Engineering Notes For Design With
Concrete Block Masonry

MASONRY CHRONICLES

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Examples of Mid-Rise Residential Construction

Photography, John Magnun, Angelus Block, Inc.

Concrete Masonry and the Boom in Mid-Rise Residential Construction

Introduction

As the demand for housing rises and real estate prices soar nationwide, particularly in the Western United States, the economics of building construction is beginning to change. There is now a need for residential housing that makes more efficient use of land by constructing higher buildings. The mixed-use building, in which the first story at street level is used for commercial purposes, while the upper floors are used for apartments or condominiums, is becoming more common. The construction of mid-rise residential buildings with about four to eight stories of multi-family housing is on the rise.

In addition to the increase in size of residential buildings, another factor that affects the economics of residential construction is the current volatility in availability and price of building materials. As a result of various factors, including the construction boom in Asia, increased shipping costs and the decrease in value of the US dollar, prices of lumber, cement, gypsum products and steel have increased significantly in the last few years. The increasing demand for housing and the scarcity of building materials have combined to create an unpredictable environment that challenges the long-standing and tested rules of thumb that have been used by the construction industry to determine the cost of building construction and viability of different materials for various types of buildings. The new construction environment also demands that designers and builders develop efficient techniques for constructing mid-rise buildings that make the most of the available construction materials, while providing the durability, fire protection, structural reliability and overall building performance that society has come to expect and demands through building codes.

Concrete masonry offers several advantages for the construction of mid-rise residential buildings when compared to other building materials such as structural steel, light-framed construction and concrete. Concrete masonry is extremely durable, sustainable and structurally efficient. Furthermore, well-designed masonry walls can serve as multi-purpose elements that provide structural strength, sound and temperature insulation and also act as the exterior façade of a building. This, in addition to other factors, makes concrete masonry quite competitive from a construction cost standpoint.

The previous edition of “Masonry Chronicles” described the cost efficiency of concrete masonry by performing life cycle cost analyses on concrete masonry walls in various types of buildings. This edition will discuss some of the design issues related to the use of concrete masonry in mid-rise residential construction.

Fire Resistance

In addition to the typical fire protection requirements for various types of construction, multi-family construction requires a minimum fire protection between units to reduce the probability that a fire starting in one unit does not spread to adjacent units in the building. Since concrete masonry is a non-combustible material that possesses excellent fire-resistive characteristics, it is an excellent choice for fire separation between units. The typical plan layout of mid-rise residential buildings usually allows these concrete masonry walls to also form part of the gravity and lateral load resisting systems of the building.

As with other building materials, the fire resistance of concrete masonry is based on results from testing of assemblies using ASTM Standard E 119, *Standard Test Methods for Fire Tests of Building Construction and Materials* [1]. Testing using the standard involves a ***fire endurance test*** to determine that an assembly can resist elevated temperatures for the required period without failure, and a ***hose stream test*** in which a stream of water is applied to the assembly at a specified pressure and distance from the wall for a specified period. The fire resistive ratings for concrete masonry walls are provided as times over which the assembly satisfies the testing criteria. The 1997 Uniform Building Code [2] (Table 7-B) and the 2003 International Building Code [3] (Table 720.1(2)) provide fire resisting ratings for various types of construction. The ratings for concrete masonry walls and partitions are shown in Table 1.

As can be seen from Table 1, the fire resistance ratings of concrete masonry walls depend on the type of aggregate used in the units and the equivalent effective thickness of the wall. When blended aggregates are used for manufacturing the concrete masonry units, the fire resistive period can be obtained by interpolating between the requirements for the various aggregate types based on the percentage of each aggregate type used.

