

A Pilot Study examining the Strength, Compressibility and Serviceability of Rendered Straw Bale Walls for Two Storey Load Bearing Construction.

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ABSTRACT: A pilot study of a wall constructed from straw bales was carried out. The objective was to examine the suitability of such walls for two-storey residential construction. The emphases were placed on the strength, compressibility and serviceability of the rendered straw bale wall. The full-scale wall was tested to failure in laboratory conditions. The result shows that it is feasible to construct a two-storey wall using such system. The test results were compared with the recommendation provided by some of the codes of practice. It was found that the wall has adequate capacity for a two-storey wall construction. Other issues, such as constructability, detailing, and compressibility were also examined in this paper.

Keywords: compressibility, constructability, infill, load bearing, render, straw bale, sustainability, wall.

1. Introduction:

This pilot study was the result of some funding being made available to the School of Construction and Building Sciences in mid 2000. The study area reflected the authors' interest in this material and was in keeping with the University's mission statement of contributing to a sustainable world through both research and teaching.¹

The authors' background is that of practising architect/lecturer and structural engineer/senior lecturer respectively. Both were aware of this style of building from a literature review and were intrigued by the structural and practical aspects of construction using this material.

Straw bale construction is not new. Early examples date to the turn of the previous century in Nebraska (USA)² where enterprising homebuilders utilised a waste material to construct well insulated walls for their houses. Put simply such buildings were constructed from straw bales as "large blocks" and then rendered or plastered with an assortment of finish to weather proof the building. Over time this became known as the 'Nebraska style', some such examples still exist to day.

There are two types of wall construction; load bearing and bale infill techniques. Each has its own unique set of advantages and is often the preference of the owner/builder and the influence of the building code officials. With respect to the code aspect, infill type techniques may be preferred, as the bales are not necessarily contributing to the stability of the frame. Usually large timber sections are employed in this type of building with all the attendant and demonstrated ability of timber structures. A practical aspect might also be the construction of the frame, allowing for a roof to be put in place ahead of the walls and therefore allowing a degree of weather protection to the straw during the course of construction.

¹ University of Western Sydney Mission Statement 1998

² Steen A, Steen B, Bainbridge D Eisenberg D 1994 The Straw Bale House, Chelsea Green Publishing Company

Either way, many straw bale buildings have been constructed around the world to date but the structural aspects of this material have not been as clearly defined compared to more 'conventional' construction materials. However codes do exist (particularly in the USA) which delineate how bales should be used on site for both load bearing and infill type construction (Austin Straw Bale Code³, Pima County Code⁴, California Code⁵ etc). Such codes stipulate limits for the ratio of height to thickness (5.5:1) and ratio of length to thickness (15.5:1) for load bearing walls.

This pilot study was set up to examine what would happen to a two-storey section of a load bearing straw bale wall as it was uniformly progressively loaded by a uniformly distributed load. The limitation of height to thickness would seem to preclude the use of load bearing straw bale walls from two-storey house construction as these limitations would only allow a wall of approximately 2500mm height to be constructed.

The significance of such research was to demonstrate either the ability of such a wall to either withstand such loading or fail and therefore contribute to the wider field of knowledge with respect to this type of construction. Two-storey load bearing construction may also allow for houses with a smaller "footprint" to be successfully constructed, therefore increasing the range and type for this form of construction. This pilot study however does not examine the effects of wind loading on such walls that will be the topic of another research effort.

Previous studies to date have been undertaken by Bou-Ali (University of Arizona)⁶, McCabe⁷(University of Arizona), Carrick (University of New South Wales)⁸ and others that indicate the structural adequacy of this type of construction. Researchers have also identified the very good insulation properties of rendered straw bales (Canada)⁹ and its attendant fire resistance qualities. However moisture in and through the wall have sounded some alarm bells for the obvious problems of rot and then eventual collapse, further studies are being undertaken in this area.

2. Current Construction Technology:

This section will be limited to a discussion on the techniques associated with load bearing construction. The main issue to be faced in dealing with straw bales is to adequately achieve pre-compression of the bales to avoid the problem of both short and long term settlement (shortening) of the wall. Such a problem obviously has a great impact upon the construction of doorways and windows not to mention the potential for cracking and damaging the render (plaster) mix applied to the wall as the finish.

