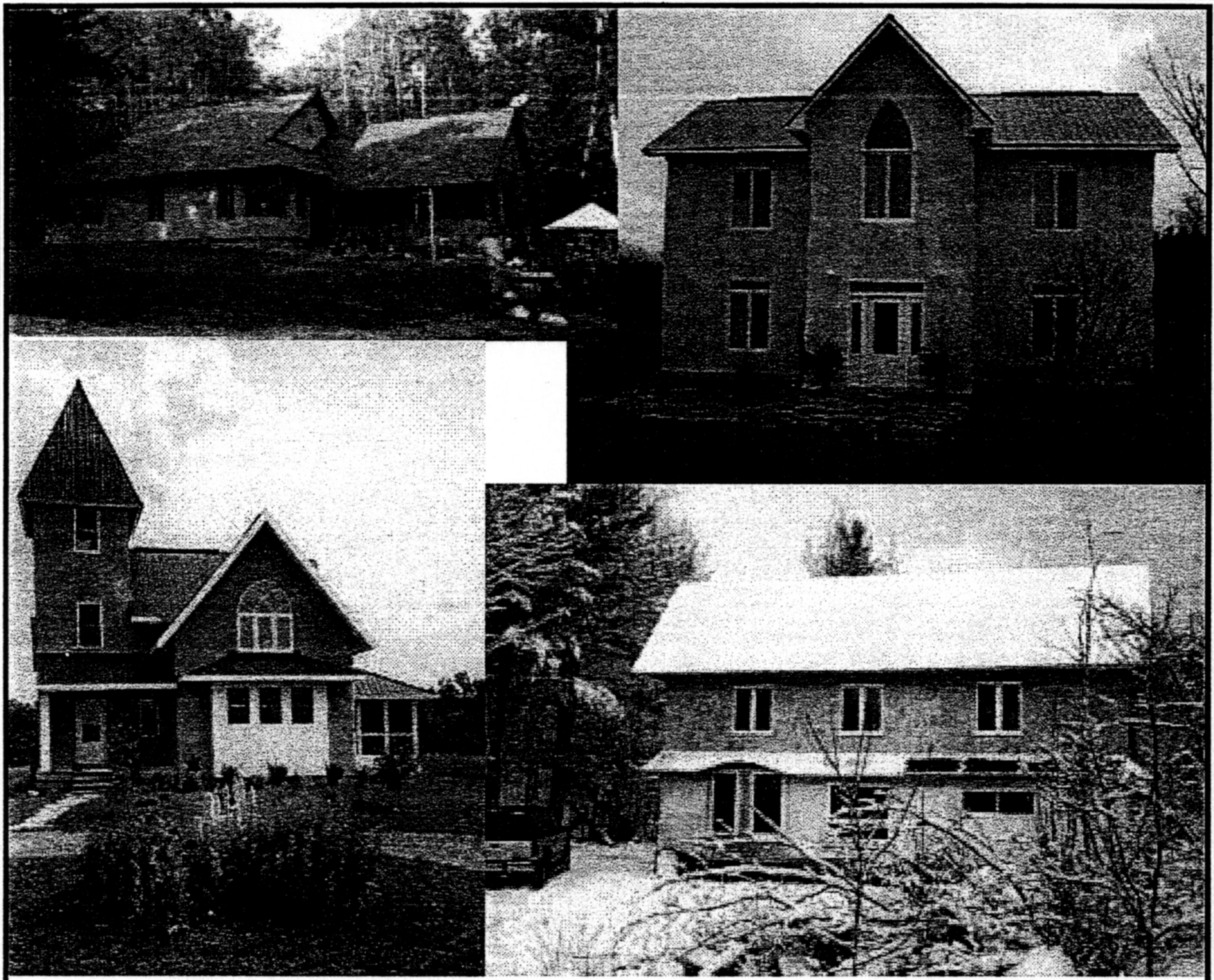

Straw Bale homes in Ontario come in all shapes and sizes. Clockwise from top left:The Smith/Marcotte home, Bancroft; the Cook home, Kanata; the Wise/Jansman home, Centreville; the Beacon/Magwood home, Madoc.

Straw Bale Building: An Information Package for Building Officials in Ontario

prepared by:
The Ontario Straw Bale Building Coalition

Straw Bale Building: An Introduction

by Chris Magwood, on behalf of the Board of Directors of the Ontario Straw Bale Building Coalition

The Ontario Straw Bale Building Coalition was formed in 2003, bringing together bale home owners, builders, designers and professionals together with interested members of the public. Its goals include providing information for people with an interest in owning a straw bale house and initiating and supporting efforts to further the base of scientific and construction knowledge about straw bale building.

Bale Building in Ontario. The first permitted bale homes in Ontario were built in the mid 1990s. Since that time, bale builders in Ontario have become world leaders in the development of successful strategies for properly integrating building code issues into durable, affordable, environmentally-sound homes. The expertise and advice of Ontario builders has been sought by architects, engineers, builders and code officials all over the world.

There are currently more than 50 permitted bale buildings in the province, including many homes, as well as commercial, agricultural and service buildings. Many "firsts" in the world of bale building were achieved in Ontario, including the world's largest load-bearing bale structure, the only three-story bale structure and the first multi-unit, co-housing structure.

Bale buildings have been permitted in the province's largest cities, as well as many rural jurisdictions.

Why Build With Bales? People building with straw bales do so because of a desire to create safe, affordable, energy-efficient, beautiful, long-lasting, non-toxic and environmentally-sound homes. Straw bale walls are unique in their ability to combine all of these features in a system that is simple to understand and construct.

Bale walls are easily integrated into designs that incorporate modern, code-approved practices for building foundations and roofs, and are therefore well-suited for adaptation into conventional construction practice.

It is rare that a building system offers both substantial performance increases along with lower environmental impacts, without any increase in costs. By doing this, straw bale building continues to grow in popularity and public interest.

The Reason for This Package. The OSBBC has developed this package of information because we are aware of the difficulties faced by building department officials when confronted by building systems that fall outside the prescriptions of the Ontario Building Code. Collectively, members of the OSBBC have worked with building inspectors in jurisdictions across the province, and have tried to reflect what we've learned in the information in this package.

Included in this package are explanations of the building system, structural tests, including compressive strength, shear strength, wind loads and seismic testing, as well as fire testing and moisture testing. These tests have been performed by accredited labs around the world, most often to ASTM standards, and in every test, straw bale walls perform above the required levels necessary for residential construction in Ontario.

We hope this information will help make your job easier when you are faced with a request for a permit for a straw bale building. If we can be of any assistance to you in assessing a set of straw bale plans, please feel free to contact us at:

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Food for Thought

The following is exerpted from Straw Bale Construction and the Building Codes: A Working Paper, *by David Eisenberg of the Development Center for Appropriate Technology (DCAT). Reproduced with permission of the author:*

When we think about building materials and their acceptance, we should consider the reality in which we already operate. Joe Lstiburek, of Building Sciences, Inc., a building consultant of the highest regard, has put the situation into perspective by describing the realities of the use of wood as a building material. He points out that wood, were it being introduced today as a new building material, could never get into the building codes. It has nearly every problem a material could conceivably have. There are hundreds of species. The strength and durability is dependent on the species, as well as some of the environmental conditions that occurred while it was growing. The strength is dependent on things like the orientation of the grain, the age of the wood, how it was dried, moisture content, and the size, location and frequency of knots. It burns, it rots, insects like to eat it. It is dimensionally unstable, it splits. And yet, in spite of all these problems, it is the material of choice in this country for residential construction, even though there are huge environmental problems associated with its profligate use. Of course it is a wonderful material. And there are reasons it is so widely used. But if a new material (like straw bale) is introduced with any one of the problems that wood has, it is nearly impossible to get it accepted into the codes!

Straw-Bale Construction:
A Review of Testing & Lessons Learned To Date

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© Bruce King, CE [for publication by the ICC in Building Standards magazine]

Bruce King is a registered Civil Engineer with a structural engineering practice in Sausalito, California, and 26 years of experience designing commercial and residential structures. He has done extensive research and work with various alternative materials, and is the author of Buildings of Earth and Straw: Structural Design for Rammed Earth and Straw-Bale Architecture, *as well as articles for Building Standards and other publications. He is the founder and Director of the Ecological Building Network (EBNet), an educational non-profit in San Francisco currently completing testing and research on straw bale construction. Mr. King has lectured around the world for engineering and building official groups on straw bale and other alternative construction systems. Additional resources on straw-bale construction (and results of the recent testing program) can be found at the Ecological Building Network's web site, www.ecobuildnetwork.org.*

INTRODUCTION. The first straw-bale structures we know of were built more than a hundred years ago by European settlers in the Sand Hills region of Nebraska. Many of those homes still exist, and a revival in straw-bale construction began in the American West in the late 1980's. As more professional architects, engineers, inventors, and builders have begun to explore this new material, a variety of styles and techniques has emerged, and straw-bale construction has spread all over the world. A recently completed quarter-million dollar research and testing project, funded mainly by the State of California, has answered some common technical questions; this article describes some of the basics of straw-bale construction, and reviews the accumulated body of laboratory and field experience to date.

