# Strawbale Construction

## Part 1: Overview and In-plane Behavior and Design

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*This is the first of a two-part series examining the engineering and design of strawbale buildings. This part provides an overview of the structural system and best practices for the design and detailing of strawbale walls to resist in-plane lateral loads. The second part will address out-of-plane response, uplift, and support of gravity loads.*

## What is Strawbale Construction?

Strawbale construction uses baled straw as stackable blocks in wall systems. Plaster is typically applied to the interior and exterior surfaces of the bales (*Figure 1*). Clay, lime, or cement-lime plasters may be used, often with reinforcing mesh.

The bales, plaster, and mesh can work together to create a composite structural system, similar in concept and performance to a structural insulated panel (SIP). The plaster and its reinforcement form a skin that is strong, stiff, and durable, bonding to the softer bales and protecting them from moisture, fire, and wear. The bales brace the plaster skins against buckling and tie them together, forming a composite section capable of resisting out-of-plane loads. Strawbale wall systems are used as load-bearing walls and as infill in post and beam framing.

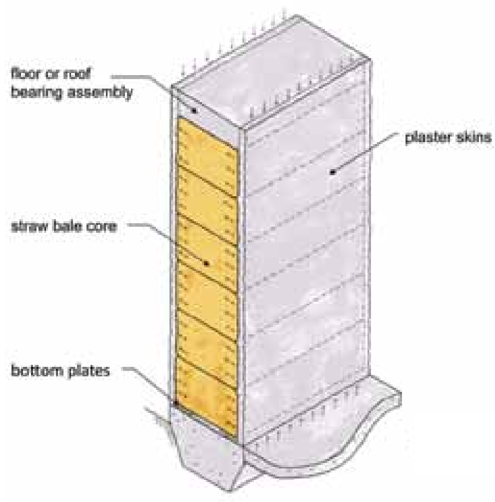


*Figure 1: The essential components of a strawbale wall. Courtesy of David Mar.*

## History

Strawbale construction originated in Nebraska (*Figure 2*) in the late 1800s, shortly after the invention of baling machines. Some of these early buildings, over 100 years old, are still in service. The practice was abandoned in the 1940s, but enjoyed a rebirth in the American southwest in the 1980s. Interest spread rapidly in this rediscovered building method, valued for its resource and energy efficiency, and aesthetic qualities. Plastered strawbale walls have substantial structural capacity when properly detailed, both as load-bearing and lateral load resisting systems.

Strawbale buildings now exist in 49 States, and variations of strawbale construction are practiced in over 45 countries, in virtually every climate. There are over 500 strawbale buildings in California alone. U.S. strawbale buildings include residences, schools, office buildings, wineries (*Figure 3, page 16*), multi-story buildings, and large buildings (over 10,000 square feet in floor area). In many of these structures, strawbale walls are used as load-bearing elements or shear walls, even in areas of high seismic risk.

## Testing and Research

The testing of strawbale construction goes back to the early 1990s, and includes structural, moisture, fire, and thermal tests. Plastered strawbale

*Figure 2: Simonton house, Nebraska, 1908.*

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The proposed code provisions along with an archive of important tests, research reports, and analyses of system behavior is available at **www.ecobuildnetwork.org**.

*Figure 3: A contemporary strawbale building. Ridge Winery, CA. Interior before plaster. Exterior finished. Courtesy of Freebairn-Smith & Crane Architects.*

walls have high thermal resistance (R-30 for a typical wall) and are very resistant to fire (full scale walls passed 1-hour and 2-hour ASTM E-119 tests). Moisture is the notable challenge for strawbale walls, but with good design, detailing, and maintenance, strawbale buildings can last indefinitely.

Since 1993, wall specimen and component structural tests have been performed. These tests include vertical load-bearing, reversed in-plane cyclic, monotonic, and out-of-plane wall specimen tests, as well as component tests on bales, plasters, and mesh anchorage. A full-scale shake table test of a small building using a system tailored to post-earthquake Pakistan was conducted in 2009 at the University of Nevada, Reno.

