# Interaction assessment and optimal design of composite action of plastered typha strawbale

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# Interaction assessment and optimal design of composite action of plastered typha strawbale

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**Abstract.** The concept design of the typha strawbale masonry came up as a result of the urgent demand for a means of constructing sustainable buildings, both in rural and urban settlement, not only suitable for dwellers but for keeping farm products by structures that will respond to the environmental eco-system, coupled with the fact that such structures are also affordable, durable and easy to maintain during their service period. The effects of contact between plaster and the stacked strawbale of a masonry needs to be established and design optimization for durability and stability of the masonry be obtained. The assessment will involve the application of plaster materials (cement and natural earth) to the wall specimen panels. Past works have shown that plastered strawbale walls have adequate resistance against the appropriate vertical loads, and further showed that the earth plaster can bear higher stress than the cement plastered straw bale. There is the implication that the collapse or response of the earth-strawbale wall is significantly higher compared to that of cement-strawbale from other straw-based masonries. Therefore the allowable stresses of plastered typha strawbale shall be predicted for their optimum values using SAP2000. The stress stability of each masonry is obtained by analytical model using the best fit variables for the wall height and thickness.

**Keywords**: typha strawbale; finite element; degradation; wood; plaster; optimal design

## 1. Introduction

Straw is a flexible (non-rigid) material that is sustainable, plentiful and non-expensive as a building material which requires easy workability in construction and somewhat differently than if it was rigid. Straws are originated from leftovers stem of harvested grain that are of different types depending on the type of grain they are derived from e.g., from rice, wheat, maize, millet, sorghum or grow wildly such as elephant grass, etc. Dry, free from leaves straws are baled together and

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compressed to bear loading when being used as post and beam system or structural bale system. In a strawbale wall, the relatively strong, stiff plaster plays a significant role as it works together with the ductile strawbale come to function as a stress skin panel. Plastering materials used for strawbale structures are of different types like earth/laterite plaster, lime plaster, cement plaster etc. According to Michael (2006), Ajamu and Adedeji (2013) and Otiki (2007), these plastering materials make the wall strong and prevent the strawbale from fire when plastered on both interior and exterior part, creating a wall system that is strong, resilient and very attractive. Design is an open-ended process, encompassing a wide range of problem solving types and approaches. It is therefore difficult to reduce all descriptions of the various design approaches to a common model.

A design can be subjected to evaluation based on a viable and strong analytical approach such as using Finite Element Method (FEM) and Finite Difference Method (FDM) to find exact or approximate solutions and apply it to optimization and search techniques. Work describes a methodology to implement microstructural data obtained from TEM tomography into finite element (FE) simulation software. In their work, Jimbert et al. (2016) showed that first approach on a tomographic reconstruction is treated with different software to create a 3D realistic model of the microstructure of the composite. Hence, realistic model is compared against 2D image-based models via FE simulations in order to compare the mechanical behavior achieved with both procedures. After this first study the results obtained with both types of model are similar. These methods are also used in design for both empirical and theoretical method of analysis and which so far produced a tremendous solution against the disastrous effect of loading on structures. This finding shows the action of contact between strawbale and plaster composition (Tokunbo 2017) under appropriate loads. Living in a straw-like structure has no harmful effects combined with plastering materials because it is natural, local and breathable material, cheap, easy to obtain and to work with and reduce cost of living. The optimal design process with the use of Finite Element Method (FEM) made the designer to identify explicitly the wall design variables.

This paper involves the use of typha straw bale plastered (rendered) with earth and cement materials, each of the walls are analyzed and optimized separately, but with the same loading and the same dimensions in application.

## 2. Generic properties of straw

Sustainability: Typha **s**traw is an annually renewable natural product, grown by photosynthesis. Approximately 2.3 million tonnes are produced surplus to requirements each year.

Sound insulation**:** There is an over whelming experimental evidence that strawbale walls offer far more sound insulation than 20$^{th}$ century wall building techniques according to Jones (2001). Strawbale homes are cozy, calm and quite. They offer a feeling of peace and there are at least two sound studios in the USA built of straw because of its acoustic property as well as in several more meditation centers. Sound insulation should not be confused with sound absorption. Sound insulation refers to the capacity of a barrier to prevent the passage of sound energy from the air on the source side to that on the far side, sound absorption refers to the inability of a material to reflect the energy received from the source as established by Jones (2001) and Adedeji (2008).

