement is usually determined by the American Concrete Institute's (ACI) 318-19 Code requirements for minimum reinforcement ratio and maximum allowable bar spacing [ACI 318-19]. Typically, it is required to design longitudinal or transverse spacing, s, not to exceed the lesser of three times the wall height and 18 inches. Some researchers have shown that acceptable performance can be achieved with reduced reinforcement ratio and increased reinforcement spacing (de Sevilla et al., 2019). This is in slight variance with ACI 318-19 Code requirements for low- and mid-rise walls, known to be more stringent.

With this study, the purpose is to explore the feasibility or otherwise of designing reinforced concrete below the ACI 318 minimum required area while satisfying the expected structural and functional performance requirements. The research is based on prior computer-simulated modeling of the performance of concrete wall specimens.

Categorization of Experimental Research Program

The research program was sectioned into two sub-categories:

1. Compressive Test Research Program
2. Flexural Test Research Program

Proposed mixes for the project were proportioned in accordance with applicable sections of ACI 211, Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete. The mixes were designed to meet a 28-day design compressive strength of 4,000 psi and a slump of 4.0 in. All specimens were prepared and cured according to the American Society for Testing and Material's (ASTM) Standard Practice for Making and Curing Concrete Test Specimens in the Field (ASTM Standard C31/C31M-22, 2023). The prepared cylinders were then tested using ASTM's Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C39/C39M-21, 2021).

All strength test reporting followed ACI's Guide to Evaluation of Strength Test Results of Concrete (ACI 214R-11, 2011).

According to the ACI specification, the reported strength test result was "the average of two or more single-cylinder strengths of specimens made from the same concrete sample (companion cylinders) and tested at the same age". Upon completion of the overall experimental program, the concrete was removed and planned for reuse according to ACI's Removal and Reuse of Hardened Concrete (ACI PRC-555-01, 2002).

A summary of the concrete mix parameters is provided in Appendix A - Appendix A.1 and A.2.

Compressive Test Research Program

Research Methodology

Smith-Emery Laboratories, in consultation with NRMCA, defined the following scope for the compressive test experimental research program:

- Provision of a suitable test frame to accommodate specimen for the required tests.
- Fabrication of four (4) test specimens measuring 12.5 ft. long, 10 ft. high and 0.5 ft. thick with various rebar configuration each.
- Installation of instrumentation devices such as strain gauges and string pots.

- Provision of test setup to accommodate the required tests.
- Measuring of the applied load and deflection performance of each specimen once the strength of concrete reached 4,000 psi.
- Safe demolition and disposal of tested specimen according to ACI's Standard Specification for Removal and Reuse of Hardened Concrete (ACI PRC-555-01, 2002).

Specimen Description

Four (4) concrete specimens measuring 12.5 ft. long, 10.0 ft. high and 0.5 ft. thick were molded using 4,00 psi concrete mix and #4 Grade 60 reinforcing bars.

Specimen No. 1 consists of vertical and horizontal bars @ 16 in. OC. Eight (8) strain gauges were installed on the vertical bars and six (6) on the horizontal bars. Additionally, a deflection monitoring device was installed on the face of the concrete. Figure 1 shows a sketch of the configuration of the compressive specimen No. 1.

Specimen No. 2 consists of vertical bars @ 48 in. OC and horizontal bars @ 16 in. OC. Similar to Specimen No. 1, eight (8) strain gauges were installed on the vertical bars and six (6) on the horizontal bars. Deflection monitoring devices were installed on the face of the concrete. Figure 2 shows a sketch of the configuration of the compressive specimen No. 2.

Specimen No. 3 consists of vertical bars @ 48 in. OC with no horizontal bar. Twelve (12) strain gauges were installed on the vertical bars only, with no horizontal bar. Deflection monitoring devices were installed on the face of the concrete. Figure 3 shows a sketch of the configuration of the compressive specimen No. 3.

Specimen No. 4 consists of horizontal bars @ 16 in. OC, no vertical bar. Installed nine (9) strain gauges on horizontal bars, no vertical bar. Deflection monitoring devices were installed on the face of the concrete. Figure 4 shows the configuration of the compressive specimen No. 4.

Figures 5 (a) and 5 (b) shows the completed reinforcement configuration in the field and the resultant cast concrete wall. The top support, strain gauge, chair and lifting anchor type used are shown in Appendix B.1. In Appendix B.2, figures showing Specimen No. 3 before and after the concrete has been poured is presented.

Test Set Up

A schematic of the compressive test set-up is provided in Figure 6 with the actual field compressive specimen tilted and ready for testing shown in Figure 7. A 100-ton double action hydraulic ram load application equipment controlled by a toggle hydraulic bi-directional valve system was utilized for testing. The load application equipment was also connected to a 30-gallon hydraulic power unit. The load progression and measurement were monitored using a 100-Kips load cell. The data acquisition system had deflection (using spring pot) and strain monitoring capabilities.