## Strawbale Construction and Building Codes

Over the last 20 years, most strawbale buildings have been permitted under the alternative materials and methods section of the building code. Only New Mexico (1996) and Oregon (2000) have adopted statewide strawbale codes. In 1995, California legislated strawbale construction guidelines for voluntary adoption by local jurisdictions. Since 1997, nine cities or counties in four other states have adopted strawbale building codes.

Most strawbale building codes are derived from the first such code, created for and adopted by the City of Tucson and Pima County, Arizona in 1996. Subsequent experience, testing, and research have shown these codes to be greatly deficient. They are often too restrictive or not restrictive enough, and are silent on many important issues.

In 2009, a strawbale code proposal was submitted by strawbale building practitioners to the International Code Council (ICC) in response to its request for alternative materials provisions to be considered for the International Green Construction Code (IgCC). The proposed section was included in the Second Draft of the IgCC but was subsequently disapproved in 2011, with opponents advising that strawbale construction belongs instead in the International Building Code (IBC) and International Residential Code (IRC). In January, 2012, a further developed proposal was submitted for consideration for the 2015 IBC.

The proposal is based on testing results and 20 years of field experience by strawbale design and building professionals. The proposal includes a two-story limit for structural use of strawbale construction. The IBC review process continues through its final action hearings, scheduled for October 24-28, 2012.

## Materials

Straw is an agricultural waste product remaining after the harvest of grains such as rice, wheat, barley and oat. Straw is baled after harvest, using mechanical baling equipment, at moisture contents less than 20%. Two-string bales are typically 14 x 18 x 36 inches. Three-string bales are typically 15 x 23 x 46 inches. Polypropylene string (with 210–280 pound knot strength) is now used nearly universally as baling twine. Consequently, bale size, density and moisture content are fairly consistent. Typical densities are 7-8 pcf, resulting in a three-string bale weighing 75-80 pounds.

A prescribed set of plasters are addressed in the proposed 2015 IBC chapter. Critical details (e.g. reinforcement, lap splices, anchorage, and sill plates) and design values are based on behavior observed in testing. So-called "hard" plasters use a binder of Portland cement with lime or with soil, or a binder of lime alone, while "soft" plasters use clay as a binder. Typical compositions of these plasters are described in *Table 1* along with typical cube compressive strengths. Baseline compressive strengths relied upon for the development of allowable gravity loads and allowable shears are also shown in *Table 1*.

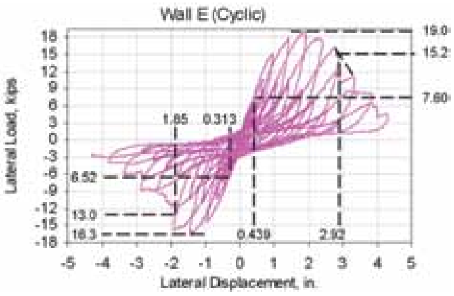
Different types of mesh are recognized as plaster reinforcement in the proposed provisions. A high-density polypropylene mesh (e.g. Cintoflex® C) may be used to reinforce the soft plasters. A welded wire mesh (2-inch x 2-inch x 14 gauge) is recognized for use in both soft and hard plasters.

*Table 1: Plaster types and typical cube compressive strengths.*

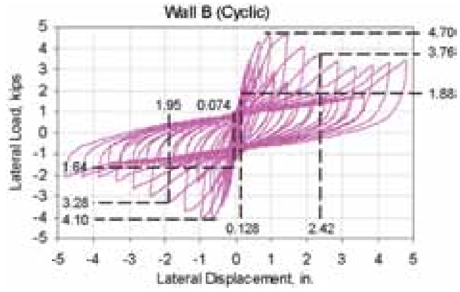
| Plaster Type | Typical Composition (parts by volume) | Typical Range of Compressive Strengths (psi) | Baseline Strength in Proposed Provisions (psi) |
|---|---|---|---|
| Clay | 1 clay: 1 sand: 1 straw | 80–250 | 100 |
| Soil-cement | 1 cement: 9 soil-sand[1] | 600–1500 | 1000 |
| Lime | 1 hydraulic lime: 3 sand | 600 – 1400 | 600 |
| Cement-lime | 1 cement: 1 lime: 6 sand | 1000–1600 | 1000 |
| Cement | 6 cement: 1 lime: 21 sand | 1400–2400 | 1400 |

