Structural Characteristics of Load Bearing Straw Bale Walls

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Abstract

Straw bales offer a renewable and affordable construction material suitable for a range of uses as both thermal insulation in walls and roofs, and for low rise loadbearing structural walls. As a co-product of food production, it places no further pressure on land use, and in common with other crop-based materials, straw captures and stores carbon dioxide through photosynthesis, offering the means to construct buildings with a net negative carbon emissions footprint. Straw also further reduces operational carbon emissions by virtue of its excellent thermal resistance. However, despite these benefits, and a successful construction history extending over 100 years in many countries worldwide, straw bale construction has still to make a major commercial impact in the wider construction market. Limited technical understanding of some fundamental performance characteristics (including structural capacity, hygrothermal behaviour, and durability), absence of technical standards, and a lack of certification and product warranty for straw bale, still remain barriers to wider acceptance. In this paper results are presented from a study on full-scale straw bale walls to evaluate the structural performance under vertical loading and lateral loading. The performance of identical straw bale walls, with and without plaster coats, is presented. The study is also unique in presenting on out-of-plane lateral loading and wall performance under eccentric vertical load cases. The research will support structural designers and enable wider uptake of this sustainable form of construction.

Keywords:

Straw bale, load capacity, Eccentric loading, Racking performance, Lateral loading.

1.0 Introduction

Concerns for the environmental impacts of construction, including global warming from increased carbon dioxide emissions and depleting non-renewable resources, continues to be a driver for the increasing use of bio-based building materials, such as timber, bamboo, straw and hemp. Plant-based building materials are efficient stores of photosynthetic carbon dioxide, but can also contribute to building performance through their high levels of insulation, acoustic insulation, and beneficial hygrothermal regulation of internal spaces [1].

Straw is the plant structure between the root and grain head of cereal crops such as wheat, rice and barley. It is mainly used for animal bedding, but it has other agricultural uses, including as a feed supplement and in mushroom horticulture. In more recent years it is used as biomass for energy production and as a feedstock for bio-fuel manufacture. Straw has been used in construction for millennia in various uses, including as an additive in earthen construction, as a floor covering material, and for thatched roofing. Despite these other uses there remains significant capacity in its supply chain for much greater use of straw as a building material [2,3].

Straw bales were first used in construction following the introduction of mechanical baling machines in the late nineteenth century. Farmers in Nebraska, USA, found particular benefit in using straw bale walls during the cold winters. Although in recent years straw bale construction has been gaining recognition, in particular in areas of France, Belgium and Netherlands [4], and in part through innovations such as prefabricated straw bale panels [5], more generally straw bale construction still remains relatively small compared to other sectors of the construction industry.

The benefits of using straw bale include its widespread availability, low cost, renewable supply chain, and carbon dioxide storage. Other advantages of using straw bales in construction include: the high insulation value provided by straw bale walls (a 450 mm thick straw bale wall has a U-value of 0.13 – 0.19 W/m^{2}K); the flexibility to use in both loadbearing and non-loadbearing construction; its lightweight construction; and, excellent fire resistance [5].

Despite the advantages, straw bale's low structural resistance and non-regulated supply chain, combined with limited research on its structural and longer-term performance, has restricted its wider uptake [2]. Although some prefabricated panel solutions using straw bales have benefitted from extensive testing and evaluation, there has been limited research on the influence of eccentric vertical loading on the structural capacity of load-bearing straw bale walls, and their lateral load resistance. The market uptake of straw bale construction is likely to remain limited without further research to assess fundamental performance of this construction method

There have been some previous studies into the mechanical performance of straw bales. In 2011 Ashour et al. [6] reported that the average compressive stress (28.4 kN/m^2) for when bales were tested flat was higher than that for on-edge orientations (21.1 kN/m^2). Similar findings have been reported by Zhang [7] and Vardy [8]. Maraldi et al [9] completed single bale compression tests, using Digital Image Correlation (DIC) technology to measure deformations under load. Their study showed that there was no significant difference in the mechanical performance between bales laid flat and on-edge. Four different unplastered straw bale wall vertical load capacity tests were completed by Walker [10] to explore the influence of different factors, including bale arrangement and the impact of using hazel pins, on compression performance, including creep tests.

Straw bales are a breathable (vapour permeable) construction material; they allow water vapour to pass through it in response to differences in Relative Humidity (RH) between two faces of a wall [11]. However, as straw is vulnerable to decay at higher levels of moisture content, it is important that moisture is not trapped with the wall construction for prolonged periods. To prevent this straw bale walls should use plaster coatings with good vapour permeability. Lime-based and earth-based plasters are considered the most suitable materials to be used [2].

As straw bale walls are rarely used without coatings, there has been more research on the performance of plastered straw bale walls, including King [12], Vardy [8], and Brojan & Clouston [13]. King [12] showed in tests that the plastered walls have better vertical load resistance than unplastered walls. Vardy [8] developed a theoretical model developed to predict the load-deflection relationship and ultimate strength in compression of plastered bale walls. Brojan and Clouston [13] discussed the effect of plaster type and loading orientation on wall performance. Bales loaded flat (Figure 1) had 50% higher load capacity than the bales loaded on-edge. Additionally, they also compared different plaster types; lime-cement plastered walls were stronger and stiffer than clay or lime plastered walls. All research to date has used the wall plate arrangement, typical in North America, which rests directly onto the plaster coats. Aschheim et al [14] completed a series of in-plane tests on full-size straw bale bales with cement: lime plaster coats, and proposed a method for assessing allowable shear. Little further research has been completed to date to understand the resistance of straw bale walls subject to in-plane lateral loading.

