COMPREHENSIVE DESIGN METHOD FOR EARTHBAG DOME STRUCTURES

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Abstract. The earthbag or superadobe techniques consist of introducing soil in degradable bags that are stacked to form adobe structures. They represent sustainable, rapid and low-cost alternatives for the construction of social housing, emergency shelter and ecovillages with the resources available at each location. Despite their potential, several aspects still compromise the efficient and safe use of these techniques. For instance, the design of the structures is currently based on empirical or semi-empirical guidelines since no general method exists on the matter. The present work focuses on the proposal of simple, comprehensive and rational design method for earthbag domes. Formulations are proposed considering the previous studies from the literature. The developments derived from this study represent a contribution towards the safe and optimized design of earthbag structures, being a valuable guide for future construction.

1 INTRODUCTION

In emergency situations (such as humanitarian crisis, wars or hazardous natural events) it is essential to provide the population affected with safe and secure shelter, quickly and at low costs. Among the possible materials for the construction of such shelters, the most abundant regardless of the location is the earth or soil available in the environment. In this context, the construction techniques of the earthbag or superadobe were developed. These techniques consist of introducing local soil and small amounts of a binder in degradable bags that serve as the formwork and as confinement of the filling. The bags are stacked one over the other with barbwire in the middle and slightly compressed to remove the air inside the bag. This allows the construction of walls and domes, as shown in Fig.1.

Figure 1: Construction of superadobe structures (sources: www.labioguia.com (a), www.domoterra.es (b, d), www.earthbagbuilding.com (c)).

Despite the advances attained, the design is still based on empirical or semi-empirical rules (Minke 2001, Wojciechowska 2001, Hunter 2004, Geiger 2011), the earthbag technique (combined behaviour of the earth and the bag with joints) is not contemplated at a national level due to the lack of theoretical models and testing methods for the characterization of the material and the structure. Generally, no structural analysis is conducted prior to building. This scenario may lead to either an overestimated or an unsafe design of structures, which contrasts with the sustainable philosophy grounded on the efficient use of the resources and raw materials associated with the technique.

The present study contributes to promote the earthbag techniques by presenting a first step towards a general design method valid for whis kind of structures. The rational approach ensures the structural safety and the optimization of the material, thus enhancing its sustainability and setting the basis for future design recommendations or codes. Besides being a valuable guide from an engineering standpoint, this study might have a positive social impact in emergency and humanitarian crisis situations.

2 EARTHBAG DOMES

2.1 Geometric considerations

The superadobe dome presents several particularities when compared with conventional continuous dome structures. The most important of them is related with the material used and the fact that the interaction between biodegradable bags has to be taken into account. Table 1 presents the equations that define geometrically typical shapes for earthbag domes.

Arch	Equation
Variable	x $=\sqrt{(\phi/2+d)^2-z^2}-d(1)$
Pointed	x $=\sqrt{(\phi+b)^2-z^2}-\phi/2-b(2)$
Parabolic	x$=\sqrt{\phi^2(1-z/H)/4}(3)$

Table 1: Equations for the possible arch curvatures.

The most common shape is the pointed arch due to its simple construction procedure and its bearing capacity. The method proposed in the next sections is valid for arch shapes, because it works also with discrete data.

2.2 Method to estimate the design forces and stresses

In the design of earthbag structures it is essential to consider that the behaviour of the adobe and the bag varies over time. This affects significantly the structure and the way the calculations must be made. For early ages, the dome may be assumed as the succession of rows piled one on top of the other, whereas in the long term the dome will behave as a shell stone structure. For this reason, the conventional dome cannot be considered as a reference in the design.

All these phenomena were taken into account during the development of the design methodology. The method allows considering the compressive and tensile strength at the same time along the perimeter, depending on the state of the materials and the presence of open spaces. The method is based on the verification that the design forces and stresses do not compromise the stability or lead to mechanical failure. A horizontal force Fh needed to center inside the kern section limits of each row the resultant of the part of the dome located above it is calculated. It is assumed that this force is withstood as shear forces between rows (Td) or hoop forces along the perimeter of the rows (σ_θ), as shown in Fig.2c. The equations for compute forces and stresses are the ones collected in Table 2.

