SHEAR STRENGTH OF STRAW BALE PLASTERS

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ABSTRACT :

Experimental studies are beginning to provide the necessary data to support the development of seismic design provisions for straw bale wall construction. A series of tests were undertaken to characterize the shear strength of several different plasters used in straw bale wall construction: an earthen plaster, a lime plaster, and a cement plaster (stucco). The plaster shear strengths, which are expected to vary with f'_c in the case of earthen plasters and $\sqrt{f'_c}$ in the case of cement plaster, where f'_c= cube compression strength, are determined for unreinforced plasters subjected to monotonic shear and for reinforced plasters subjected to both monotonic and reversed cyclic shear displacement histories. Described in this paper is a panel shear test apparatus developed for this work and results for the earthen plaster.

KEYWORDS:

Straw bale, plaster, panel shear strength

1. INTRODUCTION

The historical development of straw bale construction as vernacular architecture traditionally has relied upon the wisdom, ingenuity, resourcefulness and experience of field craftspeople and builders. Some early straw bale buildings (circa 1900-1925) in which no mesh was used in their plasters have survived very well to this day (Steen et al., 1994). The growth in popularity of straw bale construction in recent years has led to straw bale construction being used for larger buildings, buildings that operate in the public realm, and buildings located in regions of high seismicity. While mesh-reinforced plasters may not be needed in all situations, the maturation of straw bale construction as a material of construction has brought the need to standardize “best of practice” details and to enable engineering approaches to be used for design, to promote reliable performance and to secure building official approval, particularly as straw bale construction is being used in a larger range of structural applications.

Of particular interest in this paper is the use of straw bale walls as designated elements of a lateral load resisting system. In recent tests (Ash, et al., 2003 and 2004) straw bale walls provided lateral load resistance on par with or surpassing that provided by plywood shear walls. The load is carried primarily by reinforced stucco or earth plaster skins applied to each side of the bale walls; the mesh reinforcement and plaster contribute substantially to the shear and flexural strength of the wall. The aspect ratio of the specimens in the Ash et al. tests promoted the development of flexural failures over shear failures. Hence, the tests served to validate a flexural strength model, but did not provide adequate data on shear strengths to be expected of longer walls (those having more squat aspect ratios). The present work aims to better understand the shear strength of straw bale plasters.

There is some indication that the functional dependency of shear strength on compressive strength should vary with the composition of the plaster. Those plasters that derive their strength primarily from clay would be expected to have shear strength proportional to compressive strength, based on the Mohr-Coulomb failure surface for cohesive materials. Materials that possesses both “frictional” and cohesive properties, such as Portland cement-based plasters (following along the lines of Aschheim (2000) for reinforced concrete), would be expected to have shear strengths that are proportional to the square root or 2/3 root of the compressive strength. Since there are many types and variations of recipes for plasters, the main objective of the present study is to characterize the shear strength dependency on compressive strength. Also of interest is the role that mesh reinforcement may play in enhancing the shear strength of the plaster, and how the cyclic shear strength differs from the monotonic strength. Finally, whether an additive model such as is used for reinforced concrete ($V_n = V_c + V_s$) is applicable or if other models are needed is investigated.

Anchorage of the mesh reinforcement to the mud sill and roof bearing assembly also plays a critical role in the performance of the wall. The selection of suitable meshes and fasteners has been complicated by issues related to the recent introduction of wood preservatives that are highly corrosive to steel fasteners. Fortunately, Parker et al. (2006) has addressed this for several types of meshes and staples.

2. EXPERIMENTAL TESTS

Three types of tests were performed on the plaster samples: cube compression, direct shear, and panel shear. The panel shear tests were needed to determine the shear strength of samples with and without mesh reinforcement, under monotonic and reversed cyclic loading. Because nominal 2-inch meshes are used to reinforce the plasters, the samples had to be relatively large so that panel would be representative of a reinforced plaster skin, and so that boundary effects would be of secondary importance. A detailed description of the panel shear device, which was developed for these tests, is provided in the following section.

