LOAD-BEARING STRAW BALE CONSTRUCTION

A summary of worldwide testing and experience
June 30, 2003
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ABSTRACT

One hundred years of experience with load-bearing plastered straw bale structures, along with a number of laboratory tests worldwide, show these wall systems to be capable of supporting substantial service loads. When properly baled, stacked, and detailed, and plastered both sides with cement, lime, or earthen renders, straw bale walls can support at least residential scale loads, and meet typical building code criteria for strength, serviceability, creep, and durability. Unplastered bale walls have been shown to provide abundant strength reserve in the elastic range, and a ductile, energy-absorbing core under dynamic or excess loads.

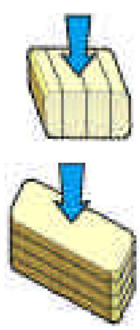
Straw-bale barrel vault house under construction, Joshua Tree, California. Design and photograph by Skillful Means Construction. Recipient of the 2002 Innovative Seismic Design of the Year Award *from the Structural Engineers' Association of California; engineering by David Mar, Tipping-Mar Associates.*

INTRODUCTION

The first straw bale structures were all load-bearing of necessity— they were erected by European settlers in the Sand Hills region of western Nebraska, USA who had at the time (late 19th century) only horse-powered baling machines and grass fibers to build with. What little lumber they had packed in had to be saved for roof framing, so the straw bale walls were made to support the roof without added structure. Several dozen buildings survive from that period (roughly 1880 - 1930), and the oldest extant survivor reached its 100th birthday in 2003.

Railroads and highways soon brought more familiar building materials to the area, and straw bale construction faded to obscurity until a series of articles and experiments in the late 1980's sparked a "revival" that has now spread all over the globe. (Farmers and ranchers worldwide have always used baled straw to insulate barns and other livestock shelters, but that was always on a temporary basis, never intended or expected to be durable.) As plastered straw bale structures have proliferated, two distinct types have evolved: load-bearing, or Nebraska style, in which the weight of roof and upper floors is carried by the bale walls, and post-and-beam, or infill, in which a structural frame carries gravity load.

This report is a summary of worldwide experience and structural laboratory testing on bales and straw bale walls, and suggests a more exact and scientific basis for designing straw bale walls to carry gravity loads. Note that the terms "plaster", "stucco", and "render" will be used interchangeably, though "stucco" is generally understood to mean a cement-based plaster.



Bales loaded "flat" are loaded perpendicular to their largest face—parallel to the plane of the tie hoops, and generally perpendicular to the straw fibers.

Bales loaded "on edge" are loaded parallel to their largest face—perpendicular to the plane of the tie hoops, and generally parallel to the straw fibers.

Figure 1: Nomenclature: bales "flat" and "on edge"

By way of introduction, it should be added that the technology of straw bale construction is still rapidly evolving. Nonetheless, a distinct trend has become apparent: we now know that plastered straw bale walls can carry substantially more load than was expected fifteeen years ago (before any formal testing had been done), but the majority of new straw bale structures are built in the post-and-beam style. Several factors explain this apparent contradiction:

1. The inherent conservatism of the construction industry resists anything "new"; building officials, mortgage lenders, insurors, and others all have to be convinced of the efficacy of anything new or different, and many building owners simply opt to use a structural frame so as to avoid the attendant, extended arguments that might hold them back. It is substantially easier to get a building permit, mortgage, and insurance for a "post and beam building with extra-thick cellulose insulation" than for a "load-bearing straw bale structure".
2. Erecting a structural frame allows the builder to put up and cover a roof before even bringing the bales onsite, allowing the walls to be erected under constant protection. This enormously reduces the risk of moisture problems—which typically occur during or as a

result of the construction process—and thus helps ensure a durable building. By contrast, the builder of a load-bearing structure must generally complete the foundation, erect the bales, install any wiring and plumbing scheduled for the walls, and install door and window bucks before the permanent roof can go on (In some cases they must also add reinforcing mesh (where called for), plaster the walls, and allow them to cure for a few weeks prior to adding a roof.) All of that constitutes a long period during which there is little sleep for fear of rain; if the bales get substantially wetted, they probably won't dry within the wall assembly and usually have to be replaced. This is another compelling reason for builders to avoid the anxiety and scheduling difficulties, and choose to use a structural frame.

3. If there ever is a moisture problem in the wall (eg a faulty window seal), the damaged bales can be removed and replaced, at least more easily, without weakening the primary structure.

With all of that said one may wonder why choose to build a load-bearing straw bale wall system at all. Again, there are several reasons:

1. Many who build with straw bales are seeking, more broadly, to build “green”, ie in as environmentally friendly way as possible. This often means minimizing the use of wood, in response to the worldwide devastation to old growth forests over the past century. As has been pointed out, there are no old growth fields of straw, so many seek to replace wood fiber with straw fiber wherever possible in the building.
2. A load-bearing structure is often simpler and faster to erect. If the project is in a location like western Nebraska of the late 1800's, where other building materials are scarce or prohibitively expensive, then the appeal becomes that much stronger. The smaller the building, the easier it is to quickly erect the bale walls and put up a roof, even prior to any plastering.
3. Initial seismic tests (see other EBNet reports) strongly show that a load-bearing structure will generally perform more effectively (ie with greater ductility and energy absorbtion) than its post-and-beam counterpart under dynamic loading.

