GFRP Spar tension and compression tests
For Energy Mass™ wall construction

R Gary Black [a]

Testing performed by Applied Materials Engineering[b]

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Abstract

Six full scale shear tests were conducted on the patented Energy Mass™ wall system to ascertain tension, pull-out and compressive strength of #4 Glass Fiber Reinforced Polymer (GFRP) rebar when embedded in 3-inch thick concrete wythes using 146 - and 34-degree hooks. Wall samples were 12" wide. Four feet tall and 22" thick with a single spar assembly connecting the concrete wythes. Results are compared with similar anchorage testing on steel rebar by Park and Paulay [1] as well as half scale Energy Mass™ wall results on #2 steel rebars with similar hooked configurations embedded in 1-1/2" thick concrete wythes conducted by Black and Mannick [2]. Samples were loaded to loads 10x greater than predicted demand and confirm, (i) there is no pull-out failure of a spar bar nor is there spalling or cracking of the concrete at the intersection between the GFRP spar and the concrete wythe, (ii) no evidence of buckling of a compression spar was observed at the approximately 10x elastic buckling load and (iii) no concrete punch through of a compression bar was observed.

1. Introduction and background

The Energy Mass™ wall construction is a sandwich construction composed of two three-inch wythes of concrete, separated by a core of insulating foam that varies in thickness from 16 inches to 4 inches. The two concrete wythes are held together by GFRP spars that are arranged in a diagonal pattern. Like the diagonal webs of a truss, the spars carry the shear forces during out-of-plane bending and serve to brace the two three-inch wythes against buckling, Fig 1.

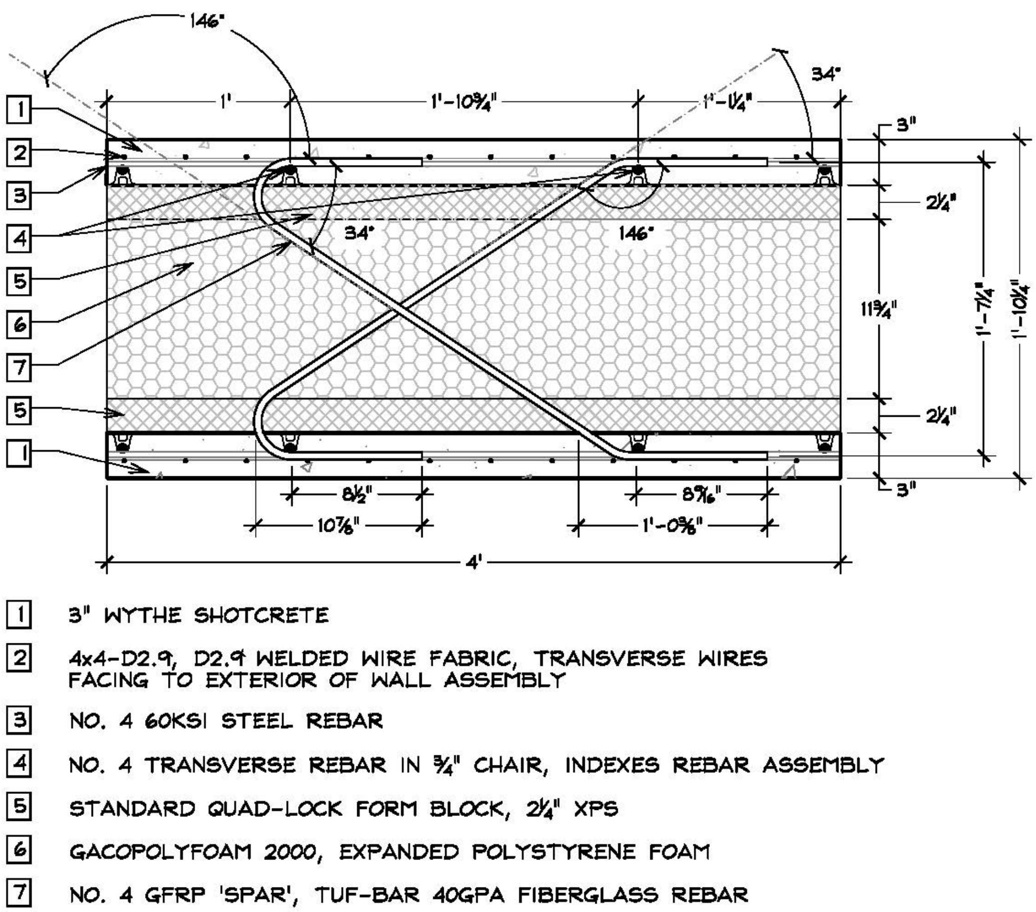


Figure 1 Cross section of test specimen

Each spar is embedded into the wythes with a 34-degree hook at one end and a 146-degree hook at the other. The typical embedment length into each wythe is 10 inches. In accordance with the Energy Mass™ wall specifications, a continuous #4 steel transverse rebar was cast into the test specimens, located at each spar end at the point where it enters the concrete. This # 4 horizontal bar, (i) indexes the spars, mesh and vertical bars, (ii) reduces concrete spall at high tensile spar forces and (iii) increases the pull-out strength of the GRFP spars by as much as 30% [1].

