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# **In-Plane Cyclic Straw Bale Shear Wall Testing**

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Senior Project: Spring 2004

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## 2. Idealized Wall Behavior

The design intent for the straw bale shear wall is to create a wall with a level of detailing that can be efficiently constructed as well as provide adequate ductility required of a lateral system. The applied lateral force induced during the in-plane cyclic loading is expected to be distributed through the box beam at the top of the wall into the wire mesh and stucco skins, down into the sill (box beam) at the base of the wall and into the anchor bolts in the foundation. The bales in the wall would create a compression strut for resistance once the stucco skins and wire mesh have been significantly damaged and yielded.

The applied loading will develop tensile and compressive stresses in the skins which redistribute as cracks and localized failures occur. In the EBN report, the best prospects for obtaining ductile behavior are: 1) rocking of the wall, 2) flexural yielding of the wall, and 3) development of compression struts in the bales after complete failure of the cement stucco. Each of these behavioral modes are described in the report. Rocking of the wall is described as the opening of a gap at the base of the wall which would allow the tensile reinforcement to yield and eventually fracture. The gravity loads present on the wall would provide a restoring moment that would resist this rocking. Flexural yielding would occur in the lower third of the wall once this gap has opened and the reinforcement is allowed to develop flexural resistance to the applied forces. In order for these two mechanisms to occur, the shear strength of the wall must be adequate and the compression zone of the wall should not fail. In order to develop compression struts in the bales the skins must be severely damaged but the reinforcing and connections at the base and top of the wall must be maintained.

The testing of the 4'x8' wall should help to validate the designs and failure modes of the straw bale shear wall in uses to resist lateral loading. The level of detailing used should be adequate to provide the level of ductility desired from the straw bale shear wall. The "medium" level of detailing prescribed in the Ecological Building Network report is intended to yield at the base level for an 8 x 8 wall. Medium level detailing includes wire mesh, anchor bolts and staples, but excludes any cross ties or heavy gage spikes between the box beams and the straw bales. Because of the different aspect ratio being tested ( 4 x8 ) flexural yielding is expected to dominate since the wall is slender compared to previously tested walls and they were also controlled by flexure.

### **3. Specimen Description**

The following sections describe the materials and process used in the construction of the straw bale wall specimen.

#### **3.1 Specimen Description**

This wall specimen consisted of six 15"x 24"x 48" (height, depth, width) three string rice straw bales. The bales were stacked vertically to create a wall with a nominal height of 7'-6" from the bottom to the top of the bales, a nominal width of 4 feet and a nominal depth of 2 feet. We used a "medium" reinforcement detail of lapped wire mesh, as described by the report presented by the Eco-Build Network in previous tests. The wire mesh was manufactured in 14 gage 2" x 2" right angle squares and was overlapped 1'-0" at the top, bottom, and around the sides of the bales. The skin of the wall was a cement-stucco applied in three different coats. Figure 3.1 details the construction of the wall specimen.

#### **3.2 Wall Construction**

The resources provided to us by the Architectural Engineering department of Cal Poly San Luis Obispo controlled the determination of a method of anchoring the wall to the High Bay laboratories strong floor. The construction of the wall specimen began with the detailing of a steel base to serve as a foundation which was then anchored to the High Bay strong floor. It is important to provide bearing for the cement stucco skin, and hence the steel base included a 2"x2"x1/4" angle oriented so that one of the 2 inch legs provided the required bearing surface. The base details are shown in Figures 3.2, 3.3, and 3.4.

The assembly of the wall began with the construction of sill and header box beams. These box beams consisted of two- 4 feet long pieces of 4 x 4 pressure treated lumber and two- pieces of 2 foot by 4 foot, 1/2 inch thick CDX plywood. A center strut of 4 x 4 pressure treated lumber was provided at the center of the box beam to resist buckling of the plywood. The box beams were nailed with 8d nails at 4 inches on center. Details of the box beam can be seen in Figure 3.1.

A layer of wire mesh was laid between the steel base and the box beam, with 1 foot of overlap on each side of the wall, in order to provide confinement in the compression zones of the specimen. The box beam was then anchored to the steel base using six- 5/8 inch diameter anchor bolts at 18 inches on center with malleable washers. Although it is common practice to use square plate washers in timber construction, malleable iron washer were used at the discretion of the students conducting the testing.

Following the anchoring of the sill box beam, six straw bales were stacked vertically. The header box beam was then placed on the top of the sixth bale. Another layer of wire mesh was wrapped over the header box beam allowing 1 foot of overlap on each side of the wall. Prior to securing the mesh, the specimen was weighted with roughly 200 plf overnight, to simulate a roof system dead load. Once the settling of the straw bales had occurred, the wire mesh was secured to the box beams using 16 gage 1 3/4" staples with a 7/16" crown at each intersection across only one row of squares. "U" shaped wire mesh with an overlap of 6" per side was also place at the ends of the wall and secured to the box beams in a similar fashion to the top and bottom "U" shaped mesh. Once the

boundary mesh was secured, panel mesh on the faces of the bales were overlapped and secured to the box beam as previously described. Thin, non-structural, wire was tied from the wire mesh on one of the walls faces, through the straw bales, and tied to the wire mesh on the opposite face. These ties were used for the purpose of pulling the wire mesh to the face of the bales to avoid gaps that would cause varying skin thicknesses. Detailing of the wire mesh can be seen in Figure 3.1.

