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Displacement in Load Bearing Straw Bale Walls Due To Concentric Compressive Loading

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Abstract: *The objective of this research was to provide structural performance data and information for straw bale home builders, building inspectors and engineers. Structural testing of 2 full-scale straw bale walls was undertaken. The tested walls were instrumented and subjected to compressive vertical loading. The results were interpreted in the light of the expected loads that must be withstood in single storey domestic applications. Two specimens of straw baled walls were tested using two techniques for measuring displacement under a maximum load of 2 ton. Pre-compression improved initial stiffness of the straw bale walls. The displacements recorded ranged between 7- 10 mm. It was concluded that placement of a wooden cap plate on top of the straw bale wall is important to insure uniform transfer of the loads along the whole length of the wall. Also this technique of building would confine the connection between the wire mesh, the straw and the plaster to insure the sandwich panel behavior in the section.*

Keywords: *Rice straw bales- compression test- sandwich panel hybrid sections- plastered straw-bale walls*

I INTRODUCTION

1.1 *General background*

In order to test the performance of plastered straw-bale walls, it is essential to understand that, once plaster is applied directly to either one or both bale surfaces, the structure is now a hybrid of straw and plaster. Effectively, any further loading will go mostly or entirely into the plaster skins. This is because of the relative stiffness, or in other words the various modulli of elasticity of the two adjacent materials. Any kind of plaster is far stiffer than the straw, and will therefore "attract" any subsequent loading. When any load is applied on a plastered straw-bale structure, the soft, flexible straw yields, and the brittle plaster skin attracts all the stresses. Unlike in a pure concrete structure, however, where such a failure of a bearing (or shear) concrete wall or column could be both sudden and catastrophic, the failure of the plaster skin would throw any loads back on the straw-bale assembly. The capacity of the bales to pick up the load yielded by cracked plaster is fairly substantial. [1]

1.2 *Sandwich Panel Behavior*

Tests conducted in various laboratories over the past 10 years have proven that an un-plastered straw bale wall can carry an appreciable amount of vertical load, as well as some in-plane and out-of-plane shear, and would therefore provide a backup against failure of the plaster skins. Furthermore, recent tests in Washington and California have revealed the surprising strength, ductility and toughness of plastered walls, even when cracked and subjected to cyclic loading. We are finding that the bale walls, when plastered on both sides, behave much more like an integral sandwich panel structure than might be expected [2]. The structural model is complex: Rigid inside and outside skins are attached to the comparatively soft straw-bale "masonry" assembly. Most important to the whole package, there is both some shear capacity in the bales and some shear transfer capacity between the bale surfaces and the skins. Though it is essential to see the plaster skins as the primary load-carrying elements, it is nevertheless also important to recognize that the straw bales are still crucial elements of the package. This is analogous to the relationship of web to flanges in a steel I-beam: The flanges (skins) carry bending loads, but rely on the shear capacity of, and connection to, the web (in this case, the straw-bale assembly). So the assembly consists of strong, brittle, thin "concrete walls" braced by, and somewhat elastically connected by, the straw-bale core. [3]

II. METHODOLOGY

2.1 *Materials*

Two batches of rice straw bales were purchased from 2 different farms located in Kafr El-Sheikh Governorate North of Cairo. The bales were harvested during the autumn months of 2012 (October- November) then compacted and stored. The bales in the first and second batches had approximate dimensions of 100 ± 2.5 cm length, 35 ± 2.5 cm height and 50 cm width and 150 ± 2.5 cm length, 35 ± 2.5 cm height and 50 cm width. The average weights of samples of three bales chosen randomly were 22- 25 kg for the batch of length 100 cm and 30-32 for the bales of length 150 cm. The bales had an average bulk density of 125 kg/m3. The average moisture content of bales recorded 18.3 % which meets the California Straw Bale Codes recommendation for a maximum of 20% of total bale weight.

2.2 *Specimens*

2.2.1 *Walls Construction*

Two wall specimens (designated A and B) each measuring approximately 360cm length x 200cm height x 50cm width were made up on plain concrete base footing of dimensions 390 cm length x 30cm height x 65cm width. The walls were constructed by stacking of bales from the two batches mentioned earlier. A 16 mm diameter steel bar was embedded in the walls with a distance of 50 cm between each bar along the full walls' length to tighten the bales. The steel bars were an in the plain concrete footing for a distance of 25cm.

