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ASSESSING THE BEARING CAPACITY AND DESIGN FOR STRAWBALE MASONRY

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ABSTRACT

The results of the physical and mechanical strength tests for cement plastered strawbale masonry have shown the masonry viability as a structural, durable and aesthetical material. Design results also show that a wall of strawbale plastered with cement, having average compressive strength 2.10 N/mm², is adequate as loadbearing element for low-storey residential building. Design approach and details should be followed as recommended in this work. The problems encountered during the construction of the prototype wall were effortlessly overcome.

INTRODUCTION

While strawbale homes are beautiful and comfortable, they are also ecologically sound and energy efficient. Conventionally, straw is used as roof cover and ceiling plates. In some parts of Nigeria, houses are built of mixture of clay/laterite and straw for wall and roof cover. Excavations at Corinth in Greece showed that temples, built around 750 BC, were thatched with straw. One of the advantages of using straw as a building material is its availability. Straw is a readily available material here in Nigeria and all over the world. It is not as costly (production) as the conventional materials due to the local availability.

The movement for the use of strawbale as wall is fuelled by the growing awareness of limited material and energy resources, increasing development impacts and adverse health effects from buildings made of 'toxic' materials.

In this country, Nigeria, use of strawbales as structural elements is yet, to the best of the author's knowledge, to be incorporated in design codes of practice. This may be due to lack of information on the behaviour of this material. This is exactly what this work intends to clarify. Construction method is based on the past woks of Jones (2001), Permaculture (2002) and Adams (2003).

This paper is based on experimental and construction programme carried out on the strawbale model wall. Locally available materials were used in the preparation of the tests specimens. Plastered strawbales specimens used for tests were sampled for the actual construction of the wall. Model foundation was constructed for the wall and wooden-box openings were made and placed in positions. The materials used include ordinary Portland cement (OPC), Fine aggregates, water and gravels (aggregate), matured elephant (wild) grass and damp proof course (DPC).

MATERIALS FOR THE TESTS

The straw used were fully dried (put in the oven for 10 hours without an appreciable difference in weight), clean and free from debris and other leaves. The matured elephant grass used were thick, long-stemmed that is free of seed heads, this type is usually available around December to February period where they are naturally dry.

Ordinary Portland cement was used and the water used in the process was clean, fit for drinking and free from organic materials or contaminants (dissolved or suspended), which could have adversely affected the strength of the resulting mortar.

The fine aggregate used was clean, sharp and a well graded fine natural sand free from salts and organic contaminations. It contains particles with a wide range of sizes. The deleterious materials were removed by sieving. The following section expresses the preparation for plastering mortar used on the strawbales.

PARTICLE SIZE DISTRIBUTION OF SAND AGGREGATE

Sieve analysis test was carried out to determine the particle size distribution of the fine aggregate used in mortar/plaster mix. Test sieves to BS410. Mechanical sieve shaker, weighing machine, sieve brush and metal tray.

1000g of dry fine aggregate sample were weighed to calculate the cumulative percentage passing and a grading curve plotted. Results obtained are shown in Table 1 and the particle size distribution curve is shown in Fig.1.

Table 1 Result of sieve analysis

Sieve Size (mm)	Sieve Size (g)	Sieve weight & Retained (g)	Retained weight (g)	Percentage Retained (%)	Cumulative Percentage Retained (%)	Cumulative percentage passing
5	-	-	-	0	0	100
4	555	558.3	3.5	0.35	0.35	99.65
2.36	480	511.5	31.5	3.15	3.5	96.5
1	521	664.5	143.5	14.35	17.85	82.15
0.5	493	765.5	272.5	27.25	45.1	54.9
0.4	479	585	106.5	10.65	55.1	44.25
0.25	481	711	230.5	23.05	78.8	21.2
0.063	451	640.5	189.5	18.95	97.75	2.125
Recording Pan	269	291.5	22.5	2.25	100	0

$$\text{Percentage retained} = \frac{\text{Weight retained}}{\text{Total weight of sample}} \times 100\% \quad (4.1)$$