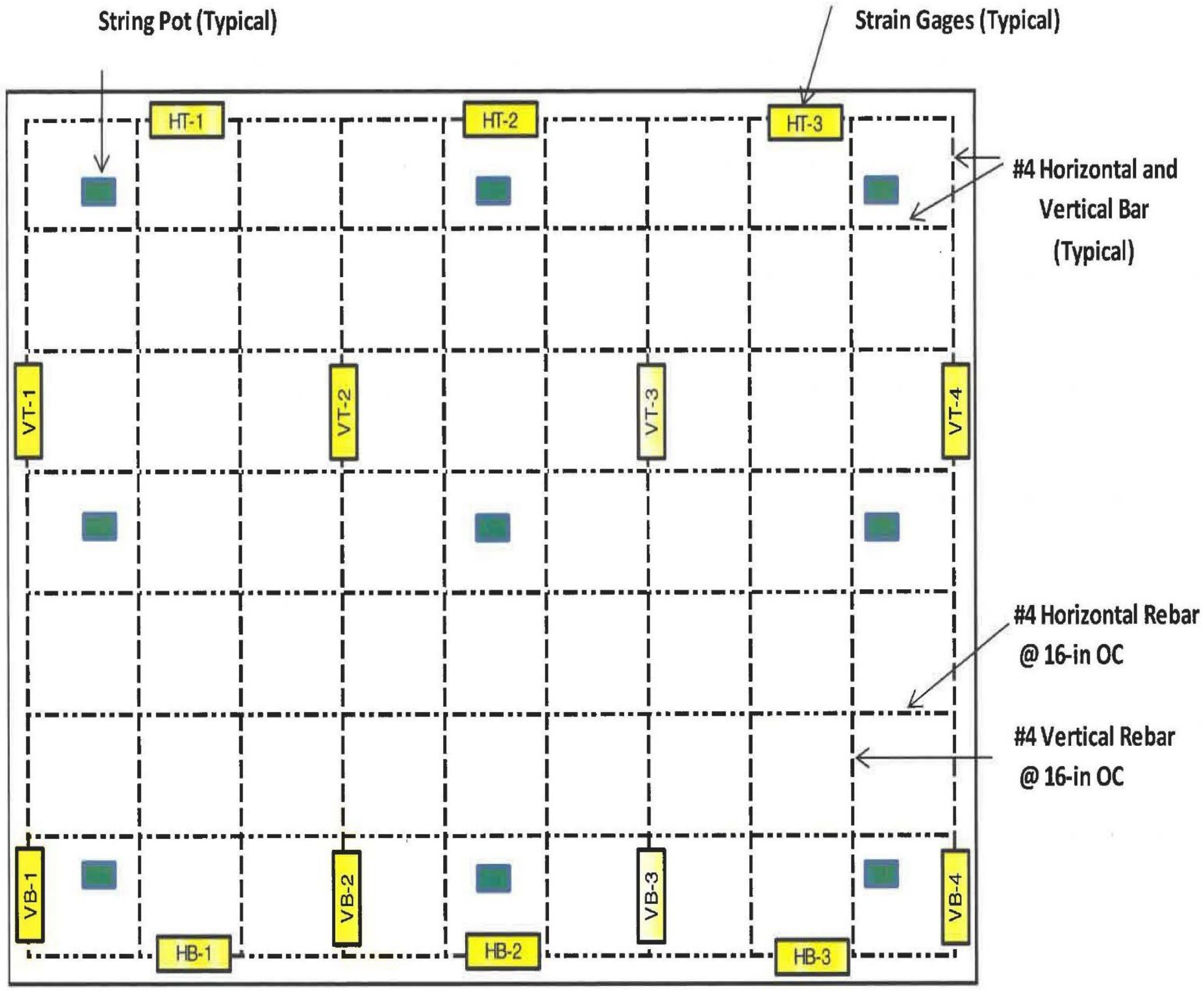


Figure 1. Configuration of Compression Specimen No. 1

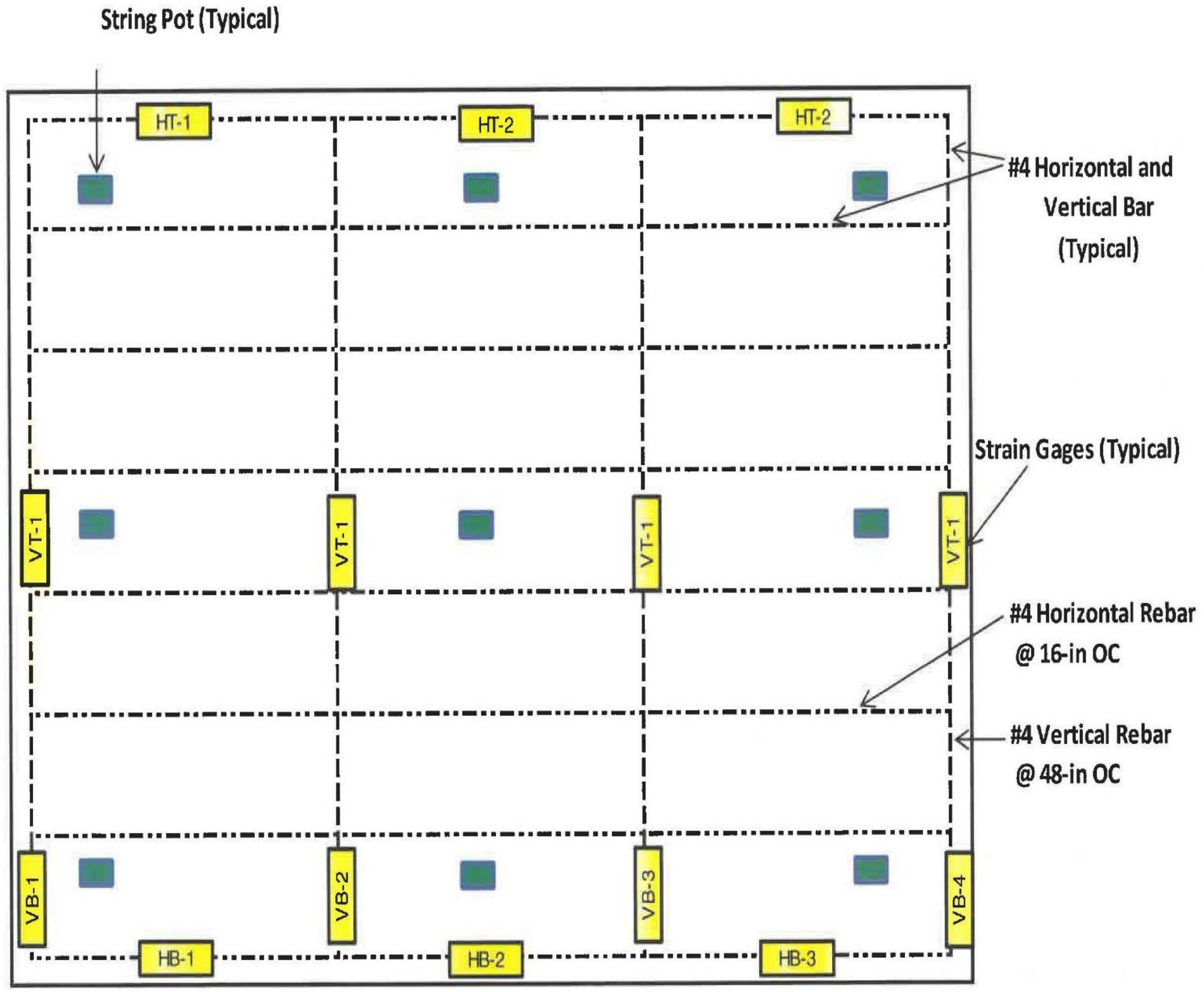


Figure 2. Configuration of Compression Specimen No. 2

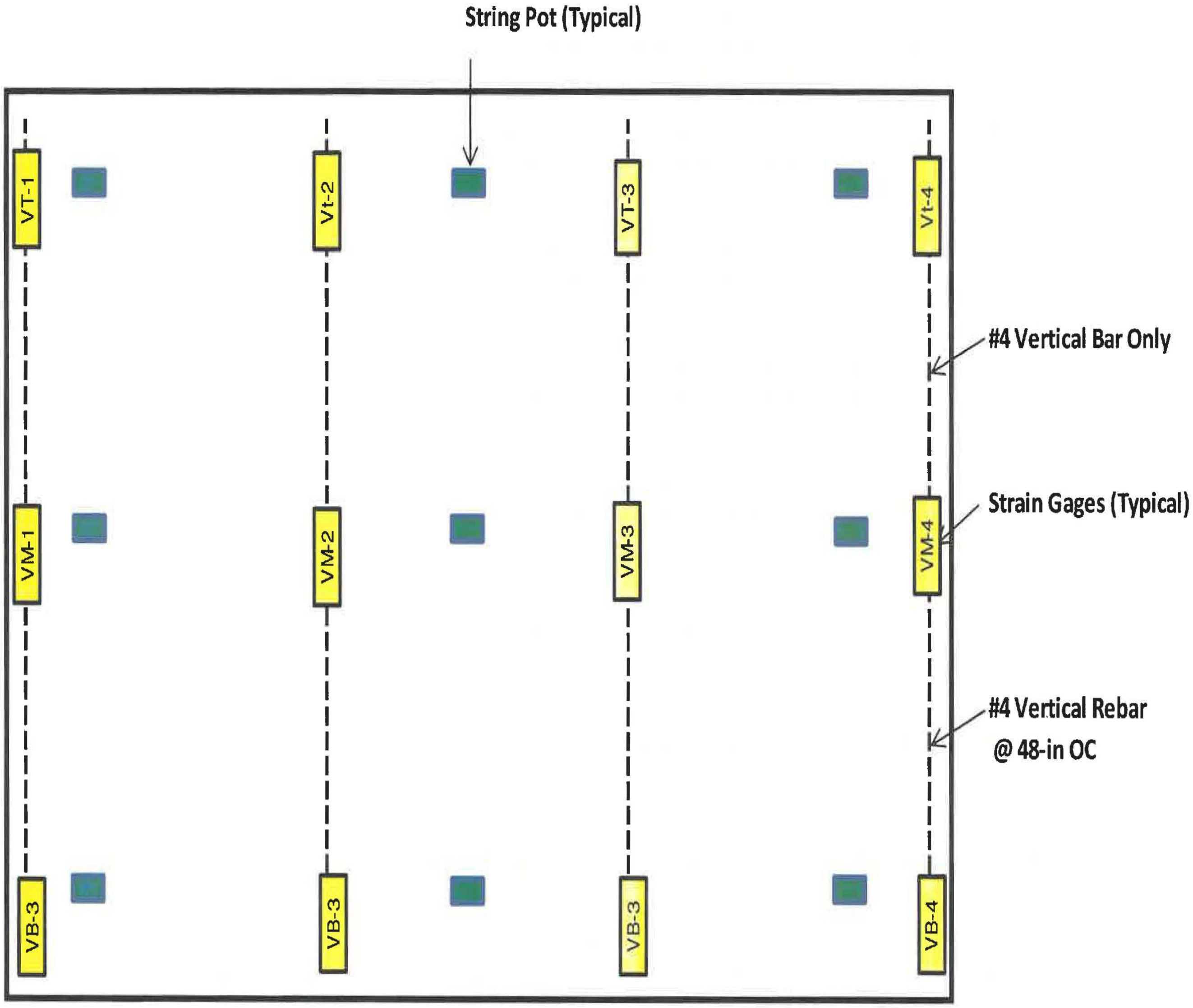


Figure 3. Configuration of Compression Specimen No. 3

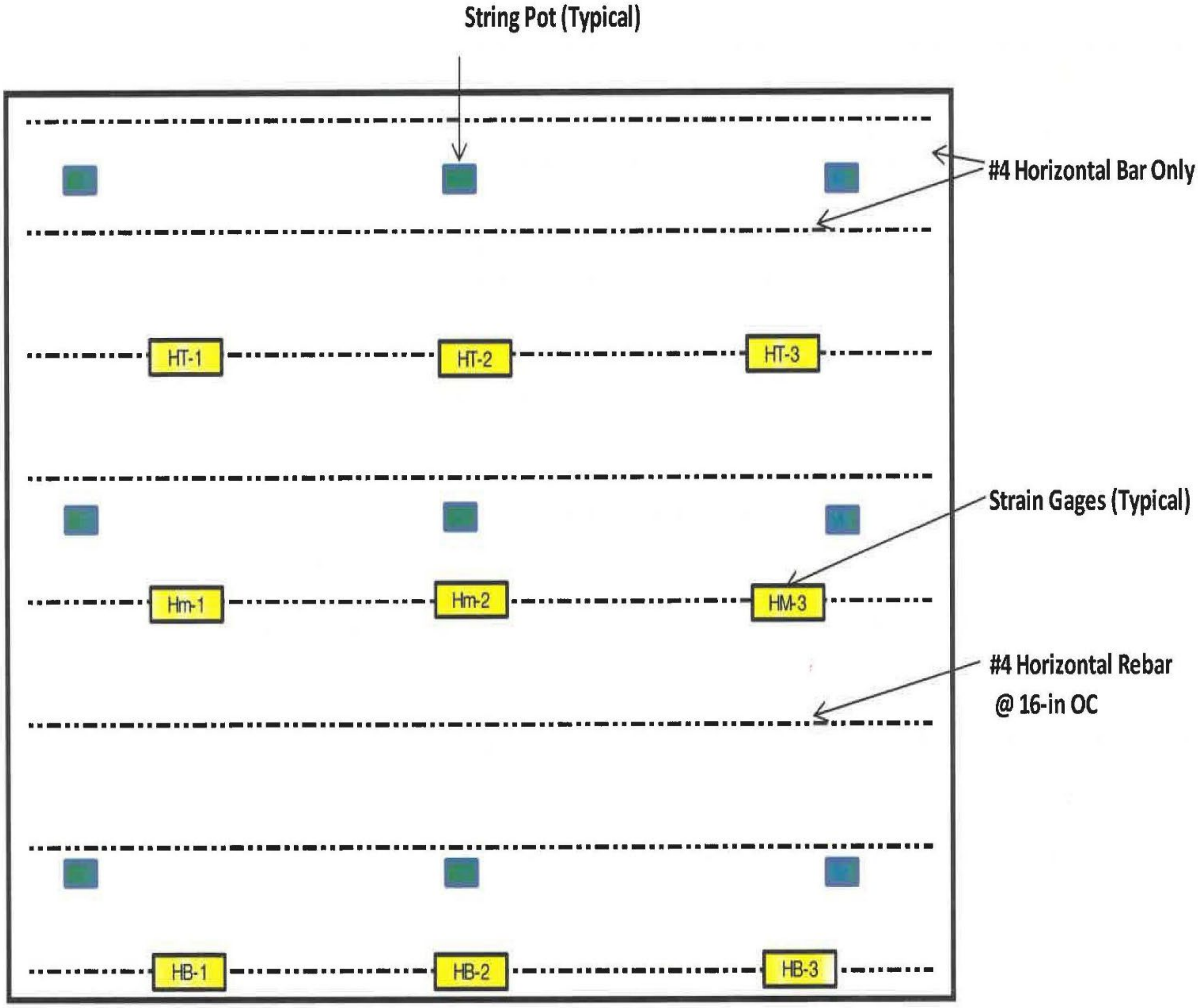


Figure 4. Configuration of Compression Specimen No. 4

a) Reinforcement placement and setup

b) Cast reinforced concrete wall

Figure 5. (a) Reinforcement placement set-up and (b) cast reinforced concrete wall

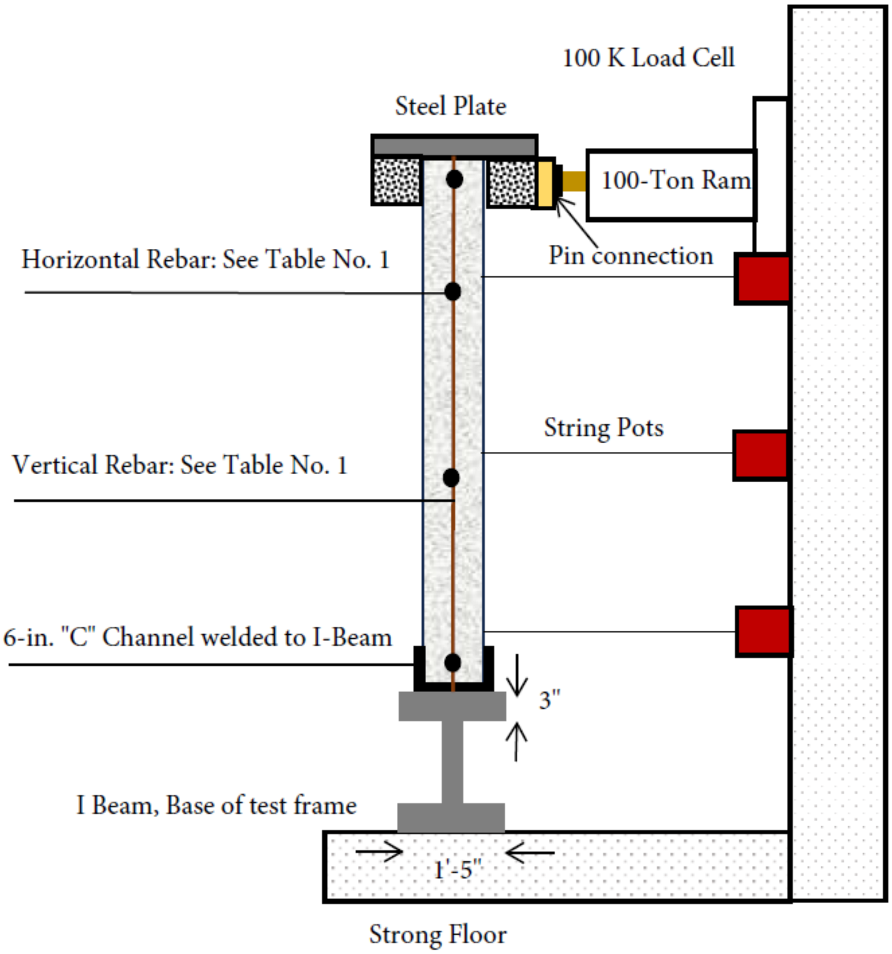


Figure 6. Schematic of the compressive test set up

Table 1. Compressive Test Specimen Reinforcement

Specimen (Wall No.)	Vertical Steel (@ OC)	Specimen Vertical Steel Area Ratio	Code Minimum Vertical Steel Area Ratio	Horizontal Steel (@ OC)	Specimen Horizontal Steel Area Ratio	Code Minimum Horizontal Steel Area Ratio
1	#4 @ 16-in.	0.0001	0.0012	#4 @ 16-in.	0.0022	0.002
2	#4 @ 48-in.	0.00005	0.0012	#4 @ 16-in.	0.0011	0.002
3	#4 @ 48-in.	0.00005	0.0012	None	0.0011	0.002
4	None	-	0.0012	#4 @ 16-in.	-	0.002

Load Application Rate

The specimens were tested when the applied horizontal load at the rate of 0.5 in. per minute reached a maximum loading displacement of 6 in. from the original position. Specimens were loaded up to failure taking into consideration the safe handling and performance behavior of each specimen. Furthermore, testing was performed in accordance with generally accepted engineering principles and practices.

Compressive Test Findings

The specimens were tested by applying a horizontal load at a rate of 0.5 in. per minute until a displacement of 6 in. from the original load position was attained. A summary of the maximum compressive loads and the resultant deflections at the top of the wall specimen is provided in Table 2. For all the four specimens tested, the general mode of failure occurred on the bottom (base) connection to the steel "C" channel as shown in Figure 8. Furthermore, any cracks and breaks location were only found on the bottom section. No identifiable structural cracks occurred on other parts of the wall. Figure 9 shows the general deflection performance when the maximum compressive load was attained for all the compressive test specimens tested. The detailed load versus average displacement performance plots for the individual compressive specimens is provided in Appendix D - Appendix D.1 through Appendix D.4

Figure 7. One of the compressive specimens tilted for testing

Table 2. Summary of compressive test's top deflection performance

Specimen (Wall No.)	Maximum Compressive Load (lbs.)	Top Deflection (in.)
1	5,300	3.179
2	1,710	2.614
3	1,407	5.777
4	595	0.628

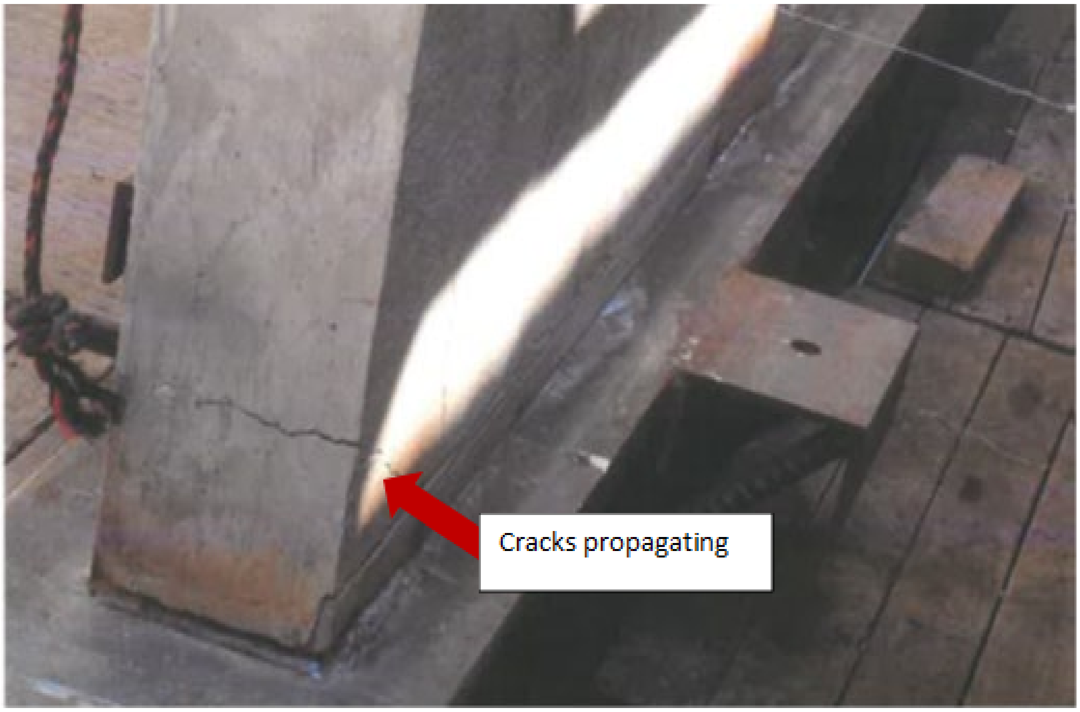


Figure 8. Typical compressive test failure mode at the base of steel connection

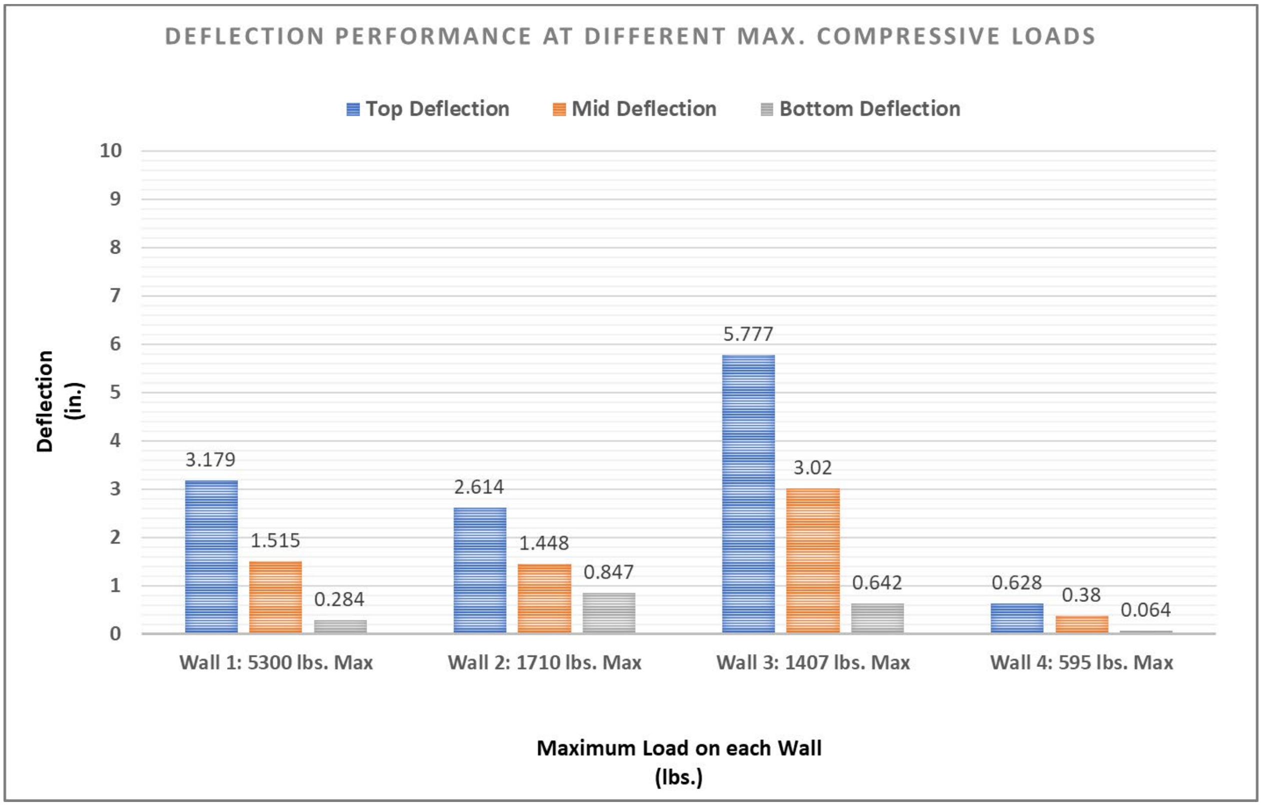


Figure 9. Graphical plot of the deflection performance due to compression loading

Flexural Testing Research Program

Research Methodology

The scope for the flexural test experimental research program comprised:

- Provision of a suitable test frame to accommodate specimen for the required flexural 3rd point loading.
- Fabrication of four (4) test specimens each measuring 10.0 ft. long, 6 and 8.5 ft. high and 0.5 ft. thick. Each specimen had a different rebar configuration.
- Installation of instrumentation devices such as strain gauges and string pots.
- Provision of test apparatus to accommodate the required tests.
- Testing of each specimen was conducted once the strength of concrete reached 4,000 psi.
- The maximum load applied, and its resultant deflection were recorded for each specimen.
- Safe demolition and disposal of tested specimen according to ACI’s Standard Specification for the Removal and Reuse of Hardened Concrete (ACI PRC-555-01, 2002).