Straw bale walls have been constructed both from in-ground conventional strip footings and from integrated footings and concrete slab. Other types have been tried, such as rubble filled footings, earth filled tyre footings usually to minimise or avoid the use of reinforced concrete.

³ Austin Straw Bale Code 1997, City Of Austin, www.io.com/~whetfunk/sbatcode

⁴ City of Tucson and Pima County Arizona Building Code, www.sustainable.doe.gov/codes/azstraw

⁵ California Code AB1314, California State Government Web site

⁶ Bou-Ali G. 1993 Straw bales and straw bale wall systems, Master Thesis University of Arizona

⁷ McCabe J. 1993 Masters Thesis University of Arizona

⁸ Carrick J 1998 Preliminary Test Results for Straw Bale Walls, Building Research Centre UNSW (unpublished)

⁹ 1995, Thermal and Mechanical Properties of straw bales as they relate to a straw house, Canadian Society of Agricultural Engineering, Ottawa, Ontario

This material is viewed as being high technology with high-embodied energy. The usual details of waterproofing, vapour control, termite and pest control are observed with a variety of techniques available for both tie down of the roof frame and pre-compression of the wall.

These range from reinforcement rod being extended from the footing, through the straw bale wall to the top plate. This is then 'screwed down' to compress the wall and for the tie down effect of the roof and/or the floor frame. Another method is to use an air bag attached to the top of the wall frame and held in place by straps (Fibrehouse system by Chapman and Platts)¹⁰. The bag is then inflated and the wall is compressed down and held firmly in place by tensioning on the straps. Once the desired compression is achieved the bag is removed.

Another method is to use high tensile fencing wire straps looped around both the footing and the top plate and tensioned by means of "gripples", similar to constructing a wire fence. The wire is usually spaced at about 450 – 600mm centres and is alternatively fastened from both sides of the wall. The tensioned wire then becomes an integral part of the structure.

Usually bales are laid on flat in a stretcher or running bond, often being pinned through their centres to the footing or floor structure and pinned to each other at corners and elsewhere as required. Construction can be quite quick, unskilled labour can be used with chain saws, mallet and 'whipper-snippers' providing the finishing effects.

If the wall is to be rendered using cement based render then a wire mesh (chicken or aviary wire) is stretched from top to the bottom plate. Walls finished in an earthen render do not usually have this mesh.¹¹ The render being applied direct to the straw bale and forced into the strands, this gives quite a good key for subsequent coats. There is some debate about the merit of using cement based renders, they are certainly good for strength characteristics but others have raised questions about the breathability of such walls to vapour. Moisture is of concern for the longevity of the wall structure.

Top plates are generally framed from 100 x 50mm or 150 x 50mm timber constructed as a ladder frame to span the width of the straw bale. Noggins at 600 or 900mm centres join the timber frame members; some advocate the use of sheet plywood. Often associated with the top plate is the roof tie down mechanism, being either a threaded rod or galvanised strap or tensioned wires. Concrete bond beams have also been used as the top plate.

3. Design and Construction of the Full Scale Wall:

The University of Western Sydney has a well-equipped construction laboratory with a very large steel reaction frame originally developed for the testing of steel and steel/concrete composite columns under axial load up to 100 tonnes. This frame was used to contain the construction of the straw bale wall. Figure 1 shows the general frame arrangement with the partly completed straw bale wall framed between the large structural steel columns. The steel beams and columns were fabricated from 25mm thick steel, 400 x 400mm "I- beam" section, courtesy of a research grant and BHP steel sections.

¹⁰ Chapman and Platts 1996 Developing and proof testing the pre-stressed Nebraska method for improved production of baled fibre housing, Fibrehouse Ltd with Scanada Consultants Ltd, Ottawa, Ontario

¹¹ Glassford J 2001 Straw Bale Building Technology Workshop Ganmain NSW (personal interview)

Figure 1 General view of steel test frame and partly completed wall (Photograph: P. Florence)



This picture shows the partly completed wall at the 8th course level contained within the steel reaction frame. A layer of 17mm thick structural plywood was added to this course and pinned to the bales. This was done to help stabilise the wall.

