Strength Design of Masonry

by

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THE MASONRY SOCIETY

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Dr. Richard Bennett is a Professor at the University of Tennessee and Mr. John Hochwalt is Director of Engineering at KPFF Engineers. Both actively serve on TMS 402/602 which contains requirements for strength design of masonry.

Dr. Bennett served as the Chair of the 2016 TMS 402/602 Committee, leading the Committee for that cycle, but also as a Chair of subcommittees and tasks groups for several cycles. He currently serves as the 2nd Vice Chair of the 2022 Committee. He has taught extensively and presented on Strength Design and many other topics for The Masonry Society and other groups, sharing insights and findings from his research and trial designs. For his tremendous efforts in leading the Committee, he received TMS's President's Award and was made a Fellow of the Society.

Mr. Hochwalt has also served actively on TMS 402/602 and currently Chairs its Seismic and Limit Design Subcommittee. He was instrumental in the drafting of the Limit Design provisions in Appendix C of TMS 402 and has taught on this topic and many others, offering practical observations from his work as a Structural Engineer.

Both authors serve as authors of TMS's Masonry Designers' Guide.

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Chapter 1
Introduction

This Guide was developed to introduce strength design principles of masonry to designers unfamiliar with the method, while helping those more experienced use strength design easily and effectively. Strength design uses the strength of structural members to determine whether the capacity is adequate for applied loads. This is in contrast to allowable stress design, or working stress design, where reduced "allowable stresses" are used in design. Strength design is often considered a more rational design method, as calculated results track closely to actual test data for the failure modes under consideration. It is the common method of design for reinforced concrete, and is used for the design of masonry, steel and wood. Because of trends within the design community, The Masonry Society developed this Guide to help designers quickly, easily, and efficiently design masonry using strength procedures. Because designers have varied backgrounds and knowledge of strength design, this Guide is divided into sections based on knowledge levels as follows:

For those new to masonry, Chapter 2 provides an introduction to masonry materials, assemblages, and properties. Those familiar with masonry can likely skip this introductory chapter.

For those new to strength design methodologies, Chapter 4 provides an introduction, discussing basic assumptions and procedures.

Later chapters deal with more complex issues and the final appendices include sectional properties and additional information.

A reinforced concrete masonry shaft under construction. Note that the reduced webs on the units allow the placement of horizontal bars and bar laps at the corners. Note also the vertical reinforcement in the cells, and in this case, the addition of ladder type joint reinforcement. Grout will be placed into at least the reinforced cells to bond the reinforcing steel and the masonry into a structural system.

Figure 1.1 Typical Reinforced Masonry Construction

1.1 Scope

This Guide focuses on the most commonly used structural materials and methods: walls constructed of either single-wythe hollow concrete masonry units (CMU) or hollow structural clay masonry units (SCU). While multi-wythe clay and concrete masonry walls (two or more thicknesses of masonry bounded together into a structural system) can be constructed, that system is not the focus of this Guide, though nearly all the design principles would apply. This Guide also does not address masonry constructed of materials such as stone, autoclaved aerated concrete masonry (AAC masonry), adobe masonry, or glass masonry, nor does it address prestressed masonry or dry-stack systems. It also does not address veneer. Information on these topics can be found in the resources listed in Section 1.4.

Chapter 2
Introduction to Structural Masonry

Masonry provides not only beauty, but is a strong, resilient material used for both its aesthetic characteristics and the structure of the building. Fire resistance, ease of construction, competitive costs, and widespread availability makes masonry popular. The addition of reinforcement makes masonry an excellent system to resist tornados, hurricanes and earthquakes. As with any material, masonry also has its limitations. It must be designed and detailed carefully, constructed properly, and maintained to perform as intended. While masonry is a familiar material, there are unique aspects that designers need to be aware of to use it more effectively. This Chapter is intended to introduce those new to masonry to this versatile material, and to some issues that need to be kept in mind when using it as a structural material.