Specimen Description

A total of four (4) concrete specimens each measuring 10.0 ft. long, 6.0 or 8.5 ft. high and 0.5 ft. thick were molded using 4,000 psi concrete mix and #4 Grade 60 reinforcing bars.

Specimen No. 1 measuring 10.0 ft. long, 6.0 ft. high and 0.5 ft. consisted of vertical bars @ 16 in. OC and horizontal bars @ 16 in. OC. Three (3) strain gauges were installed on the vertical bars and three (3) on the horizontal bars. Three (3) deflection monitoring devices were installed on the face of the concrete. See attached sketch of Flexural Wall Specimen No. 1 in Figure 10.

Specimen No. 2 measuring 10.0 ft. long, 8.5 ft. high and 0.5 ft. thick consisted of vertical bars @ 48 in. OC and horizontal bars @ 16 in. OC. Three deflection monitoring devices were installed on the face of the concrete. See attached sketch Flexural Wall Specimen No. 2 in Figure 11.

Specimen No. 3 measuring 10.0 ft. long, 6.0 ft. high and 0.5 ft. thick consists of horizontal bars @ 16 in. OC with no vertical bars. Three (3) strain gauges were installed on the horizontal bars only. Three (3) deflection monitoring devices were installed on the face of the concrete. See attached sketch Flexural Wall Specimen No. 3 in Figure 12.

Specimen No. 4 measuring 10.0 ft. long, 8.5 ft. high and 0.5 ft. thick consists of vertical bars @ 48 in. OC with no horizontal bars. Three (3) installed strain gauges were installed on vertical bars only. Three (3) deflection monitoring devices were installed on the face of the concrete. See attached sketch Flexural Wall Specimen No. 3 in Figure 13.

A summarized description of all four (4) test specimen for the flexural research program is provided in Table 3 while the configurations are also shown in Figures 10 through 13.

Test Set Up

The general set-up for the flexural laboratory test program is shown in Figure 14. The equipment used were a 40-ton double action hydraulic ram, controlled by a toggle hydraulic bi-directional valve system, connected to a 30-gallon hydraulic power unit. The load was monitored using a 50-Kips load cell. Finally, a data acquisition system comprising a deflection monitoring (using Spring Pot) and strain gauges units was used. In Appendix C.1, a figure of the flexural Specimen No. 1 before and after pouring concrete is shown. Additionally, Appendix C.2 is provided to show the flexural test set up with the strain gauge arrangements, in the loading position.

Table 3. Flexural Test Specimen Reinforcement

Specimen (Wall No.)	Vertical Steel (@ OC)	Specimen Vertical Steel Area Ratio	Code Minimum Vertical Steel Area Ratio	Horizontal Steel (@ OC)	Specimen Horizontal Steel Area Ratio	Code Minimum Horizontal Steel Area Ratio
1	#4 @ 16-in.	0.0023	0.0012	#4 @ 16-in.	0.0001	0.0020
2	#4 @ 48-in.	0.0013	0.0012	#4 @ 16-in.	0.0002	0.0020
3	None	-	-	#4 @ 16-in.	0.0002	0.0020
4	#4 @ 48-in.	0.0013	0.0012	None	-	0.0020

Load Application Rate

The fabricated specimens were tested by applying a horizontal load at a rate of 0.5 in. per minute until it reached a maximum displacement of 6 in. from the initial loading contact position of the specimen. The specimens were loaded until failure by considering each sample's safety situation and performance behavior. Testing was performed in accordance with generally accepted engineering principles and practices for third point loading of concrete specimens as outlined in ASTM’s Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading (ASTM C 78/7C 78M, 2022).

Flexural Test Findings

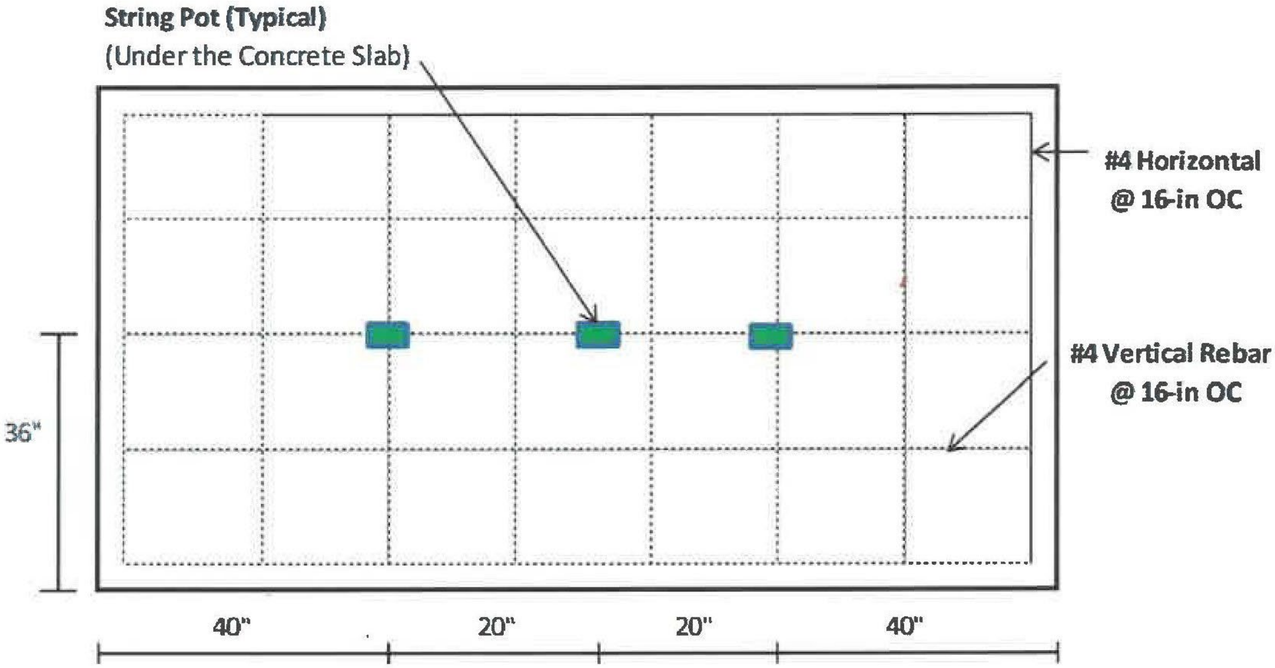
The fabricated specimens were tested by applying a horizontal load at a rate of 0.5 in. per minute to a maximum displacement of 6 in. from the initial load contact position with the specimen. The resultant mid-section deflections at the maximum flexural load conditions for all four specimens are provided in Table 4. It is noted that failure for all four specimens generally occurred inside the middle third of the span as indicated in Table 5. Deflection occurring at the north and south ends was also measured for each specimen. Wall specimen no. 1 experienced the highest deflection of 2.935 in. while wall specimen no. 2 recorded the least deflection of 0.068 in. Wall specimen no. 4 experienced the highest of the maximum load condition with 13,648 lbs. at failure condition while wall specimen no. 3 recorded the lightest among the maximum loads with 10,017 lbs. The general mechanical performance of all flexural specimens to the loading conditions is provided in Figure 15. Photographic evidence of the typical failure mode of the flexural specimen is shown in Appendix C.3. Evidence of primary and secondary crack propagation pathways in Specimen No. 4 is provided in Appendix C.4. The detailed load versus average displacement performance plots for the individual flexural test specimens is provided in Appendix D - Appendix D.5 through Appendix D.8

Table 4. Mid-section deflection performance for flexural wall specimens

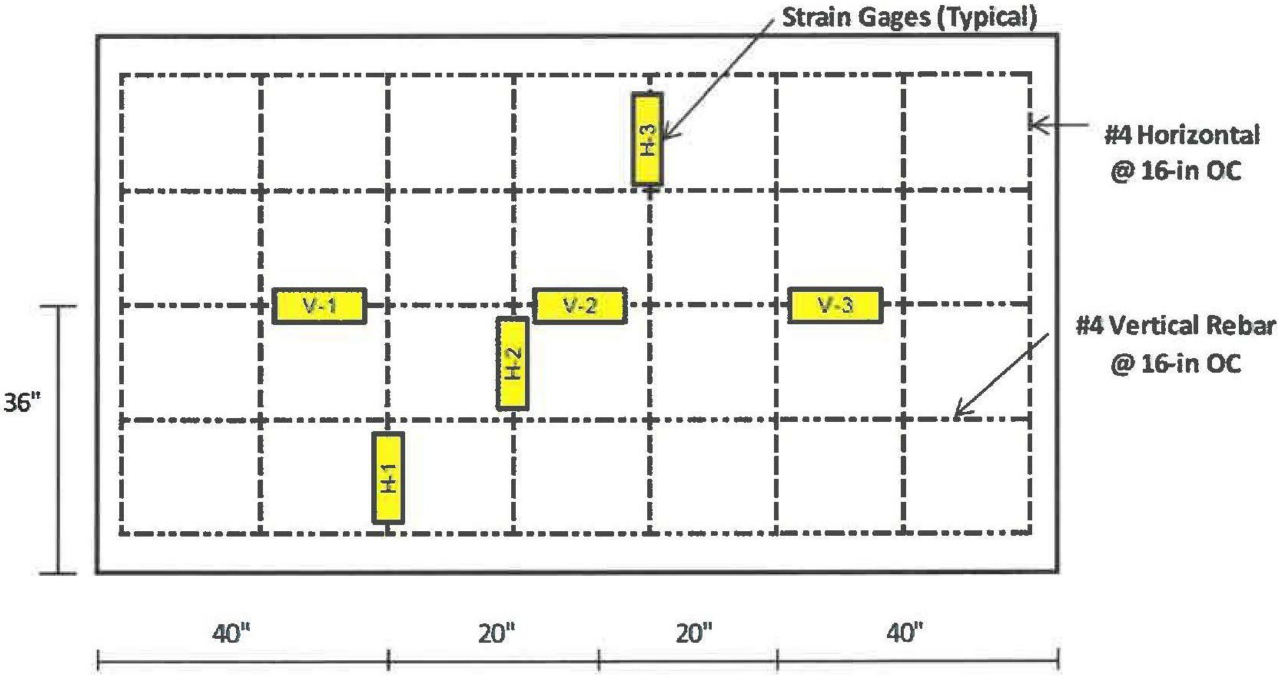
Wall Specimen No.	Maximum Compressive Load (lbs.)	Mid-Section Deflection (in.)
1	11,377	2.935
2	11,947	0.068
3	10,017	0.075
4	13,648	0.083

Table 5. General Failure Observations within Flexural Specimen

Wall Specimen No.	Mode of Failure
1	Failure occurred inside the middle third of the span.
2	Failure occurred inside the middle third of the span.
3	Failure occurred inside the middle third of the span.
4	Failure occurred inside the middle third of the span.

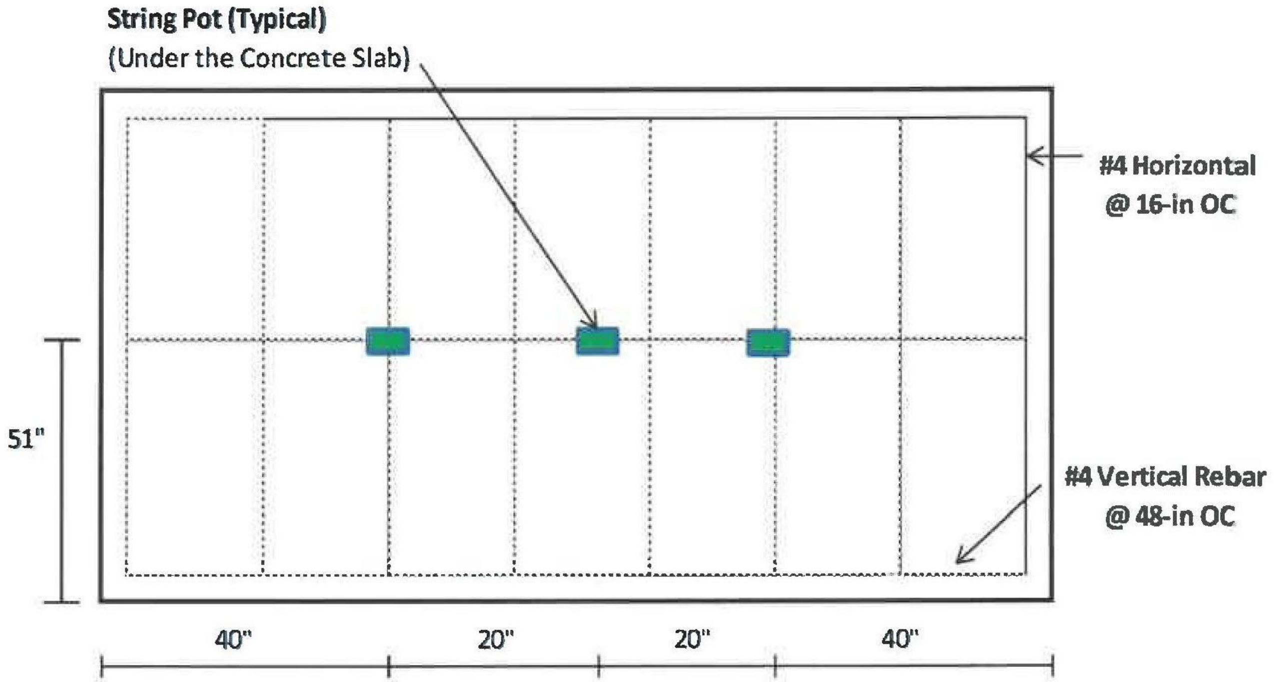


Displacement Location (3)



Strain Gages Location (6)

