Cyclic In-Plane Shear of Concrete Masonry Walls Strengthened by FRP Laminates

by M.A. Haroun, A.S. Mosallam, and K.H. Allam

Synopsis: Cyclic in-plane shear tests were conducted on six full-scale walls built from reinforced concrete masonry units and strengthened by unidirectional composite laminates. Carbon/epoxy, E-glass/epoxy and pre-cured carbon/epoxy strips were placed on one or both sides of the walls. Each wall sample was loaded with a constant axial load simulating the gravity load, and incremental cyclic lateral shear loads were applied in accordance with the Acceptance Criteria (AC-125) of the International Code Council Evaluation Services (ICC-ES 2003). Displacements, strains and loads were continuously monitored and recorded during all tests. Evaluations of the observed strength and ductility enhancements of the strengthened wall samples are made and limitations of such retrofit methods are highlighted for design purposes.
Results obtained from current tests indicated that the limit-state parameter influencing strength gain of the FRP retrofitted walls was the weak compressive strength of the masonry units, especially at the wall toe where high compression stresses exist. Despite such a premature failure caused by localized compression damage of the masonry at the wall toe, notable improvement in their behavior was achieved by applying the FRP laminates to either one or two sides of the walls. However, it should be cautioned that available theoretical models may significantly overestimate the shear enhancement in the FRP strengthened walls, if other limiting failure modes are not considered.

Keywords: FRP laminates; in-plane cyclic loads; masonry walls; retrofit and repair

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INTRODUCTION AND RESEARCH SIGNIFICANCE

Polymer composites have been accepted by the construction industry worldwide as structurally-efficient and cost-effective repair and rehabilitation systems. For the past decades, fiber reinforced polymer (FRP) composites have been successfully used to strengthen seismically-deficient and corroded reinforced concrete members, as well as masonry and wood members.

The 1994 Northridge, California, earthquake caused many structures to shift over the first story due to lack of adequate shear strength. Since then, there has been a significant research interest to study the seismic shear behavior of both reinforced and un-reinforced masonry walls. (Ehsani et al, 1999, Haroun and Ghoneam, 1997, Mosallam and Haroun, 2003, Mosallam et al, 2001). Reinforced masonry wall design is generally based on an elastic approach that focuses, mainly, on the linear behavior of the wall with no consideration of the effect of energy dissipation that occurs in the non-linear range. In addition, the majority of building codes have mainly concentrated on calculating the required vertical wall reinforcement to resist flexural moments. The small inadequate ratio of horizontal steel was shown to be incapable of resisting the seismic shear that occurred in recent seismic activities. The horizontal reinforcement considered for lateral load is not sufficient to resist high frequency earthquakes and provide ductility against the possibility of collapse. Consequently, there has been a need for utilizing more effective alternative techniques to increase the shear strength of these walls and to improve their ductility performance.

WALL SAMPLES AND TEST SETUP

The scope of this research program was to evaluate the in-plane shear behavior of masonry walls externally reinforced with FRP composite laminates. Six full-scale wall samples were tested under a combination of constant axial load with incremental lateral (push-pull) cyclic loads. As shown in Figure 1 and 2, each wall specimen was 72 in. (183 mm) high and 72 in. (183 mm) long, and constructed from one wythe of 6 in. x 8 in. x 16 in. (152 mm x 203 mm x 406 mm) hollow concrete blocks. Each wall has a base footing and a top loading reinforced concrete beam. The walls were fully grouted and detailed with five vertical reinforcing bars placed uniformly in the wall. These bars were continuous from the footing base to the top beam without any lap splice, and were strain gauged at the base-wall intersection level to capture the first yield of the steel bars. All wall specimens had a vertical steel reinforcement ratio of 0.54% with no horizontal reinforcement in the direction of the applied shear force to simulate a deficient and/or old wall construction. Four short dowels were distributed between the vertical steel bars at each interface between the wall and both the top loading beam and the footing.

As noted above, the wall specimens were built with a height-to-length aspect ratio of 1:1 to promote a shear dominated behavior under in-plane loading. Wall specimen number 1 was used as a control wall (as-built) whereas wall number 2 was cracked first and used for investigating repair techniques. The remaining four wall specimens were retrofitted with unidirectional carbon/epoxy laminates on one or two sides, E-glass/epoxy laminates on two sides, and carbon strips overlay on one side of the wall (Table 1).