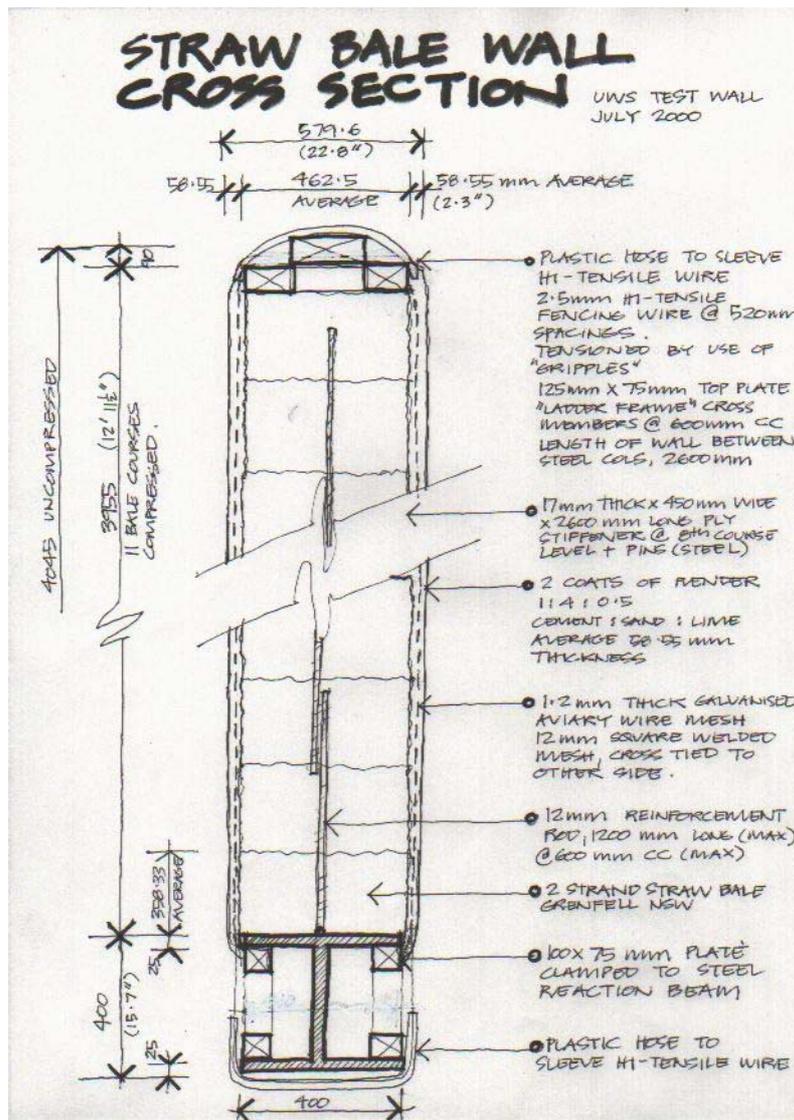
The wall was constructed to a height of 4045mm (uncompressed) being 11 courses in height; the length of the wall was 2600mm between steel columns with a layer of 17mm structural plywood placed against the steel columns to prevent the straw from expanding into the web of the columns. The general arrangement for construction can be seen in Figure 2. Bales were laid in stretcher bond pattern with a number of half bales. Bales were pinned over a 12mm reinforcement rod that had been tack weld to the frame. Pinning was continued up through the bales to the top course. The lower section of steel was assumed to simulate the concrete footing. A timber infill frame was constructed between the flanges of the bottom steel beam to allow for fixing of the wire mesh. Construction generally followed details reviewed from the literature and from interviews (Mitchell R.)¹²

The top plate was constructed from 125 x 75mm timber joined together as a ladder frame. An additional length was placed centrally to help distribute the load from the hydraulic rams. The high tensile fencing wire was run as a loop under the “footing” and carried up and over the top plate. A length of galvanised iron angle was placed at both top and bottom plates to provide for a radius turn for the wire to prevent a sharp edge from cutting the wire under load. This can be seen in Figure 3.

The high tensile wire was 2.5mm thick and is commonly used for fencing applications. The wire was sleeved in a plastic hose and the loop was joined on alternate sides of the wall. This was then tensioned by use of “gripples” and a fencing tool. The wall was compressed a total of 90 mm to give a finished height of 3955mm. Bales were then nocked into place and trimmed by “whipper-snipper”. No attempt was made to achieve a perfectly true and plumb wall, rather some irregularities remained as the authors believe that this simulates general building construction.