[1] *minimum cement: soil-sand ratio*

*Figure 4: Behavior observed in full-scale tests of strawbale walls: (a) and (b) show response of a cement plaster wall; (c) and (d) show response of a clay plaster wall.*




*(a) Load-displacement response.*




*(c) Load-displacement response.*

*(b) Flexural cracks at a displacement of 2.40 inches (2.5% drift).*

*(d) Flexural cracks at a displacement of 2.40 inches (2.5% drift).*

## Behavior of Walls Under In-plane Shear

In-plane shear tests were conducted to establish the reversed cyclic load-deformation behavior of strawbale walls designed and detailed for lateral load resistance. Details were established using a capacity design philosophy to encourage ductile behavior in the field of the plaster. Walls made with reinforced clay and cement plasters were tested at full scale; a superimposed gravity load of 200 plf was applied.

Detailed descriptions of the tests are provided by Ash et al. (2003). *Figure 4a* shows the recorded load-displacement response of Wall E, having cement-plaster skins, while *Figure 4b* shows the condition of this wall at a drift of 2.5%.

*Figures 4c* and *4d* show the response of Wall B, having reinforced clay plaster skins. The cement plaster used in Wall E had mean cube compressive strength of 2200 psi, and this led to a tension-controlled flexural failure. The lower compressive strength of the clay plaster (mean cube strength of 290 psi) led to a compression-controlled failure for Wall B. The compression failures were gradual. The mesh wires worked against and degraded the matrix of the plaster near the staples at the base of the wall. This proved to be a ductile process that resulted in the clay plaster walls (e.g. *Figure 4c*) displaying greater ductility than the cement plaster wall (*Figure 4a*). In subsequent analysis to develop R factors for use in seismic design, the cement plaster wall controlled.

Strengths of the cement plaster walls were estimated accurately using strain compatibility (moment-curvature) analyses with software normally used for reinforced concrete walls (BIAX-2 or XTRACT). Strengths of the clay plaster walls, however, could be estimated only by artificially weakening the compressive strength of the plaster used in the analyses. This is attributed to the degradation of the plaster matrix causing sandy debris to pile at the base of the plaster skin; the debris pile acted as a wedge to deflect the plaster skin laterally, thereby reducing its capacity to support the compression required for carrying axial load and moment. (Note that the individual pieces of straw comprising the bale provide substantial lateral bracing to the plaster skins, but no such lateral support is present along the vertical plane of the sill plate.) Once calibrated, the strain compatibility analyses were used in assessing effects of variations in materials strengths or axial load on flexural strength.

The tests demonstrated that moderate ductility could be obtained without risk of loss of gravity support. The reinforced plasters provide a stiff load path on par with that available from wood shear panels. However, hold-downs are not needed because the reinforced plasters provide both flexural and shear resistance. Well-anchored, robust sills carry these loads to the foundation. In this way, the reinforced plasters act much like thin reinforced concrete walls, which are braced laterally by the straw. At low displacement amplitudes, flexural behavior was dominant, with tensile and compressive zones present on either side of a neutral axis. As imposed drift levels increased, the individual wires of the mesh or their connections gradually failed, leading to a reduction in strength and the gradual development of rocking. At larger drifts, visible gaps between the individual bale courses opened and closed. Because the walls are relatively stocky (height to thickness ratios between 4 and 6 are common), and because the plaster skins help to maintain the vertical alignment of the bales, the soft strawbale core provides a redundant mechanism to support gravity loads as the skins fail. No sign of instability was apparent even through two cycles of drift to ±7%.

Longer walls would be governed by shear failure rather than flexural failure. An 8-foot high by 8-foot 7-inch long strawbale wall was tested at Cal Poly San Luis Obispo. (Nichols and Raap, 2000). The plaster was restrained along its edges, forcing deformation predominantly in shear. Just as would be expected for a longer wall, the cement plaster skins failed in shear. Following the $V_n = V_s + V_c$ formulation defined for reinforced concrete walls indicates $V_c = 3.4\sqrt{f'_c}\, b_w d$, just above the nominal $3\sqrt{f'_c}\, b_w d$ that would be accorded walls of this aspect ratio in ACI 318. This reference strength level is used to ensure that the proposed allowable shears, derived based on flexural behavior, are well below the true shear strengths.

