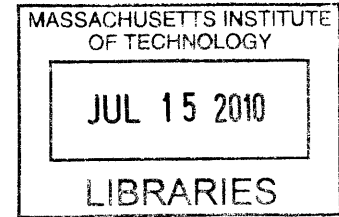


SEISMIC LOAD-RESISTING CAPACITY OF PLASTERED STRAW BALE WALLS

by

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Bachelor of Arts, Architecture
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ARCHIVES

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Seismic Load-Resisting Capacity of Plastered Straw Bale Walls

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Civil and Environmental Engineering

ABSTRACT

Straw bales have been incorporated into buildings for centuries, but only recently have they been explored in academic settings for their structural potential. Straw bale building is encountering a growing audience due to its social and economic benefits. Plastered and reinforced straw bale wall assemblies have been found comparable to wood frame construction in resisting vertical and lateral loads. A number of straw bale residences have been constructed in the highly seismic state of California, while recent efforts have expanded its presence to quake-prone areas in developing countries like Pakistan and China. As this is a burgeoning arena of research, only empirical tests have been conducted. This thesis introduces a computer simulation of a wall assembly under lateral loading, using two techniques: a multi-layer shell element and an equivalent compression strut frame in SAP2000. The models assume homogeneity, and based on the results, areas for improvement and further research are suggested.

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1. Introduction

Many countries in the developing world are suffering from a lack of structurally sound housing in seismic zones. Recent tragedies include the earthquake in Haiti in 2010, the earthquake in Sichuan, China in 2008, and the earthquake in Bam, Iran in 2003. In all of these instances, thousands of fatalities were blamed on poor structural engineering and could have been prevented with the enforcement of building codes.

Straw bale construction has historically been used as a vernacular building material in many parts of the world. Recently, it has also gained popularity in the United States as part of the green building movement, as it is well-known that it has a high insulation value and generally low environmental impact and cost. The straw itself can come from several sources, such as wheat, rye, rice, and other grains, and is an untapped resource here in the U.S. and elsewhere. For example, from 1990 to 1996, it is estimated that about 123 million tons of straw were produced from wheat and rice per year on average, with a total availability of 125 to 177 million tons from all grain types. Unfortunately, only a small percentage of straw in the U.S. is actually baled and used for construction (EESI).

Because of the relative abundance and other benefits of straw bales, research into its application for housing both in the U.S. and abroad has been growing. In particular, the straw-plaster composite wall system is being explored for its potential resistance to lateral loads. Exploiting these combined strengths, instances of straw bale housing can now be found in highly seismic areas of the world like Pakistan and China.

This thesis explores current developments in the field of lateral load-resistant straw bale housing. It attempts to recreate empirical data gathered from physical experimentation using finite element analysis in the program SAP2000. It also discusses the aforementioned instances of existing, load-bearing straw bale construction.

2. Benefits of Straw Bale

Straw bale housing has a number of benefits as a material. First, it uses local materials and local labor. As described in Section 6: Case Studies, straw bale construction makes use of a local resource commonly regarded as waste. Straw bale programs bring together local communities and train potentially hundreds of residents in the fabrication and construction of straw bale buildings.

Second, it is fully renewable. At the moment, most straw from the agricultural industry ends up being burned in the field. This only increases the amount of carbon dioxide in the atmosphere, reduces visibility, and reduces air quality, which then leads to health problems. Some straw is also used for animal bedding, or returned to the soil to ensure productivity. Incorporating straw into construction would reduce emissions in its own lifecycle as well as that of the entire building (EESI).

Finally, it offers tremendous energy savings, a benefit not only to individual homeowners but to the global community as well. One of the defining characteristics of straw bale as a building material is that it is not homogeneous. This fact influences its structural performance as well as its insulating properties (see Section 3: Properties of Straw Bale Wall Assemblies). However, research at Oak Ridge National Laboratory has determined that a plastered straw bale wall exhibits an R-value of 1.45 per in on average, where an R-value is a measure of resistance to heat flow. This can be compared to average R-values of typical building materials in the table below.

Building Materials	R-value per Inch
Brick Masonry	0.2
Poured Concrete	0.08
Soft Wood Lumber	1.25

As with other wall materials, the entire wall assembly did not perform as well as the individual components. Early R-value tests on individual straw bales yielded average results of R-40 to R-50,

considerably higher than the lab-tested values of about R-30 for walls. However, even a 2-by-6 in framed wall also tested at the Oak Ridge Laboratory yielded only a rating of R-12.8, compared to its nominal rating of R-19. Thus, straw bale still performs better than conventional walls (Steen 2000).

The R-value actually seems to depend on the orientation of the bales in construction, with a higher value when laid on edge, because the straw fibers are then oriented perpendicular rather than parallel to the flow of heat. The difference can be quantified by considering that a 24-in-wide wall of flat bales yielded the same R-value as a 16-inch wall with bales on edge.

The variability of R-values stems from a handful of circumstances. Each straw bale wall may vary in the type and moisture content of the straw itself, the kind of plaster, as well as the design of the wall itself, some of which may contain more openings than others.

Further, straw bale walls have the added benefit of sequestering carbon. However, little research has been done to determine the extent of this capability, which is likely rather insignificant in comparison to the amount of carbon emissions reduced by the high insulating value of the walls (King 2006).

3. Properties of Straw Bale Wall Assemblies

3.1 General Properties

3.1.1 Straw Bales

Like wood, straw is an organic, lignocellulosic material, leading to orthotropic properties in the overall bale. Its three main components are cellulose, hemicellulose, and lignin. Cellulose microfibrils provide tensile strength and contribute to the main structure of the tube. Hemicellulose molecules bind the cellulose fibers together, while lignin is an adhesive that creates the entire straw structure from the fibers and other small constituents like silica ash.

Straw is not to be confused with hay, which provides a rich source of protein and carbohydrates for horses and other grazing livestock. Straw is an important part of cereal plants like wheat, rice, and barley, and it refers to the dry stalk between the roots of the plant and the grain head.

While the structural properties of the different cereal grain types do not seem to differ much, many practitioners of straw bale construction tend to prefer rice straw. First, rice straw has higher silica content than its counterparts, thus providing more resistance to fire and decay. Second, as observed under an electron microscope, the surface of rice straw is slightly barbed, offering more friction and therefore more coherence in the bales, even when they are cut or untied.

Another concern when choosing straw is whether it has been organically grown. While this seems like more of an environmental concern than a structural one, and probably is, it is worth considering the specific pesticide used for the particular batch of bales. Extensive research into the health effects of having pesticides lodged inside building walls has not been conducted.

A more relevant question asks whether fertilizer has been used in growing the grain. Regardless of whether the fertilizer was organic or petrochemically based, it is known that the addition of

nitrogen will cause the straw to decompose faster, and in buildings, this translates to rot. This condition is practically an inevitability in industrialized countries.

Bales are the blocks of compressed straw that make up the elements of a wall. Ordinary bales as have been formed for generations by farmers for non-building purposes typically come in two rectangular sizes: two-string and three-string. Two-string bales range from 50 to 65 lbs, with dimensions of 15 by 18 by 36 in. Three-string bales range from 75 to 95 lbs, with dimensions of 16 by 23 by 46 in. These bales are still manageable by people, but recently, the available size of bales has increased to as large as 4 by 4 by 8 ft. Round bales are also becoming increasingly common, as are supercompressed bales or bales which incorporate other materials like plastic.

Bales are more commonly stacked flat, but can also be laid on edge, as seen below in Figure 1.

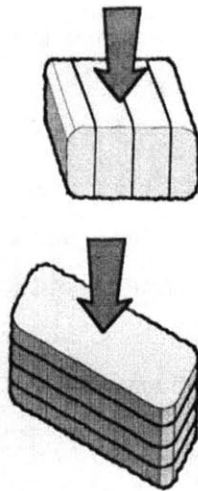


Figure 1: Bales laid flat and on-edge. Source: King

There are a number of qualities to be considered for bales that will be used for building. First, the moisture content should be as low as possible. One possible guideline is that a moisture content above 30 percent in 40-degree-Fahrenheit weather may lead to accelerated decay. Another parameter is the dry density, which should be at least six pounds per cubic foot for load-bearing walls. Finally, the average fiber length, which is determined by the type of combine used to harvest the straw, should be at least ten inches on average (King 2006).

3.1.2 Plaster

In load-bearing straw bale walls, the component which takes most of the vertical and horizontal loads is the plaster sidings, due to their considerable stiffness when compared to the straw bales. The plaster can be made of gypsum, lime, cement, or a mixture of earth, sand, and straw. A system of gunite straw bale walls has recently been patented by the Berkeley firm Integrated Structures, Inc. This technique is explored further in Section 6: Case Studies. The plaster tested in the model under lateral loads will have cement binders.

Plaster skins are usually one to three inches in thickness and serve a number of important functions for the composite wall system (see Section 3.3 Important Considerations). For instance, they are critical to the thermal performance of the wall since they prevent the passage of air in and out of the walls. Additionally, a typical bale comes out of processing with a number of surface irregularities. The plaster then fills and seals the still non-uniform surface. In good practice, the bale is trimmed before installation and plastering.

Similar to concrete, plaster is composed of three primary ingredients: a binding agent, a structural filler, and water. The binding agent can be clay, cement, gypsum, or lime, and it contributes the most to the plaster strength. As with concrete production, the plaster must be cured and dried, during which the cement, gypsum, or lime undergoes a series of chemical reactions and thus cannot be reused later, in contrast with clay. Care must be taken to ensure plaster workability and to avoid brittleness and cracking.

The filler is a non-organic element, most commonly sand but sometimes larger aggregates. The sand provides the bulk of the volume of plaster and the most strength. The ideal make-up of the sand is sharp and well-graded to ensure that the pieces are locked together well. Containing very fine silt particles is an undesirable trait. As with concrete, the proportions of the plaster mix, as well as the quality of curing, are crucial to the strength of the wall.

An integral part of the wall composite is the reinforcement for the plaster, which can be a fiber mixed into the plaster or an embedded woven or welded mesh. This provides increased tensile capacity while also improving the elasticity and ductility of the plaster. It also allows a thicker coating of plaster. There are several types of reinforcement available. When dealing with fiber,

cement plasters generally use fiberglass, polypropylene, or fine steel fibers. Fiber reinforcement for lime plaster is usually made of coarse animal hair, while earthen plasters use plant fibers. The addition of fiber increases the MOR, leaving the plaster less brittle, but has an inverse effect on the workability.

Alternatively, mesh reinforcement can be embedded into the center of the plaster skin to transfer shear loads between the plaster and roof or foundation. The mesh should be relatively light-gauge so that it can be stapled to the wood plates at the edges, and so that it can yield prior to failure of the cement plaster in compression. A widely suggested mesh is 14-gauge galvanized steel fencing. The connection to such elements is crucial to design. Due to slippage between strands, woven mesh is not as strong as welded mesh and is therefore not as common in highly seismic zones like California. Galvanized wire mesh is preferable in such regions for cement and lime plasters, because the zinc coating offers protection against oxygen and moisture. In reinforced concrete, the steel rebar is partially protected by the concrete alkalinity, but in plaster skins, the cover is too thin to provide enough alkalinity. However, it is not recommended for earth plasters due to the higher oxygen and moisture content, which may accelerate oxidation of the mesh. In such cases, welded plastic or fiber meshes are preferable. Again, the mesh should be located in the center of the plaster so as not to create a barrier to bonding between the plaster and the straw. Likewise, the holes must be large enough to allow plaster to seep through it.