Table 1: Rated Fire Resistive Periods of Concrete Masonry Walls and Partitions

Type of Aggregate in Concrete Masonry Unit	Minimum Equivalent Effective Thickness Required for Fire Resistance Rating (inches)			
	4 Hr	3 Hr	2 Hr	1 Hr
Expanded slag or pumice	4.7	4.0	3.2	2.1
Expanded clay, shale or slate	5.1	4.4	3.6	2.6
Limestone, cinders or air cooled slag	5.9	5.0	4.0	2.7
Calcareous or siliceous gravel	6.2	5.3	4.2	2.8

For fire resistance purposes, the equivalent effective thickness is the thickness of a solid wall that would be obtained if the same amount of material were cast without any voids. The equivalent effective thickness of fully-grouted walls is equal to the specified thickness of the units (i.e. 3/8-inches less than the nominal thickness). The equivalent solid thickness of partially grouted walls is obtained by multiplying the percentage of solids in the block by the specified thickness. The grout in the cells is typically ignored when calculating the fire resistance ratings of partially grouted walls. Table 2 provides the fire resistance ratings of fully grouted and partially grouted walls that are constructed with units made with calcareous or siliceous gravel aggregates. The fire resistance ratings of walls with units containing other types of aggregate may be obtained by using the values in Table 1 with the equivalent effective thicknesses in Table 2. The effective thicknesses are based on typical dimensions of concrete masonry units. Individual block manufacturers may produce units with dimensions that result in slightly different values.

Table 2: Fire Resistance Ratings for Concrete Masonry Walls Built with Units Made with Calcareous or Siliceous Gravel Aggregates

Nominal Thickness (inches)	Solid Grouted Masonry		Partially Grouted Masonry	
	Equivalent Effective Thickness (inches)	Fire Resistance Rating	Equivalent Effective Thickness (inches)	Fire Resistance Rating
6	5.6	3 hours	3.1	1 hour
8	7.6	4 hours	4.0	1 hour
10	9.6	4 hours	5.0	2 hour
12	11.6	4 hours	5.7	3 hour

Sound Insulation

The challenge of sound insulation is more critical in multi-family residential buildings when compared to other types of structures. In addition to reducing the noise transmitted into the building interior from exterior sources such as traffic, sirens, etc, there must be sufficient insulation to control the transfer of noise between occupants of adjacent units. The need for sound insulation is even more important in mixed-used buildings.

Concrete masonry is a building material that is extremely effective in preventing sound transmission over a wide range of frequencies. Noise is first reduced by reflecting some of the sound that strikes the wall. Some of the remaining sound is absorbed by the concrete masonry and the remaining sound is transmitted through the wall to the opposite surface. Figure 1 illustrates the mechanism by which concrete masonry walls reduce noise.

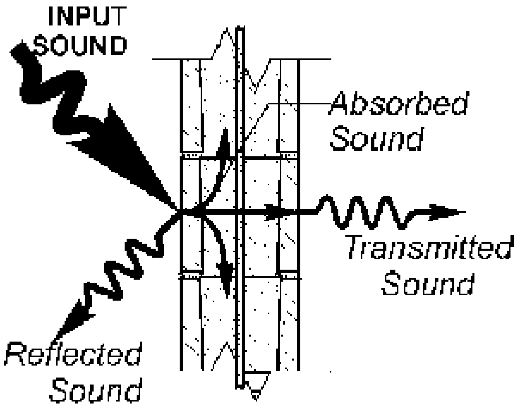

Figure 1: Noise Reduction with Concrete Masonry Walls (Adapted from NCMA TEK 13-2: "Noise Control with Concrete Masonry in Multifamily Housing" [4])

The sound absorption coefficient defines how effectively a surface absorbs noise. Thus, a sound coefficient of 0.25 indicates that 25% of the sound striking the surface is absorbed by the wall at the frequency being considered. The noise reduction coefficient (NRC) is the average of the sound absorption coefficient at frequencies of 250, 500, 1000 and 2000 hertz. Table 3 provides the approximate values of the NRC for some concrete masonry walls. The table shows that lighter material is more efficient in absorbing sound waves. Application of paint and other finishes to concrete masonry typically reduces the NRC value by increasing the amount of sound reflected by the wall.

