Spar and Membrane© Structure

– R. Gary Black and Henri Mannik; Berkeley, CA

Introduction

The structural solutions which are typically employed for straw-bale construction — load bearing bale walls and wood post and beam with bale infill — are limited in several respects: (i) it is difficult to establish compliance with standard building codes; (ii) load bearing bale walls are severely restricted in terms of the heights of walls, number of stories, and maximum span of rooms framing into the bale walls; (iii) post and beam systems often use as much or more wood than conventionally framed buildings; (iv) the in-plane and out-of-plane structural behavior under seismic forces is difficult to predict and poorly understood. This paper presents a straw-bale structural system which solves the above problems. A full scale construction mock-up is described, and the results of computer-aided finite element analyses and experimental structural tests conducted at the University of California, Berkeley are presented.

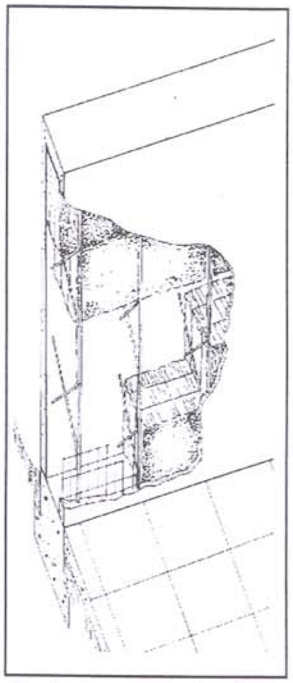

Fig 1: Axonometric of spar and membrane straw bale wall system.

Overview

The "Spar and Membrane System," is so-called because the key structural elements are the "spars" which penetrate the straw bales and connect the concrete "membranes" that form the inner and outer wall surfaces. The basic structure consists of straw bales stacked in a running bond, with a 1 inch gap left between the heads of each bale. Pre-fabricated spars[1] which run from one side of the wall to the other are placed in these gaps and are attached to vertical rebars which lie in the inner and outer wall planes. A two inch coat of gunite is shot to create the two membranes (Figure 1).

Structurally, the membranes carry the vertical (dead and live loads) and horizontal (seismic and wind forces) by in-plane membrane action. The spars tie the inner and outer membranes together — forcing them to work in concert — to create an efficient concrete honeycomb structure. The spars (a) work in tension to keep the membranes from separating, (b) brace the membranes at regular intervals, to reduce the slenderness ratio and thus prevent local buckling of the membranes, and (c) provide the horizontal shear resistance to stabilize the wall in the out-of-plane bending direction. The system makes use of the straw bales to help create the stiff structural honeycomb eliminating the need for additional wood framing members or other extraneous structure.

Structurally speaking, a traditional wall made of either wood frame, concrete block, reinforced concrete or steel offers little or no out-of-plane stiffness. Engineering assumptions about the flow of forces through diaphragms and shear walls follow from the assumption of zero stiffness in the out-of-plane direction. Introducing the spar and membrane wall with substantial out-of-plane stiffness could have either a beneficial or a deleterious impact on the overall building's performance depending on detailing. If not accounted for, a stiff wall could redirect seismic forces causing a rupture in the floor or roof diaphragms. Correctly detailed, however, this same wall could serve as part of a redundant system, to provide reserve capacity in the event of catastrophic damage from an earthquake or hurricane. This stiffness arises from the wall's geometry and method of construction and our concern about its influence on the overall building behavior led to this research.

Construction

Construction of the Spar and Membrane system is straightforward. Once the bales have been stacked in a running bond with a gap at each head, the spars are placed in the gaps. Next, vertical rebars are attached to the spars. Once the spars and vertical steel have been rigidly attached to each other and to the straw-bale wall, welded wire fabric is tied to the vertical steel. Light gauge fabric is used for non-structural walls to reduce temperature cracking, while structural walls are fitted with heavy gage mesh to provide a shear resistance of 8000 pounds per linear foot.[2] The high shear resistance makes it possible to greatly reduce the length of required shear wall, thus allowing for large expanses of glass or other openings. The extreme shear capacity also permits construction of multiple stories which add substantial additional loads. As a final step gunite is shot against the bales (Figure 2).

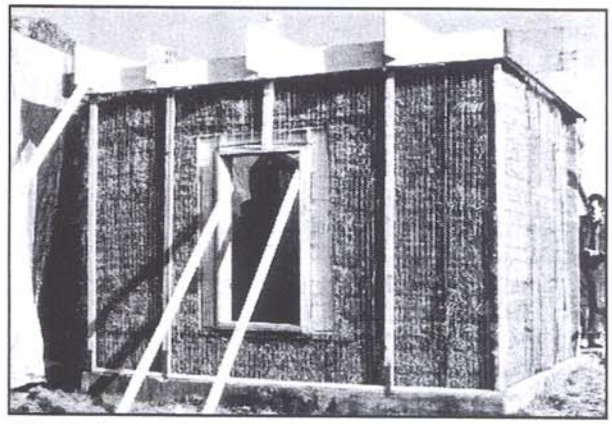

Fig 2: Straw bale wall with mesh, rebar and spar steel ready for gunite.

Code Compliance

The spar and membrane wall system satisfies the structural and fire requirements of the 1995 Uniform Building Code.

Computer Model

A three dimensional Finite Element (FEA) computer model[3] consisting of shell and frame elements was assembled for the standard wall section (Figure 3). For three and four story structures such as residential, office buildings, or shopping malls the computer analysis indicates that internal stresses and displacements would remain within code specified values. The analysis indicated stress concentrations at the interface between the spars and membranes and at the joint between the bond beam and the membrane.