TYPICAL CONSTRUCTION / STRUCTURAL MODEL

Plastered straw bale walls are remarkably simple to build— and remarkably complex in their behavior under load. You start by stacking big, fuzzy bricks of irregular length (width and height are constant but length varies due to the nature of modern baling machines), and low elastic modulus (generally about 150 to 300 psi [1 to 2 mPa]). You put in door and window bucks which may float (ie fit within the straw) or be secured at the floor or foundation below. You have innumerable voids at head joints, bucks, corners, etc that typically get packed with a thick straw-clay mix (cob) that is favored for its plastic stiffness and resistance to insects, fire, and moisture intrusion. You may or may not fasten mesh to the straw surfaces, and may or may not tie that mesh through the wall to the far side. You may have any of a number of plates or assemblies at the bottom and top of the wall, and, if you have mesh, might fasten it very well or very lightly. You might provide a direct load path from above through the stiff plaster skins, or may try to bypass them through the straw core. That is the multifaceted state of straw bale construction in 2003—one that will likely persist in the years to come.

Most engineers reduce all this complexity, roughly, to a stress skin or sandwich panel assembly, akin to structural insulated panels and some types of insulated concrete forms: a stiff, strong skin on each side of a soft, insulating core. The skins, by their relative stiffness, attract all loading, while the core straw bales serve as insulation, a shear transfer medium, and bracing for the skins. Unlike other types of stress skin systems, however, well-stacked straw bale walls also form a strong core with reserve strength to back up failed skins, and the ability to absorb energy (eg seismic load) by deforming both elastically and inelastically without collapse.

Under vertical load, there are four basic types of failure modes, and the tests conducted to date have seen each and all, either singly or in combination:

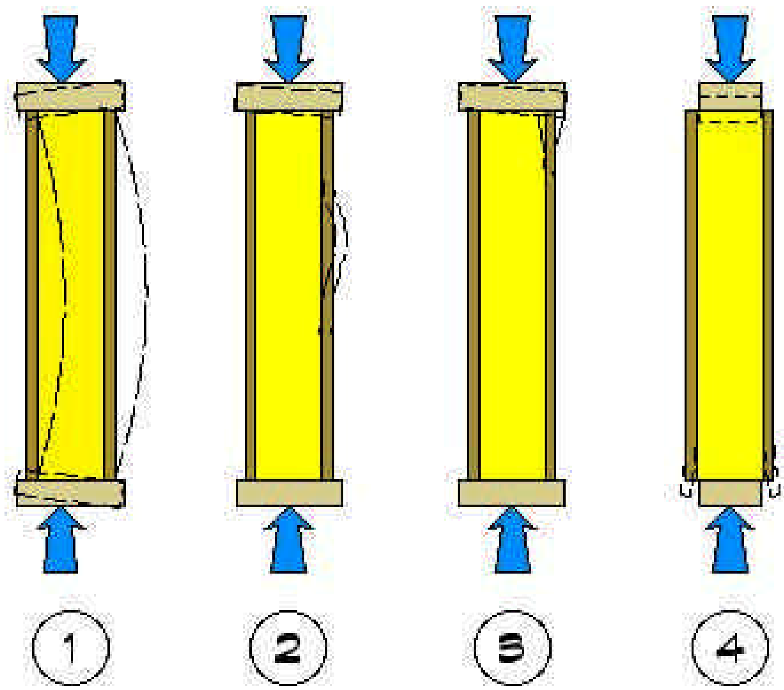


Figure 2: Failure modes for a load-bearing straw bale wall

1. Global buckling	the whole wall bends and breaks—typically when the wall is well-built, but eccentrically applied load induces bending.
2. Local buckling	part of the skin delaminates and pulls off the core, or one coat of plaster delaminates and separates from the coat beneath—the result of poor plaster application causing insufficient bond, and/or surface irregularity causing local bending.
3. Bearing	skin crushes under the top or bottom plate, and/or top or bottom plate crushes under edge of skin—the wall components have not been designed or built to sustain the focused stress at the joint.
4. Slippage	unsupported skin slips past the top or bottom plate—typically, a failure of fasteners attaching mesh to the sides of plates or beams.

SUMMARY of TESTS CONDUCTED TO DATE

Tests conducted on single bales, single plastered bales, unplastered bale walls, and plastered bale walls. Wherever possible, contact information is provided for obtaining the original reports.

1A. TESTS ON UNPLASTERED BALES

1. Bou-Ali, 1993

Bou-Ali, Ghailene, "Straw Bales and Straw-Bale Wall Systems", 1993, University of Arizona, Tucson

A variety of tests on single 3-string wheat bales and unplastered wall assemblies were conducted; see section 1B for wall test results.

Single flat bales were loaded up to 84 psi [579 kPa], deflecting to as much as half of the original height without permanent distortion. The elastic modulus was measured to be 78 to 211 psi [538 to 1455 kPa] (stiffening under load), and Poisson's Ratio was measured to be 0.30.

Single bales on edge were loaded up to 21 psi [145 kPa], and typically failed suddenly by bursting of the strings. The elastic modulus was measured to be 60 to 260 psi [414 to 1792 kPa]; Poisson's Ratio was not measured in this direction.

The authors commented that bale bearing capacity increased with bale density, and that, at least with bales flat, there was a strain hardening phenomenon—stiffening under increased load. Also of note was the fact that fully loaded flat bales, which had compressed to half their height, had fully rebounded by the next day.

