Straw Bale Shear Wall Lateral Load Test

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Abstract

In response to the growing interest in sustainable building systems and the recent developments in straw bale construction throughout the world, this test was performed in order to explore new ideas for creating stronger lateral load resisting elements while making use of the extraordinary characteristics of baled straw as a natural building material. This report contains the results of an in-plane lateral monotonic load test of a plastered straw bale wall. The specimen was constructed and tested at California Polytechnic State University, San Luis Obispo, as an undergraduate senior project. The primary purpose was to investigate the effectiveness of using lag screws in the boundary elements to transfer the lateral load to the stucco, with the intention of increasing the shear capacity of the bale wall.

Acknowledgements

We would like to thank the following people who contributed significantly to the success of this project: Jake Feldman—Thanks for all your advice, patience, and mostly for your optimism throughout the entire project. Thank you also for spurring us on…I was beginning to think the beast was never going to break! More thanks than we can express to Ray Ward—you’re a life saver; to Bruce King— for your recommendations and overall contributions to the world of straw bale construction, which remain invaluable; to Turko Semmes & Greg McMillan—Thanks for the bales and the tremendous amount of input, Ted Muller—For taking time out of your busy schedule to show two amateurs how to plaster; to James Singh & Home Depot—huge amount of thanks from two poor college students for the material donations; to Joe Stigman & Hansen Aggregates—for all of our concrete, generously donated, mixed, delivered, and poured…too nice!; to Paul Fratessa, Abe Lynn, and Vicki May for your many helpful suggestions, references, and patience; and of course Kay Riedel—how could any Cal Poly ARCE student survive without you? We would also like to thank all those students who expressed a sincere interest in this project and everyone, young and old, who will further the work of this ongoing effort.

Jake deserves all the credit for the lag screws concept…we’ll party when ICBO publishes “The Feldman Connection.”

Introduction

The use of straw bale construction in the United States has grown steadily in the past decade. As a building material, baled straw has many beneficial characteristics that make it useful for several types of structures. While many are aware of the aesthetic appeal, sustainability, low cost, and ease of construction that characterize bale buildings, others may be surprised at their ability to resist fires, their incredible thermal efficiency, and even the structural integrity of a well-designed, carefully-built bale structure.

Among all sustainable materials, straw is one of the most abundant. However, only twenty-five percent of the 140 million tons of straw that are available each year is baled and utilized[2]. Because straw is produced so rapidly in farming communities every day, there is usually too much of it left over for farmers to use or store. In California alone, "almost a million tons of rice straw are burned each fall," producing "more carbon monoxide and particulate than all of the electric-power-generating plants in the state combined."[3] By using the straw as a building material, the problems caused by burning it are lessened or avoided altogether.

The thermal efficiency of straw bale buildings far surpasses structures made of any conventional building material. Because straw itself, when bundled into tightly compressed bales, acts as an excellent insulator, there is no need for additional insulation in the walls of the structure. With an R-value that ranges from R-30 to R-40, bale walls are two times more efficient than most well-insulated wood-framed walls.[3] Since the load-bearing material itself acts as the insulation, and because it requires little or no skill to stack, erection of straw bale walls is much faster and less expensive than walls built of standard materials.

As mentioned, bale structures are also exceptionally resistant to fire damage. Although loose straw burns easily, densely-packed bales limit the amount of oxygen needed for combustion, allowing plastered walls to delay fire penetration for more than two hours.[5] In his *Report to the Construction Industries Commission of New Mexico*, Manuel Fernandez states, “The result of these tests have proven that a straw bale in-fill wall assembly is a far greater fire resistive assembly than a wood frame wall assembly using the same finishes.”[3] These impressive qualities of bale structures make straw bale construction a highly practical means of building a suitable home or office.

Structural Testing History

In 1993, University of Arizona graduate student, Ghailene Bou-Ali performed vertical compression tests, and a series of in-plane and out-of-plane lateral load tests on three separate wall panels. The results of the compression tests showed that 3-string bales laid flat (24” wide, 16” high) have a compressive resistance of 10,000 psf, while bales laid on edge have a resistance of 2,770 psf. The in-plane and out-of plane lateral load tests were performed on three unplastered wall panels 12 feet long by 8 feet high. The out-of-plane tests resulted in a maximum wall deflection of one inch or less while simulating a wind load of one hundred miles per hour. The in-plane tests resulted in an average deflection of four inches at the top of the wall with 2,135 pounds applied at the mid-height of the wall. The results proved that straw bales alone absorb a significant amount of energy, however the addition of any type of wall finish would greatly enhance the performance of the walls laterally loaded in-plane.[3]