Once the reinforcing was secured, cement stucco was applied the face of the walls. To begin, any remaining voids between the mesh and bales were stuffed with paper in order to create a more even surface for the stucco application. It is extremely important that the stucco skin be consistently 1 ½ inch thick across the face of the wall and hence any remaining voids between bales and the mesh must be filled in one form or another. This can be done easily by using loose straw or paper. In order to obtain the desired thickness, the stucco was applied in three coats with a curing time of approximately one day between coats. The scratch, brown, and final coats were all of the same material and both the scratch and brown coats were scarified. Generally a curing period of a week after each coat is optimal, but due to time constraints the stucco was applied one coat per day and allowed a curing period of four weeks. The students conducting the test of this specimen opted to hire a professional plasterer, with experience in straw bale construction to apply the stucco.

Lateral bracing was also constructed in order to prevent and minimize the wall's out of plane displacement. The bracing was constructed of four pieces of tube steel (2 ½"x2 ½"), vertically welded to the I-beam that was lying horizontally on the wall (two pieces of tube steel were located at each end of the wall). The tube steel members were welded so that there would be a very small gap between them and a beam from the strong column frame that was directly over the wall specimen, already in place in the Hi-Bay lab. 8" x 8" plates were then welded to the tube steel to ensure that the tube steel would not yield out of plane. For further explanation please see Figure 3.5.