Figure 10. Configuration of Flexural Specimen No. 1



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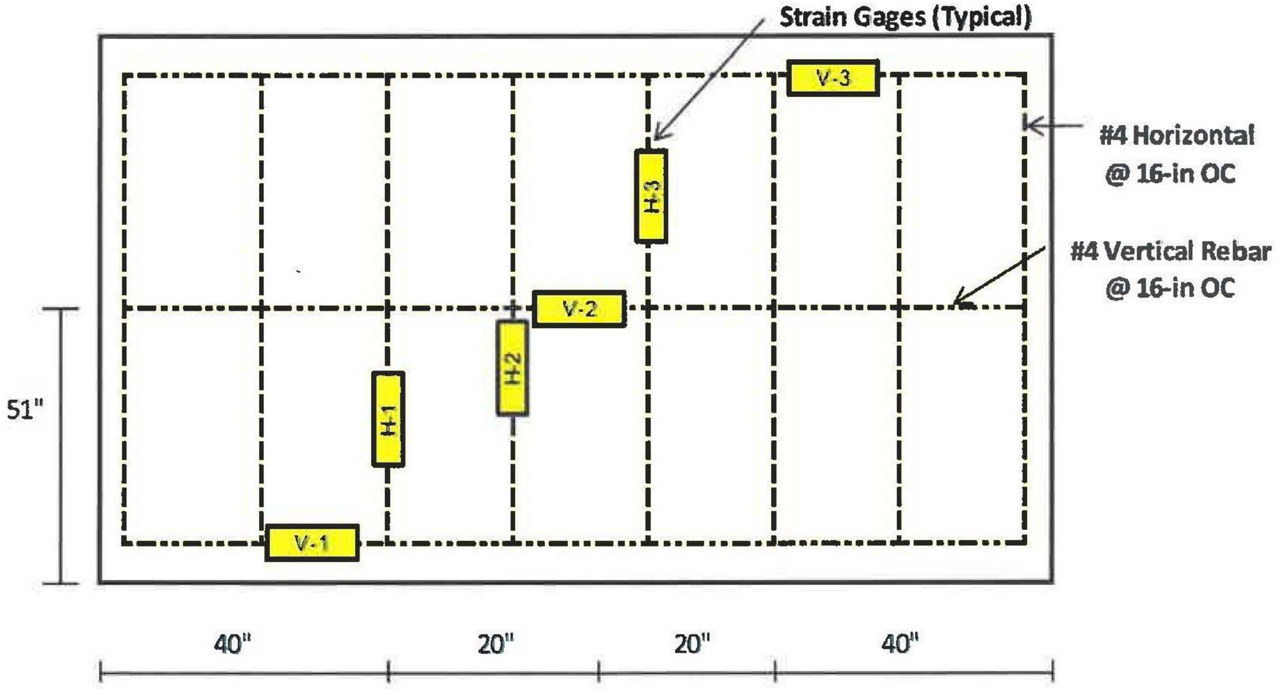
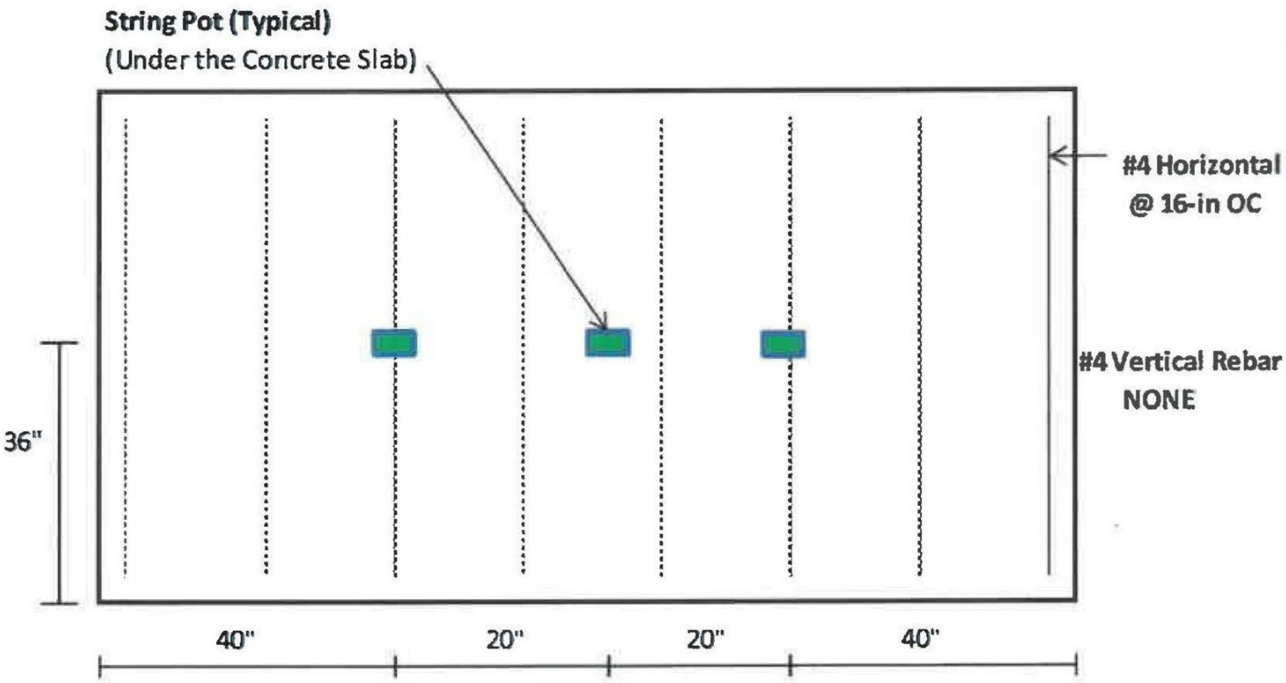


Strain Gages Location (6)

Figure 11. Configuration of Flexural Specimen No. 2



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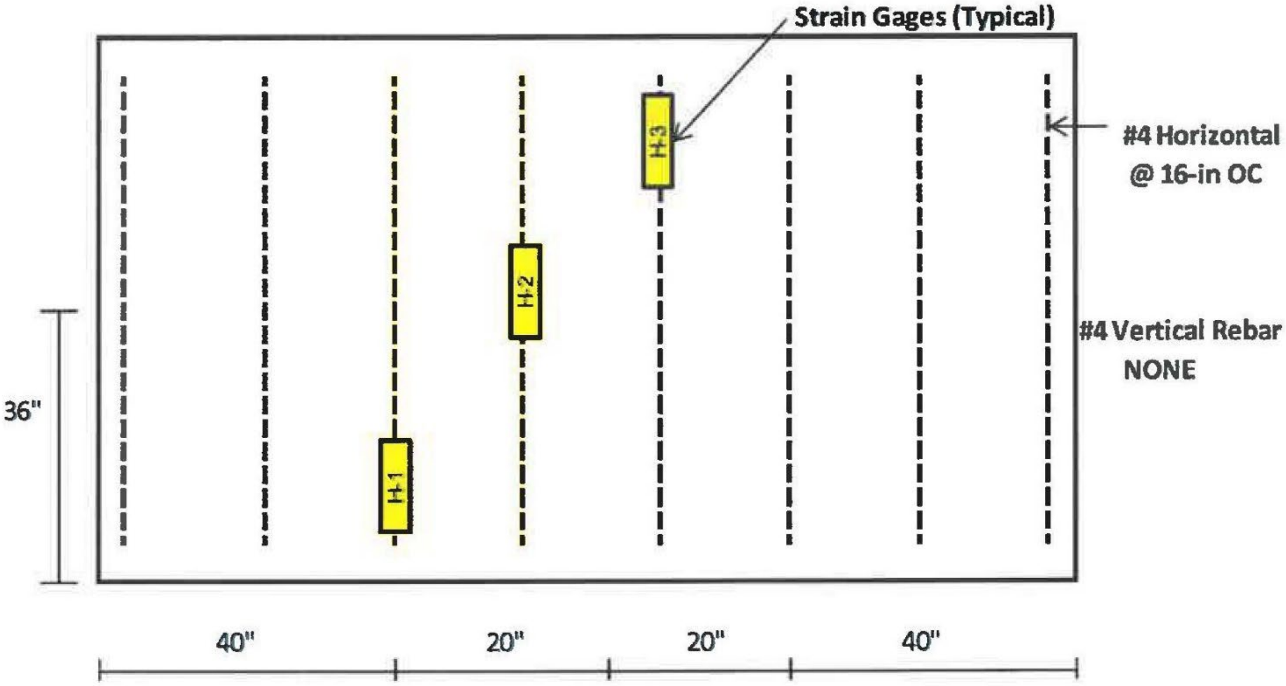
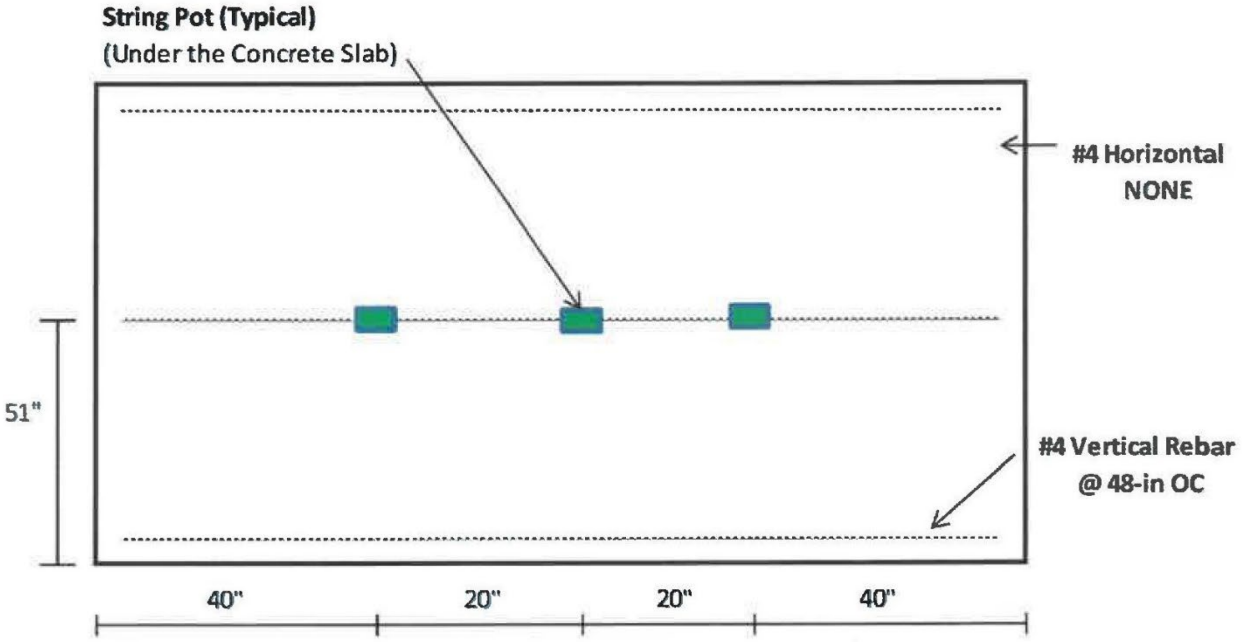
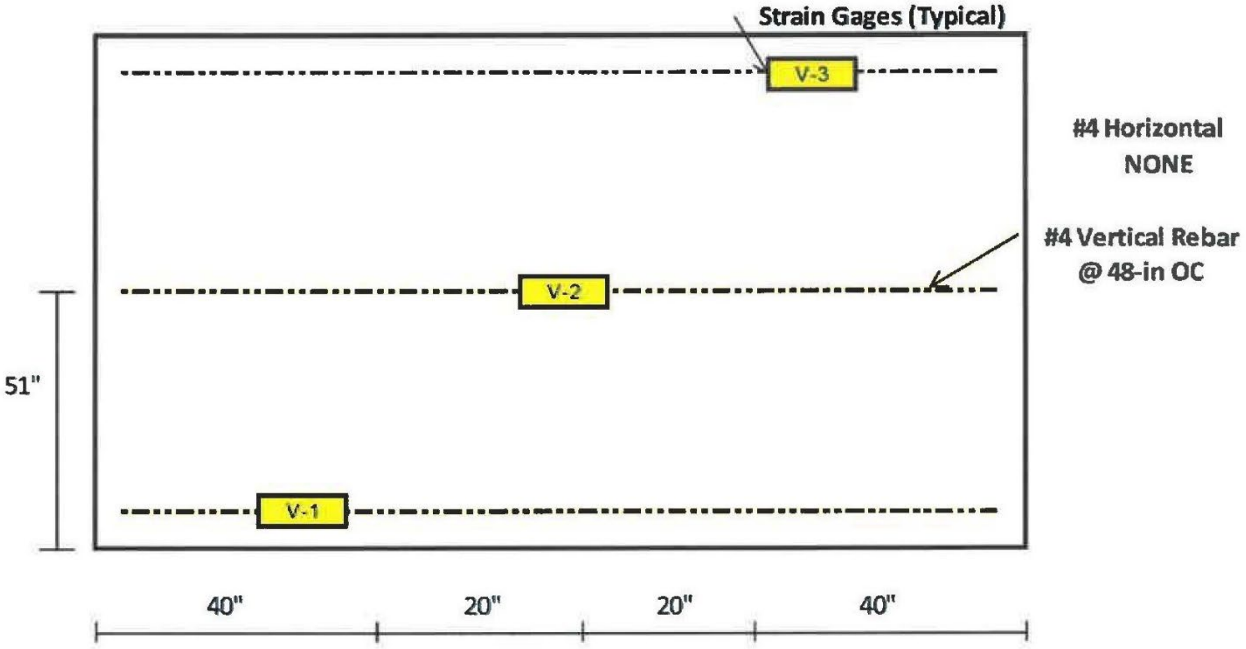


Strain Gages Location (3)

Figure 12. Configuration of Flexural Specimen No. 3



Displacement Location (3)



Strain Gages Location (3)