In response to the need to further explore the interaction between plaster and straw bales, in 1997, Cal Poly undergraduate students Nathan White and Clint Iwanicha performed an in-plane lateral load test of an 8 foot long by 6 foot high stucco-covered bale wall. The wall was loaded at the top, modeling the typical transfer of seismic load from the roof to a top plate, or box beam, and down through the lateral load-resisting material, and finally into the foundation through a sill plate. The lateral load was transferred from a TJI (“TJI” is a widely used term denoting fabricated wood I-joists) top member into a chicken wire mesh that was stapled to the TJI and a 11/2” stucco coat that was applied over the mesh. The results of the test showed the wire mesh failing at 12,300 lbs (720 plf) with a deflection of 1.15”. The wall continued to resist significant loads after the mesh failed until one of the posts failed, at which a deflection of 7.4” was recorded. It was concluded that since the stucco remains interlocked with the straw, even after the shear transfer at the top fails, the bales “will most certainly absorb a significant amount of energy, and resist substantial forces.”[4]

Purpose

The previous bale wall test (described above) exhibited the ability of plaster to transfer the lateral shear. However, because of the inadequacy of common "chicken wire" mesh to carry the same load, we were unable to see the full amount of resistance the plaster would provide. Since the mesh failure occurred before the plaster skin itself had chance to crack, this suggests that a better shear transfer configuration is necessary to make use of the plaster's full shear strength. Jake Feldman, the project advisor, suggested using lag screws that would protrude out of the boundary elements and provide some bearing area to assist in transferring the shear into the plaster skin. We also felt that using a stronger wire mesh, similar to what is currently specified in the field, would improve the capacity in combination with the lag screws (see King, 128). Since the plaster used in the previous test had a fairly low compressive strength (253 psi), another goal was to obtain a stronger plaster mix. Because one of the main advantages of straw bale homes is that they can be owner-built and do not require highly skilled labor to construct, we decided to use an inexpensive store-bought stucco mix that one would typically find at any home improvement store. This mix would be readily available to any homeowner and would reduce the possibility of an inexperienced builder mixing a poor stucco batch. The main objective of the experiment was to investigate the effectiveness of this entire configuration in transferring large lateral forces and to make full use of the plaster's ability to carry the load. The target failure would be 45° diagonal shear cracks on each face of the wall extending from the point of load application to the opposite bottom corner of the wall, indicating failure of the plaster skins.

Construction Process (refer to Fig. 1)

Concrete Foundation Construction - Three $1^{1}/_{2}$"ϕ all-thread bolts were inserted into the threaded holes in the "strong floor" of the High Bay Lab in Building 21 at Cal Poly State University San Luis Obispo. A 3/4" steel plate welded to a nut was screwed onto the first bolt to anchor the footing against uplift. Five holes were drilled in each of the 4x8 members for the anchor bolts. Formwork for the footing (24" wide x 12" tall x 10'-0") was constructed, and the 4x8 members were nailed at the top of the formwork on each side. Plastic was placed on the floor to allow for simple removal of the footing upon completion of the testing. The rebar cage was constructed and placed inside the formwork. The anchor bolts were then placed in the 4x8 sill plates. Four #4 rebar pins were tied with wire to the center of the rebar cage, extending 16" out of the top of the formwork, which would be used for attaching the straw bales to the footing. The concrete was poured, after which two Simpson "HD5A" holdowns were placed at the compression end and two Simpson "HD10A"s were placed at the tension end (see Figures 2 & 3). Four concrete cylinders were poured for testing at each 7-day interval. The footing reached its 28-day strength of 3289 psi on 11/14/2000 (14 days before the first test).

