WALL HEIGHT, THICKNESS, AND HEIGHT-TO-THICKNESS RATIOS - THE SEISMIC DESIGN AND PERFORMANCE OF ADOBE WALLS

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Abstract

The concept of safe limitations on wall height, thickness, and height-to-thickness (h:t) ratios for adobe walls is not magic. It is easy to envision that a short squat wall is harder to push over than a tall thin one. Adobe walls that have performed well through past earthquakes indicate that a h:t ratio of five or six is resistant to overturning in the most severe seismic events, a h:t ratio of no more than seven in moderate seismic events, of no more than eight in weak seismic events, and no more than 10 otherwise. However, where seismic loads are not an issue, wind loads may be of concern for wall stability and roof connections, and should not be overlooked.

Traditionally, some rather arbitrary limits on wall thickness for unreinforced adobe walls have been promoted in "adobe codes". To better understand the consequences of wall height and thickness and h:t choices on seismic performance, this paper presents a synthesis of analytical, observational (shake table and field), and practical considerations including wall repair and stabilization. The evaluation distinguishes between new construction and preservation of existing older and historic buildings.

Keywords: Wall Height, Wall Thickness, Wall Height-to-Thickness Ratios, Adobe Codes, Adobe Wall Testing, Adobe Wall Repair, Adobe Wall Stabilization

1. Introduction/Background

The concept of safe limitations on adobe wall heights and thicknesses may easily be envisioned by realizing that a short squat block is harder to push over than a tall thin one. In a second example, if one wall is twice as thick as another, while the heights remain the same, it takes four times as much force to start to tip the thicker wall and twice as much horizontal ground displacement during the shaking to actually tip it over. The actual structural behavior of adobe walls during earthquake ground motion is not quite as simplistic as this, but the basic concept is a valid rule of thumb for vertical building elements such as walls.

Wall height and height-to-thickness ratios play a significant role in determining the capability of an adobe structure to resist lateral forces due to wind and earthquakes. Some recent studies have focused upon the overturning behavior of adobe walls and rigid blocks due to seismic ground motion (Bariola and Sozen 1990, and DeJong 2012, Tarque et al. 2012). These studies are primarily concerned with the overturning failure of free-standing (fixed-free) walls. DeJong (2012) investigated the rocking behavior of idealized free-standing walls and stated that, "rocking motion, and therefore rocking collapse, is typically assumed to be impossible if the horizontal ground acceleration remains below..." g/(h/t), where g is the gravitational acceleration (9.806 m/sec^2), and h/t is the height-to-thickness (h:t) ratio of the block or wall. This assumes the wall is a rigid body that does not flex during lateral loading, which we know is not an accurate depiction of adobe walls that flex during earthquake shaking.

DeJong (2012) showed that under the right conditions (one being wall flexibility), a free-standing wall can start rocking at a horizontal ground acceleration which is less than that predicted by the static overturning moment. However, to sustain the rocking of a wall and cause overturning collapse requires that the total energy input by the ground motion exceed the impact energy dissipated by the wall as it rocks back and forth.

To better understand the consequences of constructing walls with various h:t ratios, it has also been necessary to study the behavior of existing earthen buildings during severe seismic

shaking and/or the behavior of test walls on the shake table. Bariola and Sozen (1990) tested the stability of adobe walls to earthquake loads and found the overturning failure depended on the type of ground motion, the h:t ratio and the thickness of the wall. Studies of the performance of historic and older adobes that have performed well through past earthquakes (Tolles et al. 1996, 2000) indicate that an h:t ratio of five or six is most resistant to overturning in the most severe seismic hazard zones, of no more than seven in moderate seismic hazard zones, of no more than eight in low seismic hazard zones, and no more than 10 elsewhere.