Cube compression tests were used to provide a simple way to characterize plaster strength. The cube compression tests were performed on nominal 2-inch (50.8-mm) cube samples in a universal test machine under monotonic compression. The samples were prepared by applying the plaster in parallel layers, with each layer allowed to cure before application of a subsequent layer to mimic field application. Compression was applied in the plane of the layers, so that the layers were loaded in parallel, to mimic loads applied in the plane of the plaster skin.

The direct shear tests were used to determine the cohesion and angle of friction of the plaster material to be evaluated, and provided a baseline for validating the results of the panel tests, for the unreinforced panels.

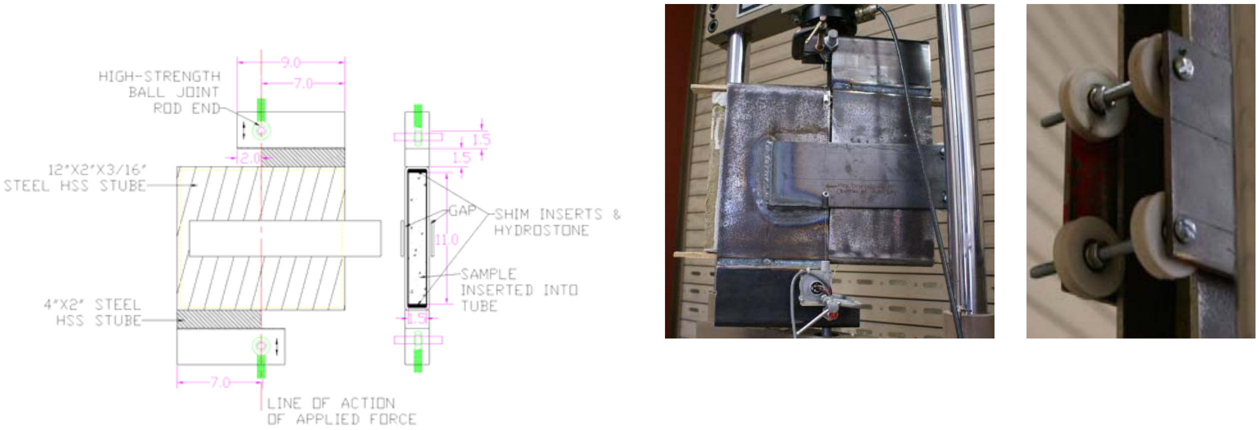
The direct shear tests were performed on a geotechnical testing machine on cylindrical samples, nominally 2.5-inch (63.5-mm) diameter by 1-inch (25.4mm) high. The direct shear tests typically were performed monotonically under different, invariant, normal loads. The normal loads used were approximately 50, 150, and 250 pounds (223, 669, 1110 N). The samples were prepared with the layers oriented vertically (parallel to the longitudinal axis of the cylinder). The shear was applied so that the layers were loaded in parallel, again simulating load applied in the plane of the plaster skin.

3. PANEL SHEAR TEST APPARATUS, SAMPLE PREPARATION, AND DISPLACEMENT PROTOCOL

The apparatus developed for the panel shear tests is shown in Figure 1. The design made use of two 2" x 12" x 3/16” (51 x 305 x 4.8 mm) high strength steel (HSS) tubes, each 7 in. (178 mm) in length, that mirrored each other and defined a shear plane. Each of these tubes was welded to another tube (2” x 4” x 3/16” (51 x 102 x 4.8 mm) HSS), which provided a 3-inch (76 mm) clearance for vertical movement, and then to a high-strength ball joint rod end with a 9813 lb (43.65 kN) capacity. A steel plate and roller system was provided to restrain relative motion of the tubes so that shear displacement at the interface of the two tubes was dominant (Figure 1c). A 5-inch (127 mm) Celesco cable extension transducer (also known as a string potentiometer) was used to measure panel shear displacements.

