STRAW IS STRONGER THAN CAMELS
Structural Tests on a Straw Bale Wall

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SUMMARY

The use of straw bale construction is continuing to spread faster than the understanding of its physical properties. This is leading to some failures, but also to under-utilisation of the abilities of straw as a sustainable material. Recent research undertaken at Victoria University of Wellington demonstrates the potential of straw to perform structurally and to minimise use of other construction materials.

INTRODUCTION

We all know that if you keep adding straw to the camel's load, there comes a point where the camels back will break. But what happens if the straw is arranged in such a way that it is actually being of structural assistance? Could the straw act as a beam to transfer the load directly over the hips and shoulders of the long-suffering animal?

In New Zealand, since the introduction of straw bale building in 1993, most of the straw bale buildings built have been of the post and beam type, using a structural frame, usually of timber, with the straw used as infill and for insulation. A few buildings have used the ability of baled straw to carry compression loads, successfully carrying the roof on pre-compressed bales. Where a load-bearing method has been used, the degree of pre-compression has been largely by guesswork.

During recent research at Victoria University of Wellington, it was found that not only does a wall of baled straw have ample strength for the vertical loads of domestic construction, but that it is also capable of resisting some shear forces and providing the web component of a large beam, and is amply capable of resisting face loads.

Consistent with baled straw being regarded as, and often chosen as an environmentally benign material, a tensioning system that also aimed at minimising environmental impact was investigated. Used car seatbelts proved an effective and simple method of providing the necessary compressive pre-load to straw bale walls.

METHODOLOGY

Sample straw bale walls were constructed using locally grown barley straw. A series of tests was conducted to determine the

$ moisture content of the selected bales
$ tensile strength of used car seat belts
$ best attachment method of seat belts to foundation and bond beams
$ compressibility of the straw under varying loads
$ vertical load capacity of the straw bale wall
$ racking load capacity of the straw bale wall
$ potential for beam action of the straw bale wall
$ face load capacity of the straw bale wall

Bale Moisture and Density

The moisture content of the bales was established by weighing a sample bale that had been shortened to about 2/3 its normal length, then oven drying and re-weighing the sample. The density of the bales used was thus also established. The original weight of a standard 900 x 450 x 350 bale was 17.5 kg. After drying in an oven at 60 C for 15 days, the weight had stabilised at 14.6 kg. The calculated original moisture content was thus 16.6% and the dry density 120 kg/m^3. This compares to a minimum density requirement in the California Straw Bale Code of 112 kg/m^3. The density of the bales used was, however, at the lower end of an acceptable range for the structural loads placed on the bales. Because there is a natural variation in the density of bales, the use of relatively loose bales for the testing gave added confidence about extrapolating the results for general application.

Seat Belts

Aside from the principal attribute of considerable insulation value, straw bale as a wall material has two other advantages that prospective owners mention frequently: low cost and low environmental impact. Unfortunately, the low cost aspect is frequently overstated. The low impact aspect is more easily justified. In keeping with these two desirable aims, real or perceived, used car seat belts were used as a readily available, cheap and low impact method of providing a compressive load to the bales.

A selection of used seat belts was tested to failure to ascertain stretch and ultimate strength of the average used seat belt. New seat belt material from a local manufacturer had an average breaking load of 24.8 kN (2.53 tonnes). Stretch, or elongation, was 13.5% at a load of 10 kN. (Wardle, 1994) The observed behaviour of samples tested by the authors showed stretch to be essentially linear for all samples. It may thus be assumed that the stretch for new belts was 1.35% per kN.

A selection of 3 used belts was tested which were in good visual condition, without obvious fading or chaffing. The average breaking load for these used belts was 13.3 kN (1.36 tonnes), with a minimum breaking load among the three samples of 12.5 kN (1.28 tonnes). The average stretch for the samples was 1.7% per kN

Used seat belts with visible fading or chafing performed less favourably, with an average breaking load, from a sample of 4, of 7.6 kN (0.78 tonnes)

Long-term creep of a loaded seat belt was not tested.

