

Out-of-Plane Design of Masonry Walls

Introduction

The design of masonry walls to resist out-of-plane loads is an important aspect in the design of masonry buildings. In most large buildings that use masonry walls as the lateral load resisting system, out-of-plane response is the critical phase of the design. This is because the common masonry warehouse-type building with few openings usually has enough walls to resist the in-plane demands generated by wind or earthquake loads. However, the large story height means that the out-of-plane demands can be quite high.

Figure 1 illustrates this concept. When the walls are loaded out-of-plane, they are not part of the

lateral load resisting system, but instead act as elements of the structure, or components, which support their own direct loads. For satisfactory structural response, the wall must span between supports and transfer lateral loads to the floor or roof diaphragm, which in turn transfers the loads to the walls that form the lateral load resisting system.

Evaluation of the walls is also complicated by the fact that since the walls are slender compared to their height, the deflection induced by the lateral loads can sometimes be comparable to the wall thickness. This means that the usual assumption of small deflections is not valid and secondary deformation effects ($P-\Delta$ effects) need to be considered in order to determine the wall demands accurately.

This article will provide an overview of the procedures required to design masonry walls that are subjected to out-of-plane forces. Methods for calculating the lateral wind and earthquake loads will be described, as well as techniques for obtaining wall forces, displacements and capacities. The paper will also provide insight on how to incorporate the requirements for deformation compatibility in the design of masonry walls and ensure that walls can sustain the deformations expected to occur under lateral loads.

Out-of-plane loads on masonry walls in buildings are usually induced by inertial earthquake forces or winds pressures. In basement walls, out-of-plane loads are also caused by lateral soil pressures, but these will not be specifically addressed in this article. This article will also not address the design of free-standing fence walls, which are also subjected to out-of-plane stresses. It should be noted that while the loads on retaining walls and fence walls are calculated in a slightly different manner, their design follows the principles described here.

The American Society of Civil Engineers (ASCE) publishes a standard that provides guidelines for determining structural design loads. The standard, "ASCE 7-02, Minimum Design Loads for Buildings and other Structures" (Ref. 1) contains various techniques that can be used for calculating the out-of-plane loads on masonry walls. Using the simplified procedure in ASCE 7-02, the design wind pressure p_{net} on masonry walls, which are considered as components or cladding for out-of-plane design, is given by the equation:

$$p_{net} = \lambda I p_{net30} \quad (1)$$

The wind pressure depends on the design wind speed at the building location, the building height, and the importance of the building. The term p_{net30} represents the net design wind pressure at a height of 30 feet for exposure B. Table 1 provides values of p_{net30} for various basic wind speeds, which are based on 3-second gusts. Positive and negative signs represent pressures acting toward and away from surfaces, respectively. It should be noted that the wind pressure is greater at wall end zones, which are defined in Figure 2. The adjustment factor, λ , which is given in Table 2, accounts for building height and exposure. The importance factor I accounts for the degree of hazard to human life and damage to property that may occur if an element fails. Its value ranges from 0.77 to 1.15.

Table 1 Net Design Wind Pressure, p_{net30} (psf)(Exposure B at $h=30$ ft. with $I=1.0$)