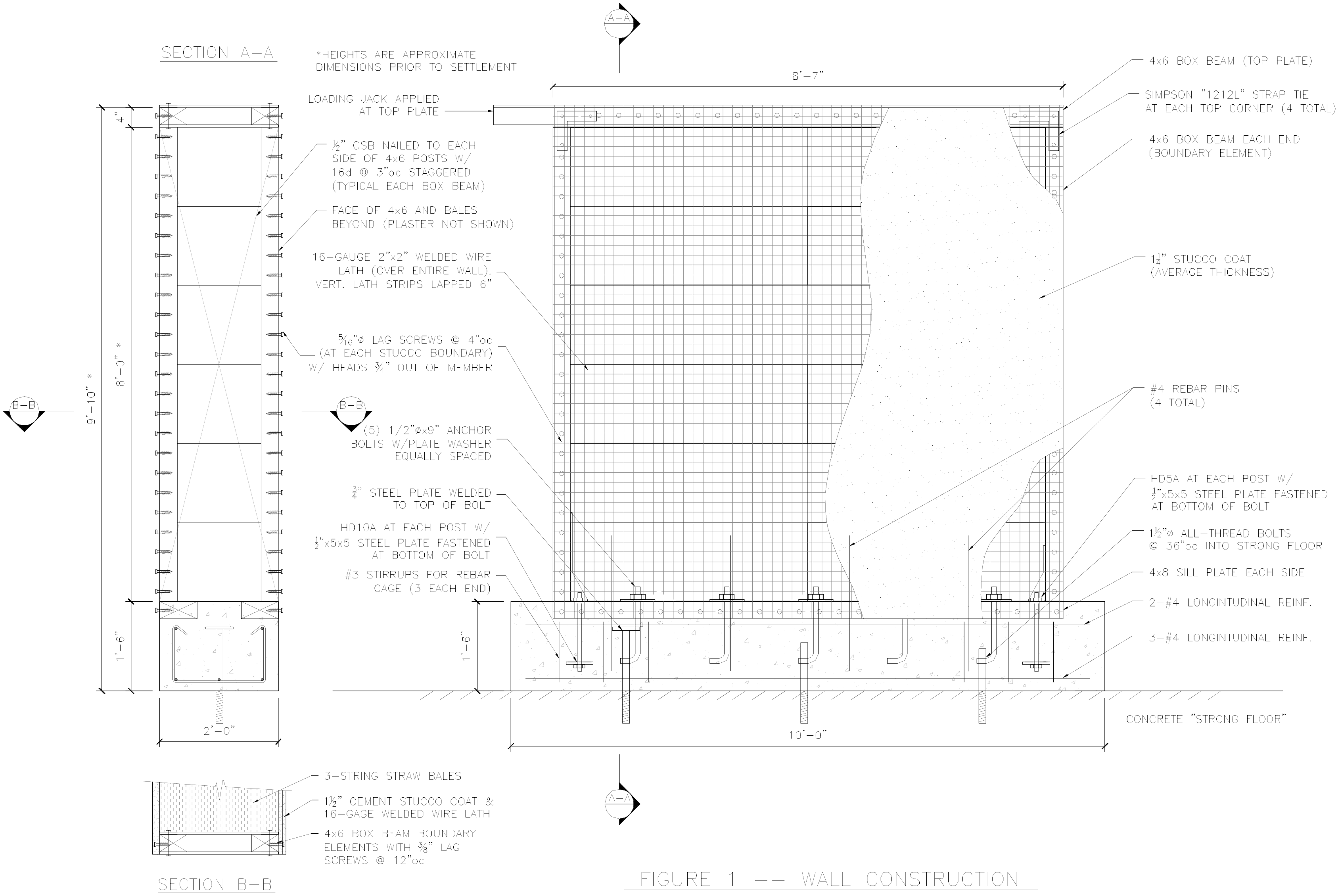

FIGURE 1 -- WALL CONSTRUCTION

Figure 2 – Side view of poured footing

Figure 3 – Front perspective

Wood Frame Construction - Three box beams were assembled, one 8'-0" long member for each end of the wall and one 10'-0" long member for the top plate, which would extend beyond the loaded end of the wall to receive the load actuator. $^{15}/_{32}$" OSB was nailed with 16d @ $2^1/_2$"oc to each side of two 4x6 members. The holes for the holdown bolts were drilled at the bottom of the two end box beams, and $^1/_8$" holes for the lag screws were pre-drilled into the 4x6 and 4x8 side members. $^5/_{16}$"ϕ x 3" lag screws were then drilled into the members at 4"oc.

Wall Assembly - Two bales were inserted over the rebar pins and placed on the footing. A total of twelve 3-string rice straw bales (24"x16"x48"), six courses high, were used for the wall. Once the bales were stacked, they were allowed to settle for several days under their own weight.[1] The wall was measured at 7'-7" tall (from the top of the footing to the top of the bales) after settlement occurred, and the box beams were cut to match that height. The 7'-7" box beams were then bolted to the holdowns at each end (see Fig. 4), and the 10’-0” long box beam was placed

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[1] Note: In a typical straw bale wall, the bales are stacked in a "running bond" pattern. Because of time constraints, a "stack bond" pattern was used for this wall to avoid having to make half-bales, but should not be used when

on top of the wall (see Fig. 7). Simpson "1212L" strap ties were installed at each upper corner of the wall (4 total) to connect the top plate to the posts. 16-gauge galvanized welded wire 2"x2" mesh (Jaenson Wire Company™) was placed on each side of the wall in 28" wide vertical strips. Each strip of wire lath was overlapped 6" (3 squares) with the adjacent strips. Because a staple gun was not readily available, 8d nails at 6"oc were used to attach the lath to the wood members, hammering the nails in half-way and bending the nail over the lath to secure it to the member.[2] It was agreed that this would be adequate for testing purposes since the lag screws would provide the primary shear transfer from the boundary elements to the plaster skins. Using a bale needler (made from a 30" long bent piece of #3 rebar), 16-gauge wire was tied through each bale to the wire mesh at approximately 16"oc, vertically and horizontally, to tighten the lath against the surface of the bales for ease of plastering (see Figs. 5 & 6).

Figure 4 – Front holdowns

Figure 5 – Mesh over bales

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constructing a straw bale structure. The bales would also be pre-compressed in a typical structure, but this was deemed unnecessary for the purposes of the test.

