VOL. 9, NO. 9, SEPTEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EFFECT OF PLASTER TYPE AND LOADING ORIENTATION ON COMPRESSION BEHAVIOR OF STRAW BALES FOR CONSTRUCTION

Larisa Brojan[1] and Peggi L. Clouston[2]
[1]University of Ljubljana, Faculty of Architecture, Zoisova, Ljubljana, Slovenia
[2]Department of Environmental Conservation, University of Massachusetts, Amherst MA
E-Mail: clouston@umass.edu

ABSTRACT

Plastered straw bales are composite building materials used as load bearing walls in sustainable structures worldwide. Structural testing of the composite is necessary to establish mechanical properties for practitioner use and for building code acceptance. This study investigates the compressive behavior of individual two-string rye straw bales when plastered using the most commonly used plasters in temperate climate zones, specifically: lime, lime-cement, and clay. A total of forty-eight specimens were tested to failure under compressive loading in two orientations: on-edge and flat. It was found that results vary not only according to plaster type but also according to bale orientation: on edge bales tended to fail due to buckling of the plastered skins while flat oriented bales failed primarily due to plaster crushing. Importantly, all cases exceeded the maximum load capacity proposed for the 2015 International Residential Code with the lowest factor of safety being 1.8 for on-edge oriented clay plastered bales. Flat-oriented bales plastered in lime-cement were found to have the highest compression capacity, with a factor of safety of 10.7.

Keywords: straw bale, green building, compression, strength, plaster.

1. INTRODUCTION

Straw bale construction is a composite building technique whereby bales of straw are stacked vertically and then plastered on both sides to form exterior walls of a structure. The walls can function as load carrying elements or merely as thermal insulation when used in combination with a structural timber frame. Research has shown the technique to be an environmentally sustainable practice primarily due to the attributes of the straw bale: specifically, the bale is a renewable material that is non-toxic, triggered biodegradable, requires little energy to produce, and sequesters carbon (Sodagar *et al.*, 2011). As a result, the method is gaining interest of late from researchers and practitioners who seek ways to counter the negative impact of building on the environment.

Straw bale construction began over a hundred years ago with the first homes being built in 19th century Nebraska (Magwood *et al.*, 2005). Today, although it is not considered a mainstream construction method, it is recognized and practiced throughout the world (Brojan and Clouston, 2014).

Despite its worldwide adoption, there are no testing standards specific to straw bale construction. However, standard test protocol are necessary to establish guidelines for parameters such as moisture content, plaster mix, and specimen preparation which have a strong influence on the straw bale composite strength properties. Lacking such standards has led to variability and inconsistencies in reported test data. In addition, there are only a few reports in the literature (relative to other building materials) on the structural properties of straw bale composites. Fewer still are presented in peer-reviewed, scientific journals. Targeted research on straw bale construction is very much needed to provide technical information for engineers and building officials and will ultimately aid in broad acceptance and industry confidence of the construction method.

A few websites offer convenient lists of research documents on straw bale testing (EB Net, 2014; The Last Straw, 2014). Much of this structural research-to-date focuses on compression response of either: single plain bales, single plastered bales, plain straw bale walls, and/or plastered straw bale walls (King, 2003). Correspondingly, the present study is focused on constitutive response of single bales both with and without plaster.

Reviewing the literature in this regard, one of the earliest studies (Bou-Ali, 1993) found that un-plastered three-string bales experienced a 100% recovery after being compressed to one-half their original height. In 2001, Zhang further explained the behavior of un-plastered single straw bales noting that the stress-strain curve could be characterized into four distinct stages (Zhang, 2001). Importantly, he demonstrated that a distinct linear elastic region exists whereby the working stiffness of the bale could be reliably determined, similar to other building materials like timber or steel. Zhang also showed that straw bales, regardless of whether they were plastered or not, have a distinct failure point indicated by a significant plateau in the stress-strain curve. In terms of plaster behavior, Lerner and Donahue (2003) investigated the basic structural capacity of earth-, cement- and lime-based plasters for straw bale construction. It was found that cement-based plasters were far more stiff than earth-based plaster and therefore would be preferable in practice for mitigating straw bale wall movement. In 2006, Vardy and MacDougall investigated compression properties of two-string wheat straw bales with a combined cement-lime plaster skin. They found that the strength of the plaster, the thickness of the plaster and the orientation of the bale all affected the strength of the composite bale. Notably, and contradictory to Zhang's work, the plastered bale stiffness was found to be highly variable and un-predictable.

