Skillful Means *Architecture and Construction*

Full Scale Straw Bale Vault Test

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Abstract

This test was conducted to evaluate the effectiveness of a straw bale vaulted roof system, proposed for a residential project in a seismically active area of California. The prototype roof vault was a composite structure of straw bales, welded wire mesh and stucco. The design to resist shear loads was based on a truss mechanism borrowed from reinforced concrete design. Similarly, the design to resist flexural loads was based on a bending model from reinforced concrete design. The test consisted of loading a four foot segment of the vault to simulate seismic effects. The structure remained stable as it was loaded well into the plastic deformation range; carrying 94% of its ultimate load (over 1.26 g) with an average displacement ductility of 12.6. Testing was concluded when the stroke of the rig was exhausted.

Introduction

Skillful Means Builders designed a residence of straw bale construction to be built in Joshua Tree, California; a seismically active region located near many active faults (see figure 1). The main feature of the design is a great room with a vaulted roof. A test was developed for a prototype vault to prove that the vaulted roof could be made only of straw bales, welded wire mesh and stucco, and satisfy the building code strength requirements to resist out-of-plane seismic loads (see figure 2). Testing was conducted by Consolidated Engineering Laboratories. A previous design using more traditional and better understood reinforced concrete shells for the roof and wall structure had to be abandoned just before the start of construction because of its tremendous cost. It was at this point that Skillful Means Builders risked more time and money to test an as yet unproven, although economically feasible composite design of straw, mesh and stucco. The vault design was based on simple calculations using mechanisms adapted from reinforced concrete design, with the straw replacing the concrete. The specific goal of the test was first to elastically resist an equivalent out-of-plane lateral load of 30% of the vault's weight. This would satisfy the code strength requirement for portions buildings such as walls (1994 UBC section 1630.2).

$$F_p = Z \times I \times C_p \times W_p = 0.3 \times W_p \text{ ; } Z = 0.40 \text{ for zone 4, } I = 1,\ C_p = 0.75$$

In recognition of the unconventional and pioneering nature of this design, the vault structure should not only be strong enough, but also tough and safe. The vaulted roof had to remain stable and absorb energy under intense earthquake shaking. To this end, it was designed to plastically deform and resist an equivalent lateral load of 100% of its weight (over 3 times code) under ultimate conditions.

Design Mechanisms

Straw bale construction is potentially well suited to resist to severe seismic loads. The bales themselves are light, and bulky, and thus the assemblages tend to be stable. There is also anecdotal evidence that bales can absorb significant amounts of energy through deformation. Tests of unplastered bales and wall assemblies conducted at the University of Arizona hint at the potential of bales to absorb energy. As part of an overall design methodology, straw bale structural systems should have an initial strength and stiffness to resist service level seismic and wind forces without damage. This initial resistance is primarily by the stiff stucco shells. However, under extreme excitations from large earthquakes the stucco shells will most likely crack and degrade. As straw bale structures soften, they need to maintain strength, and absorb seismic energy through plastic deformation. To accomplish this, the structures should have a "ductile core."

As mentioned above, the composite straw design mechanisms hypothesized are adaptations of conventional reinforced concrete mechanisms, with straw substituting for concrete. Like concrete, bales work well in compression. The major difference is in the strengths of the reinforcement relative to the straw and the concrete. In well proportioned concrete structures, the primary reinforcement is weaker than the concrete, and as such, the steel within the assemblage is designed to yield and absorb energy prior to the onset of brittle concrete crushing. The design intent for straw assemblies is that straw should be weaker than the reinforcing mesh. If the steel mesh and stucco surrounds and traps the bales, the deformation and energy absorption can occur within the straw rather than within the reinforcing steel. The tested vault segment incorporates this basic idea and proved that a well-detailed composite straw, mesh and stucco structure can be made strong, ductile and safe.

Shear Mechanism

The out-of-plane shear mechanism of the vault is a truss or strut and tie mechanism, similar to that used to design reinforced concrete beams (see fig. 3). Each bale is contained within a rectangular cell of steel mesh and stucco on the outside and inside of the vault and wire and grout between the courses. Under shear loads, the cells distort to form a parallelogram. As two diagonal corners of the cell come together, the trapped bale is compressed, forming a diagonal strut, just as concrete does. The wire cross ties, acting in tension, link the straw struts, similar to reinforcing steel stirrups in a concrete beam. The curtain of mesh in tension (shown on the outside of the vault in the diagram) acts as longitudinal reinforcing does on the tension face of a concrete beam. The stucco shell and straw in compression (shown on the inside of the vault in the diagram) act as concrete does on the compression face of a concrete beam. The key elements in this detail are the wire cross ties, which must exist to allow the straw compression struts to form. A free body cut through the section shows the shear force to be equal to the tension force in the wire ties. This equals the component of the straw diagonal strut which is perpendicular to the vault surface. During the entire test, there were only small measurable shear distortions at the ends of the vault (see figure 19 and displacement data from stations 1,2,3 and 6,7,8, figures 13 and 14).