## Design Parameters for In-plane Loading

Allowable shears and seismic design parameters (R, $\Omega_o$, and $C_d$) were developed for use in wind and seismic design. Proposed allowable shears are provided in *Table 2 (page 18)*. The allowable shears are for walls composed of two- or three-string bales having reinforced plaster on both sides of the wall.

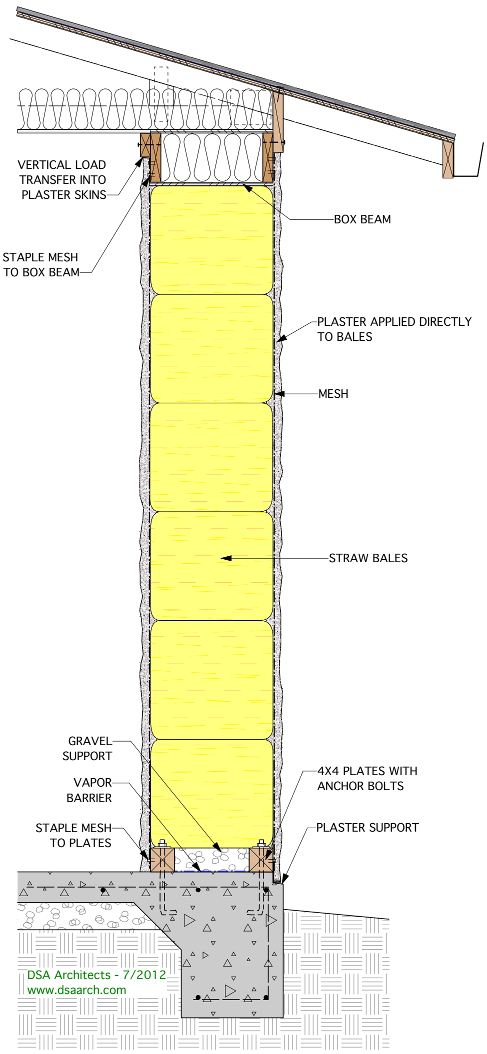



*Figure 5: Schematic section of a load-bearing shear wall.*

The derivation of allowable shears was constrained by the need to obtain elastic behavior under wind loading and to achieve seismic performance on par with other structural systems. The derivation is described by Jalali et al. (2012) and accounts for differences in the ductility capacity of clay and cement plaster walls, limitations in the number of test specimens, the use of plasters having compressive strengths conforming to the proposed code minimums, and the use of different mesh reinforcement.

R-factors for use in seismic design were developed by three approaches as described by Jalali et al. (2012): a conventional approach that considers overstrength and ductility (Uang, 1991 and FEMA-303, 1998), a comparison with established materials (e.g. light-framed walls with wood shear panels), and initial FEMA P-695 analysis results. On the basis of available results, the authors recommend R = 3.5 for bearing wall systems and R = 4.0 for building frame systems. These can be used together with $\Omega_o = 3$ and $C_d = 3$ for bearing wall and $C_d = 3.5$ for building frame systems. Similar to other instances of allowable stress design, seismic forces should be multiplied by 0.7 while allowable design values should be increased by 40% for resisting wind loads.

## Detailing for In-plane Loading

A schematic wall section for a one-story load-bearing shear wall is shown in *Figure 5*. Along the base of the wall are 4x4 sill plates attached to the foundation with ⅝-inch diameter anchor bolts at relatively close spacing (as little as 2 feet). A gravel bed is used at the base of the wall, in between the sill plates, to provide both a capillary break and a vapor-permeable support surface for the bales. Along the top of the wall is typically a wood box beam, composed of plywood skins sandwiching horizontal 4x4s. The box beam provides for attachment of roof or floor framing and transfer of lateral loads into the wall. The mesh reinforcement is anchored at the top and bottom of the wall by stapling into the horizontal wood members. Typically, 16-gauge staples are applied diagonally over every wire intersection. Stainless steel staples are used when stapling into pressure-treated lumber; electro-galvanized staples may be used in untreated lumber.