And yet, according to Schneider et al. (1993), code limits on minimum wall thickness and maximum h:t ratios, as found in the 2009 International Building Code (ICC 2009), the 2010 California Building Code (CBSC 2010b), and the 2009 New Mexico Earthen Building Materials Code (CID 2009), "...probably grew out of some compromise over what the members of a 'Code committee' felt was appropriate," and have remained unchanged for many years, despite the evidence that contradicts these norms. Both the 2009 International Building Code (ICC 2009) and the 2010 California Building Code (CBSC 2010b) specify a minimum wall thickness of 10 inches and a maximum h:t ratio of no more than 10 for laterally unsupported adobe walls.

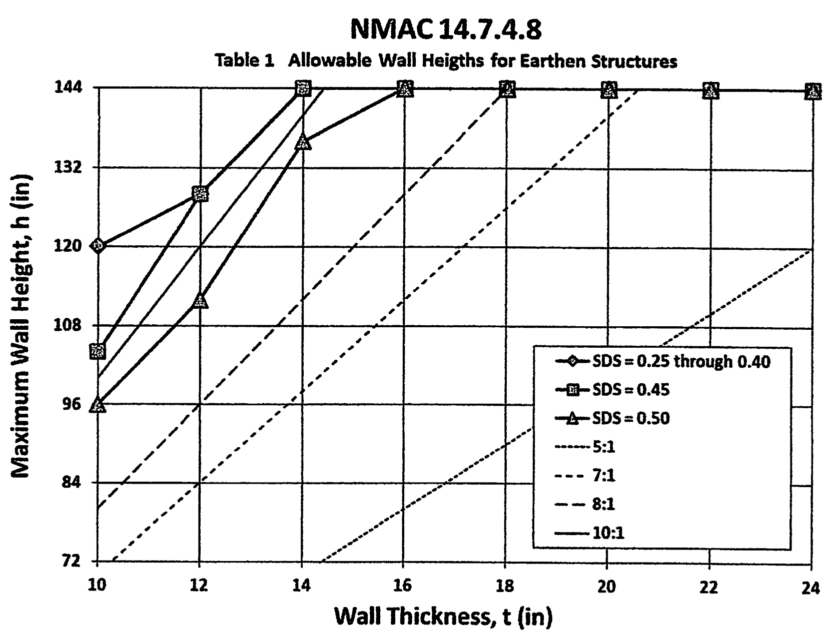

Figure 1 Comparison of h:t Ratios in NM Earthen Building Materials Code (CID 2009)

The 2009 New Mexico Earthen Building Materials Code (CID 2009) allows exterior walls to be 10 inches for single-story buildings and 14 inches for the first story of a two-story building. And Table 1 in Section 14.7.4.8 of the NM Code (shown here in graph form; see Figure 1) allows h:t ratios of 10 to 12 for walls of thickness of 14 inches or less, even in seismic zones where the S_{DS} values are as high as 0.45. S_{DS} is the Code delineated measure of seismic hazard in any location in the US, including New Mexico, and used to determine the required design seismic load for buildings and structures.

2. The Rational Allowable h:t Ratios

2.1 Basic out-of-Plane Response of a Cantilever Wall

Uplift on a wall section begins when any portion of the wall thickness experiences zero compressive stress due to the lateral loading. Since the adobe masonry cannot be relied upon to possess tensile stress capability, particularly across block/mortar interfaces, zero compression on any part of the through-wall thickness determines the onset of uplift. Uplift and overturning in an unreinforced adobe wall are resisted by the weight of the wall and by any overburden such as a parapet, a second floor and/or roof.

Figure 2 shows the stages of the out-of-plane response of a simple free-standing adobe wall to an increasing lateral load. The first stage is the elastic flexural response of the wall up to the beginning of uplift, the point at which the upstream edge of the wall experiences zero compression. Beyond this load, the wall still experiences elastic flexural deformation until only the downstream edge at the base is in compression (the rest of the through-wall thickness is no longer in compression, Figure 2b). Overturning begins at this point, overcoming the stabilizing effects of the wall weigh and overburden. The wall now acts as a rigid body, pivoting about the downstream edge, as depicted in Figure 2c. The horizontal displacement of the top of the wall, Δ, goes through two regions of elastic flexure, and then rigid body rotation (overturning) in response to the lateral load. The idealized force-displacement plot for the free-standing wall is depicted in Figure 2d. Note that as the center of gravity of the wall rotates toward vertical alignment with the point of tipping the lateral force required to tip it further and further

becomes less and less until the center of gravity rotates beyond the point of tipping and the wall tips over (overturning failure).