The objective of the current study is to provide a comparison of bale structural properties (i.e. working stiffness and load carrying capacity) for plain two-string rye straw bales as well as bales coated with three different plaster types (lime, lime-cement, and clay) while also considering the effect of straw bale orientation of flat vs on-edge loading.

2. MATERIALS AND METHODOLOGY

2.1. Specimen preparation

Two-string, rye straw bales were procured from a local farmer in South Deerfield, Massachusetts who was experienced with preparing bales for building purposes. The bales were randomly selected while special attention was paid to tightness of string and appropriate rectangular shape as described in common straw bale building references (Jones, 2009; Lacinski and Bergeron, 2000). The bales were stored indoors for approximately 3 months from harvest and were not recompressed.

Referencing Figure-1, the bales were assigned to two primary groups corresponding to 'flat' loading (group A) and 'on-edge' loading (group B). Bales loaded flat were loaded perpendicular to their largest face and generally perpendicular to the straw fibers. Bales loaded on-edge were loaded parallel to their largest face and generally parallel to the straw fibers. These groups were further split into 8 subgroups, classified by number corresponding to applied plaster: 1 for plain bales (without plaster); 2 for lime plastered bales; 3 for lime-cement plastered bales; 4 for clay rendered bales. A total of 48 specimens were tested: 9 each for plain bales in each orientation (A1 and B1) and 5 each for the other six subgroups. Plain bales were tested to establish a control set and to provide fundamental constitutive bale properties.

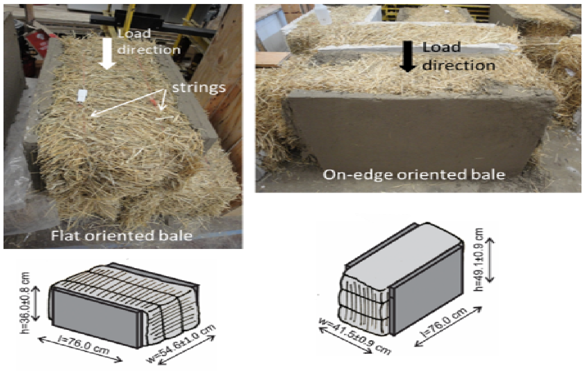

Figure-1. Bale orientation and dimensions.

Prior to plastering, the plain bales were measured in size, weight and moisture. The density averaged 93±4.7 kg/m^3. Moisture content met the required value of no more than 20% wet-weight basis (Jones, 2009): upon receiving the bales from the supplier, the moisture content averaged 11.7±2.1%. When the tests were conducted, the moisture content averaged 6.5±0.9% having equilibrated inside the university building where the temperature was constantly above 18^{o}C. Specimen dimensions, densities, moisture contents and plaster thicknesses are summarized in Table-1.

2.2. Plaster mixture

Plaster types were lime, lime-cement, and clay, which are commonly used in temperate climate zones (Lacinski and Bergeron, 2000; Jones, 2009; Racusin, 2011; Morrison and Kefee, 2012). The plaster was manually mixed and applied consistently by the first author who is experienced in building straw bale structures. The work was done in accordance with guidelines outlined by Morrison and Kefee (2012).

