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RESEARCH EVALUATION OF THE FLEXURAL TENSILE STRENGTH OF CONCRETE MASONRY

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ABSTRACT

Current allowable tensile stress design values were established in the 1960's and were based on a limited amount of available test data. This paper describes the results of a testing program intended to update the existing database of flexural tensile strength values for concrete masonry and to substantiate allowable stress design values and strength design values for concrete masonry. The program includes simply supported full-scale walls tested in flexure and prisms tested using a bond wrench apparatus. The relationship between wall and prism tests are documented. The effects of unit manufacture, wall width, curing conditions, and mortar type on flexural tensile strength are investigated.

INTRODUCTION

Plain concrete masonry relies on the bond developed between masonry mortar and the concrete masonry units to provide tensile resistance for walls subjected to lateral loads (eg., wind, soil pressures, seismic loads). The extent of flexural strength data for concrete masonry used to establish allowable tensile stresses for engineered design of plain concrete masonry was not extensive. Furthermore, results of previously available tests are considered to underestimate nominal flexural strength since the method of curing these specimens did not allow for complete hydration of the cement in the mortar. Moist curing masonry specimens to hydrate the cement in the mortar increases flexural tensile strength to a value indicative of the wall's potential flexural strength.

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SCOPE

The research included the testing of 90 walls in flexure. Walls were 1219 mm (48 in.) in length and 2438 mm (96 in.) in height and laid in running bond with faceshell mortar bedding. During testing the walls were simply supported at top and bottom over a span of 2235 mm (88 in.), and subjected to a uniform lateral load from a pressurized air bag. The lateral load subjected the wall to flexural stress acting normal to the mortar bed joint. For each wall three companion bond wrench prisms were fabricated by the mason (without the aid of jigs or alignment devices) during the construction of the wall, resulting in 270 companion prisms. The prisms consisted of two whole concrete masonry units (CMUs) laid in stack bond with a single faceshell mortared bed joint. Investigated parameters in the wall and companion prism testing included three portland cement and lime mortar types (M, S and N) and three different concrete masonry unit sizes (nominal widths of 102, 203, and 305 mm [4, 8 and 12 in.]).

Table 1: Scope of Wall and Companion Prism Testing

Nominal Dimensions of CMU used in Specimen Construction, mm (in.)	Number of Walls Constructed				Number of Companion Prisms Constructed			
	Mortar Type M	Mortar Type S	Mortar Type N	Total	Mortar Type M	Mortar Type S	Mortar Type N	Total
102x203x406 (4x8x16)	10	10	10	30	30	30	30	90
203x203x406 (8x8x16)	10	10	10	30	30	30	30	90
305x203x406 (12x8x16)	10	10	10	30	30	30	30	90
Total	30	30	30	90	90	90	90	270

CMU Investigation

Four different units (all 203x203x406 mm [8x8x16 in.]) manufactured at different geographic locations, by different manufacturers, using different aggregates and different mix designs were used in this investigation. Thirty bond wrench prisms were constructed using Type S portland cement and lime mortar and tested for each of these four units resulting in 120 total prisms.

Curing Investigation

To evaluate the effect of curing conditions on flexural strength, 30 prisms were constructed using 8x8x16 CMU and Type S portland cement and lime mortar for each of four different curing methods resulting in 120 total prisms:

Method A:	Sprayed with water 1 day following construction; then cured in sealed plastic bags for 25 days; then cured in laboratory air for two days.
Method B:	Cured in laboratory air for 28 days. Sprayed with water at 7 and 14 days after construction.
Method C:	Cured in laboratory air for 28 days.
Method D:	Cured outside for 28 days. Tops of prisms covered as protection from rain.

Mortar Evaluation

The mortar evaluation documented the relative flexural bond strength of mortar used in this research compared to a sampling of mortars from throughout the industry. Each mortar type used in the construction of the flexural walls and companion prisms was evaluated according to procedures used in a previous testing program (Hedstrom et al., 1991). The mortar in this evaluation was prepared using a 50/50 blend of standard graded and 20/30 Ottawa silica sand as the aggregate and concrete brick prisms were constructed using standard concrete brick (manufactured in accordance with UBC Standard No. 24-30) laid in stack bond with the aid of mortar templates, alignment devices, and drop hammers. Six concrete brick prisms were fabricated with five joints per prism and tested in flexure in accordance with ASTM C 1072.