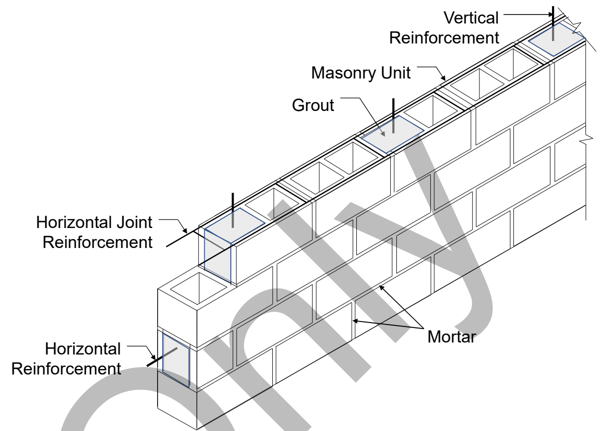


Figure 2.1 Single Wythe Masonry Wall

For the purposes of this guide, masonry is composed of individual masonry units that typically are hand placed (laid) into setting mortar. Sometimes reinforcement in the form of reinforcing bars or wires are placed in the masonry and bonded to it with grout (or mortar if the wire is in the mortar joints). Figures 2.1 and 2.2 show isometrics of a common single "wythe" (one thickness of masonry through the wall) masonry wall and identify common terms. Although multi-wythe masonry walls can be constructed, they are not covered in this guide.

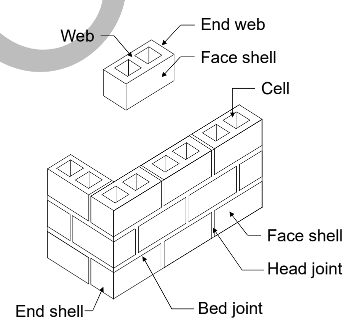
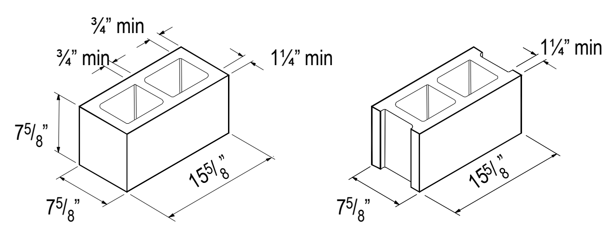


Figure 2.2 Common Terms

2.1 Masonry Units

2.1.1 Concrete Masonry Units

Hollow concrete masonry units (Figure 2.1-1) complying with ASTM C90, Standard Specification for Loadbearing Concrete Masonry Units, are ideal for reinforced masonry. They provide an economical, and often decorative form in which reinforcement can be placed and grout cast to form a strong system to withstand loads. Long ago, a modular 8 in. (203.2 mm, or if SI units are used, 200 mm) system was standardized, where masonry course heights of 8 in. (203.2 mm) were set to allow rapid and standardized construction. To reach this modular 8 in. (203.2 mm) height with a standard 3/8 in. (9.5 mm, or with SI units, 10 mm) mortar joint, concrete masonry units were manufactured to a height of 7 5/8 in. (194 mm). Lengths were also modularized and standardized to allow rapid construction. The nominal 16 in. (406 mm) unit, with a specified length of 15 5/8 in. (397 mm), is now the most used length. In some cases, 8 in. (203.2 mm) long or 24 in. (609 mm) long units can be used to meet the 8 in. module, again with a standard 3/8 in. (9.5 mm) wide mortar joint. An elevation view of a typical masonry wall is shown in Figure 1.8-3.



The drawings above show typical specified dimensions* for nominal 8 x 8 x 16 inch CMU, the left with plain ends, and the right with "ears".

The National Concrete Masonry Association has excellent information on CMU on their website at www.ncma.org. Specific manufacturers should also be contacted for information on local practices and availability of specific units and shapes.