Plaster samples were prepared that were nominally 1.5 x 11 x 14 in. (38 x 279 x 356 mm) in size. Sample preparation mimicked field conditions, with three layers of plaster built up over several days’ time. Each plaster sample is placed within the 2 x 12 inch (51 x 305 mm) tubes and secured by setting the upper and lower edges in a bed of approximately 0.25” (6.4 mm) thick Hydrostone mortar. To facilitate sample removal after failure, wood shims were located between the steel tube and the mortar bed.

Loads were applied under displacement control. Three types of loading schemes were used for testing the panels: monotonic tests were performed on unreinforced panels and on panels reinforced with mesh reinforcement, and reverse cyclic loading was applied to reinforced panels. The applied reversed cyclic displacement pattern followed ASTM E2126-02 (2002) with an assumed yield displacement of 1 inch (25.4 mm).



(a) (b) (c)

Figure 1: Panel shear test fixture (a) drawing, (b) elevation view, and (c) view of roller restraint.

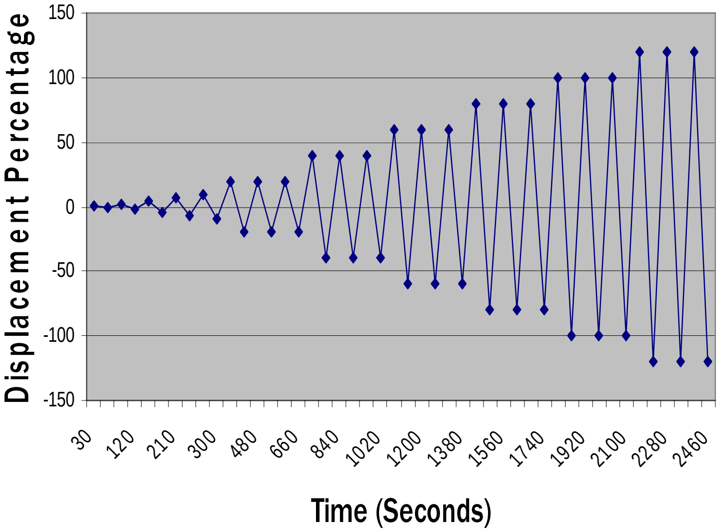


Figure 2: cyclic displacement pattern

4. MATERIALS

Earthen plasters incorporating chopped straw are commonly used in straw bale wall construction because the straw provides tensile strength and is readily available. The straw helps to control shrinkage cracks and improves toughness (King et al., 2006). The earth plaster described herein had the composition given in Table 1. Cube compression results are given in Table 2.

Table 1: Composition of earth plaster reinforced with Cintoflex C.

Component	Parts (by volume)	Description
Sand	4	Standard masonry sand (Felton Sand from American Soil Products).
Clay	1	Site clay from the Oakland Hills, slaked a minimum of 12 hrs. in water.
Straw	1	Rice straw mechanically chopped and sieved to lengths of 1± inch (25± mm).
Water	3/4	Clean potable water.

Figure 3: (a) cube compression test, and (b) Cintoflex C strand tensile test, showing failure and strand junction.

Table 2: Cube compression results

Specimen	Maximum Load	Maximum Strength	Average Strength
	(lbs.)	(psi)	(psi)
1	N/A*	N/A*	170
2	678	174.1	
3	640	165.4	

**A malfunction occurred during testing.*

Table 3: Tensile strength of Cintoflex C strands

Test #	Maximum Strength	Maximum Elongation	Average Strength	Standard Deviation for Strength
	(lbs)	%	(lbs)	(lbs)
1	598	15.87%	623	53
2	586	35.07%		
3	684	17.67%		

A material commonly used for deer fencing, Cintoflex C, was used as a mesh reinforcement for the plaster. Cintoflex C is a polypropylene plastic that is rugged and resistant to many chemical solvents, bases and acids.