$\mathrm{RI}_i = x_i (4)$	$\mathrm{RC}_i = x_i + b_i/2 (5)$
$\mathrm{RE}_i = x_i + b_i (6)$	$\mathrm{R}_{ef_{int_i}} = RI_i (7)$
$\mathrm{R}_{ef_{ext_i}} = RE_{i-1} (8)$	$\mathrm{R}_{kl_{int_i}} = RC_i - b_i/6 (9)$
$\mathrm{R}_{kl_{ext_i}} = RC_i + b_i/6 (10)$	$\mathrm{A}_{z_{ef_i}} = 2\pi RC_i (R_{ef_{ext_i}} - R_{ef_{int_i}}) (11)$
$\mathrm{W}_i = \gamma_N 2\pi RC_i b_i h (12)$	$\mathrm{Wt}_i = \sum_{j=imax}^{i+1} W_j (13)$
$\mathrm{Xg}_i = (\sum_{j=imax}^{i+1} W_j RC_j)/(\sum_{j=imax}^{i+1} W_j) (14)$	$\mathrm{Yg}_i = (\sum_{j=imax}^{i+1} W_j Z_j)/(\sum_{j=imax}^{i+1} W_j) (15)$
$\mathrm{Fh}_{min_i} = Wt_i (R_{kl_{int_i}} - Xg_i)/(Zg_i - Z_i) (16)$	$\mathrm{Fh}_{max_i} = Wt_i (R_{kl_{ext_i}} - Xg_i)/(Zg_i - Z_i) (17)$
$\mathrm{N}_{d_{v_i}} = -Wt_i \gamma_{G1} (18)$	$\mathrm{M}_{d_{min_i}} = N_{d_{v_i}} (R_{kl_{int_i}} - RC_i) (19)$
$\mathrm{M}_{d_{max_i}} = N_{d_{v_i}} (R_{kl_{ext_i}} - RC_i) (20)$	$\mathrm{T}_{d_i} = Fh_{max_i} \gamma_{G1} (21)$
$\mathrm{T}_{k_i} = Fh_{min_i} \gamma_{G2} (22)$	$\sigma_{v_i} = N_{d_{v_i}} / A_{z_{ef_i}} (23)$
$\sigma_{ext_{max_i}} = \sigma_{v_i} - 3M_{d_{max_i}}/(\pi RC_i b_i^2) (24)$	$\sigma_{h_i} = \sigma_{v_i}/K (25)$
$\sigma_{d_{\theta_{c_i}}} = (Fh_{min_i} - Fh_{max_{i-1}}) \gamma_{G1}/2\pi b_i (26)$	$\sigma_{d_{\theta_{t_i}}} = (Fh_{max_i} - Fh_{min_{i-1}}) \gamma_{G1}/2\pi b_i (27)$

Table 2: Methodology for compute forces and stresses.

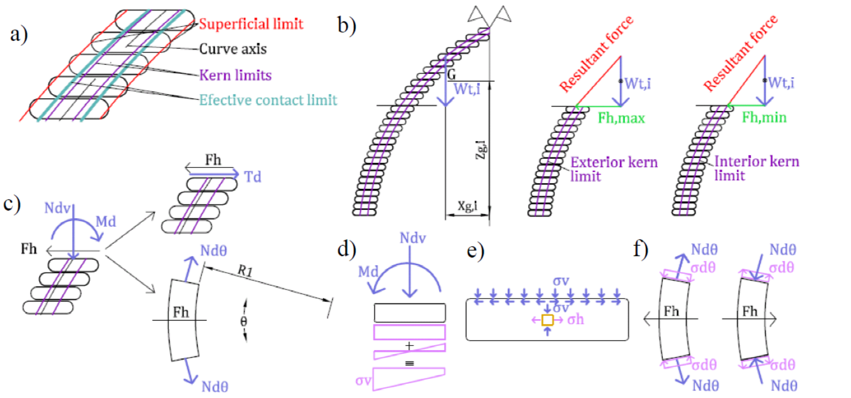

Figure 2: Detail of the calculus limits domains (a), the resultant force must be inside of the kern limits (b), force equilibrium (c), distribution of vertical stresses along the adobe section (d), horizontal stresses (d) and hoop forces and stresses due to the radial force (f).

Notice that in the methodology proposed here, the forces needed to assure that the resultant coincide with the inner and outer kern limits of the cross section are considered. This provides an envelope of forces that mark a limit condition. In safe structures, the real stress will be smaller than the defined with this method. Conversely, if the estimated stresses fall outside these limits, failure or collapse might occur.

3 Structural verification

Table 3 shows the expressions for the verification of the failure and resistant mechanisms corresponding to superadobe domes, which are depicted in Fig.3. The verifications depend on the row classification (Ds for discontinuous row, CAB for continuous row capable of bearing hoop stress and CA for continuous row not capable of bearing hoop stress). Mandatory and recommended verifications are indicated by the letters M and R, respectively.