Figure 2.1-1 Concrete Masonry Units

*See next page for a discussion on dimensions

Chapter 3
Masonry Structural Systems and Components

3.1 Masonry in Buildings

3.1.1 Structural Functions of Masonry

Most masonry in buildings occurs in the context of walls. Masonry walls in buildings can be broadly described as falling into one of the following categories based on the structural functions it performs:

- Participating Walls are walls which are part of the primary building structure, including:
  - Bearing Walls: Walls that support floors or roofs typically directly to the foundation. These walls almost always also function as shear walls.
  - Shear Walls: Walls which are part of the primary lateral force resisting system for the building, delivering wind, seismic and other lateral loads from the floor and roof diaphragms to the foundations.
  - Basement Walls: The primary function of these walls is the retention of soil, but they also typically act as bearing and shear walls.
- Non-Participating Walls are walls that are independent from the primary building structure. These walls are detailed so that that they typically support neither gravity loads nor lateral loads from the floors or roof. As such, these walls typically only resist loads due to their own mass and loads applied to the wall surface. These walls include:
  - Partition Walls: These walls occur within a building and their primary function is to divide space.
  - Backing Walls: These walls occur around the perimeter of a building and their primary function is to provide support (backing) for the building cladding as part of the building envelope.

The only masonry building components that occur regularly outside the context of walls are columns.

3.1.2 Architectural Functions of Masonry

In addition to fulfilling structural functions, masonry walls also fulfill architectural functions. This is one of the great virtues of masonry walls; only one element is needed to fulfill both architectural and structural functions.

The architectural functions of masonry walls include such roles as enclosing the building from the outside environment, separating spaces from one another for fire, acoustic, usage, or other reasons, and providing durable and aesthetically pleasing conditions inside and outside the building

In most masonry structures, these architectural functions are often more influential than the structural functions in establishing the location, length, and extent of the walls.

3.2 Masonry in the Landscape

Masonry can also be used in the landscape, most commonly as walls, in which case the walls are always classified as non-participating as they are not part of the lateral force resisting system for a building. Two common types are:

- Retaining Walls: Walls that retain soil where a change in grade occurs.
- Freestanding, or Screen Walls: These walls can perform a variety of functions – decorative, visual screening, noise isolation, or as security barriers. Figure 3.2-1 is an example of a sound wall.

The design of these walls may be driven by other design professionals such as civil engineers, architects, or landscape architects, or may be left to the discretion of the structural engineer. Out-of-plane loads from earth pressure, wind, or seismic loads will govern the design of these walls. There may be additional loads imparted to the wall by items attached to the top of wall such as fences or guardrails.

Chapter 4
General Design

4.1 Strength Design

4.1.1 History

The first strength design provisions for masonry were in the 1985 edition of the Uniform Building Code, but was limited to a strength design procedure for slender bearing walls. The first full strength design provisions for masonry were in the 1997 Uniform Building Code. Strength design first appeared in the TMS 402 Code in the 2002 edition.

Although the strength design provisions are relatively new in masonry, strength design does offer potential benefits over allowable stress design. There are three particular cases where strength design offers advantages.

1. When the dead load is a large contributor to the gravity load, or in other words, when the dead load to live load ratio is greater than 1. This is due to the load factor for dead load in strength design being 1.2.
2. When the design is controlled by seismic loading. This is due to allowable stress requiring the structure be designed for 0.7 of the nominal earthquake load, while allowable stress resistance is about 0.6 times the design strength.
3. When the masonry allowable stress controls the allowable stress design. In this case, the reinforcement is not being used efficiently in allowable stress design and strength design permits for the efficient use of both the masonry and the steel reinforcement.

4.1.2 Design Philosophy

The philosophy of strength design is given in TMS 402 Section 9.1.3: "Masonry members shall be proportioned so that the design strength equals or exceeds required strength. Design strength is the nominal strength multiplied by the strength-reduction factor." Each of the terms is discussed in the following.