¹² Mitchell R. 2000 Zone Zero Architects Springwood NSW (personal interview)

Figure 2. Straw Bale Wall Cross-Section. (Illustration M. Faine)



A layer of 1.2mm thick galvanised welded wire mesh was then stretched between top and bottom plates and fixed into position. This was also stitched to the other side of the wall to bring the mesh in close to the straw bale surface.

Figure 3: View of top plate assembly showing sleeved wire loop. (Photograph P. Florence)



Figure 4: Trimming wall to size. (Photograph P. Florence)



The wall was trimmed to remove stray fibres and nocked into a reasonable straight line prior to the wall being compressed. Once the team was satisfied with the result the rendering process began. Two coats were applied over a period of two weeks, with the coats being applied in about a day and a half by a team of four (inexperienced) renderers. The mix design was 1: 4: 0.5 being cement: sand: lime. This was a strong mix with the addition of the lime to 'self heal' any later cracking. The rendering process can be seen in Figure 5.

This was a tedious part of the process and very labour intensive. Our research funds did not extend far enough to warrant using a spray application (this process alone would have accounted for approximately 25% of our funds). Render was applied to an average depth of approximately 60mm.

Figure 5: Render application over mesh and straw bales. (Photograph P. Florence)



The straw bales used in the construction of this wall were sourced from 'Elderslie' at Grenfell NSW and were two string bales 840 x 460 x 360mm dimension. The bales were sourced from

this farm as the farmer had prepared bales for other straw bale projects and was familiar with the requirements to provide tightly bound bales. The average moisture content was calculated to be 12.11%, well within the allowable range (see appendix). The California Code permits a moisture content of up to 20% of the total weight of the bale.¹³ The New Mexico straw bale construction guideline advocates a similar limit.¹⁴

The test set up was fairly simple. Two 10 tonne capacity Enerpac hydraulic rams were coupled together and attached to the top steel reaction frame. 2 x 10 tonne load cells (HBM Agezelle) were placed in between the ram and steel spreader bars designed to distribute the load at 450 mm centres were stacked on top of the plate. The general arrangement can be seen in Figure 6.

Figure 6: Hydraulic rams and top plate assembly. (Photograph P. Florence)



The load cells were calibrated and the two electronic display units were set up to give a read out of the load from each hydraulic ram in newtons. During the test the readout from each unit would be noted against time and deflection/deformation of the wall. A steel scale had been attached to either side of the wall at the midpoint and this was to be read against a static point set up from the floor of the laboratory. Figure 7 shows the steel scale attached to the top plate and Figure 8 shows the other end of the tape and the data acquisition units.

Figure 7: View of top plate, ram and measuring tape. (Photograph P. Florence)



¹³ State of California Health and Safety Code, Guidelines for Straw Bale Construction www.skillful-means.com/CALIFORNIA

¹⁴ New Mexico Straw-bale Construction Guidelines www.earthbuilding.com/nm-straw-bale-code

Figure 8: View of electronic display units and end of tape. (Photograph P. Florence)



Two theodolites had also been set up to observe readings from pre-designated marked positions on the face of the walls to observe any lateral movement. Figure 9 shows how these measurements were to be taken and recorded as the loading progressed. These measurements were recorded to determine if the wall had moved sideways during the loading process.

Figure 9: View of lateral measurement process. (Photograph P. Love)



4. Test Observation and Results:

The test was carried out on Friday 4 August 2000 and took about one hour to complete. The process was to progressively apply more load to the wall via a hand pump hydraulic unit, note the load cell readings, time and deflection/deformation of the wall. Various members of the team had been assigned certain tasks to observe, record and photograph the event.

Figure 10 records some of the team members in action. The hand pump can be clearly seen with the theodolites set up in the background.

