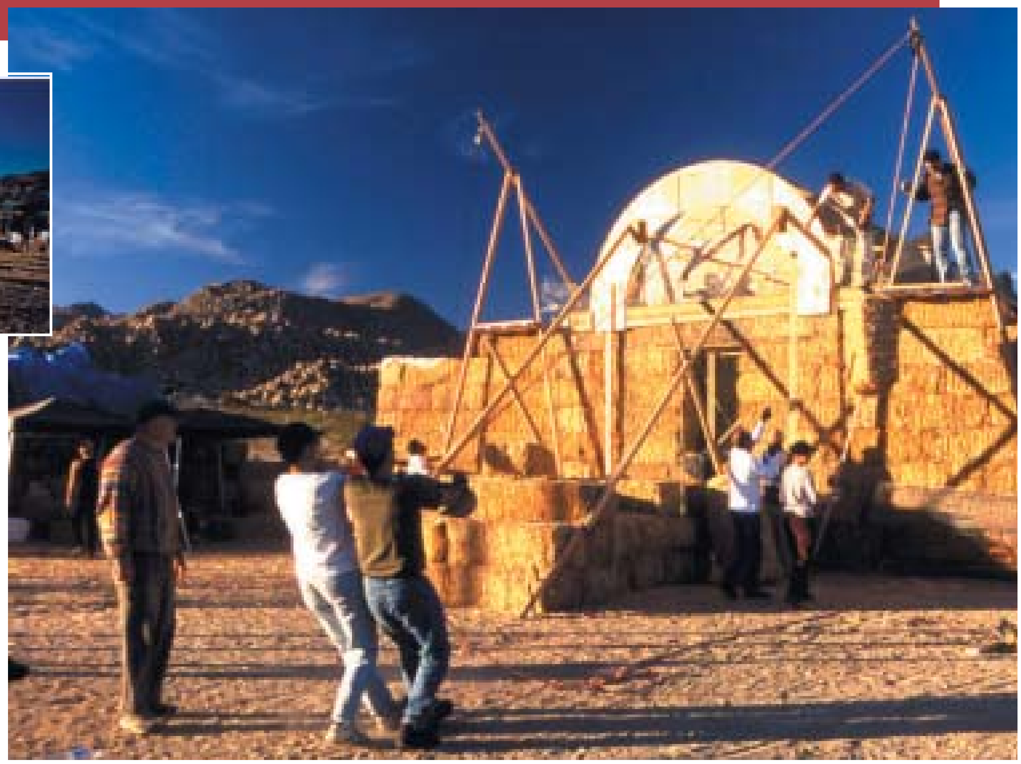
Straw-Bale Construction

A Review of Testing and Lessons Learned To Date

by Bruce King, C.E.



Straw-bale barrel vault house under construction in Joshua Tree, California. *(Engineering by Tipping-Mar Associates, design and photograph by Skillful Means Construction.)*

