



TECHNICAL NOTES on Brick Construction

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Technical Notes 39A - Testing for Engineered Brick Masonry - Determination of Allowable Design Stresses [July/Aug. 1981] (Reissued December 1987)

INTRODUCTION

Prior to the development of a rational design procedure for brick masonry, it was sufficient to know that brick masonry units and mortar used were in compliance with the standards outlined in *Technical Notes 39 Revised*, "Testing for Engineered Brick Masonry - Brick, Mortar and Grout." These quality control tests provided assurance that the same quality of materials were being used throughout the building project. This did not give any assurance or knowledge as to the actual performance of the masonry in the wall.

With the development of a rational design method, it became important that the architect and/or engineer have knowledge of the expected performance of the brick and mortar, not as individual parts of the wall, but as the total wall system. With this need in mind, this *Technical Notes* outlines several ASTM Standard Methods of Tests for Masonry Assemblages which will give the architect and/or engineer the ability to predict in-the-wall performance of masonry and determine allowable design stresses.

It is essential in all of the tests described in this *Technical Notes* that the units, mortar and construction of the assemblage be nearly identical with the materials and methods to be used in the actual construction process. Only in this way can the actual performance of the masonry be accurately predicted.

This *Technical Notes* will cover ASTM standards for the determination of all necessary design stresses for brick masonry as specified in the design standard, *Building Code Requirements for Engineered Brick Masonry*, BIA, August 1969, and the model building codes in present-day usage. It will also stipulate the revisions necessary to determine the same properties for hollow brick units. Subsequent issues of *Technical Notes* will discuss miscellaneous tests for masonry not to be used for design stress determinations. These tests will be used primarily for quality control, material comparability and in-the-wall performance predictions for properties other than strength.

STANDARD METHODS OF TESTS

The ASTM test standards with which this *Technical Notes* is concerned are contained in the *Annual Book of ASTM Standards*. The methods of tests described in the ASTM standards and listed below should be strictly adhered to; otherwise, the test performed is no longer a standard test and erroneous or misleading results may be obtained. The applicable ASTM standards for masonry are as follows:

Compressive Strength and Modulus of Elasticity:

Test Methods for Compressive Strength of Masonry Prisms, ASTM Designation E 447.

Diagonal Tension (Shear) and Modulus of Rigidity:

Test Method for Diagonal Tension (Shears in Masonry Assemblages, ASTM Designation E 519.

Method for Conducting Strength Tests of Panels for Building Construction, ASTM Designation E 72.

Flexural Tensile Strength:

In addition to the above listed standards, the brick and mortar used should conform to the standards listed in *Technical Notes 39 Revised*.

PURPOSE AND APPLICATION OF TESTS

General. If a rational design approach for masonry is employed, it is essential to establish allowable design stresses early in the design process. Present design standard requirements provide two methods to establish these values. Under these requirements, the ultimate compressive strength (f'_m) may be determined by (a) prism test, or (b) an approximation based upon brick strength and mortar properties. The prism test method is the preferred method as it provides the designer with more exact information; whereas the approximation method, of necessity, provides more conservative values.

Allowable design stresses may be determined under the design standard, once an ultimate compressive strength of masonry has been determined. However, in some cases, it may be desirable, or necessary, to establish tensile or shear strength to closer tolerances than is obtained by design standard values usually given as a function of ultimate compressive strength or of brick strengths and mortar types. Such conditions may occur when masonry is to be used in prefabricated panels, is to be subjected to unusual loading conditions or when high, early strengths are desirable.

All masonry specimens for establishing design stresses should be built using "inspected workmanship;" that is to say, all head, bed and collar joints should be completely filled (see *Technical Notes 7B Revised* for proper procedures). Once strength tests have been performed and masonry properties established, it is necessary to decide if, indeed, inspected workmanship can be achieved at the jobsite. If inspected, workmanship will be achieved, the ultimate stress, f'_m , need not be reduced. If, however, uninspected workmanship is expected, the ultimate strength for "uninspected workmanship" must be used. This value is based upon inspected workmanship in which the ultimate strength is reduced by 33 1/3, percent in the design standard.

Test methods for determining strengths and other properties of masonry necessary to establish allowable design stresses are outlined below.