The geometry of the spars and how they are embedded into thin concrete wythes [2] shows that concrete failure and pull out is not the failure mode. In half scale tests of the Spar Membrane System (later re-named Energy Mass™), the results demonstrated that when hooked spars were embedded into 1.5" concrete wythes, failure modes did not include pull-out. The spars yielded and, in some cases, snapped at tensile values equaling approximately 70 ksi. The authors report that with 608 spars tested in tension there was evidence of only one spar spalling the concrete at the point of entry and no cases (including the location of the spalling) did a spar pull out of the thin concrete wythe. The test results are in general agreement with the theoretical work of Park and Paulay [1].

This study aims to document the behavior of hooked #4 GFRP spars in tension and compression when embedded into 3" wythes of concrete.

2. Test model assembly and materials

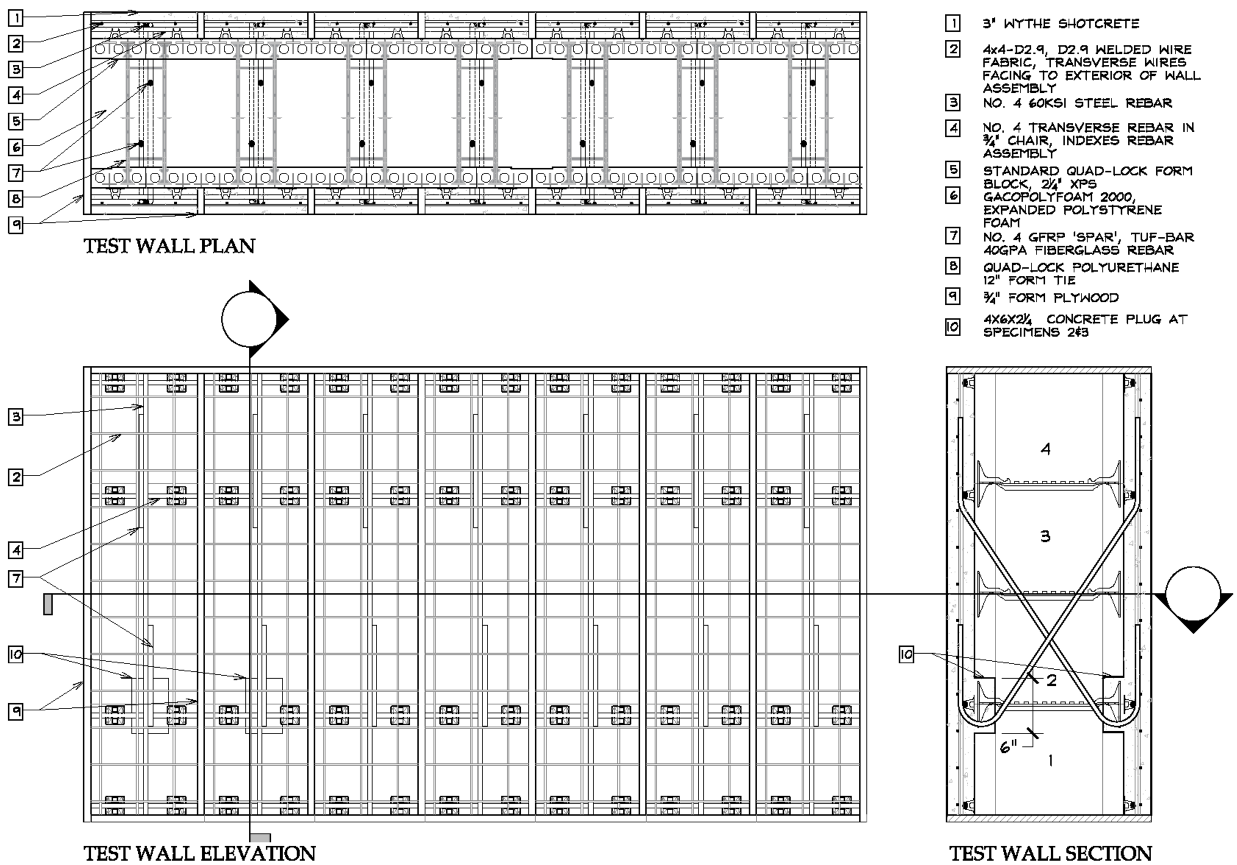


Figure 2 Test wall assembly

Seven test samples were prepared by an independent contractor [3] per the drawings shown in Fig 2. After the foam core was erected and the spars and mesh placed the test wall was shot in the vertical position with a 3000 psi, 7.5 sac Portland cement mix with maximum aggregate size of 3/8 in. and with the following admixtures; Polyheed water reducer, Delvo setting time retarder and SRA a drying shrinkage reducer. The nozzleman was Oscar Duckworth [4]. Following application of the shotcrete the test panel was screeded to produce a neat 3” wythe on both sides of the panel.

Laboratory testing [5] of shotcrete test samples confirmed an average 28-day compressive strength of 3860 psi. The shotcrete panel was water cured with a garden hose twice a day for 3 days beginning 12 hours after completion of the shotcrete to simulate the standard specifications used for shotcrete applied to an Energy Mass™ wall structure. After a minimum 28-day cure time the wall was cut along the spacer lines yielding seven 12” x 22” x 48” test samples Fig 3. The test samples were delivered to Applied Materials & Engineering, Inc. [6] who performed the testing described in the signed AME test report No. 1170988C (Appendix).

Figure 3 Test specimens

3. Experimental testing

The experimental testing and graphical results are shown in the AME report. As the ram placed load on the upper concrete wythe, Fig. 4c, it displaced laterally relative to the lower wythe causing tension and compression in the GFRP spars analogous to the shearing caused by out-of-plane bending of a full height Energy mass wall. The purpose of the tests was to determine the forces in the spars at various loads, check for pull out in tension, for buckling in compression and for breakage or distress in the spars at loads significantly greater than the expected maximum demand.

