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Earthen masonry dwelling structures for extreme wind loads

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ABSTRACT

Earthen masonry made of compressed and stabilized earth blocks (CSEBs) is emerging as a sustainable and locally appropriate construction material for affordable high-quality dwellings. Compelling features include the local availability and affordability of suitable soils, thermal insulation and humidity control properties, and small embodied energy compared with fired clay masonry. The mechanical properties of CSEBs have been the subject of several investigations. However, the research on the response and design optimization of CSEB masonry building structures is in its infancy, and a significant knowledge and technological gap exists with regard to resistance to extreme loads due to natural hazards (e.g., high winds and earthquakes). It is necessary to address this gap to understand whether engineered earth masonry can be enlisted to respond to the growing demand for hazard-resistant dwellings that are also affordable and sustainable.

This paper discusses the feasibility of using earth masonry in low-rise dwelling structures to withstand extreme winds. Hurricanes and tornadoes periodically scourge vast areas in Central and North America and the Caribbean where low-income families live, and where the demand for sustainable construction meets that for structural resistance and affordability. Feasibility is studied based on the structural analysis of the main wind force resisting system (MWFRS) of a typical one-story single-family dwelling subject to wind pressures resulting from 3-s gust speeds up to 90 m/s (324 km/h). The output consists of parametric curves that relate wind speed with masonry compressive, tensile and shear strength demand for wall thicknesses ranging from 203 to 508 mm. The structural adequacy of the MWFRS is assessed for the cases of flat and 15° gable roof. The design implications are discussed vis-à-vis strength reduction factors and design strength demands, and sustainable reinforcement options. It is concluded that it is feasible to design one-story CSEB masonry dwellings that can withstand winds loads from Category 4 hurricanes and EF3 tornadoes, provided that a rigid horizontal diaphragm is used. Grouted steel reinforcement may be used in safety shelter CSEB masonry structures to be designed for more extreme wind loads.

1. Introduction

Throughout the world, millions of people in rural and remote areas live in earthen dwellings [1] ranging from adobe to cob and rammed earth structures. Sustainability and local appropriateness draw from: local availability and affordability of suitable soils; energy efficiency due to the relatively high thermal mass and volumetric heat capacity, and ability to passively maintain the indoor relative humidity between 40% and 60%, which is the optimal range for occupant health [2–5]; and an embodied energy that can be over 80% smaller than for concrete masonry units and fired clay bricks [4,6]. However, the non-engineered nature of earthen structures often translates into an inadequacy to withstand extreme loads associated with natural hazards such as high winds and earthquakes [7–11], and makes them unsuitable for mainstream construction in developed regions. Yet, a significant part of the population in developed countries lives in hazard-prone rural and remote areas and it often includes underrepresented, underprivileged and young groups. In these areas, building with locally available and durable materials becomes key to contain housing costs, reduce homelessness, and create jobs.

The use of compressed and stabilized earth blocks (CSEBs), which are formed in a press from a soil mix with a small amount of stabilizer (e.g., ordinary Portland cement, herein referred to as 'cement'), is emerging as a means of engineering earthen masonry that pairs sustainability with structural resiliency, durability including erosion resistance [12], and extreme affordability. A striking example is offered by the Crow Tribe of Indians' 'Good