Thermal insulation**:** According to Asonibare (2007), Fadil (2007), Adedeji (2007) and Adedeji (2002) fiber glass has an R-value of about 3.7 per inch (RS1-0.26 per centimeter) and strawbales have about 3.2 per inch (RS1-0.22 per centimeter). A strawbale with a width of 450 mm has a U-value of 0.13 W/m$^2$K.

Table 1 Properties of materials

| Elements | Density (kN/m$^3$) | Modulus of elasticity, E(Pa) | Poisson ratio, $v_c$ |
|---|---|---|---|
| Roof | 24.00 | 24.82 | 0.20 |
| Foundation | 24.00 | 24.82 | 0.20 |
| Typha Strawbale | 22.30 | 22.99 | 0.3 |
| Cement plaster | 19.00 | 20.25 | 0.2 |
| Earth plaster | 19.62 | 21.20 | 0.15 |

Source: SAP7-A (1981), [7], [5] and [2]

Fire resistance**:** Although loose straw is quite flammable, once packed in a bale it is too dense to allow enough air combustion (6). By analogy, it is easy to light a piece of paper on fire, but difficult and time consuming to burn an entire story book. In a test, a gas flame blows on one side of the wall at approximately 1100$^o$C, while the temperature of the wall is continuously measured. The result of this test had no burn-through and a maximum temperature rise of 60 degree 33.3$^o$C for a 2 hours fire resistant test.

Simplicity**:** Strawbale building utilizes locally available materials, and basic construction techniques that require little specialized or proprietary materials and equipment. Inexperience builders working on their own homes have often successfully used it as identified by Adedeji (2007) and Jones (2001).

Structural sound: According to Vardy (2006) and Jones (2001), strawbale walls have passed load bearing tests both in the laboratory and empirically and are used to build at least 2-storey building.

Durability: There has been no research so far on the durability of strawbale walls in UK climate. The little research that has been done shows that there should be no need to be concerned that strawbale walls will not withstand the test of time and the rigors of our climate. Jones (2001) stated that the key to durability lies in good design and good quality work.

### *2.1 Plaster and stucco/render*

Function of plastered strawbales: Plasters serve many functions in a wall system. According to Adedeji (2007), the functions include: protection of the underlying surface, permission or prevention of the migration of vapor or liquid moisture and air current, carrying structural loads, provision of fire resistance, sound and thermal insulation, provision of smooth and hygienic surface and the resistance of surface abrasion and accepts a decorative finishes. Types of failure due to loading**.** Understanding the types of failure is important because the relationship of the plaster to the strawbale is the key to structural strength in a strawbale wall (Olaleye and Adedeji 2017, Hasssan and Mohammed 2015). Strawbale walls fail in five different ways (i) Global Buckling (ii) Local Buckling (iii) Bearing (iv) Slippage and (v) Core Crushing

## 3. Methodology

### *3.1 Data collection*

The material properties for the execution of this work were collected from the sources as shown in Table 1.

### 3.2 Optimal design of a plastered straw bale

The optimal design problem formulation embarked upon was based on conduction, convection, cost function and loadings, where the height of the strawbale wall is h, the thickness of the strawbale $t_{sb}$=28$t_p$ mm, $t_p$=thickness of the plaster (15 mm each). The total thickness of the plastered strawbale wall, t=28$t_p$ mm), the breadth of the wall=1000 mm, wind load $w_w$=0.33 kN/m according to Asonibare (2007) and Adedeji (2008).

### 3.3 Cost function

The cost functions are considered separately for cement and earth plastered straw bale masonry. Cement plastered straw bale weight is to be minimised as

$$Z_{wgt} = \rho_{CP} V_{CP} + \rho_{SB} V_{SB} \quad (1)$$

Where $\rho_{CP,}$ $\rho_{SB,}$$V_{CP}$,$V_{SB}$=densities, volumes of cement and earth plasters respectively at h, $t_{CP}$, $t_{SB}$ (=28$t_{SB}$)=height, thickness of plaster & strawbale respectively. Earth plastered straw bale weight is to be minimised as

$$Z_{wgt} = \rho_{EP} V_{EP} + \rho_{SB} V_{SB} \quad (2a)$$

$$= 1288.04 \, h \, t_{EP} \quad (2b)$$

Where $t_{EP}$=thickness of earth plaster $\rho_{CP,}$ $\rho_{SB}$=density of cement plaster and strawbale.