BALES. Straw is the plant structure between the root crown and the grain head; hay includes grain, and should not be used for building. Bales are masses of straw compressed into rectangular blocks that are bound with polypropylene twine. Building bales might be two-string (generally 16"x18"x36"+/-) or three-string (generally 15"x23"x46"+/-), and are ideally stacked in a running bond. Bales are usually stacked flat, ie with the longest dimension parallel to the wall, and the shortest dimension vertical. In other applications, the bales can be stacked on edge, ie with the shortest dimension horizontal. This saves interior space with the slimmer wall, and, interestingly, appears to offer the same net insulation value due to the slightly different orientation of the fibers.

Experience, and some laboratory testing, strongly suggest that four qualities determine the usefulness of a bale for building:

1. Moisture content. The drier the better—very generally, a moisture content hovering for an extended period of days above 30% and 40°F is considered cause for worry about decay.

2. Density. Dry density (ie with moisture content accounted for and subtracted) should generally be at least six pounds per cubic foot if the bales are intended for load-bearing or shear walls, and should be bound tightly enough such that lifting a bale by one string will leave no more than a fist-sized gap between bale and string.

3. History. Bales that have been moistened once or repeatedly will show grey or black areas where mold spores have begun proliferating. Such bales are always discarded, even if very dry at the time of construction, as they are especially likely to experience problems if the wall is ever wetted.

4. Fiber length. Some baling machines chop the straw into very short lengths before baling, resulting in bales that are not as coherent as is desired for construction. Experienced builders look for fiber lengths of at least 10 inches.

WALL ASSEMBLIES. Many details and wall systems are now in use, and dozens have been tried and discarded for one reason or another—in otherwords, straw-bale construction is still very much a developing technology. It is nonetheless true that, as with every other building material, the ideal wall assembly depends very much on area climate and seismicity, building function, and aesthetics.

Until very recently there were thought to be two basic styles of straw-bale construction: load-bearing vs. non-load-bearing (or post-and-beam), in which bales are used as infill panels between or around a structural frame. Post-and beam style predominates because it can be more adaptable, and it allows the construction of a protecting roof prior to bale delivery and placement. However, the more important distinction is really between structural straw bale construction, in which bale assemblies are designed to carry vertical and/or lateral load, and non-structural, in which the only structural demand on a wall assembly is to remain intact and in place under out of plane load.

Despite the many variations, there are several qualities common to all straw-bale buildings:

1) All straw bale buildings inevitably have dozens of oddly shaped spaces between the bales and the surrounding framing, windows, doors, etc. The convention is, prior to plastering, to fill those spaces with a straw-clay mix which dries and then acts to "pull" any intruded water away from the wood and bales, and is a fire and pest retardent as well. Alternatively, some use a sprayed insulation like cellulose to fill cavities.

2) The bales must often be braced during stacking for stability and alignment (akin to the temporary bracing of a

studwall). Internal or external pinning of the walls (with rebar dowels) has been prescribed in early straw-bale codes, but is no longer considered to provide much structural value, and should not be codified.

3) The predominant experience with straw-bale buildings is that moisture vapor intrusion is not a problem if the wall can "breathe"— that is, if both surfaces are vapor permeable. There have certainly been leaks and degradation failures, but without exception they have been due to outright moisture intrusion, not vapor intrusion. In short, and to perhaps oversimplify, it seems that water vapor should be allowed to move in and out of the wall assembly without condensing on internal surfaces, while extra care must be taken to keep liquid water out. Tops of bale walls, exposed horizontal surfaces (that is, windowsills), and joints with wood frames must be carefully sealed and designed to shed water. As with fire, the structure is especially vulnerable during construction, as bales and walls can be wetted by rains, appear to dry out, and then develop problems after the wall is completed.

4) Building permit reviews have commonly generated the requirement to cover the bales with a barrier such as plastic or asphaltic paper, but experience with straw-bale walls overwhelmingly shows that no barrier should separate the plaster and straw. This is because the straw needs to breathe (release water vapor), moisture must not be trapped against the straw/plaster interface, and the structural system depends on a thorough bonding of plaster into straw. The only exceptions are windowsills and, if used, shower stalls.

5) The foundation must keep the bales well above grade, and the roof should provide a wide overhang—the proverbial "good hat and good pair of shoes". Roofs are conventional, connecting to the walls via some manner of top plate or bond beam (most commonly a wood or concrete assembly). Windows and doors are typically framed wood bucks that either sit on the foundation or "float" in the bale wall. Cabinetry and fixtures are screwed to wooden stakes pounded into the straw, and conduit can be let into grooves carved by chainsaws or weed wackers into the straw surface. The bottom of the bale wall must be well separated from the foundation by a waterproof barrier over the supporting concrete surface, and a layer of pea gravel (capillary break) between wood sill plates along the inside and outside faces, thereby ensuring that the bales will never be sitting in water.

PLASTERING. Virtually all straw-bale wall systems are plastered straw bale, where "plastered" is used generically to include traditional earthen plasters, lime and gypsum plasters, shotcrete or gunite, common cement or lime-cement stucco, and various combinations of these. It is essential to understand that, once plaster is applied directly to either or both of the straw-bale surfaces, the completed wall assembly is now a hybrid of straw and plaster—a sandwich panel. (Put differently, stacked straw bales can be considered yet another form of Insulating Concrete Forms (ICFs). Virtually all loads, except where directed to a separate building frame, will be carried mostly or entirely by the relatively rigid plaster "skins" (effectively thin concrete walls or wide, flat columns). In contrast to a pure concrete structure, however, where failure of such a bearing/shear wall or column could be both sudden and catastrophic, the failure of the plaster skin is slowed and resisted by the straw-bale assembly. Tests conducted in various laborоratories over the past 10 years have proven that an unplastered wall can carry an appreciable amount of vertical load, as well as some in-plane and out-of-plane shear, and would therefore provide a backup against failure of the plaster skins. Furthermore, recent structural tests have revealed the surprising strength, ductility and toughness of plastered bale walls, even when fully cracked and subjected to cyclic loading. The bale walls, when plastered on both sides, behave much more like an integral stress skin panel structure than might be expected, so the assembly consists of thin concrete walls or skins braced by, and somewhat elastically connected by, the ductile straw-bale core.

In many cases, such as one-story buildings in minor seismic zones, almost any plaster can be suitable, and reasonable durability can be achieved with earthen plasters with adequate roof overhangs and/ or a modest addition of straw or stabilizer. Almost any type of plaster has some structural strength, and where structural loads are light, the preference is for a vapor-permeable plaster such as lime and stabilized earth. Generally, where the engineer wishes to use the bale walls as shearwalls in high-seismic risk areas like California, a standard lime-cement stucco (as prescribed in the UBC) has about the best combination of strength, durability, and vapor permeability.

Plaster coatings should always be worked directly into the straw, as there is a huge increase of strength from an unplastered to a plastered wall assembly when the plaster skins are bonded to the straw substrate. In areas of heavy snow, temperature extremes, or seismic risk, making use of the integrated system also requires tensile reinforcing for the plaster skin. That reinforcing can be a conventional hexagonal 17 gage stucco mesh, but for heavy loading (eg UBC seismic zones 3 and 4) should be some form of welded wire mesh with a comparatively tight weave, such as 2 inch by 14 gauge wire. Design and detailing of fasteners at boundary elements will greatly affect the ability to carry and transmit loads. Since the bond provided by working the plaster into the straw is typically quite strong, many, including this author, generally believe that mesh reinforcing need only be attached well enough to stay in place during plastering; weaving or tying mesh reinforcing to or through the bale wall is probably only necessary in high seismic zones, and for straw bale vaults.

MECHANICAL PROPERTIES:

Thermal insulation (R-value). A definitive test on state-of-the-art equipment at Oak Ridge National Laboratories yielded an R-value of 27 for an 18 inch wall, or by inference 36 for a 24 inch wall. The California Energy Commission accepts an R value of 30 for all plastered straw bale walls.

Moisture resistance and durability. This is by far the most worrisome issue for straw-bale builders and designers, as straw will obviously rot and/or mold under certain conditions. Rot constitutes a degradation of the structural core of the "sandwich panel", and mold is a potential health hazard common to any cellulose-based building material. As stated previously, all failures to date have been caused by outright liquid moisture intrusion or internal condensation; moisture vapor, if unimpeded and not allowed to condense on cold (eg metal) surfaces, will generally move through and out of a wall without causing problems.

Experience with other materials, especially wood, in contact with cementitious materials would suggest that cement plaster applied directly to the straw would lead to degradation problems. There have been some problems, typically where an unprotected wall is exposed to heavy, driven rain, but far fewer than might be expected. Decade-old walls have been investigated and shown no decay at the stucco/straw interface. It may be that the straw will eventually degrade in the alkaline cement environment, if only in conditions where the plaster "holds" water against the straw, but to date walls in many climates are performing substantially better than would be expected.

It should be noted that the historic, 100 year old cement-plastered structures in Nebraska are still in good condition, even after some neglect, and that straw in protected conditions, such as an Egyptian pyramid, has lasted for thousands of years. Straw bales are more sensitive to moisture intrusion than other materials, but durability—as with any other building material—is primarily a matter of careful and intelligent detailing of the building envelope.