2. Thompson et. al, 1995

Watts, K., Wilkie, K., Thompson, K., and Corson, J. "Thermal and Mechanical Properties of Straw Bales As They Relate to a Straw House" Canadian Society of Agricultural Engineering Paper No 95-209, Ottawa, Ontario, 1995

Wheat, oat, and barley bales with moisture contents averaging 9% were loaded flat, with at least six specimens of each. Maximum applied compressive loads were 6 to 10 psi [41 - 69 kPa] and were all in the elastic range. Modulus of Elasticity ranged from 18 to 26 psi [124 - 179 kPa] (the relatively low values being due, probably, to measuring the value from zero, ie not discarding the initial set portion of the stress-strain curve, and to not testing up to and beyond the proportional limit). Poisson's ratio was measured both longitudinally and laterally, averaging .37 and .11 respectively. The author's commented (p. 6):

a. " *There is considerable variation in the Modulus of Elasticity between bales of the same type* [ie of plant grain] *and bales of a different type* "
b. " *Bale density has a greater effect on bale strength than bale type* "
c. " *Continuous exposure to high moisture contents decreases the Modulus of Elasticity* "
d. " *Poisson's ratio in the longitudinal direction is much greater than the lateral in unconfined tests.* "

3. Stephens, Budinger, 2000

Stephens, Don, and Budinger & Associates, Inc. laboratory test July 13, 2000 Spokane, Washington
Contact: Don Stephens dsteph@tincan.org

This is the only test this author has found of the "supercompressed" bales that are being made for overseas export. Heavy hydraulic machinery compresses ordinary bales to about twice their normal density—in this case, 18 pounds per cubic foot [288 kg/m^3]—and reties them with polypropylene strings at 3" [76 mm] oc. In this test, 24" x 24" x 16" [610 x 610 x 406 mm] bluegrass bales were loaded on edge, ie on the 16" x 24" face. Unlike the Bou-Ali on-edge tests in which the bales failed suddenly by string breaking, these bales showed a classic linear behavior up to the proportional limit of 17 psi [120 kPa] with half an inch [13 mm] of deflection, and then sustained additional load as deflection increased. The Elastic Modulus was 992 psi [6839 kPa], several times larger than for ordinary bales. Poisson's ratio was not reported.

4. Zhang, 2002

Zhang, John "Load-Carrying Characteristics of a Single Straw Bale Under Compression"
University of Western Sydney, July 2000

Two-string wheat bales were tested flat and on edge, in some cases under low frequency cyclic loading. Plastered bales were also investigated—see section 2A for results and discussion.

1B. TESTS ON UNPLASTERED BALE WALLS

5. Bou-Ali, 1993

Bou-Ali, Ghailene, "Straw Bales and Straw-Bale Wall Systems", 1993, University of Arizona, Tucson

Three wall assemblies of flat, 3-string wheat bales 12 feet long by 8 feet high [366 cm x 244 cm] were each loaded axially up to 15,800 lbs. [70.3 kN], or 1317 plf [19.2 kN/m]. The researchers commented that there was deliberately no attempt to pound each bale into place (as is good bale building practice), nor was there any bracing (as is typically provided by crosswalls), so the deflections recorded were conservative. Overlapping rebar pins of unspecified size and spacing were driven through the cores, as was then the custom. The results were:

	Ultimate load	Deflection
Wall A	1317 plf [19.2 kN/m]	6.9" [17.5 cm]
Wall B	1317 plf [19.2 kN/m]	7.6" [19.3 cm]
Wall C	1317 plf [19.2 kN/m]	7.8" [19.8 cm]

Unlike individual bales which harden under load, the walls had each begun to soften at the maximum load, and wall C had begun to noticeably buckle.

6. Blum, 2002

Blum, Brandice, "Load Carrying Behavior of On Edge Straw Bale Walls", 2002
University of Manitoba, Winnepeg, Manitoba Contact: Professor Kris Dick kjdick@Ms.UManitoba.CA

Two 5-course wall assemblies of 2-string wheat bales on edge 7.5 feet long by 6.2 feet high [2.3 m x 1.58 m] were loaded axially. No rebar pins were reported used. The results were:

	Ultimate load	**Vertical deflection**	**Horizontal deflection** *(bulge perp. to plane of wall)*
Wall A	350 plf [5.1 kN/m]	2.8" [7.2 cm]	8.1" [20.6 cm]
Wall B	288 plf [4.2 kN/m]	3.0" [7.6 cm]	3.1" [7.9 cm]

Both walls partially buckled under ultimate load, and both, with load left in place for three days, lost about half of their resistance (stiffness creep). The author also made reference to an earlier test at the same University (by Ester Arbour; this author was unable to obtain that test) that tested similar wall assemblies of flat oat bales. Those results were:

	Ultimate load	**Vertical deflection**	**Horizontal deflection** *(bulge perp. to plane of wall)*
Wall C	754 plf [11 kN/m]	6.5" [16.6 cm]	1.0" [2.5 cm]
Wall D	480 plf [7.0 kN/m]	6.0" [15.3 cm]	2.0" [5.1 cm]

2A. TESTS ON *PLASTERED* BALES

7. Zhang, 2002

Zhang, John "Load-Carrying Characteristics of a Single Straw Bale Under Compression"
University of Western Sydney, July 2000 Contact: Professor John Zhang j.zhang@uws.edu.au

Two-string wheat bales were tested flat and on edge, plastered and unplastered, in some cases under low frequency cyclic loading. Wishing to also investigate load path within the wall, the author also applied load in three ways:

1. directly through straw core only top & bottom,
2. directly through straw core at top, but straw and plaster skins supported at bottom, and
3. through straw core and plaster skins both top and bottom.

