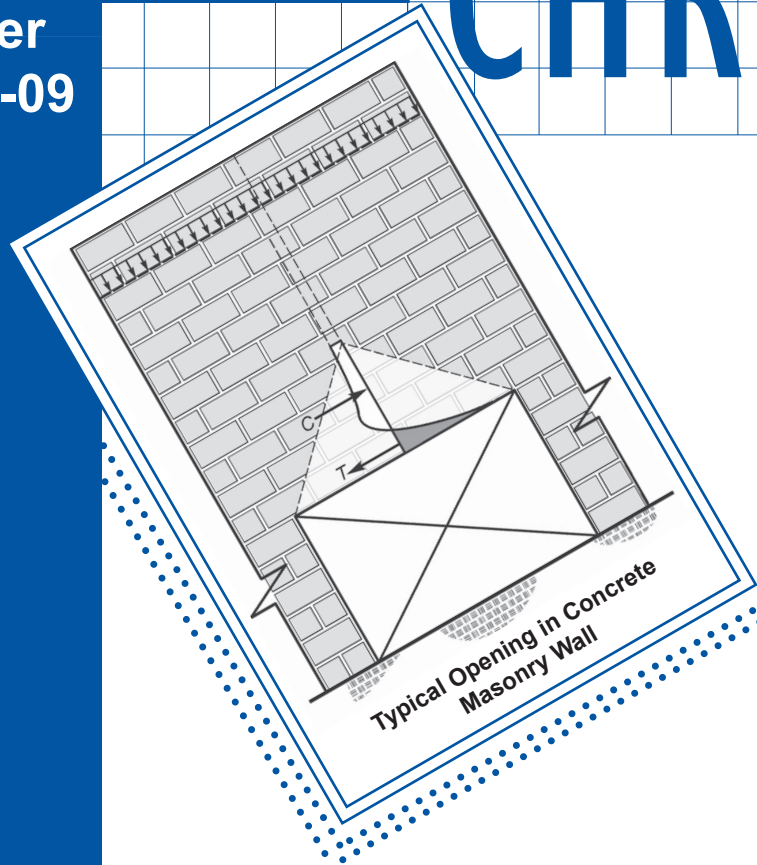Typical Opening in Concrete Masonry Wall

OPENINGS IN CONCRETE MASONRY WALLS (Part 1)

Introduction

Masonry walls almost always contain doors, windows and other openings. Therefore, when designing masonry, one must ensure that loads can be transferred around these openings. Several aspects need to be considered when designing masonry to incorporate the presence of openings:

1. Design to resist in-plane gravity loads (dead, live, snow, etc.)
2. Design to resist in-plane lateral loads (earthquake and wind)
3. Design to transfer out-of-plane laterals loads (earthquake and wind)

This edition of masonry Chronicles will discuss the design of openings in concrete masonry walls to resist gravity loads. Subsequent edition(s) will discuss the design of openings for out of plane and in plane lateral loads.

Gravity Loads Around Openings

The portion of the wall above an opening that resists gravity loads is typically called a lintel. Lintels can be constructed with numerous materials, including concrete (precast or cast in place) or structural steel. However, most concrete masonry lintels, particularly those in solid-grouted masonry, are constructed homogenously with the rest of the wall.