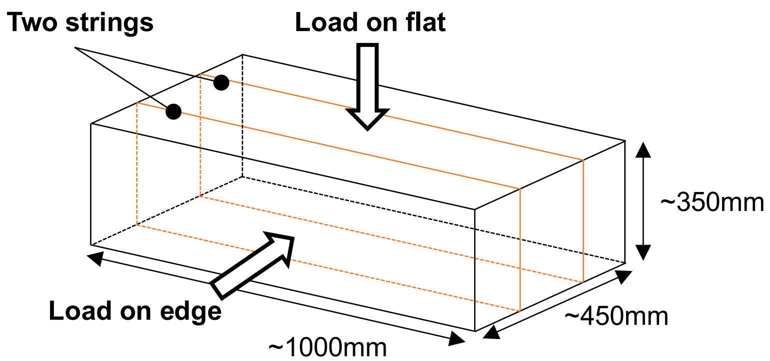

Figure 1 Loading orientations: on-flat and on-edge

To date there has been little work to develop a more generalised model to explain the structural performance of straw bale walls. The work presented in this paper is part of an on-going study on structural performance of straw bale construction. The aim of this paper is to present results from a series of representative straw bale wall tests comparing the vertical load and lateral load performance of the walls without and with plaster coatings.

2.0 Materials and methodologies

In this section the materials, construction details and test methods used in this research are presented.

2.1 Materials

Wheat straw bales were used for all tests, sourced from a farm in Keynsham, Somerset, UK. All the bales were two-string bound using polypropylene twine with nominal dimensions 1000 mm long, 450 mm wide and 350 mm high. The average measured density of the straw bales was 110 kg/m^3 (with a Co-efficient of Variation = 12%), supplied at an average moisture content of 8.7% (Co-efficient of Variation = 0.33%). Three of the bales were divided into half bales for compression testing. The two half bales from each complete bale were tested in two different orientations (flat and on edge, figure 1) to compare their different responses under compression loading. The compression testing was completed using a 2000 kN Dartec testing frame with a displacement rate of 10 mm/min using a 136 mm deep timber plate extending across the full area of the bale, with the vertical displacement measured directly by the testing frame. The stress-strain results are shown in Figure 2, using the reference for directionality given in Figure 1.

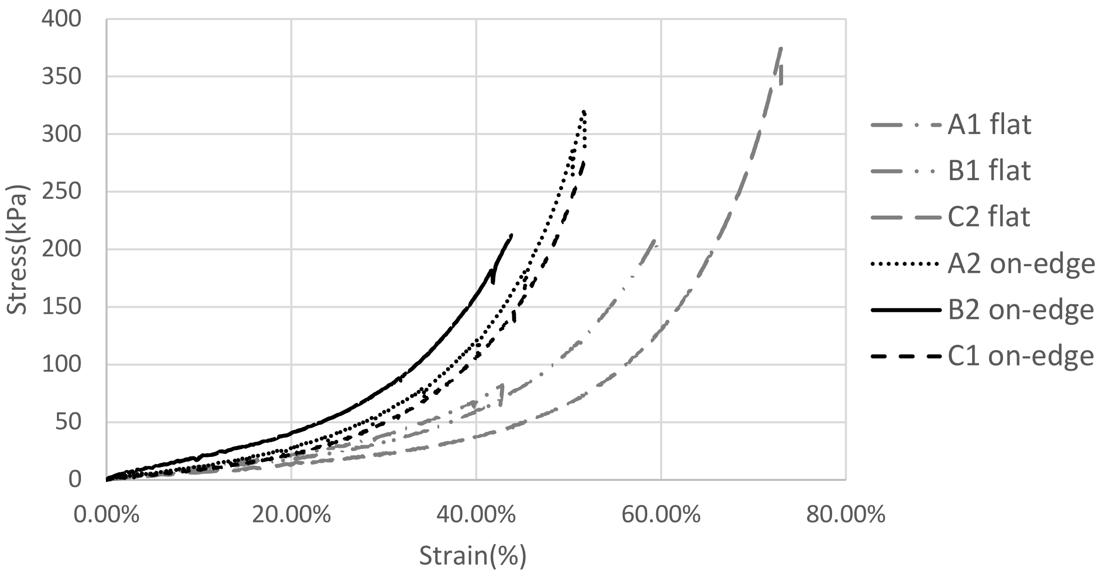

Figure 2 Stress-strain curves for half bale compression test

Lime plaster used in straw bale wall construction is commonly mixed on site. Straw Works Ltd provided the plaster mix for the two test walls and rendered both walls. The plaster was mixed using a lime putty, a pozzolanic additive (to provide earlier strength development for laboratory testing), and sand. Twelve lime plaster specimens (40 x 40 x 160 mm) were cast for strength testing in accordance with BS EN 1015 - 11 [15]. The results are shown in Table 1.