COMPONENT MATERIALS

Concrete Masonry Units

Hollow CMU were supplied by four different manufacturers (Manufacturers A, B, C, and D) Manufacturer A supplied CMU having nominal widths of 102, 203, and 305 mm (4, 8 and 12 in.) each being manufactured with the same unit mix design. Manufacturers B, C, and D each supplied CMU having a nominal width of 203 mm (8 in.) and a configuration identical to that of Manufacturer A's 203 mm (8 in.) unit, but each were manufactured with a different unit mix design. The units supplied by Manufacturer A were used in all phases of the research. The units supplied by Manufacturers B, C, and D were used only for the CMU Investigation.

Mortar

Portland cement and lime mortars were proportioned by volume (Type I portland cement : Type S hydrated lime : mortar sand) in accordance with ASTM C 270 as follows: Type M (1 : 0.25 : 3.75), Type S (1 : 0.5 : 4.5), and Type N (1 : 1.25 : 6.75).

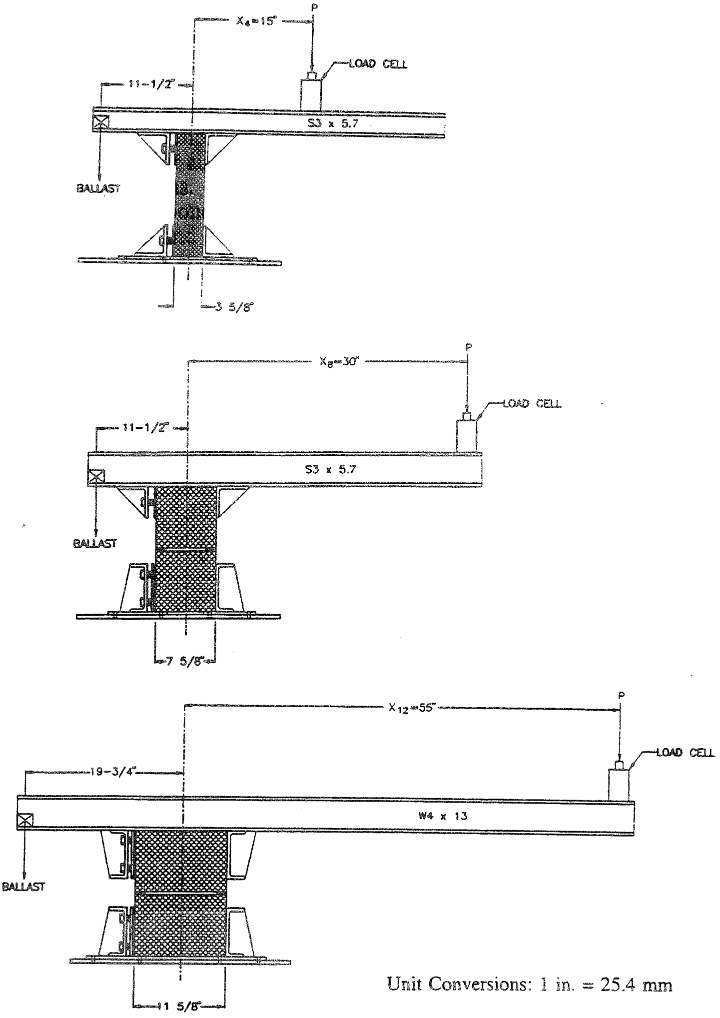
TEST PROCEDURES

Flexural Wall Tests

Flexural wall testing procedures were based on the provisions of Section 12 of ASTM E 72. The uniform lateral load was incrementally increased until the maximum flexural resistance of the wall was achieved. Testing was terminated when a fracture occurred through a mortar joint, the face shell of a concrete unit, or a combination of the two, on the tension face of the wall. The value of this maximum load was recorded.

Bond Wrench Tests of CMU Prisms

Companion prisms for the flexural wall specimens and prisms for the Curing Investigation and the CMU Investigation were tested using a bond wrench which applies an eccentric compressive force to the concrete masonry prism. Testing was performed based on the provisions of ASTM C 1072. Although this ASTM test method provides sample schematics of a bond wrench testing apparatus for testing concrete brick prisms, it does not include similar schematics for CMU prisms. For the purpose of this research, a bond wrench testing apparatus was developed to permit the testing of prisms made from concrete masonry units. The configuration of the bond wrench for each prism size is illustrated in Fig. 1. Different eccentricity distances were used for each prism size to produce an axial stress of approximately 10% of the modulus of rupture of the prism.