In the full height wall, the concrete wythes are continuous between the foundation and the bond beam and resist the out-of-plane axial spar component via bending of two 48 inch by 3-inch sections of reinforced concrete. To simulate this behavior, a wood block was loosely fit between the two wythes at the open end opposite the ram maintaining a constant distance between the upper and lower wythe.

Figure 4a Test frame

Figure 4b Steel frame testing apparatus with sample being loaded

A load deflection curve of the results of six tests are shown in the attached AME report and reproduced below in Fig 5 for convenience.

Figure 4c Elevation of testing apparatus with sample

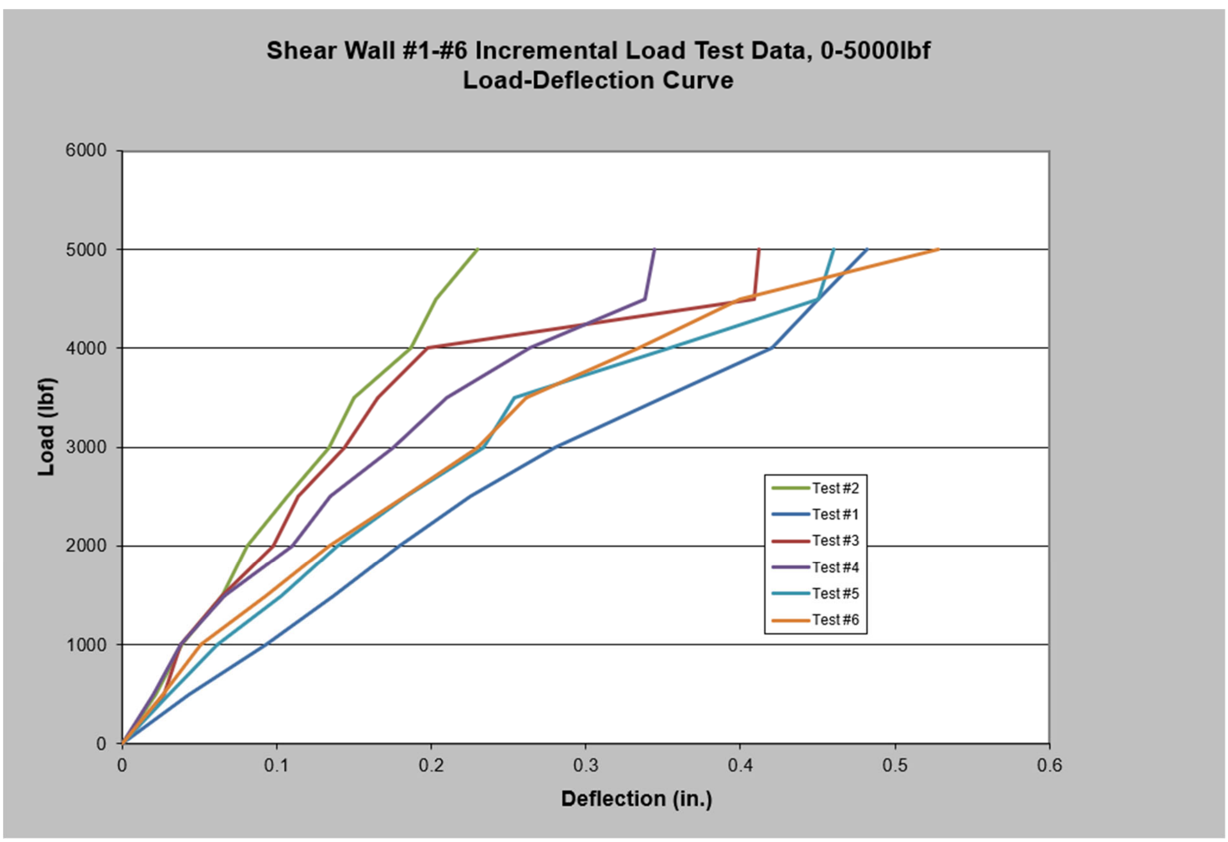


Fig 5. Graph from AME report page 3 of 7

Analysis and Discussion

As stated previously, to simulate the continuous plane of concrete, all test specimens were loaded in 500 lb increments to 5000 lbs. with a wooden block inserted into the open end of the specimen to prevent the overturning moments from crushing the foam Figs 3a and 4c. Specimen #2 and specimen #3 were cast with additional concrete around the 146-degree bend of the GFRP spar to ascertain any difference in behavior, Fig 6a and 6b.

Figure 6a samples 2&3 specimen prep

Figure 6b sample 3 post testing

To capture the forces in the spars under varying loads Finite Element Model's (FEM) were prepared representing the materials and sizes of the test specimens. The wooden block was simulated with a roller at the upper wythe of the open end (the side away from the ram). Two models were prepared, one without the additional concrete encasing the 134-degree bend (the standard 3" wythe corresponding to test specimens # 1, #4, #5 and #6) and one which included the additional concrete corresponding to test specimens #2 and #3.

The AME load deflection curves with the results of the FEM's overlaid onto the graph is shown in Fig 7a and the internal GFRP spar forces are shown in Fig 7 b.