Table 1 Lime plaster test average results

Plaster age (days)	Flexural strength (N/mm^2)	Compressive strength (N/mm^2)
15	0.19	0.39
28	0.40	0.70
75	0.47	1.10
180	0.47	1.18

2.2 Wall construction

The two straw bale walls were built in the structure laboratory at the University of Bath. Both walls were seven bales high (approximately 2450 mm) and built by experienced straw bale builders using the same construction method as typical on site. The straw bale walls were built onto a timber base plate and capped with a top timber plate. Both timber plates were 500 mm wide and were made from sawn soft wood (cross section 50 x 100 mm). The timber plates were either 2000 mm or 3000 mm long (depending on wall size). The plates were 136 mm high and were made from timber boxes. The timber was covered with 18 mm thick oriented strand board top and bottom. Hazel spikes were used in the straw bale walls to pin the bales together. The diameter of hazel spikes was 25-30 mm and were cut to different length used in the walls. The bales were then carefully stacked to ensure verticality and laid in a running bond. Due to the cut and folded sides of bales, the bales were reversed between courses during stacked (Figure 3).

Figure 3 Three-bale straw bale wall during pre-compression

The straw bales were stacked course by course until they reached seven courses high. After completing the first four courses two 1000 mm long hazel spikes were driven into the centre line of each straw bale along the course. Thereafter, for every course two further hazel pins were inserted in through each bale on the fourth, sixth and top (seventh) courses. The top wall plate was placed onto the seventh course of straw bales and pinned in place by inserting 1 metre long hazel spikes through holes in the timber. Following the straw bale wall construction, each wall was pre-compressed using ratchet straps as shown in Figure 3. The number of ratchet straps used to pre-compress the walls depended on the length of each wall. The pre-compression was controlled by the experienced practitioners; the load applied was not measured. However, both walls were compressed by about 150 mm using the ratchet straps. After pre-compressing white packaging straps were used to retain the pre compression. The height of both walls prior to testing was approximately 2300 mm.

Both walls were tested structurally in two phases: initially unplastered; and, subsequently with lime plaster coats in place. The plaster was applied to both sides of the walls following the initial unplastered structural tests. In the plastering process the lime plaster was prepared in the laboratory. The first coat of plaster, the key coat, was a lime putty: sand mix (1:2 by volume), and was rubbed into the straw to a thickness of approximately 5 mm (Figure 4). A dubbing coat, made using same lime putty: sand mix as the key coat but with the addition of short chopped straw, was applied over the key coat to even out any undulations before the main body coat was applied. The main body coats were applied in two layers of 12 mm each and finished off with a wooden float (Figure 5).

Figure 4 Initial key coat of lime plaster

Figure 5 Lime plaster coat

2.3 Wall test arrangements

Each wall was initially tested under service loading unplastered, and then retested to failure with the lime plaster in place. This allowed direct comparison between identical bale constructions with and without plaster coats. The wall tests, summarised in Table 2, included vertical loading (both concentric and eccentric loading) and lateral loading (both out-of-plane and in-plane). The two-bale long wall was used for the vertical load resistance and the out-of-plane lateral load with the three-bale long wall used for in-plane (shear) racking wall.

All tests were carried out in the Structures Laboratory at the University of Bath. The straw bale walls were constructed during November 2018, and tested unrendered later the same month, with rendering applied in December 2018 and final testing completed in January 2019. Throughout the ambient laboratory temperature was around 15-20°C.

Table 2 Experimental design

Wall	Tests undertaken
Two-bale wall	Unplastered wall out-of-plane load test (with and without vertical load)
	Unplastered wall compression test (concentric and eccentric load)
	Plastered wall out-of-plane load test (with and without vertical load)
	Plastered wall compression test (concentric and eccentric load)
Three-bale wall	Unplastered wall in-plane racking load test (with and without vertical load)
	Plastered wall in-plane racking load test (with and without vertical load)

2.3.1. Vertical Loading

The experimental set-up for unplastered and plastered conditions of the two-bale wall are shown in Figure 6 and 7, respectively. The unplastered wall and plastered wall were subject to concentric load and eccentric load tests; the loads were applied at

0 mm. 75 mm and 150 mm eccentricity with respect to the centre-line.

