Seismic testing of light frame shear walls

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ABSTRACT

Six shear walls were built from various sheathing materials. The specimen size was determined so that each specimen would be expected to resist the seismic load from a single mass. The materials tested were 3/8 inch CD plywood, 3/8 inch rated oriented strand board and ½ inch gypsum wallboard. A wall specimen made from 4-ply plywood was determined to be a baseline configuration. Force-controlled cyclic loading protocol was used for all tests. The mode of failure for all specimens was the pullout of nails through the sheathing. The 4-ply plywood and gypsum materials were shown to behave with several cycles of resistance and comparable levels of energy dissipation. In another series of tests, the behavior was compared for various fasteners used for gypsum wallboard. Design of the fastener style and geometry was seen to have a significant effect on the strength and stiffness of the fastener.

REPORT

In light wood framed construction the typical vertical elements in the seismic load path are shear walls. The shear walls are generally framed with vertical wood studs, and horizontal wood top and bottom plates. The wood framing is sheathed, on one or both sides with one of several materials such as plywood, oriented strand board (OSB), gypsum wallboard and/or portland cement plaster (stucco). The sheathing is nailed, stapled or screwed to the wood framing and provides the structural capacity to transfer the horizontal seismic forces from the top of the wall to its base. The sheathing material is usually considered to be loaded in a state of "pure shear", meaning that the sheathing only resists racking. Other elements in the wall are designed to resist any vertical forces that may occur.

<u>Shear wall capacity testing</u>

Most structures in the western United States are designed according to provisions in the Uniform Building Code (UBC) published by The International Conference of Building Officials (ICBO). The UBC provides the parameters and equations required to calculate a seismic load or demand on the entire building, or portion of a building such as a shear wall. The UBC also provides allowable strengths or capacities for various structural elements including shear walls. The UBC analysis and design methods commonly used are "static" design methods in that they are not time based although they are intended to represent the dynamic effects of an earthquake. Basically, a static equivalent lateral force, representing the dynamic load, is applied to the analytical model of the building. Linear elastic mechanics is then used to determine the force in individual portions of the building. The size and detailing of individual portions is then determined from the output of the analytical model.

It is difficult to verify the historic source of the structural capacities listed in the UBC for shear wall sheathing materials but it is believed that the plywood allowable shears were originally calculated from established nail lateral resistance values modified for diaphragms, load duration, framing width, sheathing thickness, etc. and verified by testing. The historic source of the UBC listed capacities for other sheathing materials, such as gypsum wallboard and plaster, is also not identified. Historically, testing of shear walls is often performed to verify the calculated capacities of manufactured sheathing materials, and often is conducted by industry representatives.

Current test specifications such as ASTM E72 and ASTM E564 provide test procedures to determine the capacity of shear walls but do not provide guidelines for the determination of allowable shears for design purposes. ASTM E72 is intended to provide comparative data for different construction elements or structural details and ASTM E564 provides methods for the determination of shear wall strength and stiffness. The ASTM tests are monotonic in the sense that the load applied to the test wall does not reverse. The test walls were simply subjected to generally increasing load until failure

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occurs. Tests of this nature performed by the APA indicate that the ratio of ultimate strength to design allowable strength is some value between approximately 3 and 6 for plywood and OSB.

Monotonic strength of a shear wall system is an important characteristic, but for seismic loading conditions the sheathing system's capacity to resist cyclic loading and to dissipate energy (ductility) is also critical. The engineering community has indicated that some materials are more brittle (less ductile) than others, and therefore may not perform as well in an earthquake. This poor performance may occur even though the monotonic strength is adequate. Because of this potentially poor performance, many engineers suspect that gypsum wallboard, and possibly also OSB, lacks adequate ductility.