Both cement and earthen plasters were tested, but the author did not describe the mixes or cure times other than that there were two weeks between cement coats; thicknesses averaged 1.6" [4 cm]. Bales averaged about 12% moisture content, and a density of 6.2 pounds per cubic foot [100kg/m^3]. Probably of more interest than specific results were the author's comments:

a. " *low-frequency cyclic loading has no significant impact on the load-resistance properties of the* [unplastered] *straw bales* " (p. 8)

b. " *there is always delayed (viscous) effect on the recovery of the deformation as the* [unplastered] *straw is unloaded.* " (p. 8)

c. there is substantially different adhesion of the plaster to opposite sides of the bale (p. 11) [ed. note: this is partly why experienced bale builders alternate bales in a wall between exposing the "cut side" and the "folded (or uncut) side"—a result of the baling process.]

d. there is an initial set phase of the test in which the "fluff" between bales is compressed; the author identified this as 3 to 4% of height. In otherwords, at least for these particular bales, a stacked wall of bales should ideally be precompressed 3 to 4% of its height before applying plaster. (p. 13)

e. " . . . *different from the common familiar plastic flow as seen in steel after yielding, straw bales can further develop significant amount of strength after the yielding . . . although having little significance for service load design . . . [this behavior] does offer a significant safety buffer and energy dissipation if overloading does occur.* " (pp. 13-14)

f. " *different loading regimes for the rendered tests do not make a significant difference in the load resistance behavior.* " (p. 14)

8. Mar, 2003

Mar, David "Bearing Test of Plastered Straw Bales"
Ecological Building Network, 2003 Contact: www.ecobuildnetwork.org

[See complete separate report at web address above as part of this EBNet series]
Rice straw half-bales were fabricated and stacked flat, two high (so as to fit in the testing apparatus), giving a cross section of 23" x 23" [58 cm x 58 cm] plus 1.5" [38 mm] plaster skins each side. Plasters were cured at least one month, and load was applied via a stiffened plywood plate covering the plaster edges; ultimate loads were recorded as follows:

Lime-cement stucco w/ 2" x 2" [5 cm x 5 cm] x14 gauge mesh / avg. of 3:	2810 lbs [12.5 kN]
High straw fiber earthen plaster w/ coconut fiber mesh / avg. of 3:	2340 lbs [10.4 kN]
Low straw fiber earthen plaster w/ coconut fiber mesh / avg. of 2:	1575 lbs [7.0 kN]

2B. TESTS ON *PLASTERED* BALE WALLS

9. Platts, Chapman, 1996

Platts, Bob and Chapman, Linda, "Developing and Proof-Testing the 'Prestressed Nebraska' Method for Improved Production of Baled Fibre Housing" , Canada Mortgage and Housing Corporation, 1996

A partial wall panel was formed by stacking seven wheat straw bales 14" x 18" x 32-37" [36 x 46 x 81-94 cm], then reinforced and pretensioned each side with 22 gauge [0.8 mm] hexagonal mesh. A total prestressing force of about 700 lbs/ft [10.2 kN/m] reduced the height of the wall by 3" [7.6 cm], or 3%. A 3/4" [1.9 cm] coat of premixed lime-cement stucco was then applied and cured for 11 days for an expected compressive strength of about 1000 psi [7 kPa].

The results of vertical load application were:

Initial load	Vertical deflection	Highest measured load	Vertical deflection
(*at calculated service load for two stories*)		(*at limit of testing apparatus*)	
2944 plf [43 kN/m]	0.04" [1 mm]	4500 plf [66 kN/m]	0.12" [3 mm]

10. Carrick, Glassford, 1998

Carrick, John, and Glassford, John, "Vertical Loading, Creep, Transverse Loading, and Racking Loading on Plastered Straw-Bale Walls", 1998, Univ. of New South Wales, Australia Contact: John Glassford huffnpuff@shoal.net.au

Two string rice bales were stacked in 18" wide x 9'-2" high (7 courses) x 11'-10" long [45 cm x 2.80 m x 3.6 m] wall specimens, and compressed between 4 and 8 inches [10 - 20 cm] using the Fibrehouse system (see preceding test report) and 20 gauge [1 mm] hexagonal mesh. Three walls were built and compressed; one was tested under vertical load prior to rendering, then all were rendered with a sand/cement/lime plaster in relative proportions 8:2:1. The authors do not say how long the plaster (applied in three coats) was cured before testing, but since failure mode was typically by crushing of the wooden top plates against the top edge of the plaster, the curing period can be assumed to have been at least a month. The results were:

	Ultimate failure load	**Deflection**	**Unplastered load**	**deflection**
Wall A	1617 plf [24 kN/m]	.28" [7.5 mm]		
Wall B	1412 plf [21 kN/m]	(not reported)		
Wall C	1466 plf [21 kN/m]	.18" [4.5 mm]	144 plf [4.2 kN/m]	2.6" [66 mm]

Notes: The same three wall specimens were simultaneously subjected to large racking and transverse loads—with attendant deflections—while increasing the vertical load to ultimate. This surely skewed the apparent vertical load capacity downward (note the relatively low failure loads compared against other reports which used similar specimens).