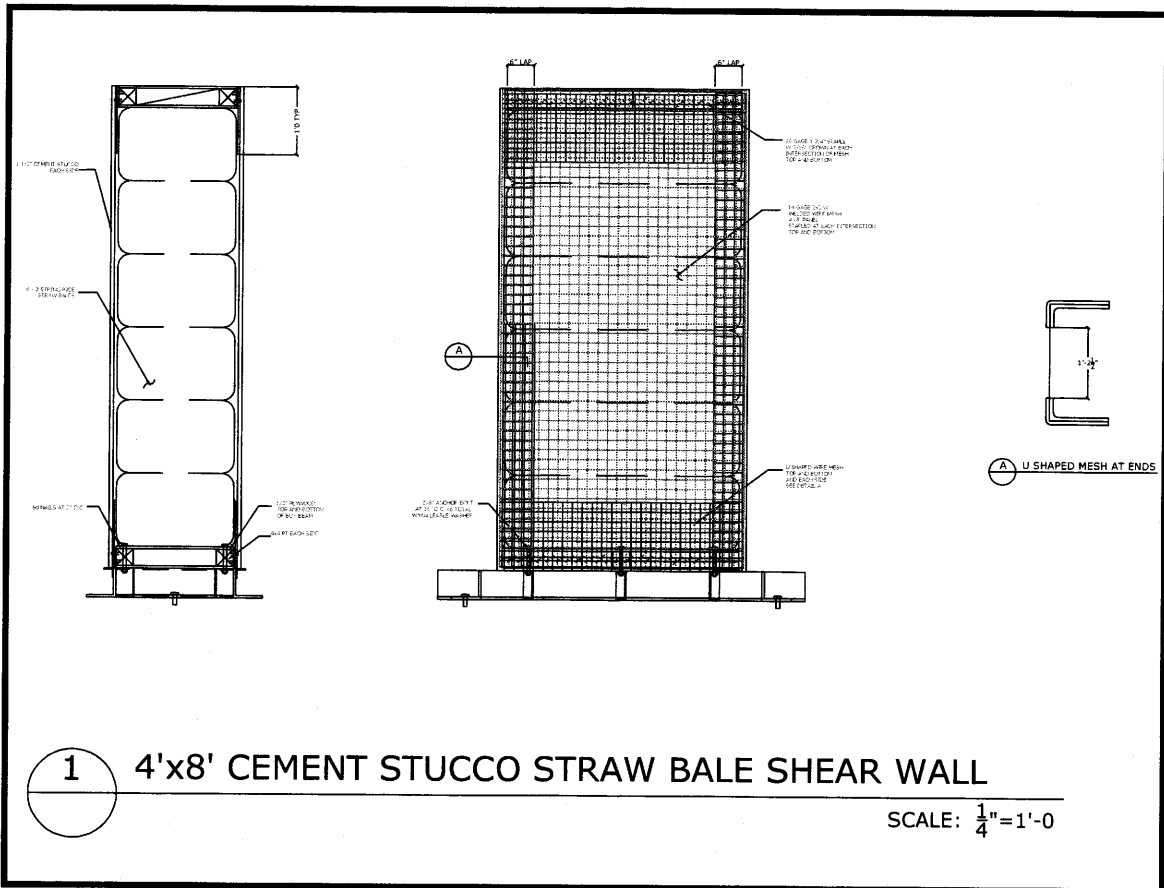


Figure 3.1-Wall Specimen Construction Detail

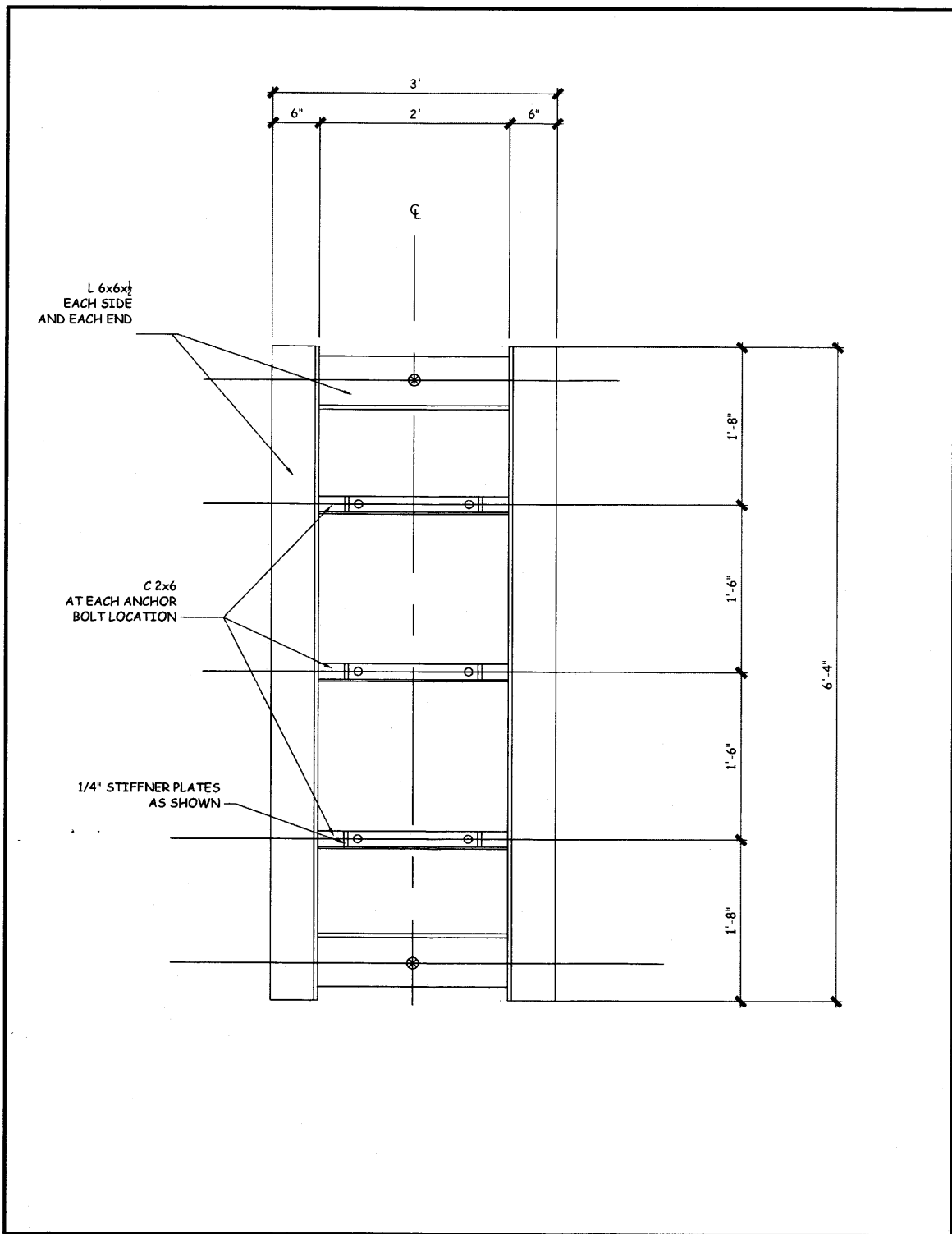
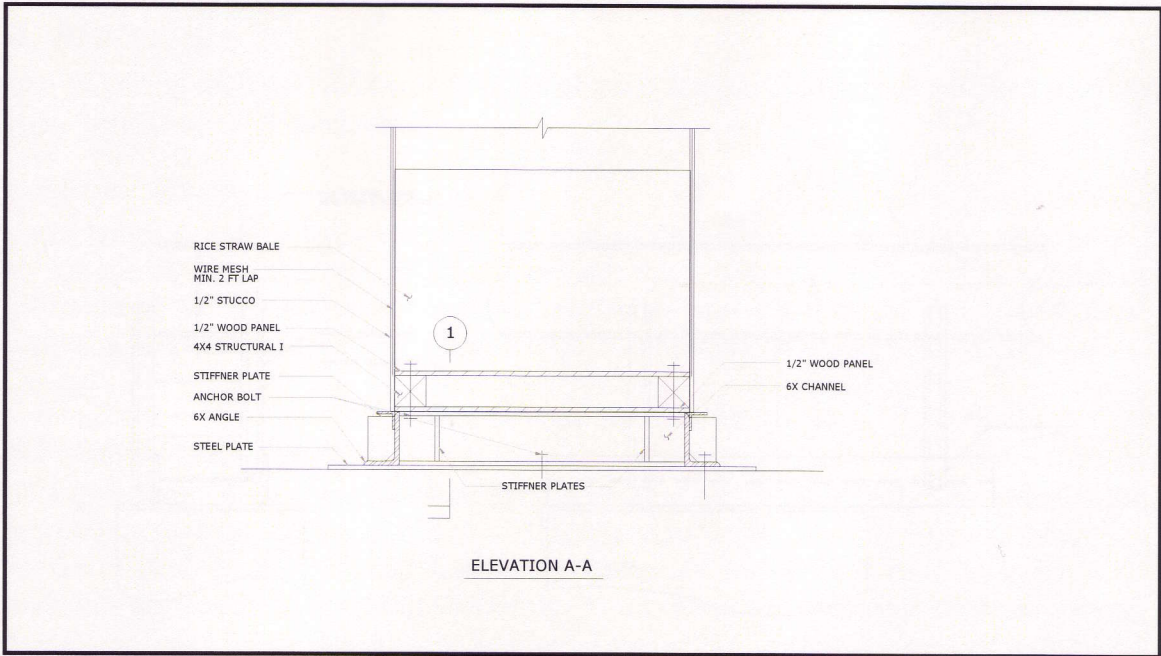