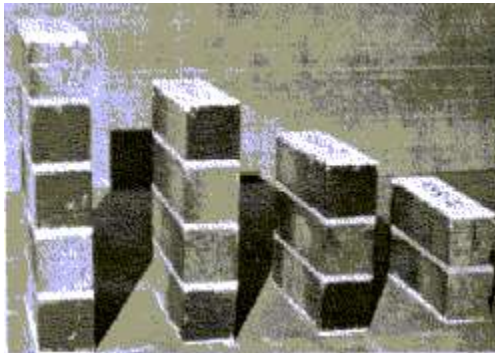
DETERMINATION OF f'_m AND E_m

The ultimate compressive strength (f'_m) of masonry may be approximated if the brick to be used have been tested in accordance with ASTM C 67 (see *Technical Notes 39 Revised*) and mortar type has been established. These values of f'_m are given in tabular format in the design standard for both types of workmanship. Values from this table for a known brick strength, mortar type and workmanship classification may be used directly in determination of f'_m , and thus the allowable design stresses.

The ultimate compression strength of masonry is best determined by testing of compressive prisms in accordance with ASTM Standard Test Methods for Compressive Strength of Masonry Prisms, E 447. There are two methods of performing this test. Method A, which is used primarily for strength comparisons of different brick and mortars, could be used in the selection process to determine what unit or mortar to use. For determination of ultimate compressive strength of a specific brick and mortar for a specific project, Method B of E 447 should be used. This *Technical Notes* will concern itself only with Test Method B.

The test specimens for Method B shall be built to conform as nearly as possible with the actual wall they represent. They should have the same thickness as the wall represented; that is, if the wall is to be a solid wall of two wythes with filled collar joint, the specimens should be the same. Use the same joint dimensions and bonding

pattern as the wall. The length of the specimen should be equal to, or greater than, the thickness. It has been general practice to construct specimen lengths equal to 1 1/2 times the thickness. The specimen height should be at least twice the thickness of the specimen or a minimum of 15 in. (3.81 cm). The height generally should not exceed five times the thickness. See Fig. 1 for prisms with h/t from two to five. The height of specimens may be controlled by the testing facilities available. Not all laboratories have testing machines of dimensions which will permit specimens of height-to-thickness of five to be placed in the machine for test. Prior to construction of specimens, a check of facilities available should be made and the specimens constructed with the greatest height-to-thickness ratio which the available machine can accommodate. Correction factors for different height-to-thickness ratios and reasons for them are discussed elsewhere in this *Technical Notes*. A minimum of three specimens representing each wall type should be constructed and tested. Less than three tests will not give a representative sample. Five specimens of each type of wall are desirable and will give the designer a more accurate ultimate compressive strength value on which he can base allowable stresses.



Compressive Prisms - Slenderness Ratios Two Through Five

FIG. 1

All compressive strength specimens on which design stresses are to be based shall be tested at 28 days. The use of 7-day tests for quality control during construction will be discussed in a subsequent *Technical Notes*. Seven-day tests should not be used for determination of design stresses. However, if for some reason only 7-day test results are available, an approximation of the 28-day strength may be made. The estimated 28-day strength can be obtained by dividing the 7-day strength by 0.90.

When prisms with height-to-thickness ratios of less than five are used for design determinations, a reduction factor must be used to determine the ultimate compressive strength of the masonry. Research experience indicates that the mode of failure of masonry walls under compressive loading is by vertical tensile splitting. Therefore, to accurately predict wall strength, the prism failures should be similar. Laboratory studies also show that masonry specimens having slenderness ratios (h/t) of five or greater consistently fail in compression by the mode of vertical tensile splitting and shorter prisms do not. Therefore, a slenderness ratio of five was selected as unity, and lesser slenderness ratio results must be corrected by the factors shown in Table 1. Research has shown a definite relationship between ultimate compressive strengths of prisms ranging from a slenderness ratio of two up to five. Table 1 is based upon this relationship.