[2] See 1997 U.B.C. Chapter 25, Table 25-C, code requirements for proper attachment of lath.

Figure 6 – Needling wire through bales

Figure 7 – Unplastered wall elevation

Plastering - The first coat of plaster was applied on November 8 *only* to the bales (see Fig. 8). However, for testing and construction purposes, it is recommended that the scratch coat also be applied over the boundary members in a bale structure or in future tests to ensure continuity between the plastered bales and the shear connection at the wood members. Since the goal of the test was to form diagonal tension cracks in the center of the plaster skins, an additional 6”-wide strip of wire mesh was attached at the boundary members before applying the second coat, as shown in Figure 9. It was believed that a second layer of reinforcement at the locations of shear transfer would prevent premature cracking of the plaster at an undesirable location during testing. The second coat was applied six days after the scratch coat (11/14), covering both the boundary members and the first layer of plaster. Three plaster cylinders were poured for the scratch coat, and two cylinders were poured for the second coat for testing at each 7-day interval and determination of the strength at the time of testing. It should also be noted that the cured scratch coat was not as rough as needed for standard construction purposes. Therefore, a wetter mix was used for the brown coat to provide sufficient adhesion between the two coats. As a result, the second coat had a significantly lower compressive strength than the scratch coat. After applying the second coat, the wall was covered with a plastic tarp to prevent the stucco from drying too quickly. After completion of the testing procedures, samples of the stucco were removed from the wall and measured for thickness. An average plaster thickness of $1^1/_8$" over the straw bales was calculated for the left side of the wall (if one were facing the wall from the loading mechanism), with and average of $^7/_8$" at the boundary members; and the right side of the wall was found to have an average thickness of $1^1/_4$" over the bales, with 1" of stucco at the boundary members.

Figure 8 – Partial scratch coat applied

Figure 9 – Partial brown coat applied

Test Setup

A $^{5}/_{4}$" steel plate, with two $^{1}/_{8}$" steel plates welded to its ends, was attached to the top box beam with six $^{5}/_{16}$" lag screws (3 each side). Two small pieces of L2x2x$^{1}/_{8}$, with 1" holes drilled in them, were welded to the center of the steel plate for attachment of the loading mechanism. The base of the load cell was bolted to the flange of the steel column, and the loading end of the ram was bolted to the angles welded to the steel plate. As a safety measure, the loading mechanism was also strapped to the overhead frame to keep the device from falling in case of failure at the connections to the wall or steel column, which happened to occur at the end of the first test. The deflection was measured at the top of the wall. The load cell and deflection apparatus were connected to their respective gages, one reading the load applied to the nearest ten pounds and the other reading the deflection to the nearest $^{1}/_{100}$ of an inch. A hydraulic jack was also connected to the ram for applying pressure to the wall (see Fig 10).

Wall Properties

The bales had an average moisture content of 9.04%, varying from 8.6% to 10.0%, and weighed an average of 68.7 pounds per bale, varying from 66 lbs to 71 lbs. At the final day of testing, the plaster scratch coat had reached its full strength, and the second coat had cured for 23 days. However, because the need for multiple tests were not anticipated, no cylinders were prepared for compression tests to determine the strength of the plaster at the time of the second and third wall tests. Based on the results of the initial plaster compression tests shown below, one may reasonably conclude that the scratch coat had a minimum strength of 4500 psi, and the second coat had reached at least 1400 psi on the final testing date.

	Day	Compressive Strength (psi)
Scratch Coat	7	3572
	13	4138
Brown Coat	7	1061
	14	1220