There are a number of properties to consider when deciding which type of plaster to use. Cement plasters have the most strength but are also the most brittle, which may pose a problem when applied to more flexible substrates. Thus, the mesh reinforcement is critical around areas where the substrate changes, such as window or door openings. One important drawback with cement plasters is the low vapor-permeability, which could lead to higher than acceptable moisture content in the straw. To avoid this, the cement must contain enough lime to increase the permeability to at least two U.S. Perms. The models investigated in this paper deals exclusively with cement plasters.

Lime plasters are less rigid and brittle than their cement counterparts. This implies less cracking, while hairline cracks are also naturally filled by the carbonation of calcium hydroxide. Large cracks can also easily be filled by a mixture of lime and water. Interestingly, the plaster also sequesters carbon dioxide over its lifetime, almost offsetting the amount of carbon dioxide emitted during production. The plaster actually becomes calcium carbonate again by the end of its lifetime,

resulting in a closed loop system. Additionally, lime plasters have the benefit of greater vapor-permeability than cement and greater moisture absorption than either cement or earth. Furthermore, lime can wick easily, and the alkalinity prevents the proliferation of mold and mildew. One drawback is that the curing process for lime requires extensive attention and is rather slow. A growing practice is to overlay a coat of earthen plaster with a coat of lime.

Earthen plaster is based in clay and is therefore hydrophilic. It tends to store water rather than wick it. This is actually beneficial in straw bale construction, because the wetter the clay becomes, the more resistant to the passage of water it is. The effect is that it takes the existing moisture out of the straw but does not let any external water enter. Earthen plasters are popular because clay is easy to work and can be repeatedly worked without degradation. However, this also means that the clay erodes easily under certain climate conditions, and is therefore often mixed with straw or fiber. Earthen plaster is also a good match for straw bale because it is very elastic. However, the quality, composition, and application of earthen plasters vary extensively and require some knowledge and skill in order to meet the desired strength and finish (King 2006).

3.2 Structural Properties

The most common type of straw bale construction today is post-and-beam, in which the straw bale walls are non-load-bearing. While this method has a number of advantages, load-bearing walls have the advantage in seismic zones of greater ductility and energy absorption. These are the kinds of walls discussed in this paper. Additionally, load-bearing assemblies are often faster and easier to build, making it ideal for emergency relief housing. It may also be considered more environmentally friendly since it does not require a wooden frame. The only disadvantage that has yet to be mitigated is that the roof is the last element to be constructed, while in a post-and-beam building, the roof can be set up before the straw bales are brought in, thus providing protection against rain (King 2006).

3.2.1 Composite Action

Load-bearing straw bale wall construction is analogous to stress-skin panel models for vertical and out-of-plane loads, and to reinforced concrete models for in-plane loads. The walls rely on composite action from the straw and plaster components. While the plaster skins take most of the load, they are reinforced against buckling by the straw bale core. Tensile reinforcement is provided

within the plaster by the fiber or mesh, while the straw is also the most ductile and deformable component. Connections are critical to the ability of the skins to resist in- and out-of-plane loads.

There have been a few proposals for the structural modeling of a straw bale wall. As stated previously, the straw ball composite wall has been likened to a stress-skin panel. Since the latter is a well-studied system, attempts have been made to model the straw bale wall using the pure bending model for out-of-plane loads on a stress-skin panel. However, empirical data did not match the results of the theoretical model, so it has since disregarded in favor of more specific models.

The latest model depicts the composite wall as a sliced transformed section. See Figure 2 and Figure 3 below. In this representation, the wall is equivalent to an I-beam, with a web of thickness proportional to a ratio of the elasticities of the straw and plaster. The model is enhanced by slices through the web that represent the vertical or horizontal joints between bales. These gaps represent a conservative estimate of the interaction between bales. It assumes no shear transfer through friction between bales, despite the fact that the friction factor between flat bales has been measured at 0.63. The model accurately assumes that shear distortion will govern over bending under out-of-plane loads (King 2006).

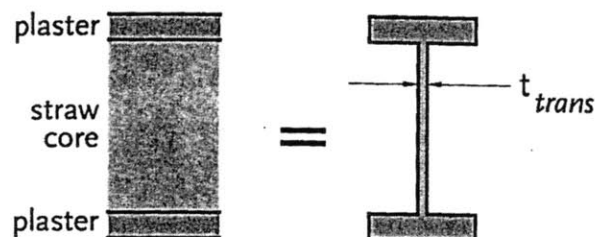


Figure 2: Transformed section. Source: King

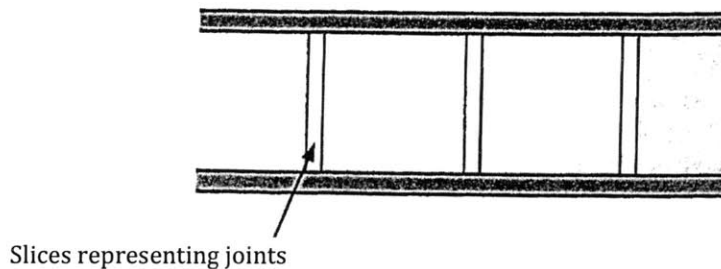


Figure 3: Sliced transformed section. Source: King

3.2.2 Strength

There are three types of plasters, grouped according to structural properties: “hard-skin,” “semi-soft-skin,” and “soft-skin.” Hard-skin plasters have mostly cement binders and are usually the least vapor-permeable. Semi-soft-skin plasters use lime binders, or low-strength soil-cement mixes. They have moderate to high vapor permeability. Soft-skin plasters have the least strength and use clay, clay-lime, or gypsum binding agents. They have the most vapor-permeable skins. Specific properties can be found in the table below.

Properties of Different Plaster Groups			
	Hard-skin	Semi-soft-skin	Soft-skin
Compressive Strength	1000 psi	300-1000 psi	< 300 psi
Modulus of Elasticity (MOE)	100000 + psi	1000 – 10000 psi	< 100 psi
Modulus of Rupture (MOR)	250 + psi	100 – 250 psi	< 100 psi

The bond between the plaster and straw is critical to the structural effectiveness of the system. The strength of a bond depends on the quality of application, which could be blown-on or hand-applied, as well as the quality of the bales. Poor compression in the bale or short straw lengths contribute to a weak bond, as loading could cause the straw to pull away from the bale. Secure embedment into the straw is critical.

For high loads, mesh on the two sides of the wall must be connected with galvanized or polypropylene through-ties in order to fully enclose the ductile straw, as well as prevent buckling in the plaster skins.

Bales are most commonly laid flat for stability. However, testing has been conducted to support the structural superiority of bales both laid flat and on-edge. Thus, a verdict has not been reached on which is structurally preferable.

Rice straw bales, commonly used in California, are quite stiff. Bales in most other places in the world are compressed a few inches under self-weight. Therefore, an increasingly common practice is to pre-compress the bales mechanically, though they can also be left to compress naturally over a few months, or cinched or wrapped by other means. This is important to prevent cracks in the

plaster skins, as well as improve the structural performance of the whole wall by providing a better substrate for the plaster (King 2006).

3.2.3 Vertical Loading

There are a number of failure modes associated with vertical loads. These include global buckling, local buckling, bearing, slippage and core crushing. See Figure 4 and Figure 5 below.

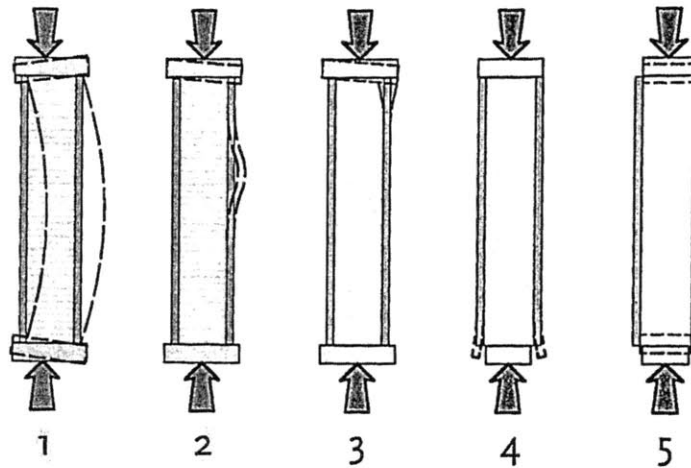


Figure 4: Failure modes. Source: King

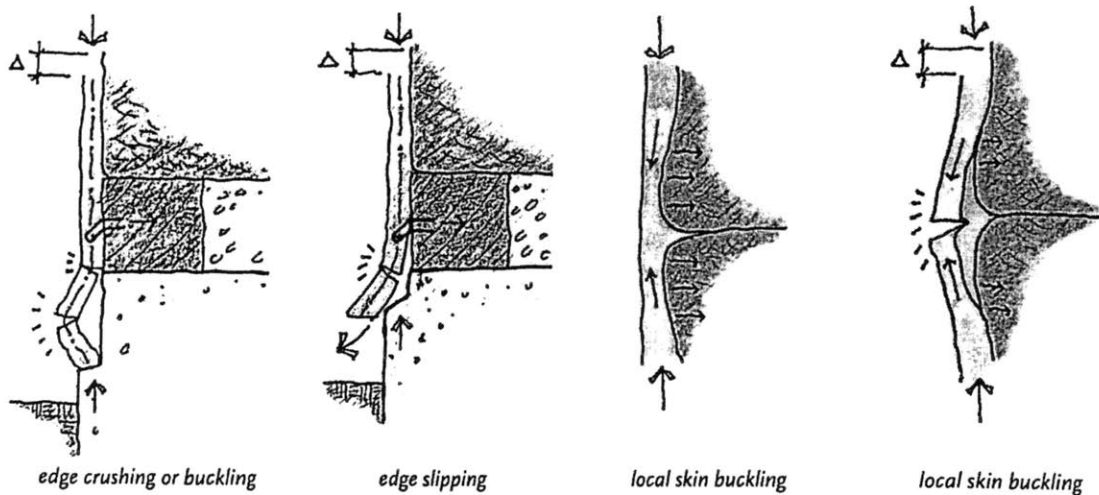


Figure 5: Failure modes in detail. Source: King

Plastered bale walls have consistently exhibited one or more of these failure modes in experimental tests. Global buckling rarely occurs in a well-constructed wall, but under an eccentric load, the entire wall may bend and break. Local buckling is more common and occurs when layers of plaster delaminate from each other or the straw. Poor construction is to blame for this. Another frequent cause of failure is bearing. This occurs at the interface of the roof-bearing assembly or the foundation, in which either the plaster skin or the plate crushes under focused stress. If the fasteners between the mesh and plates are inadequate, the plaster skin may also slip past the plates. Finally, if the connection to the plaster is inadequate, the load may be carried by the straw core alone, resulting in crushing deformation (King 2006).

A variety of tests have been performed on plaster straw bale walls to measure the vertical loading capacity. Some of the results of compressive tests on cubes and cylinders of various types of plaster are summarized below in Figure 6.

Batch	Initial Moisture Content	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
M1	0.126	1.5	1.4	1672
M2	0.132	1.2	1.3	1431
M3	0.134	1.1	1.2	2086
M4	0.144	1.1	1.3	1827
M5	0.146	1.0	1.2	1811
Batch	Drying Time (d)	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
T1	10	0.9	0.8	890
T2	14	1.0	1.1	758
T3	18	1.0	1.1	1848
Batch	Drying Environment	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
C1	drying oven (110 C)	1.8	2.1	2285
C2	laboratory	1.0	1.1	758
C3	moisture room (100%RH)	0.7	0.9	562
Batch	Sand/Soil by volume	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
R1	1.0	1.5	1.5	2500
R2	1.5	1.0	1.1	758
R3	3.0	0.7	0.8	1787
Batch	Clay Source	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
S1	commercial bagged clay	0.8	0.9	1731
S2	clayey silt soil	1.0	1.1	758
Batch	Water/Cementitious Mat.	Cube Strength (MPa)	Cylinder Strength (MPa)	Modulus (MPa)
P1	1.08	1.1	0.8	443
P2	1.18	1.1	0.7	839
P3	1.28	0.9	0.7	395

Figure 6: Compressive strength of plasters. Source: Taylor

3.2.4 Out-of-plane Loading

Straw bale walls have been found to perform more than sufficiently under out-of-plane loads such as wind forces or earthquake shaking. As the wall bends, the inside face of the wall will go into tension, which the reinforcement must resist. As this happens, the outside plaster must resist compression. In fact, even unplastered and unbraced walls were found to withstand hurricane-force winds without problems.

