Compression load testing straw bale walls

Peter Walker
Dept. Architecture & Civil Engineering
University of Bath
Bath
BA2 7AY

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1. Introduction

Over the last 10 years a growing number of loadbearing straw bale buildings have been built in the UK. Walls formed from stacked bales of straw are used as loadbearing walls in low rise, typically single storey, buildings. Data on structural characteristics, including vertical and lateral load capacity, are scarce however. Published results from load testing mostly originate from either the USA or Australia [1,2], where the form of construction often differs from that generally adopted in the UK [3]. This report describes and summarises findings from a series of vertical load compression tests on four unplastered walls [4] and one lime rendered straw bale wall.

2. Materials & Construction

2.1 Bales

Barley straw bales sourced from a farm near Devizes, Wiltshire, were used throughout this work. The bales were two-string type bound using polypropylene string. Fifty bales were delivered for the test programme. Average bale dimensions were 990 mm long, 500 mm wide and 375 mm high. The average bulk density was 125 kg/m^3 (average moisture content at testing was 13.5%), varying between 118 and 137 kg/m^3. The recommended minimum bale density varies between 100 and 110 kg/m^3 [1,3].

2.2 Timber elements

The straw bale walls were built on base plates formed from 150 mm x 50 mm softwood sections together with 18 mm OSB sheeting, figure 1. Loading was applied through a similar section wall plate. Both the base and wall plates were fabricated in accordance with recommendations of the UK guide for straw bale construction [3].

Bales were pinned vertically using 25-50 mm diameter fresh cut (green) hazel spikes. The spikes were sourced locally from hedge rows on the University of Bath's Claverton Down campus. Base (stub) pins (two per bale) were cut 250 mm long, with internal pins (also two per bale) nominally 1400 mm long.

Figure 1 Wall construction

2.3 Lime render

In one test hydraulic lime render was applied to both 990 mm wide faces of the wall. The lime render was a 1:3 (lime:coarse building sand) mix by volume. An NHL 5.0 hydraulic lime was used throughout. Moisture content of the render mix was adjusted to suit the requirements of the plasterer.

2.4 Wall construction

(a) Standard construction

Construction followed recommendations set out in UK straw bale building guide [3]. The standard construction test wall was six bales high, with each bale laid flat. Nominal wall dimensions, prior to loading, were 2250 mm high (not including the base or wall plates), 990 mm wide and 500 mm thick. The wall was founded on a timber and OSB plate with two symmetrically placed 250 mm long hazel stubs. The bales were carefully stacked to ensure verticality. During construction the cut and folded sides of the bales were systematically reversed between courses. After the first four bales were in place, two hazel pins were driven vertically down symmetrically through the centre line of the wall, figure 1. Thereafter, two further hazel pins were inserted in through both the fifth and top (sixth) bales. The wall was tested unplastered.

(b) Creep test wall

The wall was prepared for testing as described for the standard construction above, except the wall panel was pre-loaded in vertical compression under loading up to 840 kg (16.6 kN/m^2) for a period of 74 days, to evaluate the extent and rate of settlement under load. Pre-loading is standard practice in loadbearing construction prior to the application of render coatings. The wall was tested unplastered.

(c) Half bales

Straw bale walls are generally laid in stretcher (running) bond with vertical joints between adjacent courses broken by offsetting bales one half length. Though the test panels were only one bale length wide, the second, fourth and sixth course of the wall formed from two half bales to assess the influence of bonding on strength and stiffness. The half bales were formed by tying and splitting whole bales in accordance with the procedure outlined by Jones [3]. The wall was tested unplastered.

(d) No hazel pins

As described above hazel pins are in general inserted during construction to improve wall stability. Building without hazel ties could significantly simplify the construction procedure if stability could be ensured in other ways, such as external pinning. Therefore, one panel test was undertaken to assess the influence of hazel pins on compressive performance. The wall was tested unplastered.

(e) Lime render

The fifth panel was lime rendered, by an experienced lime plasterer, following compression settlement of 23 mm under a service vertical loading of 840 kg (stress 16.6 kN/m^2). Lime render was applied in two layers, one week apart. The wall was tested 29 days after receiving the top coat render. The 75 mm cube compressive strength of the lime render mix are summarised in table 1 below. The average dry density was 2000 kg/m^3. Lime cubes were tested at the time of the wall test (29 and 36 days) and also after 90 days. The average render thickness was approximately 40 mm, varying between 20 and 60 mm.