2.2.2. *Walls Plastering*

Plastering of walls was applied after the pre-compression tests. A galvanized chicken wire mesh 1mm diameter was first stapled to the top plate and bottom plain concrete footing. It was then pulled close to the bales by stitching the mesh with baling twine pulled through the bales. The final step in the construction was the application of the plaster referred to as the "skin". This was done by hand, or by trowel. The skin material is mortar of a combination between cement, sand and lime with proportions 1:6:1 respectively, but the thickness of this skin varied appreciably as it fills in the gaps and notches. The initial layer was worked into the straw. Subsequent layers were built up until the plaster was visually judged to extend beyond the edge of the top plate, sides, and bottom till reaching the concrete footing. The plaster was then allowed to stand and cure in the open air to resemble reality. As for wall A the top layer of the bales were directly subjected to the wire mesh and the plastering layer. While, on top of the bales of wall B, a wooden cap plate was inserted firmly on the bales surface over which the wire mesh and the plaster were provided.

2.3 *Testing procedures*

Two testing procedures were applied on the specimen walls A and B. The first was the "Leveling procedure" during which the settlement of some fixed points on wall A was observed using the leveling surveying technique. This method is usually used in practice for establishing fixed or temporary bench mark heights above the adopted datum Fig.1 by using a leveling instrument and a rod. In this case, the height difference in each level setup is determined by simultaneously using two rods and taking back sight and fore sight rod readings. According to the pre-specified standard specifications of leveling, the expected accuracy of rod readings is usually in the order of 1 millimeter. The second testing procedure was by using the" Linear Voltage Displacement Transducers" (LVDTs) to measure the settlement in wall B.

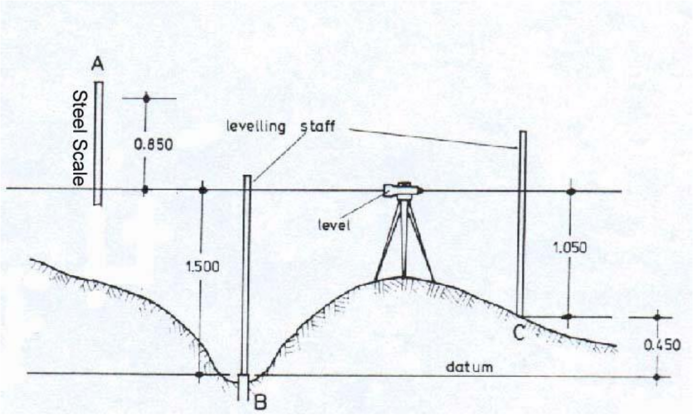

Figure 1: Leveling method with steel scale

2.4 *Pre-compression Tests*

A pre-compression test Fig. 2 was undertaken on wall A by applying one ton of cement bags on top of the bales of the tested wall directly and left for 5 days before plastering. The observed settlement just after loading is shown in Table 1 measured by the Leveling procedure.

Table 1: The settlement of the observed points at wall A in cm

point	Settlement in cm
1	7.3
2	9.7
3	9.0
4	9.9
5	6.7

Five points were fixed at the tested rice straw wall using steel bars fixed through the wall width. Also, one control point was fixed at a nearby building out of the loading area. From the control point, the levels of the five points were computed. The vertical movement (deflection) of point (T), between any two vertical positions (I and J), came from two loading cases, and were computed by subtracting the two levels of point (T) as indicated in equation (1).

$$D_T = L_j - L_I \qquad (1)$$

Where:

L_I Is the initial difference in level between the target and control point (before loading of point).
L_j Is the difference in level between the target and control point (after loading of point).
D_T Is the vertical movement of point (T).

Figure 2: Pre-compression Test of full scale wall A

Five points are fixed at the tested rice straw wall using steel bars fixed through the wall width. Also, one control point is fixed at a nearby building out of the loading area. From the control point, the levels of the five points can be computed. The vertical movement (deflection) of point (T), between any two vertical positions (I and J), comes from two loading cases, can be computed by subtracting the two levels of point (T) as indicated in equation (1).