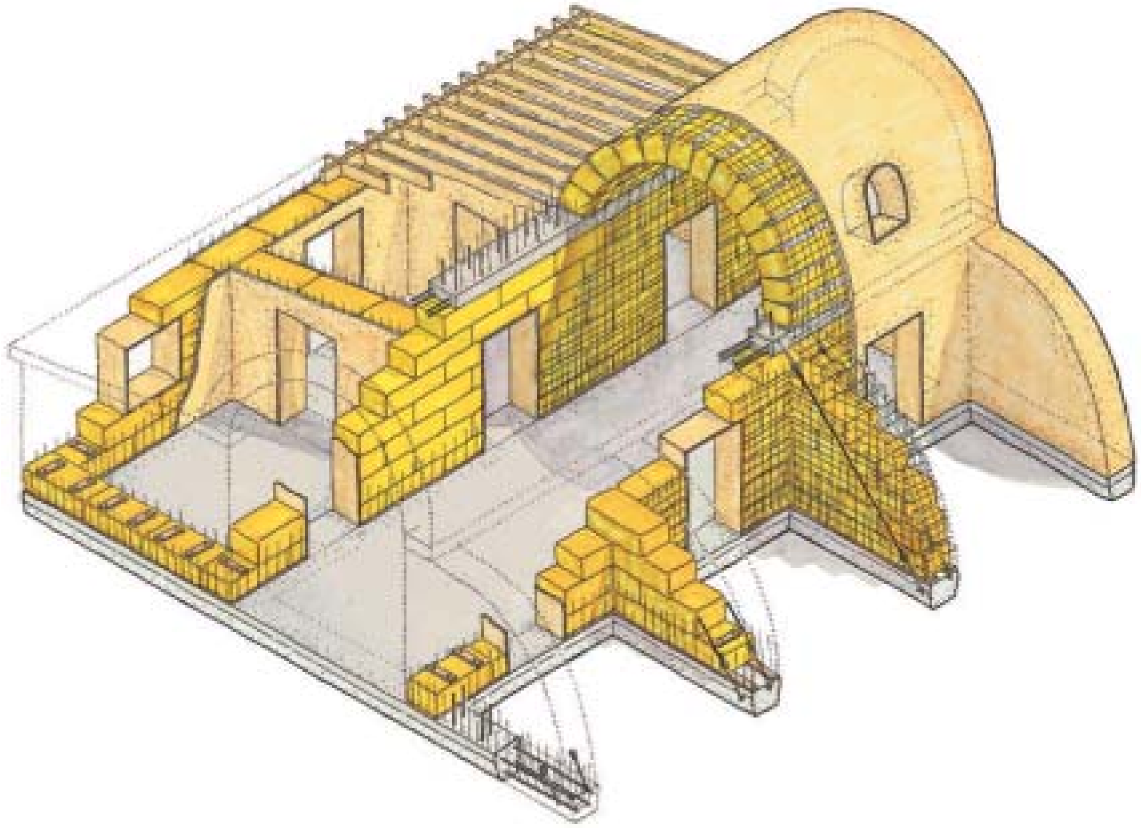
The first straw-bale structures we know of were built more than a hundred years ago by European settlers in the Sand Hills region of Nebraska. Many of those homes still exist, and a revival in straw-bale construction began in the American West in the late 1980s. As more professional architects, engineers, inventors and builders have begun to explore this new material, a variety of styles and techniques has emerged, and straw-bale construction has spread all over the world. A recently completed quarter-million-dollar research and testing project, funded mainly by the State of California, has answered some common technical questions. This article describes some of the basics of straw-bale construction and reviews the accumulated body of laboratory and field experience to date.

Bales

Straw is the plant structure between the root crown and the grain head (*hay* includes grain and should not be used for building). Bales are masses of straw compressed into rectangular blocks that are bound with polypropylene twine. Building bales might be "two-string" (generally 16" x 18" x 36" ±) or "three-string" (generally 15" x 23" x 46" ±), and are ideally stacked in a running bond. Bales are usually stacked flat, i.e., with the longest dimension parallel to the wall and the shortest dimension vertical. In other applications, the bales can be stacked on-edge, i.e., with the shortest dimension horizontal. The slimmer wall achieved with this second option saves interior space and, interestingly, appears to offer the same net insulation value due to the slightly different orientation of the fibers.

Experience (and some laboratory testing) strongly suggests that four qualities determine the usefulness of a bale for building.

- **Moisture content**. The drier the better—very generally, a moisture content hovering for an extended period of days above 30 percent and 40° F is considered cause for concern about decay.
- **Density**. Dry density (i.e., with moisture content accounted for and subtracted) should generally be at least 6 pounds per cubic foot if the bales are intended for load-bearing or shear walls, and the material should be bound tightly enough such that lifting a bale by one string will leave no more than a fist-sized gap between bale and string.
- **History**. Bales that have been moistened once or repeatedly will show grey or black areas where mold spores have begun proliferating. Such bales are always 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 chop the straw into very short lengths before baling, resulting in bales that are not as coherent as is desirable for construction. Fibers must be long enough that the bales easily remain intact during handling.



Straw-bale barrel vault house isometric. Recipient of the 2002 Innovative Design of the Year Award from the Structural Engineers Association of California. *(Illustration by David Mar, S.E.; engineering by Tipping-Mar Associates; design by Skillful Means Construction.)*

Wall Assemblies

Many details and wall systems are now in use, and dozens have been tried and discarded for one reason or another—in other words, straw-bale construction is still very much a developing technology. It is nonetheless true that, as with every other building material, the ideal wall assembly depends very much on area climate and seismicity, building function, and aesthetics.