Table 3: Approximate Noise Reduction Coefficients (NRC) for Unpainted Concrete Masonry Walls

	Surface Texture		
	Coarse	Medium	Fine
Lightweight Concrete Masonry	0.50	0.45	0.40
Normal Weight Concrete Masonry	0.28	0.27	0.26

The control of sound between units in residential construction by minimizing the transmission of sound from one side of a wall to the other utilizes both the reflective and absorptive characteristics of concrete masonry walls. The ability of concrete masonry to isolate sound in this manner is defined by the sound transmission class (STC). ASTM standard E90, *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions* [5], provides procedures for determining the STC of walls and partitions. The testing involves measuring the decrease in sound energy across a wall for a wide range of frequencies and comparing the results to a standard loss contour. In lieu of the experimental procedure outlined in ASTM E90, empirical equations have been developed to estimate the value of STC for various masonry walls. One such equation provides the following relationship between the sound transmission class and the weight of a wall:

$$STC = 23w^{0.2} \tag{1}$$

where w is the weight of the wall in psf. Table 4 provides the STC values using Equation 1 for some solid grouted walls constructed with normal weight concrete masonry units. STC values for walls constructed with different weight block or which is partially grouted may be estimated using the appropriate weight of the wall and Equation (1). Building codes generally require that the STC values between living units be no less than 40 to 50.

Table 4: Typical STC Ratings of Solid Grouted Masonry Walls Constructed with Normal Weight Concrete Masonry Units

Nominal Thickness (inches)	Weight (psf)	Estimated STC Rating
6	63	53
8	84	56
10	104	58
12	133	61

Energy Performance

Concrete masonry has a high thermal mass. This means that it remains cool after air conditioning has been turned off and remains warm after heating has been stopped. This ability to store heat makes buildings constructed with concrete masonry energy-efficient by reducing the heating and cooling demands when compared to other types of construction. It also improves occupant comfort by controlling temperature swings within a building.

On the other hand, since concrete masonry is a highly conductive material, there can be significant heat transfer through walls. In extreme climates, insulation may be used on the interior or exterior of masonry walls to reduce the thermal conductivity. In the moderate climates of the Western United States, however, the thermal characteristics of concrete masonry can usually provide excellent thermal performance without the need for additional insulation.

Structural Performance

Typically, the most challenging aspect of structural design of mid-rise buildings in the Western United Sates is the design to resist earthquake loads. Larger buildings weigh more, and since earthquake loads are directly proportional to mass, the lateral load resisting systems of mid-rise buildings will be subjected to larger loads during earthquakes. However, when concrete masonry is used in mid-rise buildings, the height of the structure can often be used to the designer's advantage. This is because relatively tall buildings usually allow for the use of tall narrow walls with large aspect ratios that will respond to earthquakes in a ductile manner. While many masonry buildings constructed with squat walls have performed well during past earthquakes, the response of taller walls is much more reliable and even better seismic performance is expected from mid-rise buildings, as shown in Figure 2.

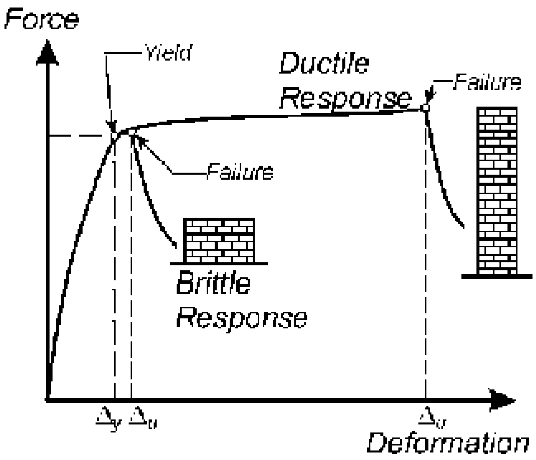

Figure 2: Ductile versus Brittle response of Concrete Masonry Walls

Building codes provide specific design requirements for masonry shear walls and earlier editions of Masonry Chronicles have discussed the seismic design and response of ductile concrete masonry walls. This section provides an approximate procedure that can be used to estimate the wall displacement at yield and ultimate limit states. The deformation-based procedure allows the engineer to control building behavior and ensure that the shear walls possess the ductility required to survive large earthquakes.