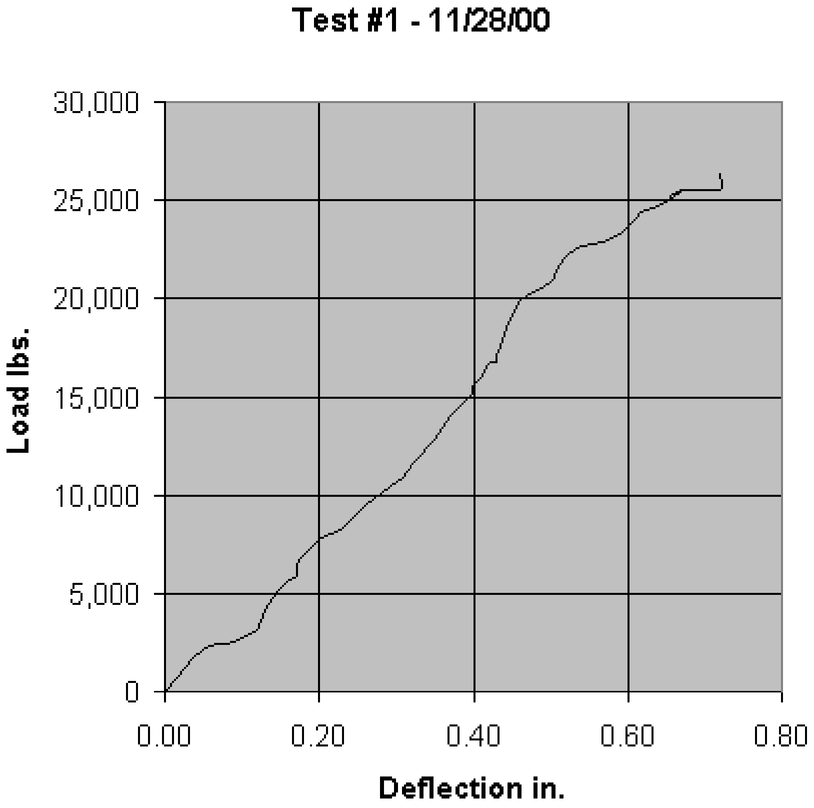
Testing Procedure & Data

Because of time limitations, the wall would initially be tested before the stucco could reach its full 28-day strength. On November 28, the day of the first test, the scratch coat had reached an approximated 20-day strength of 4400 psi (based on a 13-day strength of 4138 psi), and the second coat had a 14-day strength of 1220 psi. The wall was loaded in increments based on changes in deflection. At each slight change in deflection, the loading was halted to take readings of the applied load and its respective deflection, after which the loading would continue until the next change in deflection. Because the right face of the wall had a thicker plaster skin than the left face, the left face was the first to form cracks during the testing procedure.

Figure 10 – Wall loaded during first test

The first noticeable crack in the stucco occurred on the left face at 21,450 pounds. No significant drop in the load was observed. Significant cracks in the plaster over the bales were also observed at 25,548 pounds, and at the plaster over the boundary elements around 26,000 pounds (see Fig. 11). The test was halted when two bolts at the connection of the load cell to the steel frame sheared, and the load cell separated from the wall at 26,480 pounds, with a total wall deflection of 3.03". The connection failure was determined to be a result of the column flange displacing since the load cell was not concentrically connected to the column (the device was not centered on the column in order to ensure that the load was applied directly perpendicular to the wall and thereby preventing torsion in the wall). See the results on the next page.

Deflection (in.)	Load (lbs.)	
0.00	0	
0.05	2,110	
0.09	2,510	
0.12	3,150	
0.13	4,120	
0.15	5,250	
0.17	5,950	
0.17	6,500	
0.20	7,720	
0.23	8,380	
0.26	9,450	
0.30	10,630	
0.32	11,580	
0.34	12,370	
0.38	14,440	
0.40	15,160	
0.40	15,600	
0.41	16,010	
0.42	16,630	
0.43	16,790	
0.43	17,200	
0.45	19,230	
0.46	19,980	
0.50	20,810	
0.51	21,630	Cracks appear
0.53	22,440	
0.58	23,040	
0.61	24,110	
0.62	24,420	
0.65	24,880	
0.67	25,528	
0.65	24,880	
0.67	25,530	
0.72	25,528	
0.72	**26,480**	Load device connection failure



The wall was tested a second time two days later. Stiffener plates were installed between the column flanges to prevent the same failure from occurring. The wall was loaded in the same manner as in the previous test. At 25,050 pounds, however, the bolt connecting the load cell to the ram buckled, causing failure of the loading device itself (see test #2 results below). The wall deflected 0.81" during the second test. No additional cracks in the plaster were observed.

Deflection (in.)	**Load (lbs.)**	
0.00	0	
0.01	1,410	
0.04	2,180	
0.07	2,540	
0.13	2,840	
0.17	3,400	
0.21	3,940	
0.25	4,690	
0.29	5,200	
0.31	5,660	
0.32	6,000	
0.37	6,940	
0.43	7,990	
0.47	9,150	
0.49	9,720	
0.53	10,990	
0.57	12,430	
0.59	13,630	
0.62	14,710	
0.63	15,480	
0.66	16,920	
0.67	17,540	
0.67	17,850	
0.69	18,520	
0.72	20,100	
0.74	21,320	
0.76	22,400	
0.77	22,700	
0.77	23,030	
0.79	23,600	
0.80	24,470	
0.81	**25,050**	Failure of testing apparatus

