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For *UpStraw and The School of Natural Building*

Loadbearing capacity of strawbale walls – a summary of results from peer-reviewed literature

This report is intended to provide useful information to structural engineers, designers, and building inspectors who must always be consulted in the planning and approval of any project.

All documents referenced can be accessed in the UpStraw Zotero database – please contact School of Natural Building for details (eileen@schoolofnaturalbuilding.co.uk)

The tables below give the loading (in kN/m) of strawbale walls and single strawbales at failure point, as reported in peer-reviewed research literature. Dimensions of the tested samples are given so that kN/m_2 can be calculated if required.

All reported loads are distributed linear loads. Loading must always be distributed evenly across strawbale walls; point loads must be avoided.

In all cases failure of plastered strawbale was represented by a drop in test load without collapse, with failure usually taking the form of compression cracking of plaster. Un-plastered walls failed by buckling (a phenomenon not observed in full-scale construction, but the results highlight the importance of designing roof or intermediate floor connections to ensure loads are spread evenly and transferred to walls in plane strictly parallel to the ground).

Exact test procedures varied, but all featured hydraulically applied loading increased slowly at a compression rate of up to 2.5 mm/minute, designed to evaluate the action of operational loads. Loads were spread across the horizontal area of test specimens by timber or metal structures.

Structural behaviour of plastered strawbale walls

Plastered strawbale walls behave under load as a composite structural panel. The plaster coating increases the stiffness and loadbearing capacity to the wall, with the straw bonding the inside and outside plaster coatings to each other and providing flexural strength (Walker, 2004; Olivier *et al.*, 2011; Garas *et al.*, 2013). This indicates the importance of ensuring a good bond between straw and plaster.

Plasters such as clay and lime based plasters have a lower compressive strength than cement-based plasters but a higher resistance to fracture (Olivier *et al.*, 2011). There is some evidence that clay or lime plasters do not detach readily from straw walls (whereas cement-based plasters do) allowing the wall to behave like an H-beam, flexing together and maintaining overall strength (Forêt *et al.*, 2013).

There is agreement throughout the literature that the straw component of walls should be pre-compressed before plaster is applied, to ensure the most reliable structure (reflected in standard UK strawbale construction practice). Standard practice in the UK is also to reinforce walls by pinning courses together with hazel (or other timber) stakes, with base and wall plates similarly pinned to the bales.

Some studies have explored numerical models to predict the behaviour of plastered and un-plastered strawbale walls, based variously on the compressive strength of the plasters (Vardy and MacDougall, 2006; Vardy, 2009) or models for biconical springs (Maraldi *et al.*, 2017; Molari *et al.*, 2017). Further research to verify these models would be recommended. For simplicity and reliability, this report concentrates on simple loadbearing tests of strawbales and strawbale walls.

Results

While this report focuses on failure loads, two studies explored the creep behaviour of un-plastered strawbale walls. Maraldi *et al.* (2018) tested 6 un-plastered wheat straw bales with a density of 94 kg/m_3. The resulting mean creep coefficient was 3.4 $\psi(\infty, 0)$, said to be similar to that of masonry walls (at 3.7 – 4.1 $\psi(\infty, 0)$). Walker (2004) tested a single un-plastered strawbale wall 2.25 m high, by 0.99 m wide and 0.5 m thick, loading at 8.3 kN/m for 74 days. The greatest deformation occurred in the first two days after loading, settling to 0.5 mm/day thereafter, with overall deformation of 120 mm. In UK construction practice the walls would be pre-compressed before loading and plastering, reducing the potential for further structural creep.

The tables below separate tests of wall assemblies from tests of single bales, with results for reinforced walls given separately from non-reinforced walls. Results are then separated out for walls with different types of plaster, and no plaster. All results are reported load at failure, and the mode of failure is noted.

A mean is given for each set of results, and a 5_{th} Percentile value (representing the value met by 95% of test results). This reflects practice in the presentation of timber material data. With compiled results separated out some means and 5_{th} percentiles are only derived from 2 or 3 results; this is clear in the tables.

Table 1 summarises results for strawbale walls and strawbale with different types of plaster. Results for clay plastered strawbale walls are not given here – the only available test on such walls (from Brojan and Cloustan (2014), given in Table 2) gives a lower value than other tests on un-plastered strawbale walls, suggesting testing irregularities between different research, and a need for further testing. Given the sparsity of results a safe approach may be to assume the loading capacity of un-plastered bales, though in reality it is likely to be higher. Common practice in the UK is to use clay plaster internally and lime render externally, and it should be noted that this practice has been used in a significant number of buildings that have gained building control approval.

For comparison, the safe working load (SWL) of a standard duty masonry cavity wall lintel is 9 to 10 kN/m (depending on length), or 18 to 22 kN/m for a heavy duty masonry cavity wall lintel (Catnic, 2020).