Zone	Effective Wind Area (sf)	Basic Wind Speed (mph)																	
		85	90	100	110	120	130	140	150	170									
Interior Zone	10	13.0	-14.1	14.6	-15.8	18.0	-9.5	21.8	-23.6	25.9	-28.1	30.4	-33.0	35.3	38.2	40.5	-43.9	52.0	-56.4
	20	12.4	-13.5	13.9	-15.1	17.2	-18.7	20.8	-22.6	24.7	-26.9	29.0	-31.6	33.7	36.7	38.7	-42.1	49.6	-54.1
	50	11.6	-12.7	13.0	-14.3	16.1	-17.6	19.5	-21.3	23.2	-25.4	27.2	-29.8	31.6	34.6	36.2	-39.7	46.6	-51.0
	100	11.1	-12.2	12.4	-13.6	15.3	-16.8	18.5	-20.4	22.0	-24.2	25.9	-28.4	30.0	33.0	34.4	-37.8	44.2	-48.6
	500	9.7	-10.8	10.9	-12.1	13.4	-14.9	16.2	-18.1	19.3	-21.5	22.7	-25.2	26.3	29.3	30.2	-33.6	38.8	-43.2
End Zone	10	13.0	-17.4	14.6	-19.5	18.0	-24.1	21.8	-29.1	25.9	-34.7	30.4	-40.7	35.3	-47.2	40.5	-54.2	52.0	-69.6
	20	12.4	-6.2	13.9	-18.2	17.2	-22.5	20.8	-27.2	24.7	-32.4	29.0	-38.0	33.7	-44.0	38.7	-50.5	49.6	-64.9
	50	11.6	-14.7	13.0	-16.5	16.1	-20.3	19.5	-24.6	23.2	-29.3	27.2	-34.3	31.6	-39.8	36.2	-45.7	46.6	-58.7
	100	11.1	-13.5	12.4	-15.1	15.3	-18.7	18.5	-22.6	22.0	-26.9	25.9	-31.6	30.0	-36.7	34.4	-42.1	44.2	-54.1
	500	9.7	-10.8	10.9	-12.1	13.4	-14.9	16.2	-18.1	19.3	-21.5	22.7	-25.2	26.3	-29.3	30.2	-33.6	38.8	-43.2

Table 2 Adjustment Factor for Building Height and Exposure, λ

Mean roof Height (ft)	Exposure		
	B	C	D
15	1.00	1.21	1.47
20	1.00	1.29	1.55
25	1.00	1.35	1.61
30	1.00	1.40	1.66
35	1.05	1.45	1.70
40	1.09	1.49	1.74
45	1.12	1.53	1.78
50	1.16	1.56	1.81
55	1.19	1.59	1.84
60	1.22	1.62	1.87

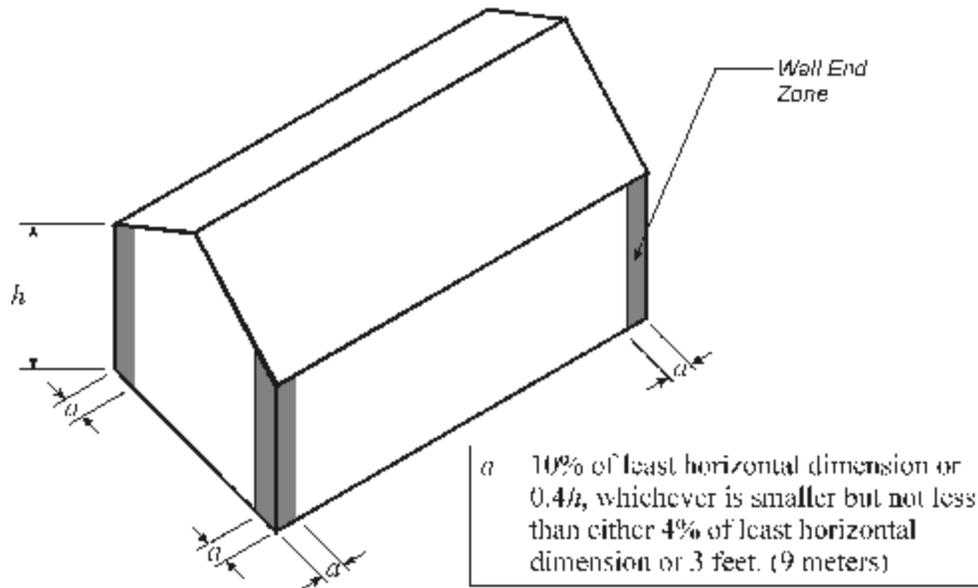


Figure 2: Definition of Wall End Zones

Out-of-plane earthquake loads on masonry walls can also be calculated using the stipulations of ASCE 7-02 for components. The following equation calculates the seismic design force F_p on the wall, which is to be distributed relative to the wall mass distribution:

$$F_p = \frac{0.4a_p S_{DS} W_p}{R_p / I_p} \left(1 + 2 \frac{z}{h} \right) \quad (2a)$$

where

S_{DS} = short period 5% damped spectral response acceleration at the building location. The value $0.4S_{DS}$ represents the effective ground acceleration at the site.

a_p = amplification factor that represents the dynamic amplification of the wall relative to the fundamental period of the structure. For most masonry walls, $a_p = 1.0$, except for parapets and un-braced walls for which $a_p = 2.5$.

