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STRAWBALE CONSTRUCTION: AN APPROPRIATE TECHNOLOGY FOR DEVELOPING COUNTRIES WITH HIGH SEISMIC RISK

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ABSTRACT

Strawbale construction uses straw, compressed and tied into bales, as stackable blocks for wall systems. The bale walls are covered with plaster that can be made from local sand mixed with local clay, or lime, or cement. This is a construction technology that is relatively easy to use. Straw is very light and can be baled with local balers, and plastering is a skill commonly found in developing countries. Straw is a by-product of grain production, so it is found throughout the world where grains are grown. It also has very good insulation properties. The combination of inexpensive, local, resource and energy efficient materials with simple building skills makes this an appropriate and sustainable technology in developing regions.

A rediscovered and redeveloped technology, modern strawbale construction has been practiced for only the last twenty years, yet is already found in over 45 countries across the globe. However, it has not yet been widely investigated or sufficiently promoted as a seismically resistant technology. Recent tests, culminating with a full scale model house tested on the NEES shake table at the University of Nevada, Reno, demonstrated excellent performance of a system that uses nylon fishing net and bamboo for reinforcement, and is being used in a number of pilot buildings in Pakistan.

EERI and IAEE's World Housing Encyclopedia is creating a tutorial on strawbale building that emphasizes its appropriateness for developing countries with high seismic risk. The tutorial examines strawbale construction's background, where it has been and could be used, design and construction guidelines, and lab testing. This paper provides an overview of the tutorial and the Pakistan projects.

1. Introduction

Choosing a Building Material or System, and Technology Transfer

A range of natural building materials and methods are available, and much research and experimentation has taken place in recent years. "Natural" building materials are ideal for developing regions because they can usually be sourced locally and require minimal processing. Many natural building materials are part of traditional methods that are still practiced, or that in some cases have been supplanted by the use of industrialized materials. Recent research has

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created a “hybrid vigor” by examining vernacular methods of construction, and combining them with state-of-the-art understanding and methods to greatly improve their performance, or to offer related and promising alternatives.

In choosing the best materials and methods of construction, the available options should be considered for the following: (1) Affordability; (2) Cultural traditions and expectations of architectural appearance and function; (3) Local material availability - with a focus on sustainability; (4) Local technology, education, and skills; (5) Buildings in seasonal hot or cold climates should be built of materials that are good insulators. Buildings in seasonal or year-round hot climates should have sufficient mass to moderate diurnal temperature swings; (6) In regions of high seismicity it is important to use materials or systems that are light, strong (especially in tension), ductile, and durable. Strawbale construction satisfies most or all of these considerations very well, especially in developing countries.

Introducing strawbale construction to populations unfamiliar with it involves a process called “technology transfer”. This process takes the dedication of many individuals and groups over long timeframes, and should include training, community gatherings, government support, experimentation, and collaboration between outside “experts” and local “trainees”. During this process, it is important to remember that the experts can learn equally from the trainees and other local inhabitants.

Introduction to Strawbale Construction

Strawbale construction uses baled straw as building blocks, usually for exterior walls, and typically finished with plaster inside and out. The stacked bales are sometimes stiffened with “pinning”, and the plaster is often reinforced with mesh. Foundation, floor, and roof systems are chosen from those commonly available, as well as various alternatives. Some of these systems, for example lightweight roofs, are more compatible with straw bale walls than others.

Strawbale buildings fit into two categories based on the gravity load carrying system: **loadbearing**, where the strawbale walls carry the weight of the roof above or **non-loadbearing**, where a structural frame carries gravity roof loads, and straw bales are infilled for insulation, enclosure, and as a surface to receive plaster. Both loadbearing and non-loadbearing buildings can use the plastered strawbale walls to resist lateral loads if designed and constructed properly. There are countless variations of strawbale wall systems utilized to date, but the basic methods described are now practiced in over 45 countries and in every climate throughout the world.