Straw bale is typically used for low construction only, and as described, it performs well under these circumstances. Should the wall become taller than what is typically constructed, the common practice now is to insert a horizontal, glulam girt between two bales around the middle of the wall height. This girt is attached to the mesh before plastering occurs and has slotted supports at the ends to allow for some vertical movement of the bales during stacking, as illustrated in Figure 7 below.

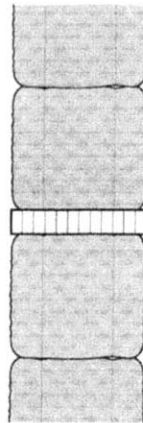
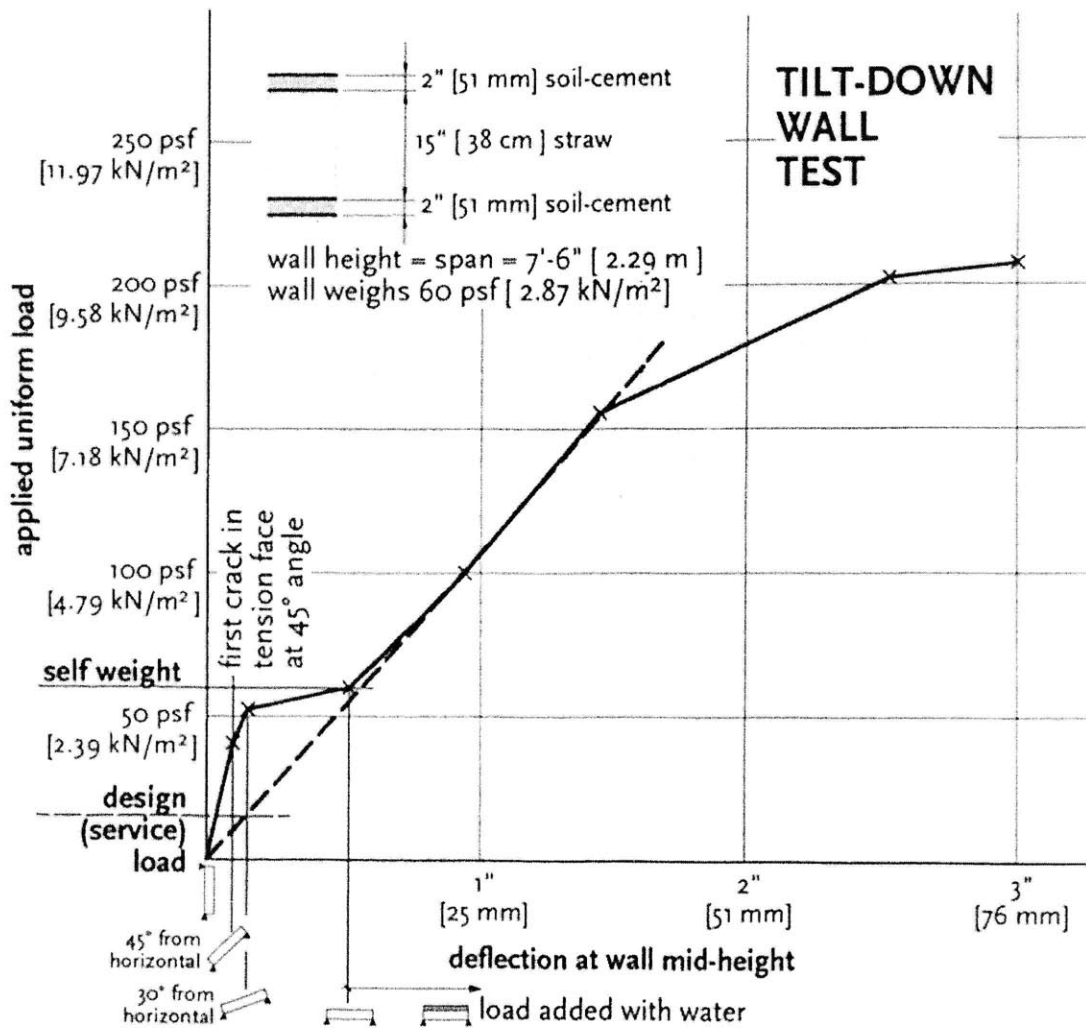


Figure 7: Horizontal girt. Source: King

Much like concrete, the behavior of the plastered straw bale composite wall is two-phased. See Figure 8. In the first phase, the wall is analogous to a stress-skin panel under bending, in which a first crack appears around mid-height when the modulus of rupture of the plaster is exceeded. Cracks also appear along course joints. However, unlike conventional building materials behaving like shallow beams, shear overwhelmingly dominates over bending because the straw bales distort from their rectangular shape due to their inherent softness. Experimental tests have shown that the plaster cracked at four or five times the predicted allowable stress.



The wall was built, plastered, and cured upright, then carefully rotated on hinged supports to the horizontal, measuring deflections at 45 and 30 degrees from horizontal. After it was flat, load was added with water in a plastic-lined box framed over the flat wall.

Figure 8: Two-phased behavior. Source: King

When the crack forms, it is actually not of uniform thickness as it would be in a stress-skin panel. Instead, the crack is wider at the tension face and rapidly narrows through the thickness of the plaster. This effectively creates a hinge in the beam-like plaster, inducing complicated behavior involving tension, compression, and bending in the skin, as well as shear in the bales. After the appearance of this crack, the reinforcement is now more fully employed to take the loads.

The first crack does not present a structural problem unless the wall is poorly constructed. In a well-constructed wall, both the reinforcement and the plaster bond with the straw would keep the wall together and continue to transmit some shear through friction in the event of subsequent in-plane loading. One concern would be the loss of moisture protection due to the crack, though a sufficient roof overhang would help (King 2006).

3.2.5 In-plane Loading

As with all buildings, structural straw bale housing must employ diaphragms and shearwalls to resist wind or earthquake lateral loads. Though straw bale is not a conventional building material, it has been found to be surprisingly robust under lateral loads. In fact, tests have shown that a steel mesh-reinforced, lime-cement plaster wall can actually resist the same range of lateral loads as plywood-sheathed stud walls. The lower strength combination of earth-plastered walls with plastic mesh reinforcing was still found to be capable of resisting the same loads as a wood stud wall with very light plywood sheathing. In some ways, the straw bale composite wall performed better, exhibiting a capacity to carry vertical loads despite dramatic displacements of seven inches at the top. This can be attributed to the strong bonds between straw and plaster, the plain thickness of the wall, and the flexibility of the bales. However, this does not preclude good design. The layout of the walls in plan, as well as the connections and detailing, is crucial. King and others present a list of generalized guidelines to heed when laying out a building plan, which is applicable to any material. Particularly, the walls should be as evenly distributed throughout the building as possible, especially over a wide area (King 2006).

Due to the seismicity of the area, straw bale housing built in California has been designed to resist high lateral loads. Typically, wood plates are placed along the top and bottom of the straw bale wall, to which the mesh reinforcement of the plaster is nailed or fastened. Tests have shown that the plaster skins can be designed like reinforced concrete members for various levels of reinforcement.

Four possible responses are considered good schemes for ductile behavior. First, the wall could rock due to over-reinforcement. In this case, gaps open up at the bottom of the wall while gravity loads provide an overall restoring moment. Second, the mesh reinforcement could yield in flexure. This behavior is similar to that which could occur in an under-reinforced concrete member. Since earthen plasters have such low compressive capacity, this could only occur with cement skins. This

may coincide with the third response, which is the development of compression struts in the straw core (see Figure 9). This only occurs when the plaster skin has already cracked and failed under cyclic loading. See Section 8: Computer Simulations for a compression strut model. Finally, the edges of the plaster skin could crush (King 2006).

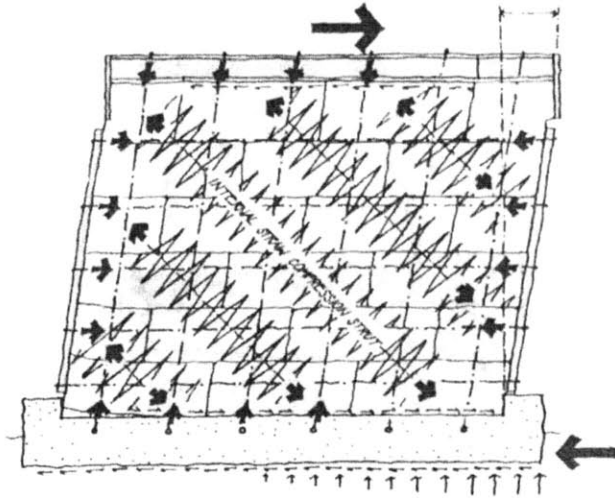


Figure 9: Compression strut. Source: King

3.3 Important Considerations

Voids are unavoidable in straw bale walls. They occur between and within bales. In order to provide continuity, fire protection and thermal and acoustic insulation, these voids must be filled. This is often achieved with a straw-clay mix or a synthetic, sprayed foam, which then dries and becomes a substrate for the plaster.

In order to keep the bales well-protected from any pervasive water, the bales should rest on a foundation well above grade. They should be separated from the foundation by a waterproof barrier, in addition to a layer of pea gravel, which is deposited between the sill plates on either side of the wall. The roof should also have a wide overhang and be connected to the walls for shear and uplift.

King and others lay out a number of general guidelines to follow when detailing against moisture. First, the areas of most concern are the exposed horizontal surfaces, such as a parapet roof or windowsill. Second, water should always be shed away from the building exterior through

overhangs or flashing. Caulks and sealants should not be the primary mechanism for keeping water out, while waterproof membranes often achieve the opposite of intentions by trapping water inside the wall. Plasters should have a certain level of vapor-permeability. Finally, the plaster should be sealed with a topical sealant like siloxane or silane in order to facilitate the shedding of water without the trapping of vapor.

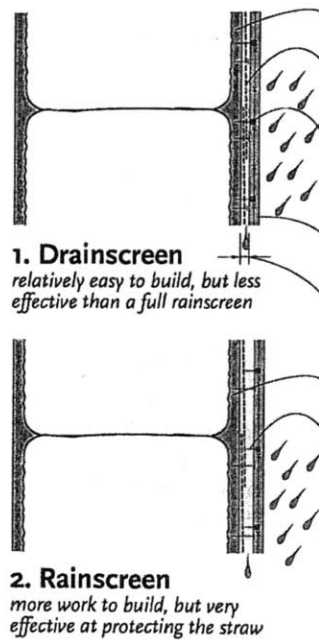


Figure 10: Moisture control. Source: King

Depending on the level of rain exposure, a drainscreen or rainscreen might be an appropriate addition to the wall, as depicted in Figure 10. In some cases, the sealant or an occasional replastering may be sufficient protection. At the interface between the wall and roof, the joint must be sealed for thermal and moisture control reasons. The roof-bearing assembly should have the capacity to be pre-tensioned in order to stiffen the bales before plastering. Holes should be drilled through the plywood sheathing of the roof-bearing assembly in order to ensure vapor permeability. At the interface between the foundation and wall, the outer plaster skin should rest on a ledge of the foundation below the sill plates. The sill plates themselves should be pressure-treated or bolted over a capillary break from the foundation, while the inner plaster should rest firmly on the foundation with insulation. Finally, the windows must incorporate flashing and drip edges that keep water away from the top of the window and off the sill.