(Tables data: Faine and Zhang, 2001; Walker, 2004; Vardy, 2009; Brojan and Clouston, 2014)

Table 1. Summary of test result means and 5th percentile values with different types of render/plaster

Render type	Mean load at failure, kN/m		5th percentile value, kN/m	
	Wall tests	single bale tests	Wall tests	single bale tests
lime:sand:cement[1]	32.26	73.23	28.48	49.60
lime:sand[2]	41.52	34.61	**** [2]	29.75
no render	17.53	17.75	11.13	11.05

[1] Excluding bale on edge and eccentric load tests

[2] single result for lime:sand wall assembly test

Table 2 summarises all the results. Table 3 gives results for all tests involving lime:sand:cement render, and Table 4 gives those involving lime:sand render. Table 5 gives results for tests of un-plastered strawbales.

Table 2. Loadbearing test results, means and 5th percentile values - all types of render/plaster

Plastered strawbale walls — **Bales Laid flat**

Study	Specimen dimensions, m (length, height, thickness)	Plaster (type, compressive strength where known, thickness mm)	Mean bale density, kg/m3	Stakes/rods	Ultimate load, kN/m	Deflection/ verticle deformation at failure, mm	Failure mode (serviceability or ultimate failure). Other notes.
Faine and Zhang (2001)	2.6, 4.05, 0.46	lime/sand/cement, steel mesh within, 55 mm		12mm full height rebar	28.08	21	plaster detached in places, no collapse, loading continued to 34.62 kN/m without collapse (serviceability). SWL well above California/Pima codes.
Walker (2004)	0.99, 2.25, 0.5	1:3 lime:sand	125	1.4 m hazel	41.52	55	Plaster cracking (serviceability)
5th Percentile					**28.752**		
Mean					**34.800**		
							No reinforcement
Vardy (2009)	0.8, 0.99, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95		32.1	1.6	Compressive crushing of plaster (serviceability). Load dropped at failure then increased again in steps. Final post-failure load maintained at 11.25 kN/m. Mean of 3 x wall tests - concentric loading.

	0.8, 2.31, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95	36.6	1.6	Compressive crushing of plaster (serviceability). Load dropped at failure then increased again in steps. Final post-failure load maintained at 11.25 kN/m. Mean of 3 x wall tests - concentric loading.
5th Percentile				**32.325**		
Mean				**34.350**		
Plastered strawbales						**Bales Laid flat**
Vardy (2009)	0.8, 0.35, 0.53	lime/sand/cement, strength 1.43 MPa, 25 mm	95	60		Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.8, 0.35, 0.51	lime/sand/cement, strength 1.43 MPa, 13 mm	95	52		Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.8, 0.35, 0.55	lime/sand/cement, strength 1.43 MPa, 38 mm	95	79.5		Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.8, 0.35, 0.453	lime/sand/cement, strength 1.12 MPa, 25 mm	95	49		Plaster cracking (serviceability). Mean of 3 x single bale tests
Brojan and Clouston (2014)	0.76, 0.36, 0.54	1:3 lime:sand	93.5	40		Crushing/cracking of plaster (serviceability). Mean of 5 tests
	0.76, 0.54, 0.36	1:3 lime:sand	93.5	29.21		Crushing/cracking of plaster (serviceability). Bale on edge. Mean of 5 tests.
	0.76, 0.36, 0.54	1:1:6 lime:cement:sand	93.5	125.66		Crushing/cracking of plaster (serviceability). Mean of 5 tests
	0.76, 0.36, 0.54	1:1:0.25 clay:sand: chopped-straw	93.5	14.61		Crushing/cracking of plaster (serviceability). Mean of 5 tests
5th Percentile				**19.72**		
Mean				**56.248**		
						Bale on edge
Brojan and Clouston (2014)	0.76, 0.54, 0.36	1:1:6 lime:cement:sand	93.5	68.68		Crushing/cracking of plaster (serviceability). Bale on edge. Mean of 5 tests.
	0.76, 0.54, 0.36	1:1:0.25 clay:sand: chopped-straw	93.5	10.53		Crushing/cracking of plaster (serviceability). Bale on edge. Mean of 5 tests.
5th Percentile				**13.4375**		
Mean				**39.605**		

					Eccentric loads
Vardy (2009)	0.8, 0.33, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95	31.62	Compressive crushing of plaster (serviceability). Mean of 3 x wall tests - Eccentric loading.
	0.8, 1.05, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95	24.22	Compressive crushing of plaster (serviceability). Mean of 3 x wall tests - Eccentric loading.
5th Percentile				**24.59**	
Mean				**27.920**	

Table 3. Loadbearing test results, means and 5th percentile values - tests with lime:sand:cement render/plaster