Seat belts from an inertia-reel unit typically have a steel eye sewn to one end, with the other end free. The sewn eye system proved to be the strongest anchorage system, exceeding the strength of the seat belt web. The existing eye attachment was used for the connection to the 'foundation' plate. Attaching another sewn fitting to the upper end was impractical for the nature of the testing, and would be awkward and expensive for a real building site. It was found that a small standard nail plate was effective at securing the seat belt to the timber top plate. A variety of nail plate sizes was tested at various angles to establish the capacity of this attachment type.

Nail plates were applied over the seat belt web and nailed into pinus radiata timber. It was found that a nail plate of 40mm width, with 4 rows of 5 teeth each was able to withstand a load of 4.9 kN, when applied to the belt in its unloaded state. If a load was applied to the belt before the nail plate was applied, the failure load increased to 6.9 kN. There was significant variation in failure load due to the moisture content of the timber, with an increasing load capacity as the moisture content reduced.

A significant out-of-plane or off-vertical variation in angle could be accommodated by the nail plate anchorage without serious loss of load capacity.

The failure mode for the nail plates was separation form the timber, especially for wetter timber, if the plate teeth were oriented in rows across the belt. This orientation presented a maximum surface area of the flat-sided nails across the direction of force. When the nail plates were oriented with the teeth parallel to the direction of force, the mode of failure was tearing of the web from under the plate. This latter failure mode was at a considerably lower load.

During testing of the straw bale wall the nail plates were used singly to secure the top end of each belt to the side of the top plate, with a second nail plate used for safety, positioned on the top of the top plate. Seat belts were tensioned on the sample straw bale wall by means of a common hydraulic bottle jack, applied between the top plate and the knotted ends of the seat belts rising up each side.

The nail plate and seat belt method proved quite satisfactory in use, and is consistent with the simple construction procedure of straw bale walls that is able to be tackled by construction novices. In New Zealand the owner-builder method is currently common for straw bale buildings, and likely to remain so for some time.

TESTS AND RESULTS

The traditional method from the pre-1900 origin of straw bale buildings was load-bearing construction. After stacking the bales the roof was placed on the wall, relying on the weight of the roof to compress the bales. Settling was normally complete after a few weeks. The early houses constructed in this 'Nebraska style' (Steen et al, 1994) survive in good condition, indicating that the cycling loads and atmospheric moisture extremes of winter snow roof loads and dry summer can be successfully tolerated by load bearing straw bale walls.

When a post and beam frame is used with straw bale infill the normal practice in New Zealand has been to attach the bales to the frame by means of ties of some sort to keep them firmly in place. In addition, pins are usually placed vertically within the various courses of stacked bales to add to the face load resistance of the wall. This is sufficiently successful, but often results in a wall that can have some movement in it, and does not have a great resistance to seismic loads.

Precompressing a load bearing straw bale wall avoids having to wait for settlement before surface finishing takes place. More importantly it stiffens up the wall. Precompression is also a feasible and more successful option for stiffening up the straw in a post and beam wall.

Compressive tests

Compressive tests were undertaken by the authors on a wall section 3 1/2 bales long (3.3m) and 5 bales high (1.8m). (Figure 1.) Load was applied by 2 hydraulic rams with the load distributed evenly over the wall. Load was applied and released 3 times. Each successive loading resulted in increased deflection for the same load.