Figure 10: Some of the test crew in action. (Photograph P. Love)



The team worked through clearly defined cycles lasting about 2.5 – 3.5 minutes to progressively load the wall, note and record impressions, note and record actual load and deformation/deflection and note the time. Each cycle represented an increase in load of approximately 5kN. The results of this cycle can be seen in Figure 11

Figure 11. Test Result data (Source: M. Faine and J. Zhang)

Straw bale test results Friday 4 August 2000												
Load 1	Load 2	left vertical	right vertical	3	4	5	6	7	1	2	Time	Comments
		south	north	Top		Middle			Edge	half		
0	0	2859	2857	91	145	109	80	90	231	185		start
1760	2506	2859	2857	92	145	109	81	90	231	185	2.53	end of cycle
3884	5001	2859	2857	92	145	109	81	90	231	188	8.32	
9899	9919	2859	2855	91	144	108	80	91	230	186	13.58	
14800	15036	2860	2853	92	145	108	80	91	231	186	18.17	
19200	20092	2861	2850	93	146	108	80	90	231	186	21.28	
25207	25209	2859	2845	92	146	110	80	91	232	186	24.42	
30193	30196	2850	2840	93	146	108	81	88	231	188	27.30	
36056	36875	2840	2834	90	146	107	83	90	232	187	30.55	
40100	40391	2822	2818	89	146	110	80	85	232	188	34.55	
45080	45345	2790	2755	85	142	[109]	78	86	231	183	39.50	
50485	50071	2790	2740	85	140	[105]	78	86	230	185	42.45	
55061	55620	2787	2730	82	140	[106]	78	85	232	187	43.35	
60496	60221	2786	2720	80	138	[110]	77	84	230	185	48.36	
62500	63286	2782	2710	82	139	[106]	76	83	231	186	52.17	
											57.50	stop

Note 1: loads in kN
 Note 2: vertical and horizontal measurements in mm
 Note 3: figures in brackets were obtained by interpolation due to sight obstruction to face of north wall

Load 1 and 2 columns refer to the two loading cells. The left and right ‘verticals’ columns (south and north respectively) refer to the vertical measurements of the steel tape measures. The numbers across the top right of the chart with some designated as ‘top’, ‘middle’ and ‘edge’ refer to the pre-determined positions on the north face of the wall that were plotted

over time by theodolite. They provide an indication of the relative movement of the wall face (either in or out of plane). Time is noted in the far right column.

For the first 14 minutes of the test no movement or cracking noises were recorded. After this time cracking noises were heard most likely from the timber at the top of the wall. By 22 minutes some render had cracked away from the wall at the top but there were no obvious signs of cracking developing on the face of the wall. By 28 minutes more cracking sounds had been recorded with the wall developing a slight 'bulge' on the southern face. By 30 minutes more cracking noises were recorded with some crushing sounds but still no sign of any cracks appearing in the surface of the render. By 35 minutes more render was falling from the top of the wall with the bulge at the centre and on the southern side becoming more obvious. At 40 minutes more render had separated from the top of the wall and at 43 minutes the render was observed to be separating from the bottom of the north face. At 46 minutes the southern side had compressed more than the north face and at 50 minutes the travel of the hydraulic rams had been exceeded. By 57.50 minutes the test was stopped.

Figure 12 shows the applied load and the deformation of both the right and left hand sides and an average figure for the wall.

Figure 12. Load versus wall deformation table. (Source: J Zhang)

Load (kN)	Vertical Deformation (mm)		
	left	right	average
0	0	0	0
4.266	0	0	0
8.885	0	0	0
19.818	0	2	1
29.836	-1	4	1.5
39.292	-2	7	2.5
50.416	0	12	6
60.389	9	17	13
72.931	19	23	21
80.491	37	39	38
90.425	69	102	85.5
100.556	69	117	93
110.681	72	127	99.5
120.717	73	137	105
125.786	77	147	112

Of interest here is the negative numbers recorded for the left hand (south face) of the wall.

The results of this table have been shown in the following chart (Figure 13.)