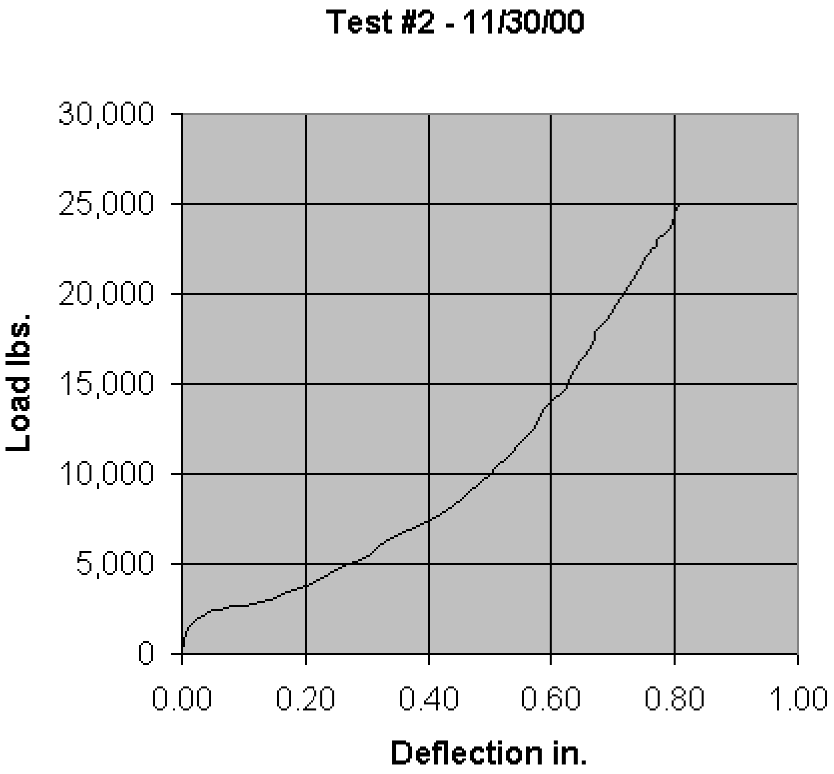


Figure 11 – Cracked left face after tests 1 & 2

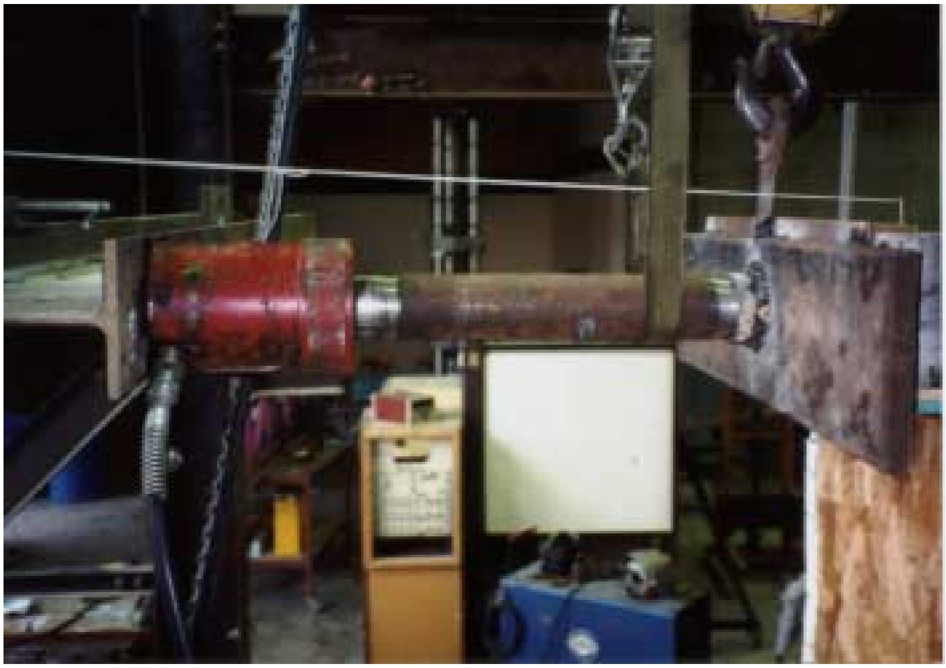


Figure 12 – Final test setup

The final test was conducted on December 7. A 60,000-pound capacity loading device was installed for the third test (Fig. 12). The wall was loaded in a similar manner as the first two tests. Additional large cracks began to form in the wall at 28,000 pounds. The plaster skin on the right face began to show cracks at 31,370 pounds, at which there occurred a slight drop in the load. Shortly after the cracks formed in the right face, the wire lath on the left side began to break in tension at the center of the wall (Fig. 13) and spalling of the plaster occurred near the upper-front corner of the wall just before ultimate failure (Fig. 14). The spalling was attributed to the scratch coat being too smooth upon curing, and therefore can most likely be prevented by using the proper tool to scratch the wet surface. Finally, at 36,840 pounds ultimate failure of the plaster skins occurred and the wall stopped taking any further load.