As one would expect, straw is a highly flammable material. However, the fire safety of straw bale walls does not have to be any more concerning than that of a wooden structure. Like a dense wood, a highly compressed bale will reduce the amount of oxygen available to sustain a fire and will significantly decrease flammability. To reduce the ability of the straw to smolder, stuffing any cracks in the individual bales, and between bales and other structural elements, with clay-coated straw is good practice. Another technique that is not so widely used yet but is extremely helpful is pre-coating the bales with an initial plaster skin before stacking.

Another concern that sometimes arises is the appeal of the straw to insects, rodents, and other animals. All of these creatures would rather descend upon an open pile of bales than a plastered bale wall. It has been found that insects may infest a moist straw bale wall, but if the wall is moist, there are many greater concerns at hand. Termites are a bigger problem for wooden houses than straw bale. While rodents enjoy warm, snug spaces, it has been found that straw bale walls are too dense to chew on, and if the home was properly constructed, the plaster provides a sufficient barrier to entry (King 2006).

4. Current Research

The research surrounding structural straw bale walls has not been extensive but has been reasonably comprehensive, covering such topics as creep in the straw bales, shear strength of plaster skins, and in-plane cyclic load tests. The tests discussed below have mostly been performed by industry leaders in partnership with university facilities.

4.1 Creep in Straw Bales

Creep is a common material occurrence that should be accounted for when designing structures. As one would expect with the softness and amount of air in straw bales, they are no exception to this phenomenon. A year-long test has been conducted in order to test the creep behavior of straw bales. It was loosely modeled on the Standard Test Method for Creep of Concrete in Compression described in ASTM-C512-87. The test included control bales of unplastered, 3-string rice straw and varied the properties of the other specimens.

Specifically, there were four groups. The base group consisted of the two control stacks, one of which experienced low loading of 400 lbs, the other high loading of 1600 lbs. The comparative group tested three properties: the type of straw used by stacking wheat straw, the thickness of the bales by using 2-string rice bales, and the direction of the grain by stacking some rice bales on edge. The third group was intended to test the effects of low and high earthquake loading by applying the load initially, removing it, and reapplying it after 44 weeks. The last group consisted of two stacks of plastered rice bales, one with a cement-lime skin and the other with an earthen plaster skin.

A comprehensive graph of the results can be seen in Figure 11:

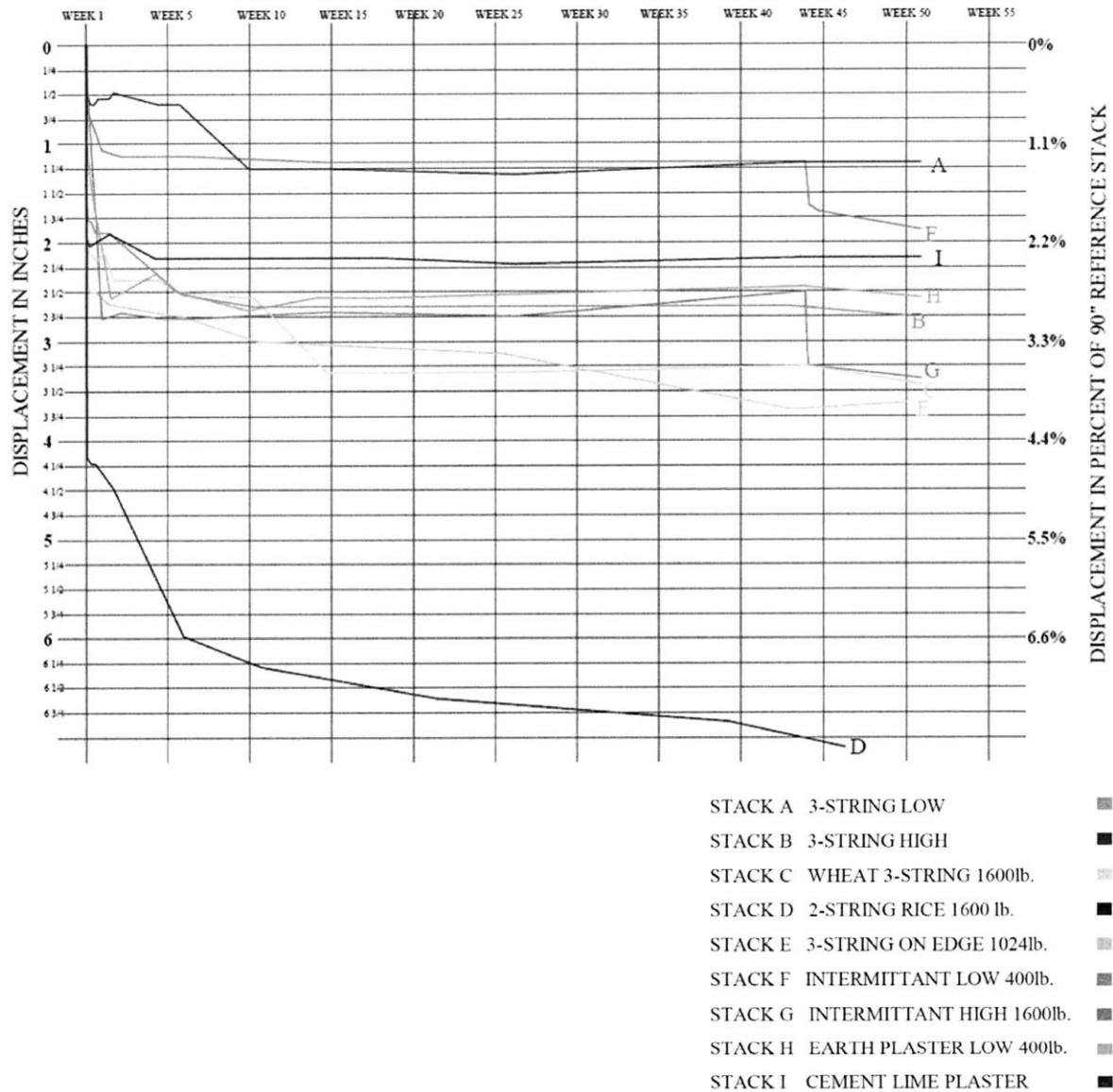


Figure 11: Creep test results. Source: Smith

As Smith summarized, the initial compression averaged 1 in for the 400 lb load and 2.25 in for the 1600 lb load. The creep seemed to occur fairly quickly during the first couple weeks, for the higher load especially, while slowing down over the next several weeks. After 10 weeks, the bales seemed to stabilize with little to no additional settlement. In the final measurement, the cement-lime plastered bale had a final deflection of about 2 1/8 in, compared to the low-load control bale deflection of about 1 1/4 in. When considering initial compression, the cement-lime plaster bale

actually exhibited the least amount of creep, which was to be expected given the service loading. In contrast, the earthen plastered bales did show some settlement: 1.5 in in the initial weeks, even after precompression, which is depicted in Figure 12. Supporting the practice of precompression of bales before plastering in seismic zones, the intermittently loaded walls showed that the bales only deformed an additional 20 to 25 percent after the first compression (Smith).

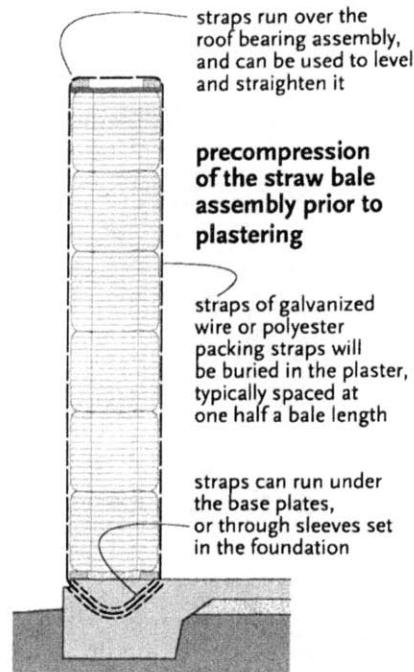


Figure 12: Precompression. Source: King

4.2 Shear Strength of Plaster

To encourage the development of seismic design provisions for straw bale construction, testing has been conducted to determine the shear capacity of the plaster skins. In a study conducted by Truong, et al., a number of different plasters were tested. Earthen, lime, and cement plasters were all studied, though only the results of the earthen plaster were presented in their paper. Their hypothesis expected that the shear strength of the earthen plaster would vary in proportion to its compressive strength, f'_c , based on the Mohr-Coulomb failure surface for cohesive materials. On the other hand, the shear strength of the cement plaster would be proportional to the square root of f'_c , based on the behavior of materials with both cohesive and “frictional” properties. Setups varied

between monotonic and cyclic loading, and included unreinforced plaster as well as plaster reinforced with Cintoflex C mesh.

The results demonstrated that the reinforcement did not significantly change the shear strength of the earthen plaster, which was expected since the mesh was quite flexible relative to the given displacements. However, it was confirmed under direct shear testing that straw, with its high tensile strength, mixed into the clay plaster did improve strength. Unfortunately, the results under reversed cyclic loading were not too valuable, since the panel shear specimens greatly disintegrated at the top and bottom surfaces due to poor setup (Truong).

4.3 Mesh Anchorage Details

As previously discussed, the connection of the reinforcing mesh to the top and bottom plates is a critical component of the overall lateral load-resisting system. Experimental tests have been conducted to compare the mesh strength, anchorage strength, and failure modes for a number of different mesh and anchorage details. With the utilization of new wood preservatives like copper azole and ACQ that are highly corrosive to steel fasteners, the choice of materials is particularly complicated.

In a test by Parker, et al., the following four mesh materials were tested.

- 14-gauge 2 x 2 in, galvanized before welding
- 16-gauge welded wire fabric, galvanized before welding
- Hemp netting, hand-knitted into an 80 x 80 mm mesh
- “Cintoflex” C 1.73 x 1.92 x 0.047 in plastic polypropylene mesh

The following four staple types were tested, where medium crown staples have a 7/16-in crown.

- Stainless steel 16 gauge x 1.75 in, medium crown chisel point
- Electro-galvanized 16 gauge x 1.75 in, medium crown
- Electro-galvanized 16 gauge x 1.25 in, medium crown
- Electro-galvanized 15 gauge x 7/8 in rounded shoulder staples, manually driven

The following three sill plates were tested.

- 4 x 4 in Hem-Fir Standard and better, treated with copper azole

- 4 x 4 in No. 2 Douglas Fir, no pressure treatment
- 1 x 2 in Pine, used in conjunction with the 4 x 4 in Hem-Fir

Finally, in order to minimize corrosion, building paper was sometimes used as a barrier between the mesh and the pressure-treated wood.

Nine configurations of mesh, mudsill, staple type, and staple orientation were explored. However, since the models in this thesis only concern mesh reinforcement, only those results will be discussed.

First, tension tests were conducted on the individual wire strands within the various meshes. Around ten samples of each mesh were tested, with failure recorded in the wire each time for the 16-gauge mesh, but in the weld three out of ten times for the 14-gauge mesh. The mean strength of the 14-gauge was higher in absolute terms but lower when considered over the area.

After a number of tests specifying the failure mode and ultimate strength, the final recommendation based on the results was to use the 14-gauge mesh with 16-gauge medium crown staples with 1 and $\frac{3}{4}$ in legs oriented diagonally over the welds. However, tests were not conducted to ascertain the sufficiency of staples with shorter legs. In the case of a pressure-treated sill, stainless steel staples must be used in conjunction with building paper or some other means of separating the mesh from the sill. This round of testing confirmed previous suggestions that the welds in 16-gauge mesh are too susceptible to failure and should not be used for structural purposes.