Table 1. Lime render details

Render	Average cube compressive strength (N/mm^2)	Average cube moisture content at testing
Under render coat at 36 days	3.2	4.4%
Under render coat at 90 days	3.9	1.1%
Top render coat at 29 days	2.6	4.1%
Top render coat at 90 days	3.1	1.1%

3. Testing

3.1 Creep tests

In preparation for static testing to failure two of the test walls were subject to a dead loading of 16.6 kN/m^2, figure 2. Vertical settlement of the panels was measured periodically for up to 74 days. Results of these settlement tests are reported below.

Figure 2 Settlement test set-up

3.2 Static load testing

All five wall panels were subject to static loading in vertical compression. Concentric loading was applied incrementally through two five tonne hydraulic jacks to failure, figure 3. The applied load was recorded using five-tonne digital load cells. The load was transferred directly to the straw bales through the timber wall plate. Vertical displacement of the straw bales was recorded using two linear voltage displacement transducers (LVDTs), placed centrally across the width of the plate, figure 3. Lateral buckling displacements under loading were also recorded using either LVDTs or by direct taping measurement. The average incremental rate of loading to failure was between 0.30 and 0.73 kN/min. In between each increment lateral displacement was measured by taping and noting the general condition of the wall.

Figure 3 Static load test

4. Results & Discussion

4.1 Creep tests

The vertical deformation (settlement) response under applied load with time is presented in figure 4. In the first test the loading was increased in three stages. Initially a load of 330 kg was applied, followed by a further 300 kg after 13 days and a further 210 kg after 20 days. On application of each load there was an instantaneous deformation. During application of each load increment the instantaneous stiffness of the bale wall did not significantly vary (15 – 19 kN/mm). Following each load increment settlement increased under constant loading, though the rate of settlement gain generally decreased with time. The greatest rate of settlement was recorded during the first two days after load application, thereafter slowing down to an average of between 0.2 and 0.9 mm/day. On removal of the load after 70 days there was an instant recovery of 22 mm, followed by further 10 mm over the following 4 days, by which time the test was terminated. The wall was subsequently tested under short-term static loading to failure.

In the second test a total service loading of 840 kg was applied in one increment. The initial stiffness of the wall, 17 kN/mm, was similar to the first test wall response. As before the deformation increased with time. The greatest rate of creep deformation was also recorded during the first two days after loading and thereafter the rate of settlement was approximately 0.5 mm/day over the following three weeks. Settlement of the wall had not ceased after 23 days when the test was ended. The wall was subsequently strapped with polypropylene strapping, figure 3, and lime rendered before load testing to failure.