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D_T Is the vertical movement of point (T).

As for wall B and due to the non uniformity of the settlement results throughout the whole length shown in wall A, a wooden U shaped cap was constructed to cover the top of the wall. On top of this plate all the loads were applied to insure uniform settlement of the bales prior plastering but no records were taken.

2.5 *After Plastering tests*

2.5.1 *Wall A*

After releasing the pre-compression load, a steel wire mesh was used to cover wall A from top and both sides before the plastering application. Cement plastering then took place for the wall and left for curing and drying for a period of 28 days before testing. On top of the bales in wall A another set of cement bags for loading were applied regularly. These cement bags were laid on a wooden platform along the length of the wall. The leveling technique was used to measure the settlement in the wall. The used surveying instruments in the experiment were calibrated and adjusted before using them. The control and target points were observed using the level, and the scale readings were recorded before loading, then after applying 1 ton of loads and finally after applying 2 tons of loads. Fig. (3) & (4) show the position of the monitored points as well as the dimensions of the wall.

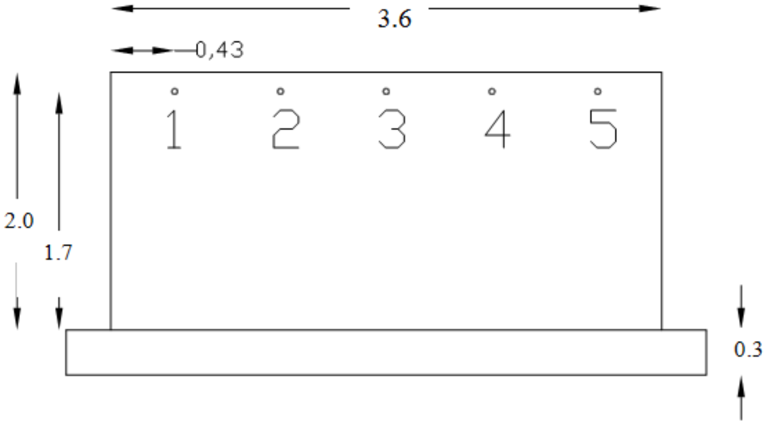

Figure 3: The position of the monitored points and the dimensions of the wall


Figure 4: The 2nd loading case after plastering the wall

The following results in Table 2 were recorded after applying 2 tons of cement bags on top of the wall.

Table 2: The settlement of the observed points at the wall in mm

point	after loading 1 ton	after loading 2 ton
1	1.0	3.5
2	1.0	5.0
3	2.0	3.5
4	1.5	4.0
5	2.0	3.0
Mean	1.5	3.8

The test never ended up till this point of loading as the plan was to keep loading the wall until we reach the failure point as shown in Fig. 5. The failure point was reached after applying over 2.5 tons of cement bags on top of the wall.


Figure 5: Failure point of loading

2.5.2 *Wall B*

This wall was plastered in a slightly different way from wall A where the top wooden cap plate was inserted on top of the bales then the wire mesh and plaster were applied. This procedure was undertaken to insure more load uniformity over the wall and to avoid the catastrophic failure seen of wall A. The loads were distributed on a wooden platform erected 35cm above the top wooden plate of the wall as shown in Fig. 6. Then 2 hydraulic jacks were set between the wooden platform carrying the load and the top wooden plate of the wall to transfer the loads gradually to the wall. Also 2 LVDTs were connected to the hydraulic jacks to record the settlement in the wall as shown in Fig. 7.


Figure 6: The loading technique on Wall B

Figure 7: The connection between the Hydraulic Jacks and the LVDTs on Wall B

III OBSERVATIONS AND DISCUSSION

As Walls A and B were 2 specimens of relatively similar local rice straw material, which was cultivated and baled in the same circumstances, it was rational to compare between the accuracy of settlement results for the 2 walls of similar length, width and height despite the difference between them in techniques of loading and instrumentation.