One additional area of research in this sort of testing would be the uniform application of a load on multiple wires, rather than the testing of individual wires first, which may have produced undue demands at the welds (Parker).

4.4 In-plane Cyclic Loading

A number of experiments have been conducted to test the seismic load capacity of plastered straw bale walls. One project looked at clay-plastered wall assemblies under in-plane cyclic loading, while another looked at both earth- and cement-skinned walls with various levels of detailing.

In the first test, conducted in conjunction with PAKSBAB (see Section 6: Case Studies), the wall system used bales that were narrower than those typically used, fishing net as reinforcement, and a gravel bag foundation. Four-foot long walls with various levels of detailing were tested. Light detailing served as the control and did not use any reinforcement. Medium detailing used #9 fishing net as reinforcement, while heavy detailing incorporated #12 fishing net with additional foundation detailing. The cyclic loads consisted of 16 steps of increasing peak displacement.

It was found that the control wall had a maximum capacity of 500 lbs with a 0.8 percent drift of 0.8 in. Wall 2 with medium detailing performed better, as the reinforcement provided ductility as well as resistance against shear and overturning moment. As expected, the heavily detailed wall performed the best, with a maximum capacity of 770 lbs and a drift of 1.2 in.

In this project, a full-scale house of dimensions 14 x 14 x 10 ft was also tested. The house was constructed by installing the fishing net reinforcement underneath the gravel bag foundation, stretching it up the sides of the walls, and nailing it to the top plates. The roof-bearing assembly was made of wood and straw clay with a corrugated metal roof. The shake table applied the 1994 Northridge earthquake, and the house ultimately withstood an acceleration of 0.82g, which was actually twice the peak acceleration of the quake. It was observed that the plaster provided damping, but after it cracked and spalled, the straw bale core actually kicked in to resist vertical and lateral loads (Donovan.) These findings are consistent with the compression strut model proposed by King, as discussed in Section 3.2.5: In-plane Loading.

In another study on the same clay-plastered, load-bearing straw bale walls, the dynamic response of the full-scale house was determined with frequencies, damping ratios, and mode shapes. Using a shake table, biaxial tests were conducted on the 14 x 14 x 10 ft house, with the 1994 Northridge earthquake as input. The load was incrementally increased beginning at 25 percent of the recorded ground acceleration, until 0.82g, as in the experiment previously described. White noise tests were conducted in between loadings to obtain the following mode shape (see Figure 13) in plan, after determining frequencies and damping.

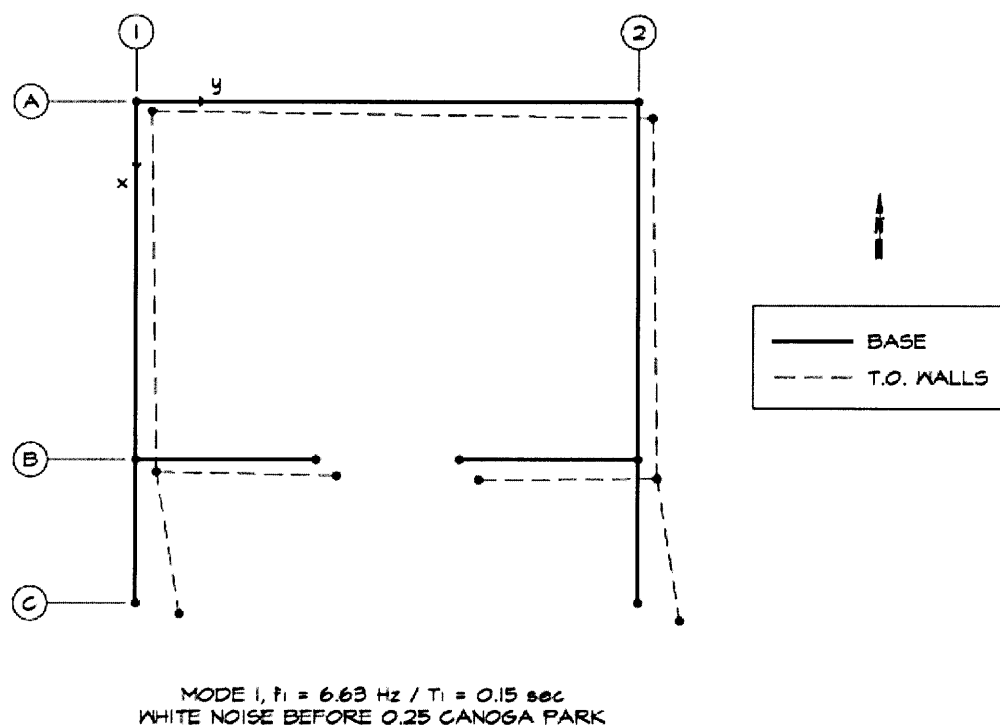


Figure 13: Mode shape. Source: Champion

The most significant finding from this experiment was that the veranda wall extensions had the greatest response to earthquake, as indicated by the above mode shape. The frequency in the Y-direction also diminished more than in the X-direction because of these wings. Therefore, this feature of the house should be reconsidered with respect to structural performance. While it would be undesirable to add stiffness because of the subsequent decrease in damping properties of the straw bales, perhaps the cantilever length could be reduced or even completely removed. However, the house still performed well with them, and depending on the desires of the occupants, the veranda might be worth keeping for aesthetic reasons (Champion).

In a separate experiment, 8 by 8 ft walls of various plaster skins and detailing were tested under in-plane cyclic loading. Three of the six walls had earthen skins while the rest had cement stucco skins with different types of mesh reinforcement. Only the results of the cement-plastered walls are discussed here.

The first cement-plastered wall had poor detailing, with 17-gauge chicken wire mesh reinforcement. The mesh was stapled to a 2 x 4 in sill and to the header beam at the top. The second wall had intermediate detailing, with 2 in x 2 in x 14 gauge welded wire mesh, stapled along a 4 x 4 in sill and into a header beam. Extra mesh reinforcement was included at the connections, as well as through-ties of 12-gauge wire at every other course of bales. This was intended to help with out-of-plane instability. The last wall with high detailing was similar to the medium-detailed wall, with more anchorage, through-ties, and spikes to anchor the header beam into the top course of the bales. The tests applied gravity loads of about 200 plf and two cycles of 7.5 percent drift, which was a testing restraint. The top of the wall was pin-connected.

The first wall had a maximum strength of 6.4 kips and exhibited rocking behavior at larger displacements. It failed in two ways. First, the chicken wire mesh at the bottom of the wall distorted and fractured. Second, the sill plate failed in cross-grain bending. The second wall had a maximum strength of 19 kips at 1.92 in and failed due to the tensile capacity of the mesh. It exhibited both mesh fracture and staple pullout. The third wall had a maximum capacity of 18.2 kips at 1.44 in and performed similarly to the second wall, suggesting that the additional elements did little to enhance performance.

A suggested path of further research is to test walls with aspect ratios other than 1:1. Additionally, the testing mechanism limited the drifts to 7.5 percent of the wall height, but all of the walls continued to carry gravity loads without signs of imminent failure. Further testing might reveal the failure limit of the walls.

Small- and medium-scale tests were performed in addition to the full-scale wall tests. Mesh lap splice tests and mesh-sill plate connection tests led to design recommendations for the lap splice length necessary to develop the strength of the mesh. For 2 in x 2 in x 14 gauge mesh in cement stucco, 6 in was found to be sufficient. For the Cintoflex plastic mesh, 12 in was necessary. The sill plate test discovered that a 14 gauge x 1.75 in pneumatically driven staple along a single line of mesh intersection at 2 in on center was adequate for both the wire and Cintoflex in transmitting tension and shear to the sill plate. As the mesh anchorage tests discussed in Section 4.3 also reveal, 16-gauge mesh was found to be brittle and is not recommended.

Shear and tension anchorage tests of the mesh-sill plate connection suggest the need for a shear band of mesh at the base of the wall between the sill plate and the bolt washer (Ash).

4.5 Roof Vault Test

A prototype straw bale residence was built in Joshua Tree, California, in the midst of several major fault lines, including the San Andreas. The most prominent feature of the plan was a large room under a vaulted roof. Originally, this house was supposed to carry a reinforced concrete shell roof, but the cost prohibited this from occurring. Instead, the builders decided to try a roof composed entirely of straw bales, wire mesh reinforcement, and stucco. They were determined to prove that these materials could create a structure that would meet code requirements in withstanding the heavy, out-of-plane seismic loads. In an experiment conducted by David Mar, the vaulted straw bale roof system was subjected to simulated wind and earthquake loads via the rig illustrated in Figure 14 below:

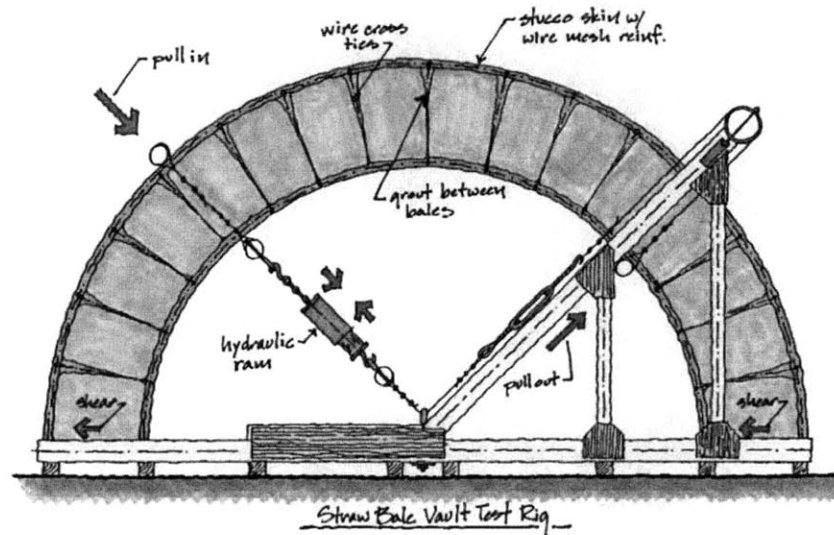


Figure 14: Roof vault test setup. Source: Mar

The assembly was intended to transfer deformation and energy absorption to the straw core as opposed to the mesh reinforcement. The function was achieved with good detailing.

Drawing more comparisons to the behavior of a reinforced concrete beam, it was found that the out-of-plane shear mechanism developed in a very similar way, as illustrated in Figure 15. As each cell of the arch distorted, the straw compressed between two corners formed a diagonal strut. Analogous to the steel stirrups in a concrete beam, the wire cross in tension ties linked these struts. Furthermore, the stucco skin and straw in compression are like the compression face of the beam, while the reinforcement in tension on the opposite side is like the longitudinal reinforcement of a concrete beam.