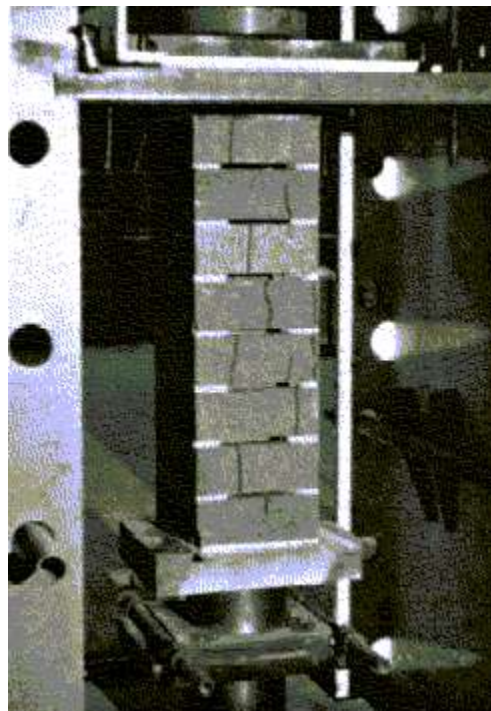
^aHeight to thickness.

^bInterpolate to obtain intermediate values.



Solid Brick Compressive Prism - Tensile Splitting Failure

FIG. 2



Hollow Brick Compressive Prism - Tensile Splitting Failure

FIG. 3

The h/t of the specimens shall be determined by dividing the actual measured height of the specimen by the actual measured thickness of the specimen. These specimen dimensions shall be determined in accordance with paragraph 6.2 of ASTM E 447.

The cross-sectional area shall also be determined based upon actual dimensions of the specimen in accordance with paragraph 6.2 of ASTM E 447. The cross-sectional area to be used for determination of ultimate compressive strength shall be the specimen thickness times the specimen length. For masonry units in accordance with ASTM C 62 and C 216, the gross cross-sectional area shall be used ($t \times l$). If units are hollow brick (ASTM C 652), the net cross-sectional area must be used for determination of ultimate compressive strength. The net cross-sectional area shall be determined as follows: the actual gross cross-sectional area ($t \times l$), using measured dimensions, less the area of voids in the total cross section as measured or determined as outlined in *Technical Notes 39 Revised*.

If the coefficient of variation (v) of the test results on the specimens exceeds 10 percent, the ultimate compressive strength to be used must be modified. This should not be confused with the 12 percent coefficient of variation requirement for the test samples of individual units as covered in *Technical Notes 39 Revised*. If less than 10 percent, the average of the specimen tests should be used for (f'_m) ultimate compressive strength. When the coefficient of variation exceeds 10 percent, modify the average compressive strength of the specimens by the following equation to obtain f'_m :

$$f'_m = \left[1 - 1.5 \left(\frac{v}{100} - 0.10 \right) \right] \bar{X} \quad (1)$$

where:

f'_m = ultimate design compressive strength, psi (Mpa)

v = coefficient of variation of the specimen samples tested, percent

\bar{X} = average compressive strength of all specimens, psi (Mpa)

The test report should include the average compressive strength, the standard deviation and the coefficient of variation. If this information is not included, they may be calculated as follows:

$$\bar{X} = \frac{\sum X_t}{n} \quad (2)$$

$$s = \sqrt{\frac{\sum (X - \bar{X})^2}{n - 1}} \quad (3)$$

$$v = 100 \frac{s}{\bar{X}} \quad (4)$$

where:

X = compressive strength of individual specimen, psi (Mpa)

X_t = total of all individual specimen compressive strengths, psi (Mpa)

n = number of specimens

s = standard deviation, psi (Mpa)

v = coefficient of variation, percent

In many instances, it is desirable or necessary to know the modulus of elasticity, E_m , of the masonry being used. The modulus of elasticity of the masonry can be determined by instrumentation of the specimens to be tested for the determination of ultimate compressive strength. General practice for obtaining the strain of masonry in compression requires the installation of strain gages on compressive prisms. These strain gages, having equal gage lengths, are installed on each end of the prism along the neutral axis of the section (see Fig. 4). It is necessary in the case of multiple wythe wall constructions and/or multiple wythes of dissimilar materials to determine the neutral axis prior to loading as the load should also be applied at the neutral axis. The gage lengths should be as long as practicable. Dial strain gages during test should be read at predetermined load levels up to approximately 75 to 80 percent of the anticipated ultimate load and then removed to prevent damage to the gages at specimen failure. The strain in the masonry is determined by averaging the strain gage readings and dividing by the gage lengths as given by the formula:

$$\gamma = \frac{\Delta V_1 + \Delta V_2}{2g} \quad (5)$$

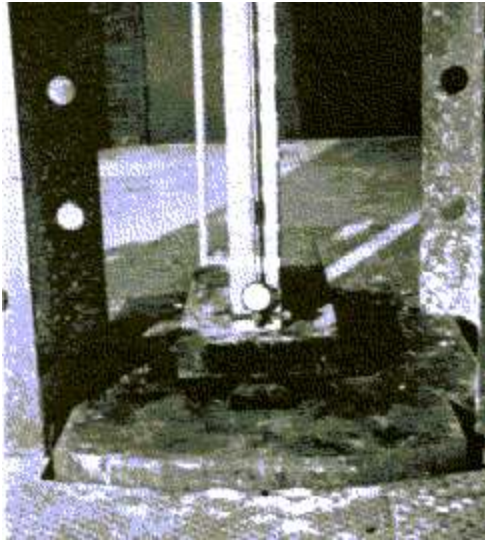
where:

γ = strain, average over entire section, in./in. (mm/mm)

ΔV_1 = dial reading gage No. 1, in. (mm)

ΔV_2 = dial reading gage No. 2, in. (mm)

g = vertical gage length in. (mm)



Compressive Prism Instrumentation for Modulus of Elasticity

FIG. 4

Once the strains at the various load levels, determined by formula (5) are obtained and stresses are calculated, a stress-strain curve for the specimen should be plotted (see Fig. 5). There are several methods of determining the modulus of elasticity from the stress-strain curve. The most common for masonry are the initial tangent modulus and secant modulus methods. The modulus of elasticity is the slope of the tangent or the secant of the curve. The secant modulus is most commonly used for masonry and is easier to determine. The two points selected on the stress-strain curve are generally at 0 psi (Mpa) and 250 psi (1.72 Mpa) stress levels and the modulus is calculated as follows:

$$E_m = \frac{f_{m0} + f_{m250}}{\gamma_0 + \gamma_{250}} = \frac{0 + 250}{\gamma_0 + \gamma_{250}} \quad (6)$$

where:

E_m = secant modulus of elasticity, psi (Mpa)