Figure 13. Configuration of Flexural Specimen No. 4

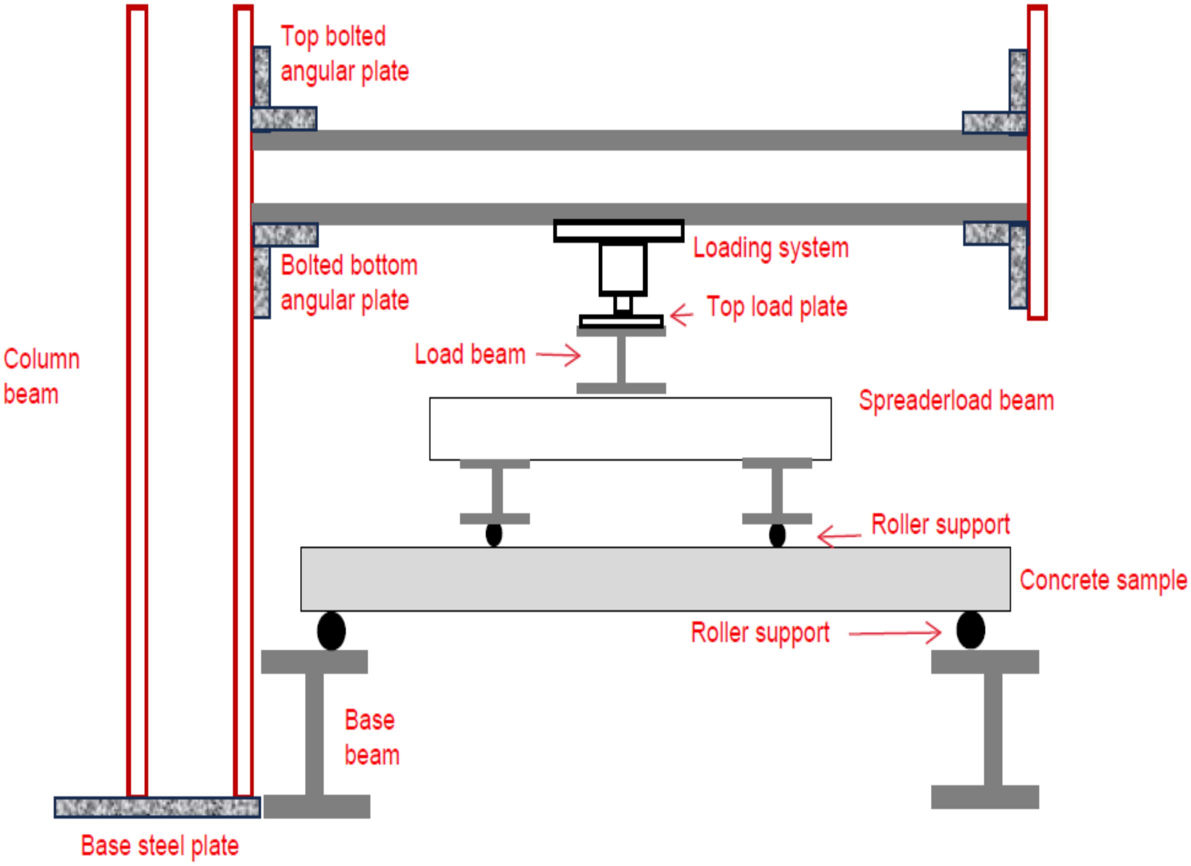


Figure 14. Flexural test set up

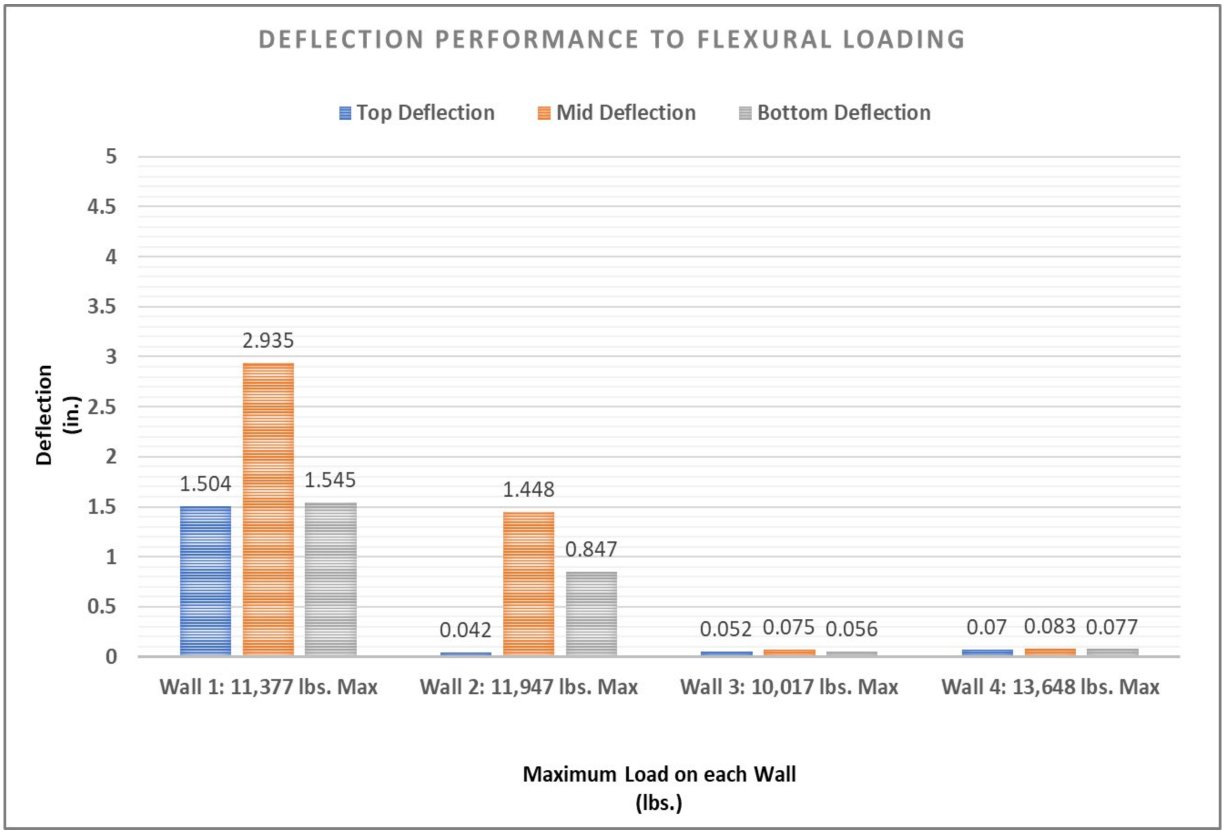


Figure 15. Deflection performance at the different maximum flexural loading conditions

Failure Energy Analysis of Concrete Specimen

For the purposes of analyzing the failure energy, the fractured concrete specimens are considered to obey the energy conservation law. As per the law of conservation of energy, energy will not disappear but will be transferred from one form into another. Specifically for this case, the acting external forces on the compressive and flexural specimens are equal to the value of the energy absorbed by the deformation under pressure.

In analyzing the failure energy, the strain energy is assumed to be equal to the energy absorbed, E_a, as indicated in equation 1:

$$E_a = \mathrm{V} \int_0^{\varepsilon_0} \sigma \, d\varepsilon \qquad [1]$$

Where:

V = specimen volume

ε_c = compressive or flexural displacement
σ = compressive or flexural stress

The areas under the compressive or flexural load-displacement curves are therefore used for energy absorption analysis (Solomon and Hemalatha, 2020). A plot of the strain energy absorbed at the top, mid-section and bottom of the compressive wall specimen is provided in Figure 16. For all the failure scenarios of the top, mid-section and bottom of the specimen, wall specimen 1 performed better in terms of absorbed energy, followed by wall specimen 2, 3 and 4 in decreasing order. It is evident that increasing the vertical spacing lead to lower energy absorption rate within the specimen. The lower the energy absorbed within the sample, the higher the susceptibility to failure beyond the peak load state.

A plot comparing the strain energy absorbed for the tested flexural specimen is shown in Figure 17. Generally, it was observed that the strain energy decreased from the middle, southern to the north ends of each test specimen. Furthermore, the strain energy decreased from Wall specimen 1, specimen 3, specimen 4 and then specimen 2 in that order. The effect of increased vertical reinforcement spacing on the strain energy of flexural specimen was ambiguous as compared to the compressive specimen.

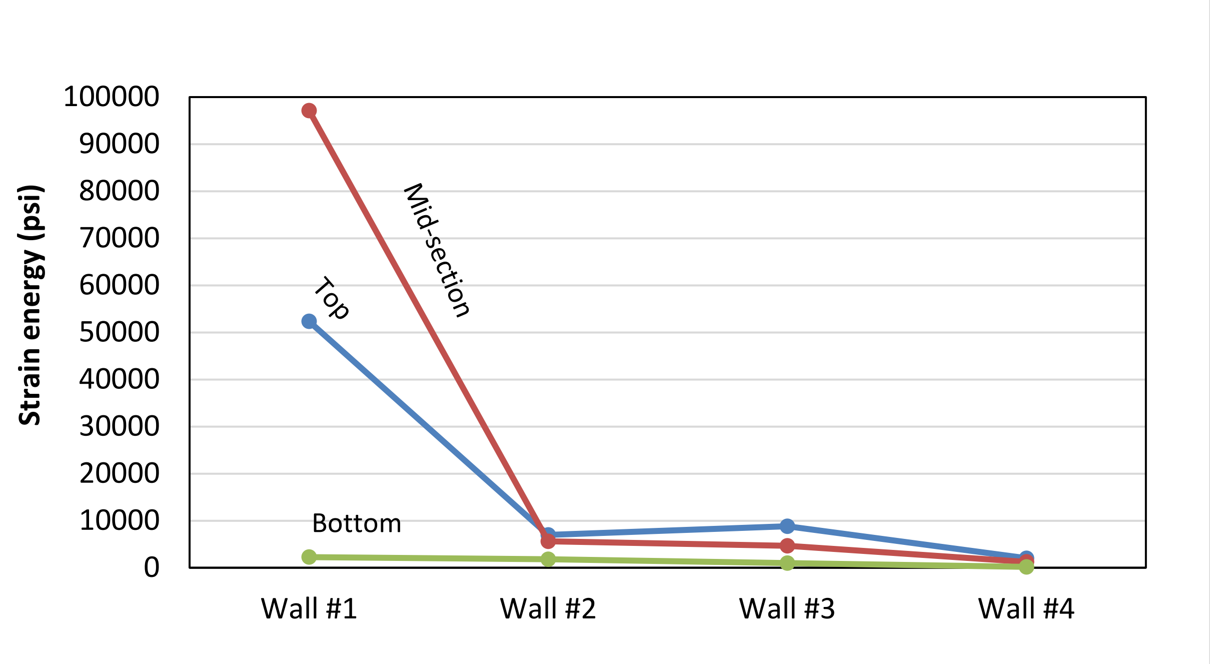


Figure 16. A comparison of strain energy for compressive wall specimens at various locations

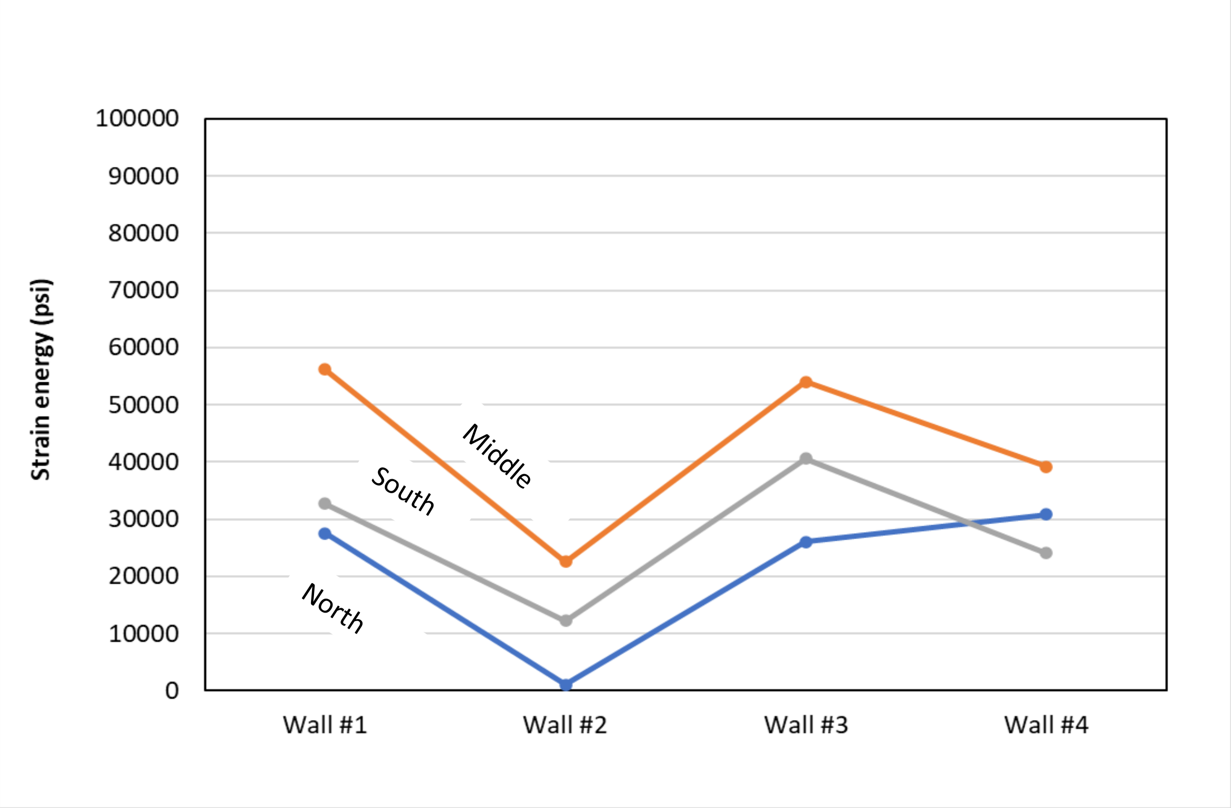


Figure 17. A comparison of strain energy for flexural wall specimens at various locations

Discussion of Results

Compressive and flexural specimen were tested during the experimental program. The deformation performance at the peak compressive and flexural loads were evaluated with field test equipment or setup.

The wall specimens were assessed for the top deflection in inches at the maximum load reached during testing. Generally, the wall with the least vertical spacing tolerated the highest maximum compressive load while the deflection trend was ambiguous between the different wall specimens. Results from more test specimens would have provided a more distinct trend.

The four compressive test specimens experienced failure at the bottom end of the specimen. Specifically, failure was observed at the base connection to the steel. The failure occurred at the 90° edge or corner of the base. The failure was wedge shaped and can be described as both in-plane shear and out-of-plane shear cracking as shown in Figure 18. Any form of resistance exerted by the base steel plate is neglected in the analysis of the cracking failure.

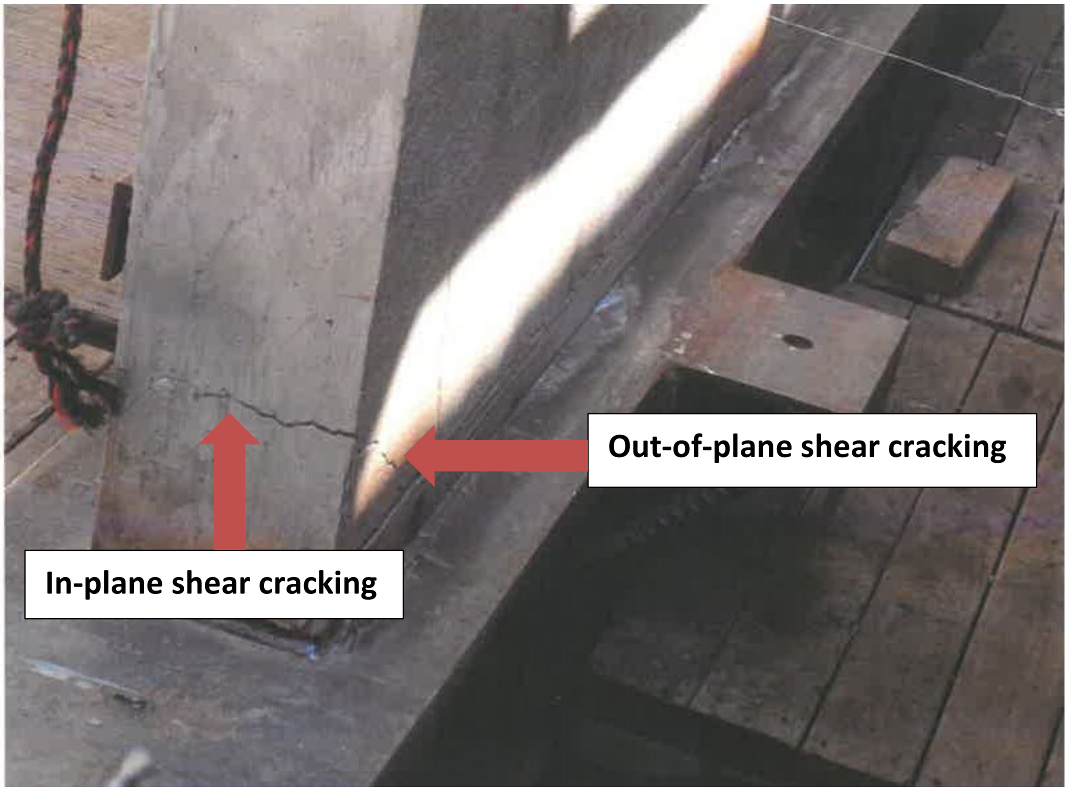


Figure 18. In-plane and out-of-plane crack evolution in compressive test specimens after failure

The maximum flexural loads recorded for all four specimens were between 10,017 and 13,648 lbs. While general failure occurred within the middle third, some cracks propagated in different directions on the in-plane and out-of-plane shear faces of the wall. The performance of wall specimen 4 was unexpected. Even though it experienced the highest maximum compressive load, the deflection performance was surprisingly low (0.083 in.).