I_p = importance factor that varies from 1.0 to 1.5.

W_p = wall weight.

R_p = response modification factor that represents the wall over-strength and ductility or energy absorbing capability. For reinforced masonry walls, $R_p = 2.5$, while for un-reinforced masonry walls, $R_p = 1.5$.

z = height of point of wall attachment with respect to the base.

h = average roof height of structure with respect to the base.

The seismic force need not exceed

$$F_{p,max} = 1.65 S_{DS} I_p W_p \quad (2b)$$

and should not be less than

$$F_{p,min} = 0.3 S_{DS} I_p W_p \quad (2c)$$

Equation (2) is based on research that studied the amplification of ground acceleration over building height in instrumented buildings (Refs 2, 3, 4). For large earthquakes, it has been determined that a roof amplification factor of three is appropriate. Figure 3 shows the distribution of earthquake force over the height of a building when calculated using Equation (2). Since the wall is supported at the bottom and top of each story, the average of the forces calculated for the floor above and the floor below is used to design walls in each story. This ensures that the earthquake forces are applied in proportion to the mass distribution of the wall.

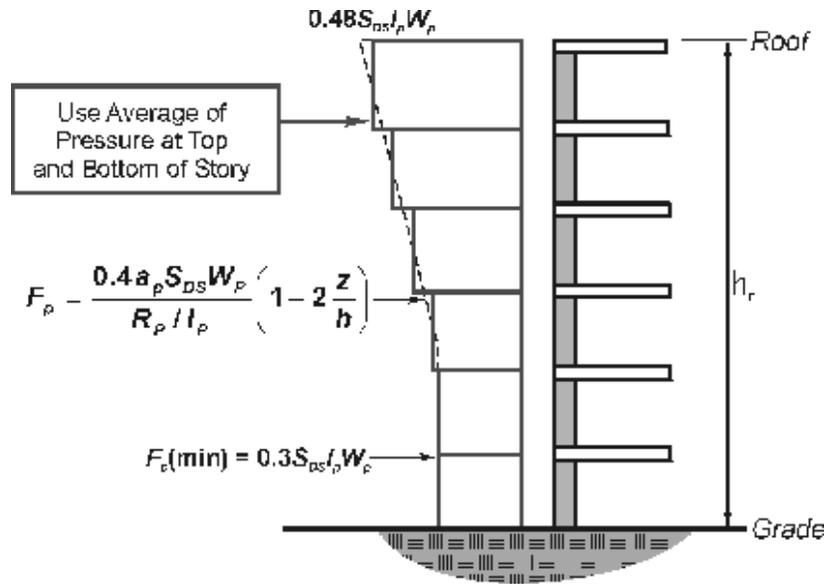


Figure 3: Distribution of Out-of-Plane Earthquake Force Over the Height of a Building with Reinforced Masonry Walls

Out of Plane Analysis of Masonry Walls

It is a common assumption that masonry walls are restrained by pin supports at the floor and roof levels. This is a reasonable design approach, since the wall to floor connection usually does not possess sufficient stiffness or strength to transfer wall moments into the floor and thus justify a rigid connection. In addition, since earthquake and wind response are dynamic phenomena, the assumption of pinned supports is consistent with the modal response of the walls subjected to earthquake and wind loads.

Masonry walls are typically analyzed differently for out-of-plane loads depending on whether working stress or strength design procedures are used. This article will concentrate on strength design procedures. Strength design analysis procedures allow the designer to account for P-Δ effects and are more representative of the actual out of plane behavior of masonry walls. The *Building Code Requirements for Masonry Structures* (Ref. 5) provides the following equation for moment at the mid-height of a wall:

$$M_u = \frac{w_u h^2}{8} + P_{yf} \frac{e_u}{2} + (P_{uw} + P_{yf}) \delta_u \quad (3)$$

where

w_u = factored out-of-plane uniformly distributed load.

h = effective height of wall.