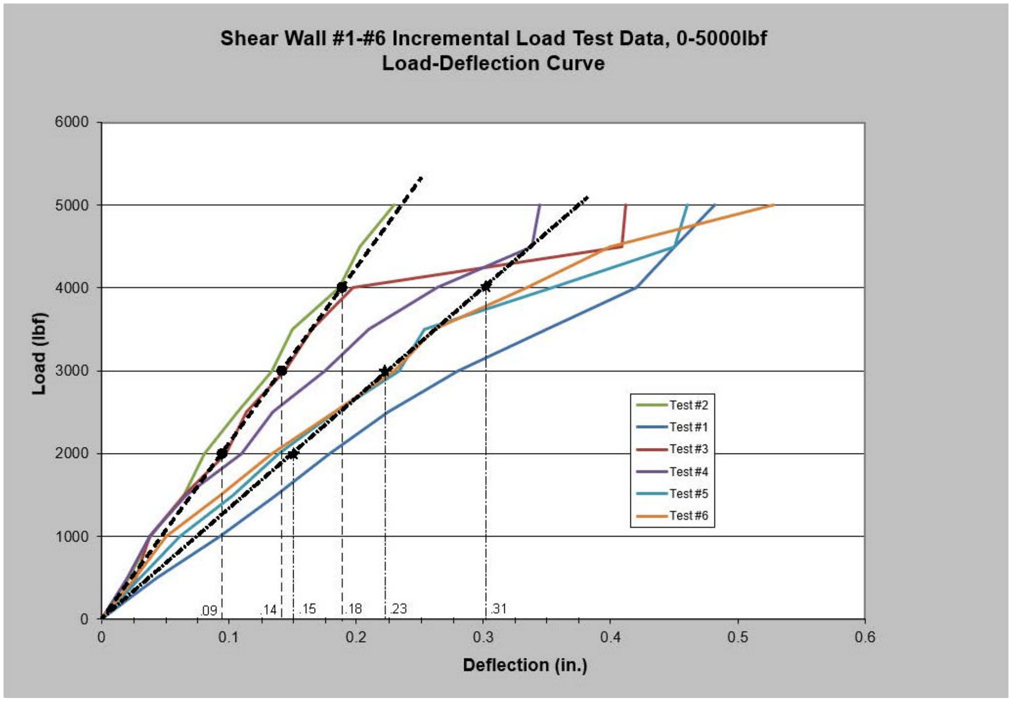


Figure 7a AME load deflection curves with FEM overlays

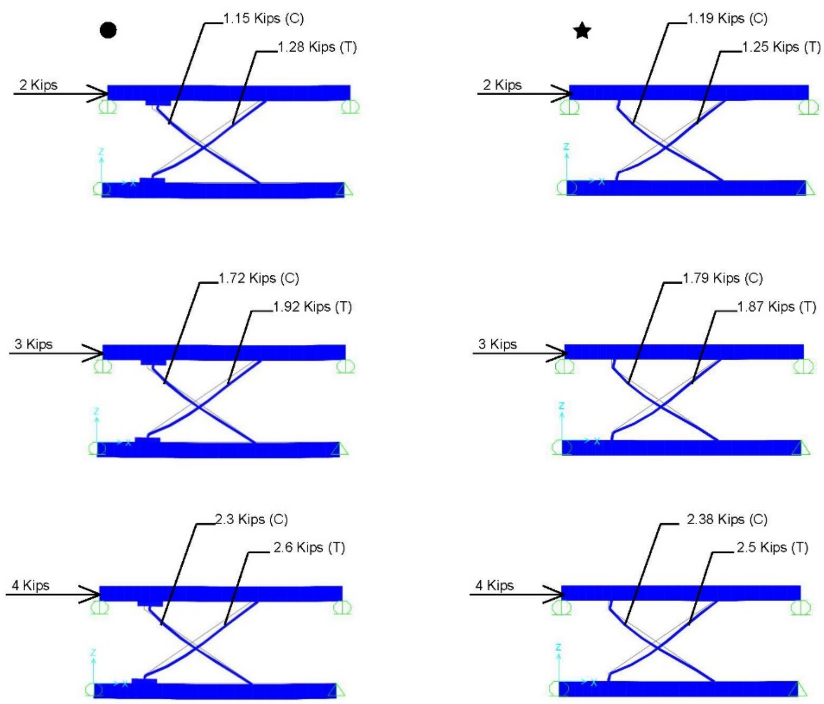
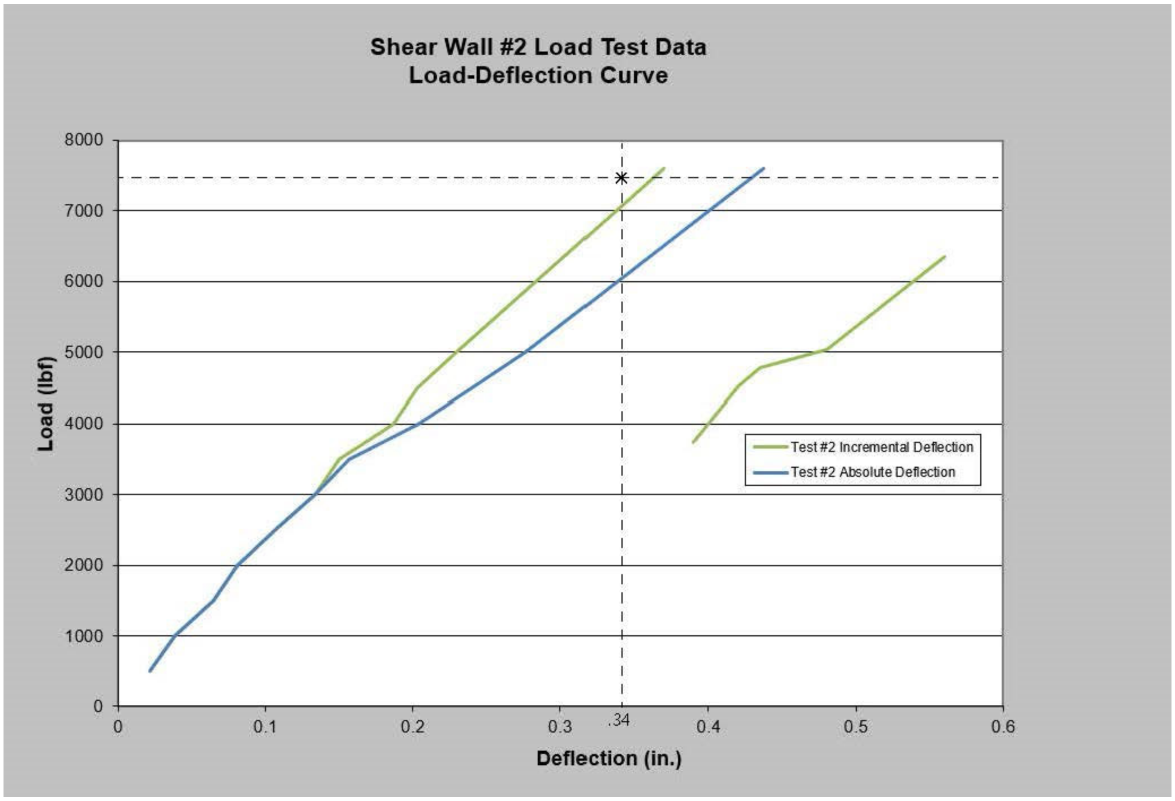