Advantages of Strawbale Construction

General advantages: (1) Strawbale construction is relatively simple. Most of the skills necessary can be learned quickly or utilize traditional skills, such as clay plastering. The entire community can participate in many aspects of the construction; (2) Construction is similar to masonry methods, and can produce buildings that fit vernacular or culturally appropriate forms; (3) Straw is an agricultural waste product and is generally locally available and less costly than other building materials. It is annually renewable, and reduces the use of non-renewable and energy intensive materials (e.g., cement, steel); (4) Plastered straw bale walls provide an excellent balance of mass and insulation. Strawbale buildings reduce the amount of coal or wood burned for heat. In addition to saving resources and cost, burning less fuel improves indoor and outdoor air quality, thus improving human health.

Advantages as a seismic-resistant system: (1) The seismic forces acting on a structure are proportional to the building's mass. Straw bale construction is lightweight, and greatly reduces those forces in comparison to brick, adobe, or concrete, which are commonly used in the developing world; (2) The large width of a strawbale wall allows the bearing reaction to stay within its footprint, reducing internal bending stresses; (3) Strawbale wall systems can deform considerably without losing capacity; (4) The straw bale core provides a backup earthquake-resisting loadpath under extreme shaking if the primary system (the reinforced plaster) fails.

Concerns and Limitations

Strawbale construction is suitable for many different regions, climates, and cultures, but there are limitations that should be considered: (1) **Moisture and Durability**: Unlike non-organic traditional materials such as stone and adobe, strawbale is susceptible to rot like other cellulose-based materials such as wood or bamboo. However, careful design, construction, and maintenance can create a very durable building. Some of the seminal strawbale buildings in Nebraska are over 100 years old. However, strawbale building may not be the most suitable system in regions of high rainfall and humidity, such as tropical climates; (2**) Fire**: Strawbale buildings are very resistant to fire when plastered. However, during construction, when the bales are exposed, and a wood-framed roof is in place, and especially if loose straw is present, the building is susceptible to fire. Site maintenance, and fire preparedness should be employed during construction to minimize this risk; (3) **Material limitations**: Clay plastered strawbale walls are not capable of carrying large gravity loads, therefore are best used for one-story buildings, unless combined with a post and beam structure; (4) **Building Footprint**: Walls are thick, so there may be concern where building sites are congested, although as a benefit, strawbale walls provide excellent acoustic insulation in congested urban environments.

Overview of Implementation and Testing

Several successful strawbale building projects in seismically active developing countries have been completed or are under way. The largest relevant projects to date occurred between 1995 and 2004 in Mongolia, and have been ongoing since 1998 in villages in northern China. Over 700 strawbale houses and three strawbale schools in six Chinese provinces, as well as over 100 residences, schools and health clinics throughout rural Mongolia have been built.

< Fig.1. Load-bearing house. Mongolia

Fig.2. > Reinf. brick & conc. frame w/ strawbale infill China (2000)

The projects were initiated and supported by Adventist Development and Relief Agency (ADRA) in cooperation with the Chinese and Mongolian governments, under the direction of American architect Kelly Lerner. The Chinese buildings generally consist of a reinforced masonry or concrete post and beam frame with strawbale infill shear panels, whereas most of the Mongolian buildings are wood post and beam with strawbale infill. Careful consideration was given to the seismic design of these buildings, with help from structural engineer David Mar of Tipping Mar and Associates in Berkeley, California. In a new chapter, ADRA is building model strawbale homes in the Sichuan province in response to the devastating 7.9 magnitude earthquake that struck the region in 2008 (Torres 2009).

Section 4 of this paper focuses on the work of Pakistan Straw Bale and Appropriate Building (PAKSBAB) which has been ongoing since 2006.

Testing

Since 1993, over 50 structural testing programs have been conducted on straw bale wall components and assemblies by universities and private foundations around the world. They include tests of individual bales, unplastered walls, mesh and plaster, as well as tests of wall specimens for gravity loads and in-plane and out-of-plane loads. These are summarized in the book Design of Straw Bale Buildings (King, et al, 2006) and on the website www.ecobuildnetwork.org. Testing of the PAKSBAB system is covered in Section 4.