Experimental tests

Two half scale wall sections were tested

Feature: Hybrid Materials and Buildings

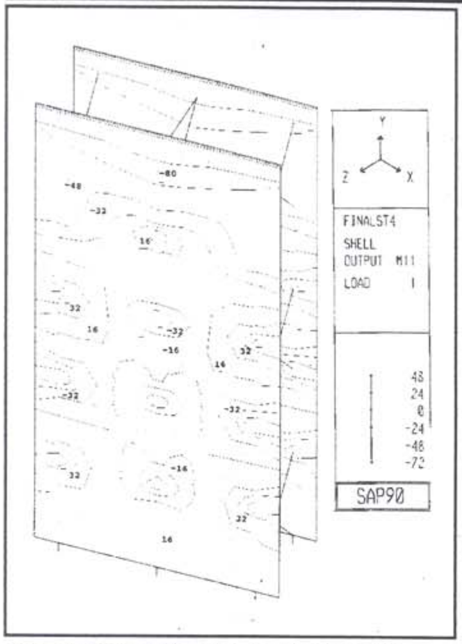

Fig 3: Finite Element Analysis model.

in the out-of-plane direction. The specimens modeled a typical section one bale long, but without actual straw, as the straw would conceal important events occurring within the specimens during testing. However, the tests showed that the presence of the straw bales would improve the performance of the walls, and subsequent tests should include the material.

Nineteen different load cycles were conducted with eleven in the elastic zone and eight in the inelastic zone. Four of the tests in the elastic Zone were loaded with a 1000 pound vertical load to simulate roof and floor loads and enable documentation of P-delta effects. Two inelastic tests were conducted at large drifts — exceeding code maximums by a factor of three.

The wall exhibited good overall performance, remaining virtually crack free at code specified load levels and exhibiting ductility ratios in excess of 45. As predicted in the FEA, initial cracking occurred at the junction between the membrane and the bond beam at a drift of 1.3% (1.6 inches top deflection for a full height wall). The specimen lost about 17% of its highest capacity but remained stable to a drift of three times the maximum code values of 4% (Figure 4). From the computer analysis we had expected the spars to punch through the concrete membrane initiating failure of the specimen; however, the spars buckled inelastically, relieving the punch-through stress on the membrane (Figure 5).

Conclusions

The Spar and Membrane wall system described is capable of providing the required structural capacity for a variety of multi-story building types even in areas of high wind or seismic activity. The following conclusions apply: (i) slenderness effects can be ignored for any wall less than 26 feet in unsupported height; (ii) the vertical load resisting strength is equal to about 25 tons per linear foot of wall; (iii) in-plane shear capacity is greater than 8000 pounds per linear foot of wall; (iv) out-of-plane bending resistance is greater than that required to satisfy hurricane level wind forces and zone four seismic forces perpendicular to the wall surface.

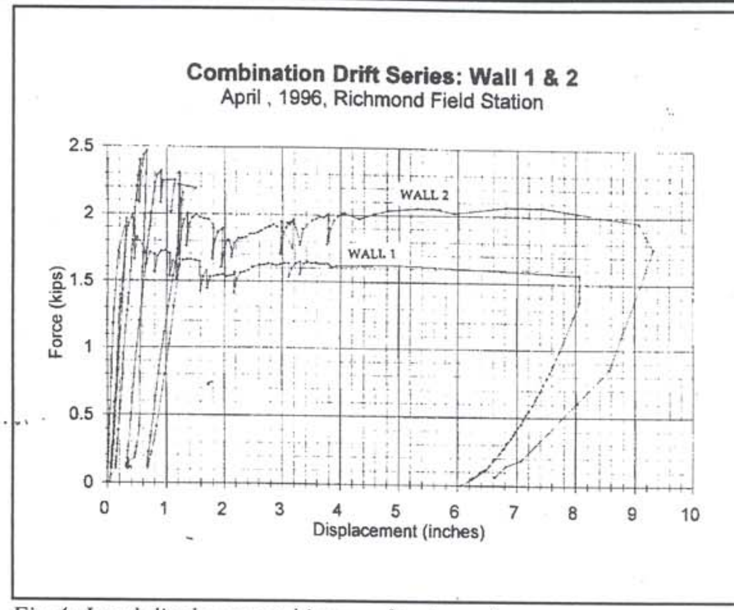

Fig 4: Load displacement history of test specimens.

Key areas of concern with this system are: (i) detailing of the straw bales, steel reinforcing, and gunite at corners and wall intersections; (ii) detailing at the junction with the foundation for shear and overturning forces; (iii) detailing at the junction between the bond beam and the membranes to insure ductile behavior of the plastic hinge, (iv) design of the spars and detailing of the connection between the spars and the membranes; (v) impact of the large out-of-plane wall stiffness on the diaphragms.

Fig 5: Loaded test specimen.

Acknowledgements

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[1]*We have designed buildings using spars made of welded wire fabric covered with gunite, epoxy coated steel X's, and high strength autoclave glass fiber reinforced panels.*

[2]*By way of comparison consider that a heavily reinforced plywood shear wall provides less than 1000 pounds of shear resistance per linear foot.*

[3]*SAP90™ by Edward L. Wilson and Ashraf Habibullah.*

Note: The "spar and membrane ©" system is proprietary and was developed by: Gary Black, James Maguire and Jerry Miller.

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