### 3.4 Design constraints

Conduction constraints.

$$Q = KA \, \Delta T_m \quad (3)$$

Where Q is Heat flow (w), K is the overall heat transfer=1.5 w/$m^2$ (James 1979). Area, A=(3×0.45=1.35 $m^2$) at the height 3 m and width of 0.45 m, $\Delta T_m$=the effective mean temperature difference (=2.5$^o$C) and $\Delta T_m$=2.5$^o$C. For cement/earth plaster strawbale, Q=5.06W. The thermal of strawbale wall can take weeks to achieve a steady flow of heat through the wall and the climate condition is undeterminate (Bruce 2003), so time is assumed at 60 secs. Stress allowable $\sigma_{allowable}$ (=W/A) is 0.22 kN/$m^2$ Therefore $\sigma_q$-$\sigma_{allowable}$≤0 is

$$\{0.3/(30t_p \text{ x } h)\} - 0.22 \leq 0 \quad (4)$$

Convection constraints: In like manner, at the convection surface (or film) coefficient, h (3-7 W/$m^2$) of W/$m^2$5, fluid bulk temperature $T_f$ (26$^o$C) and is the wall surface temperature $T_s$ (22$^o$C), $T_f$=26$^o$C (Air temperature), $T_s$=22$^o$C (Wall temperature) the convection constraints is obtained as

$$1.62/ (30t_p \text{ x } h) - 1.2 \leq 0 \quad (5)$$

$$\text{Total heat stress} = \{1.92/ (30t_p \text{ x } h)\} - 3.2 \text{ kN/m}^2 \leq 0 \quad (6)$$

Vertical stress constraints: For cement plastered strawbale wall stress constraints: at the maximum roof/floor load of 40 kN/m (Bruce 2003) and upthrust=0.5 $\gamma$hl=10 kN/m width,

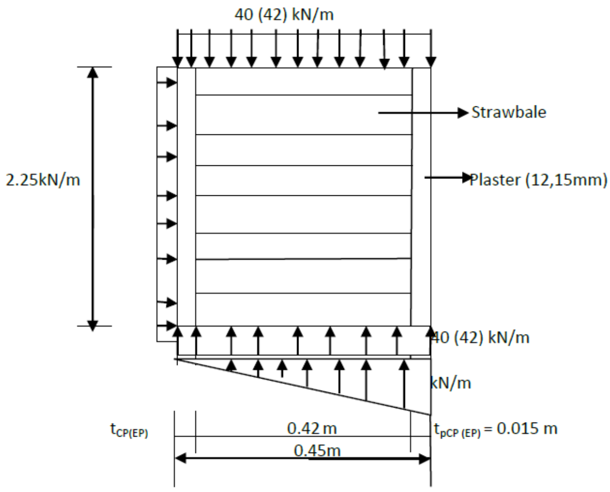


Fig. 1 Cross section of cement (earth) plastered strawbale wall

$\sigma_{allowable}$=66.7 kN/m$^2$ per metre width, the constraint is obtained as

$$90/(30t_p \text{ x } h) - 66.7 \leq 0 \tag{7}$$

For earth plastered strawbale wall, the stress constraints

$$94/(30t_p \text{ x } h) - 69.6 \leq 0 \tag{8}$$

Horizontal stress constraints (wind only): For both plastered strawbale wall; wind load is estimated as 0.33 kN/m (Asonibare 2007). The stress constraints is therefore obtained as

$$0.33/ (30t_p \text{ x } h) - 0.24 \leq 0 \tag{9}$$

### *3.5 Optimization process*

The constraints are varied and used to calculate the values of the variables t and h; t is varied within the range ($28t_p \leq t \leq 30t_p$) to obtain the values of h using constraints equations in chapter three. After what, various values of cost function, Z will be obtained through the known values of t and h based on optimal design. By referring to constraint equations (Eqs. (1) to (9)), the stress constraint are used both separately and combined (composite).