2. Materials

Straw is the tubular plant structure between the roots and the grain head of cereal grains such as wheat, rice, barley, oat, and rye. Cereal grains are grown throughout the world as a food source, and the leftover straw is used as low-grade feed for livestock, burned, or ploughed under. So straw for use as a building material is often plentiful, inexpensive, and locally available.

Straw bales are blocks of compacted straw, tied with twine or wire. They may vary in their dimensions, depending on the baling machine. In many developing countries baling machines do not exist, even where straw is plentiful. In these locations, compression moulds can be fabricated to allow manual production of straw bales. Bales should be of uniform size, about twice as long as they are wide. They should use long straw fibers and be sufficiently compacted (6-8 lbs/cu.ft.). The straw should be dry from the time it is cut in the field to the time it is plastered in a straw bale wall. Degradation will not occur at less than 20% moisture content.

Plaster is applied directly to the surface of the bale walls, with mesh or other reinforcement as required by structural design. Plaster protects the bales from moisture, fire, rodents, and mechanical damage, and provides the aesthetic finish of the walls. Plasters vary greatly in strength, stiffness, and moisture properties, and should be carefully considered (and tested) in terms of performance and interaction as part of the wall system.

All plaster mixes are composed of a binder, sand, and water. The binder (clay, lime, or cement) holds the mix together, the sand provides compressive strength, and the water aids in mixing and curing. Fibers (straw, hemp, hair) are sometimes added to provide tensile strength and aid in crack prevention.

Clay plasters have gained favor for strawbale buildings throughout the world, and are especially appropriate in developing regions. Clay is the least expensive and most widely available binding material. Clay plasters are historically common and have low environmental impact. Clay plasters exhibit greater flexibility than other plaster types, which is especially important for buildings under seismic force. Although of lower compressive strength than cement or lime plasters, they are sufficiently strong in high seismic areas when properly reinforced and designed. Also, clay is able to store large amounts of moisture if necessary, without transferring it to the bales. Clay plasters are good for builders new to plastering. They can be applied directly by hand and set slowly, allowing for adjustment during plastering. They can also be easily repaired during the life of the building. Clay plasters can have limited durability on exteriors of buildings, so they are often made with high straw content to resist weathering and/or are protected with a finish coat of lime plaster or a lime wash.

Fig.3. Clay plaster, Pakistan
(photo M.Hammer)

Wall and Plaster Reinforcement

Internal or external "pinning" is sometimes employed to stiffen walls during construction or to resist out-of-plane loads, especially for walls with a large height to width ratio. Steel, wood, and bamboo pins have been used, either driven down through the courses of bales, or, more easily and effectively as opposing external pins that are through-tied.

Mesh is often used to reinforce plaster skins, providing tensile strength in the skins and assisting load transfer from the plaster to the foundation and top plates. Mesh can be made of galvanized steel, plastic, or organic fibers. High strength mesh is crucial in areas of high seismicity, but weaker plastic or natural fiber mesh may be used in areas of lower seismicity.

In clay plasters, there is evidence that steel mesh should be avoided for its tendency to corrode. Plastic mesh is commonly used in earth plasters, and nylon fishing net is a stronger alternative tested and used in Pakistan. Hemp, jute, and coconut are examples of plant fibers used for mesh in earth plasters, but they can decay if wet for prolonged periods.

3. **Seismic Behavior of Strawbale Wall Systems**

Types of Strawbale Wall Systems

A plastered strawbale wall is a composite structural panel similar to a stress-skin panel. The reinforced plaster skins are themselves a composite material composed of plaster and reinforcing mesh or fiber. They act as thin panels that can resist compression, shear, and tension forces. The tension capacity of plaster is very low, so the tension forces in the skin are fully resisted by the reinforcing mesh or fibrous material. The structural function of the plaster skins is to resist lateral (wind and earthquake) loads on the wall. In gravity load bearing systems, since plaster skins are stiffer than the bales, they also carry the gravity loads. The structural function of the bales is to prevent the loaded plaster skins from buckling in compression or shear. The plaster, when properly applied, bonds securely to the straw bales, which provide out-of-plane support.