3.1 *Wall A*

The displacements of wall A (vertical movement) were recorded and the settlement was calculated using equation (1) . The average settlement was plotted in Fig. 8. The deflection of the wall showed that the response under loading was fairly linear up to 2 tons of distributed load indicating a uniform loading condition. The average recorded settlement in the wall was about 3.8 mm at a load 2 tons with a maximum settlement of 5mm and a minimum of 3 mm at some points. After this point and as loads were increased some cracks initiated to appear in the upper segment along the wall width especially at the tips. In applying more loads and due to difficulty in applying them in a uniform manner, a sudden failure took place in the top tip of the wall. Unfortunately, the researchers were not able to record the readings of deflection of the wall between loading 2 and 2.5 tons of cement. It should be noted that in no instance did the wall fail in a catastrophic manner. Failure was typically preceded by widespread cracking of the plaster.

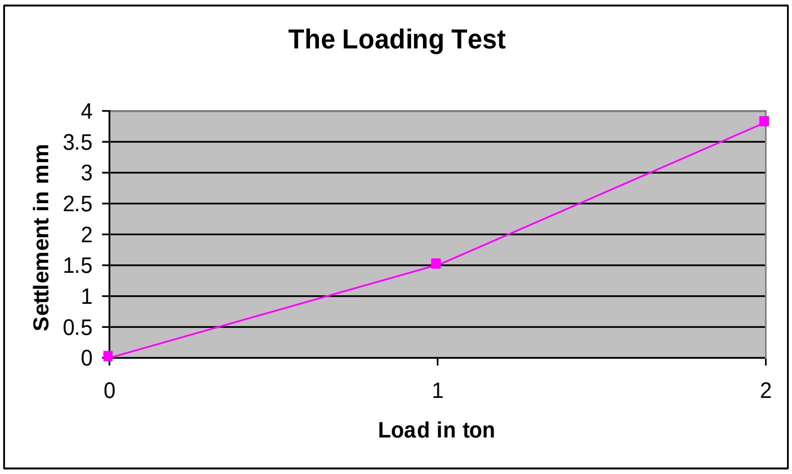

Figure 8: Average settlement of the wall

3.2 *Wall B*

Fig. 9, 10 , 11 and 12 showed typical load versus vertical deflection plot. The vertical deflections were measured by 2 linear voltage displacement transducers (LVDTs) on the edges of the wall at a distance of 0.75m from each end. The recorded readings are expressed on the charts as right and left displacement according to the deflection under each LVDT in place. Each chart begins with the initial reading under zero loading for each LVDT. The loads were increased regularly by a value of 0.4 ton distributed uniformly on the full width of the wall, till reaching the max loading value after which all loads are released and displacement recorded.

Fig. 9 showed some variance in the displacement values of both right and left LVDTs with a maximum value of 3 mm under a concentric compressive load 1.6 ton and 6mm after release of loads. This initial non-linear response can be attributed to the elasticity of the straw at the top of the wall which was not compressed enough before the top plate begins to bear on the plaster skins.

The response of the wall in the 2nd, 3rd and 4th loading phases was fairly linear up to an applied load of 2 ton and also after releasing the loads. It can be seen that in general, the load-deflection response of the wall before reaching the 2 ton load consists of an initial non-linear response, followed by linear behavior up to the maximum load. This indicates that the loading of the wall was uniform. Up till this stage of loading (2 ton) no cracks appeared on both faces of the wall.

The maximum displacement recorded in the wall was 10 mm at the 1st loading phase. After this phase the displacement in the wall decreased from a maximum of 9mm in phase 2 of loading till a constant value of 7mm in phases 3and 4 of loading. These results showed that the wall gave the same displacement after repetition of loading and unloading indicating that the plaster skin and the bales (supporting system) acted as a composite section or a sandwich panel behavior.