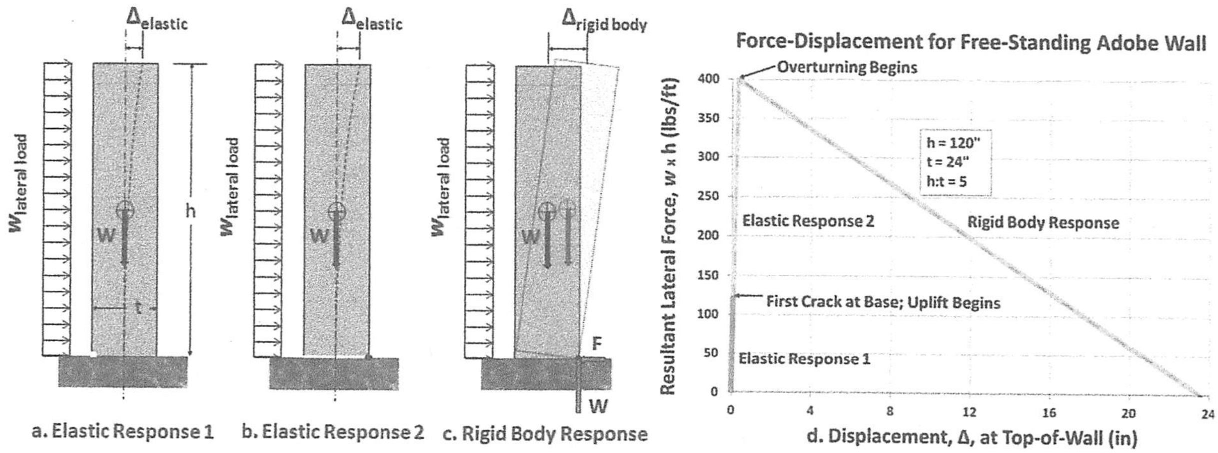

Figure 2 Displacement Response of a Free-Standing Wall to Lateral Load

Since the implicit assumption in the building codes for unreinforced adobe is that there is no allowable tensile stress that the adobe masonry can sustain, a wall must remain in compression across the thickness during lateral loading. The result is that the allowable height and h:t ratio for the design of an unreinforced adobe wall is based on the load at first cracking, i.e., when uplift begins. The factor of safety between the when uplift begins and when overturning begins is three (3) for the free-standing (cantilever) wall.

2.2 Out-of-Plane Response of a Fixed-Pinned and Pinned-Pinned Walls

The walls in older and historic adobe buildings are often free-standing due to a lack of connection between the tops of the walls and the roof structure. In fact, if the adobe has experienced coving damage at the base of the walls due to moisture wicking or lack of maintenance, this free-standing condition becomes less and less stable and extremely vulnerable to seismic loads. Add non-compatible (dissimilar) patching of cement plaster and/or concrete collars at the base and not only have you lost that original wall thickness, but moisture is retained as well, further endangering the wall.

However, for new construction there is generally lateral restraint at the tops of the walls in the form of a bond or tie beam. If in addition to lateral restraint at the top of the wall, the base is founded on a substantial footing and stem wall (i.e., the footing is wider than the wall

thickness, and the stem wall is at least as thick as the wall), and a moisture barrier is constructed between the stem wall and the adobe above, it can be considered fixed against rotation during lateral loading (see Figure 3a). This is known as the fixed-pinned condition and the critical through-wall section occurs at the 5/8 wall height. Without this rotational restraint at the base, a pinned-pinned condition occurs (Figure 3b) and the critical through-wall section occurs at mid-height. These are the locations where the walls first experience flexural tensile stresses equaling and counteracting the compressive stresses due to the wall weight and overburden load. First cracking from lateral loading starts at these locations and defines the limit of the Elastic Response Region 1 (similar to that shown in Figure 2d).