All wall samples were built at the same time, and shared materials from the same batch. The reinforcing bars were grade 60 and were tested, according to ASTM standards, to measure the tensile strength as displayed in Table 2. Strength tests at 28 days on masonry prisms, grout cylinders, and mortar cylinders yielded 485 psi (3.34 MPa), 2750 psi (18.96 MPa), and 2120 psi (14.62 MPa), respectively. For the carbon/epoxy and E-glass/epoxy laminates, a specimen from each batch, 12 in. x 12 in. (304 mm x 304 mm), was fabricated and tested to ensure the same quality for all retrofitted specimens. All such specimens were tested to obtain their ultimate strength, modulus at yield and strain at ultimate strength as listed in Table 3.

The in-plane wall displacement was monitored by three displacement potentiometers located at height 24 in. (610 mm), 48 in. (1219 mm), and 71.5 in. (1816 mm), and the loading beam displacement was measured at 82 in. (2082 mm), all from the wall base level. For all tests using FRP laminates, strain gages were bonded on the external surface of the FRP to monitor the tensile/compressive strain.

GENERAL OBSERVATIONS

For all tested specimens, each wall was cycled laterally (in-plane) following a specified load-control regime. Once yielding has been achieved, a displacement control regime is adopted. At each load or displacement level, the wall is cycled for three identical cycles.

As-Built Wall

The control as-built wall was cyclically tested to failure and demonstrated a pure shear mode. The failure of the specimen was initiated by diagonal shear cracks and developed a diagonal strut action resulting in the crushing of the wall edge boundaries under compressive stresses. The wall cracking is displayed in Figure 3 and the hysteretic loops of the wall are shown in Figure 4 illustrating the sudden degradation of strength and stiffness of the as-built wall specimen at a low ductility level.

Repaired Wall

To demonstrate the use of composite laminates in the possible repair of a cracked wall, specimen number 2 was cyclically pre-cracked and then repaired and retested. In the pre-cracked wall specimen, two major localized damages appeared: diagonal shear cracks across the wall and local compression failure of the wall toe on one side. The diagonal cracks and the wall toe were first repaired with high strength epoxy resin, and then a single layer of carbon/epoxy composite laminate was applied on each side of the wall. In addition, a U-shaped laminate was applied at the pre-damaged toe.

The failure of the repaired wall was dominated by a combination of shear and flexural modes contrary to the single shear mode of the as-built wall. The primary mode of failure was attributed to the exceedance of the compressive strength at the end elements of the wall. This failure led the wall to lose its overall stiffness and become unable to resist any further lateral load. The addition of a U-shaped laminate at the cracked wall toe resulted in increasing the strength at this location, and consequently, it pushed the failure to occur at the un-reinforced toe on the other side of the wall. When the performance of the repaired wall is compared with that of the as-built wall, it becomes clear that the repair technique has improved the strength and energy dissipation of the wall. It not only succeeded in restoring the capacity of the original wall, but also increased it to a level 120 % of that of the original wall capacity. The energy dissipation observed for repaired specimen was also increased to 167 % of that of the control wall.

Retrofitted Walls

The predominant mode of failure in all single-side strengthened wall specimens was in the form of shear failure of the un-strengthened side of the wall. This shear failure was a combination of diagonal tension cracks as well as step cracks initiated at the base of the un-strengthened face. However, unlike the as-built specimen, single-side strengthened wall specimens suffered from another mode of localized failure in the form of a compression crushing of one of the wall toes. In fact, this localized failure mode at the wall toes was the controlling factor in determining the ultimate capacity of the single-side strengthened wall specimens.

The common mode of failure of all two-side FRP strengthened wall specimens was also compressive failure of the masonry units at the bottom ends (toes) of the wall specimens (Figure 5). The application of the composite laminates to the two sides of the wall specimens contributed an appreciable stiffness gain which was evident from the displacement profiles of such specimens. However, the overall usable strength gain was limited by the masonry compression properties rather than the ultimate tensile strength of the unidirectional FRP laminates. This applies to all FRP strengthening systems evaluated in this study, including E-glass/epoxy wet lay-up laminates, carbon/epoxy wet lay-up laminates, and pre-cured unidirectional carbon/epoxy strips. The premature compression failure of the wall toes resulted in appreciable shear and flexural stiffness degradations that was amplified by the loss of the grout confinement leading to local buckling of the vertical steel bars near the ends of the walls. It is recommended to develop optimized techniques to enhance the properties of masonry at the wall toes. One simple technique, which was adopted and was proven effective in the repair application in this study, is to apply an FRP U-laminate at the bottom ends and through the thickness of the wall.