Figure 6 Unplastered two-bale straw bale vertical load test set-up (L:2000mm; W:450mm;H:2300mm)

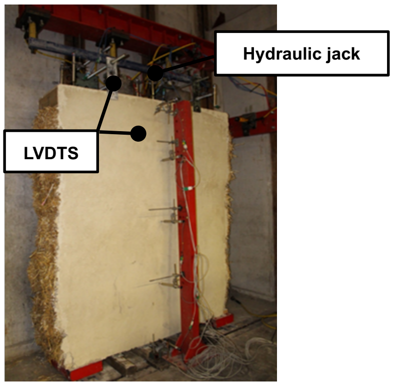

Figure 7 Plastered two-bale wall vertical load test set-up (L:2000mm; W:450mm;H:2300mm)

Loading for both walls was applied using two five tonne hydraulic jacks above the wall plate supported from the adjacent strong wall. The loading data were measured using five-tonne digital load cells, and together with six linear voltage displacement transducers (LVDTs) placed along the top wall-plate to record vertical displacement during loading, were recorded using PC data logger. The LVDTs were placed in two rows (Figure 8); the distance between the transducers along the long edge of the top plate differed between the concentric and eccentric load tests to accommodate the different loading configurations. Following the concentric load tests the wall was moved laterally 75 mm or 150 mm to ensure the required load eccentricity. Along the front of the wall five LVDTs were also positioned to measure lateral displacements (Figures 6 and 7). The wall was confined at the top by two steel plates to prevent the top plate lateral movement (Figures 6 and 7). The vertical load was monitored and controlled manually during testing. Each test comprised three cycles.

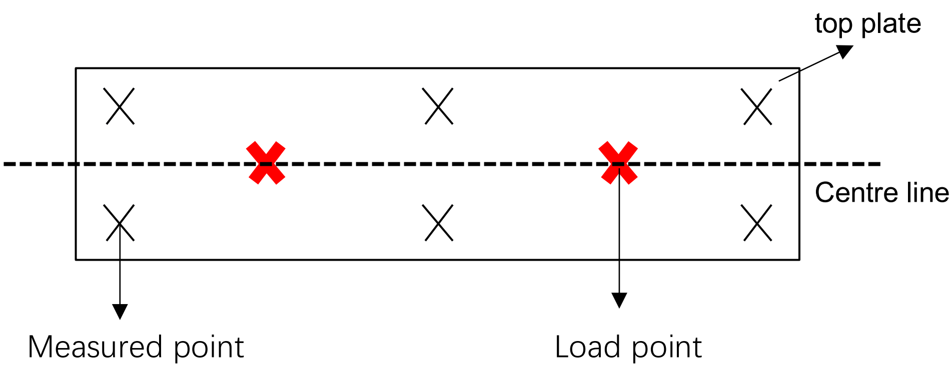

Figure 8 Plan view of top plate concentric vertical load test set

2.3.2. Out-of-plane Lateral Loading

Following the vertical load tests an out-of-plane lateral load test were completed on the two-bale wide wall. Unplastered and plastered the straw bale wall had the same experiment set-up. Five LVDTs were placed on the front of the tested wall to record lateral displacement, Figure 9. A pressurized air bag was set-up between the tested wall and a concrete reaction wall to simulate lateral wind pressure. Inflation of the air bag was regulated using a barometric pressure meter to control the applied pressure. The top plate and base plate were restrained laterally by steel elements. Additionally, the unplastered wall test was also completed under a vertical service load of 2.5 kN/m to explore the influence of vertical loading.

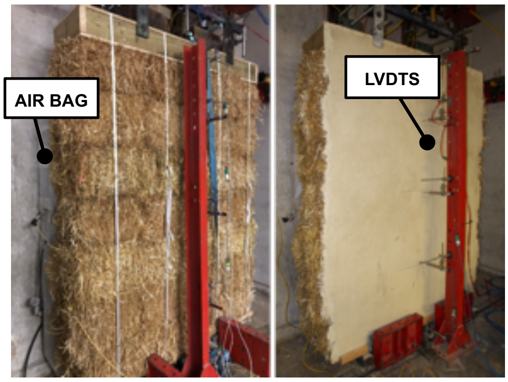

Figure 9 Unplastered wall and plastered wall out-of-plane lateral load test set-up (L:2000mm; W:450mm(500mm plastered); H:2300mm)

2.3.3. In-plane Lateral Loading

The three-bale wall was subject to a lateral in-plane racking load test. The test comprised applying a horizontal force using one horizontally mounted hydraulic jack directly onto the top plate and measuring the lateral (horizontal) deformation response of the wall with increasing force. The horizontal force represented a simulated lateral wind load. As shown in figures 10 and 11 the walls were restrained to prevent sliding and vertical uplift at the heel of the wall during the in-plane tests. The walls also were confined at the top to prevent out-of-plane movement during testing. Four LVDTs were set-up to measure the lateral displacement. For the vertical service load, three hydraulic jacks were positioned equidistant along the top plate and the vertical load was monitored and controlled manually during testing. The vertical jacks applied the load through low friction bridge bearings to accommodate the lateral displacements.

Two tests for each wall were completed. Initially the wall was subject to increasing lateral force without the application of the vertical loads. In the second test a vertical service load was applied. For the unplastered wall, the vertical load was increased to 1 kN/m (service load), whilst in the plastered test the wall was tested under vertical loads of 1 kN/m, 5 kN/m and 8 kN/m.