Strawbale wall systems can be classified as follows: **(A) Structural Systems**: In structural systems, the strawbale walls provide the building's primary resistance to lateral loads, and may also carry gravity loads. In other cases, such as post and beam construction with strawbale infill, a different system carries the gravity load, **(B) Non-structural Systems**: In non-structural systems, the perimeter strawbale walls function primarily as insulation and enclosure. Other elements in the building (such as braced post and beam, or reinforced concrete or masonry frames) carry both the gravity and lateral loads. However, the strawbale walls still carry their own weight for both gravity and lateral loads, and may be detailed for seismic energy absorption, and must remain protected from moisture. The advantages of Non-Structural Systems are: (1) Can allow for larger loads, taller buildings; (2) Often met with less resistance and skepticism culturally or by government authorities; and (3) The roof can be constructed before installation of bales and plaster, providing significant protection from rain until the wall system is weather-tight. The disadvantage of Non-Structural Systems is that they may be less energy and resource efficient than structural systems.

Lateral Loads in Walls

In-plane Loading

The goal of in-plane lateral design is for the load resisting elements (shear walls) to exhibit ductile, inelastic behavior in a large earthquake. This means a portion of the wall will permanently yield (deform) without breaking, and the building can deform significantly while still carrying the gravity loads and the lateral loads from continued shaking (King, et al 2006). Buildings must be allowed to permanently deform (be damaged) because yielding is the best way to absorb earthquake energy. An hypothesized advantage of plastered strawbale shear walls is that they may have a damping effect even during elastic behavior. That is, significant energy may be absorbed due to friction between the bales and between strands of straw within the bales, and can occur without substantial damage to the wall, especially when clay plaster is used, with its high flexibility (low modulus of elasticity) compared to stiffer lime or cement plasters.

The wall system behavior during earthquake loading (as observed in testing) includes a combination of horizontal shear failure of the plaster at the top plate or bottom plate, and horizontal tension cracks and crushing at the wall boundaries due to overturning (flexural response). Less common is diagonal shear cracking of the plaster skins, although such behavior may be preferable to connection failure, but would require that connection design be improved. In general, wall aspect ratios (height/length) should be kept low, to reduce flexural effects.

Continued shaking causes additional inelastic, partially ductile behavior that continues to degrade the plaster skins, with yielding of the mesh (usually designed to be avoided when non-ductile mesh is used), and/or localized crushing of the plaster (in earth plaster walls, the compressive strength of the plaster is low, and the plaster can be designed to crush before the mesh yields). Plaster crushing does not define failure (see Seismic Performance Goals below), as the wall is generally still able to sustain additional lateral loading.

Finally, under extensive ductile loading, the plaster skins degrade completely, and the straw bale core is forced to resist the earthquake forces (and support the gravity forces if loadbearing). It does so by developing diagonal compression struts (forces) in the bales themselves (Figure. 4). This flexible, ductile core is capable of withstanding large drifts.

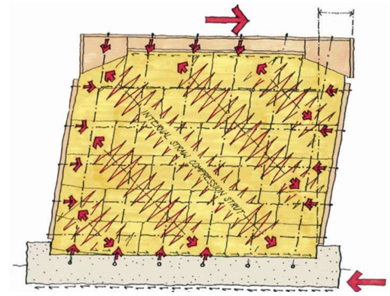

Fig.4. Diagonal compression struts
(Illustration - D. Mar)

Out-of-plane Loading

In strawbale buildings, out-of-plane load on the walls is resisted in the compression face by the plaster and in the tension face by the plaster reinforcing. The composite nature of the strawbale wall assembly allows the bales themselves to serve as the web. Additional out-of-plane resistance is often added to straw bale walls by pinning (see pg. 5), though out-of-plane failure has usually not been a concern in straw bale structures (King, et al 2006). As walls become more slender (taller walls and/or thinner bales) out-of-plane response would become a greater concern.