One important observation noted from all retrofitted test specimens, at high stress level and just before the failure, was the development of white lines parallel to the fibers at the neighborhood of the mortar lines. This can be attributed to the development of large shear deformation at the mortar lines that resulted in fracture of the non-structural cross-stitches holding the unidirectional fibers, parallel to the applied in-plane loads. This can serve as an indicator for damages of either the masonry and/or the mortar hidden under the composite laminates of the FRP strengthened walls.

Unlike the wet lay-up strengthening systems, cohesive debonding of the ends of the pre-cured carbon/epoxy strips was observed at higher stress levels following the large deformation caused by the compression failure of the masonry units at the wall toes and the local buckling of the unconfined bottom length of the vertical steel bars near the damaged masonry.

SUMMARY OF EXPERIMENTAL RESULTS

Despite the premature failure caused by localized compression failure of the masonry at the wall toes, notable gains in strength, stiffness and ductility were achieved by applying the FRP laminates to either one or two sides of the walls. Adding a single carbon layer at each side of the pre-damaged wall specimen resulted in 20% strength gain as compared to capacity of the as-built specimen that was tested to failure. For a retrofitted wall specimen strengthened with a single ply of carbon/epoxy at both sides of the wall (Figure 6), the capacity was 130% of the ultimate capacity of the as-built specimen, while the capacity of the single-side carbon/epoxy retrofitted wall was 115% as compared to the control specimen. The E-glass/epoxy double-side retrofitted wall achieved a slightly less strength gain, where the ultimate capacity was 128% of the as-built wall capacity. For the wall specimen retrofitted with carbon/epoxy strips applied to a single side, the ultimate capacity was 118% of the as-built ultimate capacity. Table 4 presents a summary of the ultimate strength of all specimens tested in this study. A strength comparison between the different wall specimens is also presented in Figure 7.

The ductility of the carbon/epoxy repaired specimen was 1.7 times that of the as-built specimen. For the retrofitted specimens, the enhancement in the ductility ranged from 3.4 times that of the as-built in case of double-side carbon/epoxy retrofit to 6 folds in the case of pre-cured carbon/epoxy strips.

ANALYTICAL EVALUATION OF WALL CAPACITY

The shear capacity of a masonry wall strengthened by FRP laminates can be divided into two components

$$V = V_m + V_f \tag{1}$$

where V is the total shear capacity of the strengthened wall, V_m is the shear strength of the masonry wall alone, and V_f is the shear strength contributed by the FRP laminates.

According to Pauley and Priestley (1992), the shear strength of the masonry wall can be estimated using the following relation

$$V_m = v_m\, d_w\, t_w \tag{2}$$

where d_w is the effective length of the wall taken as 0.8 of the actual length L_w of the wall, t_w is the wall thickness, and v_m is the masonry shear stress which empirically depends on the masonry crushing strength, the applied axial load, and the wall's gross cross sectional area. Application of Equation 2 shows that the shear strength contributed by the masonry only for all walls under consideration is 50.5 kips (225 kN).

The shear strength of the carbon/epoxy laminate was calculated based on AC-125 ICC-ES Acceptance Criteria (2003). Accordingly, the shear strength enhancement for a rectangular wall section of length L_w in the direction of the applied shear force, with a laminate thickness, t_f, on two sides or one side of the wall at an angle, θ, to the wall axis is calculated from the following relations

For a <u>two-sided</u> retrofit $$V_f = 2.0\, t_f\, \sigma_f\, L_w \sin^2\theta \tag{3a}$$

For a <u>single-sided</u> retrofit $$V_f = 0.75\, t_f\, \sigma_f L_w \sin^2\theta \tag{3b}$$

in which $$\sigma_f = 0.004\, E_f \leq 0.75\, \sigma_{uf} \tag{4}$$

where σ_f is the stress developed in the laminates; E_f is the longitudinal modulus of elasticity of the FRP composite material; and σ_{uf} is the ultimate tensile strength of the laminates. The above equations may only be applied to FRP laminates. In the case of carbon/epoxy strips, the equation proposed by Zhao et al (2002) may be used. Table 5 shows the theoretically computed shear strength of the tested wall samples, if only shear enhancement is taken into consideration. These are clearly much higher than those observed experimentally. However, if flexural behavior of the wall is also considered (Allam 2002), lower and upper bounds of the lateral load that can be resisted by the walls were calculated at 71.5 kips (318 kN) and 120 kips (534 kN), respectively, which are more consistent with test observations.