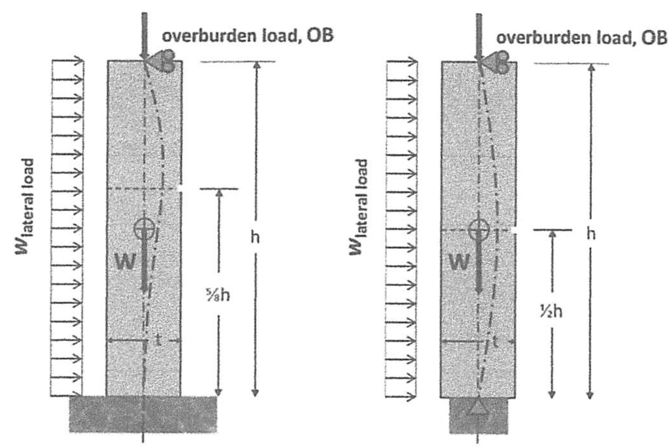

Figure 3 Elastic Responses of Walls with Base and Top-of-Wall Restraint

2.3 Code Specified Load Combinations

Current building codes, by reference to the Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 2005), require consideration of eight basic load combinations for new structures. The critical combination for determination of the allowable adobe wall height and h:t ratio is a lateral seismic load of 0.7 x 0.4 x S_{DS} x w_P, in combination with a counteracting gravity load of (0.6 - 0.14 x S_{DS}) x (W_{upper} + OB), where S_{DS} is the spectral response acceleration at short periods (see Table 1, NMAC 14.7.4.8 for S_{DS} values in New Mexico), w_P is the weight of the wall per unit height, W_{upper} is the weight of the wall above the critical height, and OB is the overburden. Codes specify a minimum OB for load-bearing walls of 200 lbs/ft of wall length. The OB for non-load bearing walls is assumed to be 0 lbs/ft. Note that for historic adobes In

California, the 2010 California Historical Building Code (CBSC 2010a) allows a seismic load of only 75% of S_{DS} be substituted in lieu of S_{DS} in the basic load combinations.

2.4 Allowable Wall Height and h:t Ratios for New Unreinforced Adobe Walls in New Mexico

Using the critical load combination specified in the codes, a zero tensile stress limitation (crack initiation), S_{DS} values of between 0.25 and 0.50, an assumption of 100 lbs/ ft^3 for the adobe wall density, and an assumption about the lateral support condition, the allowable maximum wall heights for new adobe construction in New Mexico can be plotted, as shown below in Figures 4 and 5.

