STRAW BALE

History:

The first straw bale buildings were located in the Sand Hills of Nebraska in the 1800s. European settlers were given few alternatives for building as the northern plains offered minimal lumber, stone, or sod. So they used one of the oldest known methods of construction, stacking, in combination with a new material, straw. Many of these homes still exist and, if maintained, are still in excellent shape. The oldest known straw bale construction in the world, located in Alliance, Nebraska, turned 100 years old in 2003. [1]

Straw:

Straw bale construction is an example of industrial ecology; an industry's waste is turned into another industry's food in a closed-loop system.[2] The waste-product of the cereal grain industry, including wheat, barley, oats, rye, and rice, is straw, the tubular structure of a grain plant after the seed and grain is removed. Typically, straw is left in the field for its remaining nutrients, burned, or it is baled. When baled, straw can be used as bedding or feed for livestock or it can be used for building.

There are many different types of bales ranging in size from 1400 lbs (jumbo round bales) to small two-string bales that are a mere 60 lbs. For straw bale construction, two different bale types are used: three-string bales and two-string bales. Three string bales have a dimension of 16" x 23" x 46" and a weight of approximately 85 lbs. Two-string bales have a dimension of 15" x 18" x 36." [3]

It is best to choose bales that have never been wet and generally have a low moisture content; the dryer the better. Measure bales with a moisture meter. They should be at 10% or less. Bales should also be dense, tightly bound, well tied, and have a fiber length of at least 10 inches to avoid crumbling of the bales. Try to find bales that are tied with polypropylene twine as they will not degrade like natural fiber or metal.[4] Also, choose straw NOT HAY. The grain in hay is prone to insects, animals, and rotting.

In the northern plains, straw bales can be purchased by a local farmer and delivered by flatbed truck, making straw bale a locally available material, a material from a rapidly renewable resource, and an agricultural waste conserving natural resources.

Straw bales should be stored in a dry location and care should be taken to keep bales covered and out of the rain during construction.

Construction:

Straw bale construction is done in two very different ways: as the structure, referred to as "Nebraska style" and "load-bearing," or as the infill, referred to as "post and beam" and non-load-bearing."

1 Bruce King, "Design of Straw Bale Buildings" (San Rafael,CA: Green Building Press, 2006), xxi.
2 King, xxiii.
3 King, 1.
4 Nathaniel Corum, "Building a Straw Bale House: The Red Feather Construction Handbook" (New York, NY: Princeton Architectural Press, 2005), 37-38.

Structural Straw Bale:
Structural straw bale is considered to be the "greener" or more sustainable method because it reduces the need for other materials, especially wood. It is also simpler to construct. Structural straw bale buildings are typically much smaller, usually one story, and there is no need to build a frame before wall construction begins. Plastering is completed after the bales are compressed with the roof construction. Because they are simple to construct they can be raised quickly. In many cases, the walls and roof are constructed within a few days. This makes structural straw bale a great option for post disaster housing if bales are readily available.[5]

Infill Straw Bale:
Infill straw bale is predominately used for a few reasons. First, infill is easier to meet code, get insurance, and get mortgage lenders because it is more in line with traditional methods of construction than structural straw bale. It is adaptable, fits into many architectural styles, is changeable after construction, and allows for a much larger structure. It is also easier to repair or replace damaged sections. The use of a post and beam structure allows for the construction of a roof before the bales are stacked. This allows the bales to be protected from the weather during construction.

Despite construction method, all straw bale buildings share all of the following construction practices:

Moisture Protection:
The foundation must keep the bales well above grade. As long as the bales are not able to leach water from the ground, any foundation type is acceptable, with appropriate design considerations for material weight and climate, including raised platforms, slab on grade, and a basement wall foundation. Two pressure treated sill plates or a "toe-up" must be constructed around the perimeter and filled with pea gravel, or leftover insulation from the foundation,[6] to provide a capillary break. A waterproof barrier must separate the toe-up from the foundation as well as the toe up from the bales. Traction nails are added 6" to 8" on center to keep the bottom course of bales in place on top of the toe up. Weep holes should be added to the exterior base plate to allow drainage.