Figure 3.2 Base Detail - Plan View



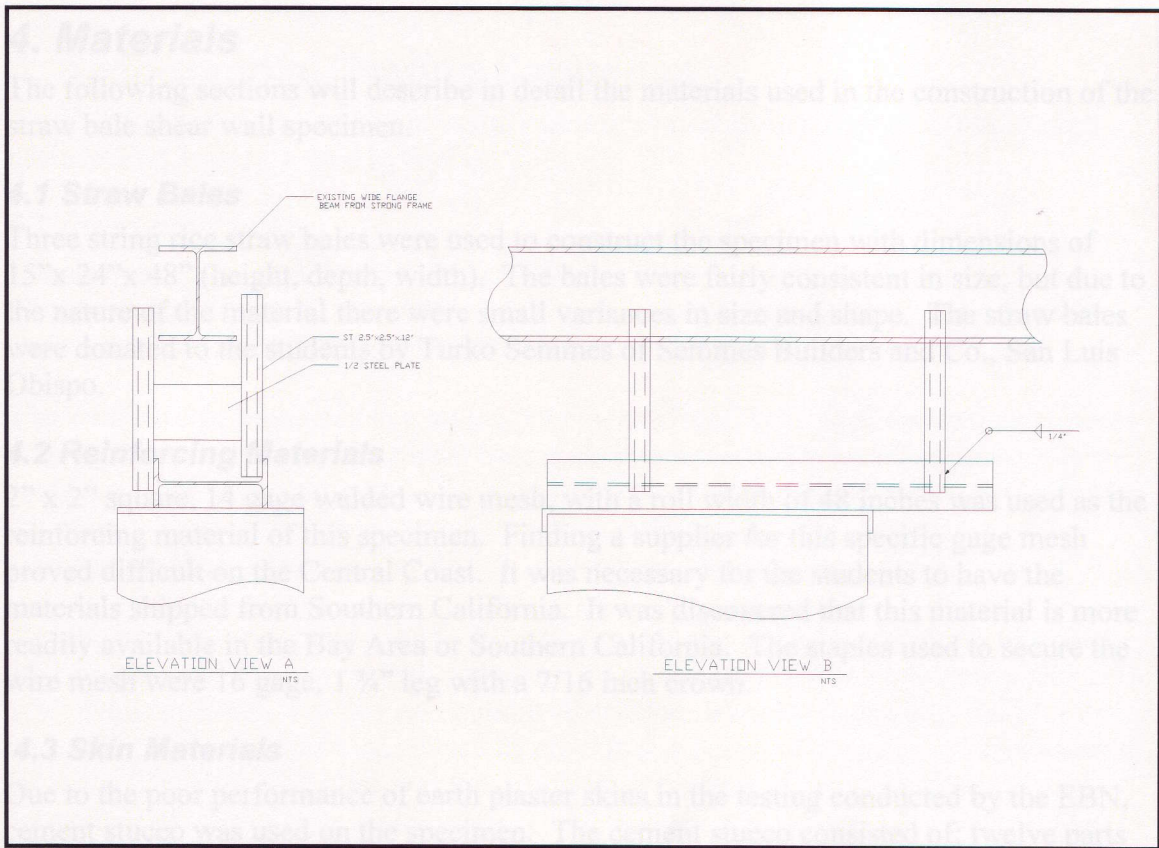
**Figure 3.3 Base Detail – Elevation**



**Figure 3.4 – Base Photo**

*Figure 3.5- Out of Plane Bracing Photo*





**Figure 3.5- Out of Plane Bracing Detail**



**Figure 3.6- Out of Plane Bracing Photo**

## **4. Materials**

The following sections will describe in detail the materials used in the construction of the straw bale shear wall specimen.

### **4.1 Straw Bales**

Three string rice straw bales were used to construct the specimen with dimensions of 15"x 24"x 48" (height, depth, width). The bales were fairly consistent in size, but due to the nature of the material there were small variances in size and shape. The straw bales were donated to the students by Turko Semmes of Semmes Builders and Co., San Luis Obispo.

### **4.2 Reinforcing Materials**

2" x 2" square, 14 gage welded wire mesh, with a roll width of 48 inches was used as the reinforcing material of this specimen. Finding a supplier for this specific gage mesh proved difficult on the Central Coast. It was necessary for the students to have the materials shipped from Southern California. It was discovered that this material is more readily available in the Bay Area or Southern California. The staples used to secure the wire mesh were 16 gage, 1 3/4" leg with a 7/16 inch crown.

### **4.3 Skin Materials**

Due to the poor performance of earth plaster skins in the testing conducted by the EBN, cement stucco was used on the specimen. The cement stucco consisted of: twelve parts sand, four parts Portland cement, one part lime, and water to the desired consistency for workability.

## **5. Experimental Testing Sequence**

The following sections will address the instrumentation and set up, as well as loading protocol and sequence used in testing.

### **5.1 Instrumentation**

The wall specimen was displaced at specific increments and the corresponding loads were recorded. The wall was displaced using a manually operated actuator. The data recorded will be used to create a hysteresis loop.

The actuator was connected to a strong column by a steel base plate and two steel plates with 1 ¼" diameter holes. The steel base plate was bolted flush with the strong column using 4 – 1 inch diameter bolts. The plates with holes were welded perpendicular to the base plate. This configuration was designed in order to allow for the rotation of the actuator arm during testing. For further explanation, see detail Figure 5.1.

The actuator was then connected to the wall specimen in a similar fashion to its strong wall connection. The connection consisted of a steel base plate and two steel plates with 1 ¼" diameter holes. For this particular wall specimen, a wide flange was used for the purpose of adding a dead load as well as providing a means of connecting the actuator to the wall. The steel base plate was welded flush to the web of the wide flange (for orientation of wide flange see Figure 5.1), and the steel plates with holes were welded perpendicular to the base plate. It was imperative that the actuator was placed to allow for the desired forward and backward stroke. For further explanation, see detail Figure 5.1.

