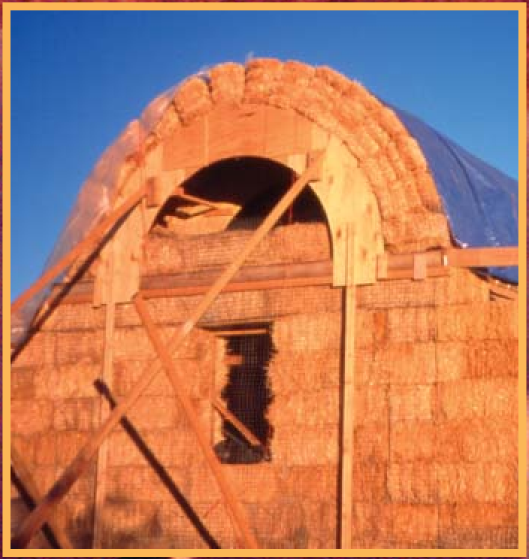
High-Performance Straw-Bale Structures



By David Mar, S.E.

The late avant-garde composer Lou Harrison conceived of a straw-bale structure for his winter studio in the desert environs of Joshua Tree, California. The roughly 1,000 square-foot building, designed and built by the California firm Skillful Means, features a large two-story high main room with a barrel vaulted roof and external buttresses, half of which form the walls of three adjoining rooms. The building, including the vaulted roof, is a load-bearing composite structure made of straw bales, wire mesh and stucco.

Unfortunately, the project got off to a rough start. Since there is little code guidance for the design of straw-bale structures,the project's original engineer took a reasonable and safe course, designing the structure with pneumatically applied reinforced concrete shells, inside and out, using the straw for insulation and no structural function. This design proved too expensive and Skillful Means was forced to look for an alternative structural system.

Around this time I was looking into straw-bale construction, and studying the use of strut-and-tie models for shearwalls adapted from reinforced concrete design, with the goal of using bales as a structural material for seismic designs. Skillful Means heard my presentation of these concepts at a California Straw Building Association (CASBA) conference and asked me to redesign the vaulted roof of the Harrison residence.

Since straw-bale is an unconventional material, most of the material knowledge and craft was acquired by builders and architects who simply built, informally experimented and learned. Consequently, the community accumulated an intuitive understanding of the material rather than a technical one.

Many in the community recognized the potential of the Harrison residence as a vehicle to demonstrate how far straw-bale could be pushed technically. Unfortunately, the San Bernardino County building department was extremely skeptcal and conservative in their treatment of non-standard construction. We invoked the Alternative Design provisions of the 1994 Unified Building Code (UBC 104.2.8-9), which allows a building department to approve a design if provided with testing and analysis proving its suitability.

Testing

We believed that the vault subjected to out-of-plane and gravity loading could be designed using strut-and-tie models adapted from reinforced concrete. Although this model offers a rational means to understand the behavior of a straw-bale vault, we saw the need to destructively test a full-scale segment of the vault to failure under out-of-plane loads to convince the building department of its adequacy. In this strut-and-tie adaptation (See *Figure 1*), the bales replace concrete as diagonal compression struts. The wire mesh reinforcement (2-inch x 2-inch x 14 ga.) on the inside and outside skin of the vault is similar to longitudinal steel in a concrete beam section. Wire ties (a loop of 12 ga. wire at 12 inches on-center) connect the inner and outer layers of mesh, and are anchored with longitudinal rebar dowels between the bale courses. The ties are similar to stirrups in a concrete beam. They also keep the inner mesh from delaminating when it is in tension due to the vault curvature. The inner and outer skins are cement stucco shells approximately 1 ¼-inch thick.

We mocked up a 4-foot wide section of the barrel vault and developed a rig to test it (See *Figure 2*).

Using a hydraulic jack in tension with the pulley configured to simultaneously push and pull the vault on the diagonal, the rig could crudely but conservatively simulate lateral seismic loads while measuring applied forces with a pressure gauge and a load cell to capture friction losses. The segment was loaded and unloaded in only one direction to avoid excessive complexity and expense in the test rig. We also successfully tested the out-of-plane shear anchorage of the base of the vault with jacks and a reaction frame prior to the complete vault test. True to the spirit of the straw-bale movement, the entire testing effort was performed with volunteer labor. Consolidated Engineering Laboratories of Oakland California donated the equipment and time to help run the experiment.