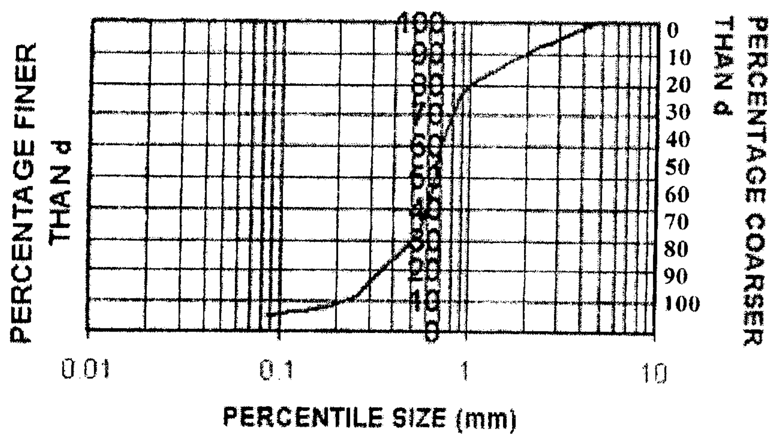


Fig 1. Particle size distribution curve

BALING OF THE STRAW

As straw baling machine has not been designed mechanically, the matured straw (Elephant grass) was taken manually, bit by bit and was cut into size with a scissors, a durable material such as twine, was used to form a bale of desired size and dimension. The bales were uniformly well compacted to reduce the void to the barest minimum in order to eradicate looseness, and increase the density of the bale. Bales of straw are shown in Fig. 2.

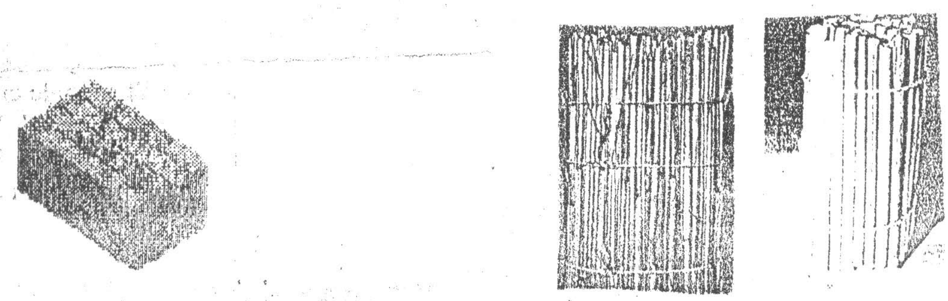


Fig. .2 Produced strawbales

BATCHING

Proportions of the Ordinary Portland Cement (OPC) and fine aggregate were used to specify the mortar/ plaster mix. The mix proportion was, by volume, determined carefully in order that the resultant mortar/ plaster meet the required standard. Batching was made by volume. The mortar was made from a mix of 1:8 of cement and sand. Adequate water was added to the batched mortar to provide sufficient workability for adequate application.

The cement and sand were thoroughly mixed dry such that no trace of unmixed cement was found in the mixture before adding water and thoroughly mixed again.

A sufficient amount of water was added to the mix to avoid shrinkage and distortion of the plaster on drying.

MOULD FOR PLASTERED STRAWBALE

Straw bales come in all shapes and sizes, from small two- string bales to larger three string bale and massive cubical or round bale. The medium sized rectangular three–string bale is preferred for building construction. Three–string bales are better structurally; they have higher thermal resistant (R-value) (New Mexico ASTM E – 119 1993, Thompson, 1995) and are often more compact.

A typical medium sized, three–string bale is (584.2 x 406.4 x 1066.8 mm). The smaller two–string bales which are easier to handle are roughly (457.2 x 355.6 x 914.4mm).

For the purpose of this project, the three-string bale size was chosen because of its properties. A wooden mould of inner size 78mm x 61mm x 127mm was constructed for a straw bale size of 58mm x 41mm x 107mm which would enable the plastered straw bale to come out with a plaster thickness of 10mm and with a smooth rectangular surface.

The wooden mould was constructed in such a way that the wooden panel can be separated for easy removal of the specimen; the use of oil for lubrication also helps the removal process. The bale compressor is shown in Fig. 3.

PLASTERING AND CURING OF PLASTERED STRAWBALE

The mortar was dumped on a mortarboard and shoveled from the board into the mould which contains the strawbale with a metal trowel; it was spread and compacted with the same trowel.

The plaster thickness of 10mm was applied on the strawbale, so as to be able to cover the strawbale properly.

In order to prevent surface evaporation and over heating from the action of sun and wind, the curing method adopted during this work was the Hessian/Straw blanket type, in which straw was spread over the plastered strawbale surface and suitably damped this is to provide insulation as well as moisture–holding medium.