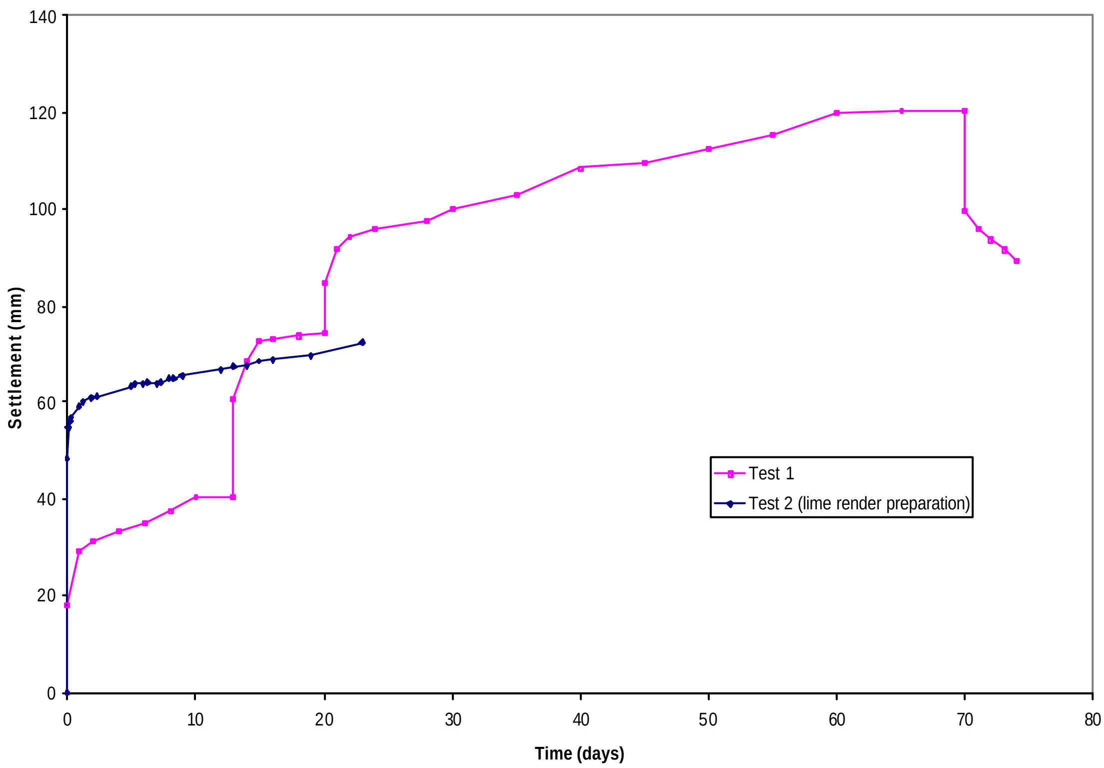

Figure 4 Load settlement tests

The deformations presented represent average settlement of the wall. For example, in the second wall the settlement was approximately 50% greater on one side arising from unequal deformation of the upper-most bale, most likely caused by inconsistent bale density. The recorded creep behaviour described above is also likely to have been influenced by variations in the temperature and humidity conditions in the laboratory: temperature varied between 10^{o}C and 23^{o}C during testing; relative humidity varied approximately between 30% and 70%.

4.2 Static load testing

The short-term static load-deformation responses of the test walls are shown in figure 5. The initial wall stiffness, maximum applied loads and total settlements are summarised in table 2. Initial wall stiffness was recorded from the recorded total settlement under a 'service load' of 9.5 kN (19.2 kN/m^2). The load reduction recorded in some walls at each increment occurred during measurement of lateral displacement and inspection of the wall.

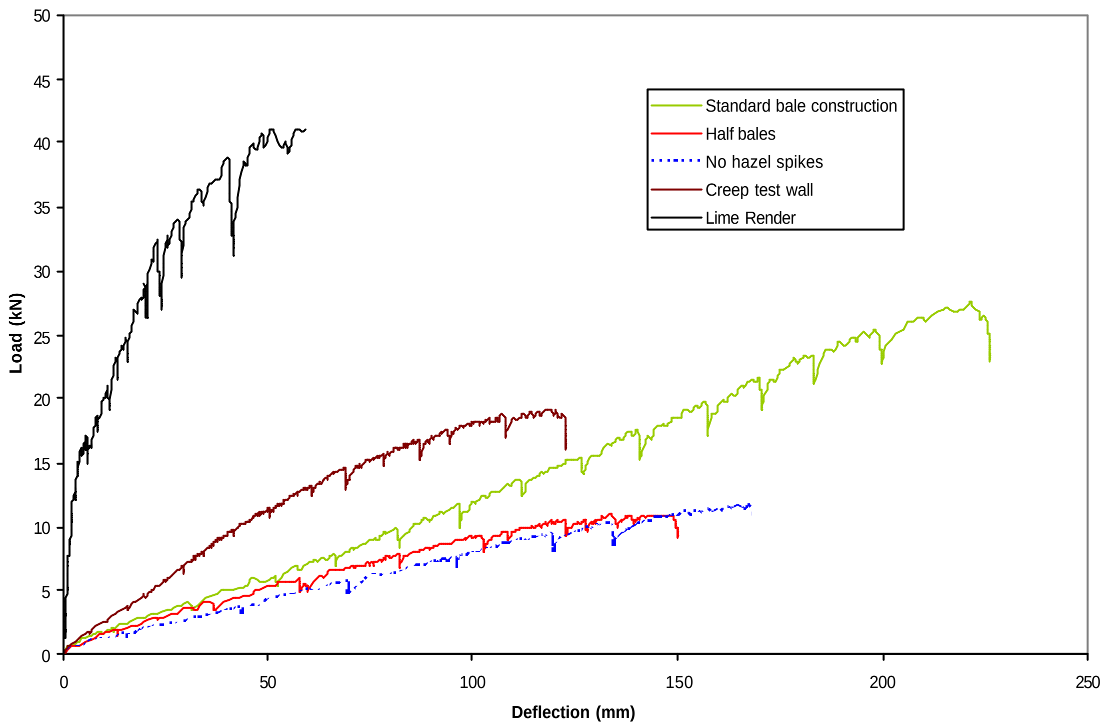

Figure 5 Static load tests

Table 2. Static load test results

Wall	Initial wall stiffness (kN/mm)	Maximum applied load (kN)	Settlement at maximum load (mm)
Standard construction	0.11	27.6	220
Pre-compressed wall	0.22	19.2	120
Half-bales	0.087	10.9	140
No hazel spikes	0.077	11.7	165
Lime rendered wall	5.62	41.1	55

All unplastered walls failed by overall buckling, figure 6, though variations in bale density, especially in the upper-most bale, led to significant unequal compression of the top plate in a number of tests, figure 7. Recorded deformations in figures 4 and 5 therefore represent averaged values. In general, the stiffness decreased as their maximum load was approached and the walls buckled in compression.