Figure 7b FEM models at different ram forces

Additionally, two specimens # 2 and #5 were loaded to 7500 lbs. Specimen # 2 was secured in the test frame as before, including the wooden block at the open end. Specimen #5 was secured into the test frame but in this case the wooden block was removed from the test setup to bracket the behavior. AME graphs for these two cases as well as the FEM results are shown in Fig 8a- 8b.



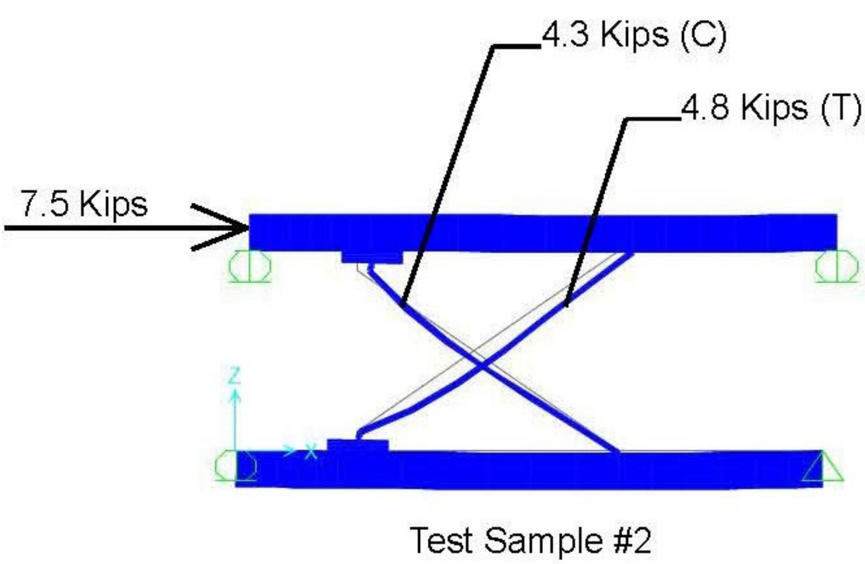
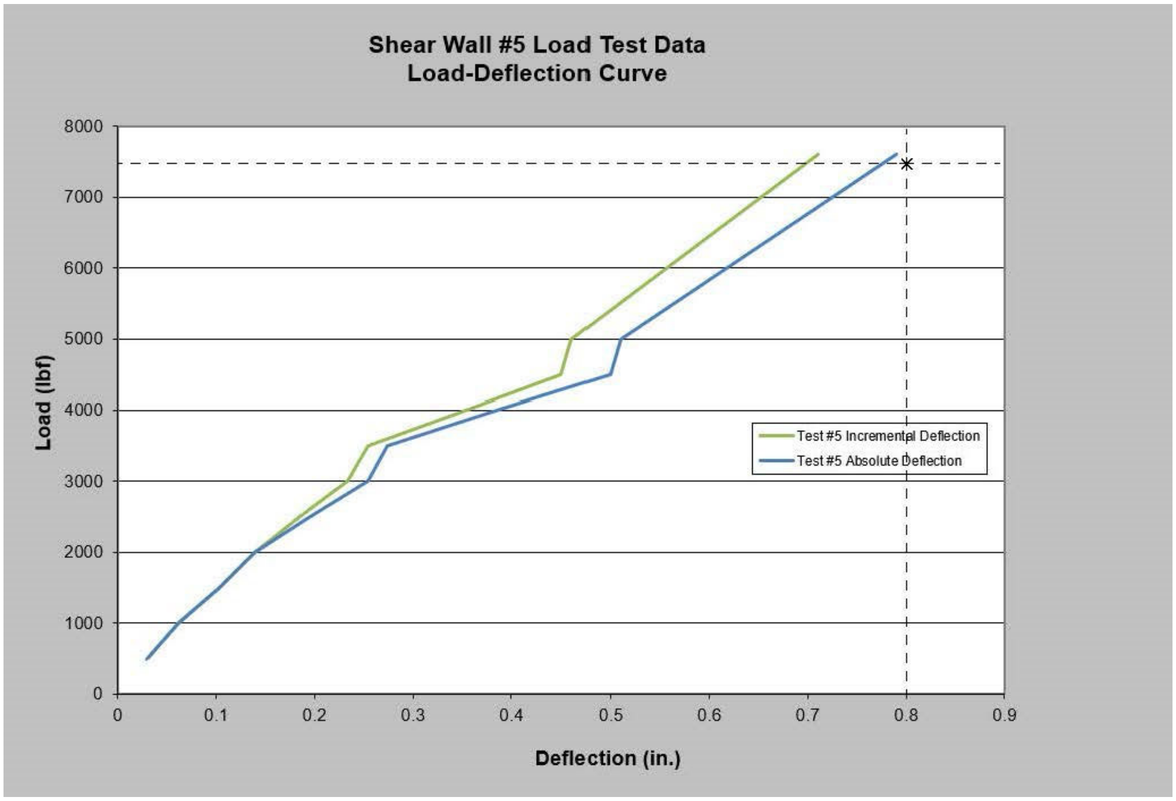