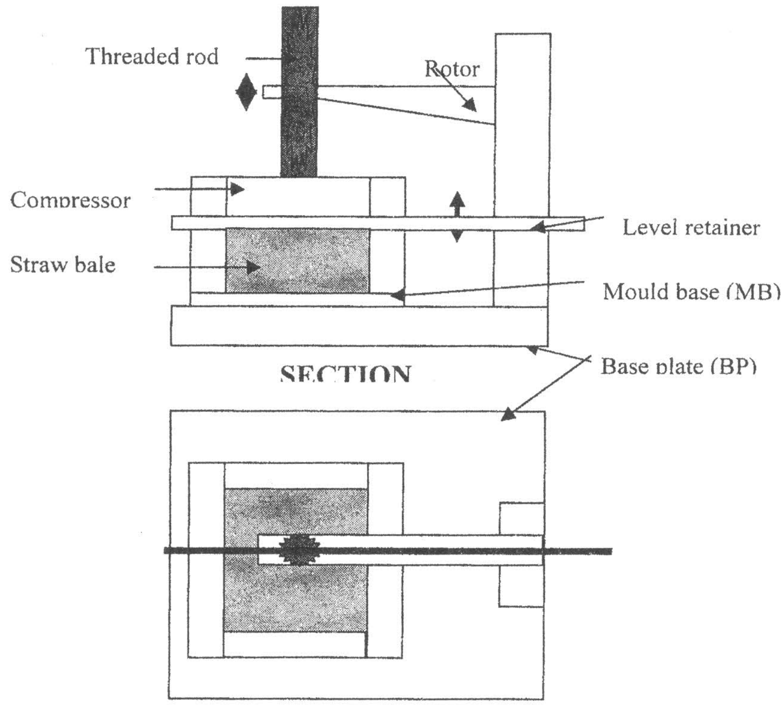


Fig. 3 Bale compressor

The specimen was moist cured for 7days and then left for 28 days altogether before testing. A mould of dimension (78 mm x 61 mm x 127mm) was constructed with partially seasoned timber, one without knot and other defect .The mould dimension was designed to create a thickness of 10mm around the straw bale. (For the standard dimension of the 3-string bale, the plaster thickness ranges between 13mm and 15mm).

Mix ration of 1: 8 was used for the plaster preparation. It was oiled for easy removal after which it was first filled to a depth of 10mm with the plaster mix from below, and the bale was placed on it and filled with plaster mix.

EXPERIMENTAL PROGRAMME

Dry Unit Weight

In the process of determining the densities of the plastered straw bale, their dry unit weight was determined. Weights of three consecutive plastered straw bales were measured with the aid of weighing balance.

Unit Density

Plastered straw bale density of gross density is the complete dry plastered straw bale unit mass divided by its gross volume. For fully plastered strawbale samples, this is determined for the applied loads in structures and handling requirements. Results of physical properties are shown in Table.2.

Table 2 Natural control test for the plastered strawbale

S/No	Length (mm)	Breadth (mm)	Height (mm)	Dry unit weight (kg)	Gross Area x 10^3(mm^2)	Gross Vol x 10^4 (mm^3)	Gross density x 10^3 (kg.m^3)
1	127	78	61	0.805	9.906	60.43	1.332
2	127	78	61	0.795	9.906	60.43	1.316
3	127	78	61	0.787	9.906	60.43	1.302
Average				0.796	9.906	60.43	1.317

COMPRESSIVE STRENGTH TEST

The compressive strength test was performed on a plastered strawbale prism. The prism specimens were tested for the effects of axial and eccentric (slenderness ratio of **h/t** = 2 and 3) loading. Each specimen was placed in the universal testing machine and each case the line intended eccentricity was aligned with the centre of the machine platen. This set the load eccentrically; the load was then applied until failure occurred. The compressive strength result values were calculated as (Adedeji 2000):

$$f_{ms} = \frac{P}{L(t-2e)} \qquad (1)$$

where P = Vertical crushing load, L = length of prism, t = specimen thickness and e = eccentricity. Tables 3 and 4 shows average compressive strength test results with respect to eccentricity: e = 0, t/3, t/6 and 5t/12 for h/t = 2 and 3).