The determination of gravity loads on a lintel is based on a number of principles. Arching action above the opening enables loads to span around the opening. When the height of masonry above an opening is sufficient (greater than half the lintel span), the structure has a natural tendency to span across openings by forming an arch, as shown in Figure 1. The masonry lintel may be assumed to support only the loads within the triangle created by two lines inclined at 45-degrees extending from the span ends. Wall gravity loads and distributed loads outside this area are resisted by the surrounding wall and by a horizontal reaction at the ends of the arch. For arching to occur, there must be sufficient lateral resistance at the ends of the arch to resist the thrust. This lateral resistance may be provided by the mass of masonry adjacent to the opening, or by specifically designing an element to resist the imposed lateral load. Note that arching cannot occur if the ends of the arch are near wall ends, corners, or control joints, or when stack bond is used. There must also be enough masonry above the arch to resist the compressive forces generated by arching action. Therefore, arching cannot occur if the height of masonry above an opening is less than half the lintel span. If arching does not occur, the entire weight of the wall above the opening and all distributed loads are applied to the masonry lintel.
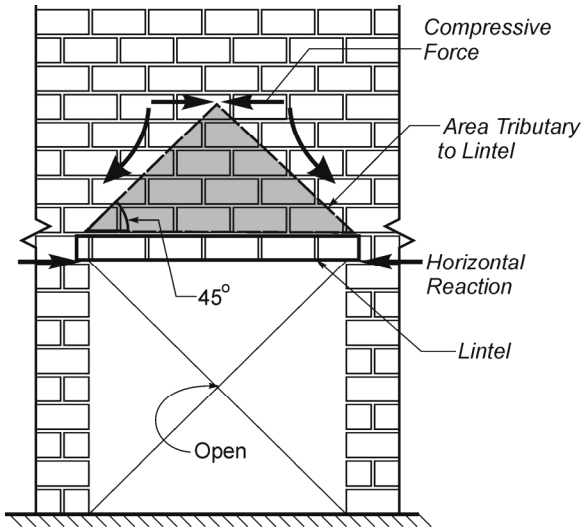
Figure 1: Arching of Masonry Around Openings

Distributed loads that are applied above the apex of the arch triangle are assumed to arch over the lintel. Distributed loads applied within the arch triangle are supported by the lintel, as shown in Figure 2. Such loads are assumed to spread out at a 45-degree angle so that the uniformly-distributed load on the lintel is reduced by the ratio of the width of load within the arch triangle and the lintel span. Distributed loads that do not extend entirely across the arch triangle may be distributed to only a portion of the lintel.

Concentrated loads are assumed to spread out at a 60-degree angle to the horizontal plane if the masonry is

laid in running bond, as shown in Figure 3. As stated in Section 2.1.9 of the MSJC code [1], the width over which the concentrated load is distributed should not exceed the bearing width of the load plus four times the wall thickness. This often results in imposed loading on only a portion of the lintel. If the wall is not laid in running bond, the concentrated load is distributed only as far as the closest vertical mortar joint.

Design of Lintels

Lintels are beams and must satisfy the building code requirements for masonry beams. The following are some of the prescriptive detailing requirements related to the design of beams:

- Beams must be grouted solid and the nominal depth of a beam should not be less than 8 inches.

- The compression face of beams must be laterally supported at a maximum spacing of 32 times the beam thickness.

- The deflection of beams and lintels providing vertical support to masonry should not exceed $L/600$ under unfactored dead plus live loads.

- The variation in longitudinal reinforcing bars in a beam should not be greater than one bar size. Not more than two bar sizes shall be used in a beam (Strength Design).
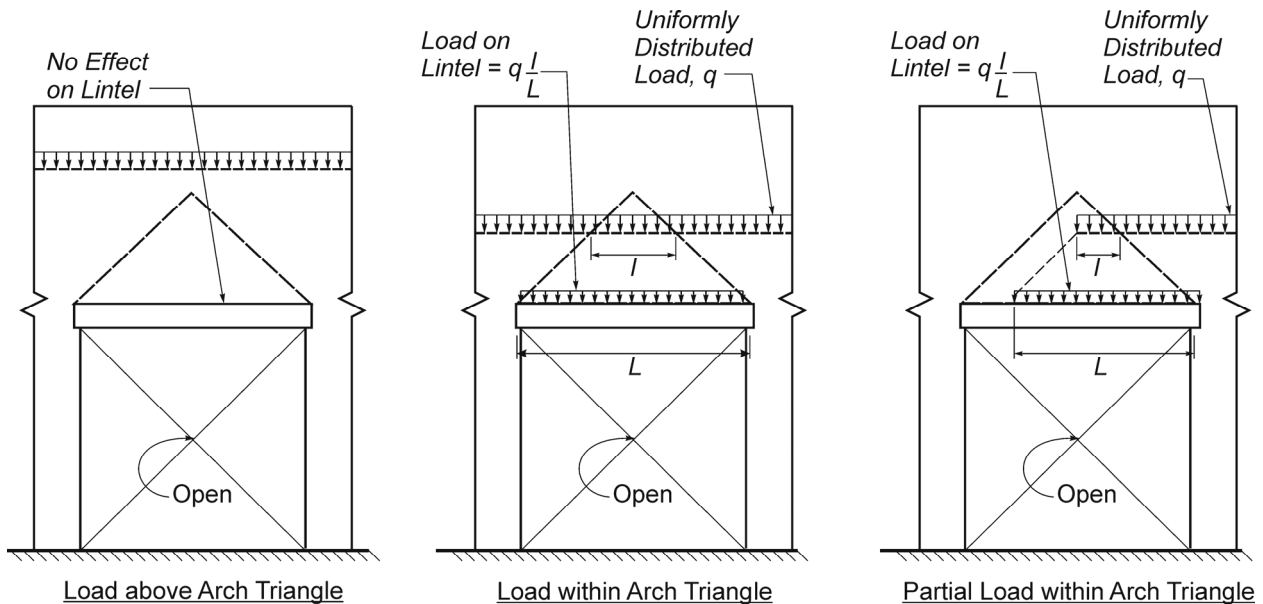