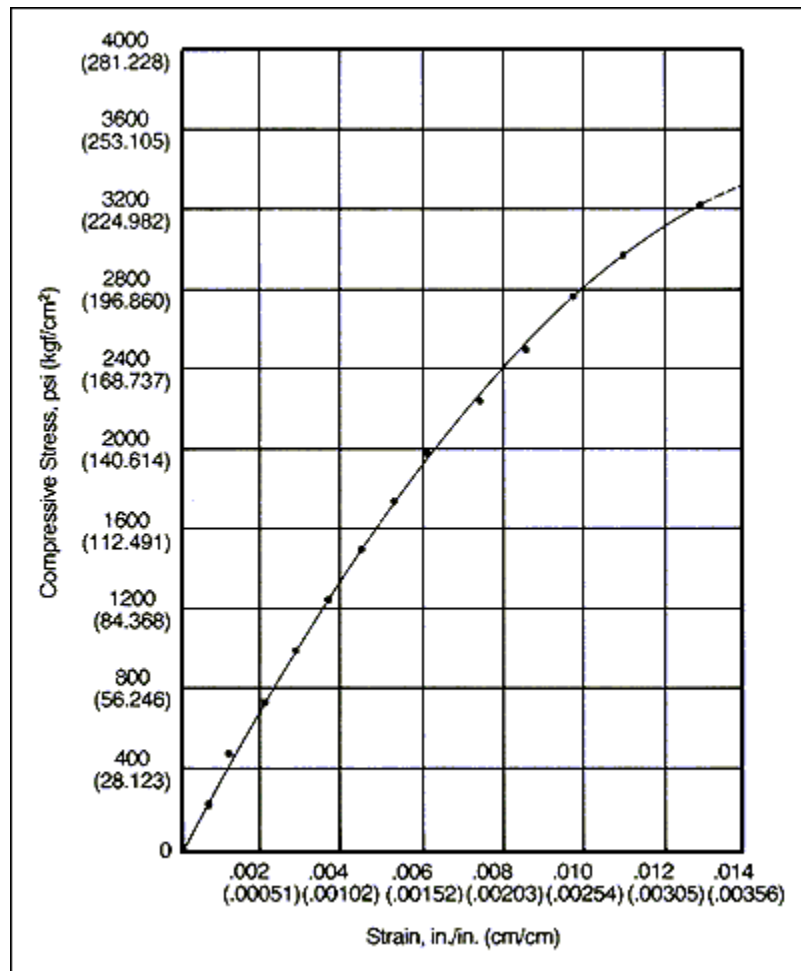
f_{m0} = 0 psi (Mpa) stress

f_{m250} = 250 psi (1.72 Mpa) stress

γ_0 = strain at 0 psi stress, in./in. (mm/mm)

γ_{250} = strain at 250 psi stress, in./in. (mm/mm)

In addition to the determination of the modulus of elasticity by actual tests, the modulus may be based upon f'_m of the compressive prism tests stated as a function of f'_m . (See Tables 3 and 4 of the design standard.)



Idealized Stress Strain Curve

FIG. 5

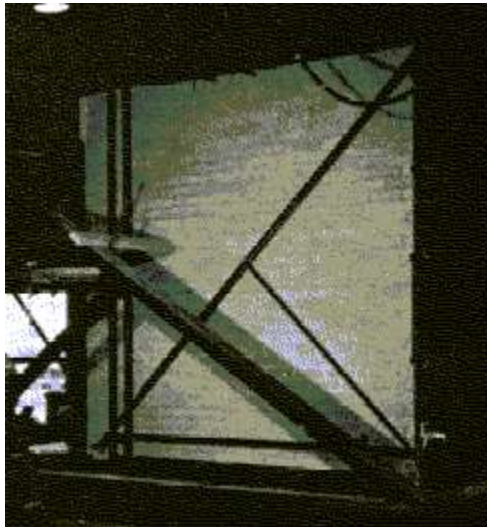
DETERMINATION OF f'_v AND E_v (V_m AND G)

There are two methods of test provided in ASTM standards for the determination of the shear strength of masonry. Shear or diagonal tensile strength is of considerable concern to structural designers, especially in geographical areas where seismic design is required. Until recently, ASTM standards provided only one method of test for determining shear strength. The method of test is described in ASTM E 72, Method for Conducting Strength Tests of Panels for Building Construction. This method of test, referred to as the racking load test in the standard, has been supplemented for masonry by ASTM E 519, Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages. The E 72 racking load test provides for testing materials and constructions of all types, while E 519 applies only to masonry.

It has long been recognized that the method of test provided for in E 72 introduces compressive stresses into the test specimen at the tie down which cannot be measured. See Figs. 6 and 7 for the testing apparatus used for this test and method of failure. The tie down is required to prevent rotation of the specimen when load is applied. In addition to the uncertainty of the tie-down stresses, this method of test requires a specimen 8 ft by 8 ft (2.438 m x

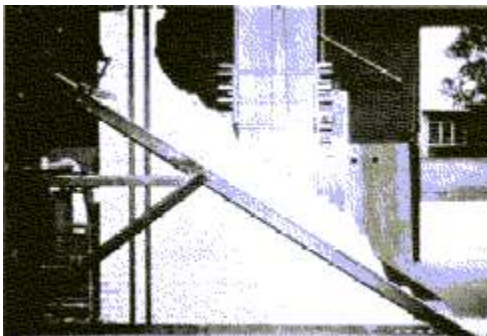
2.438 m) in size. This method of test generally is available only in large laboratories active in masonry research. On the other hand, E 519 provides a method of test which is easier to perform and provides very reliable data. The smaller specimens, 4 ft by 4 ft (1.219 m x 1.219 m), plus more simplified equipment place this method of test within the capabilities of many private testing facilities. See Figs. 8 and 9 for test setup and loading shoes required for this test.

The specimens for both E 72 and E 519 should be constructed using the brick, mortar, bonding pattern and wall thickness that will be utilized in the construction. These specimens should be constructed using "inspected workmanship" as previously described. Specimens for both tests should be cured for 28 days prior to testing.