5. DIRECT SHEAR TEST RESULTS

Three specimens were each tested until the a displacement equal to 20% of the specimen diameter was reached; this was well beyond the point of failure. As seen in Figure 4, these specimens developed a very well-defined shear plane, consistent with the constraint imposed by the test method.

Even after testing until failure, the straw that was mixed into the specimen remained attached to the plaster and held the fully sheared pieces together, as may be seen in Figure 4b. This observation confirms the idea that the straw provides additional strength to the plaster at the large displacements that took place during the direct shear testing.

Strengths are reported in Table 2, and are plotted together with normal stresses imposed during testing in Figure 5. A curve was fitted through the data of Figure 4. Based on Equation 1.1,

$$S = C + \sigma \cdot \tan(\phi) \tag{1.1}$$

Figure 4: (a) direct shear specimen with defined shear plane; (b) close-up of embedded straw

with S = measured ultimate shear strength and σ = applied normal stress, the cohesion, c, was determined to be 42.5 psi (293 kPa) and the angle of friction, ϕ, was determined to be 37.1°.

A classical Mohr-Coulomb failure surface is described by Equation 1.2:

$$\sigma_1 = \sigma_3 \cdot \left[\tan\left(45 + \phi / 2\right)\right]^2 + 2c \cdot \tan\left(45 + \phi / 2\right) \qquad (1.2)$$

where σ_1 = major principal stress (or compressive strength), σ_2 = minor principal stress, and other terms are as defined previously. Using Equation 1.2 and the properties determined from the direct shear tests, the unconfined compressive strength was estimated to be 171 psi (1170 kPa). This compares favorably with the mean cube compressive strength, 170 psi (1170 kPa), reported in Table 2. For more conventional materials, we would have expected the cube strength to exceed 171 psi (1170 kPa) by perhaps 25% due to the restraint from lateral dilation provided by the loading platens at the boundaries of the cube. Perhaps the transverse compressibility of the straw or macroscopic voids within the material significantly reduce the shear stiffness of the material, effectively limiting the extent of the confined regions to near the sample ends.

Table 4: Direct shear test results

Specimen	**Height**	**Diameter**	**Normal Load**	**Effective Normal Stress, σ'**	**Max Shear Force**	**Shear Strength, S**
	(in.)	**(in.)**	**(lb.)**	**(psi)**	**(lb.)**	**(psi)**
1	1.00	2.40	Not loaded to failure			
2	1.02	2.39	141.8	31.6	327.8	73.1
3	1.04	2.39	239	53.1	357.6	79.5
4	1.02	2.38	53.8	12.1	214.7	48.1