Fire resistance and flame spread. A number of straw-bale structures have passed intact through wildfires that completely incinerated adjacent wood buildings. This is easily explained and understood analogously by anyone who has ever tossed a telephone book in a fire and expected it to burn; fire requires fuel, flame, and oxygen to survive. Bales are too dense to provide the necessary oxygen, particularly when coated with a thick layer of plaster.

Two ASTM E-119 small scale fire tests were completed in the state of New Mexico, one on an unplastered straw bale wall panel and the second on a straw bale wall that had been gypsum-plastered on the heated side and stuccoed on the outside face. The results of those tests have been interpreted to show the equivalent of a two or even three hour firewall.

Later, a full scale ASTM E-119 test conducted in California demonstrated that plastered straw bale walls constitute at least one-hour fire-resistive construction.

An ASTM E-84 flame spread test on unplastered two-string straw bales yielded a flame spread index (FSI) of 10 and a smoke development index (SDI) of 350. The International Building and International Residential Codes require a maximum FSI of 25 and a maximum SDI of 450 for insulation. This means that the bales easily surpass both requirements and are acceptable for use in both commercial and residential construction where flame spread and smoke development ratings are required.

As an emphatic and precautionary footnote, it must be added that a straw-bale building site presents a fire hazard. During the brief period of bale placement, when the site can quickly become buried in a thick and highly flammable layer of loose straw, that straw should be regularly cleaned up, and fire hoses kept always ready.

Bearing strength. Nine eight-foot high cement-stuccoed bale wall assemblies were loaded to failure in compression, and failure loads averaged 4328 pounds per foot. A later experiment tested a single wall 13 feet high and was stopped at a load of 3327 plf. In both cases, the ability of typical plastered bale walls to carry vertical load was shown to be more than enough for typical one and two story applications.

Out-of-plane strength. In both laboratory settings and unintended field tests, many plastered and unplastered bale walls have been subjected to hurricane level winds without distress. In a separate test, a plastered straw-bale arch was point loaded out of plane to mimic seismic loads. The wall retained load-carrying capacity even after the test rams had completely punctured the stucco skins, and the author concluded: "The structure remained stable as it was loaded well into the plastic deformation range, carrying 1.26g with an average displacement ductility of 12.6".

In subsequent tests, eight foot by eight foot walls plastered with earthen and lime-cement plasters, with and without reinforcing mesh, carried loads varying from 94 psf (no plaster) to 250 psf (reinforced earth plaster) to 343 psf (reinforced lime-cement plaster).

In-plane strength. Early monotonic tests led to establishing a 360 plf allowable in-plane shear load on walls in California; the number was roughly one fourth of test failure loads, and corresponds exactly to the allowable shear for stucco-covered studwalls already given in the UBC. Subsequent cyclic tests yielded even better results, showing that a well-detailed straw bale wall has strength and ductility comparable to the strongest plywood shearwalls listed in the UBC. Based on those tests, engineers are now comfortable using well-detailed and plastered bale shearwalls to carry 750 plf.

SUMMARY

In the hundred years since straw-bale building technology was first pioneered, the basic technique has remained as straightforward as stacking the bales and plastering both sides. Our knowledge of the material properties of these walls has blossomed in tandem with the extraordinary revival of the past 15 years, and we now are now equipped to design with confidence for any conditions.

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A Straw Bale Testing Bibliography

This bibliography is adapted from an article in Issue #40 of The Last Straw Journal, *Winter 2002. Reprinted with permission of* The Last Straw Journal, *PO Box 22706, Lincoln, Nebraska 68542-2706, USA, 402.483.5135, <thelaststraw@thelaststraw.org>*

1) The Building Official's Guide to Straw-Bale Construction

The Building Official's Guide to Straw-bale Construction is published by the California Straw Building Association (CASBA), and it consolidates an impressive array of tests in one source, and frames these tests with a good introduction and resource section. Edited by architects Kelly Lerner and Pamela Wadsworth Goode, this volume includes the existing U.S. bale building codes along with extensive test documents about structural integrity, fire, thermal and moisture performance of bale walls.

The Building Official's Guide can be ordered directly from CASBA www.strawbuilding.org.

The book includes full copies of the following tests:

ASTM E72 Compression Test of Plastered Straw-Bale Walls, by Matt Fitzgerald Grandsaert, 1999, University of Colorado at Boulder, sponsored by StrawCrafters and the California Straw Building Association.

ASTM E72 80 Compressive, Transverse and Racking Tests of Load-Bearing Walls, conducted under the direction of John Carrick BE, the New South Wales Environmental Protection Agency and John Glassford at the Building Research Centre of the University of New South Wales, Australia, 1998.

Straw Bale Bending and Cement Plaster/Straw Bale Bond Testing, by Jonathan Boynton, 1999, California Polytechnical State University, San Luis Obispo.

In-Plane Lateral Loading of a Stuccoed Straw-Bale Wall, by Nathan White and Clint Iwanicha, 1997, California Polytechnic State University, San Luis Obispo.

Straw Bale Vault Test, designed by David Mar, structural engineer, and Skillful Means Architecture and Construction. Conducted by Bill Rothacher and Doug Stark of Consolidated Engineering Laboratories (CEL), 1998, Berkeley, California.

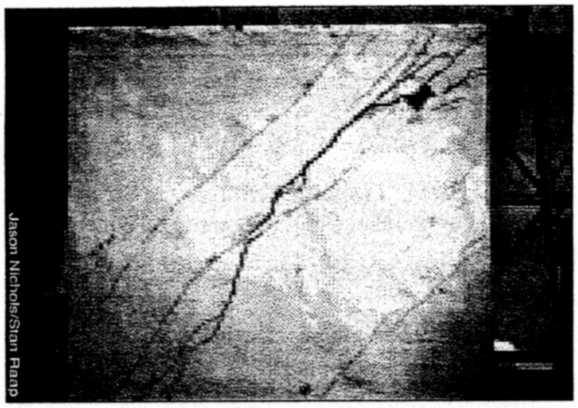
Compressive and Lateral Loading of Straw-Bale Walls, by Ghailene Bou-Ali, 1993, University of Arizona.

Thermal and Mechanical Properties of Straw Bales as They Relate to a Straw House, conducted by the Canadian Society of Agricultural Engineering, 1993, Halifax, Nova Scotia, Canada.

Straw-Bale Construction Moisture Research, by Joanna Karl, Lis Perlman and Bill Kownacki, 1995, Portland Community College.

E-119 Small Scale Fire Test, by SHB AGRA, 1993, New Mexico.

Thermal Performance of Straw Bale Walls *(a summary and discussion of several different thermal performance tests)*, by Nehemiah Stone and Tav Cummins, 1999, California Energy Commission.


Jason Nichols/Stan Raap

A bale test wall shows the cracking induced by shear testing by Jason Nichols and Stan Raap at California Polytechnic State University, San Luis Obispo.

2) EBNet Conference CD-ROM

The CD-ROM of the proceedings from the 2001 EBNet Conference *(see review, TLS#37)* included many papers presented on both strawbale and other natural building methods. Among the highlights of the CD-ROM are complete versions of the following test documents:

Straw-Bale Shear Wall Lateral Load Test, by Jason Nichols and Stan Raap, 2000, California Polytechnic State University, San Luis Obispo, Architectural Engineering Dept.

For the Land of Camels: A Straw Bale Test Wall for Seventeen Foot High Ceiling Structures in the Kingdom of Saudi Arabia, by Chris Stafford, Christopher Stafford Architects, Inc., Port Townsend, Washington.

A Pilot Study Examining the Strength, Compressibility and Serviceability of Rendered Straw Bale Walls for Two Storey Load Bearing Construction, by Michael Faine and Dr. John Zhang, 2000, University of Western Sydney, Australia.

Preliminary Report on the Out-of-plane Testing of an 8x8ft Straw Bale/PISE Wall Panel, by David Arkin and Kevin Donahue, 2001, Mill Valley, California.

Straw-Bale Construction: A Review of Testing & Lessons Learned To Date, by Bruce King, 2001.

A Status Report on the Greening of Building Codes and Standards, by David Eisenberg, 2001.

Alternative Building Materials and Systems —Understanding Technical Risk and Uncertainty, by John Straube, 2001.

CD-ROM available from EBNet www.ecobuildingnetwork.org

3) CMHC Testing Reports

The Canada Mortgage and Housing Corporation (CMHC) is another valuable source of testing data and documentation. CMHC is a government agency involved in social housing, mortgage insurance, research and advocacy on housing issues. To this end, they have provided funding for straw-bale housing research which has been important and influential.

A sampling of key CMHC tests includes:

Developing and Proof-Testing the "Prestressed Nebraska" Method for Improved Production of Bale Fibre Housing, by Fibrehouse Limited with Scanada Consultants Limited, 1995.

Strawbale Moisture Monitoring Report, by Rob Jolly, 2000.

Moisture Properties of Plaster and Stucco for Strawbale Buildings, by John Straube, 1999, University of Waterloo.

Pilot Study of Moisture Control in Stuccoed Straw Bale Walls, by Bob Platts, 1997.