*Table 2: Development of allowable shears.*

| Plaster Type | Plaster Thickness (min) | Plaster Reinforcement | Shear Strength (kips) | Factor of Safety | Proposed Allowable Shear (plf) |
|---|---|---|---|---|---|
| Clay | 1.5” | none | 1.27 | 2.78 | 60 |
| Clay | 1.5” | 2 in. by 2 in. high-density polypropylene | 3.05 | 2.78 | 140 |
| Clay | 1.5” | 2”x2”x14 ga. | 4.10 | 2.78 | 180 |
| Soil-cement | 1” | 2”x2”x14 ga. | 16.26 | 3.87 | 520 |
| Lime | 7/8” | 17ga. woven wire | 10.18 | 3.87 | 330 |
| Lime | 7/8” | 2”x2”x14 ga. | 13.97 | 3.87 | 450 |
| Cement-lime | 7/8” | 17ga. woven wire | 11.71 | 3.87 | 380 |
| Cement-lime | 7/8” | 2”x2”x14 ga. | 16.07 | 3.87 | 520 |
| Cement | 7/8” | 2”x2”x14 ga. | 16.70 | 3.87 | 540 |
| Cement | 1.5” | 2”x2”x14 ga. | 17.45 | 3.22 | 680 |

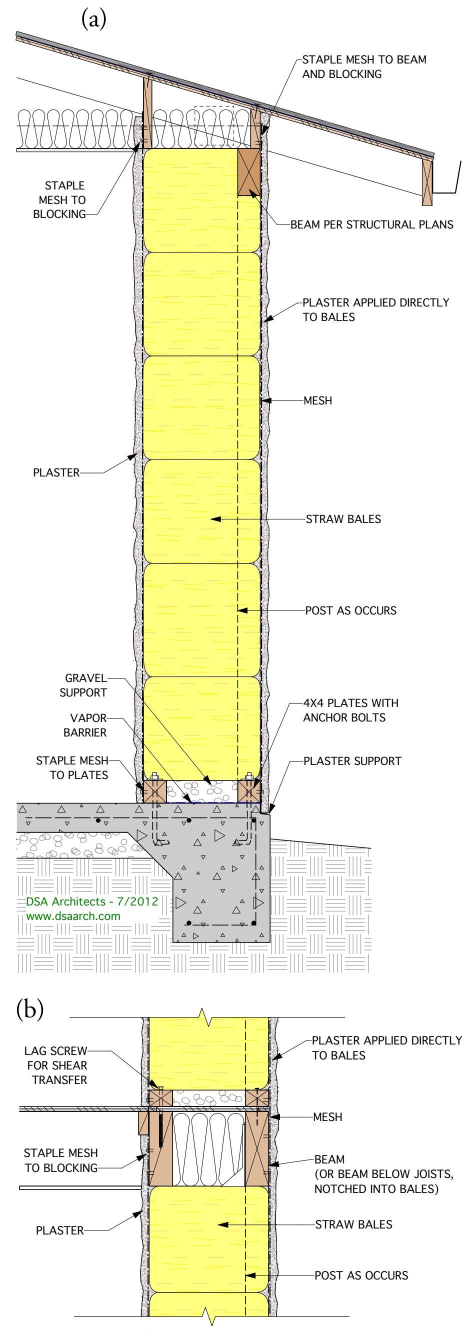



*Figure 6: Schematic infill shear wall sections. (a) One-story shear wall. (b) Detail at second floor.*

Alternatively, plastered straw bale walls may be used as infill within a post and beam system. In this application, lateral loads may be transferred into the wall as shown in *Figure 6a*. For two-story construction, connections are designed and detailed to provide for load transfer from the upper level wall to the lower level wall via the first floor. In *Figure 6b*, blocking between the joists provides a load path between the plaster skins, where the joists are perpendicular to the wall. Where the joists are parallel to the wall, a joist is provided under each 4x4 plate. Load transfer across the floor assembly must be provided. Plaster and mesh reinforcement on the exterior may be made continuous across the floor assembly with the mesh stapled to the rim joist and lapped as necessary.▪

## References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