Experimental testing of sheathing material

The objective of the experimental testing was to compare the performance of three different sheathing materials. Testing of walls is traditionally conducted using walls of the same length, and reported values are given per unit lineal wall length. However, when a home is constructed using different sheathing materials for the lateral system, different lengths of wall are required to resist the same lateral force. The fact that more lineal wall length exists for a sheathing material, may provide for better performance under cyclic loading. Thus the control variable for these experiments was the applied lateral force, rather than the wall geometry.

A testing protocol for this testing objective was not found in the available literature. For this report a force-controlled protocol was developed and used. A series of six tests were performed. Full-scale tested assemblies were built using either ½" gypsum drywall, 3/8" Oriented Strand Board (OSB), and 3/8" Grade C-D plywood. Sheathing was used on both faces of the shear wall. These experiments allow for a comparison of the ductility, strength and deformation capacity of the different shear wall sheathing materials. This protocol is also proposed for use to determine allowable strengths of new developments in sheathing materials and assemblies.

To allow for comparison of different materials, a hypothetical structure with a mass of 4800 kg was assumed. The 1994 UBC uses Equation 28-1 to determine a building's seismic base shear. For direct comparison, the seismic zone, importance factor, soil factor and period of vibration were assumed to be the same. This leaves only the structural factor system to vary: a value of 8 for wood sheathing and a value of 6 for gypsum wallboard. For the tests here, a design seismic coefficient of 0.1375 was used for the wood sheathing and a value of 0.1833 for the gypsum wallboard. Using these demand levels and the strength values provided in the UBC, a lineal length of wall was determined for each wall sheathing material.

The loading protocol for testing was set to be the UBC seismic zone factor, 0.4 times the acceleration due to gravity. The seismic acceleration was multiplied by the original assumed mass to determine the load for the testing protocol. During testing it was found that the peak force for the gypsum wallboard was unable to fail the wall after 20 cycles of loading. Specimen GB1 was originally tested at the original assumption of a lateral load of 40% of g. Since failure did not occur within 20 cycles of loading, the load was increased to 80% of g. This doubling of the load was based upon the 50% reduction in strength that had been used in design since the structure was assumed to be in seismic zone 4. At this much higher level of load, the specimen performed poorly. It was decided that the second test, GB2 would be performed at a more moderate level of 60% of g. Table 1 lists the specimens, the loads and the construction details.

The test fixtures were designed at working stress levels for the original test load (4240 pounds). The wood sill plate of the test wall was nailed to a 100x150 foundation with 20d common nails. The foundation was, in turn, attached to a steel test frame with steel brackets. A steel 150x100x9 angle was attached to the top plates with lag bolts and a hydraulic ram was used to apply the test load to the top plate steel angle. Hold downs were installed to the end post at each end of the test walls and pre-torqued to resisted the calculated uplift without displacement. The connections at both the top and bottom of the walls were arranged so that the test fixtures did not restrain the panel edges and the sheathing was only restrained in plane by the nailing.

All test walls were constructed with new construction grade Douglas Fir 50x100 studs, top plates and sills. The height of all walls was 2440 mm. The studs were placed at 400 mm on center. The hold down posts were 75x100 for the gypsum wallboard tests and 100x100 for the plywood and OSB tests. Moisture contents of all framing were measured and below 19%.

- **PW1 and PW2.** Both specimens were 3/8 inch plywood, but from different suppliers. The panel grade stamp rated the plywood for PW1 as grade C-D, Exposure 1, with compliance to PS-1-95, and rated for a span 24/0. PW1 was built with 4-ply plywood. The panel grade stamp for PW2 was grade C-D, Exposure 1, with compliance to PS-1-95 and rated for a span 24/0. PW2 was built with 3-ply plywood. The wall length was 1700 mm.

- **OSB1 and OSB2.** Both specimens were made from board from the same supplier: 3/8 inch OSB with 8d common nails at 6 inches on center along panel edges and 12 inches on center in the field. The panel grade stamp rated the board as grade Rated Sheathing, Exposure 1, with compliance to PS-1-92, and rated for a span 24/0. The wall length was 1700 mm.