Analysis of the strain energy did not reveal any identifiable trend as the vertical reinforcement spacing was increased from wall specimen 1 through 4. The cracks observed during failure either propagated further on the face of the wall or compression side of wall. Wall specimen 2 experienced a major mid-section crack with visible fractured concrete pieces on the face of the wall. A secondary crack was observed to have propagated some distance from the major mid-section crack as shown in Figure 19.

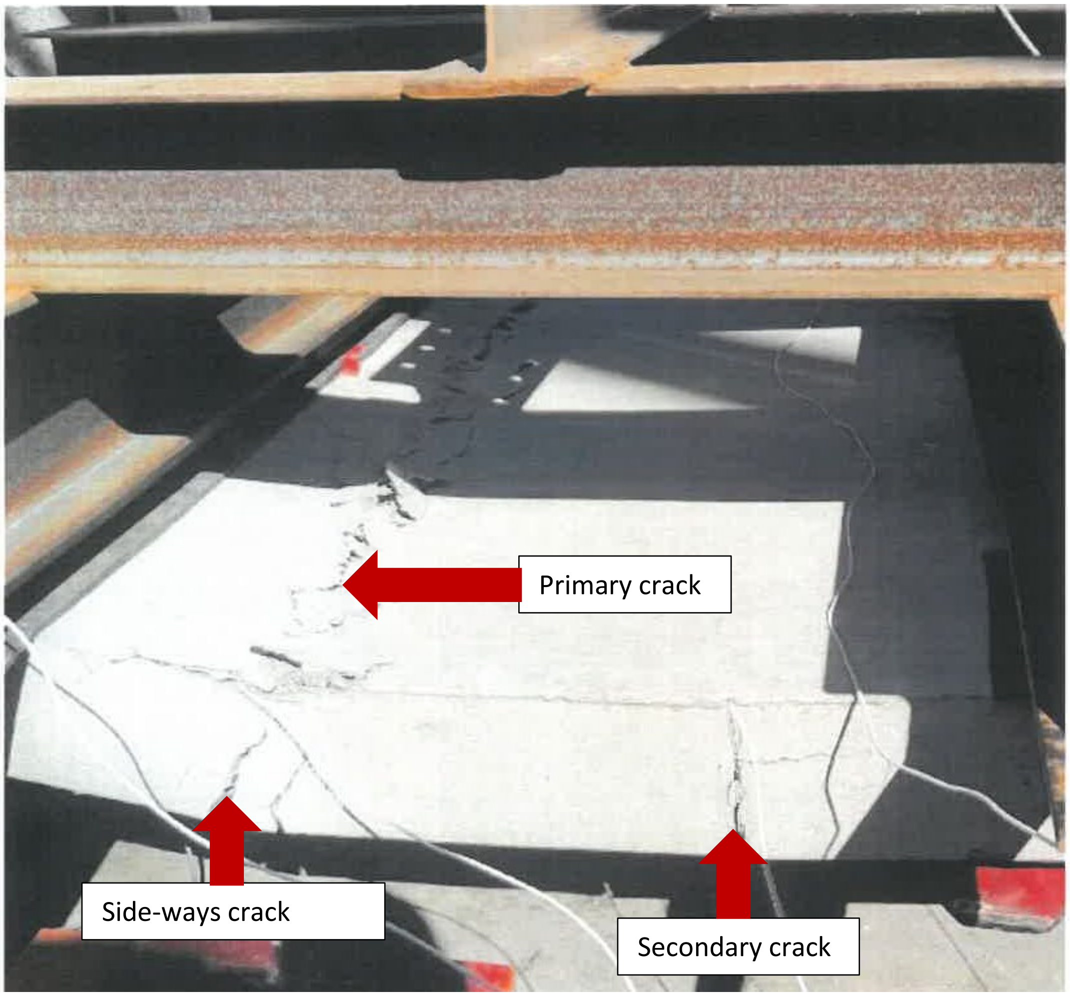


Figure 19. In-plane and out-of-plane crack evolution in compressive test specimens after failure

Conclusions

This research involved the experimental testing of concrete wall specimens configured with reduced levels of reinforcement and subjected to both compressive and flexural loading. Conclusions based on the empirical results and analysis include the following:

- Since all four compressive specimen walls cracked and failed only at the bottom section, wall base connection systems should receive critical attention and analysis if walls are to be designed with increased vertical spacing or reduced reinforcement ratios. Specifically, this includes how such walls will interact with beam, slab-on-grade, columns, basement walls, among others. Such structural interaction was beyond the scope of this research and may need to be considered for future work.
- Reduced vertical rebar ratios or increased vertical rebar spacing may likely be insufficient for stable design in certain cases, resulting in compromised structural integrity of the wall under out-of-plane loading. The reduced intersections between the vertical and horizontal reinforcement occur in such circumstances which leads to lower resistance or performance against critical load, shear, and moments.
- Aside from the development of the initial primary cracks, secondary crack propagation is likely to be an issue when reduced reinforcement ratios (increased vertical rebar spacing) is considered for certain of walls. Further studies are necessary to confirm this.
- Further research is needed to justify the use of reduced reinforcement ratios in concrete walls. Tests with different wall length and height configurations, in combination with increased rebar spacing (reduced reinforcement ratios) will be necessary to determine the optimal design conditions.
- Flexural loading and its accompanying shear and moment need to be critically assessed and analyzed compared to the same effects from compressive loading when the reinforcement ratios are to be reduced or the vertical rebar spacing increased.
- Reducing reinforcement ratios or increasing reinforcement spacing for walls cannot be recommended based on the outcome of this research. Further research is necessary to justify the increase in reinforcement spacing beyond the ACI-318 recommended limit of 18 inches.
- Proposed future experimental research could involve testing the wall specimen at a minimum area of steel ratio while increasing the spacing for bar sizes higher than a baseline or control bar requirements.

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APPENDIX A – Concrete Mix Design Test Parameters for Compressive and Flexural Specimens

APPENDIX A.1

Summary of Concrete Compressive Test Results

Design compressive strength (psi) = 4,000 psi

Slump, S (in.) = 4.00+/- 1.00

Concrete Cylinder Specimen No.	**1**	**2**	**3**	**4**
Date batch	6/28/22	7/7/22	7/22/22	8/4/22
Slump, in.	4-1/4	4-1/2	4-1/2	4-1/4
Air Content, %	2.2	2.1	1.8	2.0
Unit Weight, lb/ft^3	149.4	148.5	147.1	150.1
Air/Conc., Temp. °F	74/73	78/76	70/70	70/75
Compressive Test Results (psi)	**1**	**2**	**3**	**4**
7-Day Average	3,210	3,160	3,360	3,340
28-Day Average	4,600	4,200	4,960	4,920

APPENDIX A.2

Summary of Concrete Flexural Test Results

Design compressive strength (psi) = 4,000 psi

Slump, S (in.) = 4.00+/- 1.00

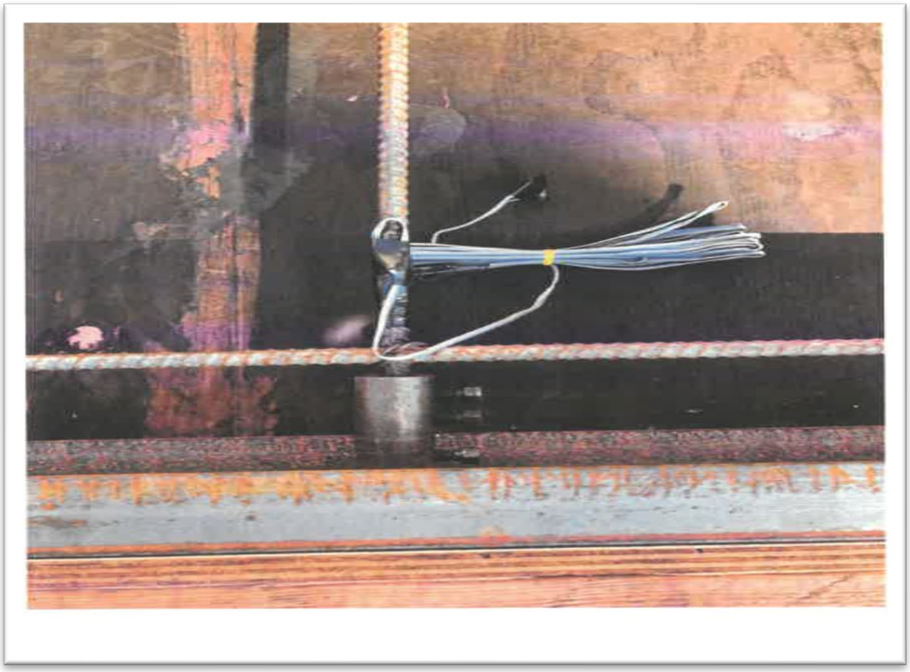
Concrete Cylinder Specimen No.	**1**	**2**
Date batch	11/29/22	01/13/23
Slump, in.	4-1/4	4-1/2
Air Content, %	2.2	1.8
Unit Weight, lb/ft^3	147.5	146.9
Air/Conc., Temp. °F	60/65	58/64
Compressive Test Results (psi)	**1**	**2**
7-Day Average	3,680	3,330
28-day average	4,620	4,750

APPENDIX B – Field Reinforcement Placement and Compressive Specimen Setup

APPENDIX B.1

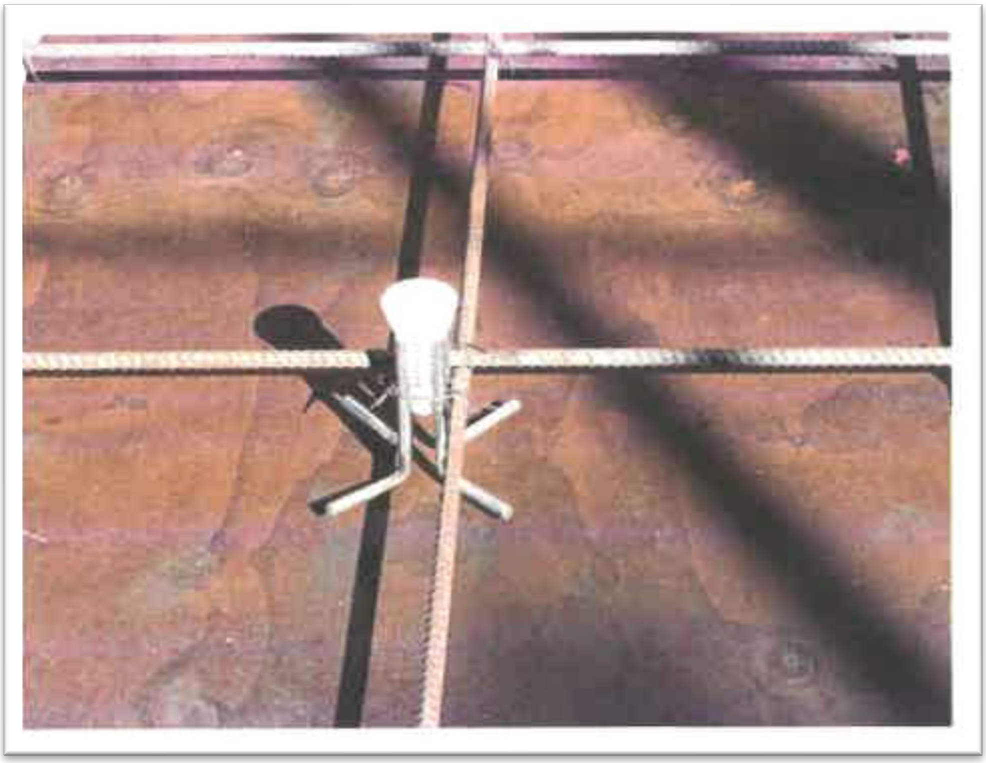
Test Setup: 1) Top Support; 2) Strain Gauge, 3) Chair and 4) Lifting Anchor

1: Top Support: HSS 7" X 7" X ½"



2: Strain Gage

3: Chair



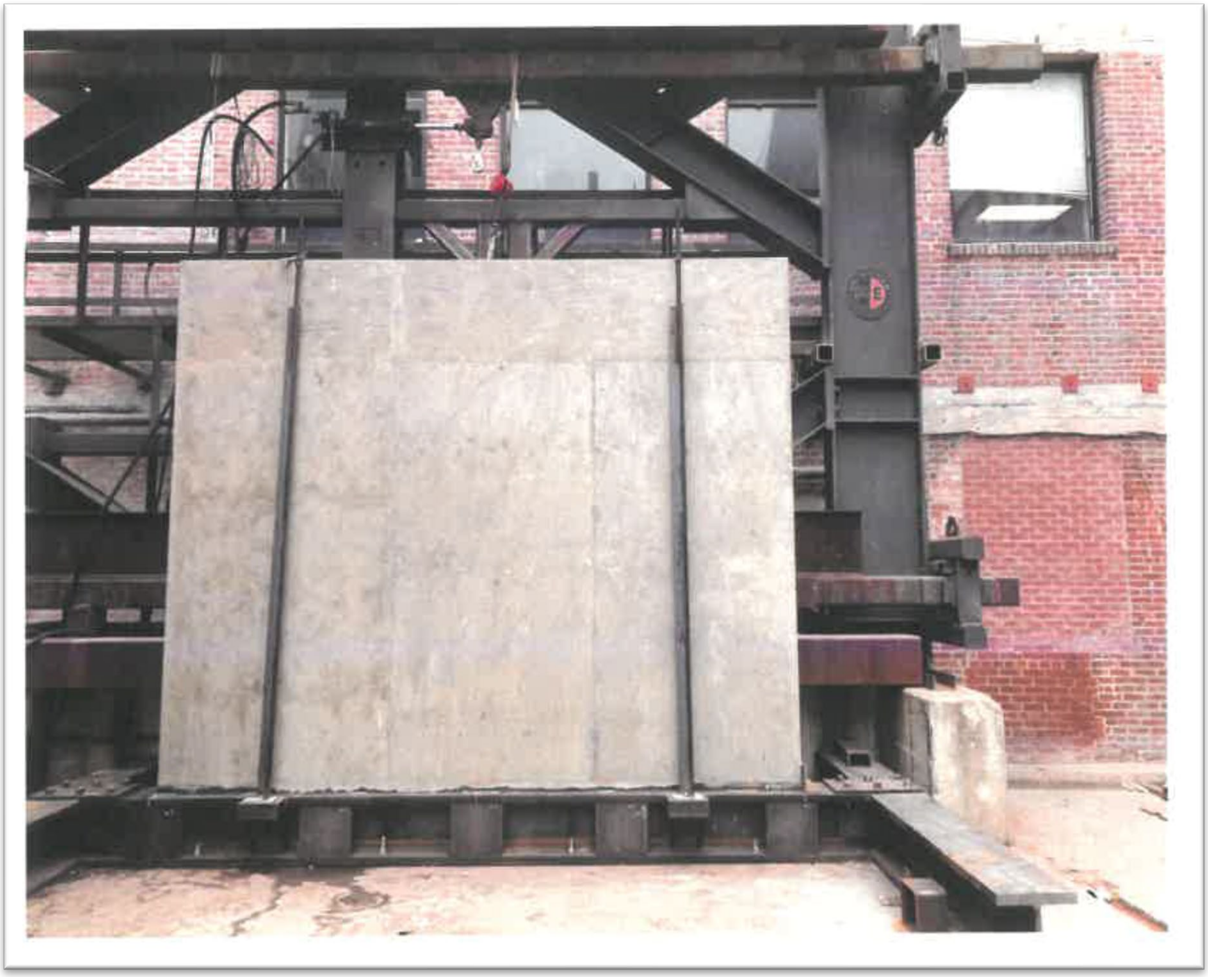
4: Lifting Anchor

APPENDIX B.2

Specimen No. 3: Before and After Pouring Concrete

APPENDIX B.3

Typical Compressive Test Set Up (Front facing)