The lime plaster mixture was prepared by following the ratio of 1:3, lime: sand. The ratio for the lime-cement plaster was 1:1:6 lime: cement: sand. In both cases, Dolomitic Hydrate Hydrated type S lime was used and in the second case, sand and Portland cement was incorporated. For the clay mixture, clay, sand and chopped straw (approx. 5 cm long) was mixed in the ratio of 1:1:0.25 where the straw acts as a binder. Local clay (as opposed to a bagged clay mixture) was used for consistency with common practice as many builders utilize clay directly from the construction site to save money and use material that would otherwise be taken away. Before the plaster was mixed, the clay was cleaned and filtered; bigger aggregates (such as stones, leaves and roots) were removed but many smaller parts such as seeds remained. During the drying period, the seeds sprouted which is not expected to affect the plaster performance.

2.3. Plaster application

Prior to application, the bale surface was lightly wetted. Two layers were applied. The first layer thickness was approximately 10 mm so that the straw was completely covered. The plaster was firmly applied with a trowel ensuring that the plaster sufficiently penetrated the straw surface. Approximately two hours after applying the first layer, the surface was scarified with a trowel to ensure optimal adherence of the second layer. Care was taken to prevent cracks from the plaster drying too quickly by moistening the surface of the first layer lightly with a fine mist sprayer periodically over several days.

Table-1. Physical properties of bale specimens**.**

Plaster material and orientation	Descriptive statistic	Width (cm)	Height (cm)	Length (cm)	Density (kg/m^3)	Moisture (%)	Plaster thickness (mm)
Plain/flat	Mean	49.4	36.4	85.0	93.6	5.7	-
	COV	0.02	0.03	0.02	0.06	0.07	-
Lime/flat	Mean	49.5	35.6	76	90	6.8	58
	COV	0.008	0.02	0	0.03	0.10	0.08
Lime-cement/flat	Mean	49.3	36.1	76	92	7.8	53
	COV	0.02	0.008	0	0.02	0.06	0.12
Clay/flat	Mean	49.4	41.4	76	93	7.0	58
	COV	0.01	0.01	0	0.04	0.06	0.10
Plain/on-edge	Mean	36.4	49.7	84.7	94.3	5.5	-
	COV	0.03	0.02	0.03	0.09	0.07	-
Lime/ on-edge	Mean	35.9	48.7	76	91	6.7	54
	COV	0.03	0.02	0	0.03	0.06	0.17
Lime-cement/ on-edge	Mean	35.7	48.4	76	95	7.1	60
	COV	0.02	0.02	0	0.02	0.03	0.12
Clay/on-edge	Mean	36.1	48.2	76	93	5.8	58
	COV	0.006	0.03	0	0.03	0.10	0.13

The second layer (with a thickness of between 15 and 25 mm) was applied 10 days after the first layer. Before applying the second coat of plaster, the first layer was again moistened. The total plaster thickness, including both layers, was 25-35mm, which is a reasonable range of depth variation. By way of comparison, Schmidt (2002) noted that machine applied plaster was a depth of 10-80mm in their study of a house in Switzerland. Our relatively small variation in plaster thickness was achieved by using a temporary wood frame around the bale to help level plaster and to create straight and parallel edges at the top and the bottom surfaces. It is noted that many straw bale builders do not strive for perfectly flat wall surfaces because they like to emphasize the naturalness of the building. In our case, leveling the surface of the plaster took significant effort particularly for single bale plastering. This also helped ensure that load was uniformly distributed over the specimen surface.

The plastered specimens were allowed to cure for approximately 3 months before the load tests were performed. During the drying period, the moisture content of the bale was monitored weekly. It was discovered that moisture content of the bale increased an average of 4% in the time that followed plaster application.

Because the testing room was too small to fabricate and store all 48 specimens, preparation took place in a different building. Specimens needed to be separately delivered to the testing room and were thus exposed to some vibration (although minimized on an industrial pallet jack) during the transport. They were manually lifted into place, which led to some surface cracks in the plaster, mostly on the lime and clay plastered bales.