Two new studies, one on lumber use in load-bearing bale walls and one on energy efficiency modelling will be available in late 2003. You can browse all of CMHC's material at www.cmhc-schl.gc.ca/ and order documents online, or by calling 1-800-668-2642 (or outside Canada, dial 613 748-2003), faxing 613-748-2016 or mailing to CMHC, Suite 1000, 700 Montreal Road, Ottawa ON K1A 0P7.

4) University of Manitoba

Design Dead Load of a Straw Bale Wall, by E. Arbour, 2000.

Design Approach for Load-Bearing Strawbale Walls, K.J. Dick and M.G. Britton, 2002.

Resistance to Shear in Stuccoed Straw Bale Walls, by Lisa Stepnuk, 2002.

All three papers available from Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, R3T 5V6, Canada, 204-474-6033, www.umanitoba.ca/faculties/afs/biosystems_engineering/overview.html

5) Other Test Documents

The following tests have been performed at university labs or by interested individuals. Many of these people will, understandably, ask for a fee for their document(s).

House of Straw: Straw Bale Building Comes of Age, by the U.S. Dept. of Energy, 1995. Available online only at www.eren.doe.gove/EE/strawhouse/. *This report studies thermal performance and construction cost issues, with positive results.*

Moisture Control in Strawbale Homes: Report to Ontario Building Code Commission, John Straube, 1999. Building Engineering Group, Civil Engineering Department, University of Waterloo, Waterloo, Ont., Canada, N2L 3G1, 519 888-4567, Ext. 2378. *An important look at how straw-bale walls handle moisture.*

Straw Bale Exterior Pinning Report, by Sustainability International, 1998. Contact Bob Bolles to purchase copies - <bob@strawbalehouse.com>. *Engineering results on a rebar-exterior-pinning system which gained approval from the Tucson/ Pima County building department.*

Community-Built Housing Solution: A Model Strawbale Home Design, by David Riley and Sergio Palleroni, 1999.

Strength Testing of Stucco and Plaster Veneer Straw-Bale Walls, by D. Riley, G. MacRae, and J.C. Ramirez, 1998. Contact Prof. David Riley, Dept. of Architectural Engineering, Penn State, 104 Engineering Unit A, University Park, PA 16802, 814-863-2079, <driley@engr.psu.edu>.

Moisture in Straw Bale Housing - Nova Scotia, by S.H.E. Consultants, 1998. Contact S.H.E. Consultants, RR#3, Comp. 308, Wolfville, Nova Scotia, Canada, 902-542-3518. *Blower door tests on several bale homes, and a "refining" of the term "breathable walls."*

Investigation of Environmental Impacts: Straw-Bale Construction, by Ann V. Edminster, 1995. Contact Ann Edminster, 115 Angelita Ave, Pacifica, CA 94044, <avedminster@earthlink.net>

Evaluation of a Straw Bale Composite Wall, by Edwin R. Schmeckpepper and Joe Allen, 1999. Contact Joe Allen, PE, Allen Engineering, 917-10th Street, Clarkson, WA 99403. *Tests performed on an unusual light-gauge steel/straw bale wall system.*

6) Code Testing Video

Straw Bale Code Testing, Black Range Films 1996. This video documents the AZ compression and lateral loading tests (3-string bales), the 1993 Nova Scotia moisture testing, and the NM lateral load and E-119 fire tests (2-string bales) with very positive results. Includes interviews with code officials. Available from Natural Building Resources www.StrawBaleCentral.com.

This list was compiled by Chris Magwood, with extensive help from Mark Piepkorn, Lars Keller, André de Bouter and many of the testers themselves.

Testing at EBNet

The Ecological Building Network (EBNet) "works to transform the way we construct shelter for the sake of these and future generations." Based in California, the non-profit EBNet has received funding to undertake a wide range of tests on bale walls. The total available funding is $250,000 - $200,000 from the California Department of Food & Agriculture, and $50,000 from EBNet, CASBA (the California Straw Building Association), the New Mexico(SBCA) and Nebraska(SBAN) straw-bale building associations, and many individuals.

All testing includes a thorough survey of similar or relevant tests done to date; each individual test will be written up as soon as possible and made available via the EBNet website as PDF documents. Wherever possible, tests will mimic or conform to ASTM standard tests. Ultimately, the entire program results will be combined into a single text, "Design of Plastered Straw Bale Structures," to be authored by Bruce King and John Straube, and due out in mid-2003.

Visit www.ecobuildnetwork.org/ for up-to-date results of their full testing program.

A Straw Bale Building Bibliography

There are many excellent published resources on straw bale construction, some concentrating on hard construction data, others on design and photographs of bale homes. Below are the main texts in the field:

Bainbridge, David A., Athena Swentzell Steen and Bill Steen. The Straw Bale House. Chelsea Green Publishing Company, 1994. ISBN 0-930031-71-7.

Bruce King, Bruce P.E. Buildings of Earth and Straw: Structural design for rammed earth and straw bale architecture. Ecological Design Press, 1996. ISBN 0-9644718-1-7.

Corum, Nathaniel. Building One House: A Handbook for Straw Bale Construction. Red Feather Development Group, 2004. P.O. Box 907, Bozeman, MT, 59771-0907, USA.

Gray, Alan, Ed. Strawbale Homebuilding. Earth Garden Books, 2000. ISBN 0-9586397-4-4

Jones, Barbara. Building with Straw Bales: A Practical Guide for the UK and Ireland. Green Books, 2002. ISBN 1-903998-13-1.

Lacinski, Paul and Michel Bergeron. Serious Straw Bale. Chelsea Green Publishers, 2000.

Lerner, Kelly and Pamela Wadsworth Goode, Eds. The Building Official's Guide to Strawbale Construction, Version 2.1. California Straw Building Association (CASBA), 2000. P.O. Box 1293, Angels Camp, CA,95222-1293, USA.

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Myhrman, Matts and S.O. MacDonald. Build It with Bales, Version 2. Out on Bale, 1997. ISBN 0-9642821-1-9.

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Structural Considerations for Load-bearing Design

By Dr. Kris Dick,
University of Manitoba

The following paper appeared in Issue #40 of The Last Straw Journal, *Winter 2002. Reprinted with permission. The paper is based on the plans for the Siegel/ Cochrane house in Severn Township, Ontario, a 1 1/2 story, load-bearing straw bale residence.*

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Introduction. The design process and parameters used for the Seigel/ Cochrane residence is considered to be a combination of generally established theory and information obtained from full-scale testing. Since this structure falls under Part 4 of the Ontario Building Code-1997 (OBC97) analysis and design procedures will be linked to these requirements.

Before proceeding to specific design details, it is important that the fundamental concepts behind the type of load-bearing straw-bale wall construction used for this project be presented. Figure 1 illustrates a typical section through the straw-bale wall used for the Seigel/Cochrane residence.

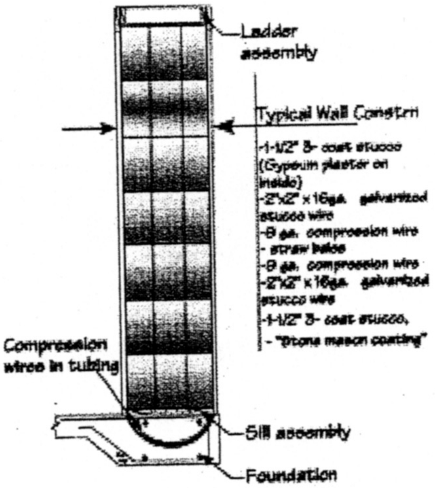

Fig.1: Section Through Strawbale Wall

Wall Assembly. As illustrated in Fig. 1, the wall assembly is comprised of Portland cement and lime-based stucco (1:1:6) applied to each side of a straw-bale wall. The straw bales used for this project are approximately 18x14x35 inches(460x355x890mm). The type of straw used is oats. The bulk density of the bales is specified to be in the range of 6.5-7.5 pounds per cubic foot(111kg/m³).

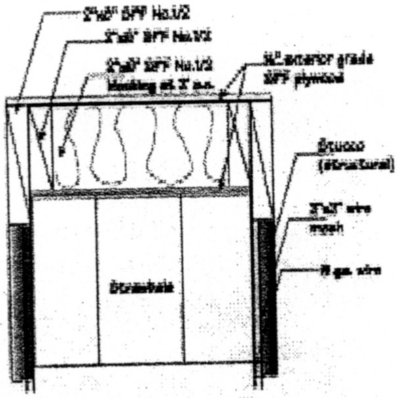

Fig. 2: Ladder Assembly

Compression. Once the bale wall is constructed, a ladder assembly is placed on top of the wall around the entire perimeter of the structure. The ladder assembly is fabricated from dimensional lumber and exterior grade plywood (Fig.2). The ladder fits over the top of the bale wall, with the outside 2x8in (40x200mm) dimensional lumber extending below the top of the bales, as illustrated. A 9-gauge galvanized wire passes between the 2x6(40x150mm) and 2x8 on each side and is looped over the top. This wire encompasses the entire height of the bale wall. It is threaded through the tubing sleeve in the concrete (Fig.1), over the top of the ladder assembly and is overlapped on the inside of the wall where sufficient length is provided to grasp the wire with a fence stretcher. Once the wires have been installed at a spacing of not greater than 4ft(1.2m) on center, a fence stretcher is used to apply a tensile force to this loop. As a result, the bale wall is compressed,

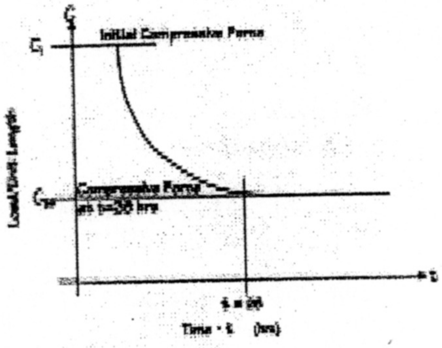

Fig. 3: Precompression vs. Time - Oat Straw
(Source: Arbour, 2000)

deforming a vertical distance. The specifications for this project indicate that once the initial compression phase is completed the wall must be allowed to settle for a minimum of 24 hours. This timeframe is based on research that indicates oat straw takes approximately 24-26 hours to redistribute the applied compression force (Arbour, 2000). The research also indicates that this reduction does not occur as a result of further deformation. Thus, using oat straw within the specified density range, a deformation criterion appears acceptable for design. The average value for the load-carrying capacity of the wall at the point at which the curve becomes horizontal (C26) was 400 pounds per lineal foot (plf).