Unit Conversions: 1 in. = 25.4 mm

Fig. 1: Configuration of Bond Wrench Apparatuses for Testing Prisms of 102, 203 and 305 mm (4, 8, and 12 in.) CMU

TEST RESULTS

Table 2: Summary of Results of Wall Tests and Companion Prism Tests

Wall Specimens	Average Modulus of Rupture, f_r, MPa (psi)	COV[1] (%)	Prism Specimens	Average Modulus of Rupture, f_r , MPa (psi)	COV[1] %
102 mm (4 in.) Walls			102 mm (4 in.) Companion Prisms		
Type M Mortar	1.99 (289)	11	Type M Mortar	1.63 (237)	19
Type S Mortar	1.97 (285)	11	Type S Mortar	1.59 (231)	16
Type N Mortar	1.19 (172)	11	Type N Mortar	1.15 (167)	27
203 mm (8 in.) Walls			203 mm (8 in.) Companion Prisms		
Type M Mortar	1.49 (216)	24	Type M Mortar	1.14 (166)	35
Type S Mortar	1.17 (162)	32	Type S Mortar	1.17 (169)	33
Type N Mortar	0.76 (110)	34	Type N Mortar	0.72 (104)	28
305 mm (12 in.) Walls			305 mm (12 in.) Companion Prisms		
Type M Mortar	1.71 (248)	16	Type M Mortar	1.04 (151)	30
Type S Mortar	0.92 (134)	26	Type S Mortar	1.15 (167)	29
Type N Mortar	0.50 (84)	13	Type N Mortar	0.79 (114)	48

[1] COV = Coefficient of Variation, calculated as the standard deviation divided by the average times 100.

Table 3: Summary of Results of Prism Tests for Unit Investigation and Curing Investigation

Prism Specimens	Avg. Modulus of Rupture, f_r, MPa (psi)	COV, %
Curing Investigation		
Curing Method A - Moist-cure in sealed bag	1.17 (169)	33
Curing Method B - Lab air-cure, sprayed at 7 & 14 days	1.00 (145)	38
Curing Method C - Lab air-cure	0.32 (46)	64
Curing Method D - Outside air-cure	0.28 (40)	72
CMU Investigation		
Unit Group A	1.17 (169)	33
Unit Group B	0.97 (141)	30
Unit Group C	0.88 (128)	25
Unit Group D	0.85 (123)	50
Mortar Evaluation		
Type M Mortar	0.98 (142)	24
Type S Mortar	0.98 (142)	17
Type N Mortar	0.52 (76)	26

[1] COV = Coefficient of Variation, calculated as the standard deviation divided by the average times 100.

CONCLUSIONS

Effect of Various Parameters on Flexural Tensile Strength

Mortar Type. Flexural tensile strength of concrete masonry constructed with Type S and M mortar is at least 40% higher than the flexural tensile strength of concrete masonry constructed with Type N mortar. Because the flexural tensile strength of wall and companion test specimens constructed with Type S and M mortar were influenced or controlled by the flexural tensile strength of the CMU, the actual relationship between the mortar types in these specimens could not be compared directly with the relationships demonstrated in the concrete brick specimens of the Mortar Evaluation. Of all the wall and companion prism specimens constructed with Type N mortar, 97% failed in bond (a separation occurred on the tension face of the specimen at the interface of the mortar and the concrete masonry units). In comparison only 54% of the specimens constructed with Type S mortar (not including the specimens of the Curing Investigation and CMU Investigation) and only 15% of the specimens constructed with Type M mortar failed in bond.

Unit Width. Flexural tensile strengths of 203 and 305 mm (8 and 12 in.) concrete masonry were approximately equal. The flexural tensile strengths of 102 mm (4 in.) concrete masonry averaged 40-60% higher than the strengths of 203 and 305 mm (8 and 12 in.) concrete masonry, indicating that there may be a strain gradient effect on flexural tensile strength as nominal wall width decreases below eight inches.

Curing. Wet curing of concrete masonry improves flexural tensile strength significantly (300% increase) compared to air curing without wetting. To realize the potential strength of concrete masonry, complete hydration in the mortar must occur. Wetting the masonry with water by spraying or precipitation, or sealing the masonry to prevent mortar moisture loss, will increase hydration of the cement in the mortar. Wet curing also reduces the variability in bond wrench test results.

Unit Tensile Strength. If concrete masonry is wet cured, as were the wall and companion prism specimens in this research, the mortar bond strength may exceed the flexural tensile strength of the concrete masonry units. In this event, the flexural tensile strength of the concrete masonry is controlled by the flexural tensile strength of the CMU.