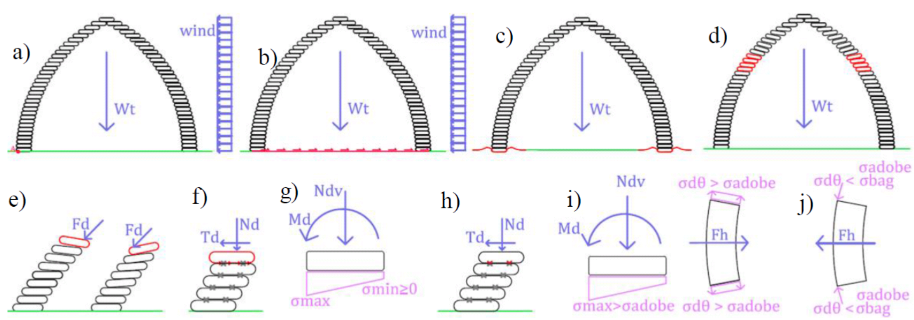

Figure 3: Failure schemes according to Table 5 (Eq. 39-51): Global roll-over (a), global slipping (b), collapse (c), buckling (d), local roll-over (e), local slipping (f), vertical compression (g), tear of the bag (h), adobe failures (i) and failure in hoop direction (j).

Mechanism	Verification	Ds	CA	CAB
Global roll-over	$\mathrm{Wt}_1\gamma_{G1}/RE_1 \geq q_{wind}H^2\gamma_{Q2}(28)$	M	M	M
Global slipping	$\mathrm{C}_{bw}A_{z_{ef_{base}}} + N_{k_{base}}\mu \geq q_{wind}H\gamma_{Q2}(29)$	M	M	M
Collapse	$\mathrm{f}_{base} \geq \sigma_{d_{v_1}}(30)$	M	M	M
Buckling	$\mathrm{E}_{adobe}b_i \geq \sigma_{d_{vmax}}(31)$	M	M	M
Local roll-over	$\mathrm{N}_{k_{v_i}}(R_{kl_{ext_i}} - RE_i)+ \geq \sigma_{d_{vmax}} + W_ib_i\gamma_{G1}/2 \geq T_{d_i}h(32)$	M	M	M
	$\mathrm{T}_{k_i}h + W_i\gamma_{G1}(RC_i - RI_{i-1}) \geq N_{d_{v_i}}(R_{kl_{int_i}} - RI_{i-1})(33)$	M	M	M
Local slipping	$\mathrm{C}_{bw}A_{z_{ef_i}}/\gamma_{wire} + N_{k_{v_i}}\mu \geq T_{d_i} * (34)$	M	-	-
Bag tear	$\mathrm{T}_{tear} \geq T_{d_i} - N_{d_i}\mu(35)$	-	-	R
Adobe failure	$\text{-}\mathrm{f}_{adobe} \geq \sigma_{d_{entmax_{t_i}}}(36)$	-	M	M
	$\text{-}\mathrm{f}_{adobe} \geq \sigma_{d_{\theta_{c_i}}}(37)$	M	M*	M*
	$\mathrm{f}_{adobe_t} \geq \sigma_{d_{\theta_{t_i}}} **(38)$	-	M*	-
Bag failure	$2\mathrm{K}_pT_{bag}/(h\gamma_{bag}) \geq \sigma_{d_{extmax_i}}(39)$	-	-	M
	$\mathrm{T}_{bag}(b_i + h)/(hb_i\gamma_{bag}) \geq \sigma_{d_{\theta_{t_i}}}(40)$	-	-	M**,*

Table 3: Structural verification for earthbag domes

$*is\ mandatory,\ but\ if\ is\ not\ satisfied\ then\ Eq.34\ must\ be$

$**ismandatorybutifnotsatisfiedthenEq.38mustbe$

4 Conclusions

The earthbag technique is an alternative to promote social housing and emergency shelters due its simplicity, fast construction and low cost. In spite of all this advantages, a lack of design methods that take into account the specificities of this type of structures might compromise its efficient and safe use. For that, several resistant mechanisms were identified and an alternative method for the design of walls and domes was proposed. This method takes into account the material properties and the capability of bearing tension on continuous hoops.

The critical failure mode for the domes is the roll-over towards the outside that occurs close to the bottom and slipping close to the top. The width of the bags and the curvature of the dome are the most important parameters governing the structural response.

5 References

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