11. Ruppert, Grandsaert 1999

Ruppert, Jeff, and Grandsaert, Matt, "A Compression Test of Plastered Straw-Bale Walls", 1999, University of Colorado, Boulder, Colorado Contact: Jeff Ruppert jruppert2@uswest.net

Three types of eight foot high [2.4 m] stuccoed barley bale wall assemblies were loaded to failure in compression. All were stacked flat and rendered with a sand/cement/lime plaster in relative proportions 4:1:1, in two coats, and cured on average at least forty days to an average tested compressive strength of about 1,000 psi [6900 kPa]. Three 12 foot [3.7 m] long samples of each type were tested by applying a linear load 1/6 eccentric to the wall centerline (per ASTM standard E-72), with results as follows:

Ultimate failure load (avg. of 3)	**Deflection (avg. of 3)**	**Apparent E_m**
Wall 1 - 24 inch [610 mm] wide 3-string bale wall with polypropylene fiber reinforcing		
3239 plf [47 kN/M]	.91 inches [23 mm]	4.1 ksi [28.3 Mpa]
Wall 2 - 24 inch [610 mm] wide 3-string wall with 20 gauge hexagonal mesh reinforcing		
3590 plf [52 kN/M]	.46 inches [12 mm]	6.9 ksi [47.6 Mpa]
Wall 3 - 18 inch [457 mm] wide 2-string wall with polypropylene fiber reinforcing		
6156 plf [90 kN/M]	.42 inches [11 mm]	12.9 ksi [88.9 Mpa]

Notes: It has been widely noted that, contrary to expectation, the 18" walls carried substantially more load than the 24" walls, and were stiffer. Though there were some irregularities in load application, and in the quality of plastering, this dramatic difference has yet to be fully explained or understood. Every possible failure mode was seen among the nine specimens (see figure 2), and the authors commented that polypropylene fiber-reinforced stucco (vs. mesh-reinforced stucco) bonded much better to the straw, as evidenced by conditions exposed during demolition. On the other hand, the presence of mesh reinforcing helped substantially in resisting local skin buckling.

12. Black, Mannik, 1997

Black, Gary, and Mannik, Henri, "Spar and Membrane Structure" The Last Straw *journal, #17, Winter 1997*

A proprietary "spar and membrane" system was developed and reported in The Last Straw (No. 17, Winter 1997), in which lightly reinforced 2" [5 cm] gunite skins are interconnected with extended "X" shaped light rebar in the bale head joints. The system was mocked up at one half scale and tested under out-of-plane load (with some nominal vertical load), and modeled and analyzed using SAP90 software. Besides being under patent, this system is somewhat unusual in that it treats the bales purely as formwork, entirely expendable after the gunite cures. (The authors do not comment or speculate as to what may happen to the bales in the event of water infiltration behind skins that are effectively moisture and vapor traps, a cause for concern with any thick cement-based plaster system.)

The authors reported very good strength and ductility in the out of plane load tests. Based on their tests and computer modeling, they also claim a vertical load carrying capacity on the order of 25 tons per foot, but did not report loading a specimen to that extent.

13. Dreger 2002

Dreger, Derek, "Compression Resistance of a Stuccoed Straw bale Wall", 2002
University of Manitoba, Winnepeg, Manitoba Contact: Professor Kris Dick kjdick@Ms.UManitoba.CA

Two-string oat straw bales were stacked in two six-course walls 7.5 ft. x 8 ft. [2.3 m x 2.4 m], reinforced with 2" x 2" [5 x 5 cm] 16 gauge mesh tied through the walls with polypropylene baling twine at 16" [41 cm] oc. All were rendered with a sand/cement/lime plaster in relative proportions 4:1:1, in two coats separated by two days, and cured about seven days. (This very short cure time will generally only bring a high lime plaster, at best, to half its ultimate strength, but as events transpired the ultimate reported test loads were limited by the loading mechanisms, not the soft plaster.) The results of vertical load application were:

	Ultimate load	**Vertical deflection**	**Horizontal deflection** *(bulge perp. to plane of wall)*
Wall A	1938 plf [28.3 kN/m]	1.1" [2.8 cm]	1.4" [3.5 cm]
Wall B	1973 plf [28.8 kN/m]	0.34" [0.9 cm]	0.2" [0.6 cm]

The author reported that the excessive bulge in wall one was largely due to unwanted flexure in the top plate causing a global bending of the wall, as well as poor (spalling) stucco. Wall two showed a 15% loss of resistance (stiffness creep) over 24 hours as load was maintained.

14. Faine, Zhang, 2002

Faine, Michael, and Zhang, John "A Pilot Study examining the Strength, Compressibility and Serviceability of Rendered Straw Bale Walls for Two Storey Load Bearing Construction" University of Western Sydney, July 2002
Contact: Mike Faine m.faine@uws.edu.au

Two different walls were constructed from 33" x 18" x 14" [84 x 46 x 36 cm] 2-string wheat bales laid flat in a running bond at 12% average moisture content. Continuing on from the preliminary work of Zhang on individual bales (see test #7), the authors were specifically interested in investigating the load-carrying capacity of walls both loaded and supported only on the straw cores (ie with plaster skins free to slide at supports). Both walls were vertically precompressed at about 20" [52 cm] oc with high tension fencing wire, which was used to cinch them down to 97-98% of original height before plastering.