P_{uf} = factored load from tributary floor or roof areas.

P_{uw} = factored weight of wall are tributary to wall section under consideration.

e_u = eccentricity of p_{uf}

δ_u = deflection due to factored loads.

Equation 3 considers the effect of wall deflection on moment demand (P-Δ effects) and can be derived from Figure 4(a), which assumes pinned supports at the top and bottom of the wall. When there is significant lateral deflection at the top of the wall, as in the case of a flexible large-span roof or floor diaphragm, compatibility of deformations must be maintained and the free-body diagram of the wall is as shown in Figure 4(b). Then, an additional term must be added to Equation (3) and the design moment can be approximated by:

$$M_u = \frac{w_u h^2}{8} + P_{yf} \frac{e_u}{2} + (P_{uw} + P_{yf}) \delta_u + \frac{P_{uw}}{4} \delta_{ur} \quad (4)$$

where δ_{ur} is the deflection at the top of the wall due to factored loads. The additional moment required to enforce deformation compatibility can be significant in large buildings with high walls.

When the moment demand is less than the cracking moment, M_{cr} . The wall deflection, δ_u is calculated from the following equation:

$$\delta_u = \frac{5M_u h^2}{48E_m I_g} \quad (5a)$$

and if $M_u > M_{cr}$:

$$\delta_u = \frac{5M_{cr} h^2}{48E_m I_g} + \frac{5(M_u - M_{cr}) h^2}{48E_m I_{cr}} \quad (5b)$$

where E_m is the modulus of elasticity of the masonry, I_g is the gross moment of inertia of the wall, and I_{cr} is the cracked moment of inertia. The cracked moment is given by:

$$M_{cr} = S_n f_r \quad (6)$$

where S_n is the section modulus of the wall cross-section and f_r is the modulus of rupture. Since the moment depends on the deflection (see Equations (3) and (4)) and the deflection depends on the moment (see Equation (5)), it is clear that a solution can only be obtained by trial and error. As will be shown in the subsequent example, the problem converges to a solution reasonably quickly when the iterations are performed in a sequential manner.

The analysis procedure described above assumes that there are pinned supports at the top and bottom of the wall, and that the wall is subjected to uniform distributed lateral load. Different formulas can be developed, using free body diagrams such as those in Figure 4, if the wall has different boundary conditions, or is subjected to a different load pattern.