Nominal strength

Nominal strength is defined in TMS 402 as "The strength of a member or cross-section calculated in accordance with the requirements and assumptions of the strength design methods of these provisions before application of strength-reduction factors." ASCE 7 defines the nominal strength as "The capacity of a structure or member to resist the effects of loads, as determined by computations using specified material strengths and dimensions and formulas derived from accepted principles of structural mechanics or by field tests or laboratory tests of scaled models, allowing for modeling effects and differences between laboratory and field conditions."

The nominal strength can be explained with a simple illustration. The nominal tensile strength of a reinforcing bar is $A_s f_y$, where A_s is the area of the reinforcing bar and f_y is the specified yield strength of the reinforcing bar. For example, the area of a No. 5 reinforcing bar is 0.31 in.^{2}. If the area of an actual No. 5 bar were measured, it would be slightly different than 0.31 in.^{2}, although on the average the area would be 0.31 in.^{2}. Thus, A_s can be thought of as a nominal area, or the area that is used in design calculations. For Grade 60 reinforcement, the specified yield strength is 60,000 psi. This is simply a value used in design. It corresponds to approximately a 5-percentile value, and the average yield strength of Grade 60 reinforcing bars is approximately 10%-15% greater than 60,000 psi. Thus, f_y can be thought of as a nominal yield strength. The nominal strength of a No. 5 Grade 60 reinforcing bar is 0.31in.^{2}(60,000psi) = 18,600 lb. This is simply a value that is used in design calculations.

Design strength

The design strength, as defined in TMS 402, is the nominal strength of a member multiplied by the appropriate strength-reduction factor. The design strength is compared to the factored loads.

Strength-reduction factor

The strength-reduction factor is also called the resistance factor. Strength-reduction factors in TMS 402 (Section 9.1.4) are given in Table 4.1-1.

Chapter 5
Strength Design of Unreinforced Masonry

5.1 General

The design of unreinforced masonry using Strength Design is very similar to the design of unreinforced masonry using Allowable Stress Design, as the structure is assumed to be linear elastic, even at ultimate strength. The nominal strengths for unreinforced masonry are given in Table 5.1-1, with the modulus of rupture values given in Table 2.5-3. The strength-reduction factors for unreinforced masonry are:

Combinations of flexure and axial load	$\phi = 0.6$
Shear	$\phi = 0.8$

For slender walls with $h/r > 45$, TMS 402 Section 9.2.4.3 requires the first-order moment, $M_{u,0}$, to be increased by a moment-magnification factor, ψ, to obtain the factored moment, $M_u = \psi M_{u,0}$.

$$\psi = \frac{1}{1 - \dfrac{P_u}{A_n f'_m \left(\dfrac{70}{h/r}\right)^2}} \qquad \text{TMS 402 Eq. 9-14}$$

The moment magnification factor, ψ, is permitted to be taken as 1 if $45 < h/r \leq 60$ and the nominal strength is reduced by 10 percent.

Section 2.6.3 provides information, and an example, on section properties, such as net area, net section modulus, net moment of inertia, and radius of gyration. Section properties for clay masonry are given in Appendix A.1 and Appendix A.2 for concrete masonry. For concrete masonry, additional section properties can be obtained from NCMA TEK 14-1B. Almost all unreinforced masonry is ungrouted, with occasionally unreinforced masonry being fully grouted for fire resistance or increased bearing strength. The section properties for ungrouted and fully grouted masonry are given in Table 5.1-2. The properties are on a per foot length of wall basis. The net area, section modulus, and moment of inertia are based on the minimum net mortar bedded area, and face shell bedding. The radius of gyration is based on average properties of the concrete masonry unit.