Bending Mechanism
The out-of-plane bending mechanism hypothesized for the vault is also adapted from reinforced concrete beam design (see figure 4). The straw bales and the stucco are like concrete in that they can only carry compression loads; they cannot resist tension loads. Tension loads are carried by the wire mesh. Bending loads are resisted by a couple formed with tension in the mesh and compression in the stucco and straw. Changes in tension and compression along the vault length (shear flow) are carried by the shear mechanism described above.

When the load causes tension in the inside layer of mesh there needs to be special anchorage details to prevent the mesh from delaminating. The mesh follows the bale profile; straight along the width of the bales and changing direction or kinking at the joints. When the mesh goes into tension, it tries to straighten at the joint and delaminate. The wire cross ties, used for shear, are also sized to prevent the delamination. The cross ties are wire ties which anchor dowels at the bale joints placed outside and trapping the mesh layers.

The Prototype Vault Design
The vault is semi-circular with an inside diameter of 12 feet and an outside diameter of 16 feet (see figures 5 and 6). In the actual building, the vaulted roof will spring from bond beams 10'-8" above grade. There were 16 bales stacked in the prototype segment, to form a section 4 feet wide and 2 feet thick. In the actual structure the bales will be placed in a running bond. The outer and inner layer wire mesh is a 2 inch by 2 inch by 14 gage welded wire fabric. An additional layer of 18 ga. chicken wire mesh was placed inside the vault to facilitate the overhead placement of stucco. Cross ties consisting of four 12 gage wire ties (12 inches on center) were placed between the bales. These ties were doubled back around #4 reinforcing dowels which trapped the inside layer of mesh, and twisted around #4 dowels which trapped the outside layer of mesh. See figures 7 and 8 for reinforcement details. The wedge-shaped space between the bales was grouted with mortar. Two of the normal three coats of cement stucco were placed on the vault; a 1 inch thick scratch coat and a 1/4 inch thick brown coat. The plasterer was specifically instructed to do a poorer than average job, so that the test results would not depend on good craftsmanship. The structural layers of mesh were anchored around the test rig. An additional mesh stirrup was added around the first bale on each side of the vault. This mesh stirrup or shear cleat was designed to catch the leading corner of the first bales and prevent them form sliding off of the test rig, or the bond beam in the case of the actual structure. Four ½ inch diameter all-threaded rods with two 2x4 wood clamps also anchor the first bales to the rig or bond beam. These test details were incorporated into the actual building design.

The design weight of the 4 foot wide vault segment was 5,980 pounds. The seismic loads were based on this weight. Of this, the straw weighed 1,440 pounds, the stucco shells weighed 2,288 pounds and the grout wedges weighed 2,252 pounds. This is 66 pounds per square foot of arch, based on the centerline length.

The Test Rig
The test rig, shown in figure 9, was designed to simultaneously pull in and push out the arch to simulate extreme seismic or wind lateral loading. The loading pattern is closest to forces created by wind pressure and suction, and more severe and destabilizing than the lateral inertial loads from an earthquake. The inward and outward acting load vectors intersect at the center of the base of the vault. They generally canceled out their vertical force components and created a net horizontal shear force.

The rig had two 6x6 wood rails, 4'-6" apart, with connecting cross pieces of 6x6 topped with plywood under the ends of the vault. Matching diagonal 6x6 wood masts were anchored at the center of the base of the vault. They went around the vault and supported a steel pipe at their top. Rigging, consisted of wire rope, shackles, turnbuckles, all-thread rods and a calibrated hydraulic jack, connected a pair of stiff pipes which loaded the vault. The jack used was a hydraulic ram made by Enerpac, model RCP-55 (see figures 19 and 20). The rigging pulled one pipe, located outside the vault, in towards the center of the base. The wire rope went through central eye bolts and around the pipe at the top of the masts, to the second pipe located inside the vault. When the jack was loaded it contracted, to simultaneously pull in and pull out the vault. Under the loading pipes, wood saddles in contact with the vault were used to spread out the loads (see figures 19 and 20). Slack and shortening in the rigging due to the plastic deformations in the vault were taken up by the turnbuckles.