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Nomenclature

A_i	tributary area for wind uplift force and dead load on wall i, in m^2
$A_{s,b}$	area of steel reinforcement in wall for balanced flexural failure, in m^2
a	width of pressure coefficient zone, in m
C_M	resultant compressive force on uncracked masonry, in N
C_R	center of rigidity
c	distance from extreme compression fiber to neutral axis, in m
E_M	elastic modulus of masonry, in Pa
e_x, e_y	eccentricity between resultant horizontal wind loads, F_y and F_x, and center of stiffness of MWFRS, C_R, along x and y, in m
F_i	shear force transferred by rigid diaphragm on wall i, in N
$F_{i,x}$, $F_{i,y}$	shear force transferred by rigid diaphragm on wall i along direction x and y, in N
F_x, F_y	resultant wind load resisted by rigid diaphragm along direction x and y, in N
f_b	compressive strength of earthen block, in Pa
f_c	compressive strength of masonry, in Pa
$f_{c,if}$	compressive strength demand of masonry for in-plane flexural failure, in Pa
f_m	compressive strength of mortar, in Pa
f_s	shear strength of masonry, in Pa
$f_{s,is}$	shear strength demand of masonry for in-plane shear failure, in Pa
f_t	tensile strength of masonry, in Pa
$f_{t,of}$	tensile strength demand of masonry for out-of-plane flexural failure, in Pa
f_y	yield strength of steel, in Pa
G_M	shear modulus of masonry, in Pa
(GC_{pf})	external pressure coefficient
(GC_{pi})	internal pressure coefficient
H	height of MWFRS walls, in m
H_r	height of gable roof, in m
I	importance factor for hurricane wind pressure calculations
$I_{i,x}$, $I_{i,y}$	principal moment of inertia of wall i with respect to axis parallel to x and y, in m^4
J_p	polar moment of inertia, in N-m
K_d	wind directionality factor
$K_{i,x}$, $K_{i,y}$	stiffness of cantilever wall i along axis parallel to x and y, in N/m
K_z	velocity pressure exposure coefficient at height z
K_{zt}	topographic factor
k_v	shear factor indicating friction resistance along mortar bed joint
L_i	length of wall i, in m
L_x, L_y	length of MWFRS footprint along direction x and y, in m
$M_{W,of}$	out-of-plane bending moment produced by wind pressure, in N-m
M_x, M_y	torsional moment in x–y plane produced by resultant wind load resisted by rigid diaphragm along direction x and y, in N-m
P_D	compressive force due to dead load of roof diaphragm, in N
P_M	compressive force due to dead load of masonry wall at reference section, in N
P_W	uplift force due to wind loads at reference section, in N
p	design windward or leeward pressure, in Pa
p_s	net wind pressure, in Pa
p_{s30}	simplified wind pressure simulating hurricane effects for Exposure B at mean roof height of 9.1 m and importance factor $I = 1.0$, in Pa
q_h	velocity pressure at mean roof height $z = h$, in Pa
T_i	amplification factor for tornado effects
t	thickness of wall, in m
V	basic wind speed (3-s gust speed at 10 m above ground in Exposure C), in m/s
x_i, y_i	coordinate of centroid of wall i along axis x and y, in m
x_R, y_R	coordinate of center of rigidity along axis x and y, in m
γ	specific weight of earthen masonry, in N/m^3
ε_M	compressive strain in masonry, in mm/mm
$\varepsilon_{s,y}$	yield strain of steel, in mm/mm
θ	angle of plane of roof from horizontal, in degrees
λ	adjustment factor for building height and exposure
σ_D	axial compressive stress produced by self-weight of diaphragm and roof, in Pa
σ_i	combined axial stress produced by self-weight of masonry, diaphragm and roof, and wind uplift force in reference section of wall i, in Pa
σ_M	axial compressive stress produced by self-weight of masonry, in Pa
σ_W	axial tensile stress produced by wind uplift force, in Pa
τ_i	shear stress produced by horizontal wind load in wall i, in Pa
ϕ	design strength reduction factor for designated failure mode

Earth Lodges' program. This initiative is the planned response to the Crow Tribe's energy-efficient housing and job demand at their reservation in Montana (USA), where the US Bureau of Indian Affairs identified a need for several hundreds of housing units. Fig. 1 [13] shows a CSEB house on a cast-in-place frost protected shallow foundation, where the dwelling replaced a nearby trailer home shown in Fig. 1b. In this case, the main goal was to maximize the use of locally-available and inexpensive soil for efficient protection against extreme temperatures, especially during cold winters, while the front protrusion (certainly not ideal for wind-resistant designs) frames large windows that facilitate natural lighting.

The incorporation of up to 10% (in weight of soil, herein denoted as 'wt%') of cement was reported to result in an increase in compressive strength by up to three times compared to compressed and unstabilized blocks (CEBs) [14]. In fact, CSEBs may attain a similar compressive strength to that of fired clay bricks [15], and the compressive and tensile strength of CSEB walls attest to the potential for safe use when designing using limit state principles that apply to traditional masonry structures [16,17]. For example, the flexural strength of single-wythe walls made with CSEBs having a cement content of about 5%, and bonded with cement and sand mortar (in a cement:sand proportion of 1:5), was determined via out-of-plane load tests as lying in the range 0.24–0.36 MPa, similar to that of fired clay brick counterparts [18]. The compressive strength of CSEBs typically exceeds the minimum requirement of 3.6 MPa that is mandated in the New Zealand NZS 4298 code [19], which is based on standard earthquake resistant design methodologies for conventional masonry [20], and that of 2.0 MPa that is specified in the state of New Mexico's 2009 building code in the USA [21]. Evidence of satisfactory performance of CSEB dwellings under seismic loads was collected in the aftermath of the 7.1 magnitude Canterbury earthquake that struck New Zealand in 2010 [10]. The applicability of a simple one-way bending model for the strength prediction of earthen masonry walls subjected to uniformly distributed out-of-plane pressures [22] was