Roof assemblies can be conventional as long as they incorporate large overhangs to protect the walls from moisture.

Virtually all straw bale constructions are stuccoed with a cement, lime, or earth based plaster for moisture control, thermal resistance and storage, fire and pest protection, and to increase structural performance.
Plasters are made up of a binding agent, the main component of the plaster, a structural filler such as sand, rock or aggregates, and water.[7] Typically, they also contain a fiber such as straw, hemp, plastic, or mesh as well as an additive. For structural straw bale, the roof assembly is completed before the walls are plastered to ensure the walls are fully compressed. For infill, plastering can be completed after pre compression. At least three layers are applied, a scratch coat, a brown coat, and a finish coat. When using cement and lime plasters a metal mesh is used as reinforcement in the plaster, while earth plasters commonly incorporate a hemp or other fiber mesh. *A moisture barrier should never be used and all paints should be breathable*.

5 King, 61.
6 Corum, 21.
7 King, 22-23.

Pinning:
In some situations, internal or external pinning is done with bamboo or rebar. External pinning, where vertical members are placed on either side of the wall and tied together through the bales can increase wall stiffness. Rebar or bamboo can be hammered into the bales at the fourth and sixth courses to offer stability during construction.[8]

Stacking Type:
The bales are stacked on the toe-ups either flat or on edge in a running bond pattern. Typically they are stacked flat, with the straw fibers perpendicular to the foundation, because the bales are more stable with the wider base. However, some studies suggest that stacking bales on edge can increase thermal performance, as explained below.

Details:
Doors and windows are framed wood bucks that sit on the foundation or within the bales. Cabinetry and fixtures are screwed to wooden stakes pounded into the straw. Plumbing should not be run within the straw bale walls, as any moisture will cause the straw to rot, though electricity is fine. A conduit can be built into grooves carved by a chainsaw or weed whacker.[9] All voids in the bales and between bales and framed openings must be filled with a straw and clay mix for thermal, acoustical, and fire protection.

Pre compression:
The walls should be pre compressed. Without pre compression, bales will settle under their own weight and cause cracking of the plaster. In the case of structural straw bale, pre compression can be completed prior to the loading of the roof or after. Often, the walls are compressed many times before the plaster is applied. Bales can be compressed by forcing them under a slightly low roof bearing assembly or by cinching them with galvanized wire or packaging straps run in a sleeve below the base plate.

8 Corum, 48.
9 King, 63.

Technical Information:

Insulation/ R- Values:
Straw Bale has an average of R-1.45 per inch of wall thickness when plastered (i.e. 16 inch wall is approx R-23 and a 24 inch wall is approx R-35).[10] Some sources state that straw bale has an estimated R value as high as R-50.

A few notes related to this value:

1. Research has found that bales laid on edge, where straw fiber is perpendicular to direction of heat flow, is slightly higher than that where bales are laid flat. Therefore, a 24 inch bale laid flat will have approximately the same R-value as a 16 inch bale laid on edge.

2. The thermal lag of a straw bale wall is around 12 hours and it can take weeks to achieve a steady flow of heat through the wall. This effect makes the average R-value act as though it is much higher than it really is, especially in climates with high day to night or 24 hour temperature swings.

3. Straw bale walls are not uniform: there is variation in the density of the straw its self, plaster has a very low R-value, and a wall without plaster does not perform well because it is very porous. Therefore, the assembly functions much better than the parts on their own.

4. Bales only function well as walls. Using them as floors and roofs are very susceptible to moisture and seismic problems. Also, bales only insulate well if they are plastered on both sides. However, there has been some success with bale insulated ceilings in non-seismic areas and with bales in floor joists when plastered on both sides and ventilated well.[11]

To view a summary of Thermal Performance testing visit:

Ecological Building Network: Thermal Performance of Straw Bale Wall Systems
http://www.ecobuildnetwork.org/pdfs/Thermal_properties.pdf

This summary includes testing done by Oak Ridge National Labs whose thermal research and analysis is presented above.