### *3.6 Typical analytical example*

To verify the capability of this numerical procedure, the following assumptions were made for the earth and cement plastered strawbale wall as the properties in Table 1 were also considered.

With the use of SAP2000, the analytical example shown below has been analyzed to shown the effect of contact between the strawbale and the plastering composition. This relates to the idea of pressure perpendicular to an interface that could be computed (Tamio 1998) as constant by this scheme throughout the equilibrium system, unlike the artificial hump in the pressure profile, which is based on used method. The loadings applied and quantities of heat transferred by conduction and convection i.e., composite (combined) stress constraint values was analysed using SAP2000,

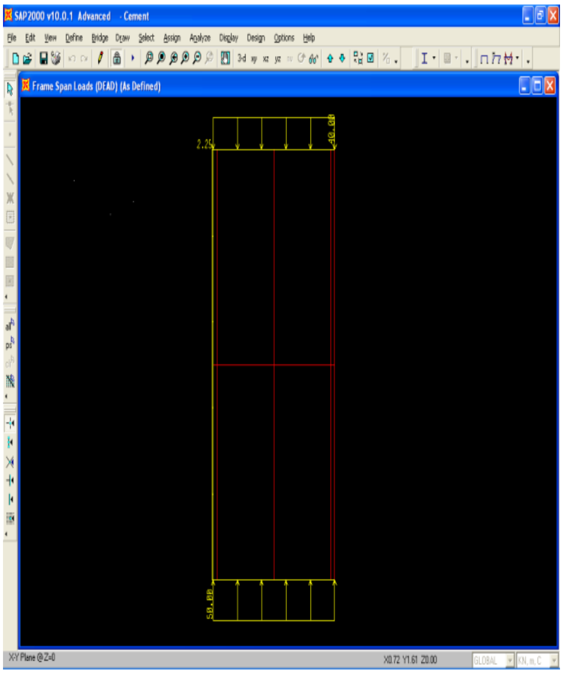