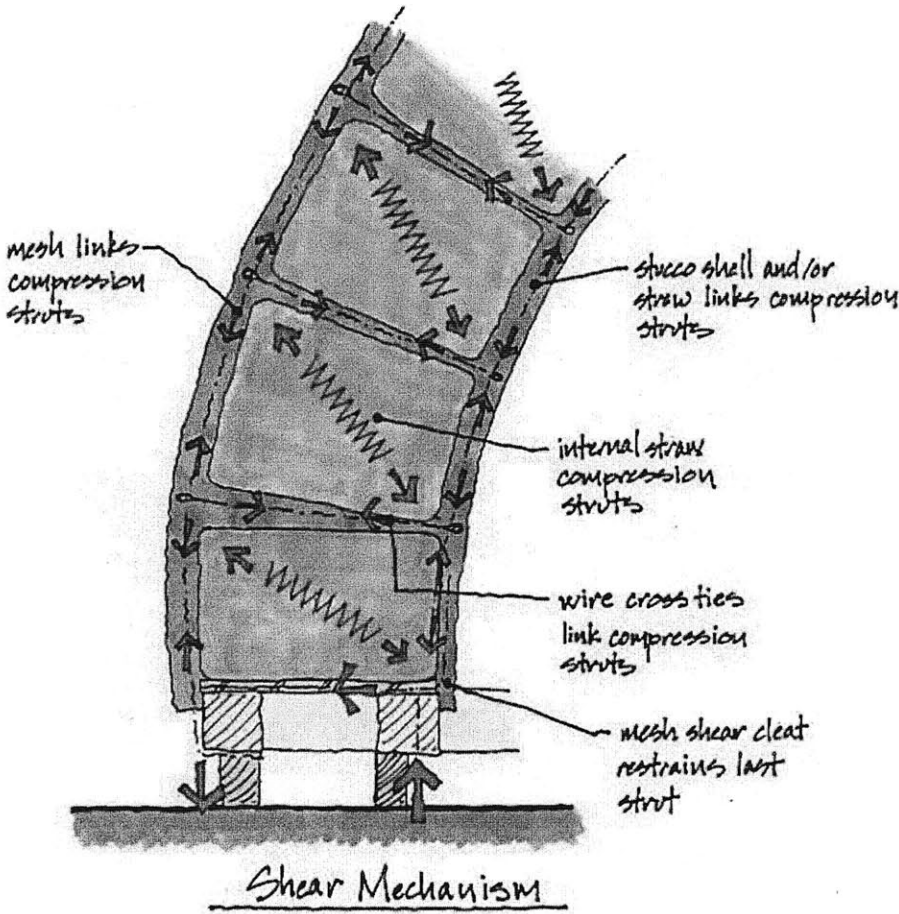


Figure 15: Shear mechanism. Source: Mar

Bending mechanisms parallel a reinforced concrete beam as well, as the bales and stucco cannot resist tension loads. For that, the assembly relies on the mesh. See Figure 16. One detail that must be included is cross ties to prevent delamination of the inner mesh when it goes into tension. Anchor dowels are placed outside the bales to keep the mesh in at the joints where the mesh kinks and wishes to straighten when in tension.

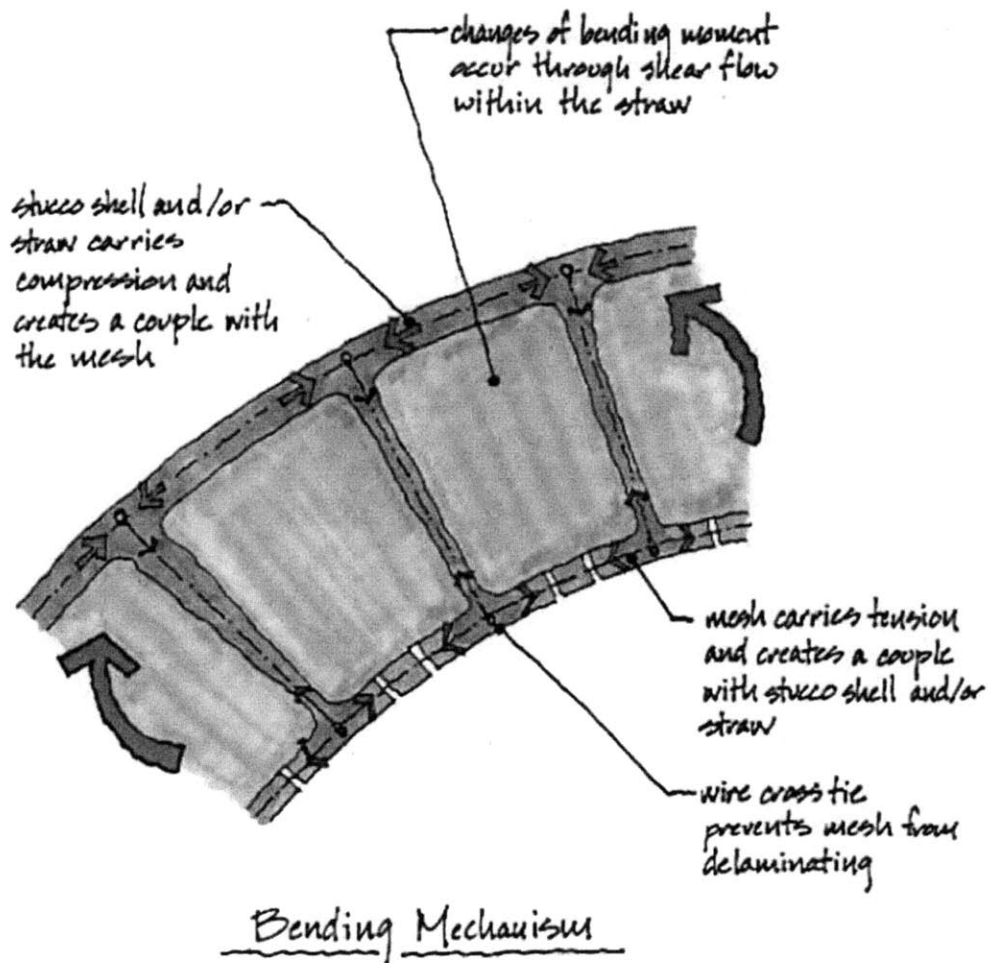


Figure 16: Bending mechanism. Source: Mar

The results demonstrate the elastic limit of the vault to be about 3000 lbs after cyclic loading. However, the vault could not be collapsed at the maximum load of 6700 lbs after 6 cycles and 6.6 in of lateral deflection at the apex. From this test, it was concluded that the ductility and toughness of

the straw bale system was more than sufficient to meet the requirements of the building code (Mar).

While the roof vault is not immediately applicable to the wall assemblies primarily discussed and preliminarily modeled in this paper, it represents an important milestone in the progression of structural straw bale construction. It demonstrates the structural potential of this sustainable building material and adds to the repertoire of knowledge about its behavior. For instance, as discussed earlier, a straw bale wall assembly is often compared to a reinforced concrete member. Following this thought, the vault was actually designed by adapting calculations normally applied to reinforced concrete design.

5. Computer Simulations

To date, only physical experiments have been conducted on the seismic performance of load-bearing straw bale wall assemblies. What follows here is an attempt to relate empirical results to computer simulations of such a wall. Two types of models are explored. First is the multi-layered shell element. Second is the straw compression strut. Both approaches apply nonlinear, static pushover analysis in order to determine the effects of cyclic earthquake loading. While these results are far from universal due to the heterogeneous nature of this type of construction, it provides a starting point from which future models can be built as a preliminary design step.

A multi-layer shell element in SAP2000 was determined to be a fitting model based on the similarities between a straw bale composite wall and a reinforced concrete wall. In a 2006 paper by Miao, et al., a multi-layered shell element was proposed to simulate in-plane and out-of-plane bending for a concrete shear wall. Based on material constitutive law, a microplane model for reinforced concrete was introduced. This model intended to better simulate the nonlinear behavior of a shear wall member. One layer was given to each rebar direction, with a concrete layer in between, as illustrated in Figure 17.

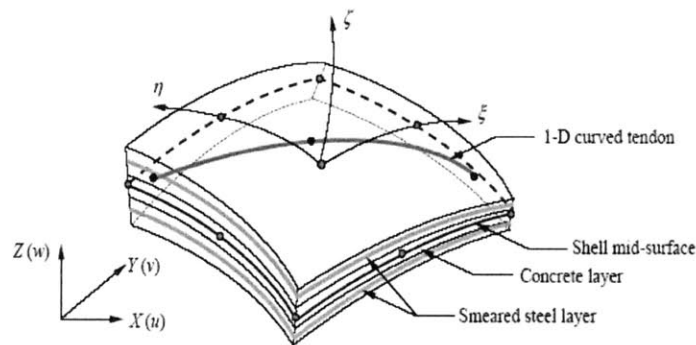


Figure 17: Multi-layer shell element. Source: Miao

Pushover analysis and static cyclic loading were performed on the shear wall in three cases. Cases 1 and 3 used a shear wall with an aspect ratio of 2:1 to simulate tall buildings. Case 2 used an aspect ratio of 1:1. Cases 1 and 2 studied in-plane bending, while case 3 looked at out-of-plane bending (Miao).

For the straw bale wall assembly an FEA model was created by assigning a multi-layered shell property to a shearwall in SAP2000. The shell was composed in the layers listed in Figure 18.

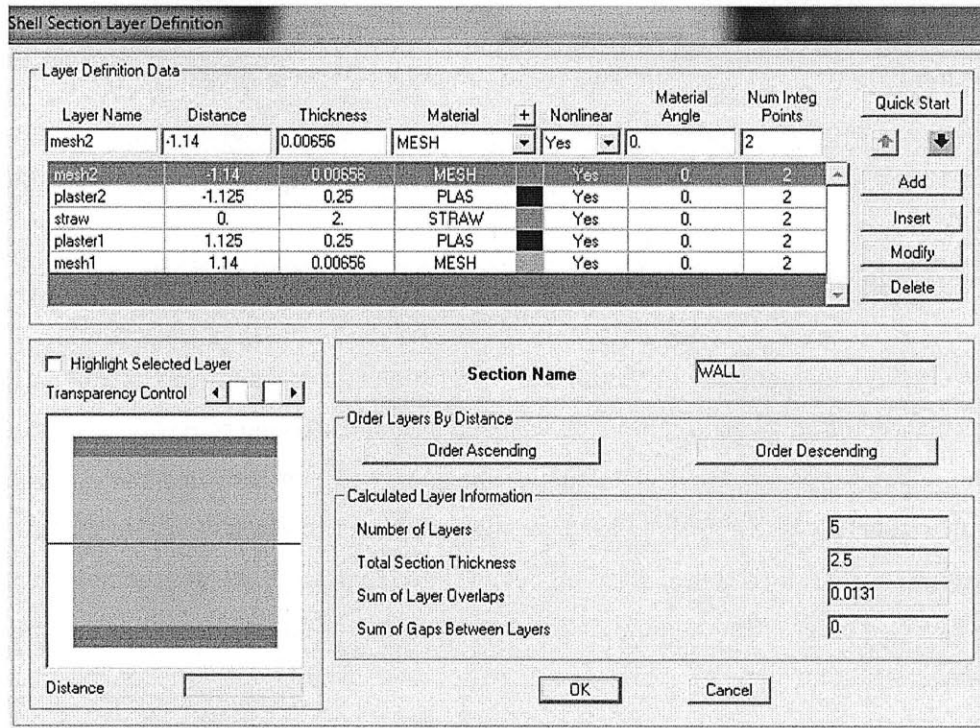


Figure 18: Shell layer definition

The dimensions of the wall followed the dimensions of the specimen used in the in-plane cyclic loading wall tests by Ash and Mar. The size was 8 x 8 ft. The specific material properties were investigated based on the materials used in the test: 14-gauge chicken wire mesh and cement stucco. To simulate the anchorage of the mesh along the base of the wall, the model was fixed at the bottom at every 2 in, which is equivalent to the mesh spacing. The wall was then divided and automatically meshed into a grid of 48 x 48 squares, as depicted in Figure 19.