Inward acting loads were directly read from the gage of the calibrated hydraulic jack. The outward acting loads were measured from the gage readings of a tension load cell made by Enerpac, model TM-5, linked in series just beyond the point of loading (see figure 19). The tension load cell is a device which can measure tension in the rigging. It was placed just beyond the point of loading so that its readings were of the actual force delivered to the vault. The differences between the hydraulic jack loads and the tension load cell readings are the friction losses in the system.

The deflections of the vault were measured via scales at 10 stations (see figure 9). The scales were connected to the fixed rig and the relative movement was the deflection in the vault. The trailing end of the vault was behind the direction of the net shear load, while the leading end was in front. Stations 1, 2 and 3 allowed measurements of translation and rotation at the trailing end of the vault, and stations 6, 7 and 9 allowed measurements of corresponding values at the leading end of the vault. Station 5 allowed measurements of the diagonal displacement inwards to the center of the vault. Station 10 allowed measurements of the diagonal displacement outwards from the center of the vault. Station 9 allowed measurements of the horizontal translation at the top of the vault. Station 4 was not used.

The Test Results
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(CEL) conducted the tests. The hydraulic jack and the tension load cell were calibrated in accordance to ASTM standards prior to testing (see calibration curves, figures 10, 11 and 12). The jack loaded the vault in 1,000 lb. increments. After each load and measurement, the load was released to record the elastic recovery and the permanent plastic deformations. After several uneventful cycles, the vault's elastic limit was reached when the first signs of stucco cracking were heard at 3,000 lbs. The vault bounced back elastically with no plastic distortion when the load was released. The vault's elastic limit was equivalent to a lateral load of 50% of its weight. This value satisfies the code minimum seismic resistance of 30% of the vault's weight for out-of-plane loading and far exceeds any code wind requirements. The vault was loaded for seven more cycles, well into its plastic and energy-absorbing range, until the throw limitations of the test rig were reached. The vault could not be collapsed by the test, even at the extreme distortions of 11.9 inches diagonally in at a point load (station 5), 6.6 inches laterally at the apex (station 9), and 6.3 inches diagonally out at the other point load (station 10). The maximum loads were reached at cycle 6 with a jack load of 6,700 pounds. This corresponds to an equivalent lateral load of 126% of the vault's weight (1.26g). This exceeded the targeted minimum ultimate lateral load strength of 100% of the vault's weight and provides a safety factor of 4.2 for minimum code requirements. As a measure of the vault's toughness, it achieved an average displacement ductility of 12.6 (ductility is the ratio of ultimate displacement over yield displacement). This is a good result, even for structures of conventional materials such as steel, reinforced concrete and plywood. The complete test results are in figures 13 and 14. The load deformation curves for stations 5, 9 and 10 are printed in figures 15, 16 and 17, respectively. Photos of the vault test are shown in figures 18 through 23).

The test revealed the ductility and toughness of composite bale systems. At an early cycle during the test, the exterior stucco shell, under the concentrated load pulling diagonally inward, completely collapsed at one edge of the saddle (see figures 20, 22 and 23) . The stucco shell was distorted to the point where it could not resist compression loads. From this point onward in the test, the bending couple on this side of the vault was solely between the straw and the tension mesh. Figure 21 shows stucco cracking at the tension mesh. The structure continued to carry increasing loads. This begs the question: can other weaker skins be effective in a composite straw-bale system?

Conclusion

The test successfully proved that the prototype vault could meet, not just the strength requirements of the building code, but also satisfy the spirit of code in regards to toughness, energy absorption, stability and safety. It also successfully demonstrated that one could predict behavior and achieve good structural performance using composite straw-bale, stucco and wire mesh construction designed using simple engineering principals and mechanisms that include the straw as a key component.

References

Bou-Ali, Ghailene, "Straw Bales and Straw Bale Wall Systems," summary of results from a Master's Thesis at the University of Arizona.

International Conference of Building Officials, Whittier, California*, 1994 Uniform Building Code*.

International Conference of Building Officials, Whittier, California, *Maps of Known Active Fault Near-Source Zones in California and Adjacent Portions of Nevada*.

King, Bruce, P.E., *Buildings of Earth and Straw*, Sausalito California, Ecological Design Press, 1996.

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