<u>Wall 1:</u> An 11 course wall 13'-1" high by 8'-6" long [4.0 x 2.6 m] was built and plastered both sides with two coats totalling 2.3" [58 mm] of cement-lime-sand plaster in proportions 2:1:8, reinforced with 1/2" x 1/2" x 18 gauge [12 mm x 12 mm x 1.2 mm] wire mesh tied through the wall at about 24" [60 cm] each way. Lapped half inch [12 mm] rebar pins 47" [120 cm] long were also driven through the wall core at about 24" [60 cm] oc.

<u>Wall 2:</u> A 7 course wall 8'-4" high by 8'-11" long [2.56 x 2.6 m] was built and plastered both sides with two coats totalling 1.5" [40 mm] of earthen plaster in proportions 3:3:1 of earth, sand, and straw chaff. The plaster's compressive strength was measured at 98 psi [680 kPa], average of 9 cylinders. A 1/8" [3-5 mm] finish coat of the same plaster with lime added was then applied; that plaster's measured compressive strength was 33 psi [230 kPa], average of 9 cylinders. [*Ed. note: the addition of lime to earthen (clay) plaster can weaken or strengthen it, depending on many things: quality of lime and clay, proportions of each, quality of mixing, application and cure, and age of applied plaster*.] This wall had no pinning or mesh reinforcing.

The results of vertical load application were:

	Yield load	Vertical deflection	Ultimate load	Vertical deflection
	(---- *at proportional limit*	----)	(---- *at failure*	----)
<u>Wall 1</u> *(two-story/cement plaster)*	1919 plf [28 kN/m]	0.8" [20 mm] (.005H)	3221 plf [47 kN/m]	4.4" [112 mm] (.028H)
<u>Wall 2</u> *(one-story/earth plaster)*	1233 plf [18 kN/m]	0.37" [0.9 cm] (.004H)	2467 plf [36 kN/m]	7.0" [178 mm] (.070H)

RELATED TESTS

Farmers have always baled hay and straw just to make it easier to store and move around. As the idea has spread of using baled straw as building blocks, the more generalized idea of packaging waste materials for construction uses has also spread. More than a few light bulbs have gone off above heads all over the world, and there is now a rapidly growing array of applications—ranging from wild ideas to prototypes to commercial products—for making effective use of waste materials. (This is very much a part of the broader movement now known as “industrial ecology”.) This paper cannot even try to be comprehensive in reviewing that broader picture, but it is still worth looking at some of the related work, and keeping straw bale construction in a larger context.

OTHER KINDS OF STRAW BALES

The typical straw bale is bound with two or three strings of polypropylene twine, though sometimes wire or fiber twine is used, and is relatively easy for one man or woman to handle. In otherwords, bales as farmers have always made them are, generally, just fine for construction. The biggest concern to bale builders is the type of combine used to harvest the straw—conventional combines that leave long straw fibers (which is good for building), and rotary combines that chop the straw into short fibers (which makes for unstable, “crumbly” bales).

With the increased industrialization of farms, other types of bales are beginning to predominate in many areas:

1. <u>Jumbo bales</u> rectangular blocks bound with six or ten strings, of a typical size like 3 feet x 4 feet x 8 feet [1 m x 1.3 m x 2.2m], which can only be handled with mechanized equipment.
2. <u>Circular bales</u> Disks bound with twine, of typical dimension 3 feet thick x 6 feet in diameter [1 m x 2 m] — also only handled with machinery.
3. <u>Supercompressed bales</u> ordinary bales (or straw) compressed to roughly twice the normal density (see test #3).

According to emails and journal articles over the past few years, each of these has been tried in building structures in (at least) North America and Australia. So far as this author knows, they work very well, and though little testing as been done, would presumably have load-bearing capacities even better than ordinary bales simply for being so massive.

OTHER KINDS OF BOUND STRAW

This is a huge and rapidly growing topic. Innumerable versions of straw blocks, “lumber”, panel sheathing, and extruded shapes have already been envisioned or developed, and the general trend is clearly for more and more straw-based products to enter the construction industry. Some involve very sophisticated processing of the straw combined with modern binders such as cement or polyisocynurate, and can produce blocks, “lumber” and sheathing comparable in mechanical properties to the wood fiber panels and framing now abounding. There are also low density panels and blocks made simply by applying heat and pressure to straw , thus bringing out the natural lignins in the straw to act as a weak binder that will hold molded shapes.

At the other end of the technology spectrum, the age-old method of using packed straw-clay in walls (“leichtliem” in Germany) has been brought forward by, among others, Bill and Athena Steen in Arizona. Taking the basic ideas of an adobe brick (mostly sand and clay with a bit of straw fiber, bound by the dried clay), and at the other extreme a straw bale (all straw, bound by string), they drew a line between and arrived at the straw-clay block. They have put the idea into very practical use, and are building durable, low-cost structures in Ciudad Obregon, Mexico with various combinations of local straw fibers and clays (see www.caneloproject.com). There is enormous appeal to the idea, as a straw-clay block can be easily made onsite almost anywhere, and have high density for load-bearing application, or very low density for insulation purposes, or anything in between.