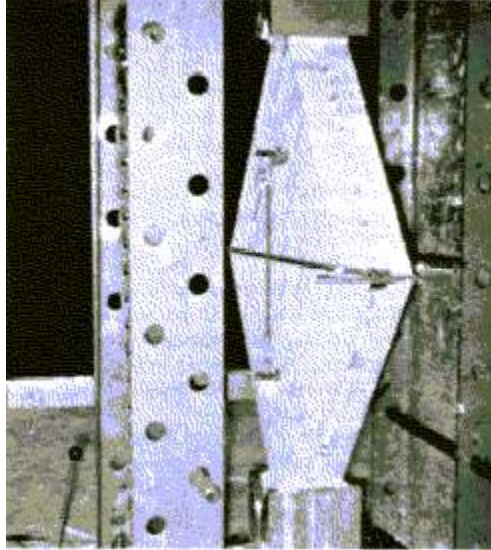
Racking Test Frame and Specimen

FIG. 6



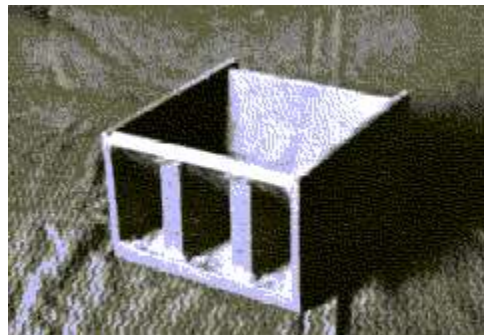
Racking Test Frame and Specimen After Testing

FIG. 7



Diagonal Tension Test Instrumentation for Modulus of Rigidity

FIG. 8



Diagonal Tension Loading Shoe

FIG. 9

The E 72 method of test calls for three 8-ft by 8-ft (2.438 m x 2.438 m) specimens. The panel can be instrumented as shown in the standard and the horizontal deflection plotted against the load applied in graph form as described in the standard. It has been common practice within the masonry industry to slightly modify this test. In lieu of the instrumentation shown in the standard, a series of strain gages are placed to measure horizontal displacement of the panel under load. These gages are placed along the vertical face of the panel where tie downs and load devices do not occur. The horizontal displacement or strain is then taken at various load levels. The strain is the calculated average of all dial readings at a particular load. The shear stress is calculated by dividing the horizontally applied load by the panel width times the panel thickness. From these data stress-strain curves may be plotted. The instrumentation should be removed at approximately 75 to 80 percent of the calculated load and the specimen tested to failure. Data pertinent to the determination of allowable design stresses are (f'_v) ultimate shear stress, a plotted stress-strain curve and the modulus of rigidity at predetermined stress levels, usually 20 percent and 50 percent of ultimate shear stress.

The E 519 method of test also specifies three specimens. Instrumentation of the specimens is provided along the vertical and horizontal diagonals, as shown in Fig. 8. The vertical diagonal instrumentation measures the shortening along that diagonal. The horizontal instrumentation measures the lengthening along that diagonal.

The calculations for shear stress for specimens constructed of solid units shall be based on gross area, while the shear stress for hollow unit specimens shall be based on net area. The shear stress shall be calculated as follows:

$$S_s = \frac{0.707 \times P}{A} \quad (7)$$

where:

S_s = shear stress on gross or net area, psi (Mpa)

P = applied load, lb (N)

A = average of the gross or net areas of the two contiguous upper sides of the specimen, sq in. (mm²)

Formula (8) shall be used when specimens are built of solid units and formula (8a) shall be used for specimens of hollow units.

$$A = \frac{(t \times l)_1 + (t \times l)_2}{2} \quad (8)$$

$$A = (t + l) \cdot A_{\text{net}} \quad (8a)$$

where:

$(t \times l)_1 \dots (t \times l)_2$ = thickness and length or gross area of the two upper contiguous sides of the specimen, sq in. (mm²)

$(t \times l)$ = thickness and length or gross area of upper side of specimen built of hollow units, sq in. (mm²)

A_v = area of voids of the upper side of specimen built of hollow units, sq in. (mm²)

The shear strain shall be calculated as follows:

$$\gamma = \frac{\Delta V_1 + \Delta H_2}{g} \quad (9)$$

where:

γ = shearing strain, in./in. (mm/mm)

ΔV = vertical shortening, in. (mm)

ΔH = horizontal lengthening, in. (mm)

g = vertical gage length, in. (mm)

ΔH must be based on the same gage length as ΔV .