- **GB1 and GB2.** Blocked 1/2-inch gypsum wallboard with 1-5/8" drywall nails at 4 inches on center to all framing. The nails used measured 41 mm long with a 7.4 mm diameter head and a 2.3 mm diameter shank. The wall length was 3990 mm.

The force-controlled loading function was applied for 20 full cycles or until failure, whichever occurred first. If the specimen had not failed after 20 cycles, the load was increased and the test restarted. The applied load was controlled and monitored by means of a load cell. A signal generator provided the loading function and the hydraulic ram was controlled by a servo-controller. The sinusoidal lateral load was applied at 0.2 hertz and data for all channels was sampled at 100 hertz.

Results

Figures 1 through 3 are the force-drift relationships recorded for the six specimens. Drift is calculated as the lateral displacement divided by the height of the specimen. Figure 1 shows the significant difference in the two plywood specimens. Both record similar strengths but PW2 shows much higher drifts in the early cycles of loading. Figure 2 shows the oriented strand board, and both specimens behave much the same. Figure 3 is for the gypsum wallboard. Here the two specimens have different peak force levels for the cyclic loading. Initially GB1 was loaded as described above but carried 20 cycles of loading without visible damage to the specimen. The load was then doubled, to simulate the expected loading if the 50% strength reduction mandated in the Uniform Building Code was not considered. At this higher level of loading GB1 failed after a few additional cycles as shown in the graph. For GB2 a loading level at the average of the two levels for specimen 1 was used.

All of the specimens show pinching behavior during the testing, most likely as a result of damage around the fasteners. This appears especially in the plywood and gypsum wallboard specimens. The 4-ply plywood used in test PW1 provided significantly more ductile capacity than the plywood used in PW2 and the OSB of tests OSB1 and OSB2. Specimen PW1 had a gradual increase in displacement as additional cycles of loading were applied. A similar behavior was seen in GB2.

Table 2 provides a summary of the test results. The most common mode of failure seen was nails pulling through the sheathing material. The results in the table are normalized to the PW1 specimen behavior to allow for easier comparison of the different tests. The gypsum wallboard tests provided relatively higher strength (for zone 4) and comparable energy dissipation to the 4-ply plywood.

The number of cycles that the specimen survived is also an important measure of the performance of the shear wall since significant ground motion generally occurs for several cycles during a design magnitude earthquake. The test loading, which was based on the EPGA expected by the UBC, represents a ground motion intensity that will probably last more that one cycle during a major earthquake.

If the results of PW1 are accepted as a baseline for determining an acceptance criterion, then the gypsum wallboard samples provided adequate strength, ductility and durability as represented by the number of load cycles resisted. The low quality plywood and the OSB did not provide adequate ductility and durability.

Specimen GB1 was subjected to two tests. In the first loading (GB1-a) a full 20 cycles of 0.4 g loading was applied and no failure occurred. It was then decided to subject the specimen to 0.8 g loading (GB1-b) to represent non-zone 4 UBC design capacity. Since the 1988 edition, the UBC has required the design capacity of gypsum wallboard shear walls be reduced by 50% when used to resist earthquake forces in seismic zones 3 and 4. The wall failed very quickly under this high loading. However, the total energy dissipated during the two tests was 134% of the energy dissipated in the baseline PW1 test.

For specimen GB2 it was decided to apply a 0.6 g loading because the 0.4 g loading of GB1-a was too low and the 0.8 g loading of GB1-b apparently was too severe. The wall performed very well and dissipated 94% of the baseline test energy while surviving 11 full load cycles.

The OSB specimens performed poorly. Their performance was comparable to the low quality plywood. Both OSB1 and OSB2 failed after about 0.75 cycles of loading and dissipated less than 50% of the baseline test energy.