OTHER KINDS OF BOUND MATERIALS

Newspaper, waxed cardboard, pine needles, rags and many other waste materials have all been baled and tried in building structures, but little is known about their relative durability and strength. There are now also tire bales, made by highly compressing waste tires into large rectangular blocks (about the size of jumbo straw bales), and binding them with heavy steel wire. These have also been tried in buildings, but again little is known about durability and performance. There are undoubtedly other materials being bound and tried in building structures that this author is unaware of, and many more combinations will appear in the years to come (See Summer/2003 issue of *The Last Straw*).

Also, experimental structures of various sorts have now been erected in (at least) Canada, the UK, and Australia using preassembled, precompressed, and sometimes pre-plastered straw bale wall panels. This branch of straw bale technology is still in its infancy, but holds great promise, and may prove the means by which straw bale construction becomes a mainstream building method in the industrialized world.

CONCLUSIONS

Testing to date has confirmed and emphasized an emerging standard of care for load-bearing straw bale construction that had already been born of and shaped by experience and common sense. There is still much to be learned, and a maddening variety of types of bales, plasters, and wall assemblies, but a few basic guidelines can be laid out as follows.

BALES

Four qualities determine the usefulness of a bale for building:

<u>Moisture content</u> The drier the better; decay can begin at 20% or more moisture content above 40ºF [5ºC]. Moisture content will depend on the circumstances at the time of baling and during subsequent storage and transport; quality control and inspection of a straw-bale job requires the use of a bale moisture meter, available from farm supply houses.

<u>Density</u> Bale density will vary depending on the type of grain, moisture levels and the degree of compression provided by the baler, but is an indirect measure of the really important and distinct quality, compactness. Dry density (ie with moisture content accounted for and subtracted) should generally be at least seven pounds per cubic foot [112 kg/m^3] if the bales are intended for load-bearing walls.

History The history of the bale's storage and protection, from harvest through to construction, can either be documented by the supplier or inferred from visual inspection. Bales that have been moistened once or repeatedly will show grey or black areas where mold spores have begun proliferating. Such bales are typically discarded, even if very dry at the time of construction, as they are especially likely to experience problems if the wall is ever wetted.

Fiber length Some baling machines (eg rotary combines) chop the straw into very short lengths before baling, resulting in bales that are not as coherent as is desired for construction. Experienced builders look for fiber lengths of at least 10 inches [25 mm].

Other qualities have proven to not matter so much:

Type of plant grain Rice straw appears to be somewhat better than others for its high silica content and resistance to decay, but the difference is not big. It appears that just about any kind of straw, properly compacted and bound, can serve well in a building structure.

Organically grown straw Many types of fertilizers, pesticides, and herbicides are routinely used in the farming of cereal grains. Though some decompose naturally before the straw becomes a bale, many people understandably prefer not to have unknown quantities of unknown substances with unknown health effects in their buildings, and thus use organically-grown straw. In doing so they may be averting health risks, but they are not improving the structural quality of the straw bales. Plants that are fertilized, whether by petrochemicals or animal manure, grow more rapidly than their unfertilized counterparts, and thus tend to have weaker straw fibers. Thus, the useful (structural) distinction for builders is between fertilized vs. unfertilized straw. As a practical matter, this may be a trivial, as nearly all bales to be found in any given area very likely come from fertilized plants.

BALE WALLS

A few rules for the wall assembly have become apparent:

1) Typically, the bales are stacked in a running or stack bond directly atop one another; early experiments with adding cement mortar between courses created thermal bridges while giving no clear benefit. In load-bearing buildings, it is essential to pound each bale into place so as to minimize later settling.

2) All straw bale buildings inevitably have dozens of oddly shaped spaces between the bales and supported framework, framing, windows, etc., and the convention is to fill those spaces with loose straw (what's left on the ground after the walls are erected) coated with a clay slip and packed tightly into the crevices. This borrows on the lessons learned from five hundred year old timber frame buildings in Europe: hydrophilic straw-clay acts to "pull" any intruded water away from the wood and bales, and is a fire and pest retardent as well.

3) Though they are basically stacked like masonry, straw bales are comparatively soft and do not exactly behave like bricks. Except where surrounded by a sturdy frame of posts and beams, the bales must be braced during stacking for stability and alignment (akin to the temporary bracing of a studwall). Internal pinning of the walls (with bamboo or rebar dowels) has been prescribed in early straw-bale codes, but is falling out of favor, for it is unclear whether internal pins contribute appreciably to the strength of the finished wall assembly. Much testing to date has been on pinned walls, but field reports and tests strongly suggest that exterior pinning—paired rebar or bamboo dowels against the bale surfaces that are tightly connected

through the wall with heavy wire—is both easier to build and stronger. Other structural testing has shown that completely unpinned walls, if well built, can also carry service loads.

4) The predominant experience with straw-bale buildings is that moisture vapor intrusion is not a problem if the wall can "breathe"; that is, if both surfaces are vapor permeable. There have certainly been leaks and degradation failures, but without exception they have been due to outright moisture intrusion, not vapor intrusion. Although moisture control is strongly related to the climate, design must largely focus on preventing leaks. In short, and to perhaps oversimplify, it seems that water vapor should be allowed to move in and out of the wall assembly, and not allowed to condense on internal surfaces, while extra care must be taken to keep liquid water out. Tops of bale walls, exposed horizontal surfaces (that is, windowsills), and joints with wood frames must be carefully sealed and designed to shed water. As with fire, the structure is especially vulnerable during construction, as bales and walls can be wetted by rains, appear to dry out, and then develop problems after the wall is completed. Extra effort must be made to store and protect the bales all the way from the field of origin to the completed building.