Figure 10 Unplastered wall in-plane racking load test set-up (L:3000mm; W:450mm; H:2300mm)

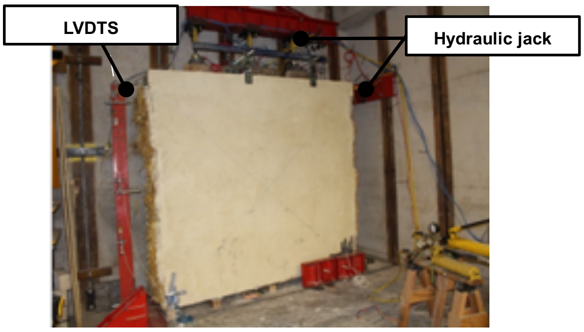

Figure 11 Plastered wall in-plane racking load test set-up (L:3000mm; W:450mm; H:2300mm)

3.0 Results and Analysis

3.1 Vertical load tests

For the concentrically loaded wall tests the vertical displacement reported is an average of the six displacement transducers set along the top wall plate. The vertical displacements for both eccentric load tests were measured by two rows of three transducers (arrangement shown in Figure 7). The vertical displacement of the wall reported below for the two eccentric tests have been calculated for the extreme loaded edge based on recorded data and assuming wall plate moved rigidly under loading. The load-displacement curves for three tests on two different walls are presented on Figure 12 below, which show similar trends for each wall series.

The load-displacement plots for all tests are non-linear and show hysteresis on load removal. The maximum applied vertical deformations for the unplastered and plastered straw bale walls in this test were 44.5 mm and 21 mm respectively. The compression capacity of the walls is limited by deformation in compression (wall stiffness). Table 3 presents the measured load resistances of the walls at 11.5 mm and 23 mm (approximately 0.5% and 1% of initial wall height: 2300 mm) vertical displacement are presented.

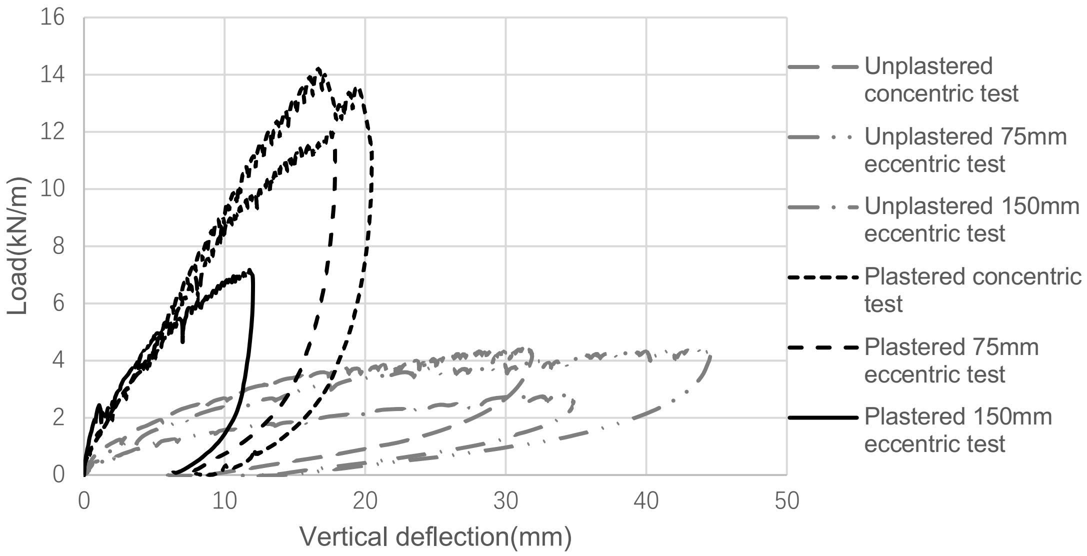

Figure 12 Load-deflection curves of unplastered and plastered wall test

As expected, the results of vertical tests show that increasing eccentricity of load decreases the wall compressive resistance. In the unplastered wall tests the load resistance for load eccentricity 75 mm (1/6 of the wall thickness) test has reduced capacity by about 18% and 9% at 11.5 mm and 23 mm deformation respectively (when compared to the concentric load test). The reduction in load resistance when the eccentricity was increased to 150 mm (1/3 wall thickness) was 45% and 40% respectively for 11.5 mm and 23 mm deformation limits. The measured vertical deflections in the plastered wall tests was less than 23 mm; at 11.5 mm vertical deformation load resistance reduced 9.5% at 75 mm eccentricity and 33.3% at 150 mm eccentricity. Load resistance reduced by a further 32-34% when the eccentricity increased by a further 75 mm to 150 mm.

Table 3 Load resistance in vertical load tests

Wall test	Load eccentricity	Measured load resistance (kN/m)	
		@11.5 mm displacement	@23.0 mm displacement
Unplastered wall	0 mm	3.00	3.85
	75 mm	2.45	3.50
	150 mm	1.65	2.30
Plastered wall	0 mm	10.50	-
	75 mm	9.50	-
	150 mm	7.00	-