Consider the wall shown in Figure 3. Assuming a triangular distribution of lateral load, the yield displacement of a wall with primarily flexural deformation, is given by:

$$\Delta_y = \frac{11 M_y h_w^2}{40 (EI)_y} \tag{2}$$

where M_y and $(EI)_y$ are the yield moment and stiffness of the wall cross-section at the yield limit state. Since the yield curvature $\varphi_{y\ y}$ is equal to:

$$\varphi_y = \frac{M_y}{(EI)_y} \tag{3}$$

Equation (2) can be rewritten as follows:

$$\Delta_y = 0.275 \varphi_y h_w^2 \tag{4}$$

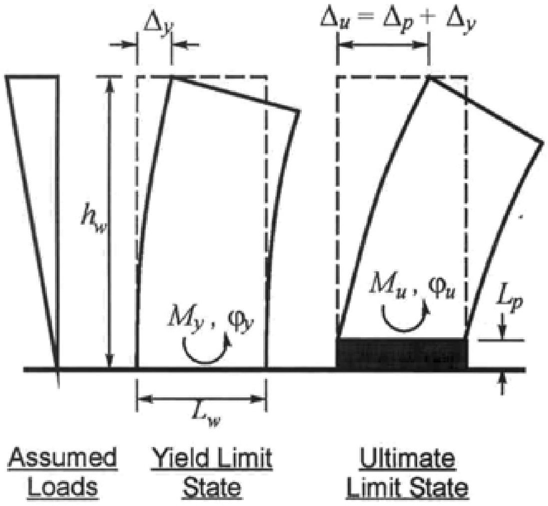

Figure 3: Response of Wall to Lateral Loads

Research has shown that the yield curvature of flexurally-dominated wall can be approximated by the following equation [6]:

$$\varphi_y = \frac{0.0035}{L_w} \tag{5}$$

Substituting Equation (5) into Equation (4) we obtain:

$$\Delta_y = 9.625 \times 10^{-4} \frac{h_w^2}{L_w} \tag{6}$$

At the ultimate limit state, the displacement at the top of the wall is given by:

$$\begin{aligned}\Delta_u &= \Delta_p + \Delta_y \\ &= \left(\varphi_u - \varphi_y\right) L_p \left(h_w - L_p / 2\right) + \Delta_y\end{aligned} \tag{7}$$

where φ_u is the ultimate curvature, L_p is the plastic displacement and Δ_p is the plastic hinge length. rearranging Equation (7), we obtain:

$$\varphi_u = \frac{\Delta_u - \Delta_y}{L_p \left(h_w - L_p / 2\right)} + \varphi_y \tag{8}$$

Since Δ_y and φ_y are known from Equations (5) and (6), the required curvature at the ultimate limit state can be computed from Equation (8) if the ultimate displacement is known.

Figure 4 presents a technique for obtaining the force and displacement demands on a building. First, the engineer plots the damage level ground motion at which yielding is to occur and the design level ground motion in the Acceleration-Displacement Response Spectra (ADRS) format. The yield displacement, which is given by Equation (5), can be converted to a spectral displacement using the standard relationship of structural dynamics:

$$S_{dy} = \frac{\Delta_y}{\phi_1 PF_1} \tag{9}$$

where ϕ_1 and PF_1 are the roof level amplitude and participation factor for building the first mode, respectively. S_{dy} can be calculated using typical values of ϕ_1 and PF_1 and used to obtain the spectral acceleration at first yield, S_{ay}. If perfectly plastic behavior is assumed, the coordinate for S_{ay} can be extended horizontally to intersect the spectrum for the design level earthquake to obtain the ultimate spectral demand, S_{du}. Typical values of ϕ_1 and PF_1 can be used though the values selected are not critical since, for most shear wall buildings, S_{dy} is in the constant acceleration region of typical design response spectra. The ultimate spectral displacement can be converted using an equation similar to Equation (9) and the yield base shear V_y is given by:

$$V_y = S_{dy} \alpha_1 W \tag{10}$$

where W is the building weight and α_1 is the modal mass coefficient for the first mode.