2.4. Compression tests

All specimens were tested monotonically in compression on a 150kN capacity Material Testing System (MTS) testing machine. Figure-2 demonstrates the test setup. The test speed was 2.5 mm/min for all plastered bales and 17.8 mm/min for the less rigid plain bales to ensure that failure consistently occurred between 5 and 20 minutes for all specimens. A loose fitting plastic sheet was used around the specimen to collect spalling plaster upon failure. Load and cross-head displacement was recorded via real-time computer data acquisition during the tests.

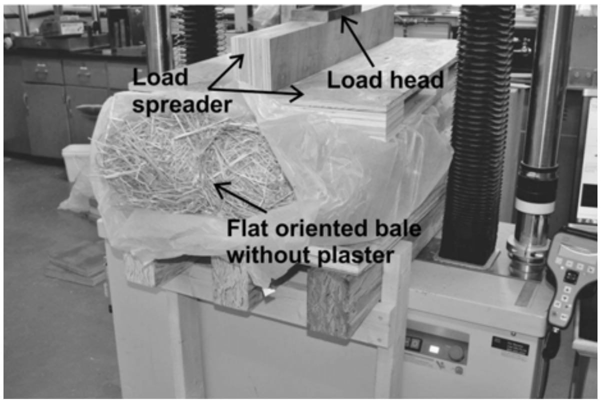

Figure-2. Straw bale compression test setup.

3. RESULTS AND DISCUSSIONS

Compression load capacity and bale stiffness were investigated and compared between plaster treatments and bale orientation. Results were compared to ‘allowable wall bearing capacities’ for different plaster types proposed by Hammer (2013) for inclusion into the 2015 International Residential Code.

3.1. RESULTS

3.1.1. Plain bales without plaster

Figure-3 illustrates the stress-strain behavior of plain bales loaded in both orientations. The stress path follows four distinct stages in keeping with that found by Zhang (2001). After an initial pre-compaction stage (from 0% to approximately 3% strain), there is an increase in resistance which is evident from the increased steepness of the curve. In the region of 4% to 10% of the strain for edge oriented bales and approximately 5% to 14% strain for flat laid bales, stress increases linearly with strain. This behavior is similar to conventional building materials, but with much lower stiffness. A bale stiffness parameter was calculated based on the slope of the line in this region. The result, termed working stiffness for the bale, was calculated and is summarized in Table-2. At the end of this region, there appears to be a distinct yield point indicated by a softening in the stress-strain curve. Beyond this however, a new phase of strain-hardening-like behavior occurs from densification of the straw which is confined within the twine. It is presumed that this behavior would continue until specimen failure, well beyond the range of service loads, brought on by broken twine.

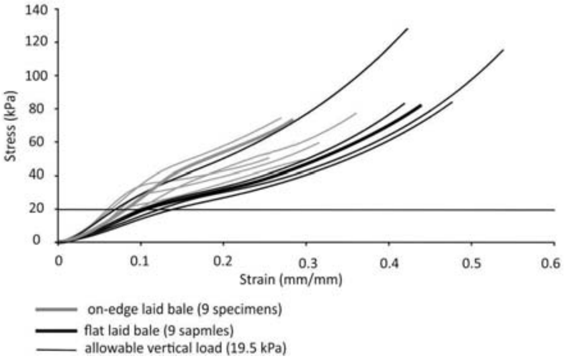

Figure-3. Stress-strain behavior of straw-bales without plaster.

The upper limit of allowable vertical stress of 19.15kPa per the construction and building code requirements of Austin City Code (Chapter 36, section 3605.5) is indicated on the graph for comparative purposes. Without plaster, the bales are able to withstand this stress. However, the mean strain of flat specimens at this allowable stress is 0.11±0.02, (or a displacement of 39.2±7.1mm) which is clearly unacceptable in practicality. Similarly, the mean strain of on-edge bales is 0.08±0.01 (or a displacement of 38.4±6.0mm).