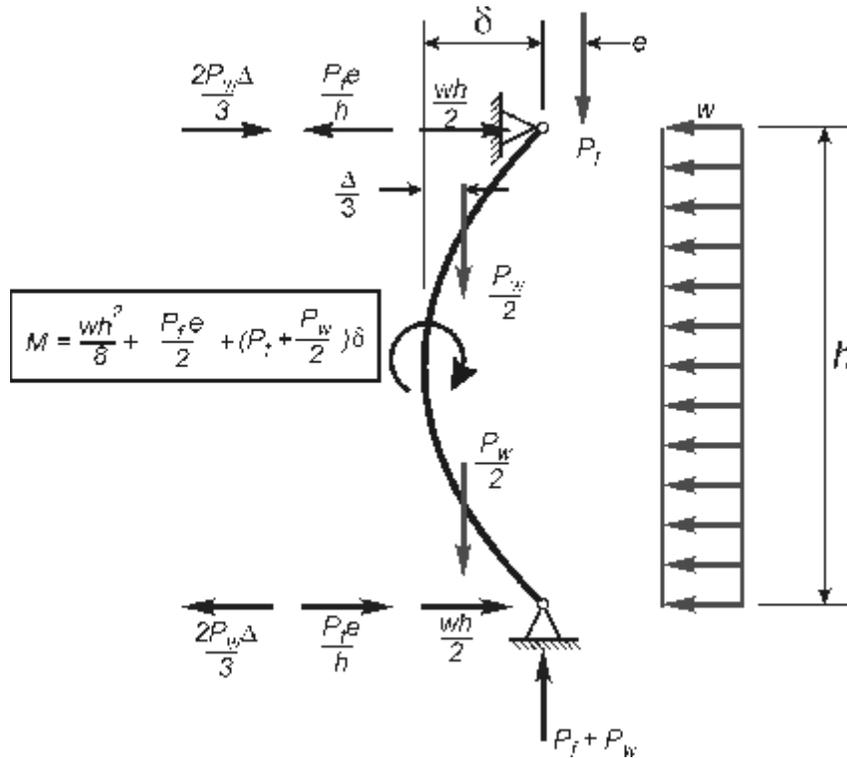


Figure 4(a): Free-Body Diagram of Wall with no Top Displacement

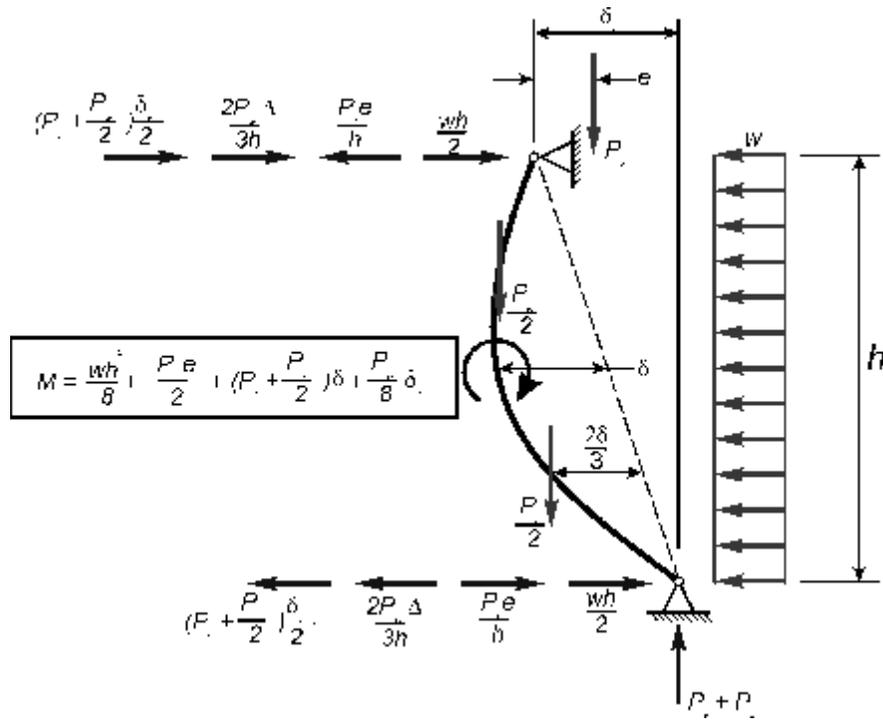


Figure 4(b): Free-Body Diagram of Wall with Top Displacement to Enforce Deformation Compatibility

Design of Wall Cross-Section

Once the moment and shear demands have been determined, the wall must be designed to resist the calculated loads. The primary task in the design of the wall cross-section is the determination of the reinforcement required to resist the out-of-plane bending moment. The wall should also be checked to ensure that the out-of-plane shear is adequate and that it meets the serviceability criteria.

The *Building Code Requirements for Masonry Structures* provides the following equation for checking the flexural capacity of a wall subjected to out-of-plane loads:

$$M_u \leq \phi M_n \quad (7)$$

where M_u is the factored load demand and the nominal moment capacity M_n is given by:

$$M_n = \left(A_s f_y + P_{uw} + P_{uf} \right) \left(d - \frac{a}{2} \right) \quad (8)$$

where f_y is the yield stress of the steel reinforcement and d is the distance from the extreme compression surface to centroid of the reinforcing steel. The strength reduction factor ϕ is equal to 0.9 for walls in flexure and the depth of the compression block, a is given by:

$$a = \frac{\left(A_s f_y + P_{uw} + P_{uf} \right)}{0.8 f'_m b} \quad (9)$$

where f'_m is the masonry compressive strength and b is the effective width of the wall cross-section. Equation (8) is valid for walls with one layer of vertical reinforcement placed at the center of the wall. In very high walls, it is often more practical to use two layers of reinforcement and take advantage of the large moment arm that results when the bars are placed closer to the wall exterior. To simplify the calculations, the compression steel can be ignored and the moment capacity calculated from:

$$M_n = \left(A_s f_y + P_{uw} + P_{uf} \right) \left(d - \frac{a}{2} \right) - \left(P_{uw} + P_{uf} \right) \left(d - \frac{t}{2} \right) \quad (10)$$

Figure 5 illustrates the derivation of Equation (10). Moment curvature analyses show that ignoring the compression steel underestimates the moment capacity of the wall by about ten percent.