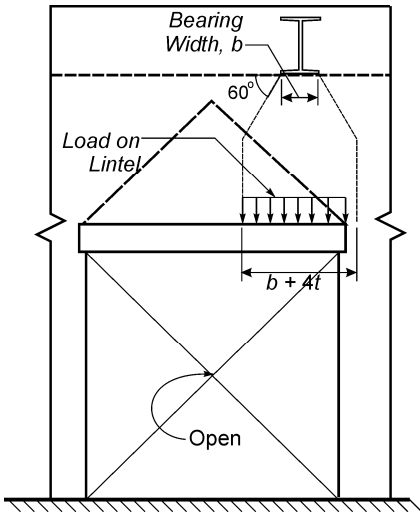**Figure 2: Lintel Loads from Uniformly-Distributed Loads**

Figure 3: Lintel Loads from Concentrated Loads

When the distance between the top of a solidly grouted wall and the bottom of the lintel is large, the depth of the lintel is not clearly defined. An effective depth of half the span may be used. This is based on Figure 4, which shows that the sum of flexural tension and compression stresses above a lintel are approximately equal at a height of 0.6 times the span. An effective depth of 0.5 times the lintel span is thus a conservative value. A maximum depth of half the lintel height is also consistent with the assumption of a triangular arch shown in Figure 1. Note that when the height of masonry above the opening is less than half the lintel span, the lintel depth cannot exceed the height of masonry above the opening. In addition, if the wall is partially grouted, only the fully grouted portion of the masonry above the opening may be used as a lintel.
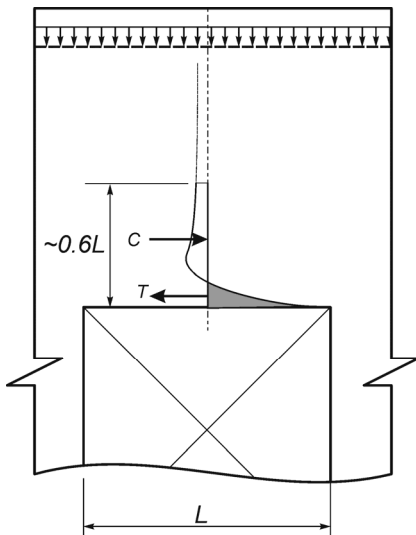

Figure 4: Flexural Stresses Above a Lintel

It is common practice to locate control joints at wall openings for aesthetic reasons. This is done to conceal cracks that may occur at the corners of openings due to stress concentrations resulting from lateral loading or shrinkage. Figure 5 illustrates how a control joint may be used at an opening to control the appearance of cracking. Since the lintel reinforcement must extend a sufficient distance beyond the opening, grout is continuous across the joint. The wall is weakened by the use of a continuous vertical mortar joint that is typically raked backed and protected with sealant, as shown in Figure 6. This increases the likelihood that any crack that occurs will be located in the joint and will be less visible.
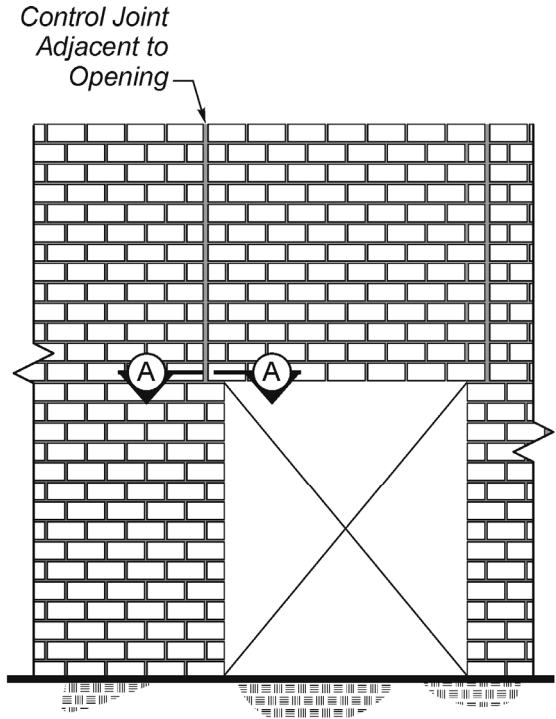