Acoustics:
A straw bale wall with one inch of plaster on interior and exterior falls around 55 in STC (Sound Transmission Class) meaning only very loud sound such as a radio or musical instrument can be faintly heard though mostly inaudible.[12]

Structure:
It is important to note that un-plastered walls can carry a very small load before compressing beyond acceptability or buckling. Plastered walls, on the other hand, increase drastically in strength, especially if they are detailed to carry vertical loads through the skin or plaster.

Understanding the types of failure is important because the relationship of the plaster to the straw bales is the key to structural strength in a straw bale wall. Straw bale walls fail in five different ways:

10 King, 187.
11 King, 186-193.
12 King, 200-201.

1. **Global Buckling**: The wall from floor to roof bends and eventually breaks. This is a rare type of failure.

2. **Local Buckling**: Part of the plaster pulls away from the straw or the coats of plaster delaminate. This is caused by poor plaster or mesh application and is a common type of failure.

3. **Bearing**: The plaster crushes at the roof or the floor because the wall is not designed to sustain the stress at the joint. This is a common type of failure.

4. **Slippage**: The skin slips vertically past the floor or roof joints caused by the failure of mesh fasteners at the joints.

5. **Core Crushing**: The straw is crushed because the vertical load is not transferred through the skin or plaster.[13]

There is substantial variation in the compressive strength of plasters, ranging from 60 psi for lower quality lime plasters to 711 psi for high quality lime cement plasters. The table below shows the compressive strengths for four common plaster mixtures:[14]

Compressive Strengths of Fully Cured Plasters:
Lime/Cement/Sand Plaster (1:1:6 Ratio) = 426-711 psi
Lime/Cement/Sand Plaster (1:2:9 Ratio) = 284-426 psi
Lime/Sand Plaster (1:3 Ratio) = 60-190 psi
Earth/Sand/Straw Plaster (2:3:3 Ratio) = 90-130 psi

A Factor of Safety of at least 4 should be used to determine the allowable compressive force of the material. This means the allowable compressive force ranges from 15 psi to 177.75 psi. The table below shows the allowable compressive forces for the plaster mixtures above:

Allowable Compressive Forces of Fully Cured Plasters:
Lime/Cement/Sand Plaster (1:1:6 Ratio) = 106.5-177.75 psi
Lime/Cement/Sand Plaster (1:2:9 Ratio) = 71-106.5 psi
Lime/Sand Plaster (1:3 Ratio) = 15-47.5 psi
Earth/Sand/Straw Plaster (2:3:3 Ratio) = 22.5-32.5 psi

Structural Test Summaries by the Ecological Building Network:

Load Bearing Straw Bale Construction
A summary of testing by Bruce King
http://www.ecobuildnetwork.org/pdfs/Load-Bearing_SB_Const.pdf

Properties of Earth, Lime, and Lime-cement Plasters
Compressive strength, Modulus of Rupture, shrinkage, erosion, and Modulus of Elasticity by Kelly Lerner, Architect and Kevin Donahue, SE.
http://www.ecobuildnetwork.org/pdfs/Plaster_tests.pdf

Load-bearing and Creep
Long-term deflection on walls with different combinations of plaster and load by Dan Smith.
http://www.ecobuildnetwork.org/pdfs/Creep_report.pdf

13 King, 69.
14 King, 84-85.

In-Plane Cyclic Tests of Plastered Straw Bale Wall Assemblies
Capacity of walls with different combinations of plaster and mesh to resist load parallel to the face by Cale Ash, Mark Aschheim, University of Illinois, and David Mar, Tipping-Mar + Associates.
http://www.ecobuildnetwork.org/pdfs/InPlane_Wall_Tests_Small.pdf

Moisture:
Moisture Test Summaries by the Ecological Building Network:

Monitoring the Hygrothermal Performance of Strawbale Walls
by John Straube and Chris Schumacher
http://www.ecobuildnetwork.org/pdfs/Winery_Monitoring.pdf

How Straw Decomposes: Implications for Straw Bale Construction
by Matthew D. Summers, Sherry L. Blunk, Bryan M. Jenkins
http://www.ecobuildnetwork.org/pdfs/How_Straw_Decomposes.pdf

Moisture Properties of Plaster and Stucco for Strawbale Buildings
by John Straube
http://www.ecobuildnetwork.org/pdfs/Straube_Moisture_Tests.pdf