Figure 6 Buckling failure

Figure 7 Rotation of wall plate

The standard bale construction wall settled under increasing load with little change in stiffness until a maximum load of 27.6 kN was reached. As expected the initially pre-compressed wall exhibited increased stiffness compared to the standard construction, table 2, though the maximum load was reduced although higher than both the half-bale and no hazel wall tests.

The wall built with half bales showed a significant reduction in maximum load and initial stiffness. The half bales were not as dense as the original bales and the inclusion of vertical joints in alternative courses was also expected to impair stiffness and strength. Removal of hazel spikes from wall construction had a significant impact on both wall stiffness and load capacity, table 2. Hazel spikes contribute to wall resistance mainly through frictional resistance passing through the bales, as evident by the difficulty in driving them during construction, figure 1.

Lime rendering of the wall had greatest impact on strength and stiffness. Initial stiffness was increased by over 50 times and the maximum applied load by nearly 50%. Stiffness of the wall under load decreased noticeably at around 15 kN as the lime render cracked. The wall failed as a result of the lime render separating from the straw on one side beneath the top plate. Though the lime render was applied to the straw bales outside the full width of the top bearing plate, a slight bearing of the top plate onto the edge of the render of one side resulted in unequal settlement of the top plate, figure 8, contributing to the observed failure mode. Other failure modes reported for rendered walls include overall buckling of the wall, local buckling of the plaster, and bearing failure of the plaster [2].

Figure 8 Lime rendered wall failure

The addition of render or plaster coats to straw bale changes mechanical behaviour. The much stiffer and stronger render outer coats attract a much greater proportion of the vertical loading, resulting in a more complex composite sandwich form of construction, as proposed by King [1]. The importance of render coats to the strength and stiffness of straw bale walls has significant consequences for the construction sequence and maintenance (repair or replacement) of render coats.

The maximum loads and initial stiffness of the walls are comparable with previously reported experimental values [1,2]. The maximum loads for unplastered straw bale walls has been reported at between 4.2 and 19.2 kN/m, depending on bale type, orientation (laid flat or on edge) and the use of internal reinforcing bars. Reported displacements at a maximum load of unplastered walls similarly vary between 72 and 198 mm. The maximum reported loads for plastered bale walls, of comparable construction, vary between 21 and 66 kN/m.

A maximum permissible service load of approximately 19 kN/m^2 (9.6 kN) is often used in straw bale wall design. The maximum applied load of the lime rendered wall was over four times greater. However, the maximum load of one unplastered wall was only 13% higher, though the standard bale wall achieved a maximum loading nearly three times higher.

5. Conclusions

Significance of these results presented here must of course be considered in light of the variability of straw bales. However, the following conclusions may be drawn from these tests:

- Under sustained loading unplastered straw bale walls demonstrated visco-inelastic behaviour. The walls creep with time under load following an initial instantaneous deformation, immediately recovering some deformation on load removal, followed by further time dependent recovery but exhibiting a final permanent deformation.
- Pre-compression improved initial stiffness of the straw bale test wall.
- Maximum vertical load capacity and initial stiffness was improved by the inclusion of hazel spikes.
- Maximum vertical load capacity and initial stiffness was impaired by the use of half bales.
- The failure mode of unplastered walls was by global buckling but local deformation, due to variation in bale quality (density), also significantly influenced performance. By testing a small, one bale, cross-section wall performance was more influenced by imperfections in straw bales. More generally the comparatively large unit size of straw bales renders the form of construction susceptible to local reductions in strength and stiffness when individual bales are of poorer quality.
- As reported in previous work application of a lime render significantly strengthens and stiffens the straw bale test wall. The stiffer and stronger render coat attracts and sustains a higher proportion of the load in a complex composite sandwich panel behaviour. The bond between the render coating and bales enables transfer of the load and improves compression resistance of the render.
- The importance of render coats to the structural performance of straw bale walls has significant consequences for render mix design and construction, the overall construction sequence and the maintenance and repair of rendered bale walls. The use of render coats will generally, however, reduce susceptibility of walls to bale defects and variations.

References

1. King, B. (1996) *Buildings of earth and straw*. Ecological Design Press.
2. King, B. (2003) *Load-bearing straw bale construction*. Ecological Building Network, June 30, 2003.
3. Jones, B. (2002) *Building with straw bales: a practical guide for the UK and Ireland*. Green Books.
4. Hickman, D. (2003) *Straw bale construction*. BEng final year dissertation, Dept. Architecture & Civil Engineering, University of Bath.

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