Figure 8a Load deflection curve and FEM sample 2



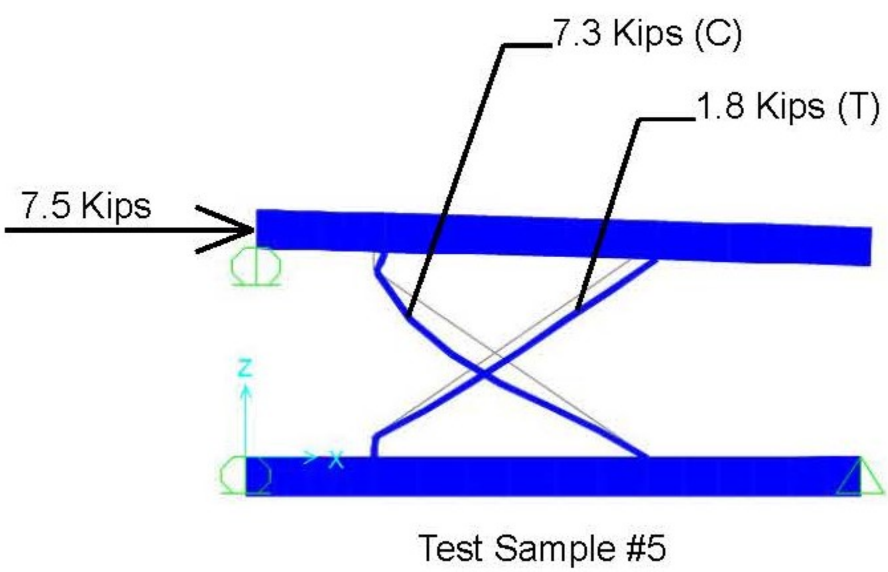


Figure 8b Load deflection curve and FEM sample 5

Conclusions

Tests were conducted on six Energy Mass™ wall samples built with GFRP spars. Under the testing regime the spars resisted both compression and tension. All six samples were tested to a maximum ram load of 5,000 lbs. Two of the test samples (one with and one without the block) were further tested to a maximum ram force of 7500 lbs.

The maximum tension reached by a spar (at the 7500 lb. ram force) was 4,800 lbs. Maximum compression force of 7,300 lbs. was reached in the spars without the end block. Following testing, the samples were investigated by cutting away the internal foam core exposing the spars and their attachment at the inner side of each wythe Fig. 9. No concrete spalling, or cracking was observed at the point of entry of the spars into the concrete wythes, and, no deterioration of the spars was observed

Figure 9 Spar attachments to concrete wythes

along their length or at the intersection with the concrete wythes. There was no evidence of compression spar buckling which was consistent with predictions because the spars are restrained from buckling by a continuous matrix of 2 lb density closed cell polyurethane foam encasing the spar throughout its' length.

The two specimens (#2 and #3) with the additional concrete plug at the 146-degree bend exhibited greater stiffness. This is most likely due to bending of the spar at the intersection with the concrete wythe in the specimens without the plug. When the additional shotcrete is placed around a pre-cut hole in the foam (Figs 6a and 6b), the concrete encases the bent portion of the spar, reducing the ability of the hook to bend under tension or compressive loads giving rise to greater stiffness. We note, however, that at the loads tested there was no difference in the *strength* of the system, with or without the concrete plug.

The samples were not tested to destruction due to limitations of the testing set-up and equipment. Consequently, failure modes were not observed as part of this test. However, in a comparison of testing results and ACI code limitations, the following limits were observed or calculated:
(i) Code limitations ACI 440.1 R-15 [7] 6.2.1 (tensile strength at bends). 9,800 lbs.
(ii) Mechanics of materials limitations (elastic buckling) P_c = 830 lbs.
(iii) Physical testing [2] tension failure at 14,000 lbs.
(iv) Physical testing of GFRP spars (not to failure), 7,300 lbs. compression, 4,700 lbs. tension

Currently the design practice for the Energy Mass™ wall is to limit the spar forces to the theoretical elastic buckling load of the #4 bar discounting the restraining capacity of the foam. This limits the in-service design loads to roughly 8% of the code limitation of 9,800 lbs. or an omega value of 12.