Unit Manufacture. Differences in unit manufacture were shown to result in a 17% difference in flexural tensile strength. Differences in unit manufacture that may influence mortar bond strength include, but are not limited to: mix design, surface texture, physical unit properties, production methods and curing techniques.

Relationship Between the Mortars Used in this Research and Available Mortars in the Industry

Because the methods used to fabricate, cure, and test the prisms of the Mortar Evaluation of this research were the same as those used in a previous study [Hedstrom et al., 1991] the modulus of rupture values from both reports may be compared directly. If the results of the bond wrench tests from the Mortar Evaluation of this research are included with the results of the 12 different mortar combinations of each mortar type from the previous study, the resulting average of 13 different mortar combinations would be 1.33 MPa (194 psi) for Type M mortars, 1.14 MPa (165 psi) for Type S mortars, and 0.82 MPa (119 psi) for Type N mortars.

If it is assumed that these 13 mortars of each mortar type represent the range of bond strengths of mortars supplied throughout the industry, it can be argued that the bond developed by the Type M, S, and N mortars used in this research are 37%, 16%, and 57% respectively below the bond developed by the range of mortars supplied throughout the industry (Table 4).

Table 4: Relationship of Mortar to Typical Mortars

Mortar Type	Mortar Used in this Research {1}	Typical Mortar Used Throughout the Industry[1] {2}	Ratio of {2}/{1}
Type M Type S Type N	142 psi 142 psi 76 psi	194 psi 165 psi 119 psi	1.37 1.16 1.57
		Average	1.37

[1] Based on the test results from the Mortar Evaluation of this research and a previous study (Hedstrom et al., 1991)

Correlation of Wall and Prism Test Results

As shown in Table 5, the average correlation factor between the modulus of rupture values of walls and prisms is 1.1 (wall f_r divided by prism f_r). It is recognized that this correlation factor is derived by comparing a single joint specimen to a multiple joint specimen. Because the correlation factor is only prescribed for relating these two types of specimens, no additional statistical evaluation considering number of joints is necessary.

Table 5: Correlation Factors for Wall and Prism Test Results

CMU Nominal Width, mm (in.)	Mortar Type	Average Wall Modulus of Rupture, f_r, MPa, (psi) {1}	Average Prism Modulus of Rupture, f_r, MPa, (psi) {2}	Correlation Factor (Wall:Prism) {1} / {2}
102 (4)	Type M Type S Type N	1.99 (289) 1.97 (285) 1.19 (172)	1.63 (237) 1.59 (231) 1.15 (167)	1.22 1.23 1.03
203 (8)	Type M Type S Type N	1.49 (216) 1.12 (162) 0.76 (110)	1.14 (166) 1.17 (169) 0.72 (104)	1.30 0.96 1.06
305 (12)	Type M Type S Type N	1.71 (248) 0.92 (134) 0.58 (84)	1.04 (151) 1.15 (167) 0.79 (114)	1.64 0.80 0.74
			Average	1.11

Adjusting Test Results to Account for Typical Construction Materials. Efforts were made in this research program to document how the flexural tensile strength values determined from the wall and companion prism tests may have been affected if "typical" construction materials were used rather than those arbitrarily selected for this project. It was noted that the units used in the construction of the wall and companion prisms may provide 17% greater bonding characteristics than the average of units supplied throughout the industry. Therefore, in determining expected flexural tensile strengths of concrete masonry, the results in this research should be multiplied by a factor of 0.83 to account for differences in unit characteristics. Because the mortar used in this research may have lower bonding characteristics than "typical" mortar, the results in this research should be multiplied by a factor of 1.37 to account for differences in mortar bonding characteristics. Therefore, the expected flexural strength of concrete masonry can be calculated as shown in Table 6.

Table 6: Calculation of Expected Flexural Tensile Strength of Concrete Masonry Using Typical Construction Materials

Specimen Description	Average Tested Modulus of Rupture[1], f_r , MPa (psi) {1}	Unit Adjustment Factor {2}	Mortar Adjustment Factor {3}	Expected Strength of Concrete Masonry, MPa (psi) {1}x{2}x{3}
<u>4" Concrete Masonry</u>				
Type M Mortar	1.72 (250)	0.83	1.37	1.96 (284)
Type S Mortar	1.68 (244)	0.83	1.37	1.91 (277)
Type N Mortar	1.16 (168)	0.83	1.37	1.32 (192)
<u>8" Concrete Masonry</u>				
Type M Mortar	1.23 (178)	0.83	1.37	1.39 (202)
Type S Mortar	1.15 (167)	0.83	1.37	1.31 (190)
Type N Mortar	0.73 (106)	0.83	1.37	0.83 (121)
<u>12" Concrete Masonry</u>				
Type M Mortar	1.21 (176)	0.83	1.37	1.38 (200)
Type S Mortar	1.10 (159)	0.83	1.37	1.25 (181)
Type N Mortar	0.73 (106)	0.83	1.37	0.83 (121)