Table 3 provides a comparison for the strength and drift levels for the different tests. Listed is a comparison between the code rated strength value and the strength achieved during testing. The gypsum wallboard is as much as 4.3 times the rated strength while the plywood is as much as 2.9 above the rated strength. It can also be seen in the table that the strength of the OSB is comparable to the plywood, although the hysteretic behavior appears far less suitable than PW1. Also listed is the drift achieved in the different cycles. An excursion is assumed to achieve full load if its' highest load is at least 95% of the highest load recorded during the testing. This 5% cushion is to account for the variation in force reading from the load cell and the slight strength degradation developed during loading. A negative sign indicates that the event occurred in a negative excursion of loading.

Wall fastener tests

In a related study a test was performed to compare the relative behavior of different fasteners for wallboard construction. A test specimen was built using five short wood studs aligned in a vertical soldier arrangement. Wallboard was attached to the two sides of the studs, allowing for a 50 mm space between the base and the middle studs. The middle studs were loaded with monotonic force and the gypsum was placed in shear by the relative displacement of the middle and end studs. The tests were conducted with ½" gypsum and used two different fasteners: 41 mm phosphate coated drywall nails and 32 mm black fine drywall screws. The gypsum was attached to the end studs with three fasteners in a row, thus 12 fasteners were tested each time. The gypsum was attached to the middle studs using twice the number of fasteners to eliminate movement during the testing; no movement at these fasteners was seen.

Figure 4 shows the monotonic strength of the different fasteners. A third configuration was tested by placing a small washer around the head of the drywall screw. This configuration simulated the use of a screw with a larger diameter head to see if this fastener alteration would significantly affect the results. As seen in Figure 4 the added washer significantly increased the strength and energy dissipated by the fastener. The maximum strength of the original screw and nail configuration was comparable. However the figure clearly shows that the screw fastener results in a much stiffer arrangement, with rapid strength degradation after the peak load is achieved.

Conclusions

Several conclusions were drawn from the tests, including:

- Pinching of hysteresis loops occurred in all wall sheathing test specimens. This appears to be due to the gap created by cyclic loading between the nails and the sheathing material.
- The stiffness of gypsum drywall is higher than the plywood and oriented strand board. Thus, gypsum drywall shear walls may attract significant load during the initial stages of an earthquake.
- The energy dissipated by the gypsum shear walls was higher than one of the plywood specimens and both of the OSB specimens.
- OSB specimens resisted fewer cycles and dissipated less energy than the plywood specimens.
- Fastener design can affect the strength and stiffness of gypsum wallboard systems.

It is also recommended that a new testing method be implemented for wall sheathing material. Manufacturer's rated strengths should be evaluated for the number of cycles to failure, energy dissipated and the hysteretic behavior. Specimens should be designed into prototypes that are expected to resist the lateral forces created during an earthquake for a standard mass. This testing evaluation method is needed to allow for consistent approval of new and innovative wall panel constructions.

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Table 1. Description of Test Panels

Specimen (1)	Design capacity (N) (2)	Test loading (N) (3)	Test loading (g's) (4)	Sheathing material (5)	Nail size (mm) (6)	Nail spacing (mm) (7)
PW1	6494	18860	0.4	3/8" CD	8d common	150 all edges, 300 field
PW2	6494	18860	0.4	3/8" CD	8d common	150 all edges, 300 field
OSB1	6494	18860	0.4	3/8" Rated	8d common	150 all edges, 300 field
OSB2	6494	18860	0.4	3/8" Rated	8d common	150 all edges, 300 field
GB1-a	8763	18860	0.4	1/2" gyp	41 x 2.3	100 all framing, blocked
GB1-b	8763	37720	0.8	1/2" gyp	41 x 2.3	100 all framing, blocked
GB2	8763	28290	0.6	1/2" gyp	41 x 2.3	100 all framing, blocked