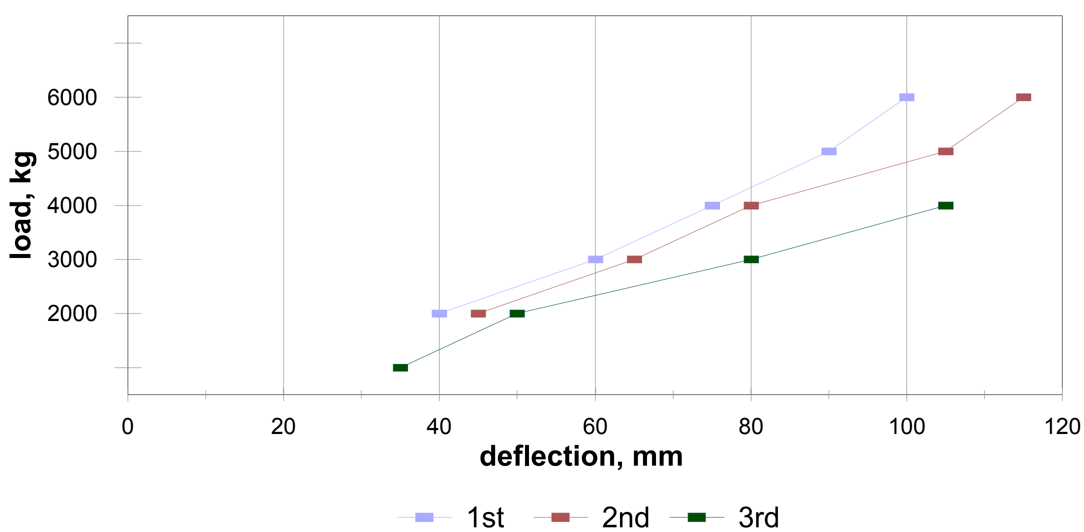

Figure 1. Vertical load / deflection tests

After each of the 3 tests the wall recovered its full height when the load was released. After some weeks under load, however, the wall recovered only about 40% of the deflection when the load was released. Each test demonstrated a rising stiffness in the straw with increasing load.

Two North American codes, the Tucson/Pima County Straw Bale Building Code, and the California State Straw Bale Building Code give the maximum dead plus live load for a straw bale wall as 360 and 400 lbs per square foot respectively (17.24 to 19.15 kPa)(Eisenberg, 1996). This equates to between 790 and 880 kg per linear metre of wall, using standard 'small' 450mm wide bales. At such compressions deflection is predicted by the codes to be around 3%.

The vertical load / deflection tests performed by the authors showed a compression ranging from 3.2% to 4.2% approximately at a load of 835kg per linear metre of wall. The relatively low-density bales used in the tests account for this slight discrepancy with the 3% predicted by the codes.

Given an expected maximum dead plus live load of up to 880kg per linear metre, a pre-compression load of 1000kg would provide the necessary compression. At a load of 1000kg per linear metre of wall, the deflections were 3.8%, 4.1% and 5.2% respectively for the successive tests.

Tests have not been performed to establish how straw behaves after many repeated cyclic loads, or whether it creeps under constant high load. The examples of early Nebraska straw houses suggest that straw walls stabilize after initial compression (Steen et al, 1994).

Racking tests

A series of in-plane racking tests was performed by the authors on the constructed wall. (Figure 2.) The limit of 60mm deflection was imposed on the test by the size of the test wall and the available test equipment.

It can be seen that increasing pre-compression, or pre-load, increases the shear resistance of the wall. In each case there was a reducing resistance to shear with increasing load. In the test with only 3 tonnes pre-load, the shear resistance of the sample appears to have been reached at 650 kg. This may have been due to sliding between the top plate and bales, which were not pinned with steel or other pins, as is often done during construction.

The 6tonnes of pre-load, or 1.8tonnes per linear metre, is unlikely to be used in actual construction. Unplastered straw bale walls thus present a wall system that may be too flexible without added bracing. The stiffness of the usual plaster systems or cladding systems, however, is likely to add usefully to the bracing capabilities of straw bale walls. No plastered wall systems were tested.