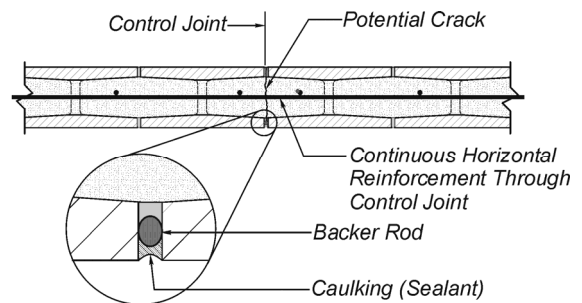**Figure 5: Control Joint as Wall Opening**

Figure 6: Control Joint Detail

The following example illustrates the procedures for designing lintels to resist gravity loads using allowable stress design and strength design.

Example

Determine the reinforcement in the lintel above the 17'-6″ wide opening shown in Figure 7. The wall is constructed with 12-inch thick (nominal) solid-grouted concrete masonry that weighs 124 psf. The masonry specified compressive strength is 1500 psi and reinforcing steel is Grade 60. Type S mortar is used.
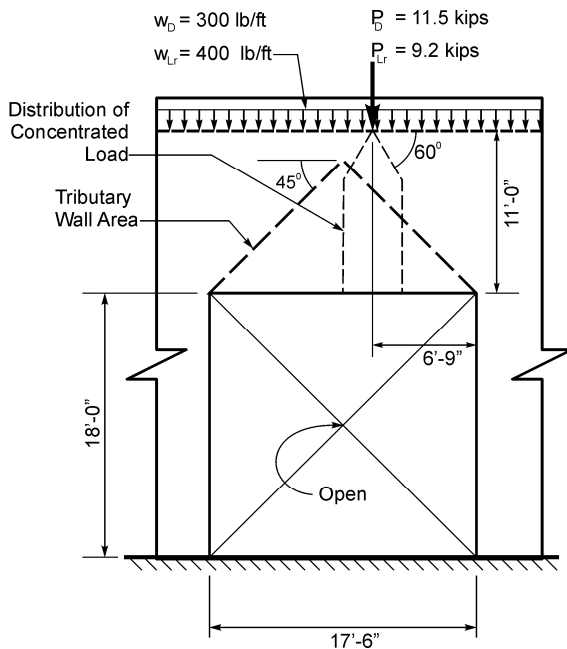

Figure 7: Lintel Design Example

Solution

Since the distributed roof loads are above the apex of the assumed triangle arch, they do not contribute to the loads on the lintel. In addition, the weight of masonry outside the arch is assumed to be distributed to the sides of the opening by arch action. Therefore, the weight of wall supported by the lintel is:

$$W = 124\left(\frac{1}{2}L \times \frac{L}{2}\right)$$

$$= 124\left(\frac{17.5^2}{4}\right) = 9494 \text{ lbs}$$

We can conservatively ignore the bearing width of the concentrated load. Then, assuming the concentrated load is transferred to the lintel with a 60 degree angle, the length over which the concentrated load is distributed on the lintel is given by:

$$L_c = 2\tan 30(11) = 12.7 \text{ ft}$$

Recall however, that concentrated loads cannot be distributed over a length greater than the width of bearing plus four times the wall thickness:

$$L_{c,max} = b + 4t = 0 + 4(11.63) = 46.5 \text{ in}$$
$$= 3.88 \text{ ft}$$

Therefore, the corresponding uniformly distributed load on the lintel is:

$$w_{P_D} = \frac{11.5(1000)}{3.88} = 2964 \text{ plf}$$

$$w_{P_{Lr}} = \frac{9.2(1000)}{3.88} = 2371 \text{ plf}$$

Figure 8 shows the loads on the lintel and the corresponding bending moment and shear diagrams, which are calculated assuming the lintel acts as a simply supported beam.