GSD Tip: Almost all unreinforced masonry, whether loaded in-plane or out-of-plane, is controlled by flexural tension. Thus, the first equation to check is:

$$-\frac{P_u}{A_n} + \frac{M_u}{S_n} \leq \phi f_r$$

where:
- P_u = factored axial load
- A_n = net area (Table 5.1-2)
- M_u = factored moment
- S_n = net section modulus (Table 5.1-2)
- ϕ = strength-reduction factor (0.6)
- f_r = modulus of rupture (Table 2.5-3; TMS 402 Table 9.1.9.2)

Since the axial load is reducing the flexural tension, the first load combination to check is either $0.9D + W$, or $0.9D - E_v + E_h$.

Chapter 6
Strength Design of Reinforced Masonry

6.1 General

6.1.1 Design Assumptions

TMS 402 Section 9.3 addresses the design of reinforced masonry by the strength design approach. TMS 402 Section 9.3.2 lists the design assumptions, which are:

(a) Strain compatibility exists between the reinforcement, grout, and masonry.

(b) The nominal strength of reinforced masonry cross-sections for combined flexure and axial load is based on applicable conditions of equilibrium.

(c) The maximum usable strain, ε_{mu}, at the extreme masonry compression fiber is 0.0035 for clay masonry and 0.0025 for concrete masonry.

(d) Strains in reinforcement and masonry are directly proportional to the distance from the neutral axis.

(e) Compression and tension stress in reinforcement is E_s multiplied by the steel strain, but not greater than f_y. Except for determination of maximum area of flexural reinforcement, the compressive stress of steel reinforcement does not contribute to the axial and flexural resistance unless lateral restraining reinforcement is provided in compliance with the requirements of TMS 402 Section 5.3.1.4.

(f) Masonry in tension does not contribute to axial and flexural strengths. Axial and flexural tension stresses are resisted entirely by steel reinforcement.

(g) The relationship between masonry compressive stress and masonry strain is defined by an equivalent rectangular stress block with a stress of 0.80 f_m' acting over a distance a = 0.80c.

6.1.2 Nominal and Design Strength

Table 6.1-1 summarizes the nominal strengths for reinforced masonry. The design strength is the strength-reduction factor multiplied by the nominal strength. The strength-reduction factors for reinforced masonry are:

Combinations of flexure and axial load: $\phi = 0.9$

Shear and shear-friction: $\phi = 0.8$

Strength design has limitations on material properties in TMS 402 Section 9.1.9.1 which are summarized in Table 6.1-2. Note that the requirements refer to the specified strengths. For example, the specified strength of the grout, f_g', may not exceed 5000 psi (34.47 MPa) for concrete masonry. However, it is acceptable if the grout tests stronger than this.

Chapter 7
Reinforcement & Anchor Bolts

7.1 Introduction

Reinforcement requirements and details are in TMS 402 Section 6.1. This includes splice and development length requirements. Anchor bolt requirements are in TMS 402 Sections 6.3 and 9.6.

Refer to Section 2.4 for additional information on material properties and sizes of reinforcement bars and wires. For those not familiar with the placement of reinforcing steel in masonry, they are referred to industry resources including online technical notes, *Reinforcing Steel in Masonry* and the *Reinforced Concrete Masonry Inspector's Handbook* which have excellent drawings and photographs to show the requirements of Tables 7.2-1 and 7.2-2.

7.2 Reinforcement Requirements

A summary of TMS 402 requirements for bar reinforcement is given in Table 7.2-1 (including specific requirements for strength design). A summary of the requirements for wire reinforcement is given in Table 7.2-2.

7.2.1 Development and Splice Length

The development length provisions are given in Table 7.2-3 and the splice length requirements are given in Table 7.2-4.

Lap Splice Lengths:
Using the principles of Example 7.2-1, Table 7.2-5 is developed, which gives the splice length for centered Grade 60 bars in 6 in. (152 mm), 8 in. (203 mm), and 12 in. (305 mm) thick walls, and for walls of all thicknesses with bars having a 2 in. (50.8 mm) cover. The table is based on units with a specified thickness of 3/8 in. (9.5 mm) less than the nominal thickness. Some clay units have a specified thickness of ½ in. (12.7 mm) less than the nominal thickness. This would result in slightly longer splice lengths, typically 1 to 2 in. (25 to 50 mm). With larger bar sizes, mechanical splices may be more economical than lap splices.