References

[1] Park R. and Paulay, T. Reinforced Concrete Structures, Wiley and Sons, 1979; pp. 410-415.
[2] Black G, Mannik, H, Spar and Membrane Structure, The Last Straw, Winter 1997 pp. 10-11.
[3] Muhareem Laz, Mario, Euro Design Construction, 1322 Shattuck Ave. Berkeley CA 94709.
[4] Duckworth, Oscar, Valley Concrete Services, 3200 Canfield Road, Sebastopol, CA.
[5] Kleinfelder, 9969 Horn Road, Sacramento, CA.
[6] Tajirian, A, P.E., Ph.D., Applied Materials & Engineering 980 41st street, Oakland, CA
[7] ACI 440-1R-15.

APPENDIX

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November 26, 2018

Mr. Gary Black
Integrated Structures, Inc.
1250 Addison Street, Suite #214
Berkeley, CA 94702

Project Number 1170988C

Subject: Concrete Wall Shear Laboratory Load Testing

Dear Mr. Black:

As requested, Applied Materials & Engineering, Inc. (AME) has completed testing concrete sample walls for lateral (shear) load capacity.

SAMPLE DESCRIPTION

Each concrete wall construction is composed of two 3" thick concrete panels separated by a core of insulating foam. The concrete panels are connected by GFRP spars as illustrated in Figure A1.

TEST PROCEDURES & RESULTS

1. Shear Load Test

A total of six samples were tested for shear load capacity using a five-ton capacity hydraulic ram with 2" stroke. The lower concrete panel of each sample was rigidly constrained to the test fixture and a lateral load was applied to the top concrete panel. The top concrete panel was constrained to lateral displacement by restraining vertical displacement at the ram side during loading. As load was applied, a dial gauge with .001" precision measured the lateral displacement of the upper concrete panel relative to the fixed lower concrete panel. The samples were loaded up to 5000 lbf in 500 lbf increments; deflection was recorded at each increment. Between each incremental increase of 500 lbf, the load was released and the system allowed to equilibrate before re-loading the sample. Load-deflection data of the six tests can be found in Figure 1.

Based on our testing, the average deflection at 5000 lbf shear load was 0.409". Images of test setup can be found in Appendix B.

Respectfully Submitted,

APPLIED MATERIALS & ENGINEERING, INC.

Joseph Gapuz
Joseph Gapuz
Laboratory Manager

Reviewed by:

Armen Tajirian, Ph.D., P.E.
Principal

REGISTERED PROFESSIONAL ENGINEER
ARMEN TAJIRIAN
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TABLE I

SHEAR LOAD TEST RESULTS

CONCRETE SAMPLE WALLS

PROJECT NUMBER 1170988C

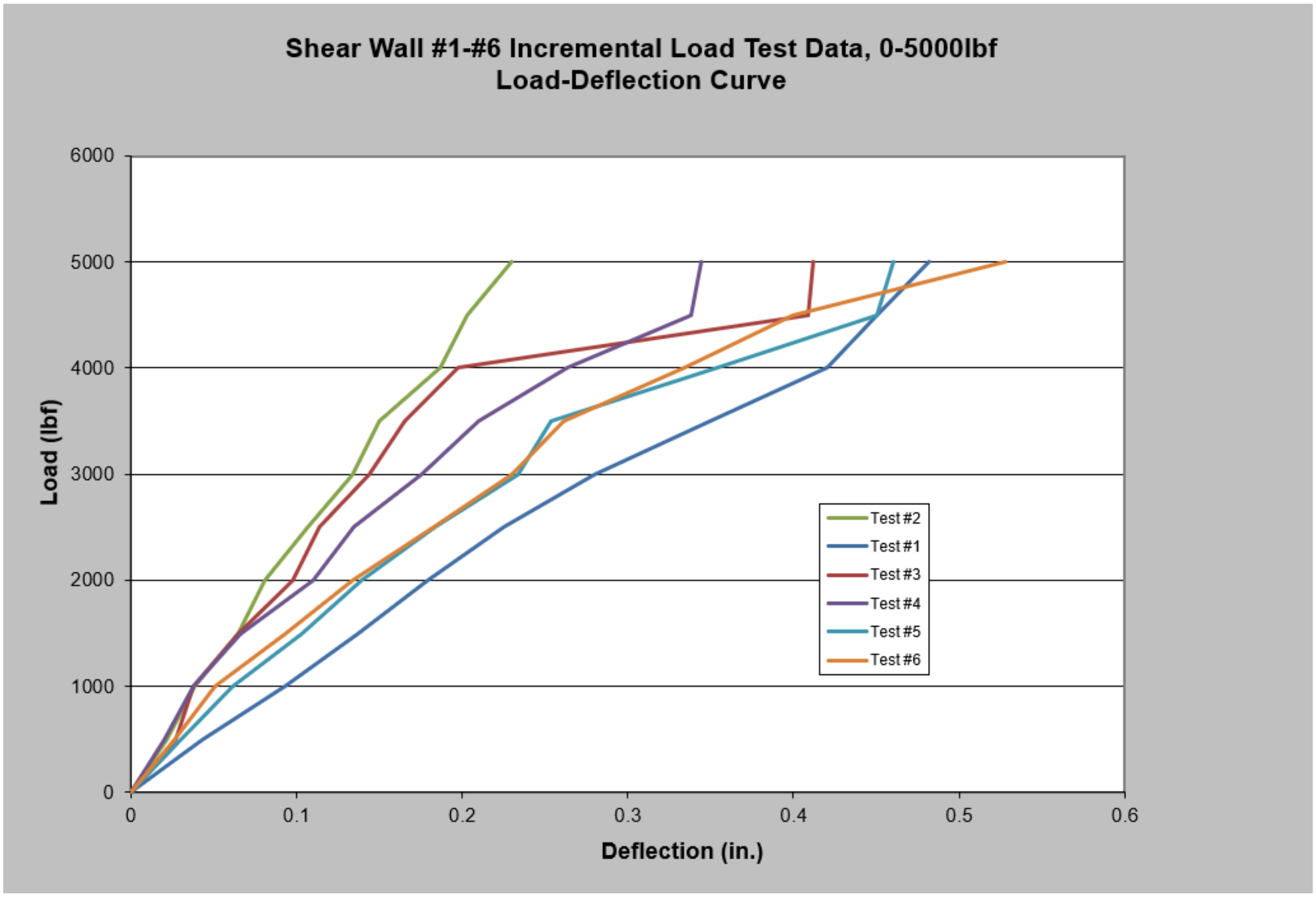
SAMPLE	DEFLECTIONS AT 500 LBF INCREMENTS (in.)									
	500 lbf	1000 lbf	1500 lbf	2000 lbf	2500 lbf	3000 lbf	3500 lbf	4000 lbf	4500 lbf	5000 lbf
#1	0.043	0.093	0.137	0.179	0.225	0.280	0.350	0.420	0.450	0.482
#2	0.022	0.039	0.065	0.081	0.107	0.134	0.150	0.187	0.203	0.230
#3	0.027	0.038	0.065	0.098	0.114	0.144	0.165	0.198	0.409	0.412
#4	0.020	0.038	0.066	0.110	0.135	0.175	0.210	0.264	0.338	0.344
#5	0.030	0.062	0.103	0.139	0.184	0.234	0.254	0.354	0.450	0.460
#6	0.026	0.051	0.093	0.134	0.183	0.230	0.261	0.334	0.400	0.528
AVERAGE	0.028	0.054	0.088	0.124	0.158	0.200	0.232	0.293	0.375	0.409