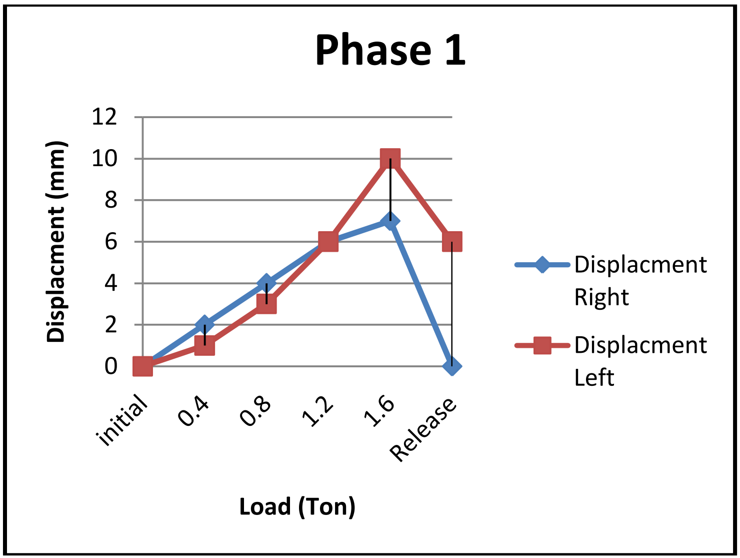

Fig 9: 1st phase of loading

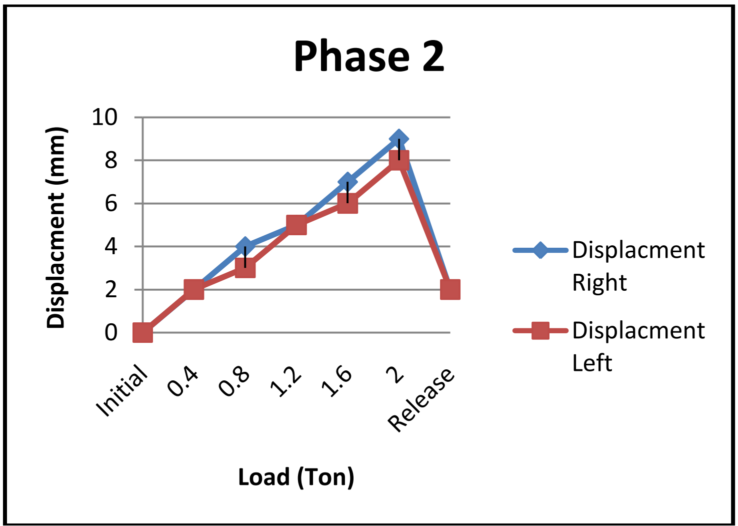

Fig 10: 2nd phase of loading

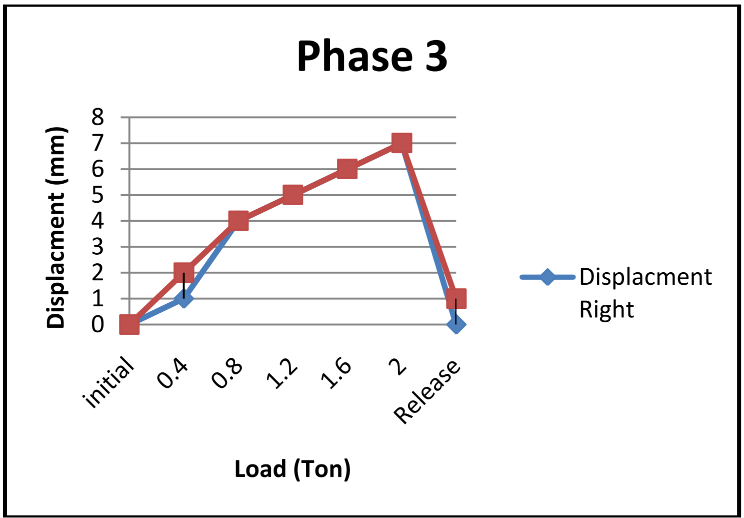

Fig 11: 3rd phase of loading

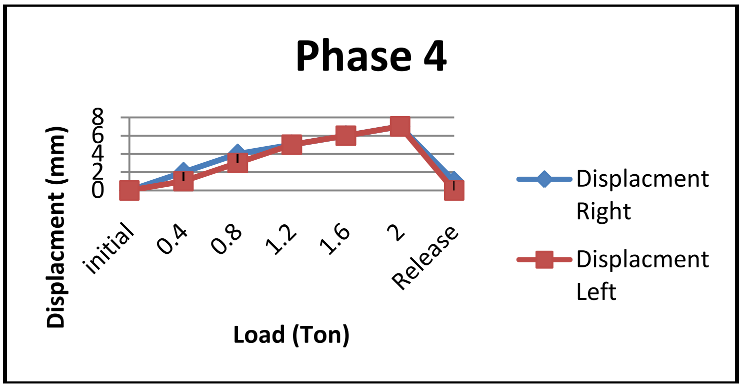

Fig 12: 4th phase of loading

These results does not coincide with the results recorded for Wall A conducted using the leveling technique which presented an average maximum settlement (displacement) of 3.8 mm at a maximum load 2.0 ton. This diversion in the results reinforces the idea that the leveling technique was inaccurate and the loose top wooden plate over which the loads were laid in the 1st experiment failed to give the effect of a cohesive composite section with the plastered wall. As a result it is highly recommended that during the construction of any load bearing straw bale wall, a wooden cap plate should be inserted on top of the wall to insure uniform transfer of the loads along the whole length of the wall. Also this technique of building would confine the connection between the wire mesh, the straw and the plaster to insure the sandwich panel behavior in the section.

Despite the variance in specimens' materials, dimensions , construction techniques, as well as loading and displacement measurements procedures' undertaken by scientists interested in straw bale construction, the authors found it valuable to make an absolute comparison between local and previously reported experimental values of compressive testing results.

In accordance to the Egyptian case of study the un-plastered rice straw wall recorded displacements ranging between 67 and 99 mm. This result falls within the range of displacements of un-plastered walls reported by Bhattarai P. et al, 2012 [4] that varied between 72 and 198 mm. Similarly, Carrick J. et al [5] reported vertical displacement of un-plastered straw bale walls of 66m.

This behavior was attributed to 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. Researchers agreed that pre-compression improved initial stiffness of the straw bale wall.

In case of plastered walls, the maximum loads applied in the Egyptian case of study was 2 ton with a displacement ranging between 7-10 mm. This result contradicts with the Indian case conducted by Bhattarai P. et al, 2012 showing a displacement of 55 mm under a load of 4.1 ton while Carrick J. et al [5[reported an average displacement of 5.1mm under an average vertical load of 7.5 ton.