It is clear, and expected, that the plastered wall had better compressive resistance than the unplastered wall. In Figure 12, the six load-deflection plots can be divided into two different trends. Results for the unplastered wall had lower maximum load and greater deformation. Inversely, the plastered wall had higher maximum load with less deformation. Comparing the concentric load test with the unplastered wall and plastered walls: the maximum load for the plastered wall was around 28 kN, about three times more than that of the unplastered wall result (9 kN). Deformation in the plastered wall (21 mm) reduced by about 34% compared to the unplastered wall (34 mm). Additionally, the load resistance at 11.5 mm displacement for the plastered wall tests were between 3.5 and 4.2 times (Table 3) higher than the corresponding unplastered walls, confirming the results above. The stiffness of wall decreases with increasing load, with two clear stages (Figure 13) of wall stiffness as reported Table 4. Figure 13 represents only the tests at 150mm eccentricity; while all the walls show similar behaviour, under these conditions they are the most pronounce. Comparing the stiffness of different tests, the plastered walls are stiffer than the unplastered walls, and the eccentricity further reduced the wall stiffnesses. The plaster coats used in the straw bale walls improved both their structural performance and compression stiffness. Additionally, the change in slope in Figure 13 may be due to previous testing densifying the straw and improving the initial stiffness response of wall.

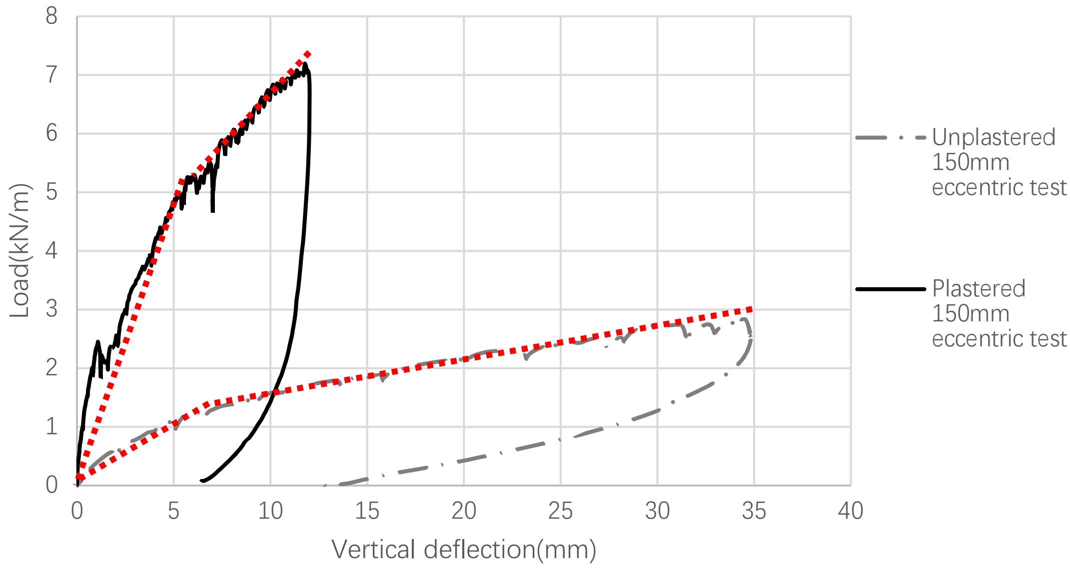

Figure 13 Two stages in the load-deflection curves

Table 4 Measured compression stiffness of straw bale walls in vertical load tests

Wall test	Load eccentricity	Stiffness of wall (kN/m)	
		Stage1 (Range of deflection)	Stage2 (Range of deflection)
Unplastered wall	0 mm	0.6 (0-15mm)	0.34 (15-31mm)
	75 mm	0.5 (0-9mm)	0.11 (9-44mm)
	150 mm	0.4 (0-6mm)	0.12 (6-44mm)
Plastered wall	0 mm	1.6 (0-16mm)	-
	75 mm	1.4 (0-11mm)	0.80 (11-17mm)
	150 mm	1.5 (0-5mm)	0.66 (5-11mm)

The load resistance for the unplastered walls are comparable with results previously reported under concentric loading (Walker, 2004). However, the results were significantly lower in the plastered wall where permissible vertical load resistances between 10 kN/m-30 kN/m have been reported by King [12], Walker [10] and Vardy & MacDougall [16]. Unlike King [12] and Vardy [16] the load plate in these tests, similar to Walker [10], rested onto the straw bales and not directly onto the plaster coats as is more common in North America. Therefore, comparison with the test presented here is best suited to the earlier tests by Walker [10]. The initial stiffness response of the plastered wall test was similar to Walker [10], though the earlier test had much higher maximum load (Table 5). In the previous test the lime plaster had much greater strength, and thickness, than used here. The tests reported here used lime plaster with an average thickness of about 20 mm. In Walker's tests [10], the average plaster thickness was about 40 mm. The lime plaster used a 1:3 (NHL5 hydraulic lime: sand) mix by volume and strengths are compared in Table 5; the lime plaster in this report was around three times weaker.