CONCLUSIONS

The main purpose of this study was to evaluate the gain in the shear strength of reinforced masonry walls when repaired or retrofitted by FRP laminates. However, results obtained from current tests indicated that the limit-state parameter influencing the strength gain of the FRP retrofitted walls are the weak compressive strength properties of the masonry units, especially at the wall toes where high compression stresses exist.

Despite the premature failure caused by localized compression failure of the masonry at the wall toes, notable gains in strength, stiffness and ductility were achieved by applying the FRP laminates to either one or two sides of the walls. However, it should be cautioned that available theoretical models significantly overestimate the shear enhancement in the FRP strengthened walls. For this reason, serious modifications to these equations must be made to reflect the actual performance of the strengthened walls in shear and to consider other major limiting factors on the strength gain of such walls.

RECOMMENDATIONS

It is recommended to develop optimized techniques to enhance the properties of masonry at the wall toes. One simple technique, which was adopted and was proven effective in the repair application in this study, is to apply an FRP U-laminate at the bottom ends and through the thickness of the wall. For field applications, a slit can be made at the ends of the walls for about 1 to 2 feet (0.3 to 0.6 meters) above the footing or the floor level, where a thin wet lay-up laminate can be applied in a U-shape on both sides of the wall and through the wall thickness. In order to validate this concept, both experimental and analytical studies should be conducted.

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REFERENCES

Allam, K. H. (2002), "In-Plane Cyclic Behavior of Concrete Masonry Walls Enhanced by Advanced Composite Laminates," Master Thesis, University of California, Irvine, USA.

Ehsani, M., Saadatmanesh, H., and Velazquez, J.L. (1999), "Behavior of Retrofit URM Walls under Simulated Earthquake Loading," Journal of Composites Construction, Vol. 3, pp. 134-142.

Haroun, M.A., and Ghoneam, E.H. (1997), "Seismic Performance Testing of Masonry Infilled Frames Retrofitted by Fiber Composite," Proceedings of the International Modal Analysis Conference, Vol. 2, Orlando, Florida, pp. 1650-1656.

International Code Council – Evaluation Services ICC-ES (2003), "Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber Reinforced Polymer (FRP) Composite Systems," AC-125, Whittier, California.

Mosallam, A.S., and Haroun, M.A. (2003), "Seismic Strengthening of Unreinforced Thick Masonry Walls Using Polymer Composites," Proceedings of 10th Structural Faults and Repair Conference, London, United Kingdom (CD).

Mosallam, A., Haroun, M., Almusallam, T., and Faraig, S. (2001), "Experimental Investigation on the Out-of-Plane Response of Unreinforced Brick Walls Retrofitted with FRP Composites," Proceedings of 46th International SAMPE Symposium, Vol. 2, California, pp. 1364-1371.

Paulay, T., and Priestley, M. J. N., Seismic Design of Reinforced Concrete and Masonry Buildings, John Wiley & Sons, 1992.

Zhao, T., Zhang, C.I., and Xie, J. (2002), "Study and Application on Strengthening Cracked Brick Walls with Continuous Carbon Fiber Sheet," Proceedings of 1st International Conference on Advanced Polymer Composites for Structural Applications in Construction, Southampton, United Kingdom, pp. 309-316.

Table 1 -- Test Matrix

Test #	Wall #	Test Code	Test ID
1	1	WU1	Control (ultimate)
Description: As-built.			
2	2	WU2	Control (cracked)
Description: As-built to be repaired with carbon/epoxy laminates.			
3	2	WU2-C-R	Carbon/epoxy repair
Description: Single layer of carbon/epoxy laminate on each side of the repaired wall.			
4	3	W3-C-RT	Carbon/epoxy retrofit
Description: Single layer of carbon/epoxy laminate on one side of the retrofitted wall.			
5	4	W4-C-RT	Carbon/epoxy retrofit
Description: Single layer of carbon/epoxy laminate on each side of the retrofitted wall.			
6	5	W5-E-RT	E-glass/epoxy retrofit
Description: Two layers of E-glass/epoxy laminate on each side of the retrofitted wall.			
7	6	W6-CS-RT	Carbon strips retrofit
Description: Horizontal strips spaced 4 in. (101 mm), on center, on one side of the retrofitted wall.			