Table 2. Comparision of Test Results

Specimen (1)	Load (g) (2)	Cycles to failure (3)	Percent of baseline cycles (4)	Energy (J) (5)	Percent of baseline energy (6)	Mode of failure (7)
PW1	0.4	7 1/4	100	6180	100	Nails sheared off
PW2	0.4	1 1/4	17	1590	26	Nails pulled through
OSB1	0.4	3/4	3	2740	44	Nails pulled through
OSB2	0.4	3/4	3	1200	20	Nails pulled through
GB1-a	0.4	21		1490	24	No failure
GB1-b	0.8	2 1/4		4030	65	Nails pulled through
GB1-sum		23 1/4	321	5520	89	
GB2	0.6	11 1/4	155	8260	134	Nails pulled through

Table 3. Experimental Results

Specimen (1)	Strength according to 1997 Uniform Building Code (N/m) (2)	Maximum strength during test (N/m) (3)	Drift at peak load for first loading cycle (radians) (4)	Drift at last full strength cycle (radians) (5)
PW1	3790	11130	0.0118	0.0256
PW2	3790	10800	-0.0183	-0.0312
OSB1	not rated	10600	-0.0179	no full cycle
OSB2	not rated	10750	-0.0145	no full cycle
GB1	2190[3]	9500	-0.0011	-0.0120
GB2	2190[1]	7130	-0.0046	-0.0156

[3] Strength of gypsum wallboard is reduced for seismic zones 3 and 4.

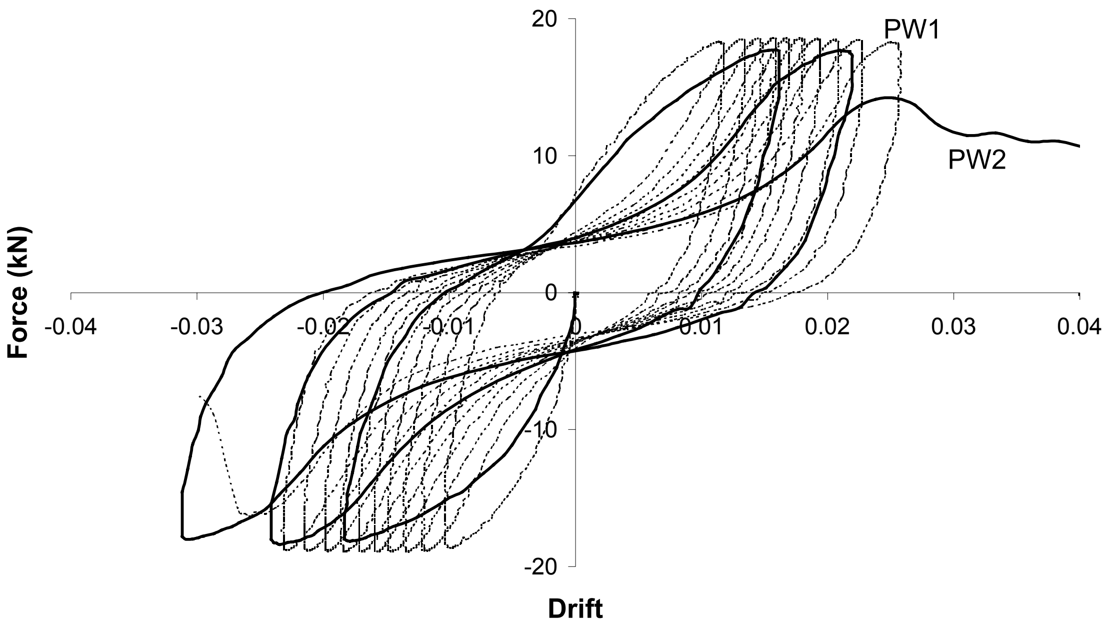

Figure 1. Lateral Force vs. Wall Drift for 2440x2440 Plywood Shear Walls.