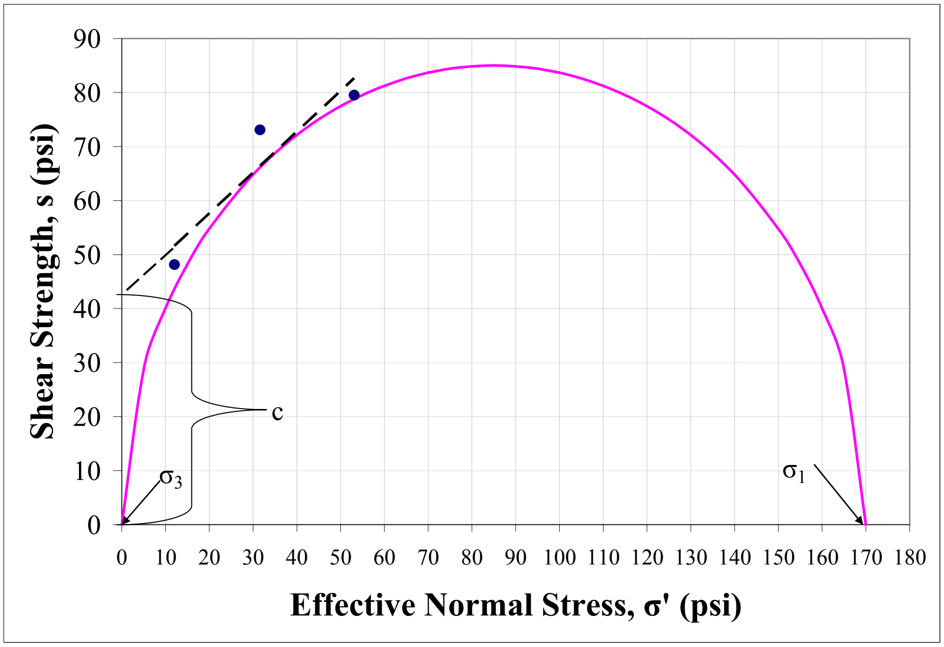


Figure 5: Direct shear test results, determination of c and ϕ, and estimation of compressive strength.

6. PANEL SHEAR TEST RESULTS

Unreinforced panels subjected to monotonic loading developed diagonal cracks along the shear plane, as seen in Figure 6. The panels reinforced with a single layer of Cintoflex C mesh subjected to monotonic loading all failed in a similar way, with vertical cracks developing as shown in Figure 7. The Cintoflex reinforcement did not rupture because it is flexible relative to the displacements imposed by the test fixture.

Figure 6: Unreinforced earth plaster panel specimen, after failure.

Figure 7: Earth plaster panel specimen reinforced with Cintoflex C mesh, after failure.

Table 5 presents shear strength data for the reinforced and unreinforced panel specimens. The ultimate strength was determined as the peak load divided by the shear area. The shear area is the cross sectional area along the line of action of the applied force, shown in Figure 1a, not the length of the inclined fracture surface.

Table 5: Panel shear test results (monotonic)

Test	Specimen	Ultimate Shear Strength (psi)	Mean Ultimate Shear Strength (psi)	Standard Deviation (psi)
Unreinforced	1	80.49	67.48	17.08
	2	73.82		
	3	48.14		
Reinforced with Cintoflex C	1	71.96	65.60	5.88
	2	60.38		
	3	64.44		

Table 5 suggests that the presence of reinforcement actually reduced the shear strength, but by a very small amount. The statistical significance of the difference in mean strengths was evaluated using an equal tails *t*- test. It was found that the null hypothesis, that the means are equal, cannot be rejected at the 5% significance level. Thus, the small difference in empirical means is not significant. Comparison of Figures 6 and 7 demonstrates that the presence of the Cintoflex caused the inclination of the failure surface to change, even though the load at failure was not significantly different, relative to the unreinforced panels.

The reversed cyclic tests were the most time consuming and meticulous test of the three shear tests. The earthen plaster test specimens did not fail in shear, but instead both top and bottom surfaces crumbled to the point that the reinforcement was exposed, as seen in Figure 8. This appears to be a boundary effect, and is not a shear failure as such. Thus, these tests do not represent panel shear strengths, and suggest that refinements are needed in the method used to set the specimens in the test fixture. Further testing will use a thicker bed of Hydrostone and will not use wood shims, so as to provide more uniform stress conditions and perhaps provide some confinement to the earth plaster.

Figure 8: Reinforced shear panel specimen with showing edge failure under reversed cyclic loading

7. CONCLUSIONS

On the basis of the experimental results completed to date and limited analysis presented herein, we conclude that:

1. The earthen plaster was determined to have angle of friction, ϕ, equal to 37.1° and cohesion, *c*, equal to 42.5 psi (293 kPa). These properties provided a very good estimate of the cube compressive strength, under the assumption that no confining stress is present. Perhaps this may be attributed to macroscopic voids in the material and/or the presence of the straw.

2. The presence of the Cintoflex C mesh causes a change in the angle of the shear failure plane, but did not significantly affect the shear strength of the earthen plaster.

3. Under reversed cyclic loading, the panel shear specimens disintegrated at their top and bottom edge surfaces, suggesting that improvements are needed in the manner in which the specimens are set into the tubes of the panel

shear test device.

Additional plaster types are in the process of being tested, and results for these and for the reversed cyclic tests will be presented at the conference and in future publications.

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