### **5.2 Loading Protocol**

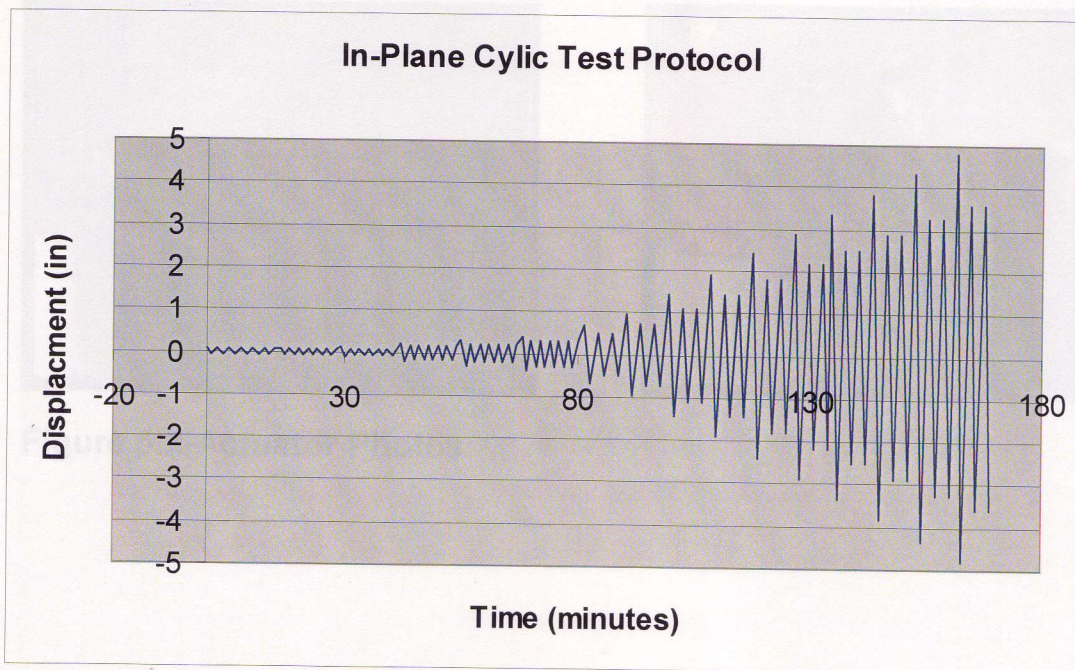
Previous tests completed by the Ecological Building Network provided the testing protocol to be used for the in plane-cyclic testing of this specimen. The protocol outlined in "In-Plane Cyclic Testes of Plastered Straw Bale Wall Assemblies" was researched and determined to be a suitable protocol that would not result in premature yielding of the specimen. For more detailed information on the research and protocol, reference the above mentioned report. The loads were applied in plane with the 4' length of the wall, and bracing in the out of plane direction was provided to simulate the roof system that would be present in typical construction.

The load protocol had sixteen steps, increasing in displacement, including trailing cycles to follow each peak cycle. The load steps are shown on the following page in Table 5.1.

**Table 5.1- Loading Protocol**

Wall Height (in)	96
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Load Step	Drift (%)	Peak Displacement (in)	Trailing Cycle Disp. (in)	# of Trailing Cycles
1	0.05	0.048	0.048	5
2	0.08	0.072	0.054	6
3	0.10	0.096	0.072	6
4	0.20	0.192	0.144	3
5	0.30	0.288	0.216	3
6	0.40	0.384	0.288	3
7	0.70	0.672	0.504	2
8	1.00	0.960	0.720	2
9	1.50	1.440	1.080	2
10	2.00	1.920	1.440	2
11	2.50	2.400	1.800	2
12	3.00	2.880	2.160	2
13	3.50	3.360	2.520	2
14	4.00	3.840	2.880	2
15	4.50	4.320	3.240	2
16	5.00	4.800	3.600	2



**Figure 5.1 –Cyclic Test Protocol**

The table and graph on the previous page represents the ideal testing protocol to be implemented. In Table 5.1 there are both peak displacements and trailing cycles. The peak displacements consist of maximum displacements for that particular load step, followed by a specific number of trailing cycles of smaller displacements. This type of loading was used to model cyclic loading and is also depicted in Figure 5.2. The peak displacements steadily increase until a maximum displacement for the specimen is reached. As described in section six, the peak displacements shown here were not reached for our specimen.

### 5.3 Testing Sequence

When the wall construction was completed the stucco surface was whitewashed in order to increase the ability to identify cracks of the specimen and provide an even background for photographs and video.

The wall specimen was tested as discussed in the previous section. Occasional pauses were taken to mark and record cracks and document the specimen's response to the loading.