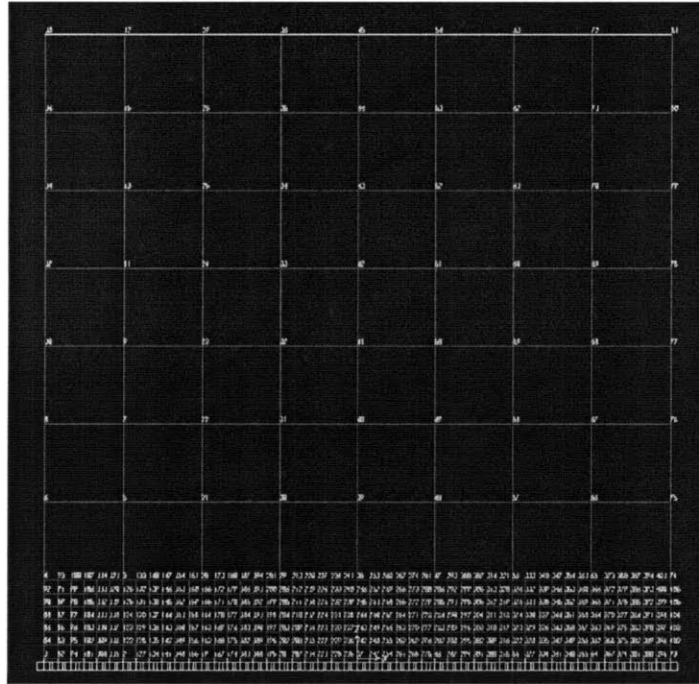


Figure 19: Multi-layered shell wall

Dead and live loads were applied in the direction of gravity. In the first trial, nonlinear pushover analysis followed a lateral load pattern, which depended on a static point load applied to the top of the wall in the positive x-direction. In the second trial, the load pattern followed the modal shape of the wall. Both analyses were displacement-controlled.

Though the results of the analysis did not yield information matching empirical data, the shell presented interesting insights into the challenges of modeling a plastered straw bale wall. One influential factor to consider is the heterogeneity of the material. One simulation can only accommodate the properties of one combination of plaster, reinforcement, and straw. Additionally, even after these materials are specified, a widespread consensus has not yet been reached on the properties of straw. Similarly, the procedure for inputting chicken wire mesh as a reinforcement layer is not dictated. This simulation used the smearing principle described in the model by Miao. Moreover, the overall applicability of the layered model depends on the constitutive laws of reinforced concrete. As straw is a vastly different material from concrete, it is possible that the shell model is inapplicable.

The force-displacement graph obtained was linear in nature, indicating that the steel mesh never yields. Also, the displacements that the model suggested the wall could undergo were tremendous, especially relative to the forces applied, which were also very large. This behavior suggests that the model of the wall was far stiffer than an actual wall. An 8 x 8 ft wall modeled as a shell has a monolithic quality that may not accurately represent the assembly. A time history analysis with the 1994 Northridge earthquake as input yielded the same results, with the maximum displacement being mere hundredths of an inch.

The second type of model employed frame elements with a diagonal compression strut crossing in two directions. This would be analogous to a concrete wall with brick masonry infill. The width of the equivalent compression strut of straw, a , was obtained using the recommendation below from FEMA 306 (Kose).

$$a = 0.175(\lambda_1 h_{col})^{-0.4} r_{inf}$$

$$\text{where } \lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4E_{fe} I_{col} h_{inf}} \right]^{\frac{1}{4}}$$

$$\text{and } \theta = \tan^{-1} \left(\frac{h_{inf}}{L_{inf}} \right)$$

where h_{inf} = height of the infill wall

h_{col} = height of the column

r_{inf} = diagonal length of the infill wall

E_{me} = expected modulus of elasticity of infill walls

t_{inf} = thickness of the infill wall

E_{fe} = expected modulus of elasticity of frame elements

I_{col} = moment of inertia of column

L_{inf} = length of infill wall

This is partially depicted in Figure 20.

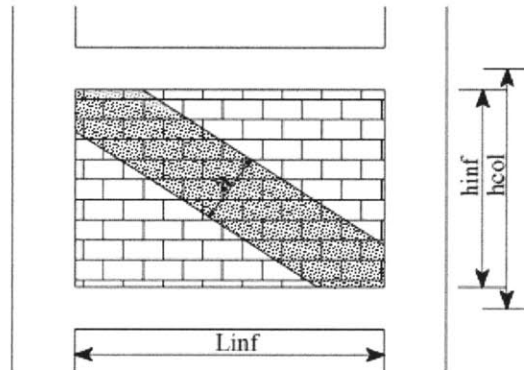


Figure 20: Equivalent compression strut. Source: Kose

For the straw core, the width came out to 29.9 in, with a thickness equivalent to the bale thickness of 24 in. In the first trial, the columns were given the properties of a transformed section of bale walls, representing the two perpendicular walls. However, perhaps given the low elasticity of this section, the pushover analysis did not produce realistic results. Therefore, the beams and columns were instead given the properties of the smallest I-section possible, which was W4x13, as seen in Figure 21. In this way, it was hoped that the steel would yield quickly, and the large strut would take most of the loads afterwards.

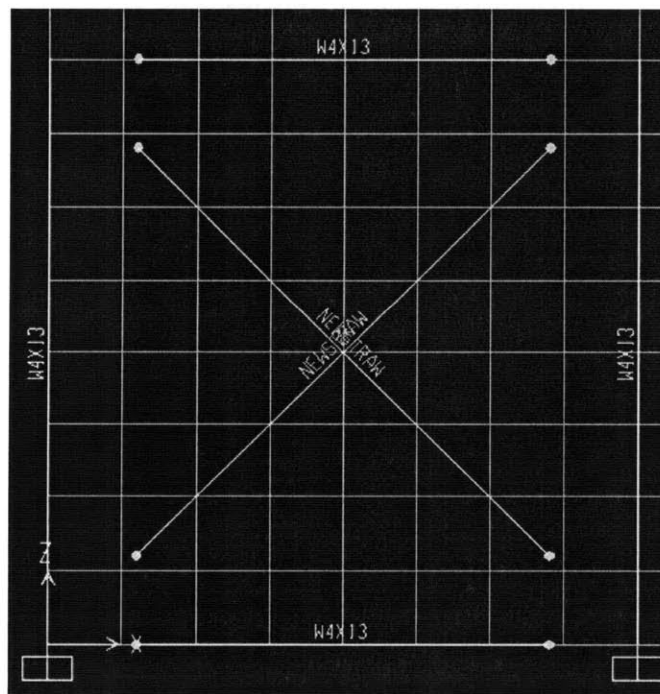


Figure 21: Equivalent compression strut model

In accordance with pushover protocol, hinges were assigned to all elements. The beams and columns were assigned default M3 hinge properties, while the struts were assigned hinge properties based on the following stress-strain curve suggested by Kose in Figure 22.

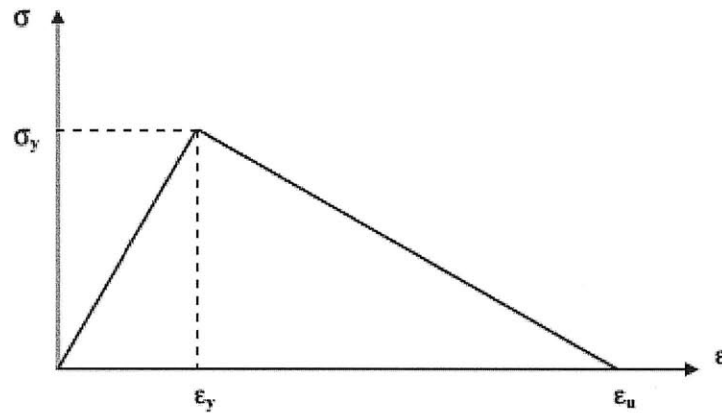


Figure 22: Stress-strain curve for equivalent compression strut. Source: Kose

Pushover analysis using modal lateral load patterns gave accurate force distributions, with the struts taking most of the load in the form of compression only. However, it was found that the hinges still did not form. Similar to the multi-layered shell model, the performance of the model may be attributed to the generalized properties used to make the strut. Accurate physical properties are difficult to assign to such a member.

Additionally, the compression strut model does not account for the plaster skins. Since the plaster skins should crack before the compression strut activates, the absence of the skins was considered appropriate for the model. However, they may provide some initial stiffness that affects the results of the pushover analysis. Further research may attempt to include these skins as area or shell elements attached to the strut.

Finally, existing equivalent compression strut models necessitate a frame, which the strut crosses. This is one weakness of the strut model, since in the case of load-bearing straw bale walls, this frame does not exist. Therefore, a low-strength frame such as the one used in this model was deemed fitting. However, this may not be an accurate representation given the large difference in elasticities.

6. Case Studies

6.1 Kashmir, Pakistan

In October 2005, a devastating, magnitude-7.6 earthquake in the mountainous region of Kashmir, Pakistan, killed around 80,000 people, many in their collapsed homes, and left over 3 million homeless (Champion). In response to this tragedy, a nonprofit organization called Pakistan Straw Bale and Appropriate Building (PAKSBAB) formed. Their continuing mission is to bring affordable and safe building methods to the poor living in areas with extreme conditions, be it seismic or weather-related. Primarily they have been exploring straw bale construction as a suitable and even desirable alternative to conventional building. As of October 2009, the group reports the completion of eleven straw bale homes in the North West Frontier Province, each with a material cost of around \$2250 (PAKSBAB). Construction typically requires the efforts of five men over three months (Champion).

PAKSBAB pursues its goals through the generosity of private donors. While this may not be a reliable model for future expansion, it demonstrates the industry interest in developing this building material. PAKSBAB is also committed to the use of local labor for its projects. In this way, the community also benefits from the creation of jobs and the attainment of a new skill set. Unfortunately, none of the straw bales from Pakistan are suitable for building purposes. However, communities are still able to obtain straw locally and have developed an innovative method of compressing it themselves with manually operated farm jacks and locally made molds, as demonstrated in Figure 23 (PAKSBAB “Straw Bale Fabrication”).



Figure 23: Local bale fabrication. Source: PAKSBAB “Straw Bale Fabrication”

By contrast, in industrialized countries, baling is a mechanized production in which straw is stuffed into chambers in pulses, then cut on one side and tied and bound with two or three strings of polypropylene twine or sometimes wire or hemp (King 2006).

PAKSBAB has also undertaken independent research ventures into seismic performance of load-bearing, straw bale wall assemblies, as discussed previously in Section 4.4: In-plane Cyclic Loading. A typical home studied in these tests was laid out as shown in Figure 24:

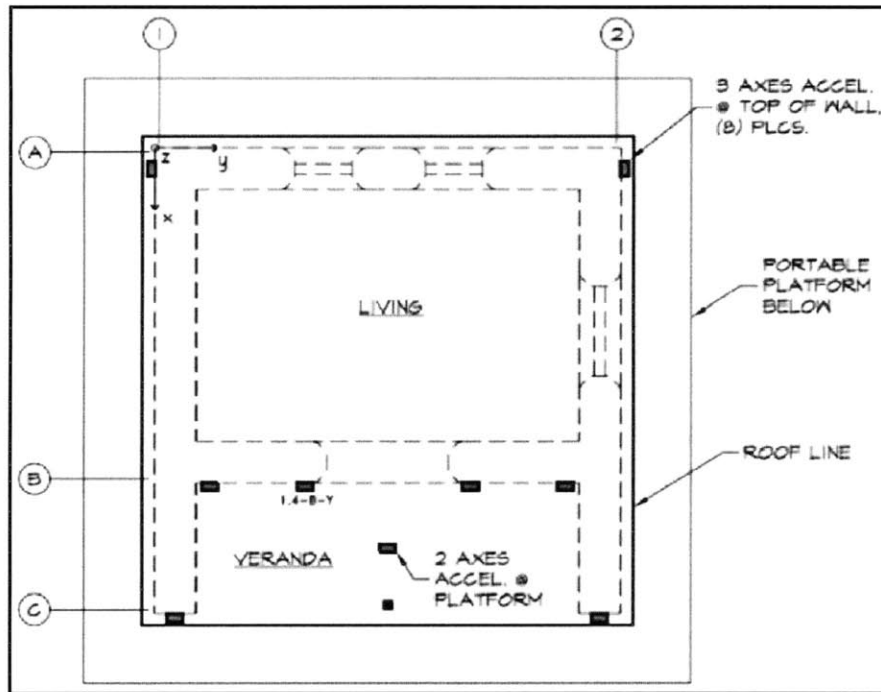


Figure 24: PAKSBAB home in plan. Source: Champion

The house has a simple square shape, with two rooms, three windows, a veranda, and an optional kitchen (PAKSBAB). The load-bearing walls rest on foundations of gravel bags encased by soil cement (Champion).