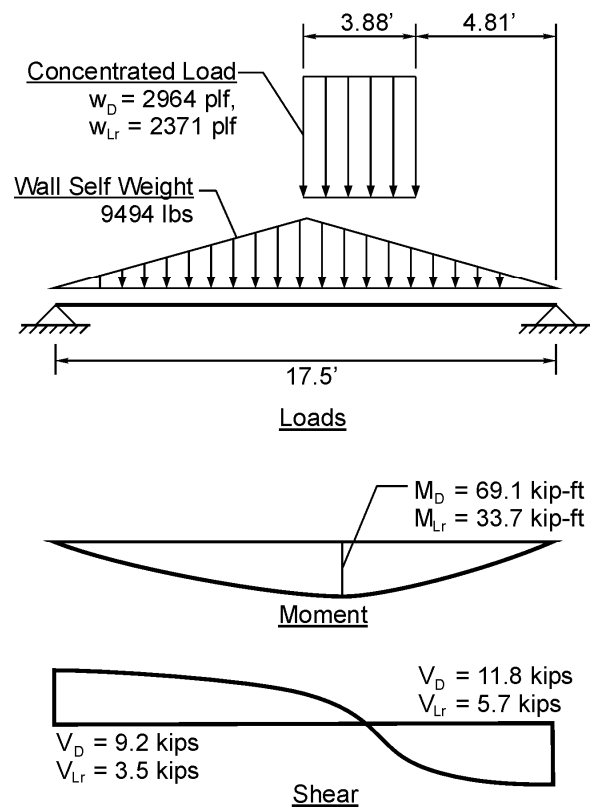**Figure 8: Loads on Design Example Lintel**

Allowable Stress Design

Assuming lateral support for the compression zone of the lintel is provided only at the supports:

$$\frac{L}{b} = \frac{17.5(12)}{11.63} = 18.1 < 32 \quad ...\underline{OK}$$

Assume that the depth of the lintel is equal to 0.5 times the span (8.75 feet). Then:

$$d \approx 8.75(12) - 6 = 99 \text{ in}$$

The modulus of elasticity of steel is given by:

$$E_s = 29,000,000 \text{ psi}$$

and the modulus of elasticity of the masonry is obtained from Section 1.8.2.2.1 of the code:

$$E_m = 900f'_m = 900(1500) = 1,350,000 \text{ psi}$$

Therefore the modular ratio, n, is given by:

$$n = \frac{29,000,000}{1,350,000} = 21.5$$

The allowable stresses for masonry and steel are as follows:

$$F_b = \frac{1}{3}f'_m = \frac{1500}{3} = 500 \text{ psi}$$

$$F_s = 24,000 \text{ psi}$$

We can try 2-#7 bars

$$\rho = \frac{A_s}{bd} = \frac{2(0.60)}{11.63(99)} = 0.001$$

$$n\rho = 21.5(0.001) = 0.022$$

$$k = \sqrt{(\rho n)^2 + 2\rho n} - \rho n$$

$$= \sqrt{(0.022)^2 + 2(0.022)} - (0.022)$$

$$= 0.189$$

$$j = 1 - \frac{k}{3} = 1 - \frac{0.189}{3} = 0.937$$

The stresses in the steel and masonry are thus equal to:

$$f_s = \frac{M}{A_s jd} = \frac{(69.1 + 33.7)12000}{(2 \times 0.60)(0.937)(99)}$$

$$= 11,083 \text{ psi} < 24,000 \text{ psi} ...\underline{OK}$$

$$f_b = \frac{2M}{jkbd^2}$$

$$= \frac{2(69.1 + 33.7)12000}{(0.937)(0.189)(11.63)(99)^2}$$

$$= 122 \text{ psi} < 500 \text{ psi} ...\underline{OK}$$

The stresses in the steel and masonry are less than the allowable stresses. Therefore, the beam design is adequate for the applied moment.