The modulus of rigidity shall be calculated as follows:

$$E_v = \frac{S_s}{g} \quad (10)$$

where:

$E_v = G$ = modulus of rigidity, psi (Mpa)

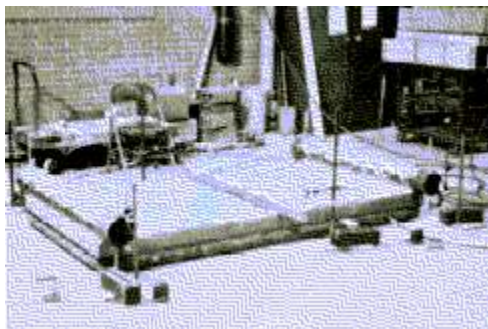
The modulus of rigidity is calculated for predetermined stress levels, usually at approximately 20 percent and 50 percent of ultimate load.

The allowable shear stress should be determined by dividing the ultimate shear strength of the specimens by a safety factor selected by the designer, when E 72 or E 519 are used to determine allowable design values. The safety factor used should be based upon the designer's experience, type of workmanship expected, type of loading the masonry will be subjected to, or as recommended in the design standard or *Recommended Practice for Engineered Brick Masonry*.

DETERMINATION OF f'_t

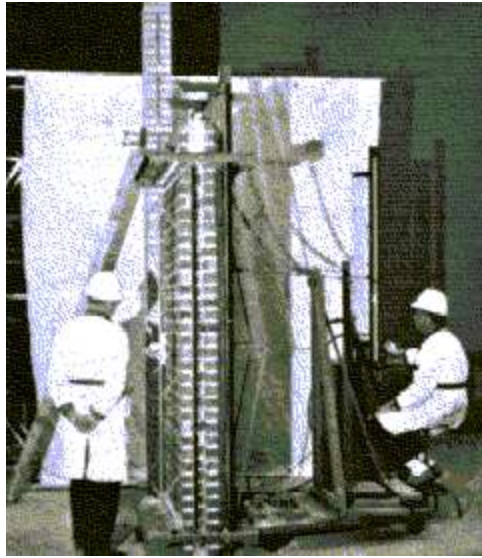
At present, only one method of test is available in ASTM standards for determining the ultimate and design flexural tensile strengths for masonry. This method of test is covered in ASTM E 72. Recently ASTM adopted E 518, Standard Test Methods for Flexural Bond Strength of Masonry. This test, however, is to be used only as a compatibility test for brick and mortar or as a quality control test and should not be used for determination of flexural or transverse design stresses. ASTM E 518 will be more fully discussed in a subsequent issue of *Technical Notes 39 series*.

ASTM E 72 provides four methods for testing the large scale panels. The specimen may be tested in either a horizontal (Fig. 10) or a vertical position (Fig. 11). In addition to these methods, the orientation of the masonry panel itself within the loading frame will have great effect on the results obtained. If the span is normal to the bed joints, simulating a wall supported by floor and roof framing in normal construction, the ultimate strengths obtained will be considerably less than those with spans parallel to the bed joints. The panel oriented with a span parallel to bed joints simulates a wall which in normal masonry construction is laterally supported by columns or pilasters.



Transverse Test - Horizontal Uniform Loading (Air Bag)

FIG. 10



Transverse Test - Vertical Uniform Loading (Air Bag)

FIG. 11

The specimens for this method of test should be at least 4 ft by 8 ft (1.219 m x 2.438 m) and the same thickness as the proposed project walls. Three specimens are required for this method of test. The specimens should be built using the type of brick, mortar and bonding pattern proposed for the construction project. The specimens should be built using inspected workmanship as described earlier.

The test procedure is as follows: The specimen once placed in the test frame, which usually has a span of 6 in. (152.5 mm) less than the specimen size, is instrumented only to measure the center of span deflection. The concentrated load method, whether the specimen is vertical or horizontal, applies two equal loads at a distance of one quarter of the span length from each support.