The prototype surpassed the design goals of developing an elastic strength greater than 0.3 g (actual 0.55 g) and ultimate strength greater than 0.9 g (actual 1.15 g). The test was ended, after obtaining peak strengths, when the throw limits of the rig were reached. The final displacements were 11.9 inches of movement diagonally inward, 6.3 inches of movement diagonally outward, and 6.6 inches of translational deformation. There was no measurable shear deformation at the base of the vault. During the test, the diagonal inward loading saddle broke through the outer skin, causing flexural moments to be carried with a couple formed

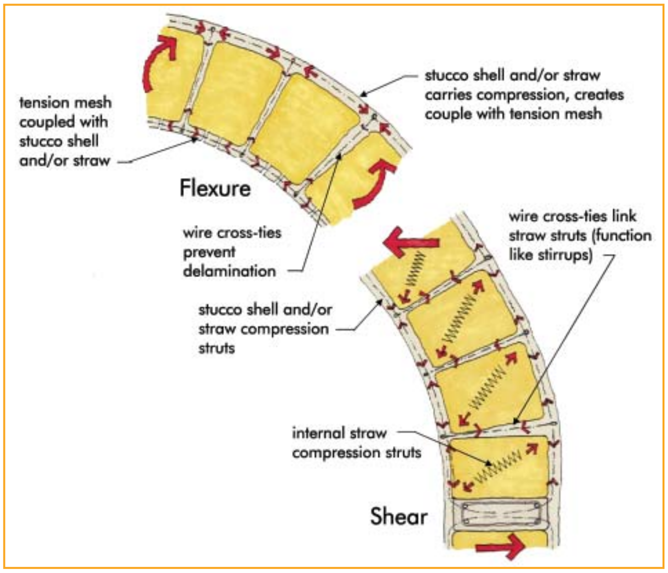


Figure 1

between the mesh in tension and the straw in compression. The moment continued to increase beyond this event as the straw was able to carry reasonably large crushing loads. This event caused the plastic hinge to transition from mesh yielding in tension (under-reinforced) to the straw yielding or crushing in compression (over-reinforced). Unlike reinforced concrete sections, both conditions are stable and ductile. The vault segment proved to be strong and extremely tough with displacement ductility of over 16, based on the ratio of ultimate deflection over the yield deflection.

Redesign

The successful vault test led to the redesign of the entire structure based on the details developed for the vault and the lessons learned. *Figure 3* shows the diagram of the overall structural system. The next challenge was the design of the load bearing walls. A comparison of elastic modulii show straw bales to be much less stiff than stucco skins. Vertical loads are carried mostly in the stiff skins, while the softer bales prevent the skins from buckling through direct adhesion of the stucco to the bales. This load path requires direct skin bearing from the vault to the foundation.

The skins also dominate the behavior of the walls under shear and flexure generated from lateral loads. We find that the most reasonable conceptualization is to consider the walls as thin reinforced concrete panels, with buckling precluded by the bales. This assumption was verified through subsequent testing funded by the California Department of Agriculture and conducted by the Ecological Building Network. Flexural loads are resisted through a moment couple between the panel mesh in tension and the stucco skin in compression. Shear loads are transferred through a strut-and-tie mechanism. The mesh reinforcement (2-inch x 2-inch x 14 ga.) for each skin provides uniform reinforcement in the vertical and horizontal direction. Mesh reinforcement is anchored in the foundation and lap spliced to the panel reinforcement. The transfer of loads between the skin and foundation is a critical construction joint for the transfer of mesh tension loads, skin compression, shear friction and dowel shear. To provide redundancy for the transfer of uplift and shear, the first course of bales is clamped to the foundation with long anchor bolts. It is worth noting that this design, and most current designs, forgo using segments of rebar as dowels driven vertically in the center of the walls to add stability during the stacking.

To prevent brittle crushing under shear and flexure demands, the bearing pressures in the 1 ½-inch thick skins were kept low under gravity loads (35 psi under dead loads and 47 psi under dead plus live loads). The average design shear stress, under code loading, was 232 pounds per lineal foot for the walls. The recent testing of a similarly detailed wall (*see sidebar*) developed 1,250 pounds per lineal foot at yield and 2,000 pounds per lineal foot ultimate strength.

The longitudinal walls under the vault are linked with common continuous footings. Similarly, the buttresses and transverse cross walls are linked with continuous footings. At the time of the design, we had little confidence that we could control the upper bound ultimate strength of the walls and ensure a ductile mechanism. *Figure 4* shows how the vault, walls and continuous footing form a ductile flexural mechanism if the walls become too strong. Foundation hinging allows the overall system to fuse and preclude potential brittle failures such as sliding shear in the wall. The longitudinal walls and footings under the vault can form similar flexural mechanisms.