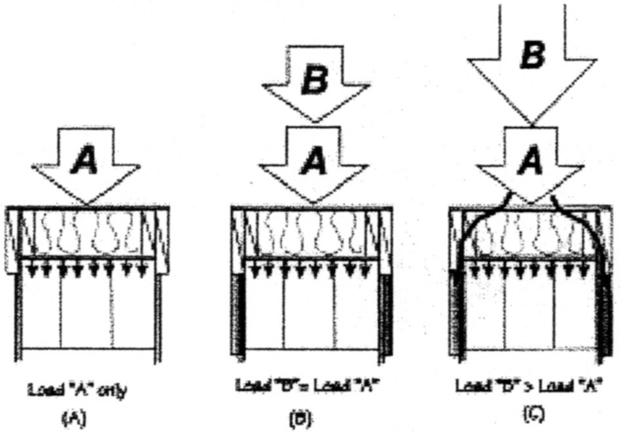

Fig. 4: Load Transfer into Wall System

Figure 4 illustrates the concept behind a load-bearing straw-bale wall. A precompression force "A" is applied to the wall prior to any stucco application (Fig. 4A). The straw bales in the wall will continue to "see" this load or, in other words, provide load carrying capacity equivalent to the precompression force. Once the stucco process is complete, subsequent loading "B" can be applied. As load "B" is increased, the wall system does not react to it until load "B" approaches the magnitude of the precompression force - load "A" (Fig. 4B). Once load "B" is in excess of "A" it is assumed to follow a load path through the stucco skin (Fig. 4C).

Design Process. Three fundamental structural parameters are evaluated in the design of a load-bearing straw-bale wall. The wall must provide resistance to: (i) vertical load, (ii) lateral load and, (iii) racking resistance.

Vertical Load. The wall must support gravity and live loads from the second floor and roof system. The load applied to the top of the wall through the ladder follows a load path through the stucco skin, as described in the previous section and illustrated in Fig.5. A theoretical load capacity may be determined based on the following design assumptions:

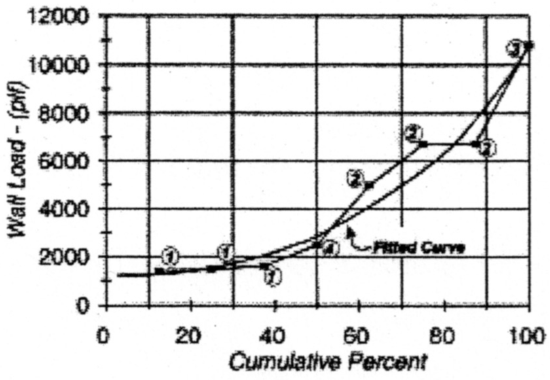

Fig. 5: Vertical Design Load Plot

(Source: 1) Grandbaert, 1999. 2) Carrick, 1998. 3) Theoretical. 4) Dick, 2002)

(i) Unreinforced, type N mortar with a compressive strength of 750 psi(5.17MPa). A value of 300 psi(2.06 MPa) will be used for theoretical values.

(ii) Stucco skins that are 1-1/2in(38mm) thick on each side and reinforced with 16 ga. galvanized 2x2in(50x50mm) wire mesh on the inside face.

(iii) The skins are laterally supported with ties each way that are fastened to the wire mesh on each side and pass through the straw bales. The ties are spaced at not greater than 16in(400mm) on centre each way, linking the two skins together with straw sandwiched in between.

Using the assumption of 300 psi for the compressive strength of the mortar in conjunction with a 1-1/2in stucco skin on each side of the bale wall, a theoretical strength may be determined for one lineal foot of wall, as follows.

For every lineal foot of wall there is:

$$\left(\frac{1.5\text{in}}{12\text{in}} \times 1\text{ft}\right) \times 2 \text{ skins} = 0.25\text{ft}^2 / \text{ft of wall}$$

Based on a 300 psi compressive strength,

$$300\,\frac{\text{lbs}}{\text{in}^2} \times 144\,\frac{\text{in}^2}{\text{ft}^2} = 43200\,\frac{\text{lbs}}{\text{ft}^2}$$

A theoretical vertical load-carrying capacity may be determined as:

$$\text{TheoreticalValue} = 43200\,\frac{\text{lbs}}{\text{ft}^2} \times 0.25\,\frac{\text{ft}^2}{\text{ft of wall}} = 10{,}800\,\frac{\text{lbs}}{\text{ft}}$$

Figure 5 contains a plot of vertical load values obtained from various test results and theoretical calculations. The design value used for the Seigel/Cochrane residence was 2000 pounds per lineal foot(plf)(3000kg/m). Based on the data contained in Fig. 5, this represents approximately the 40th percentile. The largest factored wall load encountered in the design of the residence was 1200 plf. This represents approximately 60% of the design value. Tests conducted at the University of Manitoba in January 2002 indicate that the design value used for the Seigel/Cochrane residence is considered to be acceptable.

Lateral stability of the stucco skins is considered to be provided by the ties that run through the bale wall, connecting the wire mesh on each side of the wall together (Fig.10). A nominal load of 300 plf(450kg/m) is considered to be carried by the compressed bales. This leaves 900 plf(1350kg/m), or 450 plf(675kg/m) along each stucco skin. Based on a 16-inch tie spacing and a 5% lateral force[1], the ties are required to provide 30 pounds resistance, which is

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[1] 5% of the wall load is considered a conservative value when compared to wood or steel design that typically uses 2% of the axial compressive force to represent the lateral bracing force.

considered to be provided with this system. Since the stucco skins act as a compression member, this restraint provides for lateral stability of the wall system. With a tie-spacing of 16-inch on center, the slenderness ratio is then determined to be:

$$\text{Slenderness Ratio} = \frac{1}{0.3h} = \frac{16\text{in}}{(0.3 \times 1.5\text{in})} = 35.5$$

Based on slenderness criteria as prescribed in Clause 10.15.2 in CSA-A23.3-M94, slenderness effects are not considered to be critical to the overall performance of the wall system.

Lateral Load - Wind. Wind acting on the structure requires the wall system provide resistance to lateral loading. This loading can create conditions the wall system must resist: (i) Flexural stress and deformation in a wall when the load is transverse to the wall face, and (ii) Shear stress in walls parallel to the direction of the wind.

Flexural Stress in Wall Panel. Flexural stresses are created in the wall system as a result of the external and internal pressures as a result of wind acting on the structure (Fig.11). Based on Section 4.1.8 of the NBCC-1995, the reference velocity pressure for the Orillia (Ontario) area is given as: $q_{1/30} = 0.32$ kPa (6.68 psf).

The specified external pressure was determined to be[2]:

$$p = q \times C_e C_p C_g$$

$$p = 0.32 \times 0.9 \times 1.3 = 0.37 \text{ kPa } (7.8 \text{ psf})$$

The specified internal pressure was determined to be:

$$p_i = q \text{ X } C_e \text{ X } C_g \text{ X } C_{pi}$$

$$p_i = 0.32 \text{ X } 0.9 \times 1.0 \text{ X } 0.7 = 0.2 \text{ kPa } (4.2\text{psf})$$

Based on the above loading, the wall is subjected to a total of 12 psf. Using a 1ft(300mm) strip of the wall, a uniformly-distributed load of 12 plf was used to determine the simply-supported bending moment in the wall. In the determination of the flexural stress, the moment of inertia of the wall assembly must be considered. The moment of inertia used in the design of this structure was calculated to include the stucco skins and a portion of the straw acting as a unit. It is apparent from both research and anecdotal evidence that there is a significant bond established between the stucco and the straw. For the purposes of a design check, however, it was considered appropriate to use only the stucco skins in the moment of inertia calculation. The moment of inertia for the section was determined to be:

Based on the following assumptions:

- a wall height of 8ft(2.4m),
- a live-load factor of a_L=1.5,

$$I = \left(\frac{bd_1^3}{12}\right) - \left(\left(\frac{bd_2^3}{12}\right)\right)$$

$$= \left(\frac{12 \times 21^3}{12}\right) - \left(\left(\frac{12 \times 18^3}{12}\right)\right) = 3429 \text{ in}^4$$

- neglecting the straw's contribution to the moment of inertia,
- neglecting any precompression in the bales due to the assembly process and dead weight of the roof, and,
- a simply-supported moment, the flexural stress was calculated as:

$$\sigma_f = \frac{M\,y}{I} = \frac{\left(\left(\frac{1.5 \times 12 \times (8)^2}{8}\right) \times 12\right) \times \frac{21}{2}}{3429} = 5.3 \text{ psi}$$

The resulting flexural stress is considered to be minimal. If the maximum tensile stress in the mortar is limited to 5% of the compressive design stress, then the maximum allowable stress in tension would be 300 psi x 0.05 = 15 psi. Thus, the design meets this criterion. If the straw component is included in the moment of inertia calculation the flexural stress becomes 2.9 psi.