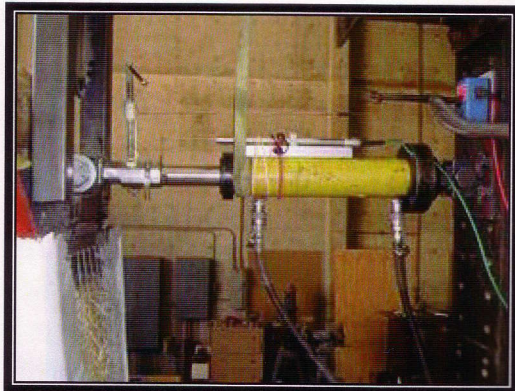
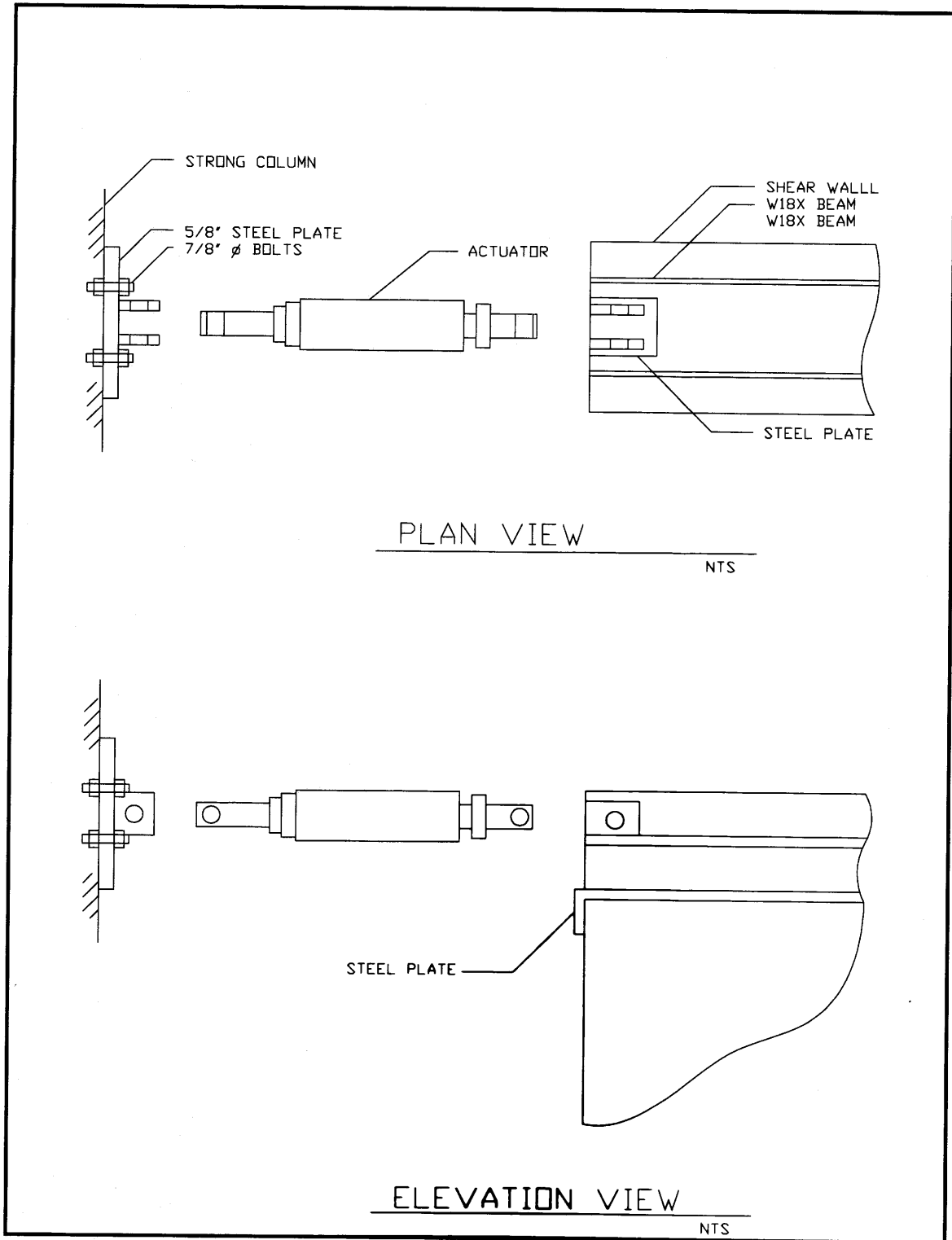


Figure 5.2-Actuator Photos

Figure 5.3-Actuator Connector Detail



**Figure 5.3-Actuator Connection Detail**

## **6. Testing Results**

### **6.1 Actual Testing Procedures**

In order to control displacement increments, as well as reaching loads up to eight kips as estimated, it was necessary to implement the use of a hand pump. This was due to the limitations of equipment and technology available at the university. The hand pump included a valve that allowed for the slow release of pressure in order to capture data in both forward and reverse (pushing and pulling) directions.

Due to the small displacement steps required in the initial load steps of the loading protocol, readings up to .288" were recorded using a Linear Displacement Transducer (LDT). The LDT was attached to the actuator and measured displacements of the actuator rod. Due to the movement in the pin connections of the actuator, the small data readings recorded included a large amount of relative error. At the point of .288", it was concluded that the use of a potentiometer (wire pod), attached to the strong column and the wall itself, yielded more accurate data.

With our simplified testing methods it was deemed appropriate to only record data for the values listed as peak and trailing displacements and disregarded values in between those maximum values at two times during the testing process: at the beginning of the testing and again after the specimen had experienced large plastic deformations. In the early phases of testing the required displacements were so small and there was movement in the pins, the LDT was measuring higher displacement values than the wall was experiencing. Starting with a displacement of .672", load step displacement readings were taken incrementally. This produced a better representation of the loads and displacements the wall was experiencing, and was used to create hysteresis loop as can be seen in Figure 6.1. At load step 13, 3.36", readings were taken incrementally for the peak displacement value only, and the trailing cycles were ignored. It was decided that the trailing cycles would not yield any further useful data as the specimen had already experienced large plastic deformations and loads were beginning to decrease indicating that the specimen's ultimate capacity had been reached. Additional readings were taken at peak displacements 3.84" and 4.32", in order to ensure that the maximum load capacity had been reached.