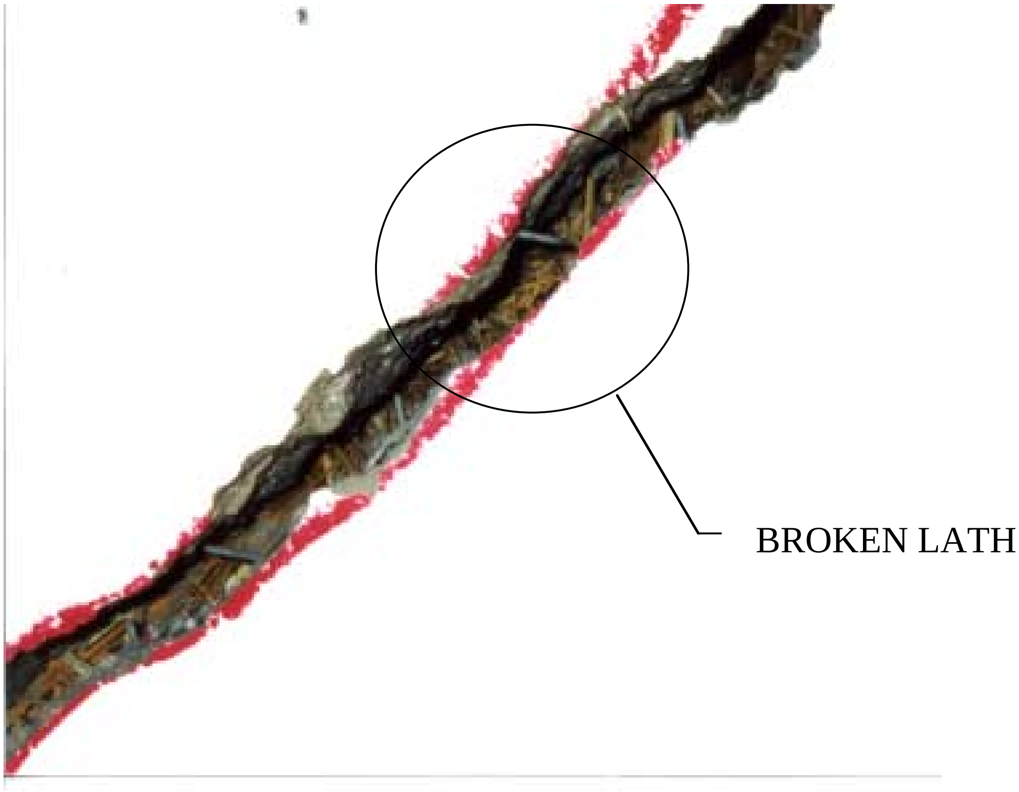
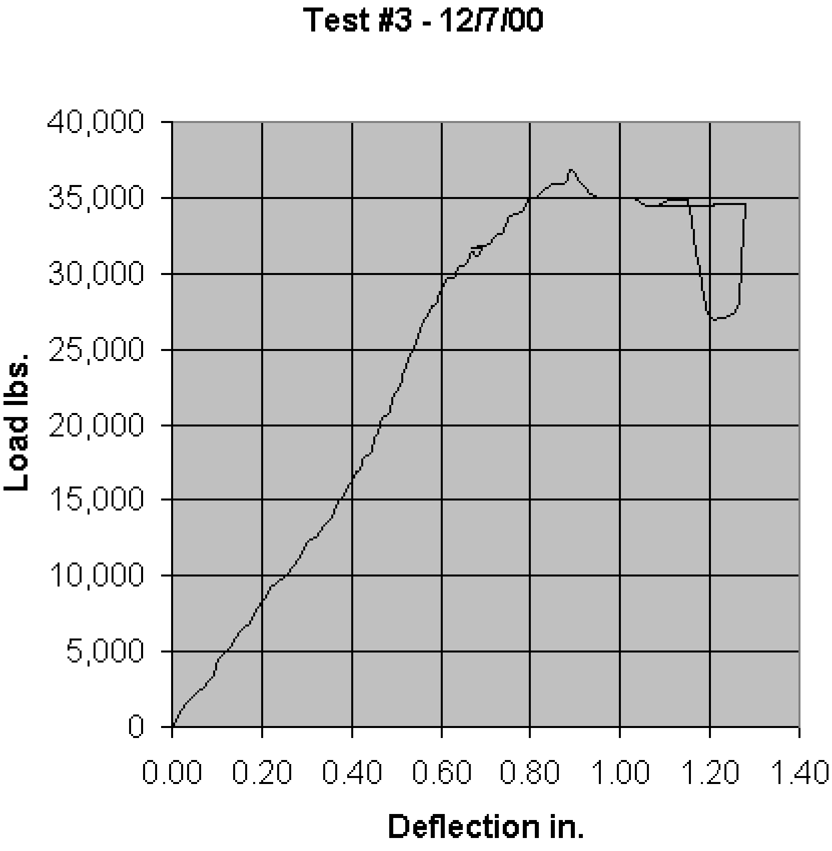


Figure 13 – Large shear crack in left face

Figure 14 – Spalling on left face

Deflection (in.)	Load (lbs.)
0.00	0
0.03	1,605
0.08	3,035
0.10	4,145
0.13	5,307
0.15	6,395
0.17	6,785
0.19	7,865
0.21	8,595
0.25	9,885
0.29	11,415
0.32	12,515
0.35	13,715
0.37	14,925
0.39	15,695
0.41	16,865
0.42	17,035
0.44	18,065
0.45	19,105
0.47	20,395
0.49	21,745