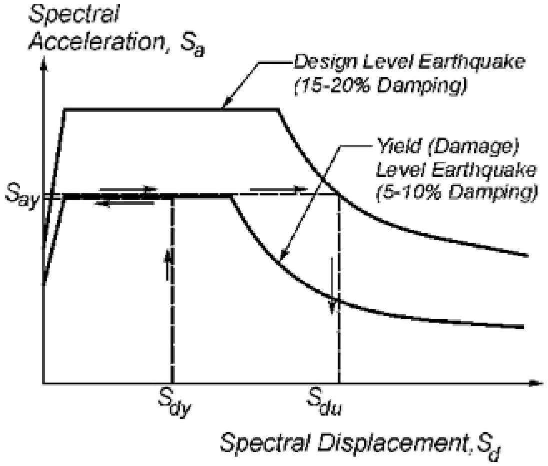

Figure 4: Calculation of Building Demands using Spectra in the ADRS Format

Other Factors

In addition to the above-mentioned advantages, concrete masonry offers several other benefits for mid-rise residential construction. Because it consists of modular construction using relatively small units, concrete masonry can be easily constructed on sites with severe space limitations that restrict the use of bulky equipment or construction using large construction modules. Concrete masonry is also extremely durable and water resistant and deterioration due to termites or other pests or decay is essentially non-existent.

Conclusion

The changing economics of the construction industry emphasizes the benefits that concrete masonry brings to mid-rise residential construction. In addition to being an extremely durable and cost-effective building material, the unique characteristics of concrete masonry allow it to provide structural resistance, fire protection, noise control and superior energy performance, while providing the distinctive aesthetic qualities that make concrete masonry one of the most beautiful building materials available.

References

[1] ASTM, Standard E 119-00a, *Standard Test Methods for Fire Tests of Building Construction and Materials*, ASTM International, Conshohocken, PA, 2000.

[2] International Conference of Building Officials (ICBO), *1997 Uniform Building Code*, International Conference of Building Officials, Whittier, California, 1997.

[3] International Code Council (ICC), *2003 International Building Code*, International Code Council, Inc., Falls Church, Virginia, 2003.

[4] NCMA TEK 13-2: "Noise Control with Concrete Masonry in Multifamily Housing", National Concrete Masonry Association, Hendon, Virginia, 1997.

[5] ASTM standard E90, *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions*, ASTM International, Conshohocken, PA, 2000.

[6] Ekwueme, C.G. and Kubischta, M.A., "Deformation-Based Design of Shear Wall Buildings", Proceedings of the 7th US National Conference on Earthquake Engineering, Boston, Massachusetts, July, 2002.

About the Author

Dr. Chukwuma Ekwueme received his BSCE from the University of Nigeria, Nsukka, Nigeria 1987, in Civil Engineering, his MSSE, at the University of California, Los Angeles, CA, 1990, in Earthquake and Structural Engineering, a DEng, (Degree of Engineer) from the University of California, Los Angeles, CA, 1992, and his PhD, from the University of California, Los Angeles, CA, 1994, in Structural Engineering. He is a registered Structural Engineer in California and has worked for Hart-Weidlinger in many capacities since 1992. There he has been working as a Senior Associate since 2004.

Dr. Ekwueme is a member and leader of many organizations and committees such as ASCE, SEI, EERI, SEAOC, ACI and TMS. He has written several publications and co-authored CMACN's *Seismic Design of Masonry Using the 1997 UBC* and our soon to be released 2005 edition of *Design of Reinforced Masonry Structures*. He has also received awards for his outstanding work as a structural engineer.

Precast concrete and masonry are often selected to satisfy minimum code requirements and provide superior construction, which offers more durable, comfortable, and safer housing.

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