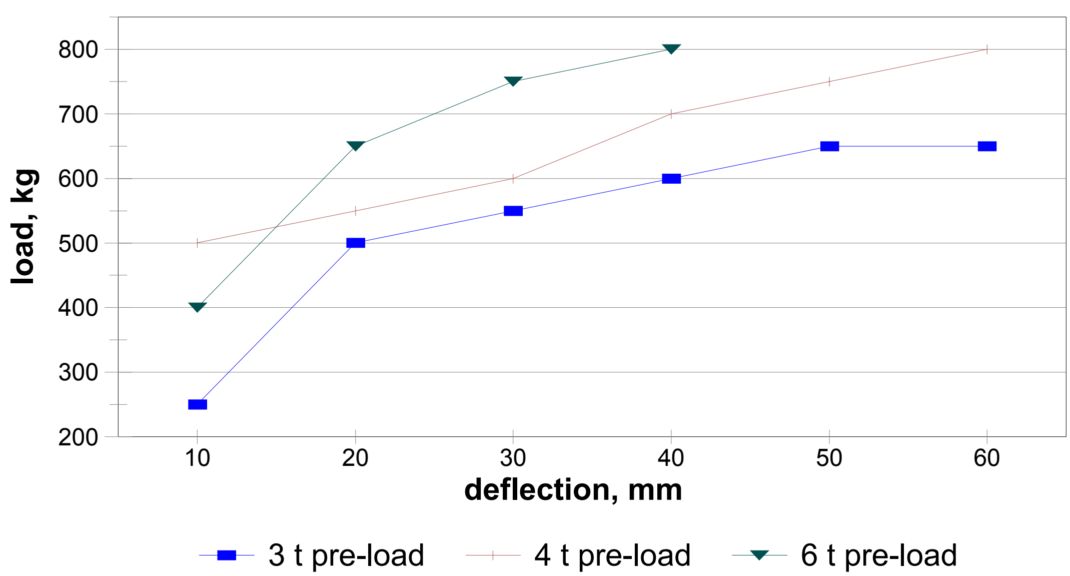

Figure 2. Racking tests

Beam tests

A test of the constructed wall was undertaken to establish the ability of a straw bale wall to act as a deep beam. The ends of the wall were supported on rollers, and a central point load introduced by a hydraulic ram. The top and bottom plates for the wall formed the chords of the 'beam'. These were constructed of ex 150x50 pinus radiata on edge, with 7mm ply completing an open box beam.

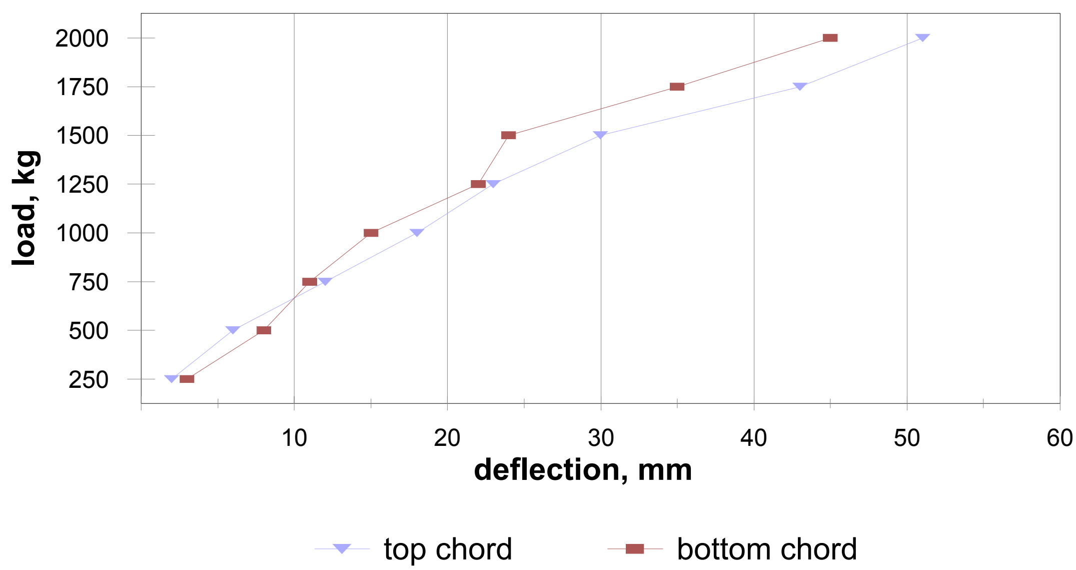

Figure 3. Beam test

Top and bottom plates were oriented with the 150x50 timber fitted over the bales and the ply on the outside. Notches were cut in the bale edges to accommodate the timber. This allowed an extra course of bales in the test rig, but weakened the whole wall assembly to some extent, especially during the out-of-plane tests.