Table 3 Result of compressive strength of plastered prism strawbale ah h/t =3

Test S/No.	Eccentricity e	Length (mm)	Width (mm)	Depth (mm)	Load@ break (kN)	Stress@ break N/mm^2
CS1	0	127.00	78.00	61.00	14.000	1.33
CS2	t/3	127.00	78.00	61.00	2.900	0.78
CS3	t/6	127.00	78.00	61.00	3.100	0.41
CS4	5t/12	127.00	78.00	61.00	3. 040	1.35
Min.		127.00	78.00	61.00	2.900	0.78
Mean		127.00	78.00	61.00	5.750	0.97
Max.		127.00	78.00	61.00	14.000	1.33
SD		0	0	0		0.101

CS = specimen No., Min. = minimum, Max. Maximum, SD = Standard deviation
COV = 8.35% (<10%), Prototype compressive strength $f_{ms,p}$ = 2.15N/mm^2. See Eq.(2))

Table 4 Result of compressive strength of plastered prism strawbale ah h/t =2

Test S/No.	Eccentricity e	Length (mm)	Width (mm)	Depth (mm)	Load@ break (kN)	Stress@ break N/mm^2
CS1	0	127.00	78.00	61.00	16.500	1.44
CS2	t/3	127.00	78.00	61.00	3.500	0.91
CS3	t/6	127.00	78.00	61.00	6.500	0.83
CS4	5t/12	127.00	78.00	61.00	3.044	1.60
Min.		127.00	78.00	61.00	3.004	1.81
Mean		127.00	78.00	61.00	7.386	1.10
Max.		127.00	78.00	61.00	16.500	1.44
SD		0	0	0		0.116

CS = specimen No., Min. = minimum, Max. Maximum, SD = Standard deviation
COV = 8.06% (<10%), Prototype compressive strength $f_{ms,p}$ = 2.45N/mm^2 See Eq.(2)).

Considering that the results in Tables 3 and 4 are for the model prism, the prototype prism ($f_{ms,p}$) can be calculated using the formula:

$$f_{ms,p} = \frac{D_{prtt}}{D_{mod}} f_{ms} \qquad (2)$$

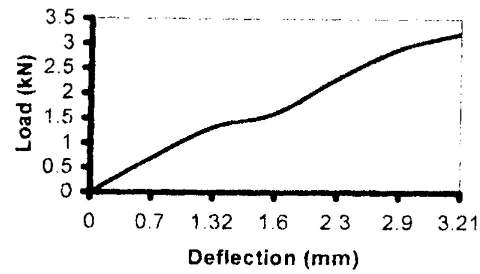
where D_{prtt} (406.4mm) and D_{mod} (61.00mm) = depth of prototype and model panel respectively.

FLEXURAL STRENGTH TEST

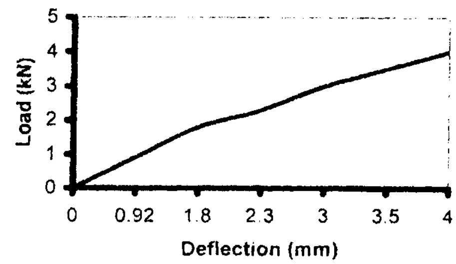
The flexural test used was a three point load test, which was intended to determine the deflection of the straw-bale prism from different application of load as proposed by Okunola, 2001. The prisms were tested under the flexural testing machine, which gives the loading value and the deflections of the prism simultaneously.

Loading values for different deflections was obtained, until the prism failed, and the loads at peak with the deflection at peak were recorded. Each specimen of strawbale was plastered with mortar and cured for 28 days.

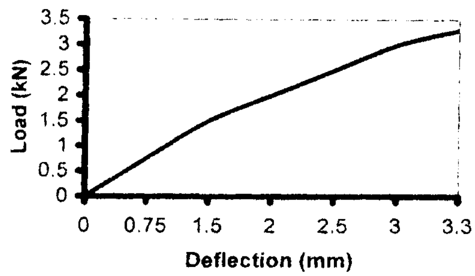
The bar specimens were tested on the 28day after preparation. The specimen was then placed on support with span of 50mm $\pm$ 2mm and in such a manner that the faces of the bar that were in contact with the surface of the mould are placed in contact with the surface of the loading nose and support. The testometer was the put on to apply the load at the centre and simultaneous load deflection readings were taken, the readings were shown on the visual display unit of the computer linked



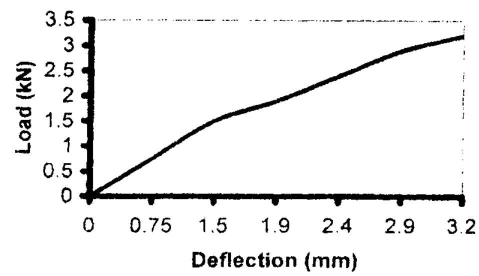
(a) h/t = 1



(a) h/t = 2



(c) h/t = 3



(d) h/t = 4

to the testometer, load-deflection curves were also plotted to determine the flexural strength (modules of rupture).