Until very recently there were two basic styles of straw-bale construction: *load bearing* and *nonload bearing* or *post-and-beam*, in which bales are used as infill panels between or around a structural frame. Post-and-beam style predominates because it is more adaptable and allows the construction of a protecting roof prior to bale delivery and placement. However, the more important distinction is really between *structural* straw-bale construction, in which bale assemblies are designed to carry vertical and/or lateral loads, and *non-structural* construction, in which the only structural demand on a wall assembly is to remain intact and in place under out-of-plane load.

Despite the many variations, there are several qualities common to all straw-bale buildings.

- All straw-bale buildings inevitably have irregular spaces between the bales and the surrounding framing, windows, doors, etc. The conventional practice is to fill these spaces prior to plastering with a straw-clay mixture, which draws any intruded water away from the wood and bales as it dries, as well as serving as a fire and pest retardant. Alternatively, some builders use a sprayed insulation like cellulose to fill the cavities.
- The bales must often be braced during stacking for stability and alignment (akin to the temporary bracing of a stud wall). Internal or external pinning of the walls with rebar dowels has been prescribed in early straw-bale codes, but is no longer considered to provide much structural value.
- 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 exposed 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. In short, it seems that water vapor should be allowed to move in and out of the wall assembly without condensing on internal surfaces, while extra care must be taken to keep liquid water out. Tops of bale walls, exposed horizontal surfaces (i.e., windowsills) and joints with wood frames must be designed to shed water and carefully sealed. As with fire, straw bale structures are especially vulnerable to water damage during construction, as bales and walls can be wetted by rains, appear to dry out, and then develop problems after the wall is completed.

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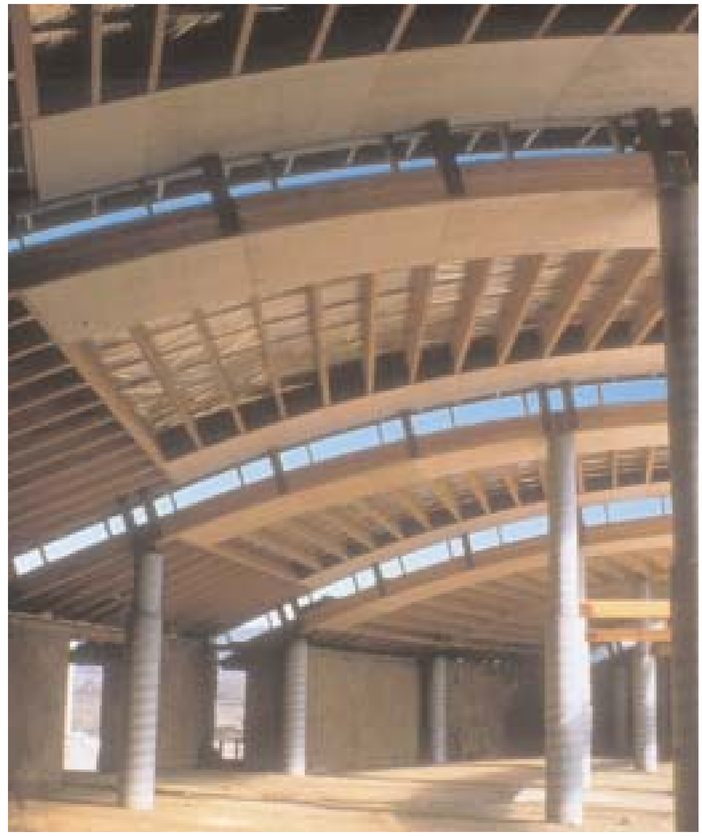
- Building permit reviews have commonly generated the requirement that bales be covered with a barrier such as plastic or asphaltic paper, but experience with straw-bale walls overwhelmingly shows that no barrier should separate the plaster and straw. This is because the straw needs to breathe (release water vapor), moisture must not be trapped against the straw/plaster interface, and the structural system depends on a thorough bonding of the plaster and straw. The only exceptions are windowsills and, if used, shower stalls.
- 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). Windows and doors are typically framed wood bucks that either sit on the foundation or "float" in the bale wall. 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 by a waterproof barrier over the supporting concrete surface and a layer of pea gravel (capillary break) between wood sill plates along the inside and outside faces, thereby ensuring that the bales will never be sitting in water.



The Real Goods Solar Living Center in Hopland, California, is constructed of straw-bale and employs passive solar heating and cooling, daylighting and energy efficient lighting and equipment, a utility grid with photovoltaic and wind electricity generation, an outdoor oasis cooled by evaporation immediately adjacent to the building, and greywater irrigation.