[1] These values were obtained by averaging the test results of all wall and companion prism specimens, approximately 40 total specimens. Example: Using 102 mm, Type M mortar modulus of rupture values from Table 2, [(1.99 MPa x 10 walls) + (1.63 MPa x 30 prisms)] ÷ 40 specimens = 1.72 MPa

As the bond developed between mortar and concrete masonry unit increases, so does the possibility that the flexural tensile strength of the concrete masonry will be controlled by the flexural tensile strength of the concrete masonry unit. The average modulus of rupture for all specimens with "block" failure modes for each unit size was calculated to be 1.68 MPa (244 psi) for 102 mm (4 in.) concrete masonry, 1.30 MPa (189 psi) for 203 mm (8 in.) concrete masonry, and 1.23 MPa (179 psi) for 305 mm (12 in.) concrete masonry. Because no standard test method exists for determining the flexural tensile strength of CMU, this property was not determined for the units used in the research. The flexural tensile strength of concrete, including concrete masonry, is assumed to be proportional [ACI 318.1-89] to the square root of its compressive strength. The minimum required net area compressive strength of load bearing CMUs complying with ASTM C

90 is 13.1 MPa (1900 psi). Therefore, the minimum flexural tensile strength of CMUs complying with ASTM C 90 of 102, 203, and 305 mm (4, 8, and 12 in.) nominal widths can be determined in accordance with the following factor:

$$\text{Flexural Tensile Strength Adjustment Factor} = \frac{\sqrt{\text{Min. Required Unit Compressive Strength}}}{\sqrt{\text{Avg. Unit Compressive Strength}}} \qquad [1]$$

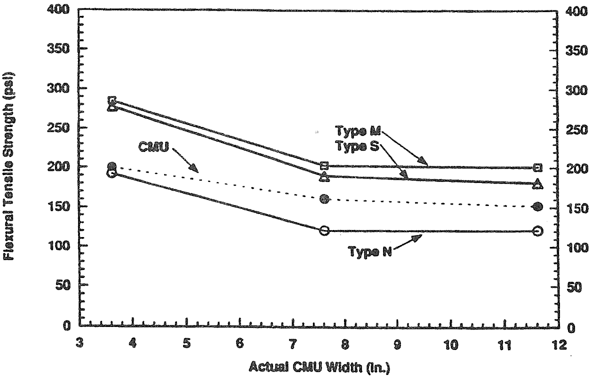
The expected flexural strength of typical CMU is therefore determined from Table 6.

Table 7: Expected Flexural Tensile Strength of CMUs

CMU Nominal Width, mm (in.)	Average Unit Compressive Strength[1], MPa (psi) {1}	Unit Flexural Tensile Strength Adjustment Factor[2] {2}	Average Tested Flexural Tensile Strength of CMU[3], MPa (psi) {3}	Expected Flexural Tensile Strength of CMU, MPa (psi) {4} = {2}x{3}
102 (4)	19.3 (2800)	0.82	1.68 (244)	1.38 (200)
203 (8)	18.0 (2610)	0.85	1.30 (189)	1.11 (161)
305 (12)	17.9 (2600)	0.85	1.23 (179)	1.05 (152)

[1] Average unit compressive strength for each masonry unit width tested determined by ASTM C 140
[2] Unit Flexural Strength Adjustment Factor calculated by dividing the square root of 13.1 MPa (1900 psi) by the square root of the value in column {1}
[3] Tested Flexural Strength of CMU determined by averaging the test results of those wall and companion prisms with a "block" failure mode.

The expected flexural bond strengths of concrete masonry constructed using similar construction and curing procedures as used in this research, with typical construction materials and Types M, S, or N mortars is plotted in Fig. 2. Also plotted in Fig. 2 is the expected flexural tensile strength of typical CMUs.