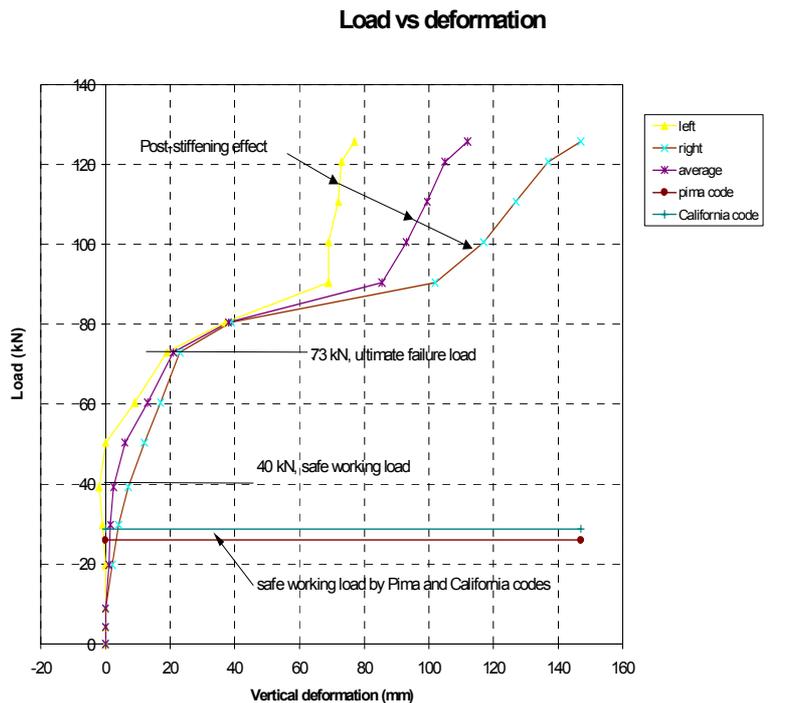


Figure 13 Load Deformation Curve (Source J. Zhang)

The wall demonstrated some interesting and fascinating structural characteristics. Apart from the obvious failure region when the load reaches about 80 kN, it also reveals that the post-failure behaviour has a distinct feature of post-stiffening effect due to the compressibility of the material.

When the wall is first loaded, the behaviour follows a typical linear path. The left side deformation reading is negative indicating it is moving upward instead of downward as one would expect. This is due to the eccentricity in the applied load and in the wall itself. This eccentricity creates a significant bending effect so that the wall is bent toward the right hand side.

For this reason the average deformation between the left and right provide a more meaningful interpretation of the result. It can be seen on the average curve at the load level of just above 40 kN, there is a significant increase in deformation, demonstrated by the change of slope in the curve. One would stipulate that due to the compression of straw bale, the interaction between the straw and the cement render becomes less significant resulting in the 'softening' of the wall. As the load increases the wall starts to 'yield'. At the load level of 70 kN there is a significant increase in deformation, which marks the failure of the wall. This failure is probably due to the significant separation between the straw bale and the cement render. As the load increases further, the straw bale becomes fully compressed, therefore becoming more solid as the load starts to increase further. Although this post-failure capacity cannot be used in the design of straw bale wall, it does illustrate that the post-failure behaviour is rather stable.

The maximum allowable stress that a straw bale wall can support depends on a number of factors. Of these the wall slenderness (height/thickness) and the unsupported length ratio (unsupported wall length/thickness) are the major influencing factors. The Pima County, Arizona, Straw bale building code limits h/t ratio to 5.6 and L/t ratio to 13. The maximum permissible stress provided by the straw bale alone is limited to 2.5 psi (17.24 kPa) in the Pima Code. California's model straw-bale code allows an L/t ratio of 15.7 and a maximum allowable load of 2.77 psi (19.10 kPa). These allowable values are for straw-bale alone. Virtually all straw-bale walls are rendered, the contribution by renders is significant, however this contribution is difficult to quantify. King¹⁵ suggests that the render should be regarded as a thin wall restrained by straw bale at a discrete distance, and the strength model for the concrete column/wall be applied. However that treatment only works if both straw-bale and renders are directly loaded at the top. In this experiment only straw bales are loaded, the loading applied to the render is indirect through the interaction due to bonding. The maximum allowable values given in both the Pima and California codes are also plotted in Figure 13. If the ultimate failure load is taken as 73 kN (48.44 kPa) and the safe working load is taken as 40 kN (26.55 kPa) when the loading curve 'softens' significantly, this gives an equivalent safety factor of 1.82. When compared with both the Pima and California codes, their safety factors are equivalent to 2.81 (Pima code) and 2.51 (California's code), respectively.

The wall did not fail as expected; most of the team were anticipating that the wall would buckle under load with parts of the render falling away from the face of the wall. In fact very little cracking was observed to have formed in the face of the wall. Both faces of render had acted like a 'curtain' and followed the compression of the wall. This can be clearly seen in Figure 14, a view of the bottom plate of the wall. The high tensile wire loop has become slack and has fallen as the wall had compressed, the render has stayed remarkably intact on both faces.