The mid-height deflection was calculated based on an moment of inertia that only included the stucco skins. A composite modulus of elasticity Ecomp for the stucco/straw assembly was taken to be 82,650 psi (570 MPa) based on relative areas of straw and stucco (E value of straw based on Watts, 1995). The mid-height deflection was calculated based on a simply-supported flexural member and found to be:

$$\triangle = \frac{5\,wl^4}{384EI} = \frac{5 \times 12 \times (8 \times 12)^4}{384 \times 82{,}650 \times 3429} = 0.047 \text{ in.}$$

This value corresponds to a deflection with respect to wall height of L/2042, well within acceptable limits.

Shear Resistance in Wall Panel. Shear forces may be present in a wall panel as a result of lateral forces applied to the face of a wall due to wind, and also from load transfer into end shear walls. The bond between the stuccoed skin and straw substrate in straw-bale walls provides considerable shear resistance. Shear has been researched based on both shear flow (force per unit length - plf) and shear stress (force per unit area - psf). The following represent examples of typical values for these shear parameters:

Shear Flow: - 750 plf (White and Iwanicha, 1997)
- 1005 plf (Boynton, 1999)

Shear Stress: - 42 psf (Riley et al., 1998)
- 60 psf (Dick and Britton, 2002)

Within the context of the Seigel/Cochrane project, the factored shear at the stucco/straw-bale bond for the wind load discussed in the previous section was determined to be 27.21 plf (shear flow) or 0.1 psi (shear stress) for a 1-foot wide strip of wall.

These values are considerably below test results and were considered to be acceptable for the design of the Seigel/Cochrane structure.

Shear Flow = f =

$$\frac{V\,Q}{I} = \left(\frac{48 \text{ lbs} \times 162 \text{ in}^3}{3429 \text{ in}^4}\right) \times 12 \;\frac{\text{in}}{\text{ft}} = 27.21 \text{ plf}$$

$$\text{Shear Stress} = t = \frac{V\,Q}{Ib} = \left(\frac{48 \text{ lbs} \times 162 \text{ in}^3}{3429 \text{ in}^4 \times 12 \text{ in}}\right) = 0.19 \text{ psi}$$

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[2] The above relationship assumes the end section 1E with wind predominantly perpendicular to the ridge of the structure as per Fig.B7, NBCC supplement.

Conclusion. The basis for key aspects for the design of the Seigel/Cochrane straw-bale residence have been presented in this report. Based on theoretical calculations and research data, it is the opinion of the designers that the structural integrity of the straw-bale building discussed herein will meet or exceed the requirements for imposed loading for the Seigel/Cochrane residence in Severn Township, Orillia, Ontario.

References. *See testing documentation article, pg 16.*

Moisture Control in Straw-Bale Construction

by Chris Magwood

This article is adapted from an article in Issue #40 of The Last Straw Journal, *Winter 2002. It is reprinted with permission. It is based on the plans for the Siegel/Cochrane residence in Severn Township, Ontario.*

Straw-bale Characteristics and Moisture. Straw shares a similar chemical composition with wood, being a cellulose fiber. In a prior report to the Ontario Building Code Commission (99-56-712), building envelope engineer John Straube characterized the moisture-retention properties of straw bales as follows:

> "Several tests of the properties of the straw bales themselves have been conducted. In many respects, straw bales behave like cellulose insulation, sawdust, or wood shavings, cellulose-based materials with which we have many years of widespread experience in cold, warm and mixed climates. The advantage of straw is the tubular shape of its stalk. This creates more void ratio for the same density of cellulose material and provides good R-value as well as reduced capillary suction, e.g, straw bales do not "wick" water very effectively. The very limited capillary suction of straw means that a separate capillary break in the form of building paper is not strictly necessary (water will definitely not wick from the exterior stucco to the interior).
>
> "Water vapour is stored in straw bales in the same way as wood or cellulose insulation, e.g., in the winter the equilibrium moisture content will be about 8-12% moisture content by dry weight, and the moisture content can rise to at least 20% before moisture problems begin. Hence, for an 8 pcf bale, more than one pound of water in vapour form can safely be stored per square foot of wall area.
>
> "...The ability of a wall assembly to store moisture may be an important measure of its durability because storage acts as a vital buffer, or capacitor, between deposition and removal of moisture. However, if the volume of stored water exceeds the safe level for a material and is present for long enough, deterioration can occur, i.e., rot of wood and straw, freeze/thaw damage of masonry, and corrosion of metal. Therefore, the two most important characteristics of moisture storage are: how *much* moisture can be stored and for what *duration* without crossing a performance threshold.
>
> "*Sorption* of water vapour by hygroscopic materials is an important storage mechanism. A significant amount of moisture can be stored within a porous material as water vapour molecules adsorb to the large internal surface areas of materials such as straw, wood, concrete and masonry. When a porous material has absorbed all the moisture it can, further moisture will be stored in the pores and cracks within the material by capillary suction, or by *absorption*. Only when all pores are filled with water is a material saturated.
>
> "Safe storage capacity depends on the material. Wood and straw can generally store about 20% moisture by weight without danger of mold growth. ...The ability to safely store significant amounts of moisture means that the drying period can occur a long time after wetting, perhaps several months. This improves the chance of a moisture balance being struck."

While a 15-20% moisture content is accepted and used as the maximum allowable in bale construction, actual extractions of straw from walls displaying moisture content readings of greater than 20% often showed no signs of wetness, mold or decay (Rob Jolly, 2000).

Straw, it can be summarized, does not display any unusual propensity for moisture damage in normal conditions in a wall system, and in fact shows many characteristics that enhance its moisture performance and drying ability. Therefore, if unusually large amounts of moisture are prevented from entering the wall on a continuous basis, straw walls will continue to perform with the same durability as wood and other cellulose products. Identifying potential areas in which large and continuous amounts of moisture can enter the wall is an important step to guarding against such conditions.

Moisture Sources in Straw Bale Walls.

(1) Capillary action. Straw bales do not display any meaningful capillary action (Straube, 1999 and S.H.E. Consultants, 1998). Moisture that is occasionally contained in the plaster skins after direct wetting is not readily "wicked" by the adjacent straw, and does not present a significant moisture control problem.

(2) Vapour Diffusion. Vapour diffusion into wall cavities occurs during any season when there is a difference in the absolute moisture content of the air, when vapour is "driven" into the wall. Continuous poly vapour barriers, used in standard frame construction, are not necessary to control vapour diffusion in bale walls, because both theory and practical testing have shown such barriers are not required to keep moisture levels in the bale walls well below acceptable levels. A 1:1:6 cement/lime/sand mixture at 40mm thick on a bale wall offered a permeability of 10.3 ng/Pa s m (or a

permeance of about 5.13 US Perms for a 40mm thickness) in laboratory testing. John Straube's studies into vapour diffusion in bale walls resulted in the following finding:

> "Vapour diffusion is not a concern for straw-bale homes because the interior plaster is able to resist a sufficient amount of vapour diffusion to control diffusion. ...The air barrier provided by applied reinforced stucco is excellent, better than most other systems. Laboratory tests have confirmed that the small cracks that typify a stucco finish are not big enough or continuous enough to allow significant airflow."

The moisture cycles noted in the two studies which monitored moisture content in existing bale walls both found that average moisture contents in all the homes examined reached their lowest levels during the winter months, when moisture content from diffusion *should* be highest.

"The graphs...show a fairly distinct curve of high MC in walls (all orientations) that begins in March and peaks in July, then falls through the heating season until December/January." (S.H.E. Consultants, 1998)

"Interior humidity control seemed to have little affect on exterior bale moisture content." (Rob Jolly, 2000)

These results indicate that very little vapour diffusion occurs through the interior plaster skin (even when untreated with paints), and what little vapour diffusion does occur is within the capability of the bales to manage, exiting the wall system through a natural drying process to the drier, exterior air.

> ***"There are no real technical obstacles to the use of straw bales in a manner that meets the intent of most building codes. Practical moisture-related concerns such as the need for air, vapour and rain control can be met."***
>
> **-John Straube**

While vapour diffusion through the skins is not a concern, direct air leakage *could* be. Several of the bale homes tested by S.H.E. Consultants were found to be very leaky, with the main areas of leakage being very similar to those in frame construction: electrical outlets, door and window openings, wall/ceiling junction, wall penetrations and those areas of the wall uncovered by plaster/sheathing. While none of the leaky homes showed actual moisture damage at the time of testing, proper construction details for avoiding such leakage in bale walls are available, and those used in the Seigel/Cochrane residence are outlined in this report.