Table 5 Maximum load and wall displacements

Wall tests	Wall plaster Average thickness (mm)	Wall plaster Average compressive strength (N/mm^2)	Maximum concentric load (kN/m)	Vertical displacement at maximum load (mm)
Experimental tests				
Unplastered wall	-	-	4.5	32
Plastered wall	20	0.70	14.0	17
Walker (2004)				
Unplastered wall	-	-	27.6	220
Plastered wall	40	2.9	41.1	55

3.2 Out-of-plane lateral load tests

The response of the two-bale straw bale walls under the applied lateral pressure is presented in Figure 14. The out-of-plane wall deflections were measured using a displacement transducer placed at mid-height. Three plots shown in Figure 14 are non-linear and there was little recovery of the wall after load removal. Comparing the two unplastered wall tests, the wall with an applied vertical service load of 2.5 kN/m was slightly stiffer. For the unplastered straw bale wall, a lateral deflection of h/150 was about 15 mm. When the deflection reached 15 mm, the applied pressure was 0.33 kN/m^2 (with no vertical load) and 0.41 kN/m^2 (with 2.5 kN/m vertical loading). As with the vertical load tests the wall's load carrying capacity was governed primarily by stiffness rather than strength considerations. The plastered wall test result showed significant improvement compared to the unplastered wall. The maximum lateral pressure more than doubled and the mid-height maximum lateral deflection was 6.1 mm, which was much less than the maximum deflection in the unplastered wall (48.7 mm).

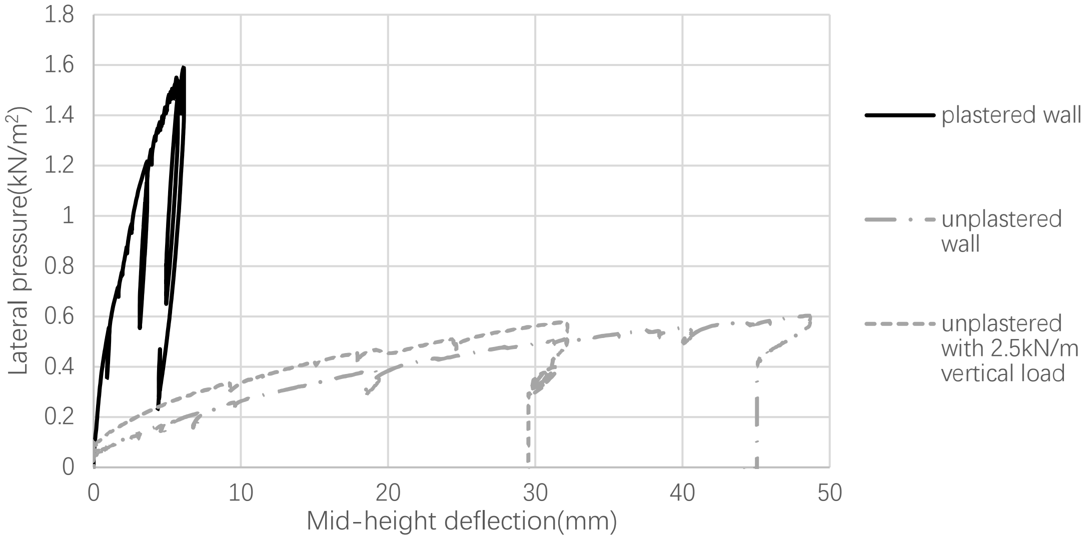

Figure 14 Load-deflection curves for out-of-plane lateral load tests

3.3 In-plane racking load test

The in-plane racking load test results are presented in Figure 15, showing responses of the unplastered and plastered wall without a vertical load, and with a vertical service load of 1 kN/m. The measured deflection responses are the lateral displacement of the top plate under the two loading cases.

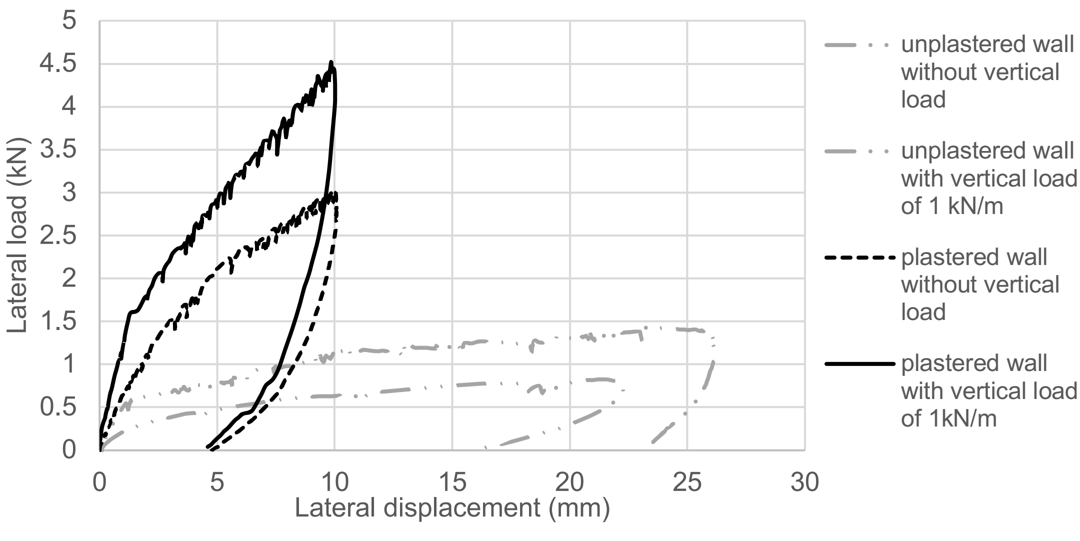

Figure 15 Load-deflection curves for unplastered and plastered walls in plane racking load test

In all four tests, the wall response was non-linear under the racking load and on load removal there was little recovery of the lateral deflection, especially in the unplastered wall tests. As expected, the wall response was stiffer and initially linear when carrying the vertical loading of 1 kN/m according to the comparison in Table 6. As with the other tests the wall's capacity was governed primarily by its stiffness response (also observed by Maskell et al. [1]. Additionally, the test results for the plastered wall were much improved compared to the unplastered wall, which confirmed that the plaster coat improves the structural performance of the straw bale walls.