Note that TMS 402 Section 6.1.2.5 limits the bar size to 1/8 of the least nominal dimension, or a No. 6 (152 mm) bar for a 6 in. wall and a No. 8 bar for an 8 in. (203 mm) wall.

In addition to the splice length requirements given in Table 7.2-4, TMS 402 Section 6.1.6.1.1.2 permits the required splice length to be reduced when adequate transverse reinforcement is provided across the splice, because such transverse reinforcement helps control splitting of the masonry along the spliced bars. The transverse reinforcement must meet the following requirements:

- Be a No. 3 bar or larger
- At least one transverse bar 8 in. (203 mm) or less from each end of the lap
- Clear space between transverse bar and lapped bar not greater than 1.5 in. (38.1 mm)

The reduced lap splice length is determined by multiplying the lap splice length from TMS 402 Equation 6-1 by a confinement factor, ξ. The confinement factor is determined from TMS 402 Equation 6-4.

$$\xi = 1.0 - \frac{2.3A_{sc}}{d_b^{2.5}} \qquad \text{(TMS 402 Equation 6-4)}$$

where: $\frac{2.3A_{sc}}{d_b^{2.5}} \le 1.0$

A_{sc} is the area of the transverse bars at each end of the lap splice and shall not be taken greater than 0.35 in.^{2} (226 mm^2). The reduction in lap splice lengths resulting from this provision can be substantial. The lap splice length cannot be less than $36d_b$. The minimum splice length of $36d_b$ can sometimes be greater than the splice length determined using TMS 402 Equation 6-1. In that case, the splice length of Equation 6-1 can be used.

Wire Splices:
Typically, two sizes of wire are used in joint reinforcement, W1.7 or W2.8. Based on a required splice length of $48d_b$, the required splice length is 7 in. (178 mm) for W1.7 wire and 9 in. (229 mm) for W2.8 wire. These splice lengths are only required if the joint reinforcement is used for structural purposes. If the joint reinforcement is used just for crack control, only a 6 in. (152 mm) splice length is required (TMS 602 Article 3.4. B.10 (b)).

Chapter 8
Construction

While there are no special construction techniques or requirements for masonry designed specifically by the Strength Design Method, there are tips that will help facilitate successful masonry construction independent of the design method.

8.1 Construction Drawings

Successful construction starts with a complete, clear, and buildable set of construction drawings. Some items specific to masonry that should be considered in developing the construction drawings include but are not limited to:

- Design and detail as much of the project as possible to be modular to reduce excess cutting which can increase costs, make construction and placement of reinforcement more difficult, and potentially affect the aesthetics of the structure.
- Use common masonry sizes, which for concrete masonry, is 8 x 8 x 16 in. units. Where units of greater thickness are needed, have discussions with local manufacturers and contractors to verify available sizes. Clay units are not standardized to the same degree as concrete units; consult with local manufacturers and distributors to determine available sizes.
- Use standard masonry strengths, such as f'_m of 2,000 psi for concrete masonry laid in type S mortar. Where higher strengths are needed, have discussions with local manufacturers to determine typical strengths that can be economically produced. For clay masonry, f'_m of 3,000 psi is a safe assumption for initial design; it is advisable to confirm the actual unit strength and corresponding f'_m prior to final design and use that f'_m to optimize the design.
- Consider the size, quantity, and bends or hooks of reinforcing bars when designing and detailing to avoid congestion and allow adequate space for grouting. Preferably, the resulting clearances allow the use of coarse grout.
- Consider the affect the available grout space will have on the grouting procedures. While the contractor typically decides whether to place grout using high-lift or low-lift techniques, the designer should recognize that some decisions they make can force the contractor to use low lift grouting which may be less economical. As noted in TMS 602, Article 3.5, maximum pour heights, as well as the grout type (fine or coarse) are influenced by clear space/clear width available in the cores/space, which is reduced by the amount of horizontal reinforcement in those spaces. Information on grout lifts is contained in Article 3.5D and excellent discussions on high-lift and low-lift techniques are included in Chapter 6 of the *Reinforced Concrete Masonry Construction Inspector's Handbook* and in Section 4.2.5 of the *Masonry Designer's Guide*.
- Use smaller bar sizes (No. 4 – No. 7) at reasonable spacings with larger bars only being used when absolutely necessary due to problems of weight during placement and congestion at laps and bends. Some designers try to select two common bar sizes on a job, that are separated by a bar size so bars are not accidentally confused in the field: for example, using No. 4 bars with No. 6 bars where larger bars are needed, or using No. 5 bars with No. 7 bars.
- Coordinate with other disciplines to ensure reasonable placement of movement joints, pipes, conduits, and wall openings that do not compromise the integrity of the masonry. Too often, holes are cut after a masonry wall is constructed to place large ducts. Sometimes, their placement compromises the integrity of the masonry system.
- Communicate clearly through the contract documents the design intent and needs, with accurate and sufficiently detailed plans that include quality assurance (testing and inspection) requirements, appropriate lap, lintel and other schedules and tables, requirements for sample panels/mock-ups, and other critical aspects of the project.

Several of the above topics along with other topics related to detailing masonry for constructability, are addressed in TMS Responds, March 2016. In addition, Technical Notes from masonry industry organizations, the Masonry Designer's Guide, and numerous other publications have excellent information on masonry construction and specification.

Appendix: Material and Section Properties; SI Conversions

This Appendix is provided for easy reference by the user. Some Tables are used in Example problems. These are based on ASCE 7, NCMA TEK 14-1B and BIA Technical Notes The complete technical notes can be downloaded from their websites at www.gobrick.com and www.ncma.org. It should be noted that some minor differences occur between this Appendix and the BIA and NCMA Technical Notes because of differences in assumptions made or data provided. Designers should carefully review these materials to make sure they are using the information correctly for the conditions of their project.

A.1 Clay Masonry Section Properties

Some clay masonry units are similar to concrete masonry units, and Tables A.2.1 through A.2.5 can be used to determine section properties. Other clay units use a 6 inch module. Tables A.1.2 through A.1.5 are based on a 6 inch module and a 6 inch grouted cell length. The specified thickness is taken as ½ inch less than the nominal thickness and the face shell thickness is taken as the minimum face shell thickness in Table A.1-1. Net section properties are based on the net area with face shell bedding. The average radius of gyration is based on average section properties, which includes the webs of the units.

Table A.1-1 Minimum Thickness of Face-Shell and Webs – ASTM C 652 Units

Nominal Thickness of Unit, in. (ASTM C 652 calls this width)	Minimum Face Shell Thickness, in.	Minimum End Web Thickness, in.
4	3/4	3/4
6	1	1
8	1-1/4	1
10	1-1/4	1
12	1-1/4	1

Table A.1-2 Net Area – ASTM C652 Structural Clay Units (in.^{2}/ft)

Grout Spacing	Nominal Thickness (in.)				
	4	6	8	10	12
No grout	18.0	24.0	30.0	30.0	30.0
48 in o.c.	21.0	29.3	37.5	40.5	43.5
40 in. o.c.	21.6	30.3	39.0	42.6	46.2
36 in o.c.	22.0	31.0	40.0	44.0	48.0
30 in. o.c.	22.8	32.4	42.0	46.8	51.6
24 in o.c.	24.0	34.5	45.0	51.0	57.0
18 in o.c.	26.0	38.0	50.0	58.0	66.0
12 in o.c.	30.0	45.0	60.0	72.0	84.0
Full Grout	42.0	66.0	90.0	114.0	138.0