Next we must design the lintel to resist the applied shear loads. Since there is no axial load, the beam is subjected to net tension. The shear stress is therefore given by:

$$f_v = \frac{V}{bd} = \frac{(11.8 + 5.7)1000}{11.63(99)} = 15.2 \text{ psi}$$

The allowable shear stress on the masonry alone is given by:

$$F_v = \sqrt{f'_m} = \sqrt{1500} = 38.7 \text{ psi} > 15.2 \text{ psi}$$

Since the allowable shear stress obtained by considering only the masonry is greater than the demand, reinforcement does not need to be provided to resist the shear. The minimum vertical reinforcement needed to satisfy the wall detailing requirements may be used.

Strength Design

$$M_u = 1.2(69.1) + 1.6(33.7) = 136.8 \text{ kip-ft}$$

$$V_u = 1.2(11.8) + 1.6(5.7) = 23.3 \text{ kips}$$

Try 2-#7 bars (A_s = 1.2 in^2). Then:

$$\phi M_n = \phi f_y A_s \left(d - \frac{f_y A_s}{1.6f'_m b} \right)$$

$$= 0.9(60)(1.2)\left(99 - \frac{60(1.2)}{1.6(1.5)11.63} \right)\frac{1}{12}$$

$$= 521 \text{ kip-ft} > M_u ...\underline{OK}$$

The moment strength of the cross-section must be compared with the cracking moment. Cracking is determined by the modulus of rupture of the masonry, which is provided in Table 3.1.8.2.1 of the MSJC code.

For lintels and other beams, the direction of flexural tensile stresses is parallel to bed joints. Thus, from Table 3.1.8.2.1, the modulus of rupture is 200 psi.

Then:

$$M_{cr} = S_n f_r$$

$$= \frac{(11.63)(8.75 \times 12)^2}{6} 200 \frac{1}{12000}$$

= 356 kip-ft

$$1.3 M_{cr} = 1.3(356) = 463 \text{ kip-in} < M_n \quad ...\underline{OK}$$

From Section 3.3.3.5 of the MSJC code and commentary, the maximum reinforcement ratio is equal to:

$$\rho_{max} = 0.64 \left(\frac{f'_m}{f_y} \right) \left(\frac{\varepsilon_{mu}}{1.5 \frac{f_y}{E_s} + \varepsilon_{mu}} \right)$$

$$= 0.64 \left(\frac{1.5}{60} \right) \left(\frac{0.0025}{1.5(60)/29000 + 0.0025} \right)$$

$$= 0.0071$$

$$\rho = \frac{A_s}{bd} = \frac{1.2}{11.63(99)} = 0.00104 < \rho_{max} \quad ...\underline{OK}$$

Check the maximum shear strength:

$$V_{n,max} = 4 A_n \sqrt{f'_m} = 4(11.63)(105)\sqrt{1500}$$

$$= 189 \text{ kips} > V_u \quad ...\underline{OK}$$

The shear strength provided by the masonry is given by:

$$\phi V_m = 0.8(2.25) A_n \cdot \sqrt{f'_m}$$

$$= \frac{0.8(2.25)(11.63 \times 105)\sqrt{1500}}{1000}$$

$$= 85 \text{ kips} > V_u$$

The shear strength provided by the masonry is sufficient to resist the demand and no shear reinforcement is required.

Deflection of the lintels can be calculated by assuming that the lintel is simply supported and has a depth equal to half the height of masonry above the opening, as assumed when designing the lintel to resist loads. This approach is conservative since there is some continuity at the ends of the lintel and its actual depth is greater. Deflections may be calculated using the following effective moment of inertia:

$$I_{eff} = I_n \left(\frac{M_{cr}}{M_a} \right)^3 + \left[1 - \left(\frac{M_{cr}}{M_a} \right)^3 \right] \le I_n$$

where I_n is the moment of inertia of the lintel net cross-section and M_a is the maximum moment in the member due to applied loading for which deflection is being computed. For example:

$$M_a = (69.1 + 33.7) = 120.8 \text{ kip-ft}$$

$$I_n = \frac{bh^3}{12} = \frac{11.63(105)^3}{12} = 1.122 \times 10^6 \text{ in}^4$$