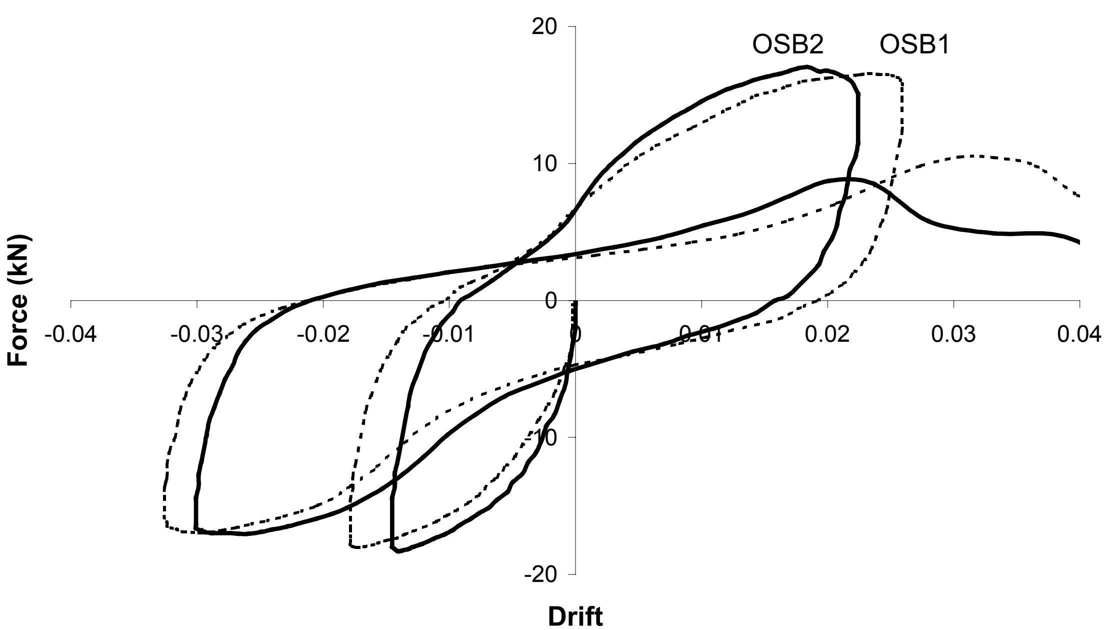

Figure 2. Lateral Force vs. Wall Drift for 2440x2440 Oriented Strand Board Shear Walls.