Flexural Strength Tests Results and Calculation.

This test was carried out to determine the maximum load a straw-bale prism can support before failure and also the determination of load deflection behavior of the material.. The flexural strength (modules of rupture) which is equal to the maximum stress at the moment of cracks or break is calculated as follows.

$$S = 3\ PL/2bd^2 \qquad (3)$$

where S = Stress I the specimen at midspan (N/mm^2), P= Load at the moment of crack (N), L=Span (mm), b = idth of prism tested (mm), d = Depth of prism tested (mm).

Results of flexural strength tests for a cement plastered strawbale prism are shown in Table 5, while the load-deflection graphs for various slenderness ratio are shown in Fig.4.

Table 5 Results of Flexural strength of plastered strawbale

Test S/No.	Length (mm)	Width (mm)	Depth (mm)	Load@ peak (KN)	Deflection @ peak (mm)	Stress@ peak N/mm^2	Load@ break (N/mm^2)	Stress@ break N/mm^2	Bending Modules (N/mm^2)
FS1	127.00	78.00	61.00	4.66	1.25	1.89	4.16	1.89	25.15
FS2	127.00	78.00	61.00	5.24	2.03	2.38	5.24	2.28	56.83
FS3	127.00	78.00	61.00	5.56	1.19	2.53	5.31	2.42	66.79
Min.	127.00	78.00	61.00	4.16	1.19	1.89	4.16	1.81	52.15
Mean	127.00	78.00	61.00	4.98	1.49	2.27	4.90	2.23	58.59
Max.	127.00	78.00	61.00	5.56	2.03	2.53	5.31	2.42	66.79
SD	0	0	0	732.2	0.47	0.33	644.2	0.29	7.48

FS = specimen No., Min. = minimum, Max. Maximum, SD = Standard deviation

Fig.4 Load-deflection relationship for various slenderness ratios

CONSTRUCTION TECHNIQUE OF STRAWBALE WALLED BUILDING

This section expresses the construction of the strawbale masonry prototype using the prepared specimens as in the tests of materials.

Construction Problems

Construction problems encountered in this work include:

- Bailing of the straw has to be in a rectangular shape and the use of twine to bind the straw together constituted a probl
- Plastering of the Straw Bales: - The plastering was done using a mould made of timber. The positioning of the straw in order to get the accurate thickness of the plaster was also a problem.
- Dimensioning of the Strawbale: - Getting the accurate dimension of the straw bale was difficult due to the shape of the straw (i.e. the cylindrical shape of the elephant grass).

Construction of Foundation

In order to achieve a solid, stable base that will distribute the weight of whatsoever is built upon it over the ground beneath , and to be sure that there is no unequal settlement throughout the building, the poured concrete type of foundation was selected (Huntington, 1975).

The form work was made of wood in an L- shape of dimension (70mm x 120mm x 600mm) and (70mm x 120mm x 65mm) the height of the foundation was chosen in order to raise the bale above the ground considerably to about (45mm). The mould was oiled for easy removal and the wood used for the construction was free of knots and other defects. Mix ratio used for the foundation was 1 :3:6 (cement: sand: gravel), with metal rebar inserted in the foundation during construction to hold the bales to the foundation. This is shown in Fig. 5.

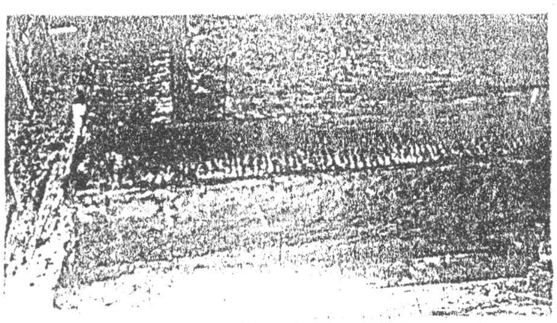


Fig. .5 DPC laid on foundation of the straw

Making of Opening Box Frames

The window and door openings were constructed in a way so that they can support the weight of the bales, and roof over them. Due to the flexibility of straw, the use of concrete or steel lintels is inappropriate and in fact would create problems.