Plastered strawbale walls							**Bales Laid flat**
Study	**Specimen dimensions, m (length, height, thickness)**	**Plaster (type, compressive strength where known, thickness mm)**	**Mean bale density, kg/m^3**	**Stakes/rods**	**Ultimate load, kN/m**	**Deflection/ verticle deformation at failure, mm**	**Failure mode (serviceability or ultimate failure). Other notes.**
Faine and Zhang (2001)	2.6, 4.05, 0.46	lime/sand/cement, steel mesh within, 55 mm		12mm full height rebar	28.08	21	plaster detached in places, no collapse, loading continued to 34.62 kN/m without collapse (serviceability). SWL well above California/Pima codes.
Single value: no mean or 5th percentile							
							No reinforcement
Vardy (2009)	0.8, 0.99, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95		32.1	1.6	Compressive crushing of plaster (serviceability). Load droped at failure then increased again in steps. Final post-failure load maintained at 11.25 kN/m. Mean of 3 x wall tests - concentric loading.
	0.8, 2.31, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95		36.6	1.6	Compressive crushing of plaster (serviceability). Load droped at failure then increased again in steps. Final post-failure load maintained at 11.25 kN/m. Mean of 3 x wall tests - concentric loading.
5th Percentile					**32.325**		
Mean					**34.350**		

Plastered strawbales					**Bales Laid flat**
Vardy (2009)	0.8, 0.35, 0.53	lime/sand/cement, strength 1.43 MPa, 25 mm	95	60	Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.8, 0.35, 0.51	lime/sand/cement, strength 1.43 MPa, 13 mm	95	52	Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.8, 0.35, 0.55	lime/sand/cement, strength 1.43 MPa, 38 mm	95	79.5	Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.8, 0.35, 0.453	lime/sand/cement, strength 1.12 MPa, 25 mm	95	49	Plaster cracking (serviceability). Mean of 3 x single bale tests
	0.76, 0.36, 0.54	1:1:6 lime:cement:sand	93.5	125.66	Crushing/cracking of plaster (serviceability). Mean of 5 tests
5th Percentile				**49.6**	
Mean				**73.232**	
					Bale on edge
Brojan and Clouston (2014)	0.76, 0.54, 0.36	1:1:6 lime:cement:sand	93.5	68.68	Crushing/cracking of plaster (serviceability). Bale on edge. Mean of 5 tests.
Single value: no mean or 5th percentile					
					Eccentric loads
Vardy (2009)	0.8, 0.33, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95	31.62	Compressive crushing of plaster (serviceability). Mean of 3 x wall tests - Eccentric loading.
	0.8, 1.05, 0.53	4.5 sand, 1.25 lime, 0.25 cement, 0.783 MPa, 25 mm	95	24.22	Compressive crushing of plaster (serviceability). Mean of 3 x wall tests - Eccentric loading.
5th Percentile				**24.59**	
Mean				**27.920**	

Table 4. Loadbearing test results, means and 5th percentile values - test with lime:sand render/plaster

Plastered strawbale walls

Study	Specimen dimensions, m (length, height, thickness)	Plaster (type, compressive strength where known, thickness mm)	Mean bale density, kg/m^3	Stakes/rods	Ultimate load, kN/m	Deflection/ verticle deformation at failure, mm	Failure mode (serviceability or ultimate failure). Other notes. (bales laid flat)
Walker (2004)	0.99, 2.25, 0.5	1:3 lime:sand	125	1.4 m hazel	41.52	55	Plaster cracking (serviceability)
Single value: no mean or 5th percentile							

Plastered strawbales

Study	Specimen dimensions, m (length, height, thickness)	Plaster (type, compressive strength where known, thickness mm)	Mean bale density, kg/m^3	Stakes/rods	Ultimate load, kN/m	Deflection/ verticle deformation at failure, mm	Failure mode (serviceability or ultimate failure). Other notes. (bales laid flat)
Brojan and Clouston (2014)	0.76, 0.36, 0.54	1:3 lime:sand	93.5		40		Crushing/cracking of plaster (serviceability). Mean of 5 tests
	0.76, 0.54, 0.36	1:3 lime:sand	93.5		29.21		Crushing/cracking of plaster (serviceability). Bale on edge. Mean of 5 tests.
5th Percentile					**29.7495**		
Mean					**34.605**		

Table 5. Loadbearing test results, means and 5th percentile values - un-plastered strawbale walls

Plastered strawbale walls

Study	Specimen dimensions, m (length, height, thickness)	Plaster (type, compressive strength where known, thickness mm)	Mean bale density, kg/m^3	Stakes/rods	Ultimate load, kN/m	Deflection/ verticle deformation at failure, mm	Failure mode (serviceability or ultimate failure). Other notes. (bales laid flat)
Walker (2004)	0.99, 2.25, 0.5	1:3 lime:sand	125	1.4 m hazel	41.52	55	Plaster cracking (serviceability)
Single value: no mean or 5th percentile							

Plastered strawbales

Study	Specimen dimensions, m (length, height, thickness)	Plaster (type, compressive strength where known, thickness mm)	Mean bale density, kg/m^3	Stakes/rods	Ultimate load, kN/m	Deflection/ verticle deformation at failure, mm	Failure mode (serviceability or ultimate failure). Other notes. (bales laid flat)
Brojan and Clouston (2014)	0.76, 0.36, 0.54	1:3 lime:sand	93.5		40		Crushing/cracking of plaster (serviceability). Mean of 5 tests
	0.76, 0.54, 0.36	1:3 lime:sand	93.5		29.21		Crushing/cracking of plaster (serviceability). Bale on edge. Mean of 5 tests.
5th Percentile					**29.7495**		
Mean					**34.605**		

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