Seismic Performance Goals

When designing for developing countries where resources can be scarce or prohibitively expensive, seismic performance goals are often lower than in the US or other industrialized nations. Still, the performance goal must at least be to prevent full or partial collapse of the building for the typical Design Earthquake (usually the earthquake design force in the building code) and to minimize loss of life in the maximum credible earthquake (often about 50% higher than the building code). By comparison, the performance goals of the current International Building Code (IBC) are intended to control damage for the Design Earthquake.

One advantage of simple, load-bearing, single-story strawbale construction (as often practiced in poor rural areas and as exemplified by the PAKSBAB system) is that loss of life can be prevented *even with* partial building collapse**.** The relatively light, plastered bale walls, when combined with a light-framed roof (in a single story building) are unlikely to cause death (when compared to traditional systems that use brick, stone, or adobe walls). This is especially critical in developing regions where quality control of materials and construction can be challenging.

4. Pakistan Straw Bale and Appropriate Building (PAKSBAB)

A strawbale building system developed in Pakistan in response to the devastating 2005 Kashmir earthquake has been well tested and documented, and was the first to undergo full scale shake table testing, in 2009 at the University of Nevada. It has been used to construct small, loadbearing, affordable homes in northern Pakistan. The construction system is carefully tailored to regional conditions, has been embraced by the local cultures, and has been reviewed by

Pakistan’s Earthquake Reconstruction and Rehabilitation Authority (ERRA).

California engineer Darcey Donovan founded PAKSBAB (www.paksbab.org) in 2006 and has since devoted herself full-time to its mission. Through collaboration with colleagues, and local builders and authorities, a system was developed using locally sourced materials, and indigenous tools and skills. The typical home is 24’ x 24’ with 2 rooms and a veranda, and costs about $2800 USD. (The ERRA approved concrete block home costs about $6000 USD.) Seventeen homes have been built to date (Figs. 4 and 5). (Donovan 2008)

Figures 4 and 5. A PAKSBAB house under construction, and completed (2009). (photos D.Donovan)

Figure 6 (next page) shows the wall system. The foundation consists of a perimeter trench footing of gravel filled geotextile bags stacked to 8” or more above grade. The bales have a dimension of 12”x12”x24”. Since no baling machines are used agriculturally, steel compression molds have been fabricated by local welders, and fitted with farm jacks imported from China (Figure 6). One worker operating this baler can make 15 bales a day. A two-room plus veranda PAKSBAB home requires about 300 bales.

Additional homes are being built and the program is set to expand through partnerships with charitable development groups. So far occupants of these homes have expressed satisfaction: they are comfortable, they use less fuel for heating, and thus the air is cleaner, and the communities have expressed interest in expanding the program.

Figures 6, 7, 8. (L to R) Bale fabrication; Monotonic wall test; Shake table assembly. (photos M.Hammer)

In 2008 and 2009 Darcey Donovan directed testing of the PAKSBAB system at the NEES facility at the University of Nevada, Reno. It included small component tests, and in-plane monotonic tests (Fig. 7) of wall specimens with light, medium, and heavy reinforcement detailing. Best performance was realized with heavy detailing, with heavier gauge nylon fishing net as well as additional layers of fishing net to reinforce the horizontal boundary plane between the bottom of the straw bales and the top of the gravel bags. Nonetheless, the failure mode of these walls was still horizontal shear failure at that bottom of wall boundary plane, as well as crushing failure of the plaster at wall ends due to overturning (flexural behavior). Full scale shake table testing of a model house followed (Fig. 8). (Heavy detailing was used in the shake table test, as shown in the wall section drawing (Fig. 9)). It demonstrated the same failure mode as the wall tests, but was a great success. The house specimen was subjected to shaking with at least 140% the acceleration of the 2005 Kashmir earthquake, and despite the local failures, the building remained standing with considerable residual strength, and the damage may have been repairable. The testing received substantial media exposure including by the New York Times (Revkin 2009) as well as extensive internet viewing of the shake table video around the world.