Referencing Table-2, the flat bales had 38% lower mean stiffness than the on-edge bales, which is as expected because it is reflective of typical anisotropic material response. The stiffness ranges between 0.18 MPa and 0.48 MPa considering both orientations. This is consistent with findings from King (2003) who found stiffness to range between 0.12 and 1.8MPa. Tests of flat oriented specimens were slightly less consistent in stiffness than ones tested on-edge (23.2% vs. 19.5%, respectively).

Table-2. Working stiffness of plain bales: flat and on-edge.

Descriptive statistic	Working stiffness	
	Flat	On-edge
Mean (kPa)	226.1	363
COV	0.23	0.20
Count	9	9
Minimum (kPa)	178	276.1
Maximum (kPa)	352	478.4

3.1.2. Lime plastered bales

Figure-4 presents the load-displacement behavior of the lime plastered bales. The bale capacity is measured by ultimate load, rather than by ultimate stress because the bales would be used in wall assemblies with the given on-edge or flat dimensions. Also, using ultimate load facilitates comparison of the results to the allowable wall bearing capacity as set out by Hammer (2013).

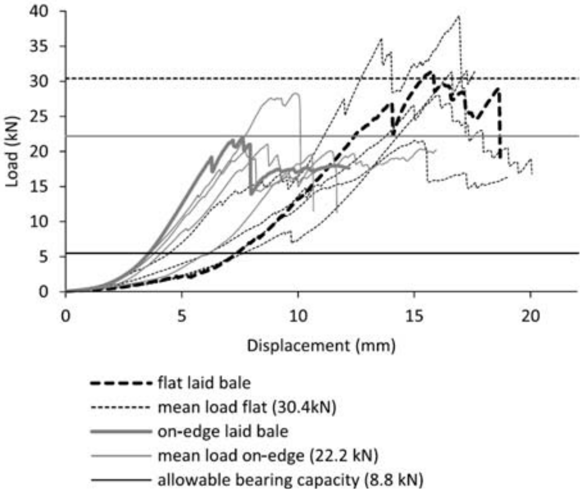

Figure-4. Load-displacement results for lime plastered bales.

A relatively long period of initial pre-compaction is observed in the graph, especially for the flat laid specimens. This response was a result of compression of plain straw prior to the load plate coming into contact with the plaster. In all cases, localized brittle failures (Figure-5) were observed in the plaster at failure and were clearly evident on the graphs as sharp drops in load with stress recovery. The flat specimens took approximately 37% more load than the on-edge specimens whose average maximum load was 22.2 kN. For both orientations, the mean maximum loads were higher than the allowable bearing capacity of 5.5kN (Hammer, 2013).

Figure-5. Brittle failure of lime plastered specimen loaded flat.

3.1.3. Lime-cement plastered bales

Figure-6 shows that for lime-cement plastered bales, the flat oriented bales took approximately 82% more load, on average, than the edge oriented bales. For both orientations, however, the mean maximum loads were higher than the allowable bearing capacity of 8.8kN (Hammer 2013).

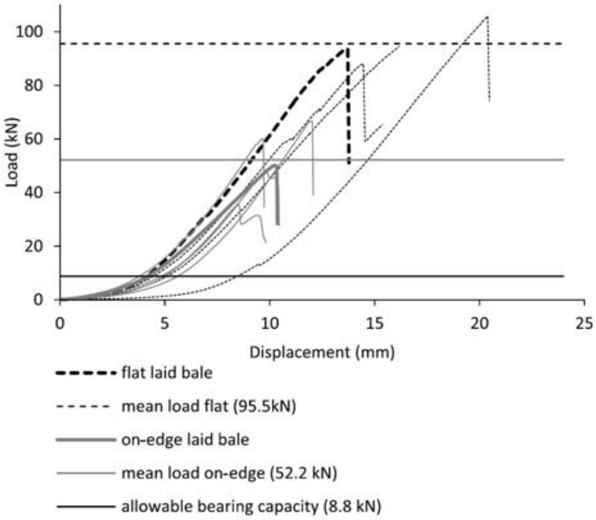

Figure-6. Load-displacement results for lime-cement plastered bales.