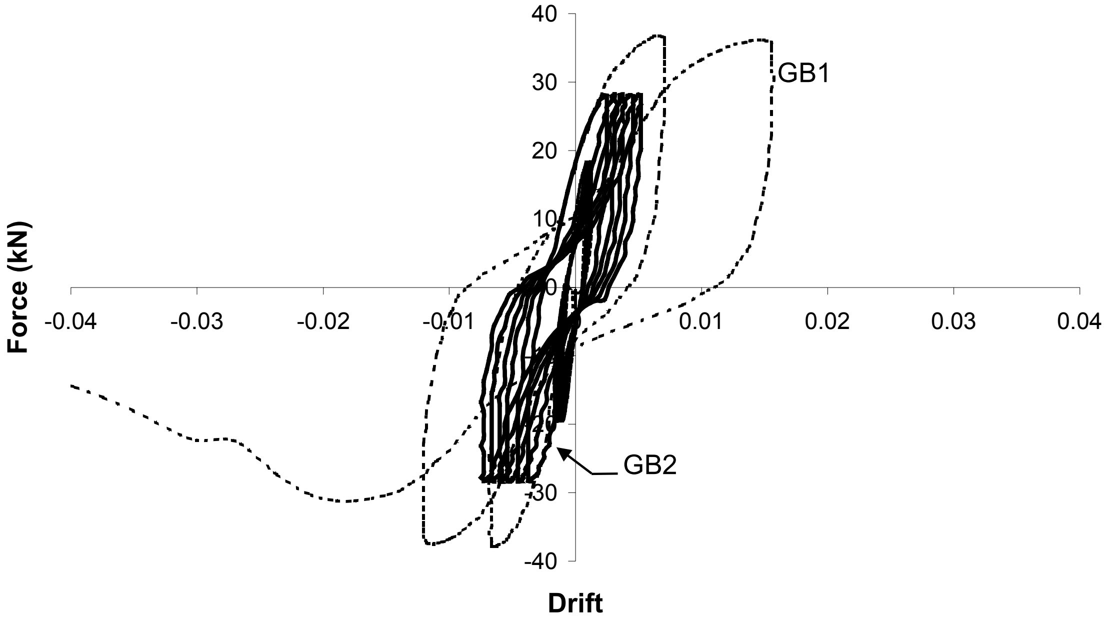

Figure 3. Lateral Force vs. Wall Drift for 2440x2440 Gypsum Wallboard Shear Walls.

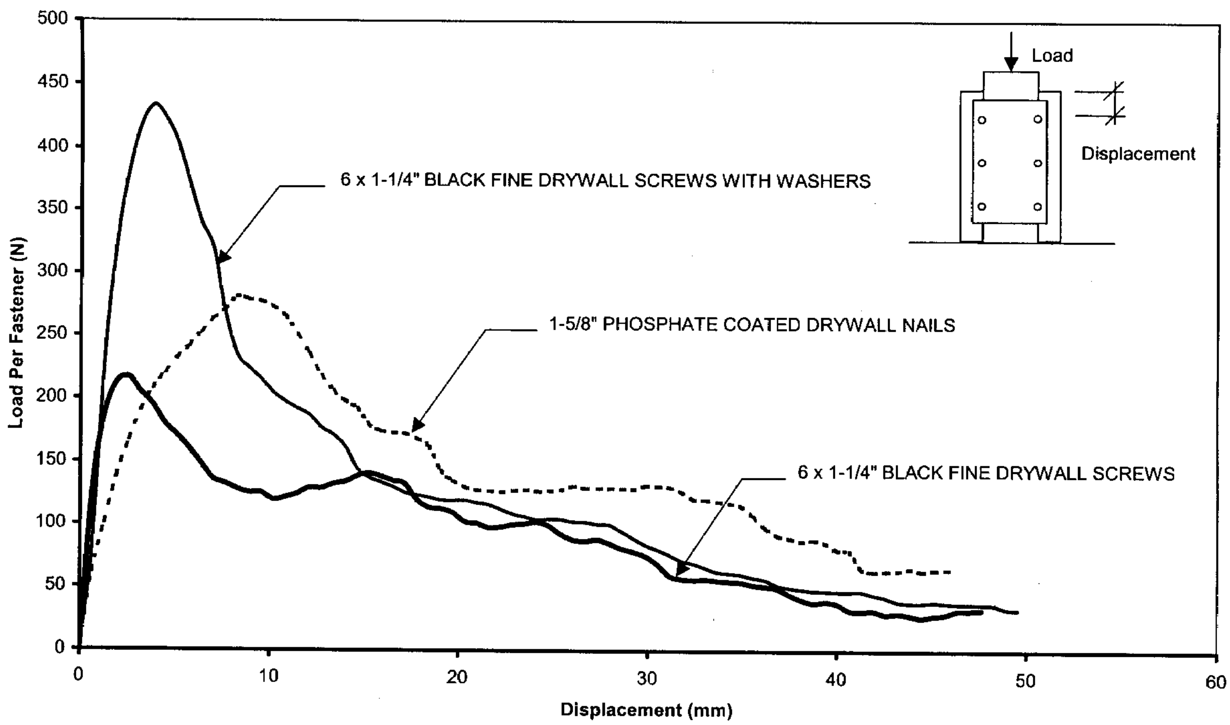

Figure 4. Comparison of Force-Displacement for Gypsum Wallboard Fasteners.