Fig. 2 Applied loadings on cement plastered typha strawbale wall

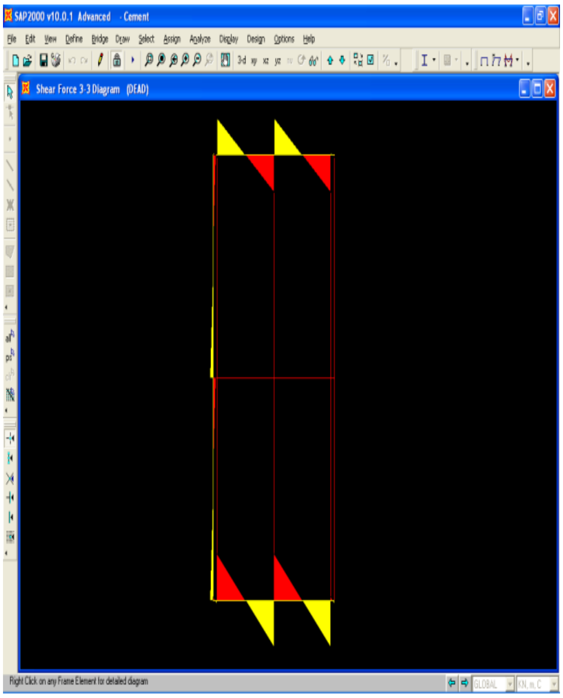


Fig. 3 Shear force diagram of cement plastered typha strawbale wall

Taking height, h=1 m and total thickness, t=0.45 m

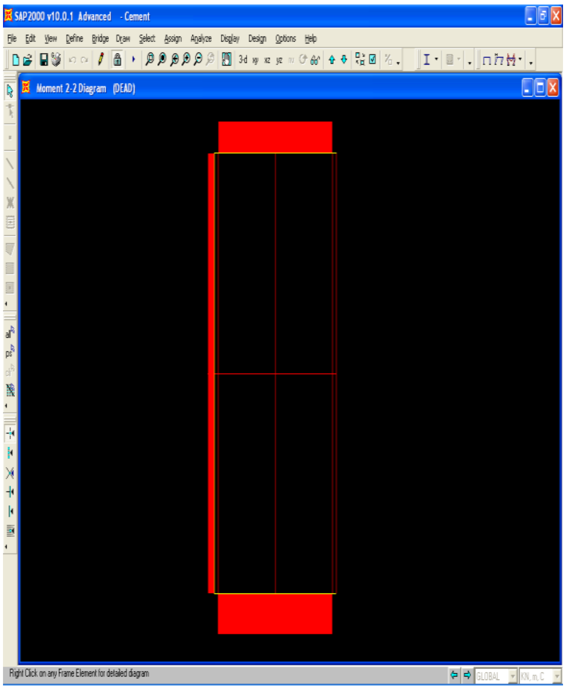


Fig. 4 Bending moment diagram of cement plastered strawbale wall


Fig. 5 Maximum stress diagram of cement plastered strawbale wall

Stability analyses: The loading on the strawbale structure used in this work is basically the

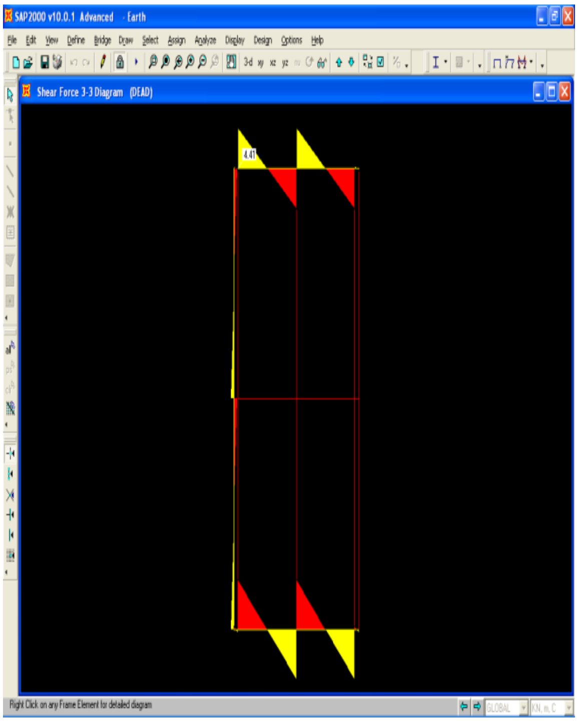

Fig. 6 Shear force diagram of earth plastered typha strawbale wall

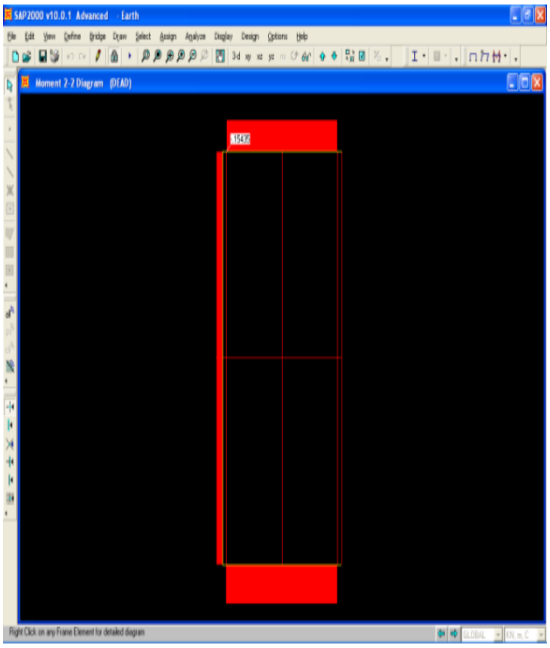

Fig. 7 Bending moment diagram of earth plastered typha strawbale wall

static loading i.e., applied loads (both vertical and horizontal loading), the load due to the self