5) This leads to the most important, unusual, and seemingly counterintuitive feature of accepted straw-bale construction: no moisture or vapor barriers should be used except for windowsills and tops of walls. Building permit reviews have commonly generated the requirement to cover the bales with a barrier such as plastic or tar-impregnated paper, but experience with straw-bale walls overwhelmingly shows that no barrier should separate the plaster and straw. This is because the straw needs to breathe (release water vapor), moisture must not be trapped against the straw/plaster interface, and the structural system depends on a thorough bonding of plaster into straw. [See other EBNet moisture tests in this series.]

6) The foundation must keep the bales well above grade, and the roof should provide a wide overhang—the proverbial "good hat and good pair of shoes". Roofs are conventional, connecting to the walls via some manner of top plate or bond beam (most commonly a wood or concrete assembly, though many variations have been tried). Windows and doors are typically framed wood bucks that either sit on the foundation or "float" in the bale wall, and require expanded metal lath strips over paper or bituthene to tightly reinforce the plaster at straw/wood joints. (As with any other wall system, windows and doors are both the largest labor cost, and the usual location of water intrusion failures. Cabinetry and fixtures are screwed to wooden stakes pounded into the straw, and conduit can be let into grooves carved by chainsaws or weed wackers into the straw surface. The bottom of the bale wall must be well separated from the foundation; at the very least, a waterproof barrier should be laid over a supporting concrete surface to halt any wicking moisture from below. Additionally, builders are typically placing a layer of pea gravel between wood sill plates along the inside and outside faces, thereby ensuring that the bales will never be sitting in water.

7) Builders have found that an 8-foot [2.444 m] bale wall can lose up to 4 inches [13 to 102 mm] of height in a few weeks from its own and added roof weight. These deflections are drastically reduced if bales are well-compacted and emphatically stomped into place (or virtually zero if very high-grade bales such as the rice bales of California are used). Knowing that any appreciable settling of the straw will induce unwanted stresses, and possibly cracks, in the rigid plaster skins that are already in place, builders have historically let the loaded walls settle as long as possible before applying plaster. More recently, however, rather than waiting for the roof weight to compress the bales, many builders have been precompressing the walls mechanically. Zhang (7) demonstrated that this precompression must be about 3 or 4% of wall height, at least

for the wheat bales he worked with; others (9) found similar values with other bales. This is most commonly done with elastic polyester package strapping or heavy gage (fencing) wire wrapped over the wall and down through the footing, in both cases "cinching down" the bale assembly to the foundation at close intervals, such as 2 feet [610 mm] on center.

8) Virtually all straw-bale wall systems are *plastered* straw bale, where "plastered" is used generically to include traditional earthen plasters, lime and gypsum plasters, shotcrete or gunite, cement stucco, and various combinations of these. Whether or not the plaster is reinforced with embedded fibers or metal mesh, it will by its higher stiffness attract structural loads. How all these materials work together is not yet fully understood, but here is a summary of the highest wall loads previously reported on a variety of systems:

Test #	**Maximum wall load** *plf / kN/m*	**Comments**
5	1317 / 19	unplastered bales
9	4500 / 66	failed testing mechanism before wall
10	1617 / 24	simultaneous high racking and out of plane loading
	1412 / 21	" "
	1466 / 21	" "
11	3239 / 47	average of three walls
	3590 / 52	" "
	6156 / 90	" "
13	1938 / 28	failed testing mechanism before wall
	1973 / 29	" "
14	3231 / 47	two story cement-plastered wall
	2467 / 36	one story earth plastered wall

These numbers all compare favorably with California's "straw bale code", ie Health and Safety Code #18944, which allows an 800 plf [11.7 kN/m] vertical load on a wall with cement or lime-cement plaster. Many have also investigated and commented on the reserve strength provided by the straw bale core alone (eg test #5).

Perhaps the most important test of all, not yet mentioned, is the one provided by Nature. There are now load-bearing straw bale structures all over the world, from one to one hundred years old, using every possible combination of bales, plasters and assemblies, and this author has yet to hear of a structural failure, or even significant structural problem. At the very least, we can conclude that this is a very promising building technology, deserving both more study by and acceptance in the construction industry.

SUMMARY

In the hundred years since straw-bale building technology was first pioneered, the basic technique has remained pretty much as straightforward as stacking the bales and plastering both sides. Our knowledge of the material properties of these walls has blossomed in tandem with the extraordinary revival of the past fifteen years, and we now are now equipped, at least roughly, to design for any conditions. Codes written to date for load-bearing straw bale buildings appear to be conservative, but not excessively so, and can be refined as we learn more.

There are also enormous environmental benefits to straw bale construction, so every strategy to move the construction industry towards a sustainable course must allow for, and encourage, this intriguing new building technology. In particular, grain growing regions with available straw and extreme temperatures stand to benefit from the insulating properties of straw bale construction. Hybrids between traditional adobe earthen blocks and straw bales—straw-clay blocks—presents another building material more resistant than bales or adobes to water problems, easy to field fabricate with any straw and clay, not requiring baling machines, and capable of providing both structural and insulative properties. Both straw bales and straw-clay blocks hold great promise for both disaster-relief and permanent housing throughout the world.

photo courtesy of Bill Steen

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