Figure 14. View of bottom plate after test (Photograph P. Florence)



The top plate was also observed to have rotated during the test. It is possible that the load was slightly off centre or that the straw was less stiff on one side. Another possibility could be that

¹⁵ King B. 1996 Building of Earth and Straw Ecological Design Press

the wall was not perfectly plumb and square when constructed but was within reasonable limits for a bale wall. Figure 15 records a view of the top plate after the test.

Figure 15. View of top plate after the test. (Photograph P. Florence)



The top plate had twisted progressively under load and possibly would have ‘tumbled over’ if the test had been continued.

Following the test the wall was demolished. This was a difficult task to achieve until all the wire strands and mesh had been cut by angle grinder. The wall was then pushed over by the use of a forklift truck and the render skins peeled off (with some difficulty).

5. Recommendation and Conclusions:

From this test there are at least two aspects worth considering. The first relates to the construction detail of a straw bale wall. It goes without saying that achieving the best pre-compression of the bales (by whatever method) is very important. Pinning of the bales by using reinforcing rod is probably ‘overkill’ but some pinning is required as the wall progresses for practical reasons (stability). Providing some lateral stiffness was required at the 8th course level to prevent the wall from ‘swaying’ under the construction loads. This too was pinned to the bales and together with the top plate construction formed a type of bond beam.

The location of the top plate in relation to the render finish is another important practical aspect. This test allowed for loading of the straw bales in compression, as the top plates did not directly bear on the render finish. At the safe working load of 40kN the deformation (average) is about 5mm, quite tolerable but requiring careful detailing of the finish of the render against adjacent surfaces (floor or slab) to avoid cracking of the finish.

The test also confirmed that this technique is suitable for two-storey construction but the practical aspect of building in the first floor structure needs to be considered. Spray application of the render finish would be preferred as hand application is very tedious work.

The second aspect worth considering is that of the structural behaviour of the test wall. The safe working load limit of 40 kN is approximately 10 kN above the limits set by the Pima and California Codes. These codes may be very conservative and further testing of straw bale walls is warranted to determine 'type' characteristics suitable for inclusion into building codes.

At the ultimate failure load of 73 kN some interesting comments can be made about straw bale walls. Once this load limit has been reached straw bale walls compress unimpressively, in fact the failure mode was unspectacular. For those of us watching the test in the laboratory this was an unremarkable way to end the experiment. However it does mean that should a straw bale wall be overloaded in residential construction the house owner could reasonably expect to have a slightly 'shortened home', still carrying load.

Further work needs to be done on the interaction of the straw to render bond to determine exactly how this behaves as a construction material. The bond between the straw and the render was observed to be very strong, particularly at the time of demolition. This test has shown that this material is excellent for constructing walls for residential purposes from a structural point of view.

6. Appendix:

Table 1: Calculation of bale density and moisture content. (Source M. Faine)

Size of bales and weights as noted						
	length	width	depth	kg 26 May	kg 6 June	kg 9 June
Bale 1	800	460	360	16.7	15.61	15.63
Bale 2	840	470	350	15.23	14.27	14.29
Bale 3	830	465	360	15.48	14.87	14.82
Bale 4	830	470	360	14.71	13.89	13.9
Bale 5	810	470	360	15.69	14.97	14.93
Bale 6	790	460	360	16.41	15.56	15.53
Bale 7	860	460	360	14.79	14.16	14.09
Bale 8	870	470	360	14.95	14.3	14.2
Bale 9	880	455	350	17.22	16.52	16.32
Bale 10	880	440	360	16.43	15.63	15.48
Bale 11	820	460	360	16.24	15.63	15.52
Bale 12	850	470	360	17.19	16.55	16.47
Averages	838.33	462.50	358.33	15.92	15.16	15.10
Note: Moisture content of straw bales was calculated at 12.11%						
Note: 6 June reading 10:45 a.m. 11.2% R.H. 34.5 deg C						
Note: 9 June reading 12:30 p.m. 10.9% R.H. 34.6 deg C						

Note: random sample of 12 bales taken from the load delivered to the construction laboratory.