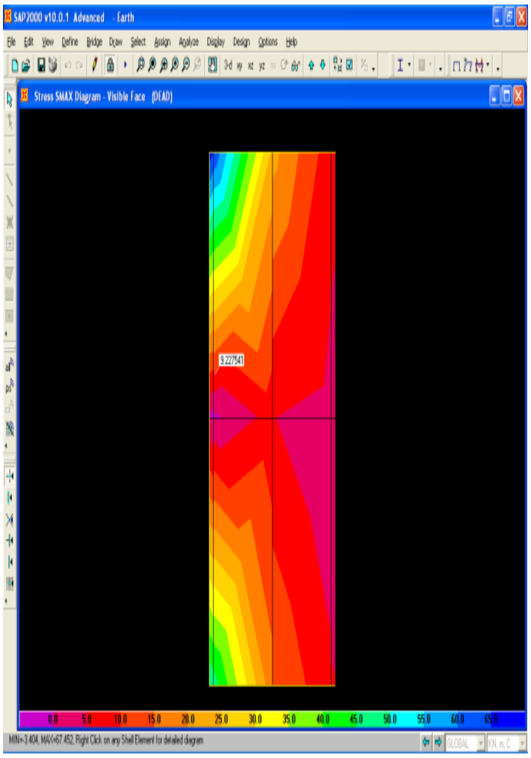


Fig. 8 Maximum stress diagram of earth plastered typha strawbale wall

weight of the wall and the upthrust. Total vertical loading=40.01 and 42.24 kN/m for earth and cement respectively. The total horizontal loading due to wind and heat transfer is 2.25kN. Sliding criteria by the factor of safety net vertical loading to net horizontal loading is satisfied for 18.23 (18.67) kN>1.6, Hence, sliding criteria is favorably satisfied (Fig. 1).

Stress analysis using SAP2000: Figs. 2-8 show the diagrammatic procedure for the combined loading from SAP2000 on the structural analyses for the cement plastered typha strawbale wall on the interfaces.

For earth plastered strawbale wall.

## 4. Results and discussion

Constraints created in form of variables were used to evaluate the cost function and stresses. They were then selected and their values obtained in form of variables. Four constraints were produced and the best of the other constraints were determined using the values of t and h. The best fits of results were the values of t and h at 0.45m and 1m respectively for both plaster composition. It was observed that from the analysis the minimum and maximum stresses between the plaster compositions and the strawbale material showed that, the use of earth plaster can hold a strawbale from deflecting if proper construction technology is employed than that of cement plaster. The adequacy of this type of design can be measured in terms of the minimum acceptable drift of the strawbale work system.

Table 2 Minimum and maximum stresses for the plaster compositions and the strawbale material.

| Plaster composition | Outside plaster | | Inside plaster | |
|---|---|---|---|---|
| | Minimum stress | Maximum stress | Minimum stress | Maximum stress |
| Cement | -9.8 | 9.6 | -19.3 | 18.3 |
| Earth | -60.4 | 64.2 | -6.3 | 6.8 |

Table 3 Differences between the allowable and calculated stresses for both plaster composition.

| Wall composition | Maximum allowable stress | Maximum calculated stress using SAP2000 |
|---|---|---|
| Cement plastered strawbale wall | 70.14 kN/m$^2$ | 18.836 kN/m$^2$ |
| Earth plastered strawbale wall | 73.14 kN/m$^2$ | 67.452 kN/m$^2$ |

The minimum acceptable drift by the constraint is 1 m≤H≤4 m and 0.36 m≤t≤0.45 m at the maximum height (h) and thickness (t) of the strawbale wall. This is in line with Olaleye and Adedeji (2017) results on the buckling effects of strawbale wall element. Further analysis showed that for the strawbale wall of 1m and the thickness of 0.45m, the maximum stresses allowable calculated using SAP2000 are shown in the Table 2, while Table 3 shows the differences between the allowable and calculated stresses for both plaster composition and the cement and earth plaster composition.

## 5. Conclusions

Based on the results of this work, the comparison of the results between the earth and cement plastered strawbale walls indicated that cement plastered straw bale is been stressed 7 times of the earth plastered strawbale wall. This implies that the collapse or response of the earth-based plastered straw bale is significantly higher compared to that of cement plastered straw bale. Also, maximum allowable stress of 70.14 E3 N/mm$^2$ and 73.14 E3 N/mm$^2$ for cement and earth plastered strawbale wall are higher than the stresses analysed and computed by sap2000 of 18.836 and 64.2 kN/m$^2$ for the cement and earth plastered strawbale walls respectively. The results obtained showed that the earth plastered strawbale wall is stabie are adequate to carry the load it is designed for.

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