It is impractical to use shear reinforcement to increase the out-of-plane shear capacity of masonry walls. Thus, the shear capacity is equal to the shear strength provided by the masonry V_m , which is given by:

$$V_m = \left[4.0 - 1.75 \left(\frac{M}{Vd} \right) \right] A_n \sqrt{f'_m} + 0.25P \quad (11)$$

The value M/Vd need not exceed 1.0. The shear design equation is then given by:

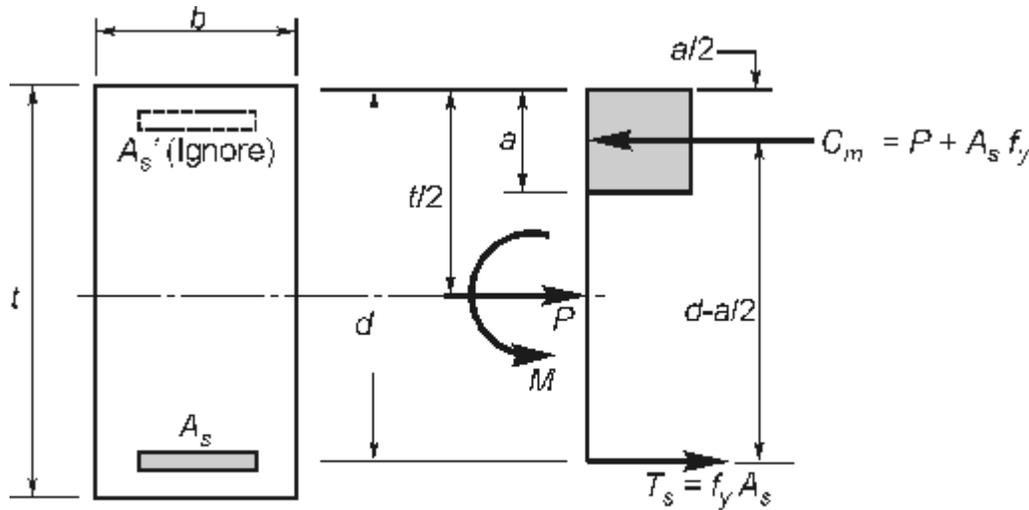
$$V_u \leq \phi V_m \quad (12)$$

where the strength reduction factor ϕ is equal to 0.8 for shear. In addition to strength requirements, the wall must

also satisfy the deflection following serviceability deflection requirement:

$$\delta_s \leq 0.007h \quad (13)$$

where δ_s is the deflection when the wall is subjected to service loads. The requirement in Equation (3) is intended to limit the amount of aesthetic cracking in the masonry and damage to attached materials.



Taking moments about T_s :

$$M = (P + A_s f_y) (d - a/2) - P(d - t/2)$$

Figure 5: Equilibrium of Wall Cross-Section with Two Layers of Reinforcement

Conclusions

The article has presented a systematic procedure for designing masonry walls to resist out-of-plane forces. Since out-of-plane wall resistance is the critical aspect in the design of most large masonry buildings, the design must be performed correctly in order to achieve acceptable building performance. The design process must consider the secondary effects displacements on the wall demands and the additional forces required to enforce the compatibility of deformations with the rest of the structure.

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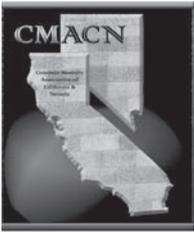
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This issue of "Masonry Chronicles" was written by Chukwuma Ekwueme of Hart-Weidinger.



Concrete Masonry Association
of California and Nevada
6060 Sunrise Vista Drive, Suite 1990
Citrus Heights, CA 95610
(916) 722-1700
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