Plasters

Virtually all straw-bale wall systems are plastered with traditional earthen, lime or gypsum plasters; shotcrete or gunite; common cement or lime-cement stucco; or some combination of these materials. As such, a discussion about straw-bale walls should include the properties of the plaster used.

It is essential to understand that once plaster is applied directly to either or both of the exposed straw-bale surfaces, the completed wall assembly is now a hybrid of straw and plaster: a sandwich panel (or, considered from another perspective, stacked straw bales could be thought of as a variety of insulating concrete forms). Virtually all loads, except where directed to a separate building frame, will be carried mostly or entirely by the relatively rigid plaster "skins"—effectively, thin concrete walls or wide, flat columns. In contrast to a wholly concrete structure, however, in which failure of a bearing/shear wall or column can be both sudden and catastrophic, the failure of the plaster skin is slowed and resisted by the straw-bale assembly.

Tests conducted in various laboratories over the past 10 years have proven that an unplastered wall can carry an appreciable amount of vertical load, as well as some in-plane and out-of-plane shear, and would therefore provide a back-up against failure of the plaster skins. Furthermore, recent structural tests have revealed the surprising strength, ductility and toughness of plastered bale walls, even when fully cracked and subjected to cyclic loading. When plastered on both sides, the walls behave much more like an integral stress skin panel structure than might be expected, such that the assembly can be conceived of as thin concrete walls or skins braced, and somewhat elastically connected, by the ductile straw-bale core.

In many cases, such as one-story buildings in low seismic zones, the use of earthen plasters with a modest addition of straw or other stabilizer and adequate roof overhangs provides acceptable strength and durability. Almost any type of plaster has some structural strength, and where loads are light the preference is for a vapor-permeable plaster such as lime and stabilized earth. Generally, when an engineer wishes to use bale walls as shear walls in high seismic risk areas like California, the application of a standard lime-cement stucco mixture has proven to result in an excellent combination of strength, durability and vapor permeability.

Plaster coatings should always be worked directly into the straw, as there is a huge increase of strength from an unplastered to a plastered wall assembly when the plaster skins are bonded to the straw substrate. In areas prone to heavy snow, temperature extremes or seismic activity, the plaster skin of the system will require tensile reinforcing. This can be achieved through the use of conventional hexagonal 17-gage stucco mesh, but for heavy loading should take the form of welded wire mesh with a comparatively tight weave, such as 2-inch × 2-inch, 14-gage wire. The design and detailing of fasteners at boundary elements will greatly affect the ability of the skin to carry and transmit loads. Because the bond provided by working the plaster into the straw is typically quite strong, many (including this author) generally believe that mesh reinforcing need only be attached well enough to stay in place during plastering; weaving or tying mesh reinforcing to or through the bale wall is probably only necessary in high seismic zones or for straw-bale vaults.

Mechanical Properties

Thermal Insulation (R-Value)

A definitive test using state-of-the-art equipment at Oak Ridge National Laboratories yielded an R-value of 27 for an 18-inch-thick straw-bale wall (and, by inference, a value of 36 for a 24-inch-thick wall). The California Energy Commission currently accepts an R-value of 30 for all plastered straw-bale walls.

Moisture Resistance and Durability

Due to the nature of the material, moisture resistance is by far the most worrisome issue for straw-bale builders and designers. Rot constitutes a degradation of the structural core of the "sandwich panel," and mold is a potential health hazard common to any cellulose-based building material. As previously indicated, all failures to date have been caused by outright liquid moisture intrusion or internal condensation; moisture vapor, if unimpeded and not allowed to condense on cold (e.g., metal) surfaces, will generally move through and out of a straw-bale wall without causing problems.

Experience with other materials, especially wood, in contact with cementitious materials would suggest that cement plaster applied directly to the straw would lead to degradation problems. There have been some problems, typically where an unprotected wall is exposed to heavy, driven rain, but far fewer than might be expected. Decade-old walls have been investigated and exhibited no decay at the stucco/straw interface. It may be that the straw will eventually degrade in the alkaline cement environment, if only in conditions where the plaster "holds" water against the straw, but to date walls in various climates are performing substantially better than would be expected.

It should be noted that the historic, 100-year-old cement-plastered structures in Nebraska are still in good condition, even after some neglect, and that straw in protected conditions such as an Egyptian pyramid has lasted for thousands of years. Straw-bales are more sensitive to moisture intrusion than other materials, but—as with any other building material—durability is primarily a matter of careful and intelligent detailing of the building envelope.