IV. Conclusion

This testing was undertaken with a view to determining the structural properties of the rice straw plastered walls for applications in domestic construction. The load applied for testing the specimens complied with the California Straw bale Codes [6] that recommended an allowable vertical load of not more than 2.15 ton/m^2 (400 pounds per square foot) on load bearing walls. Two specimens of straw baled walls of dimensions 360cm length x 200cm height x 50cm width were tested using two techniques for displacement measurement under a maximum load of 2 ton. Pre-compression improved initial stiffness of the straw bale walls. It was concluded that placement of a wooden cap plate on top of the straw bale wall is important to insure uniform transfer of the loads along the whole length of the wall. Also this technique of building would confine the connection between the wire mesh, the straw and the plaster to insure the sandwich panel behavior in the section. The displacements recorded ranged between 7- 10 mm. No hair cracks appeared on both surfaces of plastering during repetitive loading till reaching the maximum load.

References

[1]. King, B. (2006) "Design of straw bale buildings." Green Building Press, San Rafael California. 259 pp.
[2]. King , B. (2001) "Straw-Bale Construction A Review of Testing & Lessons Learned To Date" Ecomaterials Conference.
[3]. King, B. (1998) "Straw Bale Construction" Building Standards/ September- October
[4]. Bhattarai, P., Raj Dhakal, D., Neupane, K. and Chamberlin, K., " Straw Bale in Construction of Building and its Future in India", International Journal of Modern Engineering Research (IJMR), Vol. 2, Issue 2, Mar-Apr 2012 pp-422-426.
[5]. Carrick, J., and Glassford, J. (1998), "Compressive, Transverse and Racking Tests of Load-Bearing Walls," *Research Report*, Building Research Centre, University of New South Wales, Australia.
[6]. California Straw Bale Code, Bill Number: Ab 1314 Chaptered (10/16/1995) ,Chapter 941 Introduced By Assembly Members Sher, Richter, and Woods (Coauthor: Senator Johannessen)