Fire:
Fire Test Summaries by the Ecological Building Network:

1-Hour Fire Resistance of a Non-Loadbearing Wall w/ Earth-Plaster
http://www.ecobuildnetwork.org/pdfs/Non-Bearing_Clay_Wall.pdf

2-Hour Fire Resistance of a Non-Loadbearing Wall w/ Cement-Stucco
A lime-cement plaster mixture with an average total thickness of 1 inch and applied over a metal mesh was tested per ASTM standard E119. The wall easily passed a two hour test. By the end of two hours, the plaster on the burned side was bulging away from the straw by as much as 10 inches though the mesh was still holding the plaster together. There were no cracks on the non burned side of the wall.
http://www.ecobuildnetwork.org/pdfs/Cement_Stucco_Wall.pdf

Resources:

Videos:

The How To Guide to Building with Straw Bales (Post & Beam) DVD
by Andrew Morrison

This video is a step by step visual instruction manual for building a post and beam, or infill, straw bale structure. It covers necessary tools, foundations, framing, toe-ups, tips for selecting, preparing, cutting, and stacking the bales, adding doors and windows, adding electrical details, applying wire mesh, and finishing.

The How-To Guide to Plastering with Natural Hydraulic Lime Plaster DVD
by Andrew Morrison

This video covers scratch coat, brown coat, and finish coat applications as well as smoothing, texture, and rounding techniques for hydraulic lime plaster.

The How To Guide to Building with Straw Bales (Load Bearing) DVD
by Andrew Morrison

This video covers the techniques used to build a load bearing or Nebraska style straw bale structure. It covers building the foundation, installing toe-ups and box beams, stacking the bales, bale pre compression, building the roof, adding doors and windows, applying wire mesh, and finishing.

Books:

Design of Straw Bale Buildings; The State of the Art
by Bruce King
http://www.amazon.com/dp/0976491117/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=0976491117&creative=373489&camp=211189

Building with Straw: Design and Technology of a Sustainable Architecture
by Gernot Minke and Friedemann Mahlke
http://www.amazon.com/dp/3764371714/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=3764371714&creative=373489&camp=211189

More Straw Bale Building: A Complete Guide to Designing and Building with Straw (Mother Earth News Wiser Living Series)
by Chris Magwood and Peter Mack
http://www.amazon.com/dp/0865715181/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=0865715181&creative=373489&camp=211189

Practical Straw Bale Building
by Murray Hollis
http://www.amazon.com/dp/0643069771/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=0643069771&creative=373489&camp=211189

Building a Straw Bale House: The Red Feather Construction Handbook
by Nathaniel Corum and Jane Goodall
http://www.amazon.com/dp/1568985142/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=1568985142&creative=373489&camp=211189

Serious Straw Bale: A Home Construction Guide for All Climates (Real Goods Solar Living Book)
by Paul Lacinski and Michel Bergeron
http://www.amazon.com/dp/1890132640/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=1890132640&creative=373489&camp=211189

The Beauty of Straw Bale Homes
by Athena Swentzell Steen and Bill Steen
http://www.amazon.com/dp/1890132772/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=1890132772&creative=373489&camp=211189

The New Strawbale Home
by Catherine Wanek
http://www.amazon.com/dp/1586852035/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=1586852035&creative=373489&camp=211189

Small Strawbale: Natural Homes, Projects & Designs
by Bill Steen, Athena Steen, and Wayne Bingham
http://www.amazon.com/dp/1586855158/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=1586855158&creative=373489&camp=211189

Straw Bale Details: A Manual for Designers and Builders (Natural Building Series)
by Chris Magwood and Chris Walker (Illustrator)
http://www.amazon.com/dp/0865714762/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=0865714762&creative=373489&camp=211189

The Good House Book: A Common-Sense Guide to Alternative Homebuilding
by Clarke Snell
http://www.amazon.com/dp/1579902812/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=1579902812&creative=373489&camp=211189

Strawbale Construction Curriculum (Facilitator Guide)
by Owen Geiger and Chris McClellan
http://www.amazon.com/dp/B000I2UT7E/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=B000I2UT7E&creative=373489&camp=211189