(3) Direct Wetting. In field testing and monitoring, only those bale homes in which the walls were subjected to repeated, direct wetting showed any adverse moisture content results. Such conditions can usually be traced to poor design and/or construction detailing. However, because direct wetting can have an adverse affect on the moisture content of bale walls, these issues must be addressed seriously.

Rob Jolly's study resulted in the following list of potential design and detailing flaws to be avoided:

"i. Minimal or absent overhangs.
ii. No capillary break between foundation parging and above-grade stucco.
iii. Structures subject to extreme interior wetting without drainage.
iv. Below-grade bales.
v. Inadequate backsplash protection.
vi. Northern exposures."

John Straube concurs with the need to address direct wetting issues: "Precipitation, often the largest source of moisture in buildings, is always a concern for straw-bale buildings." He goes on to outline the performance of bales as "mass walls" under direct wetting conditions:

> "Providing a water-resistant barrier behind the stucco is not practical in straw-bale construction because it breaks the structural bond between the plaster and the straw bale and reduces the ability of a wall to dry outward. Hence, rain control in straw-bale walls employs the mass wall approach. The ability of a wall to store and dry rain water deposited on the surface is very important for mass wall systems, no less for straw-bale systems. The mass and absorption provided in every mass system must be balanced with the drying capacity and the exposure to driving rain. For example, split-faced concrete block is a highly absorptive, but highly massive, wall system. Provided such walls are not exposed to too much rain, they will not leak and they will dry out. It is for these same reasons that good drying capacity and reduced driving rain exposure are so important to straw-bale walls. Stucco is less massive, but less absorptive, than split-faced block.
>
> "Research and long experience have shown that overhangs are very effective in reducing the amount of rain deposition. Buildings, trees and terrain around a house can also provide significant protection. Finally, the closer to the ground a building is, the less driving rain deposition that occurs. Driving rain deposition can be reduced to such a level by even one or two of these measures acting alone that even the storage mass of the 25mm (1in) stucco skin can store the rain that penetrates and is absorbed. All straw-bale houses should control rain exposure through the use of generous overhangs, eavestroughs, and by keeping walls to two-storeys or less in height. The size of the overhang will depend on exposure and building shape, but a minimum of 400mm(16in) for a one-storey building and 600mm(24in) for a two-storey building is recommended by this author."

Keeping direct wetting from adversely affecting the walls and keeping the exterior sealed and flashed against direct leakage is largely a matter of following common construction practices and applying them appropriately to bale walls, as outlined in the following section.

Design of Seigel/Cochrane Residence Regarding Moisture Concerns. With an understanding of potential moisture concerns for bale walls, effective and simple construction details can be designed and executed to minimize risks.

> *"Laboratory tests have confirmed that the small cracks that typify a stucco finish are not big enough or continuous enough to allow significant airflow."*

(1) Vapour Diffusion. As vapour diffusion has not proven to be problematic for bale walls in our heating climate, the application of 40mm of cement/lime stucco (25mm is considered adequate) to the interior face of the bale walls, continuously, and overlapping the sill plates and door and window rough framing, is adequate protection against diffusion.

(2) Air Leakage. There are many potential points for air leakage from the walls of a home. The Seigel/Cochrane residence used the following strategies to minimize leakage:

2.1 Electrical outlets. Each electrical outlet fastened to a bale wall is shielded by a 6-mil poly vapour barrier wrapped behind the electrical box, sealed to the wires entering and exiting and extending a minimum of 75mm(3in) behind the plaster. The plaster around each box is reinforced with additional expanded metal lath.

2.2 Wall/Ceiling Junction. The transition between the plaster and the wood framing at the top of each wall is protected from air leakage by a 6-mil poly vapour barrier caulked to the interior face of the 2x6 (38x140mm) ladder assembly and extending down a minimum of 75mm(3in) behind the plaster and up to a caulked or taped seam with the vapour barrier used on the ceiling.

2.3 Wall/Floor Junction. In addition to extending the plaster over the sill plate into direct contact with the floor slab, the sill plate was caulked/glued to the slab during installation.

2.4 Window/Door Frames, Interior. The plaster finish is wrapped over the rough frame window and door bucks, covering any seam with the framing by a minimum of 38mm(1.5in). The plaster butts against the finished door or window frame, and is additionally caulked along this seam behind the final coat of plaster. Where the plaster is covering door and window rough frames, the wood is separated from the plaster with 6-mil poly or tar paper, and extra reinforcement is provided by expanded metal lath.

2.5 Other Wall Penetrations. Penetrations through the wall for plumbing, wiring, gas service and venting are made with PVC conduit through the bales, and the plaster seam around the conduit is reinforced with additional expanded metal lath and caulked behind the final coat of plaster. All plumbing, with the exception of hose fittings, was routed through interior, stud-framed walls.

2.6 Separation from Foundation. The bales are separated from the concrete foundation by a layer of 6-mil poly vapour barrier, 38mm sill plates with rigid insulation between the two plates, and another 6-mil poly vapour barrier.

2.7 Interior Drainage. The bale walls are built upon a 38mm(1.5in) sill, and adequate drainage provisions have been made in the slab floor to prevent water leaks in the building from accumulating to a depth greater than 38mm.

2.8 Mechanical Ventilation. In accordance with the Ontario Building Code requirements, a Lifebreath-brand heat-recovery ventilation system is configured and installed in the home by a professional installer. This system will prevent interior humidity levels from reaching levels that are potentially problematic.

(3) Direct Wetting.

3.1 Siting. The building is sited in a small clearing amidst dense and tall trees. The widest clearing between the house and the tree cover is on the south side. The tree cover is very close to the home on the north, east and west sides (3-10m). These sides of the home are well-protected from wind-driven rains.

3.2 House Design. The building presents only a one-story wall to the north, protected by minimum 600mm(24in) roof overhangs. The section of the building presenting two stories is on the southeast, protected by 600mm overhangs, where exposure to direct sun provides a suitable drying regime for the limited amount of rainfall blown from that direction. Rob Jolly's study concluded that "Walls with southern exposures were generally much drier than other exposures and were able to handle significantly more exterior wetting."

Gable overhangs on the east and west are also a minimum of 600mm. The base of the plastered walls is a minimum of 210mm(8in) from the adjacent grade, which is suitably sloped away from the building.

3.3 Window Sills. Framing for all window sills is sloped toward the exterior of the building, and all seams in the rough bucks are glued/caulked. Windows with built-in drip edges were installed, with the drip edge extending a minimum of 25mm (1in) from the face of the plaster below.

3.4 Base of Wall. The exterior wall base is protected by a continuous metal flashing that extends 50mm(2in) up the face of the straw wall behind the plaster, continues horizontally over the edge of the foundation and sheds water from a drip edge beyond the face of the foundation parging, preventing water from penetrating the seam between the wall and the foundation. The plaster covering this flashing was reinforced with additional expanded metal lath.

3.5 Window/Door Frames, Exterior. A drip edge flashing was installed over each door and window opening, extending 50mm(2in) up the face of the bales, behind the plaster. The plaster over these flashings was reinforced with additional expanded metal lath. Exceptions are made when tops of openings are less than 600mm(24in) from the top of the wall and well-protected by the roof overhangs.

3.6 Plaster Seam Between Floors. Between the first and second floor on the exterior, the plaster runs stop at the rails of the wooden ladder assembly. This seam is protected by appropriate flashings and caulking, and the plaster is given extra reinforcement by expanded metal lath.

3.7 Splashback Protection. Where roof

> ***"All straw-bale houses should control rain exposure through the use of generous overhangs, eavestroughs, and by keeping walls to two-storeys or less in height."***

water is shed on the north and south sides of the building, adequate eavestroughing has been specified to prevent splashback against the walls.

Drying. Regardless of the style of construction and the techniques used, some moisture will penetrate the wall system. The combination of plaster skin and straw bales is capable of storing a great deal of moisture, and of drying out through a combination of surface evaporation and vapour diffusion, as long as the exterior finish does not provide any barriers to the drying process. John Straube's report concludes that:

> "In practice, water that penetrates stucco (from any source) will evaporate, diffuse to the back of the stucco and either pass through to the exterior or condense on the back face. Any vapour that condenses will wick to the exterior surface from where it can quickly evaporate. This drying mechanism is one reason not to introduce building paper between the stucco and straw."

The Seigel/Cochrane residence uses an exterior plaster 40mm thick(1.5in), and composed of a 1:1:5 mixture of portland cement, lime and sand. This plaster strikes a balance between the low-absorption qualities of a cement plaster and the vapour permeability of a lime plaster, which allows for a drying regimen more than adequate for the minimal wettings the walls will receive.

Conclusion. Moisture management in straw-bale walls does not present a theoretical or practical barrier to use of the wall system in an Ontario climate. Experience and testing have both shown that moisture problems only arise when proper construction practices are ignored or improperly implemented. The Seigel/Cochrane house was designed and built with full knowledge of these issues, and appropriate steps were taken to provide the best possible solutions for managing moisture issues.