6.2 Sichuan, China

In May 2008, a magnitude-8.0 earthquake struck the Sichuan province in China, killing an estimated 88,000 people and destroying or severely damaging over 10 million homes. Straw bale houses have actually been built in China since 1998 with help from the Adventist Development and Relief Agency (ADRA) International. However, a new program was launched in June 2009 specifically for the Sichuan area, with the help of leading designers specializing in “eco-building.”

The ADRA has also been working on a project for the environmental refugee population in rural northeastern China, which has won numerous housing and engineering awards in 2005. As mentioned in Section 2: Benefits of Straw Bale, straw bale housing incorporates both social and environmental sustainability. For this particular project led by Kelly Lerner with help from the ADRA, community members contribute valuable input to the housing design and participate in the

acquisition of materials. Their involvement even extends beyond the immediate project into village education. In this way, the community feels a sense of ownership over this building material and supports its longevity. Designs were particular to each village, and a local leadership team had to ensure political commitment by matching funds and managing the project with total transparency. By 2006, nearly 500 people had been trained to build houses across 59 villages in five provinces in northeastern China, with a total output of 603 houses.

In this area of rural China, the current housing stock is largely composed of poorly insulated and structurally unsound brick housing. This mud, rock, and brick construction lacks toughness and proper connectivity, resulting in the possibility of collapse even during minor earthquakes. The result is that a significant number of the 160 million-person population spends much of their insufficient income on heating during winters where temperatures can drop to -40 degrees Celsius. Additionally, they often burn sulphurous coal, which compounds their financial woes with health problems. The introduction of straw bales into the community has reduced the consumption of brick for construction by one-third, thus decreasing the energy inputs required for building, as well as saving 68 percent more energy per comparable-sized house in heating costs. The net carbon reduction is 0.6 to 1.2 tons per year per house. Soil conservation has also increased due to decreased demand for brick, as precious topsoil is no longer removed.

Straw bale housing was an apt choice for this region given the climate and locally available straw waste. As mentioned above, some buildings had been built nearby since 1998 and had withstood an earthquake of magnitude-5.6, while nearby older buildings had not fared so well. The characteristics of this house were particular to the situation and were dictated by a very tight construction budget of about \$4 per square ft. Cement grouted, reinforced stone footings were used at the base in place of traditional dry-stacked stone. The house used cement-mortared brick columns in place of the traditional load-bearing, mud-mortared brick walls. Straw bale infill walls plastered with cement stucco provided the seismic resisting capacity. Both the brick columns and straw walls were reinforced with wire mesh, while steel wire ties were cast into the foundation and extended upwards into the columns and walls. The columns were also connected with a reinforced concrete bond beam, on top of which rests a timber roof. These features are illustrated in Figure 25.

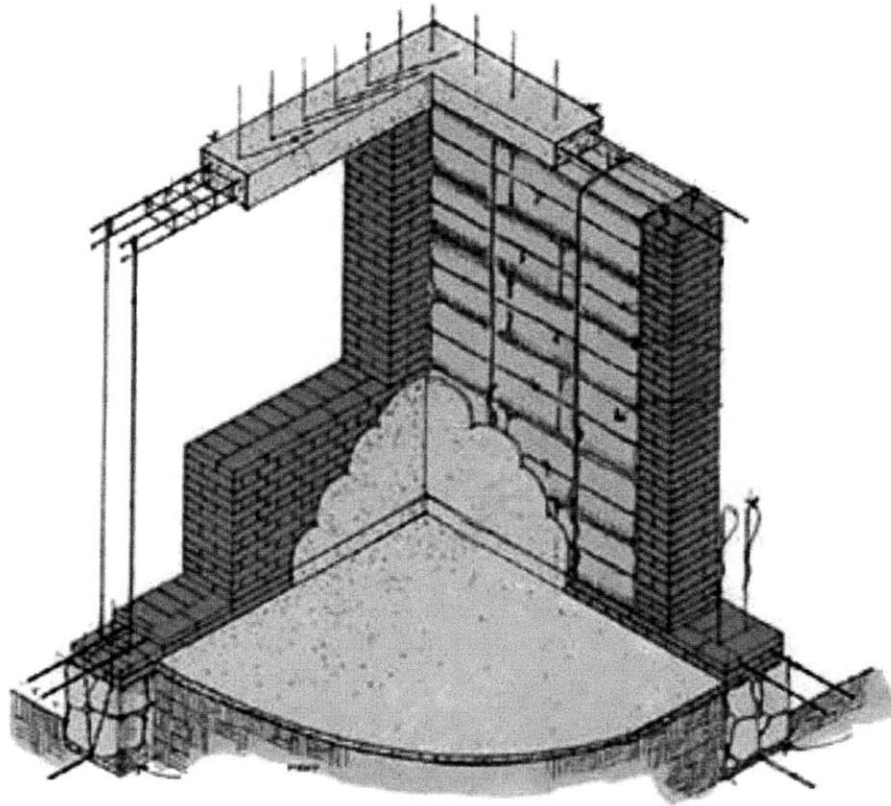


Figure 25: Straw bale assembly in China. Source: Mar poster

According to the results of a post-occupancy survey, 90 percent of 159 families surveyed were satisfied with the layout and design of the houses. The addition of warmth at a lower cost and improved indoor air quality means greater health and happiness (Mar poster).

6.3 Bam, Iran

In late 2003, a magnitude-6.6 earthquake struck this desert region in northwest Iran, killing more than 26,000 people and injuring 30,000 more. The destruction was particularly devastating since most of the city was built with non-seismically resistant mud brick buildings, which failed to comply with earthquake building codes set by the national government in 1989. An estimated 85 percent of the buildings in Bam were damaged or destroyed.

The climate in Iran bears some similarity to California, making the country a logical candidate for straw bale building. In part of the country, they have winter snow in the mountain ranges and mild summer temperatures, while in another part, it becomes quite hot during the day but very cold at night. Thus, the insulating properties of straw are appreciated.

Professor Gary Black at U.C. Berkeley has proposed a patented straw bale building system known as the Spar and Membrane System (SMS) for this quake-ravaged area. A two-story, 3600-square-ft home with this structural system would take about two weeks to build. Like much of straw bale construction discussed earlier, the system is very low-cost and utilizes a readily available waste material. The particular benefit of the SMS system is faster and lower-cost construction due to an innovative way of stabilizing the bales during construction with the spar assembly, thus eliminating the need for temporary wood or bamboo bracing. Steel bars are used to hold the bales in place. Gunitite is then applied to the walls, with a weight one-fourth to one-fifth that of the same thickness of mud or adobe. Additionally, fire tests have been performed to show that the SMS walls can withstand fire for at least two hours (Maclay).

7. Building Codes

At the moment, there is no set building code anywhere in the world for straw bale construction. Proponents of straw bale therefore adapt current provisions to apply to straw bales. For instance, King and others assert that the creep exhibited by the plastered straw bales conforms to California's "current straw bale code." They are referring to the Health and Safety Code #18944, which allows 800 plf of vertical load on a wall with cement or lime-cement plaster. This actually does not account for the extra strength provided by only the straw core alone and suggests a factor of safety of 4.0, given the latest allowable load data value of 3289 plf.

While straw bale housing still manages to be built around the codes, the lack of provisions only serves to hinder this burgeoning construction type when it comes to insurance and financing. However, since the methodical study of straw bale is still young, there is also a faction of people who would rather not see it implemented into building codes yet. They believe such standardization would hamper experimentation and new developments.

The status of straw bale buildings in the eyes of codes around the world usually falls into one of numerous situations. The two extremes are no building code of any type or a ban on straw bale construction, which has been known to happen unofficially in some jurisdictions due to the opinions of individual building officials. An official straw bale building code actually exists in two countries, Belarus and Germany, and in two states of the United States. There is a spectrum of less official provisions as well. In the U.S. for example, accessory units of fewer than 120 square ft are exempt from the building code. Some states provide general guidelines, but often, straw falls into the "Alternative Materials, Design, and Methods" section of the code. California has actually developed an unofficial "Straw Bale Code," which is used as a set of guidelines for builders and has been adopted in a few counties as law (King 2006).

Since this paper focuses on the use of straw bale in developing countries, only these are investigated in more detail. In Central America, straw bale has been used for building in Nicaragua, Costa Rica, and other locations, where there are usually no enforced building codes. However, straw bale is also not a preferred material in some regions with a tropical climate. In China, hundreds of straw bale homes have been built, as described previously in Section 6: Case Studies. China has no straw bale code, but the homes that have been constructed were government-sanctioned, with more on the way through an approved design competition. In Mexico, a permit is not necessary for straw bale buildings, perhaps because in places like Oaxaca, a permit is not needed for adobe construction. The efforts of Kelly Lerner in China can also be seen in abundance in Mongolia, where more than fifty straw bale homes and health clinics have been built with government approval. Lerner is also trying to implement a national straw bale building code in Mongolia but has run into many bureaucratic obstacles. South Africa has three methods of permit approval, including one specifically for housing. However, these have proved rather tedious, and as a result, residential straw bale housing has tended to be owner-built and -financed, while non-residential building, though more readily permitted, faces difficulties in financing and insurance. In South America, a number of straw bale buildings have been built without a permit, but as in Central America, the climate is prohibitive, and the insulating value of the walls is not as beneficial (King 2006).

Though straw bale construction is still in the early stages of development, King and other experts advocate the implementation of a thorough straw bale code. This is to avoid the dangers of poor building. Additionally, they believe that straw bale provisions in major codes like the IBC or the Eurocodes would lead to widespread acceptance, use, and adoption of the material.

8. Conclusion

Recent experimentation described previously demonstrates that straw bale construction is a burgeoning field in both practice and research. The vertical and lateral load capacity of plastered straw bale wall assemblies is comparable to that of existing building materials.

Straw bale buildings have a high potential for use in highly seismic areas around the globe. Though it is limited in height, the design possibilities for residential or other low-rise facilities are boundless. As described above, a number of small residences built with load-bearing straw bale walls have been constructed in various locations around the world. They have been found successful in resisting earthquake loads, as well as in using local labor and materials.

While modeling straw bale walls using computer simulations is still in its nascent stages, there are a number of alternative descriptions to investigate. This thesis viewed a composite straw bale wall as similar to a reinforced concrete shear wall. The subsequent multi-layer shell was subjected to cyclic lateral loading much as a physical model would be, in the form of a pushover analysis. Though the simulation did not match empirical results, it represents an initial step in future simulation developments.

The compression strut model responded to pushover in a manner closer to physical behavior, suggesting even more promise as a subject for future research. Suggested areas of improvement are the properties of the straw material and a substitute for the frame elements.

A third type of model could be an equivalent frame that employs the idea of the sliced transformed section derived from stress-skin panels, as discussed in Section 3.2.1: Composite Action.

Further exploration of seismically resistant, load-bearing straw bale walls will certainly yield an even safer, more affordable option for earthquake-prone areas around the world.

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