APPENDIX C – Field Reinforcement Placement and Flexural Specimen Setup

APPENDIX C.1

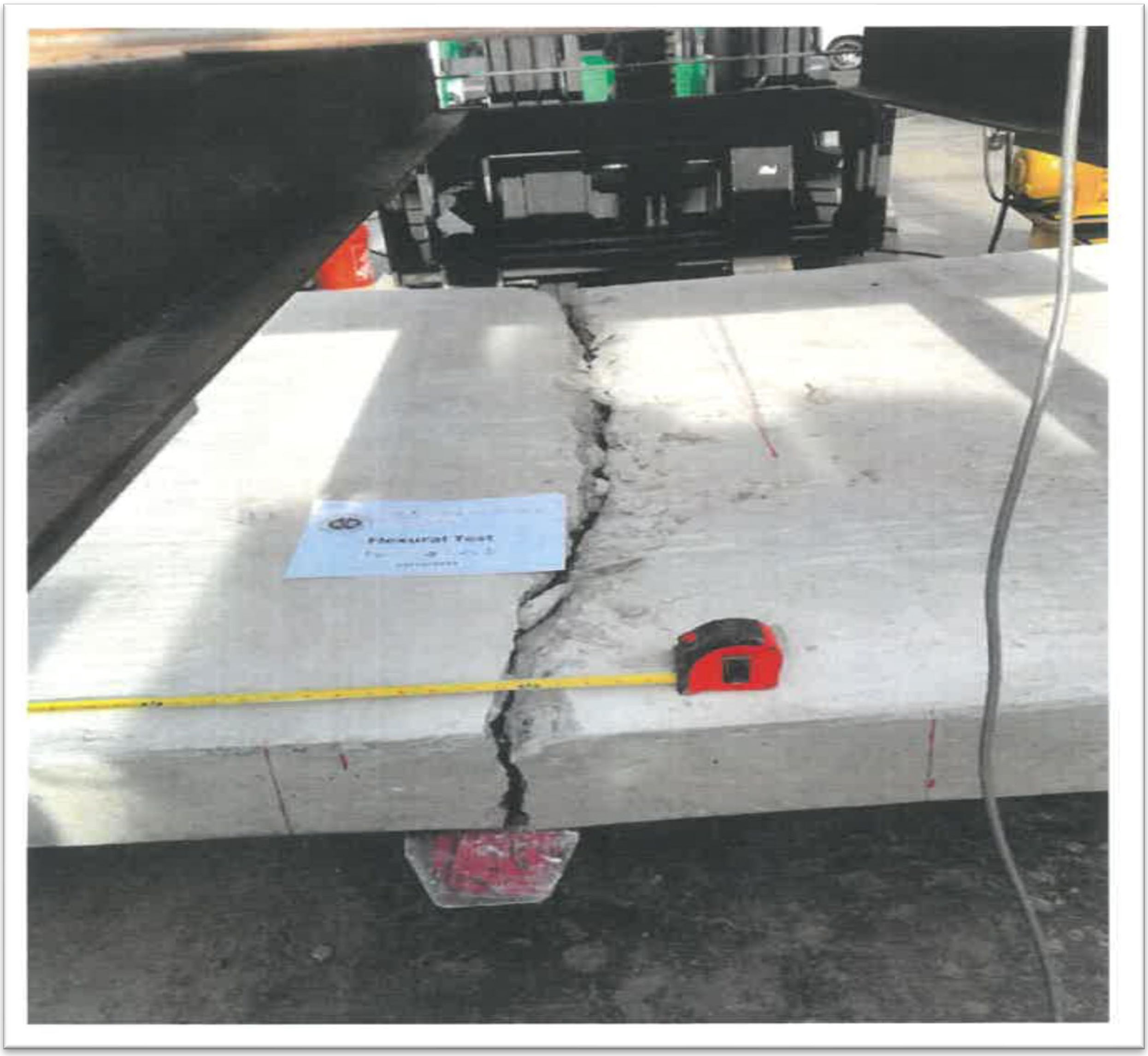
Specimen No. 1 Before and After Pouring Concrete (Flexural Loading)

APPENDIX C.2

Flexural Loading Test Set Up 1 with Strain Gauge Arrangements

APPENDIX C.3

Sample Failure Modes of Flexural Specimen

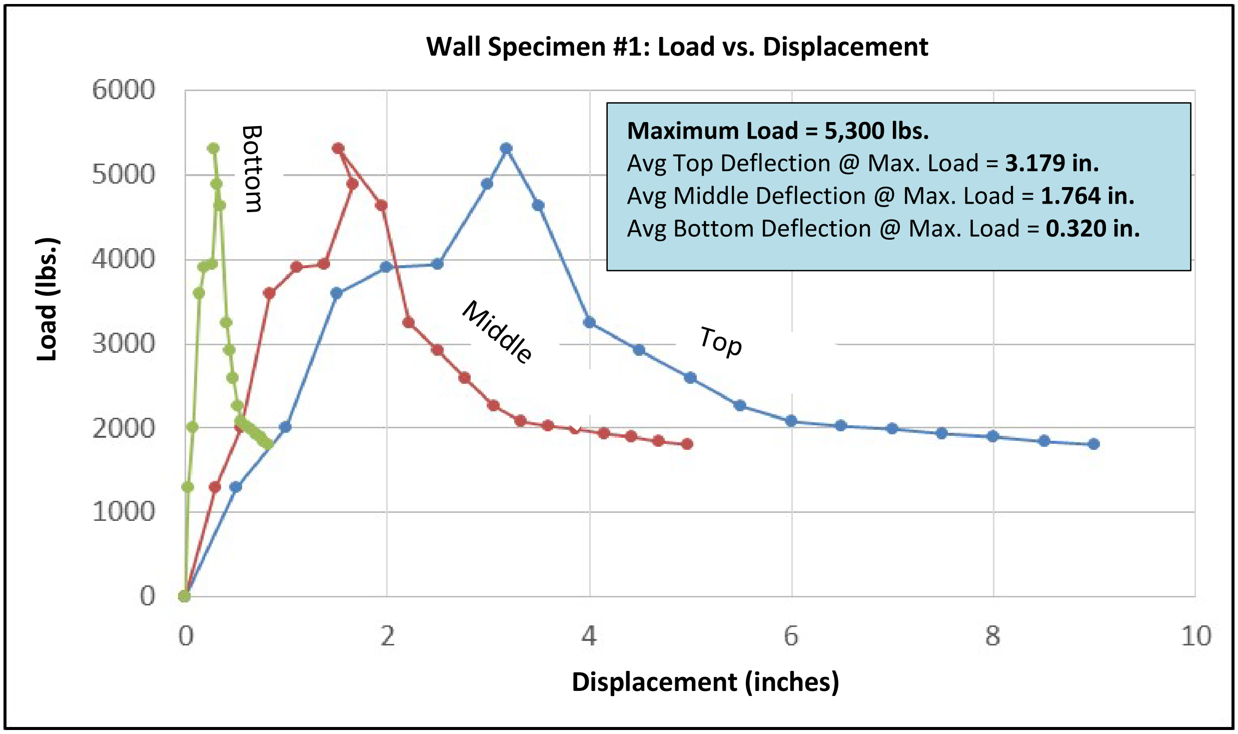


APPENDIX C.4

Flexural Test Sample No. 4 Failure Showing Primary and Secondary Cracks

APPENDIX D – Load vs. Displacement Performance for Both Compressive and Flexural Specimens

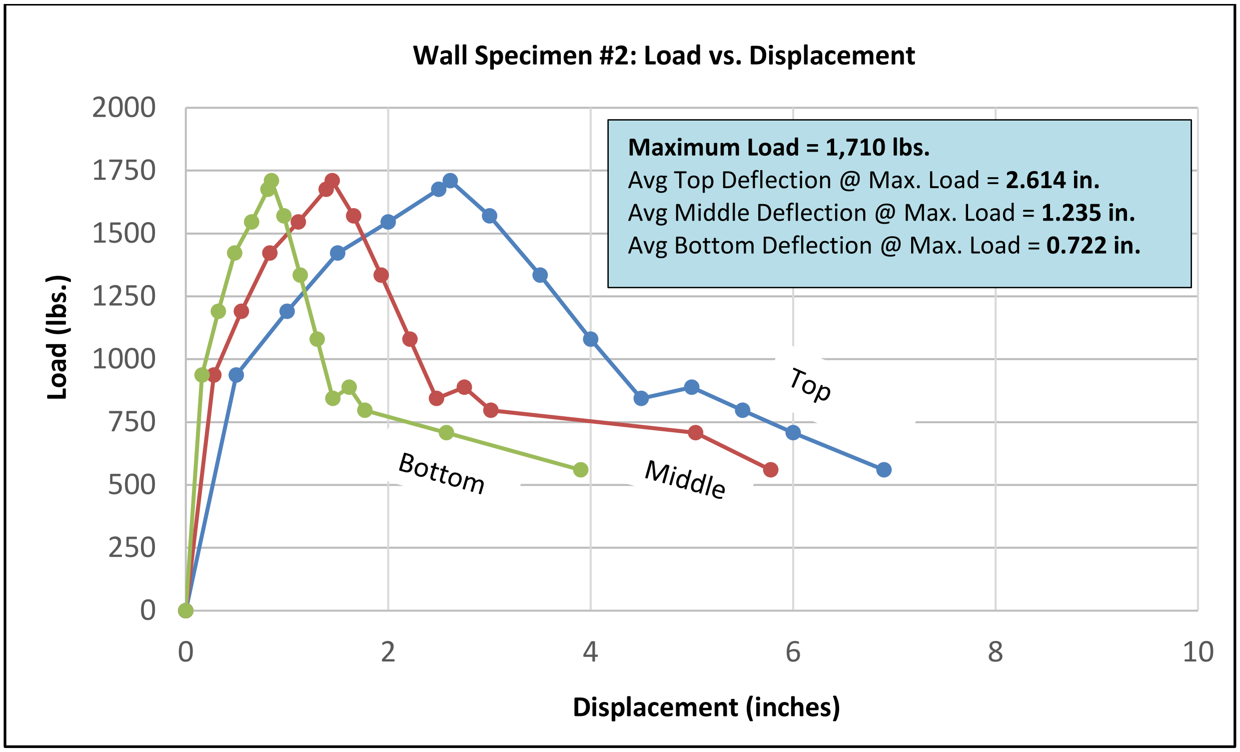
APPENDIX D.1 - Load vs. Average Displacement Performance for Compressive Specimen No. 1



Wall Specimen #1: Load vs. Displacement

Maximum Load = 5,300 lbs.
Avg Top Deflection @ Max. Load = **3.179 in.**
Avg Middle Deflection @ Max. Load = **1.764 in.**
Avg Bottom Deflection @ Max. Load = **0.320 in.**

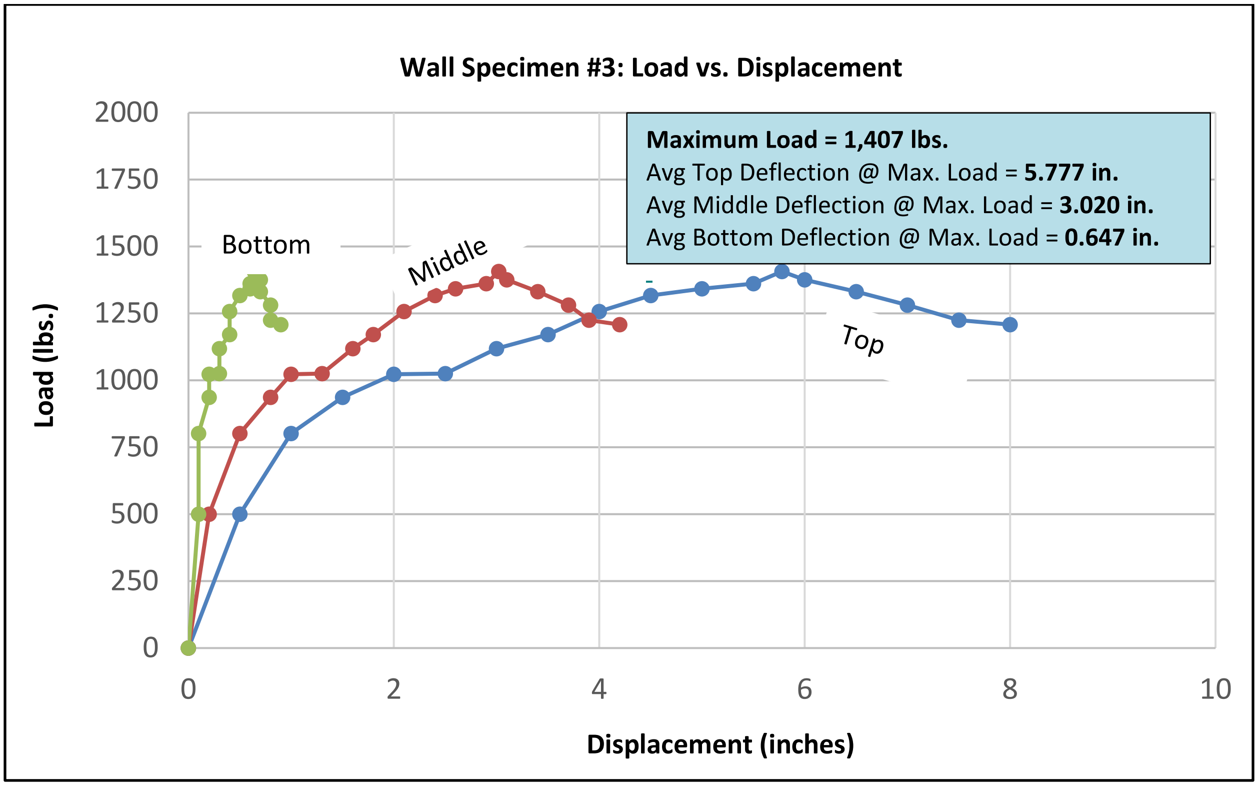
APPENDIX D.2 - Load vs. Average Displacement Performance for Compressive Specimen No. 2