John Straube summarizes his report to the Ontario Building Code Commission on moisture management for bale walls this way:

> "In summary, there are no real technical obstacles to the use of straw bales in a manner that meets the intent of most building codes. Practical moisture-related concerns such as the need for air, vapour and rain control can be met."

The Seigel/Cochrane house blends the best of modern moisture control techniques with a wall system that has proven itself in testing and in practice to be capable of handling the moisture loading presented by our climate.

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Fire Safety: A Review of Testing and Experience

by Bob Theis - California, USA

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Introduction. We are accustomed to building our walls with extremely flammable material; wood studs with air spaces around each one burn extremely well. With this as the cultural baseline, our building codes do not typically concern themselves with, "Does it burn?" as much as they ask, "Can people escape while it's burning?"

These building codes express the fire safety of walls as a function of fire resistance, meaning how long a conflagration can exist on one side of the wall in question before enough heat is transmitted through the wall to ignite materials on the other side, even if fire has not actually breached the wall. So while a wall made, say, of a single slab of steel is not going to burn under normal fire conditions, it is not fire resistive because the heat of the fire would pass so quickly through it. The fire resistivity of a wall is expressed as a function of this time of heat transmission: a "one hour wall" has kept a set of flame throwers heating a furnace to over 1500°F (840°C) from heating the opposite side of the wall 250°F (139°C) over its initial temperature for one hour.

Bales Burn Badly. It seems counterintuitive that a bale wall would increase the fire safety of a building, as the straw is so obviously flammable. However, fire requires high temperatures, fuel, and oxygen; compressing the straw into a dense block dramatically decreases the ability of oxygen to feed a fire at the straw. After the surface of a bale or bale wall has been charred (providing that the wall of exposed bales remains intact), the worst it will generally do is smolder. Fire departments actually utilize this quality, and ignite wire tied bales as smoke generators for training exercises.

Plaster Produces Permanence – Laboratory Test Results. In general, once a bale wall has been plastered on both faces, the combination of an incombustible surface and an insulative interior that neither burns well nor melts makes a straw bale wall a very fire resistive assembly. This has been verified in the lab tests to date:

1) 1993. Two small scale ASTM E-119 fire tests at the SHB Agra lab in Sandia, New Mexico – one test wall with plastered faces, the other bare bales – showed bales to be very fire resistant. The unplastered bale wall withstood the heat and flames of the furnace for 30 minutes before flames penetrated a joint between bales. The plastered bale wall was naturally much better, resisting the transmission of flame and heat for two hours.

2) 1996. A full scale ASTM E-119 fire test at the University of California Richmond Field Station easily passed the criteria to qualify as a one hour wall. In the opinion of the experts present at the test, the wall would probably have passed as a two hour assembly.

3) 2001. The Appropriate Technology Group at Vienna Technical Institute conducted an F90 test (similar to the ASTM E-119 test), which gave a plastered straw bale wall a 90 minute (1.5 hour) rating.

4) 2001. The Danish Fire Technical Institute tested a plastered straw bale wall with exposed studs on the fire side as a worst -case scenario, and got these results: in a 30 minute test with an 1832°F (1000°C) fire on the exposed side, the unexposed side rose just 1.8°F (1°C). The maximum average increase permitted to pass the test is 144°F (80°C).

5) 2002. Bohdan Dorniak and members of AUSBALE tested individually plastered bales to the Australian standard simulating the heat of a bushfire front. Subject to a maximum heat intensity of 29 kilowatts per square meter, none of the nine plastered bales ignited, or even developed visible cracks. According to Mr. Dorniak, this qualifies them as non-combustible under the current Australian Bushfire Code AS 3959.

Flame Spread and Smoke Density. The issue has sometimes been raised that bales inside a wall should conform to the code criteria for insulation, which specifies minimum surface burning characteristics based on a standard test (ASTM E84-98). According to Professor R. Brady Williamson, who was one of the authors of this section of the Uniform Building Code (UBC section 707), this notion is misguided, as this part of the code is meant to address insulation installed within a cavity in a wall, whereas in typical straw bale construction the insulation is the wall, more like the situation in a log cabin. With no concealed draft tunnels for fire to rise up through, surface burning characteristics, as measured in what is commonly called a "tunnel test", are not especially relevant.

In some buildings, though, people have indeed inserted bales between extra deep "studs" to construct walls. With that in mind, Katrina Hayes sponsored an ASTM E84-98 test on straw bales in 2000 at the Omega Point Laboratories. They passed the test easily; where the Uniform Building Code allows a flame spread rating of no more than 25, the test produced a flame spread of 10; where the codes allows a smoke density rating of no more than 450, the bales produced a smoke density of 350.

Still, It Burns; Field Reports. The author has collected 14 reports of fires in straw-bale buildings during and after construction. These range in severity from the inconsequential flash of flames across the loose surface straw of an unplastered wall, to the complete loss of the structure.

This field data begins to indicate where the most fire danger resides in straw bale construction. If sorted by stage of construction and extent of damage:

- 11 fires occurred during construction; of them, 6 had local damage; 5 were a total loss.
- 3 fires occurred after occupancy; of them, 2 had local damage; 1 was a total loss.

However, the best single correlation with extent of damage seems to be whether the plaster was in place at the time of the fire:

- 6 fires occurred after plastering; of them, 5 had local damage; 1 was a total loss (in which the fire began in the roof framing)
- 8 fires occurred before plastering; of

them, 2 had local damage; 6 were a total loss.

The most typical pattern of fire, reported in 5 instances, was where a construction activity ignited loose straw on the ground, which ignited loose straw on the surface of an adjacent wall. Regardless of the source of fire, in all 5 instances in which a fire climbed an unplastered wall on which framing lumber stood unprotected, the framing ignited, and complete loss of the structure resulted. In the 2 instances that were timed, the collapse of the roof occurred within 25 minutes of the fire's beginning.

In at least 5 of the reported fires, the fire smoldered in the spaces between bales, and was difficult or impossible to fully extinguish with a water hose. New protocols for dealing with this new kind of fire are evidently necessary, because in most of these smoldering instances, substantial sections of sound wall were demolished simply to get at the fire in the crevices.

Understanding the Hazard. Most needed, however, is universal knowledge of the basic safety measures that have become standard on straw bale construction sites.

1. Make certain everyone on site, but especially tradespeople, understand the flammability of exposed straw, and that extra precautions are required.

2. Remove all loose straw from the site during construction. The straw on the ground must be removed continuously.

3. Have pressurized water hoses at ready everywhere on site. It must be within one minutes' access to make the difference in controlling the start of a fire.

4. Stuff the vertical cracks between bales with clay-coated, not loose, straw, to reduce its ability to smolder. Trimming the bulges at the ends of bales prior to stacking substantially reduces the amount of this stuffing required.

5. Get the initial plaster coat on the bales as soon as possible. The practice of precoating the bale surfaces that will remain exposed, prior to stacking, while not yet widely practiced, would reduce fire vulnerability tremendously (see TLS#44, about pre-dipping bales in clay slip).

Conclusions. Our knowledge of the fire resistive properties of straw-bale construction is incomplete, but tests and field experience to date have been very encouraging. Most of straw-bale construction to date has been low density single family dwellings, which the building code allows to be built with essentially zero fire resistance. Within this context, fire safety concerns simply don't come up as a significant issue; the standard, as set by wood frame construction, is very low.

Fire safety concerns rise as building and population density increase, but straw-bale construction would require little or no additional testing to be readily acceptable for uses such as urban infill, row housing, commercial, retail, and educational buildings. There, the additional attributes such as its excellent acoustic insulation would also be appreciated.

Straw-bale construction has achieved its remarkable growth in use largely due to its aesthetic characteristics, its environmental credentials, and its excellent insulation value. In all these aspects, it compares favorably with stud construction. Those of us who have worked with it for years find it, in fact, a far superior wall system, whose potentials are barely tapped. When its fire resistive qualities are better known, we may see new economies realized where it can, for example, be substituted for concrete block, or remove the need for fire safety measures such as sprinklers.

Published straw bale fire tests:

1. Transverse Load Test and Small Scale E-119 Fire Test on Uncoated Straw Bale Wall Panels and Stucco Coated Wall Panels, 1993 by Bryce Simons, P.E. of SHB Agra, Inc. Available from Natural Building Resources, 505-895-5652; www.strawbalecentral.com

2. ASTM E84-98 Surface Burning Characteristics, (on) Straw Bale 2000 by Guy Haby and William E. Fitch, P.E. of Omega Point Laboratories, Inc. Available from Development Center for Appropriate Technology (DCAT), 520-624-6628; www.azstarnet.com/~dcat

3. Wall Systems of Renewable Resources ("Wandsysteme aus nachwachsenden Rohstoffen") which includes an F90 (European fire resistivity test) and B2 (European flammability test), 2001 by Robert Wimmer, Hannes Hohensinner, Luise Janisch and Manfred Drack of the Gruppe Angepasste Technologie (GrAT) an der TU Wein (the Appropriate Technology Group at Vienna Technological University); posted (in German) as a PDF document at www.grat.tuwein.ac.at