The box frames were constructed with wood and the cavities left in them are filled with straw but covered with plywood. This was meant for insulation purpose. The door frame was fastened into the foundation with bolts. Fig.6 shows window and door frames

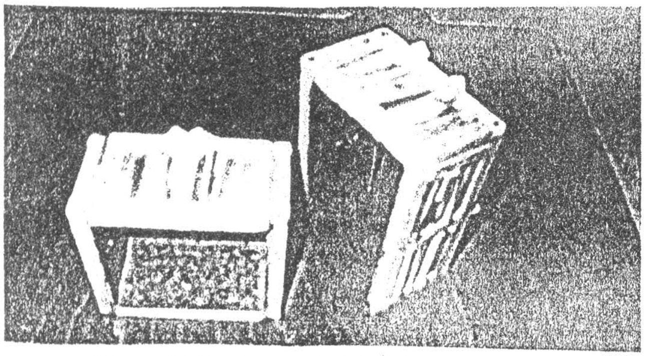


Fig. .6 Window and door box frames.

Bonding of Plastered Strawbales

The bonding type used for the prototype was the stretcher bond. The plastered straw- bales were laid in regular courses, each lapping a half length on the blocks of the lower course. Mortar of mix ratio 1:5 was then used to hold the plastered straw bales together. Fig.7 illustrates this arrangement. Walls were plastered using mix ratio of 1: 8 for the first layer and 1:10 for the second layer Curing of the construction was done by wetting with water.

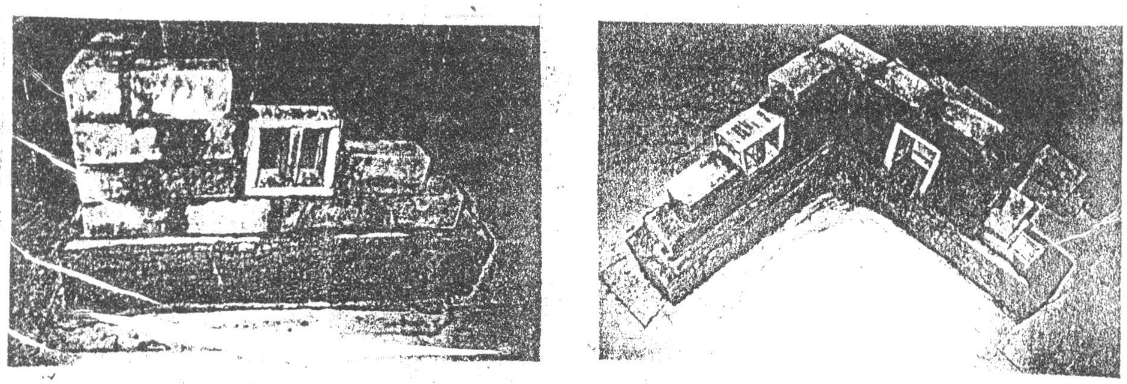


Fig. .7 Bonded plastered strawbale

DESIGN OF STRAWBALE WALL

Strawbale Wall design Method

In the design of a load bearing strawbale wall, the following factors are taken into consideration:

i. *Wall Effective Height (H_e)*. The wall is considered as pin-ended (floor is simply placed on wall which is not restrained from rotation) as the bottom of the wall will be damp-proved. The effective height of the wall is its actual height, H, (floor-to-floor).

ii. *Wall Effective thickness (t_e)*. It is recommended here that for a solid wall (built with hollow bricks), the effective thickness is taken as actual thickness of the wall.

iii. *Assessment of eccentricity*: The load transmitted by a single floor is assumed to act at 1/3 of the depth of the bearing areas from the face of the wall. The load is assumed acting at a distance of t/3 (t = wall thickness) from the face of the wall, which is where the resultant stresses is considered to be acting. (See Fig.8.a,b.) For the external wall, the eccentricity is given as:

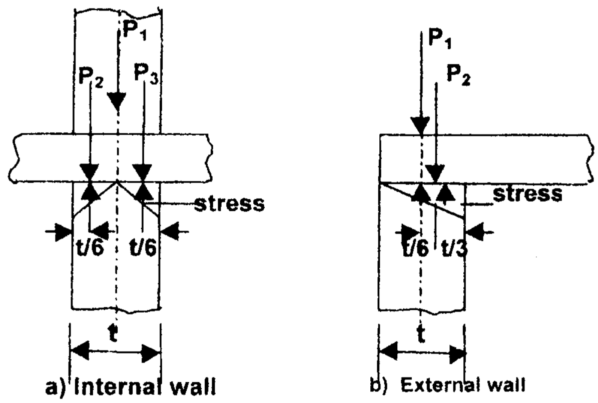


Fig.8. Wall eccentricity

$$e = \frac{t}{6}\frac{P_2}{P_1 + P_2} \quad (4)$$

and for an internal wall:

$$e = \frac{t}{3}\frac{(P_3 - P_2)}{(P_1 + P_2 + P_3)} \quad (5)$$

Analysis of Wall Section

Axial (Vertical) Load: At the ultimate load, earth material experiences a plastic distribution of stress, which will act over the whole compressive strength zone of its sectional area. The reduction of the load capacity is calculated based on this assumption. In practical cases, however, the vertical load always applied eccentrically so that the load is reduced. The vertical load per unit length of the wall is expressed as:

$$N_r = \frac{\beta f_k t}{\gamma_m} \quad (6)$$

and the capacity reduction factor is expressed as:

$\beta = 1.1(1 - 2e/t)$ (7)

where, f_k - characteristic strength of the wall (average $1.2N/mm^2$), t = wall thickness and $\gamma(_m$ = factor of safety for earth material (= 3.3, Medubu, 1997). Value 1.1 is a factor of stress is as used for sandcrete material. For any protected wall.

Combined Vertical and Lateral Loads

The lateral capacity of the wall is calculated as given in BS 5628, part 1, 1985:

$$q_{lat} = \frac{8N_r t}{H^2\gamma_m} \quad (8)$$

In a case where the floor slabs are strictly in two directions (i.e., precast floor slab), hazel stub (columns) within the thickness of the wall must be provided. (Fig.8a).

where, H is the height of the wall. Lateral load capacity is the obtained as:

$F_{lat} = 0.021G_k$ (9)

In which G_k is the characteristic dead load above any level under consideration. In static equilibrium. therefore:

$q_{lat} > F_{lat}$ (10)

Simplifying, the wall thickness, t, can be calculated as:

$$t = \frac{1}{8}\frac{\beta F_{lat} H^2\gamma_m}{N_r} \quad (11)$$

Moment of resistance of the wall: Assuming an elastic distribution, clause 36.4.3 of BS 5628 is suitable for this condition, and it is expressed as:

$$M_u = \frac{f_{kx} Z}{\gamma_m} \quad (12)$$

where, f_{kx} = flexible characteristic strength of wall, while Z the wall sectional modulus, is a function of height and thickness. Assessing the effect of load then:

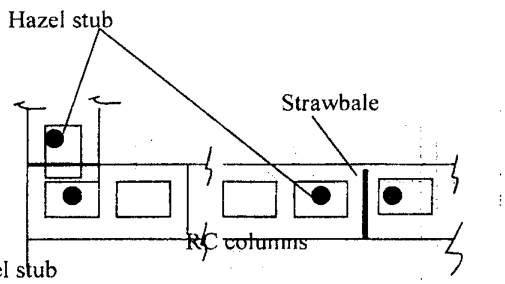
$M_u = m = F_H\gamma_f H^2$ (13)

where, γ_f = partial safety for load depending on wall support conditions, orthogonal and aspect (of brick size) ratio (= 0.0125 for pin-ended wall), and F_H = characteristic load.

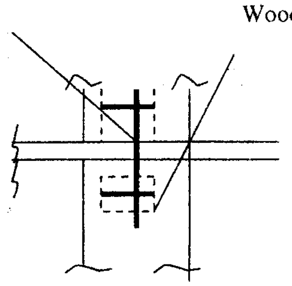
Design Detail

A primary detail for the lateral restrain to the walls provided by the floors is shown in Fig. 8b.

To minimize the effects of the friction, electrometric strips can be introduced as bearings for the reinforced concrete slabs, if used. This will prevent the slab for crushing the leading edge of the wall plaster due to rotation of such slab. A long wall requires vertical joints to control cracks caused by thermal, moisture, and expansion and shrinkage movements. This may not be necessary for the strawbale walls though, normal joint spacing for this wall (of a residential building) may not be less than 10m



(a) Hazel stub



(b) Floor tie as restraint to wall

Fig.8 Strawbale connection detail

Design Example

Fig.9 shows a section and plan of the upper floor of a two storey residential building, built of strawbale walls with a minimum characteristic strength of 1.22N/mm^2 and a vertical design load of 80.83kN/m acting at the external wall (A - B) and ultimate lateral load of 1.05kN/m, while the internal.