Table 2 -- Properties of Reinforcing Steel

Bar size	Yield Stress, ksi (MPa)	Ultimate Strength, ksi (MPa)
# 6	60 (414)	94 (648)

Table 3 -- Properties of FRP Composite Materials

Type	Thickness (t) inch (mm)	Ultimate Strength ksi (MPa)	Strain at Ultimate (μ strain)	Modulus of Elasticity ksi (GPa)
Carbon/epoxy	0.045 (1.14)	154 (1,061)	0.012	14×10^3 (96.5)
E-glass/epoxy	0.045 (1.14)	74 (510)	0.022	3.5×10^3 (24.2)
Carbon strips	0.047 (1.19)	420 (2,896)	0.018	22×10^3 (151.7)

Table 4 -- Summary of Ultimate Strength of Tested Wall Samples

Sample ID	Description	Ultimate Strength, kips (kN)
WU1	Control (ultimate)	83 (369.18)
WU2	Control (cracked)	62 (275.78)*
WU2-C-R	Carbon/epoxy repair (two sides)	100 (444.8)
W3-C-RT	Carbon/epoxy retrofit (single side)	95 (422.6)
W4-C-RT	Carbon/epoxy retrofit (two sides)	108 (480.38)
W5-E-RT	E-glass/epoxy retrofit (two sides)	106 (471.49)
W6-CS-RT	Carbon strips retrofit	98 (435.9)

*Maximum load at which the cracking test was stopped.

Table 5 -- Theoretical Shear Strength of Tested Wall Samples

Sample ID	Masonry Strength kips (kN)	FRP Strength kips (kN)	Total Strength kips (kN)
W3-C-RT	50.5 (225)	134.1 (596)	184.6 (821)
W4-C-RT		357.7 (1,591)	408.2 (1,816)
W5-E-RT		181.4 (807)	231.9 (1,032)

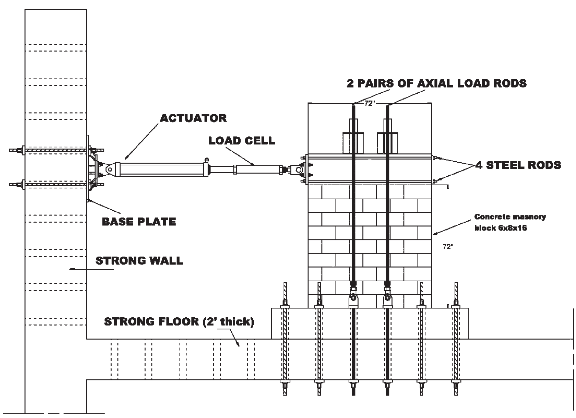

Figure 1 — Test Set-Up.

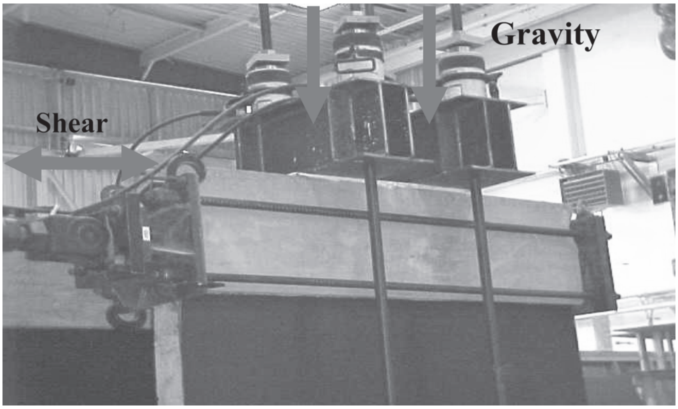

Figure 2 – Gravity and Cyclic Shear Loading on Typical Wall.

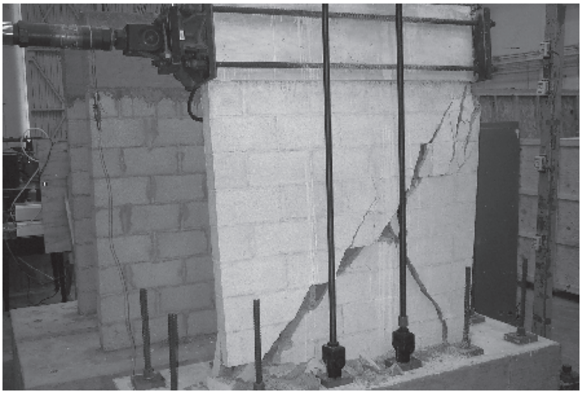

Figure 3 — Shear Failure of the As-built Wall Sample.