3.1.4. Clay plastered bales

As seen in Figure-7, the clay plastered specimen behavior was similar to the lime plastered specimens except that the maximum loads were substantially less, as expected. Many localized failures occurred in the clay up to the displacement of approximately 20 mm. After this, however, the load increased somewhat smoothly as the straw bale itself continued to support the load. The flat bales took approximately 39% more load, on average, than the on-edge oriented bales. Still, for both orientations, the mean maximum loads were higher than the allowable bearing capacity of 4.4 kN (Hammer, 2013).

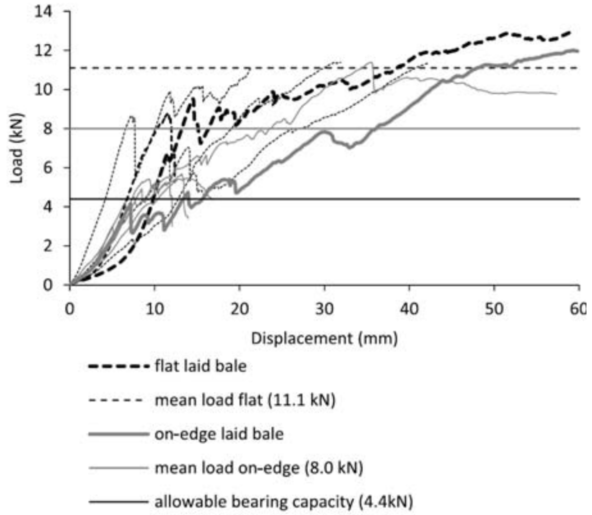

Figure-7. Load-displacement results for clay plastered bales.

3.2. Comparative study

3.2.1. Load-displacement comparison

Figures 8a and 8b depict the characteristic load-displacement behavior of the plain bales and the three plaster material groups for each orientation by potting one representative specimen from each group. There is a clear distinction in load carrying capacity and stiffness between groups: lime-cement plastered bales being the strongest and stiffest and plain bales offering the least strength and stiffness. Also interesting is that the displacement of all specimens oriented on-edge is higher compared to displacement to flat specimens with the same plaster. This result is similar to that of Vardy and MacDougall (2006) who investigated compression properties of two-string wheat straw bales covered with lime-cement based plaster. In this study, it was found that the strength of plastered bales oriented flat was 36% greater than those oriented on-edge.

3.2.2. Working stiffness comparison

Table-3 presents a summary of stiffness for the plastered specimens. On-edge oriented specimens, in general, had higher stiffness than bales oriented flat regardless of the type of plaster material. An Analysis of Variance (ANOVA) concluded that only the results for lime and lime-cement plastered bales were statistically different at a 5% level of confidence. The high variability of the clay specimens likely affected the comparison and showed no significant difference between the means. As expected, clay plastered bales had the lowest stiffness and lime-cement plastered bales had the highest stiffness.