A House of Straw: A Natural Building Odyssey (Paperback)
by Carolyn Roberts (Author)
http://www.amazon.com/dp/1890132306/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=1890132306&creative=373489&camp=211189

Strawbale Homebuilding
by Alan T. Gray and Anne Hall
http://www.amazon.com/dp/0958639744/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=0958639744&creative=373489&camp=211189

Building Green: A Complete How-To Guide to Alternative Building Methods
by Clarke Snell and Tim Callahan
http://www.amazon.com/dp/1579905323/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=1579905323&creative=373489&camp=211189

Strawbale Home Plans
by Wayne Bingham and Colleen Smith
http://www.amazon.com/dp/1586858610/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=1586858610&creative=373489&camp=211189

Build It With Bales: A Step-By-Step Guide to Straw-Bale Construction, Version Two
by S. O. MacDonald and Matts Myhrman
http://www.amazon.com/dp/0964282119?_encoding=UTF8&tag=hartworkscom-20&linkCode=as3&camp=15041&creative=373501

Building Your Straw Bale Home
by Brian Hodge
http://www.amazon.com/dp/0643092420/ref=nosim?tag=hartworkscom-20&link_code=as3&creativeASIN=0643092420&creative=373489&camp=211189

The Straw Bale House (A Real Goods Independent Living Book)
by Athena Swentzell Steen, Bill Steen, and David Bainbridge
http://www.amazon.com/dp/0930031717/ref=nosim?tag=hartworkscom-20%20&link_code=as3&creativeASIN=0930031717&creative=373489&camp=211189

Websites:
Ecological Building Network
Straw Bale Testing Program provides testing reports on structure, moisture, and fire tests on straw bale construction.

International Straw Bale Building Registry
http://sbregistry.greenbuilder.com/
An international database of structures utilizing straw bale construction.

Natural Homes
http://naturalhomes.org
An international website featuring natural building construction techniques. Contains information on upcoming workshops, books, case studies, and links.

Strawbale.com
http://www.strawbale.com/
Provides workshops, articles, photos, and a wealth of information on straw bale construction.

The Last Straw: The International Quarterly Journal of Straw Bale and Natural Building
http://www.thelaststraw.org/
Publishes a quarterly journal about the development of straw bale construction. Since 1993, TLS has written about case studies, up to date techniques, and research.

Articles:
Straw: The Next Great Building Material? from BuildingGreen.com
http://www.buildinggreen.com/auth/article.cfm?fileName=040301a.xml

Products:

ModCell
Located in Bristol, UK, ModCell has designed a pre manufactured straw bale panel system. ModCell designs the panels, connects with a local farmer for straw bale supplies and assembly facilities, and constructs the panels usually within 10 miles of the building site. ModCell claims the panels last for 100 years.

Case Studies:

SDSU Straw Bale Conference Space
Located in the McCrory Gardens, the straw bale was completed as a workshop for SDSU students. It was designed and organized by SDSU Associate Professor of Interior Design, Dean Isham. The project will provide 900 sq. ft. of classroom space for a new Children's Gardening and Education Center at McCrory Gardens.

Straw Bale Winery
Located in Renner, just north of Sioux Falls, the Straw Bale Winery produces an assortment of wines produced from local growers. The wine tasting room is a post and beam straw bale construction which utilizes timber from fallen trees due to a windstorm in Minnesota as well as other reused surfaces.

Susan's Live/ Work Studio
Located in Grantville, Kansas, this small home utilizes load-bearing straw bale walls on the north, east, and west facades for thermal mass and insulation and a glazed south façade to maximize solar gain. It was designed and built by a small contractor with the help of the home owner. The home exhibits a number of sustainable features including a Rasta Block foundation with concrete collar and infill; a compacted earth floor to minimize the amount of concrete used in the project.

References:

Corum, Nathaniel. "Building a Straw Bale House: The Red Feather Construction Handbook." New York, NY: Princeton Architectural Press, 2005.

King, Bruce. "Design of Straw Bale Buildings." San Rafael,CA: Green Building Press, 2006.

Ecological Building Network. "The Straw Bale Testing Program." http://www.ecobuildnetwork.org/strawbale.htm