Recognizing that the building could have significant inelastic demands during a major earthquake, it was critical to tie the structure together and consider the overall mechanisms. Linking the vault and the supporting walls below is a concrete bond beam at the spring point. This member creates an anchorage for the vault and walls, and transfers out-of-plane lateral loads from the vault and walls to exterior buttresses on one side of the vault, and transverse walls on the other side.

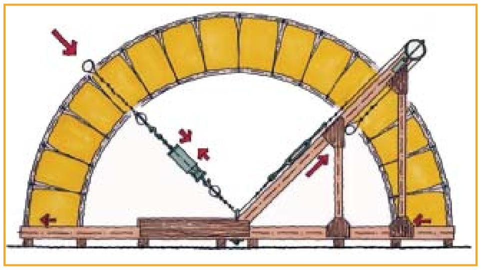


Figure 2

The last technical issue addressed was the out-of-plane design of the walls. Through

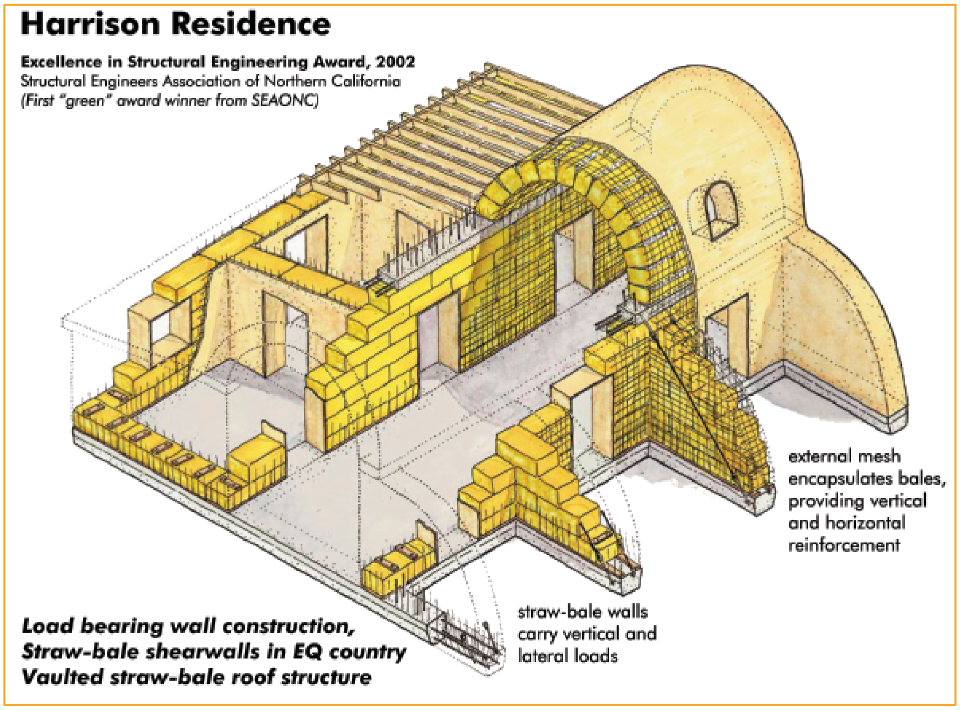


Figure 3

ties linked the inner and outer skins together on a 24- by 24-inch grid. Subsequent testing by the Ecological Building Network found that the out-of-plane capacity of walls without cross ties to be more than adequate for wind and seismic loads.

Obtaining the Permit

We naively assumed that the technical challenges of designing the structure would present the biggest obstacle to getting it built. By the end of the design and testing process we successfully proved the vault structurally sound, while solving the design challenges and keeping the building cost effective.

To our surprise, the design was initially rejected by the building department because of questions arising about the vault. After a long negotiation, the building department agreed to abide by the recommendations of an acceptable third party peer review. Sig Freeman S.E. of Wiss, Janney, Elstner Associates was selected based on his expertise with seismic behavior of structures.