Fire Resistance and Flame Spread

A number of straw-bale structures have passed intact through wildfires that completely incinerated adjacent wood buildings. This is easily explained and understood analogously by anyone who has ever tossed a telephone book into a fire and expected it to burn. Fire requires fuel, flame and oxygen to survive, and straw-bales are simply too dense to provide the necessary oxygen—particularly when coated with a thick layer of plaster.

Two ASTM E119 small-scale fire tests were completed in 1993 by SHB Agra Engineering and Environmental Services Laboratory in Albuquerque, New Mexico: one on an unplastered straw-bale wall panel, and the second on a straw-bale wall that had been gypsum-plastered on the heated side and stuccoed on the outside face. The results of those tests have been interpreted to show equivalency to a 2- or even 3-hour firewall. A subsequent full scale ASTM E119 test conducted at the University of California, Berkeley, Richmond Field Station demonstrated that plastered straw-bale walls constitute at least 1-hour fire-resistive construction. Finally, an ASTM E84 flame spread test conducted in 2000 by Omega Point Laboratories in Elmendorf, Texas, on unplastered two-string straw-bales yielded a flame spread index (FSI) of 10 and a smoke development index (SDI) of 350. The 2000 editions of the *International Building Code®* and *International Residential Code®* require a maximum FSI of 25 and a maximum SDI of 450 for insulation. This means that the bales easily surpass both requirements and are acceptable for use in both commercial and residential construction where flame spread and smoke development ratings are required.

As an emphatic and precautionary note, it must be added that a straw-bale building site presents an extreme fire hazard—most especially during the brief period of bale placement, when the area can quickly become buried in a thick and highly flammable layer of loose straw. This debris should be cleaned up regularly and fire hoses kept at the ready.

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Bearing

In a 1999 test conducted at the University of Colorado, Boulder, three types of 8-foot-high cement-stuccoed straw-bale wall assemblies were loaded to failure in compression and averaged failure loads of 4,328 pounds per foot. A later experiment testing a single 13-foot-high wall was stopped at a load of 3,327 pounds per foot. In both cases, it was concluded that the ability of typical plastered bale walls to carry vertical loads was more than enough for typical one- and two-story applications.

Out-of-Plane Strength

In both laboratory settings and unplanned field tests, many plastered and unplastered straw-bale walls have been subjected to hurricane-level winds without distress. In another test conducted in 1998 by Consolidated Engineering Laboratories, a plastered straw-bale arch was point loaded out-of-plane to mimic seismic loads. The arch retained load-carrying capacity even after the test rams had completely punctured the stucco skins, and abstract author David Mar, S.E., observed that "the structure remained stable as it was loaded well into the plastic deformation range, carrying 1.26g with an average displacement ductility of 12.6."

In a series of subsequent tests conducted in late 2003, various eight-foot by eight-foot walls plastered with earthen and lime-cement plasters, with and without reinforcing mesh, carried loads varying from 94 pounds per square foot (no plaster) to 250 pounds per square foot (reinforced earth plaster) to 343 pounds per square foot (reinforced lime-cement plaster)

In-Plane Strength

Early monotonic tests led to establishing a 360 pound-per-linear-foot allowable in-plane shear load on walls in California, which was found to be roughly one-quarter of test failure loads. Subsequent cyclic tests yielded even better results, showing that a well-detailed straw-bale wall can perform as well as the strongest plywood shear walls listed in the IBC, with allowable loads of over 700 pounds per linear foot.

Summary

In the hundred years since straw-bale building technology was first pioneered, the basic technique has remained 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 15 years, and we are now equipped to design with confidence for any conditions. ◆

***Bruce King, C.E.**, is a registered Civil Engineer with a structural engineering practice in Sausalito, California, and 26 years of experience designing commercial and residential structures. He has done extensive research and work with various alternative materials, and is the author of* Buildings of Earth and Straw: Structural Design for Rammed Earth and Straw-Bale Architecture*, as well as several magazine articles on the subject.*

King is the founder and Director of the Ecological Building Network (EBNet), an educational non-profit organization in San Francisco currently completing testing and research on straw bale construction. Additional resources on straw-bale construction and results of a recent testing program can be found at the EBNet web site, which is located at www.ecobuildnetwork.org.