Table 6 Total lateral loads (kN) and deflections (mm)

Wall tests	Total lateral load (kN) at different lateral deflections		
	5 mm	10 mm	15 mm
Unplastered wall without vertical load	0.47	0.63	0.75
Unplastered wall with 1kN/m vertical load	0.76	1.11	1.21
Plastered wall without vertical load	2.12	3.00	-
Plastered wall with 1kN/m vertical load	2.89	4.37	-

A lateral deflection limit of h/250 (9.2 mm), commonly used as the allowable inter-storey drift limit under wind load, has been selected as a serviceability limit. The total applied load for the unplastered wall without vertical load and with 1 kN/m was 0.60 kN and 1.0 kN respectively. Due to the increase stiffness provided by the application of the render, the lateral load for the plastered wall without vertical load and with 1 kN/m was 2.8 kN and 4.3 kN respectively.

4.0 Discussion

The addition of lime plaster coats has clearly improved structural resistance in all the tests (Figures 12 - 13). The stiffer lime plaster coats improve the wall stiffness in compression, flexure and shear. In the vertical load tests the maximum load capacity of the plastered wall improved by around 200% compared to the unplastered wall test. In the out-of-plane lateral load test the deflection of the unplastered wall under the same load was nearly 30 times higher than the equivalent plastered wall. In the racking load test the load capacity of the plastered wall was over 4 times higher than that of unplastered wall. The plaster coats act as skins in a form of construction analogous to structural insulated panel composites (King [12]). The bond and shear connection between the lime plaster coats and straw is key to performance and remains subjects of further research.

Increasing load eccentricity in compression decreased the resistance of both the unplastered and plastered wall tests. When load eccentricity increased from 0 to 150 mm ($^{t}/_{3}$), the load resistance of the straw bale walls decreased by 45% (unplastered wall) and 33% (plastered wall). Load eccentricity reduced wall stiffness as well as load capacity.

Assuming a linear strain profile, with a linear-elastic material, stresses across an eccentrically loaded wall section can be predicted from:

$$\sigma_{max} = \frac{F}{b\mathrm{h}}\left(1 + \frac{6e}{h}\right)$$

where: e = load eccentricity; F is vertical force; b = section thickness; h = section width. Assuming a linear stress distribution across the section, the expected reduction in load capacity (for equivalent strain deformation) for a load eccentricity e = 75 mm (b/6) is 50% (the stress distribution would be triangular compared to a rectangular uniform stress distribution). However, the measured reduction in load capacity for unplastered walls for b/6 was only 18% (displacement 11.5 mm) reducing to 10% when displacement doubled to 23 mm. The load-deformation responses of individual straw bales are non-linear, with increasing stiffness under load, which, in part at least, explains the lower than predicted reduction in load capacity. For a linear strain profile, the non-linear stress distribution will develop higher net load resistance.

The measured compression resistance for the plastered walls, varying between 7.0 – 10.5 kN/m depending on load eccentricity, confirm the suitability of straw bale walls for loadbearing applications in single and two-storey residential and similar forms of construction. Similar to the additional restraint masonry walls receive from return walls and adjoining structure, the measured load-resistance of the bale walls in complete buildings might well be expected to exceed that measured. The measured load-resistance of the unplastered walls can also be considered structurally suitable for some single storey applications. Similarly the out-of-plane lateral load resistance tests on the walls confirm adequate resistance for most likely applications.

In the racking load test, the vertical load had significant beneficial impact on improving the load capacity of straw bale wall. The maximum lateral racking load of the plastered wall, with 1 kN/m vertical loading, improved by about 50% compared to the plastered wall without applied vertical loading.

5.0 Conclusions

The initial work presented here reports on novel tests comparing structural performance of the unplastered straw bale walls directly with lime plastered walls under vertical compression, out-of-plane and in-plane loading. Vertical compression loading was applied concentrically and eccentrically. The following conclusions may be drawn from these initial tests:

- The load-deformation responses of the vertical load tests are broadly consistent with previously reported data;

- Load-deformation responses under vertical and lateral loading are governed by stiffness and are generally non-linear, with significant hysteresis on unloading;
- Load eccentricity reduces the vertical load resistance of the unplastered and plastered walls;
- Vertical loading improves the lateral out-of-plane and in-plane load resistance of straw bale walls;
- Measured load carrying resistance of unplastered wall assemblies is lower than those reported for plastered walls;
- Plaster coatings improve the structural performance of walls under vertical and lateral loading. The stiffness of the walls is significantly improved.

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