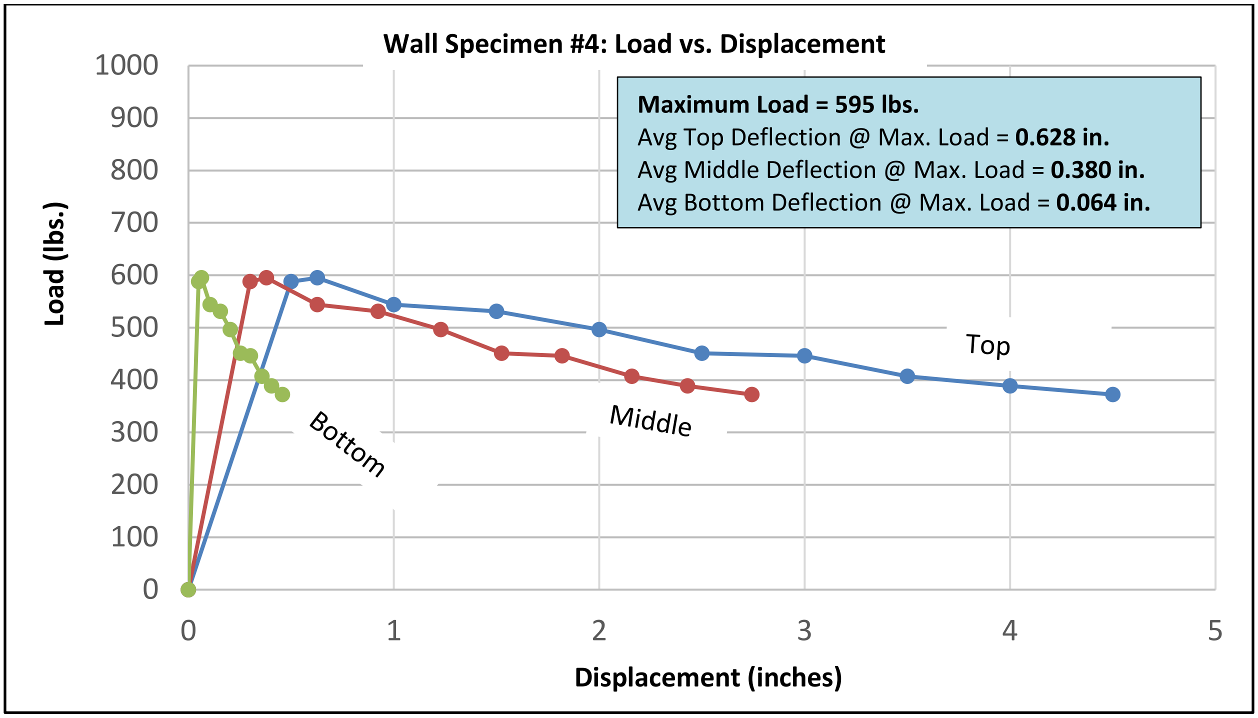
Wall Specimen #2: Load vs. Displacement

Maximum Load = 1,710 lbs.
Avg Top Deflection @ Max. Load = **2.614 in.**
Avg Middle Deflection @ Max. Load = **1.235 in.**
Avg Bottom Deflection @ Max. Load = **0.722 in.**

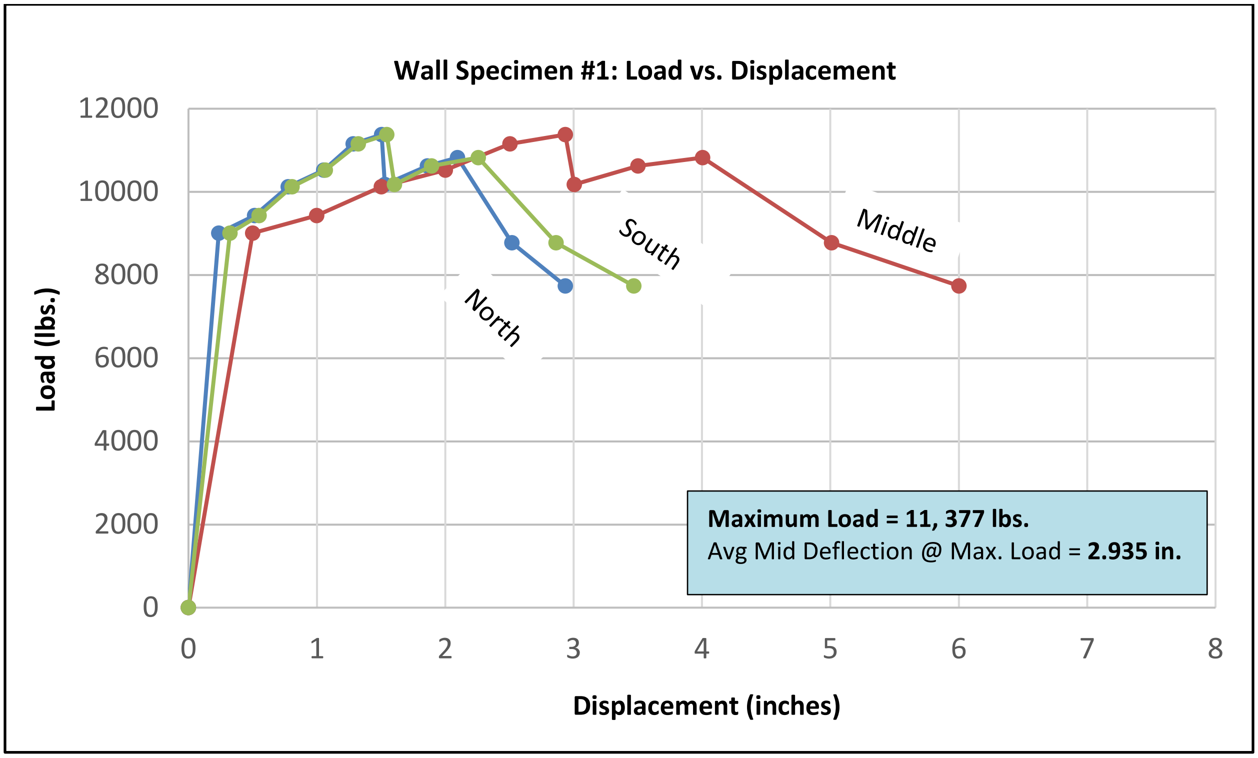
APPENDIX D.3 - Load vs. Average Displacement Performance for Compressive Specimen No. 3



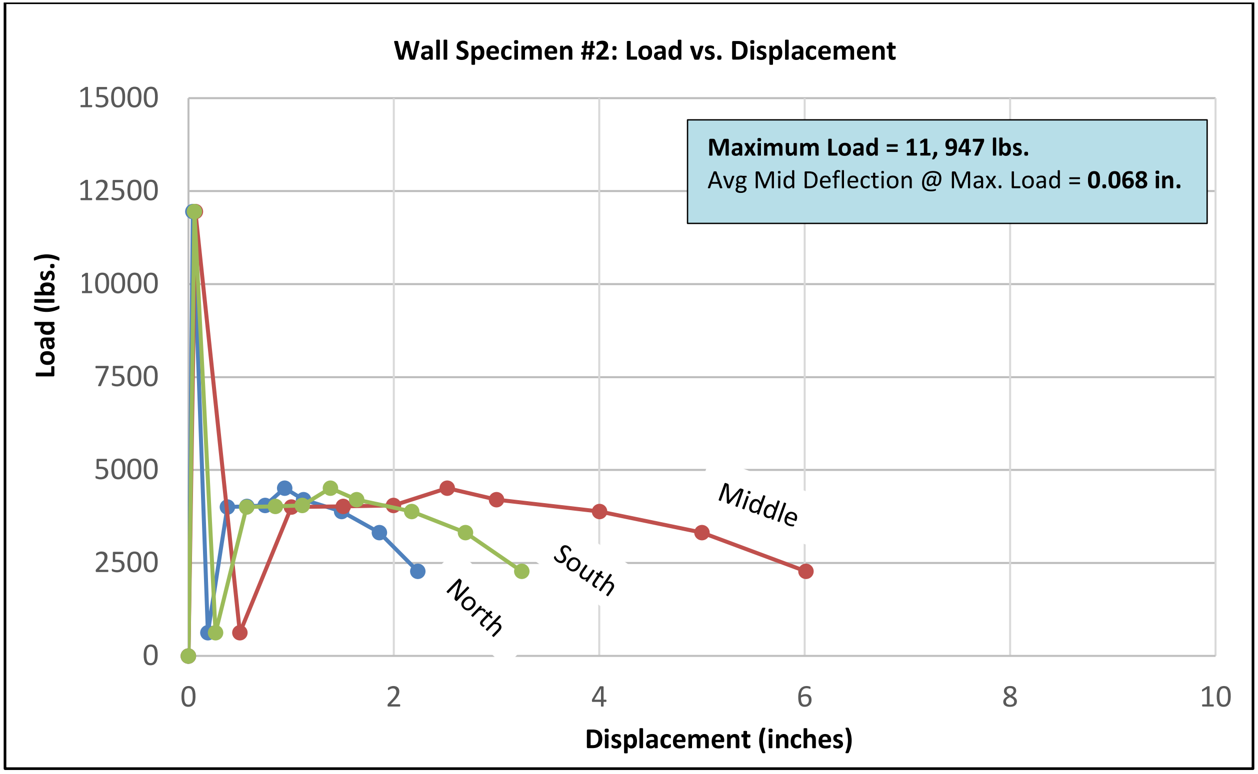
APPENDIX D.4 - Load vs. Average Displacement Performance for Compressive Specimen No. 4



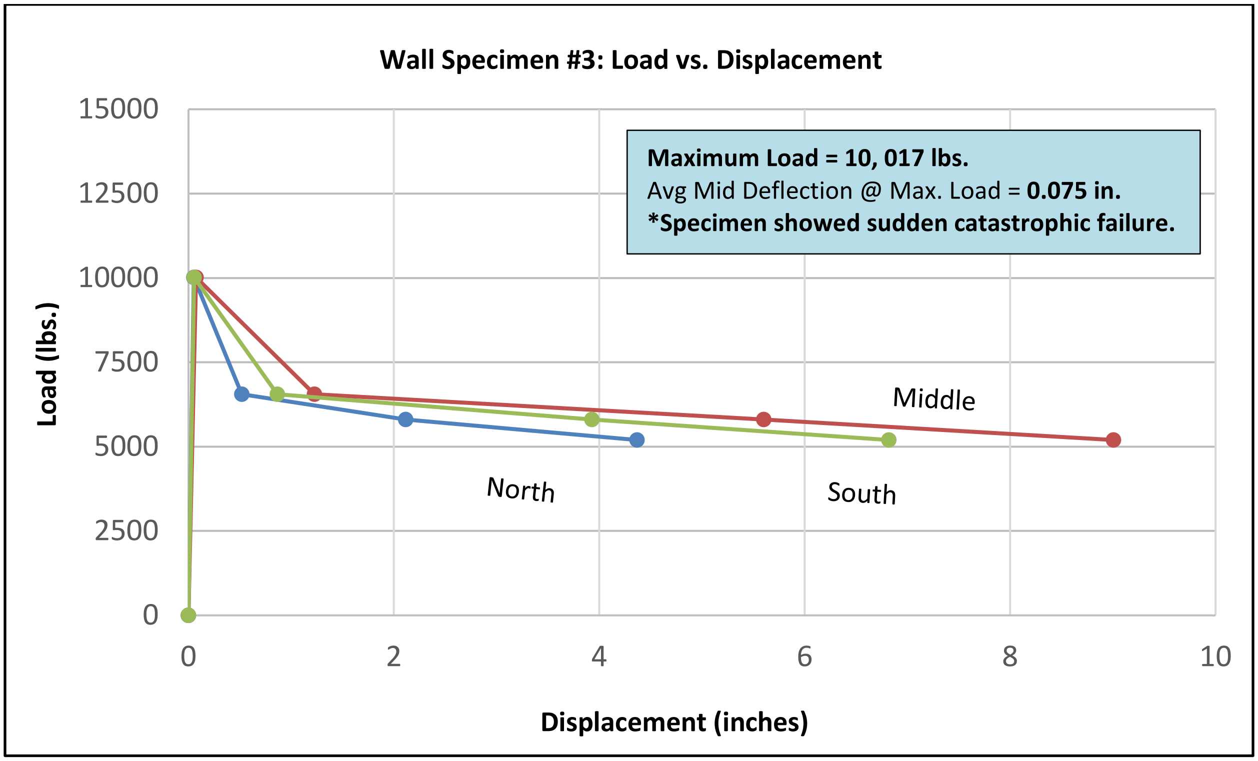
APPENDIX D.5 – Load vs. Average Displacement Performance for Flexural Specimen No. 1



APPENDIX D.6 - Load vs. Average Displacement Performance for Flexural Specimen No. 2



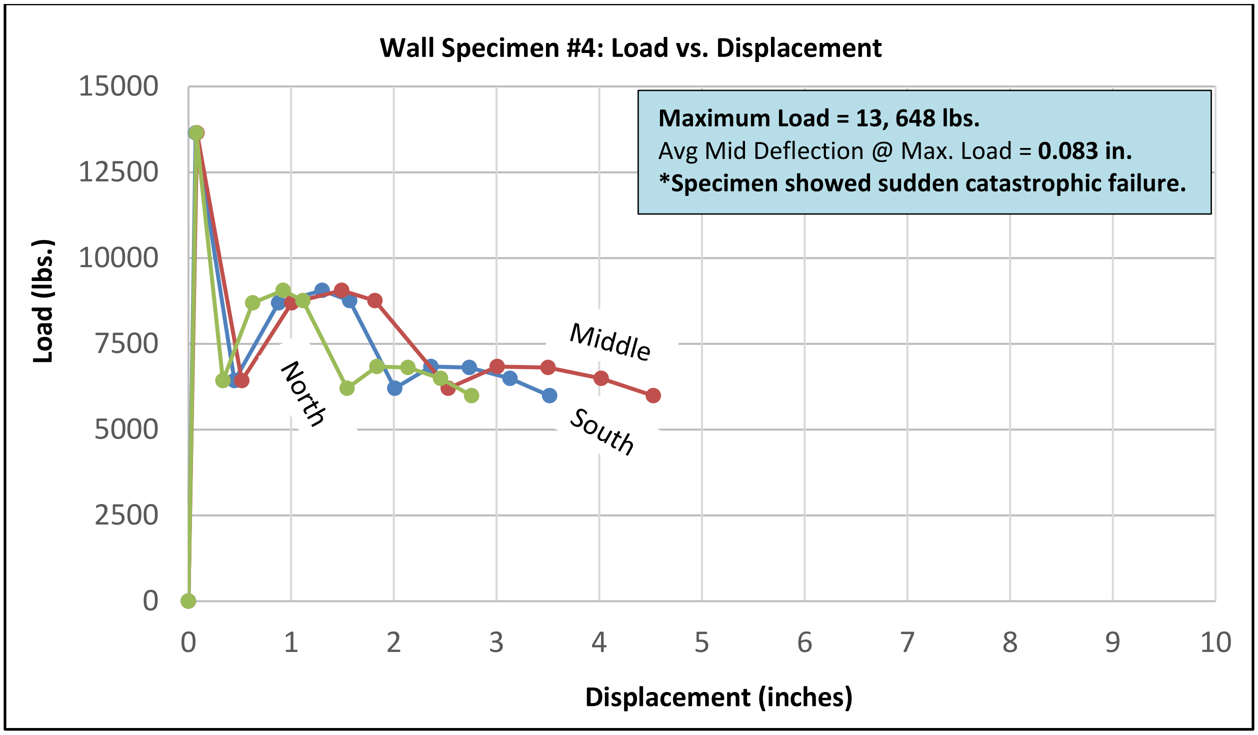
APPENDIX D.7 - Load vs. Average Displacement Performance for Flexural Specimen No. 3



Wall Specimen #3: Load vs. Displacement

Maximum Load = 10, 017 lbs.
Avg Mid Deflection @ Max. Load = **0.075 in.**
***Specimen showed sudden catastrophic failure.**

APPENDIX D.8 - Load vs. Average Displacement Performance for Flexural Specimen No. 4



Wall Specimen #4: Load vs. Displacement

Maximum Load = 13, 648 lbs.
Avg Mid Deflection @ Max. Load = **0.083 in.**
***Specimen showed sudden catastrophic failure.**

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