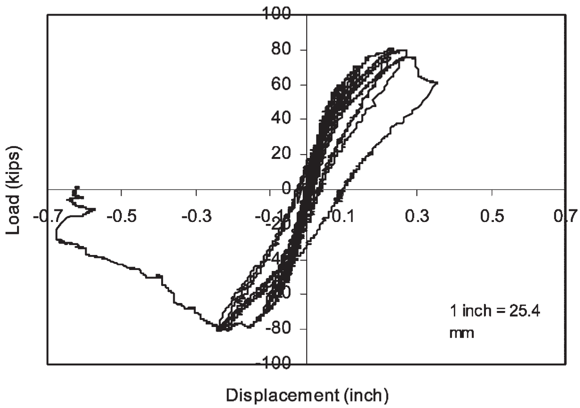

Figure 4 — Hysteretic Loops of the As-built Wall Sample.

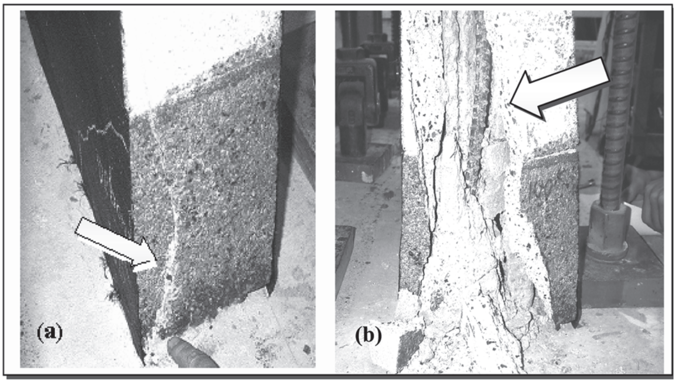

Figure 5 — Premature Compression Failure of Masonry Units at Wall Toes
(a) Crack Initiation (b) Local Buckling of the Far-End Vertical Steel Rebar.

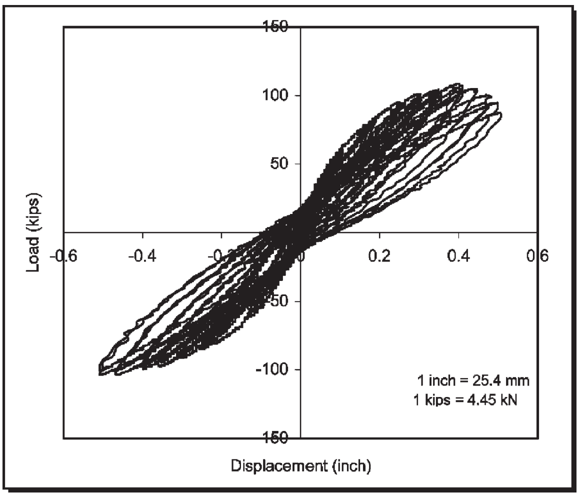

Figure 6 – Hysteretic Loops of Retrofitted Wall Sample W4-C-RT.

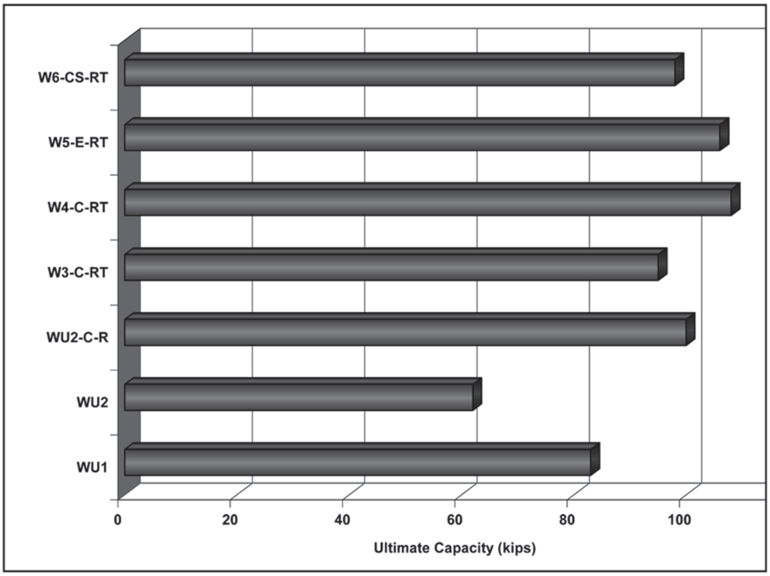

Figure 7 — Strength Comparison of Tested Wall Samples.