### **6.2 Loads and Displacements**

Based on the previous testing results a maximum load was estimated to occur at the maximum relative peak displacement of 4.8" required by the loading protocol. It was estimated that a load of about 4.75 kips would correlate to such a displacement, but a smaller load was expected as a result of our aspect ratio (See calculations on page 15). As can be seen in the hysteresis loop of Figure 6.1 the maximum load experienced by the specimen was 7000 lbs. (7 kips), with a corresponding displacement of 2.44". The maximum displacement the specimen reached was 4.32" with a corresponding load of 393.6lbs. It can be concluded that at displacements beyond 2.44", the compression block of the cement stucco had been greatly reduced as a result of spawling. This decreased the internal moment capacity of the specimen. The deformations imposed beyond 2.44"

resulted in continually decreasing loads due to the remaining capacity of the steel mesh and each vertical wire strands subsequent failure. This phenomenon, known as the zipper effect, began at a deformation of 3.38" with at a load of 3500 lbs. Although the zipper effect did not occur until 3.38" it is expected that the loads decreased after 2.44" due to plastic deformation of the steel.

### Expected Maximum Lateral Load of 4x8 Shear Wall

(Based on the Moment Capacity of 8x8 Shear Wall)

$$f_{4x8} = f_{8x8}$$

$$(M * y / I)_{4x8} = (M * y / I)_{8x8}$$

$$[M * (y / 2) / ((b * (y / 2)^3) / 12)]_{4x8} = [M * y / ((b * y^3) / 12)]_{8x8}$$

$$M_{4x8} = M_{8x8} / 4$$

$$F_1 * H = F_2 * H / 4$$

$$F_1 = F_2 / 4$$

b = thickness of the shear walls

$$M_{4x8} = H * F_1$$

$$M_{8x8} = H * F_2$$

F = the maximum tensile stress of the shear wall

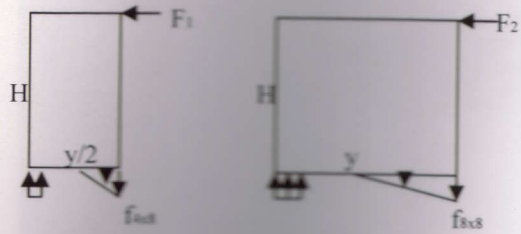


Figure 6.2 - 1" Crack Photos

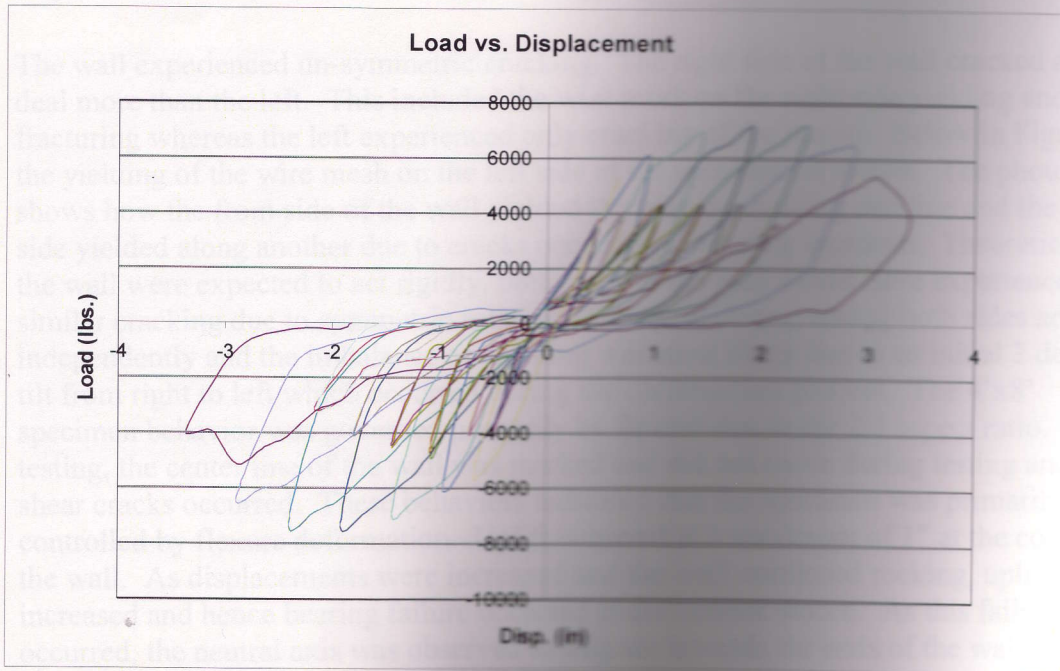
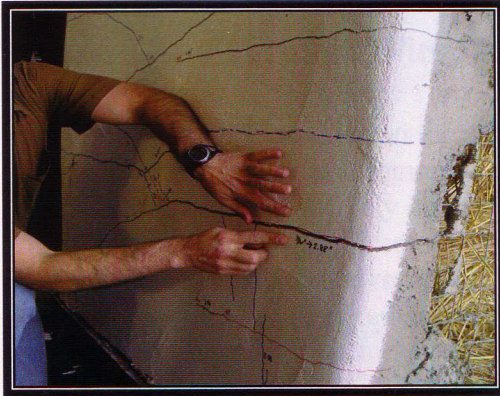