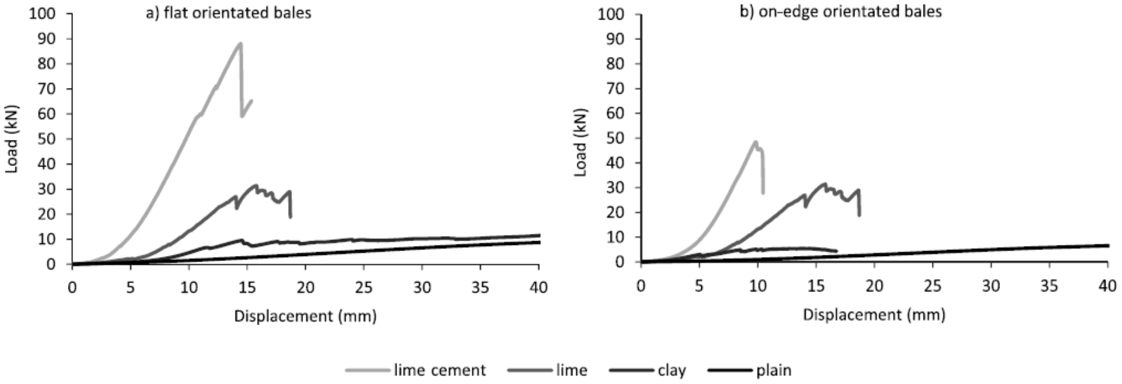

Figure-8. Characteristic load-displacement results: a) flat oriented bales and b) edge oriented bales.

3.2.3. Maximum load comparison

Differences in bale orientation strength have been concluded from previous studies (Kim *et al*., 2012; Ashour *et al*., 2011; Vardy and MacDougall 2006). The results presented in Table-4 concur with these results: for all groups, the flat oriented specimens have higher mean wall load carrying capacity than on-edge specimens. However, ANOVA concluded that only the means for lime and lime-cement plastered bales were statistically different at a 5% level of significance. Again, the high variability of the clay specimens likely contributed to this outcome. It was observed that the failure mechanisms were distinct regarding specimen orientation: in the case of flat oriented bales, the failure was mostly a result of crushing of the plaster while the failure of the on-edge plastered bale was a result of buckling of the plaster skins.

Lime-cement plastered bales have the highest load capacity, which is approximately three times higher than that of lime plastered bales and eight times higher than that of clay plastered bales. Disregarding the plaster material, flat oriented bales have approximately 39% higher load carrying capacity in comparison to on-edge oriented bales.

Comparing the results to allowable wall bearing capacities (Hammer 2013), all results are higher; the biggest difference is for flat lime-cement specimens at a factor of 10.7 more and the least difference is for clay specimen's on-edge at a factor of only 1.8. Flat specimens are able to sustain 36.9% more load than on-edge specimens.

4. CONCLUSIONS

This study was conducted to expand the general knowledge base of how rye straw bales respond under compressive load when plastered with different types of plaster and loaded in different orientations. It was found that, independent of plaster type, orientation of bale had a significant effect on compression strength and to a lesser extent, stiffness; in general, flat oriented bales had higher load carrying capacity by approximately 50% than edge oriented bales. Other specific key findings were as follows:

The bale itself, with no plaster and regardless of orientation, had the ability to take adequate load but the displacement was unacceptable for practical use. A significant difference was found (at 5% level of significance) in plain bale behavior between flat and on-edge orientation.

All specimens exceeded the maximum load capacity proposed by Hammer (2013) for inclusion into the 2015 International Residential Code. The largest factor of safety was in the case of flat oriented lime-cement plastered bales (10.7), while the smallest factor of safety was for on-edge oriented clay plastered bales (1.8). Thus,

Table-3. Comparative summary of working stiffness for plastered specimens.

Descriptive statistic	Lime plastered bales			Lime-cement plastered bales			Clay plastered bales		
	Flat	On-edge	% difference	Flat	On-edge	% difference	Flat	On-edge	% difference
Mean (MPa)	2.35	5.9	151.0	8.3	12.5	33.6	0.87	1.34	35.1
COV (%)	43	19	129	7	19	63	46	22	105
Count	5	5	-	4	5	-	5	5	-
Minimum (MPa)	1.7	4.5	62.2	7.7	8.8	12.5	0.3	1.0	70.0
Maximum (MPa)	3.8	7.4	48.6	9.2	15.1	39.1	1.2	1.8	33.3

Table-4. Comparative summary of maximum load for plastered specimens.