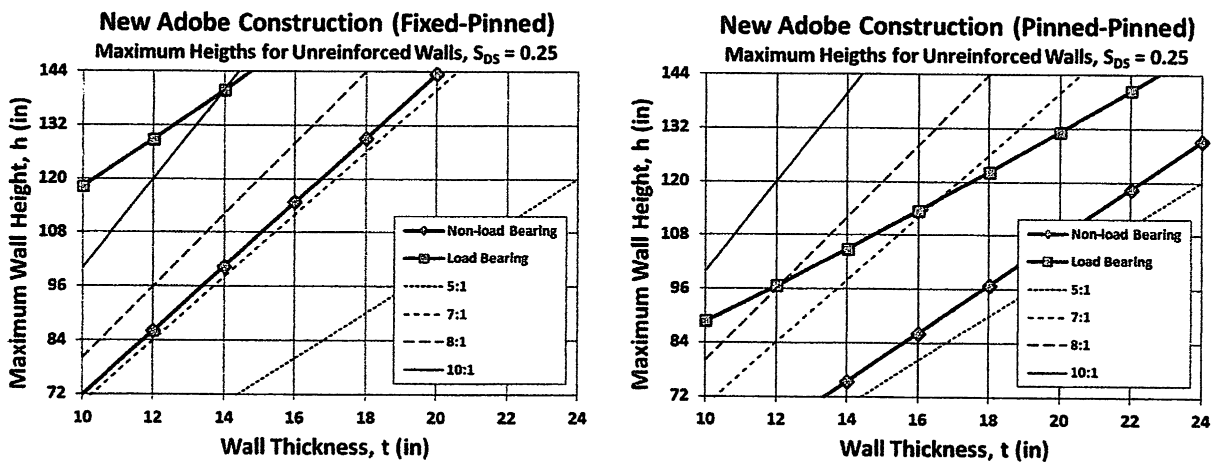

Figure 4 Allowable Wall Heights for New Unreinforced Adobe for Regions of $S_{DS} \leq 0.25$

As Figure 4 indicates, for non-load bearing walls, an allowable maximum wall h:t ratio for much of New Mexico (i.e., $S_{DS} \leq 0.25$) closely follows h:t = 7:1 rather than the 10:1 as show in Figure 1. However, for load-bearing walls, an h:t = 10:1 appears to be appropriate, at least for wall thicknesses of 14 inch or less. Obviously, if the foundation/stem wall condition approximates a pinned restraint rather than a fixed one, the allowable maximum for non-load bearing walls more closely follows h:t = 5:1.

For the most severe seismic hazard zone (S_{DS} = 0.50), much more restrictive allowable maximum wall heights and h:t ratios govern, as shown in Figure 5 for both fixed-pinned and pinned-pinned support conditions.

Walls that fall outside these limits, taking into consideration the S_{DS} of the building site, and the base and roof-level lateral support need to be reinforced and no longer considered unreinforced for purposes of design.

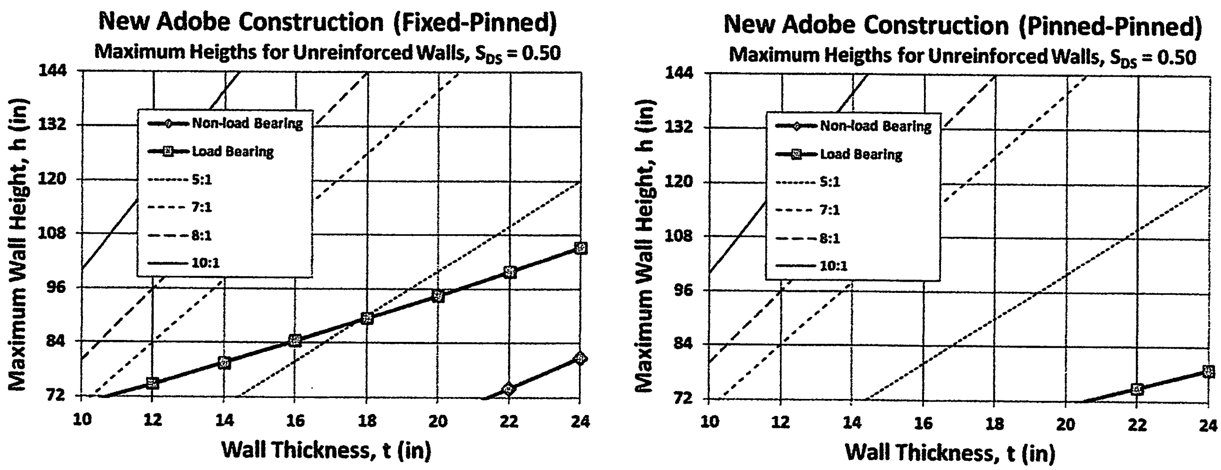

Figure 5 Allowable Wall Heights in for New Unreinforced Adobe for Regions of S_{DS} = 0.50

3. Conclusions

The plots presented herein of maximum wall heights and h:t ratios for unreinforced adobe walls in New Mexico should be considered stimulus for revisiting and possibly revising the current requirements in the 2009 New Mexico Earth Building Materials Code and other adobe codes.

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