Since the applied moment is less than the cracking moment, the uncracked moment of inertia can be used. For simplicity, calculate the deflection at mid-span:

$$\Delta_D + \Delta_{Lr} = 0.0023 + 0.0011 = 0.0033 \text{ in}$$

this is significantly less than the code-imposed limit of $L/600$ (0.35 inches). Figure 9 shows the design of the reinforcement around the opening for gravity loads. The figure shows only the requirements for flexural and shear resistance to in plane gravity loads. The reinforcement required for out of plane and in plane lateral loads will be discussed in subsequent editions of Masonry Chronicles.
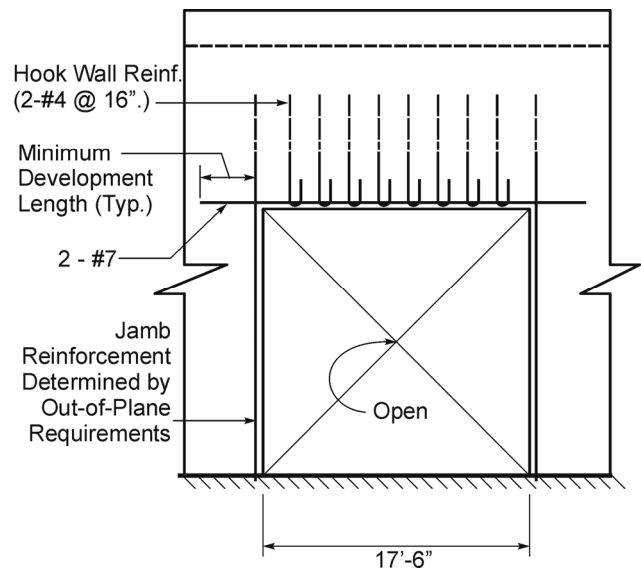

Hook Wall Reinf. (2-#4 @ 16".)

Minimum Development Length (Typ.)

2 - #7

Jamb Reinforcement Determined by Out-of-Plane Requirements

Open

17'-6"

Figure 9: Reinforcement on Loads on Design Example Lintel

Nomenclature

A_s = Area of reinforcing steel

b = width of cross-section

C = compression force

d = effective depth of reinforcement

f_b = calculated compressive stress in masonry due to flexure

F_b = allowable compressive stress available to resist flexure

f'_m = specified masonry compressive strength

f_r = modulus of rupture

f_s = calculated tensile or compressive stress in reinforcement

F_s = allowable tensile or compressive stress in reinforcement

f_v = calculated shear stress in masonry

F_v = allowable shear stress in masonry

f_y = yield stress of reinforcing steel

I_{eff} = effective moment of inertia

I_n = moment of inertia of beam net cross-section

L = span of lintel

L_c = bearing length of concentrated load

M_a = maximum moment in member due to applied loading for which deflection is being computed

M_{cr} = nominal cracking moment strength

M_n = nominal moment strength

M_u = factored moment

n = modular ratio, E_s/E_m

P = concentrated load on lintel

T = tension force

w = uniformly distributed load

W = total load

ϕ = strength reduction factor

ρ = reinforcement ratio

ρ_{max} = maximum reinforcement ratio

References

[1] Masonry Standards Joint Committee (MSJC), Building Code Requirements for Masonry Structures (ACI 530.1-05/ASCE 6-05/TMS 602-05), Masonry Standards Joint Committee, Boulder, Colorado, 2005.

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Dr. Chukwuma Ekwueme is an Associate Principal with Weidlinger Associates, Inc. He received his BEng from the University of Nigeria and MS, DEng, (Degree of Engineer) and PhD Degrees from the University of California, Los Angeles. He is a registered Civil and Structural Engineer in the State of California.

Dr. Ekwueme is a member of the Masonry Standards Joint Committee (MSJC) and on the Board of Directors of the Masonry Society (TMS). He is also active in several other organizations such as the American Society of Civil Engineers (ASCE), Structural Engineers Association of California (SEAOC) and the American Concrete Institute (ACI).

Dr. Ekwueme has written several publications and co-authored CMACN's "Seismic Design of Masonry Using the 1997 UBC," and the "2006 edition of Design of Reinforced Masonry Structures". He has also received awards for his work as a structural engineer.
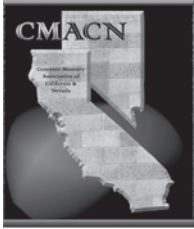
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