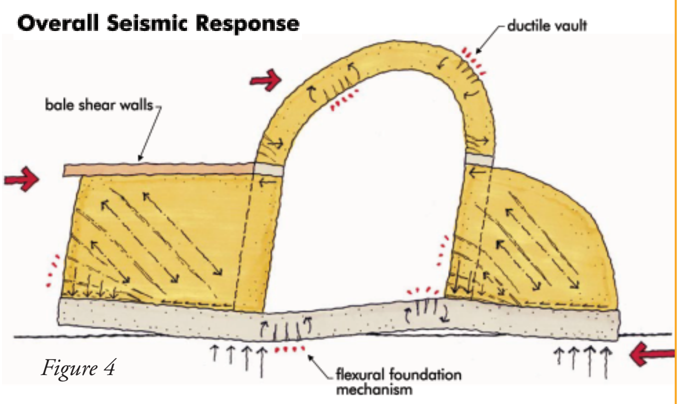


Figure 4

Mr. Freeman found the vault design to more than meet the code demands. He used a Capacity Spectrum Approach with the actual pushover curve from the test to show that the vault had sufficient strength and ductility to resist demands from a seismic event, with a 2% chance of exceedence in 100 years. The permit was soon granted, one year after its initial submission.

The building went together very nicely, despite the somewhat intricate details tying the structure together. The project is a successful demonstration of the structural potential of straw-bale construction and a good example of creativity and technical rigor applied to alternative materials.▪

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Straw-Bale Construction

Builders, architects and owners of straw-bale buildings have formed loose but committed communities promoting the environmental and architectural virtues of the material. The earliest straw-bale buildings were load bearing plastered structures, built in the Sand Hills region of Nebraska in the early 1900's by farmers homesteading in an area with little timber. Twenty-one of these structures are still in existence, with the oldest surviving example constructed in 1903. In the 1970's, straw-bale construction experienced a revival, gaining popularity initially in Arizona and New Mexico. Today, straw-bale construction has spread throughout the U.S. and numerous examples exist in other parts of the world.

The southwest was a natural birthplace for the straw-bale revival. Bale buildings can perform exceptionally well with regards to comfort and energy efficiency in this sunny and dry climate, because they combine good insulation (over R30) with good thermal mass from the inside layer of plaster.

Straw-bale buildings need much of the same care in design to resist environmental forces as wood structures. Like wood, the straw is cellulose. It comes from the stems of cereal grains such as wheat and rice, which are typically considered a waste product after harvest. Rice straw, used for many bale buildings in California, needs an especially long time to decompose. As with wood buildings, moisture and termites are straw-bale's biggest threats. However, good detailing practices can mitigate potential problems. Basic good practices to protect bale walls include generous roof overhangs and lifting the base of walls above grade. The building discussed in this article uses a vapor permeable but rain resistant coating over the vaulted roof. Recent spot testing of the vault bales have shown moisture content to be around 6%. Moisture content below 19% is considered stable against decay in most environments. A plastered bale wall is also very fire resistant. Even un-plastered bale are fairly fire resistant because of the bale's high density, as long as the binding strings remain intact.

Straw buildings differ from most wood structures in that they do not typically use any form of moisture barrier between the bale and the outside plaster. The plaster skins do not seal in the bales from moisture, rather, they allow vapor to flow through the walls as needed. The skins typically are of cement stucco, lime plaster, earth plasters, and often of various blends of cement and earth, and cement and lime. Cement stucco skins are the strongest and least vapor permeable. Earth plaster skins are the weakest, while they have the advantage of being the most vapor permeable.

Most buildings in seismically active California are of post and beam wood construction, with bales forming the outside walls with little structural function. Lateral resistance is typically from light steel tension-only bracing within parts of the wood frame.

Until recently, the development of any type of engineering theory and design properties for straw-bale structures has been generally sporadic and informal. Most knowledge comes through hands-on empirical learning from building and testing, led and shared by builders, architects and engineers within the straw-bale community. The California Straw Building Association (CASBA) is a good resource for anyone wishing to tap into the shared knowledge stream.

www.strawbuilding.org

To date, the most ambitious program to develop the building science and engineering theory of straw-bale construction is being undertaken by the Ecological Building Network, led by Bruce Kink, P.E. The California Department of Agriculture provided a grant of $200,000, with CASBA also contributing funds, to the Ecological Building Network. The testing program studied structural issues, moisture effects, thermal performance and fire resistance. The structural tests were of plaster properties, connections, walls loaded out-of-plane and walls loaded with in-plane shear. The tests covered a range of detailing practices from low-tech to high-performance, with both earth and cement stucco skins. In every case of in-plane and out-of-plane wall testing, the walls assemblies proved to be exceptionally tough and stable. The test reports can be found at **www.ecobuildnetwork.org**.▪