Figure 6.1 - Hysteresis Loop of Loads vs. Displacements



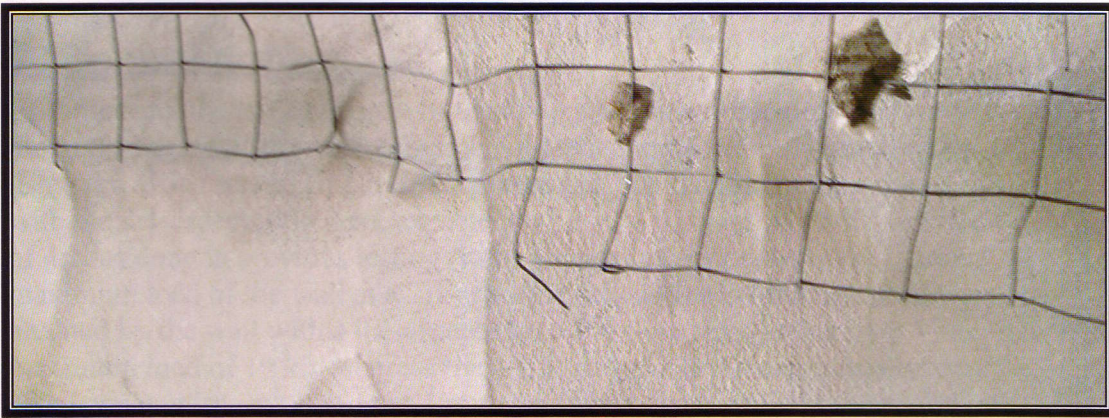
### 6.3 Specimen Behavior

The first signs of permanent damage occurred in the form of cracks at a displacement of .67". Cracks continued to form, eventually causing spawling on the rear left side at a displacement of 1.68" and a corresponding load of 6500lbs. It was expected that the cement stucco would act in compression and bear on the angles provided until cracks were large enough to engage the steel wire mesh. The largest opening of a crack was measured to be 1" on the right side of the specimen, and occurred above the one foot area where the bottom U-shaped wire mesh overlapped with the panel wire mesh. The 1" crack can be seen in Figure 6.2 below.



**Figure 6.2 – 1" Crack Photos**

The wall experienced un-symmetric cracking. The right side of the wall cracked a great deal more than the left. This included the wire mesh on the right side yielding and fracturing whereas the left experienced only cracking of the stucco. Below in Figure 6.3, the yielding of the wire mesh on the left side of the specimen is shown. The photo below shows how the front side of the wall yielded the wire mesh along one line and the back side yielded along another due to cracks occurring at varying locations. Theoretically if the wall were expected to act rigidly, both sides of the wall would have experienced similar cracking due to symmetric rotation. However, during testing both sides acted independently and the imbalance of cracking was most likely due to an initial 2 degree tilt from right to left which occurred during the construction process. The 4'x8' specimen behavior was governed primarily by flexure due to the 2:1 aspect ratio. Before testing, the center line of the wall was marked and did not move during testing and few shear cracks occurred. These behaviors indicated that the specimen was primarily controlled by flexure deformation. Uplift occurred at a maximum of 1" at the corners of the wall. As displacements were increased and the wall continued rocking, uplift increased and hence bearing failure occurred in the cement stucco. As this failure occurred, the neutral axis was observed to migrate towards the ends of the wall, slowly decreasing and thereby engaging the wire mesh more. Once the main crack spanned across the length of the specimen, the neutral axis began returning toward the center of the wall as the rocking action occurred primarily at the crack location instead of the base of the wall.



**Figure 6.3 – Fractured Wire Mesh from Right Side of Specimen**

The connection of wire mesh to the 4"x4" sill plates, nor the staples in the connection experienced any failure and remained intact. The 4"x4" sill plates cracked vertically down their centers, most likely due to uplift and the edge distance of anchor bolts on each end. The plywood remained connected to the 4"x4" sill plates with little sign of uplift. When the anchor bolts were removed from the box beam indentations from the washers could be seen as a result of uplift.



**Figure 6.4 Base Connection Post Testing**

## 7. Conclusions

In comparing the testing results of the 4 x 8 specimen to previous tests of 8x8 specimens, the performance of the 4 x 8 specimen exceeded expectations. Based on the calculations using the difference in length of the specimens, the maximum load values of the wall with the 2:1 aspect ratio were expected to be 25% of those of a wall with an aspect ratio of 4:1, as done in previous testing (refer to calculations on page 15). The actual maximum load of the wall at a 2:1 aspect ratio was approximately 37% of the loads attained by the wall with a 4:1 aspect ratio. Previous tests with an 8 x 8 wall reached a maximum load of 19 kip whereas the 4 x 8 wall reached a maximum load of 7 kips. The discrepancy of the expected maximum load value is most likely due to the ratio of area of overlapped steel to area of single layer steel. The lengths of overlapped mesh from U-shaped pieces on the top and bottom and both sides of the wall were set at 1 foot and 6 inches respectively. This same amount of overlap was used on the wall with a smaller aspect ratio thereby increasing the percentage of area of the wall that had overlapping layers.

The location of cracks on the wall performed as expected. In previous testing, the major flexural cracks formed just above the cutoff of the overlapping layers of wire mesh. This phenomenon was also observed on the 4 x 8 specimen. These behaviors were similar due to the fact that both walls, the 8 x 8 and the 4 x 8, were governed by flexure. Cracking in these locations is desirable in comparison to cracks forming near the base of the wall which would result from a lack of the 1 foot overlap, and would decrease the specimen's bearing capacity.

The analysis of the data collected yielded a hysteresis loop that reflects the capabilities of a straw bale shear wall to dissipate energy effectively. The hysteresis loop of 8 x 8 walls is very similar to that of the 4 x 8 wall in shape and behavior with the only major difference being decreased capacity due to the decrease in aspect ratio.

## **Acknowledgements**

We would like to convey our sincere gratitude to those individuals who aided and guided us through the construction and testing processes.

We would like to thank David Mar for his guidance and expertise in the construction process, testing procedures, and general engineering concepts; as well as his financial donations and solicitations of further funding. Special thanks to Ray Ward for his hard work and continual help in the construction of the wall, as well as his knowledge and assistance in facilitating the testing procedures. Turko Semmes for his donation of straw bales and continual support, in addition to always being available to answer questions. Ted Mueller for his generosity in plastering labor. Finally, Kevin Dong for the direction he provided, keeping us on task, overseeing our project, and his general engineering knowledge.