Solution

Wall (1 - 2) carries vertical design load of 42.36 kN/m and ultimate lateral load of 0.57 kN/m.

Design for external wall (A - B):

For vertical load design: **e** = 0.02t, at **t** = 300mm and β = 0.86

Therefore, $\mathbf{N_r}$ =98.5 kN/m

This shows that **Nr** > **N** (design load) ...**design OK** ***For horizontal load design***: F_{lat} = 1.05kN/m, $\mathbf{q_{lat}}$ = 9.05 kN/m

Therefore, ultimate moment, **m** = 0.119 kN/m

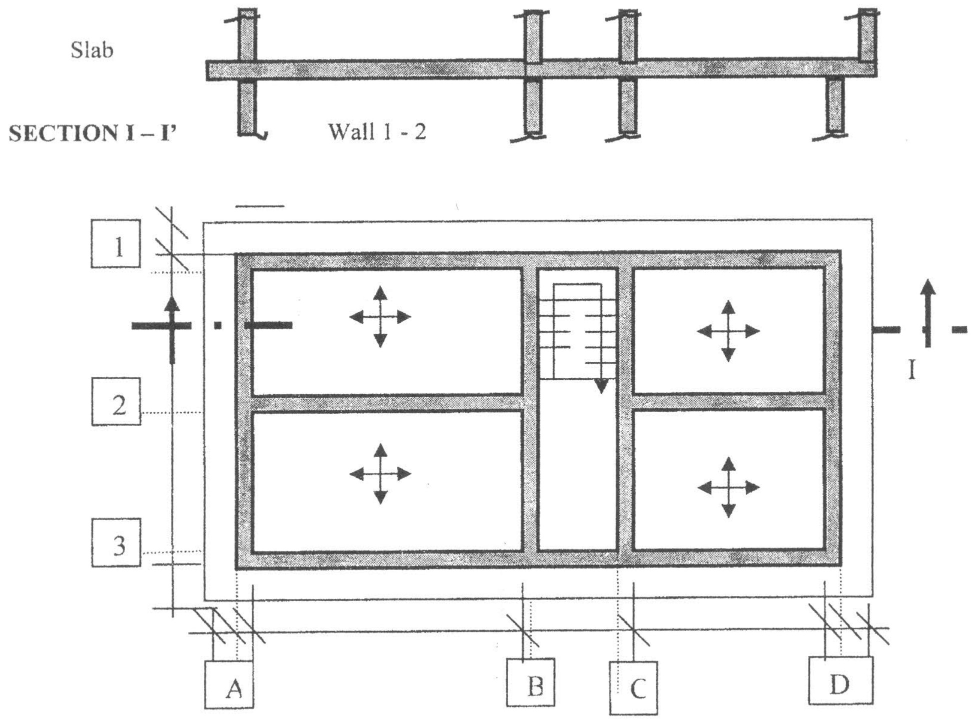
Ultimate moment of resistance, $\mathbf{M_u}$ =3.160 kNm

This shows that $\mathbf{M_u > m}$ ...**design adequate**

Design for internal wall (1 - 2):

For vertical load design: **e** = 0.3t, at **t** = 300mm and β = 0.44

Therefore, $\mathbf{N_r}$ = 49.8 kN/m.



PLAN - UPPER FLOOR
Fig. 9 Two-storey residential building

This shows that **Nr > N** (design load) ...**design OK**
For horizontal load design: F_{lat} = 0.55kN/m, q_{lat} = **4.43** kN/m
Therefore, ultimate moment, **m** = 0.064 kN/m
Ultimate moment of resistance, $\mathbf{M_u}$ = 3.108 kNm
This shows that Mu > **m** ....**design adequate**

CONCLUDING REMARKS

The results of the physical and mechanical strength tests of cement plastered strawbale masonry have shown its viability as a structural, durable and aesthetical material. The problems encountered during the construction of the prototype wall of were effortlessly overcome. Design results also show that a wall of strawbale plastered with

Deep crack formation is the highest occurring rating values for a masonry element, A rational structural design method for the strawbale masonry formulated and a specific example given showed that strawbale wall is adequate as a load-bearing element for a residential

cement, having average compressive strength 2.15 N/mm^2 is adequate as load-bearer for low-storey residential building. Design approach and details should be followed as recommended in this work. Design details are very necessary for strawbale masonry, as this is a natural, porous material.

building. A strawbale wall of 300mm thick was found capable of carrying both the axial and lateral (of 1.5% characteristic dead load) load in a two storey residential building.

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