For the beam test, the wall was pre-loaded to 4 tonnes, or 1.2 tonnes per linear metre of wall.

The top and bottom plates were designed for speed and ease of construction, rather than for strength as the chords of a beam. Final failure of the 'beam' occurred by the bottom chord ply separating at a joint under the tensile loads imposed on it. The use of larger dimension timber, a ply web with adequately strong joints, or the addition of steel strapping at the lower edge of the bottom chord would have significantly improved the overall performance of the wall system as a deep beam.

Overall deflection at the maximum load of 2 tonnes was some 1.5%. There was more deflection in the top chord, representing compression of the straw, but at a lower rate than in the original compression tests.

The test wall demonstrated a useful ability to act as a beam. Greater performance could be expected with the 1.8m depth of the beam increased to the standard wall height of 2.4m. Further improvement could be expected with an improved bottom chord, and with the wall being plastered, as in usual construction practice.

Face load test

The wall unit was tested for simulated wind loading and out-of-plane seismic loading by laying it on its side and supporting it along the 'top' and 'bottom' edges. Because it was difficult to fit the horizontal wall into the test rig it was loaded by student volunteers sitting and standing on top. As many people as could be fitted on were asked to stand on the wall. The total load was 1.7t. Under this load the deflection was less than 10mm, or no more than 0.5%. Pre-load was 7.5 tonnes, with seat belts at 400mm centres.

The wall was eventually fitted into the test rig to enable a greater face load to be applied. A uniformly distributed load was applied along the centre line of the wall. A maximum load of 4.5 tonnes was applied, producing deflection of 185mm. Under a load of 2 tonnes the deflection was 100mm. The wall returned to its original shape after the load was removed. It could be observed that the notched bales were the site of much of the deformation. Using flat unmodified bales would have reduced the deflection.

The lateral forces applied to the wall were far in excess of what could be expected during the life of a building. The load capacity of the wall under face loading was greater than when acting as a deep beam. This can be attributed to the greater pre-compression of the bales, and to the increased strength of tensile members in the form of tensioned seat belts.

CONCLUSION

The sample straw bale wall demonstrated useful structural abilities, especially in compression and out-of-plane loading. Further research is needed to establish the performance of compressed straw over time. Tests that load the straw under normal conditions of temperature and humidity variations over a long term should indicate more accurately the abilities and shortcomings of load bearing straw bale construction. Useful further testing would include:

- Plastered walls tested under realistic conditions to show the tendency of the straw to transfer loads to the plaster 'skins', and the ability of the plaster to accept those loads (King, 1996).
- Repeated cyclic loads applied to establish the ability of straw to perform under seismic and wind loads.
- Pinning or other connections between straw and top and bottom plates to gain a more realistic assessment of racking load resistance.

While further testing will reveal more detail about the structural abilities of straw bale construction, there is adequate evidence to support the assumption that load bearing straw walls, as evidenced in early Nebraska and recent New Zealand buildings, are a practical construction solution.

While a load of straw may break a camels back, a straw bale wall when loaded with the equivalent of many camels, barely bends at all. Camel drivers, like straw bale house designers, need to utilize the structural capabilities of straw more.

REFERENCES

Eisenberg, D.E., *California Code AB1314*, http://solstice.crest.org/efficiency/straw_insulation/code.txt, 1996

King, Bruce, *Buildings of Earth and Straw, Structural Design for Rammed Earth and Straw Bale Architecture*, Ecological Design Press, California, 1996.

Steen, A., Steen, B., Bainbridge, D., and Eisenberg, D. *The Straw Bale House*, Chelsea Green Publishing Company, White River Junction, Vermont, 1994.

Wardle, S.C., *Certificate of Test No. 570/94 Auckland Plant Laboratory*, Donaghys Industries Ltd., Auckland, 1994