Unit Conversions: 1 psi = 0.00689 MPa, 1 in. = 25.4 mm

Fig. 2: Expected Flexural Tensile Strength of Concrete Masonry

Nominal Flexural Tensile Strengths of Concrete Masonry. Figure 2 demonstrates that the flexural tensile strength of wet cured walls is controlled by the flexural tensile strength of the CMUs. The nominal flexural tensile strength of concrete masonry constructed with these two mortar types becomes the curve of expected flexural tensile strength of the CMU.

Table 8: Nominal Flexural Tensile Strength of Concrete Masonry, MPa (psi)

Masonry Type: Normal to Bed Joints, Hollow Units, Ungrouted Construction					
	Nominal Width of Wall, mm (in.)				
Mortar Type	102 (4)	152 (6)	203 (8)	254 (10)	305 (12)
M or S	1.38 (200)	1.23 (178)	1.08 (157)	1.08 (157)	1.08 (157)
N	1.32 (192)	1.08 (157)	0.83 (121)	0.83 (121)	0.83 (121)

Note: The expected values for 203 and 305 mm (8 and 12 in.) masonry were nearly identical (within 6%). Expected strengths for these two wall thicknesses were averaged to determine a single nominal strength for both (maximum error of 3%).

Strength Reduction Factors. The design flexural tensile strength of masonry is based on the nominal flexural tensile strength adjusted by a strength reduction factor, ϕ. The strength reduction factor accounts for the effect of variations between tested and field construction conditions including variations in materials, construction, and curing. The strength reduction factor also accounts for the inherent variability in flexural tensile strength properties of masonry. It is difficult to accurately document most of the effects on flexural tensile strength. Therefore, engineering judgement must be used in establishing appropriate adjustments to the nominal flexural tensile strength values. Previous research (Hedstrom et al., 1991) indicated that different representative portland cements used in mortar resulted in coefficient of variation in flexural tensile strengths of 12 to 17% in concrete brick bond wrench prisms. The results of this research indicated that different representative concrete masonry units resulted in coefficients of variation in flexural tensile strength values of 25 to 50% in CMU bond wrench prisms. Other conditions affecting the flexural tensile strength of masonry include:

- field mixing of mortar
- weather conditions during construction
- techniques used in placing units in the wall
- field curing conditions

The design flexural tensile strength of masonry should be a conservative value having a 90 to 95% confidence level. For masonry constructed in accordance with the Building Code Requirements for Masonry Structures (ACI 530/ASCE 5/TMS 402), which specifies quality materials in accordance with established standards, and quality workmanship, the variation in flexural tensile strength is minimized. Furthermore, if walls are cured by periodically spraying them down during the first few weeks after construction then a strength reduction factor of 0.65 is considered appropriate. Where no special curing is used a strength reductions factor of 0.50 is recommended.

$$\text{Design Strength} = \phi \times \text{Nominal Strength} \qquad [2]$$

where: ϕ = 0.65 — for cured masonry constructed in accordance with ACI 530/ASCE 5/TMS 402
ϕ = 0.50 — for masonry constructed in accordance with ACI 530/ASCE 5/TMS 402

The flexural tensile stress in masonry is assumed directly proportional to strain. This is consistent with the modulus of rupture values determined in accordance with this research program which are determined by dividing the maximum resisting moment by the section modulus of the wall's cross section. This linear relationship between stress and strain should also be used in the design of masonry.

These strength design provisions are intended to be used with factored loads and load combinations given in the Minimum Design Loads for Buildings and other Structures, ASCE 7.

Allowable Stress Design Values for Flexural Tension. Allowable stress design (ASD) requires flexural resistance to equal or exceed flexural stresses due to unfactored loads acting on the section. The ratio of nominal flexural tensile strength to the allowable flexural tensile stress typically ranges from 2 to 5 with an average of approximately 3. Based on this traditional method of establishing allowable flexural tensile stresses the values in Table 9 are recommended to replace the allowable stresses currently in ACI 530/ASCE 5/TMS 402 for concrete masonry. These recommended values are based on the nominal flexural tensile strength values presented in Table 8 divided by three.

Table 9: Allowable Flexural Tensile Stress Recommended for Concrete Masonry, MPa (psi)

Masonry Type: Normal to Bed Joints, Hollow Units, Ungrouted Construction					
	Nominal Width of Wall, mm (in.)				
Mortar Type	102 (4)	152 (6)	203 (8)	254 (10)	305 (12)
M or S	0.46 (67)	0.41 (59)	0.36 (52)	0.36 (52)	0.36 (52)
N	0.44 (64)	0.36 (52)	0.28 (40)	0.28 (40)	0.28 (40)

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