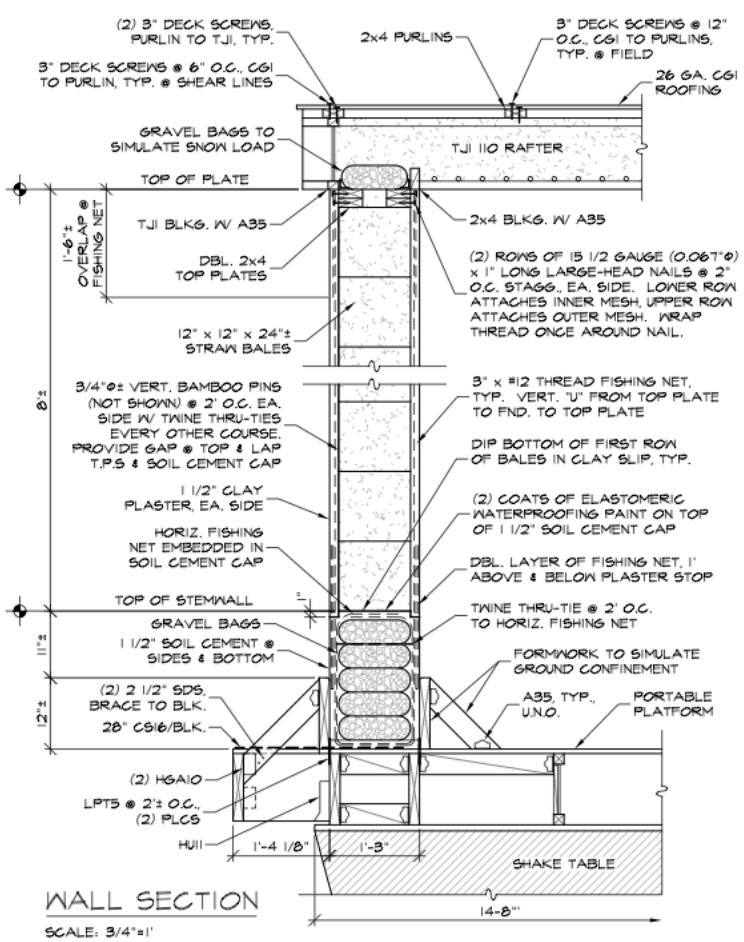

Figure 9. PAKSBAB house wall section (shake table assembly) (drawing - D.Donovan)

5. Conclusion: Moving Forward

The first edition of the strawbale construction tutorial is due to be completed in 2010 and will be distributed widely by the World Housing Encyclopedia's global network of academics and engineers. The tutorial will also be available for free download from the WHE website, and feedback on the first edition will be beneficial in improving the tutorial for its effective use.

In order for this technology transfer to succeed in permanently changing building practices on a large scale, the following steps will be necessary:

- ADDITIONAL TESTING, DEVELOPMENT OF DESIGN PROCEDURES, QUALITY CONTROL PROCEDURES, AND PRESCRIPTIVE AND PERFORMANCE BASED CONSTRUCTION GUIDELINES –To support the local population, authorities, and builders in learning, enforcing, and disseminating this technology.

- SPREAD THE WORD – The first edition of the tutorial will be used as a tool for raising awareness and soliciting implementation assistance from the widest audience of influential parties, including: (1) Local, regional and national government agencies; (2) NGOs involved in construction, disaster response and preparedness in developing countries, such as Adventist Development and Relief Agency (ADRA), Mercy Corps, UN-Habitat and many others currently working on regional and local levels; (3) International funding agencies, such as USAID and United Nations Development Program (UNDP); (4) Leaders in local and regional building and earthquake engineering communities including engineers, architects, planners, and academics.

  This effort will create a direct link between the written WHE document and implementation strategies and opportunities, a link that has so far been missing from the other WHE tutorials. This final step is especially important with straw bale technology since many of the countries and regions that could benefit are unaware of it.

- PREPARE FOR FUTURE EARTHQUAKES – Major earthquakes in developing regions often cause massive casualties and property damage, opening the local population to new ideas about building. These events also unleash waves of international assistance and resources for redevelopment. Experience shows these are often the best times to implement new concepts and methods of construction. Alas, the attention and awareness are often short-lived, thus it is important that resources are ready and available for immediate use.

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