Descriptive statistic	Lime plastered bales			Lime-cement plastered bales			Clay plastered bales		
	Flat	On-edge	% difference	Flat	On-edge	% difference	Flat	On-edge	% difference
Mean (kN)	30.4	22.2	36.9	95.5	52.2	83.0	11.1	8.0	38.8
COV (%)	21	16	34	8	23	66	74	43	74
Count	5	5	-	4	5	-	5	5	-
Minimum (kN)	21.6	19.6	10.2	88.0	35.5	147.8	8.7	5.2	67.3
Maximum (kN)	39.3	28.3	38.9	105.8	66.7	58.6	13.0	12.0	8.3
Allowable load (kN)*	5.5	5.5	-	8.9	8.9	-	4.4	4.4	-

current building guides' tips and recommendations would insure structural safety and would meet straw bale building regulations.

Across all four groups, flat oriented bales had higher load carrying capacity compared to edge oriented bales both with and without plaster.

The failure mechanism of flat oriented bales was primarily crushing of the plaster, while failure of the on-edge plastered bale was a result of buckling of the plaster skins. Lime-cement plastered bales performed stronger and stiffer than lime or clay plastered bales.

It is important to note that when selecting plaster for straw bale building, while mechanical properties are critical factors for design, other factors, such as environmental, physical and economic characteristics of the material are also important to consider.

REFERENCES

Ashour T., Georg H. and Wu W. 2011. Performance of straw bale wall: A case of study. Energy Buildings. 43: 1960-7.

Atkinson C. 2008. Energy Assessment of a Straw Bale Building. London: University of East London.

Austin Building Code. 2013, September 25. Retrieved from http://www.dcat.net/.

Bou-Ali G. 1993. Straw Bales and Straw Bale Wall Systems. M.Sc. Thesis, Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, Arizona.

Brojan L. and Clouston P.L. 2014. Straw bale building: the state of the art based on a world-wide survey. In press: Journal of Architectural and Planning Research.

EBNet. 2014, June 5. Ecological Building Network. Retrieved from http://www.ecobuildnetwork.org/projects/research/straw-bale-test-program.

Hammer M. 2013. Straw bale construction code. Building with straw bales, Retrieved from <http://www.ecobuildnetwork.org/projects/straw-bale-code-supporting-documents>.

Jones B. 2009. Building with straw bales. Devon, Green books.

Kim Y.J., Reberg A., Hossain M. 2012. Bio-Building Materials for Load-Bearing Applications: Conceptual Development of Reinforced Plastered Straw Bale Composite Sandwich Walls. J. Perform. Constr. Facil. 26: 38-45.

King B. 2003. Load-bearing Straw Bale Construction. Ecological Building Network. Retrieved from <http://www.ecobuildnetwork.org>.

Lacinski P. and Bergeron M. 2000. Serious straw bale. Chelsea Green Publishing Company, Vermont.

Lerner K. and Donahue K. 2003. Structural testing of plaster for straw bale construction. Ontario straw bale building coalition. Retrieved from <http://www.osbbc.ca>.

Magwood C., Mack P. and Therrien T. 2005. More straw bale buildings - A complete guide to designing and building with straw. New Society Publishers, Gabriola Island.

Morrison A. and Kefee C. 2012. Modern look at straw bale construction. Straw Bale Innovations, LLC, Colorado.

Racusin J.D. 2011. Final Report for Energy Performance of Straw Bale Buildings Research Program. New Frameworks Natural Building, LLC, Montgomery, VT.

Schmidt W. 2002. Strohhaus Braun-Dubuis. Straw bale house. Retrieved from <http://www.atelierwernerschmidt.ch> (Sept. 25, 2013).

Sodagar B., Rai D., Jones B., Wihan J., Fieldson R. 2011. The carbon-reduction potential of straw-bale housing. Build Res Inf. 39: 51-65.

The Last Straw. 2014, June 5. Retrieved from http://thelaststraw.org/resources/straw-bale-codes-testing-research/.

Vardy S. and MacDougall C. 2006. Compressive testing and analysis of plastered straw bales. J. Green Build. 1(1): 63-79.

Zhang J. 2001. Load carrying characteristics of a single straw bale under compression. Ecological Building Network. Retrieved from http://www.ecobuildnetwork.org.