The uniform loading is applied in either position, using an air bag. See Figs. 10 and 11. The loads should be applied in increments with deflection readings taken and recorded at each increment. Instrumentation should be removed at approximately 75 to 80 percent of anticipated ultimate load to prevent damage to the instrument at failure.

The report of the test should provide a stress-deflection curve and ultimate transverse strength. The transverse stress at ultimate may be calculated as follows:

$$f'_t = \frac{M}{S} \quad (11)$$

where:

f'_t = ultimate transverse stress, psi (Mpa)

M = bending moment for 1-ft (305 mm) wide strip in.-lb (N-m)

S = section modulus of the specimen for 1-ft (305 mm) wide strip, in.³ (mm³)

The moment for uniformly loaded specimens is calculated as follows:

$$M = \frac{wl^2 \times 12}{8} \quad (12)$$

where: w = uniform load, psf (Mpa)

l = span length, ft (mm)

The moment for the concentrated loading may be calculated as follows:

$$M = \frac{Pl + 12}{4} \quad (13)$$

where:

P = concentrated loads at the quarter points for 1-ft (305 mm) wide strip, lb (N)

The section modulus for the specimen must take into account whether the masonry units are solid (up to 25 percent cored) or hollow (26 to 40 percent cored). Calculations for the section modulus of solid units would be as follows:

$$S = \frac{bd^2}{6} \quad (14)$$

where:

b = width of 1-ft (305 mm) wide strip, in. (mm)

d = thickness of specimen, in. (mm)

The calculation for the section modulus of hollow units becomes somewhat more complicated and is as follows:

$$S = \frac{bd^3 - (b_1d_1^3 + b_2d_2^3 + b_3d_3^3 \dots b_nd_n^3)}{6d}$$

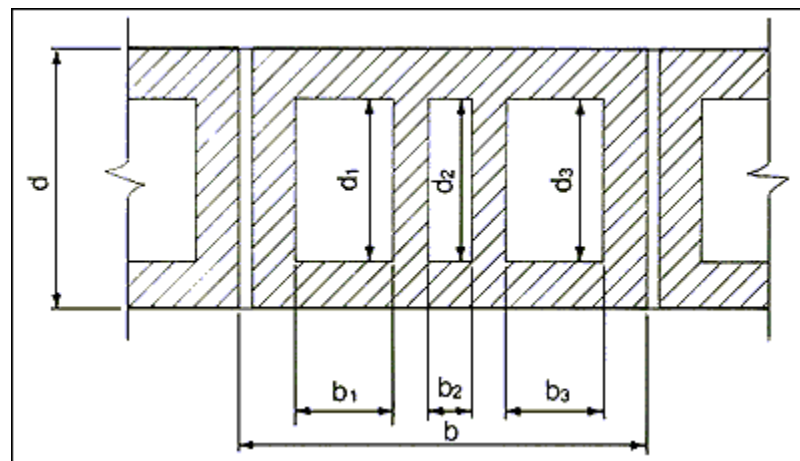
where:

$b_1 \dots b_n$ = width of cores, in. (mm), see Fig. 12

$d_1 \dots d_n$ = depth of cores, in. (mm), see Fig. 12

The illustration for this calculation method, Fig. 12, is based on a 3-core unit with nominal length of 12 in. (305 mm). However, the formula can be adapted to fit other sizes of units and coring patterns. All dimensions shall be actual dimensions.

Once the ultimate transverse strength has been determined by the test of three specimens, the designer should select a safety factor to apply to arrive at an allowable design stress. This safety factor should be based upon the designer's experience, type of workmanship expected, the in situ loadings expected or as recommended by the design standard.



Typical Hollow Brick Cross Section

FIG. 12

CONCLUSION

The methods of tests described in this *Technical Notes* provide the design professional with methods to determine allowable design stresses which may be used in the rational design of brick masonry. The values derived from tests will remain valid only so long as the brick properties, mortar properties and workmanship remain relatively close to that specified. The next issue of this *Technical Notes* series will detail the quality control tests available to insure the designer that he is obtaining masonry properties of sufficient quality to achieve the performance desired.