0.51	22,765
0.52	23,945
0.53	24,625
0.54	25,085
0.56	26,885
0.58	27,885
0.59	28,035
0.60	29,035
0.64	30,445
0.67	31,365
0.73	32,545
0.75	33,695
0.78	34,035
0.80	34,955
0.83	35,465
0.84	35,585
0.85	35,955
0.87	35,935
0.88	36,015
0.89	**36,835**
0.93	35,195
0.97	35,035
1.01	34,935
1.07	34,435
1.28	34,525
1.09	34,495
1.11	34,885
1.15	34,885
1.19	27,915
1.22	27,035
1.26	27,735
1.28	34,635

The deflection for the final test was 0.89" at the point of failure. The wall continued to resist load up to 34,640 pounds and the test was ended shortly thereafter (see test #3 results above).

It was not possible to accurately determine the total deflection of the wall since it is not known how much deflection the wall sustained after the first two tests. Although the wall did not return to its original position after the first and second tests, the deflection sustained after the first two tests was small enough to conclude that the total cumulative deflection from all three tests did not exceed 2 inches. The ultimate shear capacity for the wall was calculated at 4,600 pounds per linear foot, or 2,300 plf for each side.

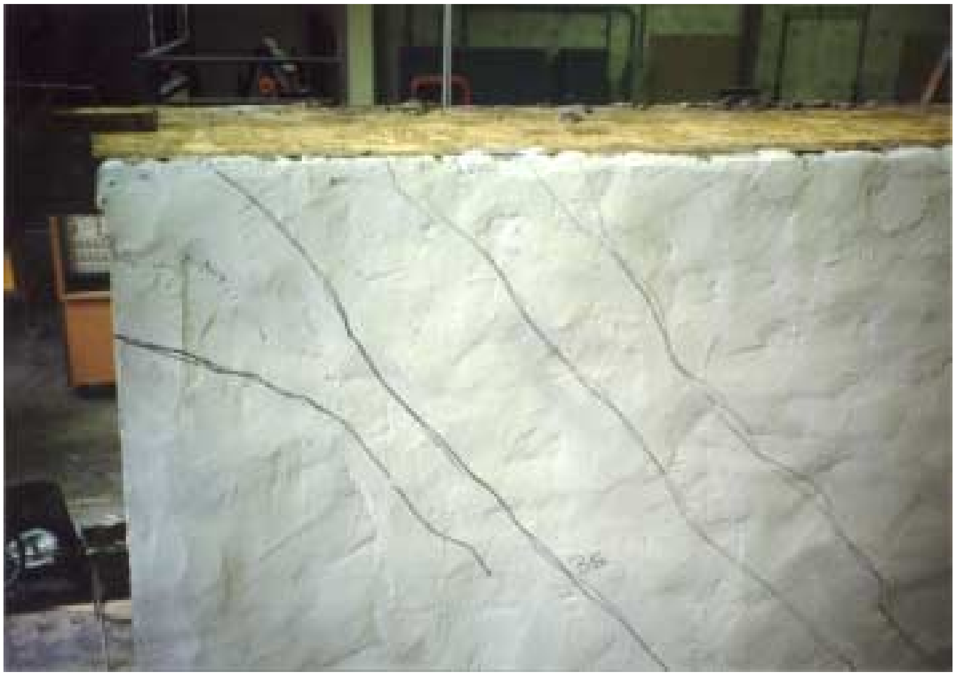


Figure 15a – Right face cracks during final test

Figure 15b – Outer shear cracks in right face

Conclusion

The remarkable ability of plaster to resist high in-plane loads was demonstrated during the testing, as was the ability of this material to resist these loads multiple times. The nature of wind and earthquakes is such that repeated demands are placed on the structure throughout its serviceable life. The ability of the wall to continue to resist significant loads after ultimate failure shows how a plastered wall can also prove to be a significant energy absorber in seismic events where sizeable aftershocks continue to threaten further damage to a building. Assigning a factor of safety of 3 results in an allowable working stress of approximately 770 plf for each plaster skin, thus the wall compares favorably with even the strongest UBC wood shear wall. The results clearly show that a plastered straw bale wall may be designed to meet even the most severe demands determined for residential and light commercial construction. Where wood walls have been substituted to resist high lateral forces in the past, we can now, with confidence, use bale walls to ensure aesthetic and thermal continuity throughout our structures. Although it would not be practical to use this type of wall design for each shearwall in a structure, it would certainly be sensible to use this wall where high lateral forces are calculated within the structure while using a more common configuration for most of the walls where normal loads occur. As straw bale design research continues, it is evident that bale structures can hold their own in the world of residential and light commercial construction.

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