FIGURE 1

SHEAR LOAD-DEFLECTION TEST RESULTS

CONCRETE SAMPLE WALLS

PROJECT NUMBER 1170988C



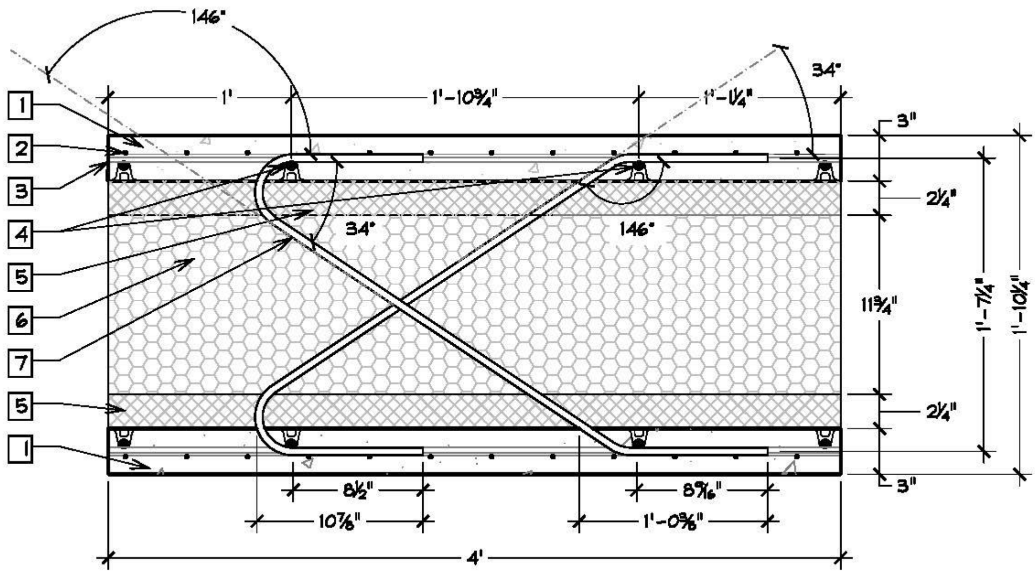
Lateral displacement of upper concrete panel relative to lower concrete panel when sample wall is loaded in shear.

APPENDIX A

FIGURE A1

CONCRETE SAMPLE WALL DIAGRAM

PROJECT NUMBER 1170988C



1. 3" WYTHE SHOTCRETE
2. 4x4-D2.9, D2.9 WELDED WIRE FABRIC, TRANSVERSE WIRES FACING TO EXTERIOR OF WALL ASSEMBLY
3. NO. 4 60KSI STEEL REBAR
4. NO. 4 TRANSVERSE REBAR IN ¾" CHAIR, INDEXES REBAR ASSEMBLY
5. STANDARD QUAD-LOCK FORM BLOCK, 2¼" XPS
6. GACOPOLYFOAM 2000, EXPANDED POLYSTYRENE FOAM
7. NO. 4 GFRP 'SPAR', TUF-BAR 40GPA FIBERGLASS REBAR

APPENDIX B

<u>**FIGURE B1**</u>

Figure B1a. Steel frame test apparatus with sample being loaded.

Figure Blb. Elevation of testing apparatus with sample.