

EVALUATION OF DESIGN PROVISIONS
FOR IN-PLANE SHEAR IN MASONRY WALLS

By

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To the Faculty of Washington State University:

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Abstract

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This research investigated current and proposed design procedures for in-plane shear in masonry walls. Procedures considered include both strength design and allowable stress design provisions in the 2008 MSJC *Building Code Requirements and Specifications for Masonry Structures*, the New Zealand masonry design standard NZS 4230:2004, the Canadian masonry design standard CSA S304.1-04, provisions in the 1997 Uniform Building Code, and proposed design equations developed by Shing et al in 1990 and by Anderson and Priestley in 1992. Predicted shear strengths from the various procedures were compared with results from a wide range of tests of masonry walls failing in in-plane shear. The test data encompassed both concrete masonry walls and clay masonry walls, all of which were fully grouted. Statistical analyses were performed to compare the overall effectiveness of each set of provisions or proposed equation. Parametric studies were also performed to evaluate the ability of the provisions and equations to account for the effects of specific parameters. The current MSJC strength design provisions were found to provide the best shear predictions over a wide range of wall parameters. Based on the results of this study, recommendations were made to improve the current MSJC strength design and allowable stress design provisions.

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CHAPTER 1

INTRODUCTION

1.1 Background

Design provisions for shear in masonry structures vary widely in building standards existing around the world. Variations in the provisions include differences in format, assumptions of structural behavior under shear loadings, separate provisions for unreinforced and reinforced elements, treatment of in-plane and out-of-plane shear loading, accounting for partial and full grouting, factors of safety, and reductions in shear strength in plastic hinging regions. In the US design standard *Building Code Requirements and Specifications for Masonry Structures* (MSJC, 2008), which provides separate design provisions for allowable stress design and for strength design, fundamental differences in the two sets of shear provisions can produce substantially different designs.

In response to the variations in the shear provisions, a number of experimental studies on the shear performance of masonry walls and other structural elements has been conducted over the last 25 years. Current and proposed design methods were evaluated for their effectiveness to predict measured shear strengths. Two comprehensive studies (NEHRP, 2000; Voon and Ingham, 2007) collected shear data from around the world and compared the data with predicted strengths from a broad collection of existing and proposed shear provisions. The NEHRP study provided recommendations for shear design that were largely based on the equations developed in the National Science Foundation (NSF) - funded Technical Coordinating Committee for Masonry Research (TCCMaR) program. The TCCMaR equations are the basis for the strength design provisions in the MSJC Code. The Voon and Ingham study also found that the TCCMaR

equations provided a good prediction of the collected shear strengths. However, Voon and Ingham proposed several modifications to the TCCMaR equations, and their final recommendations for shear design were incorporated into the 2004 New Zealand Standard (NZS, 2004).

The research reported in this thesis builds upon the previous studies by NEHRP and Voon and Ingham. The shear data collected in both previous studies is incorporated into this research, and the methods for evaluating the effectiveness of the various provisions closely resemble those used in those studies. This research expands on this previous work to include consideration of additional codes as well as the allowable stress provisions of previously evaluated codes. The goal of this research is to provide recommendations for improvements to the existing MSJC shear provisions.

1.2 Scope and Objectives

The primary objective of this research is to evaluate the accuracy of various code provisions and proposed equations for predicting the in-plane shear strength of masonry walls. Statistical analysis of each equation was performed, and evaluations isolating the effects of wall parameters were made. The parameters examined include masonry compressive strength, amount of shear reinforcement, level of axial compressive stress, amount of vertical reinforcement, displacement ductility, and wall aspect ratio.

1.3 Organization

This thesis is comprised of five chapters. Chapter 2 contains a review of current and past code shear provisions as well as predictive equations. The review includes a detailed description

of each set of provisions. Chapter 3 provides a short summary of previous laboratory tests of masonry shear walls producing shear failures, including presentation of the test setup and data. Data from four different sources is included. Chapter 4 reports on a statistical analysis and comparison of the various provisions and equations with respect to predicting the shear strengths in the collected data set. Chapter 4 also provides an evaluation of the ability of the provisions and equations to account for various test parameters. Chapter 5 presents conclusions reached in this study along with recommendations for improvements in the current MSJC shear provisions.

CHAPTER 2

REVIEW OF CODE PROVISIONS

2.1 MSJC Building Code

The Masonry Standards Joint Committee (MSJC) *Building Code Requirements and Specification for Masonry Structures* (MSJC, 2008) contains two sets of provisions for shear design. Provisions based on Allowable Stress Design (ASD) are given in MSJC Chapter 2, and provisions based on Strength Design (SD) are given in MSJC Chapter 3. The MSJC SD provisions for shear design are the same as those developed through the National Earthquake Hazards Reduction Program (NEHRP, 2003).

2.1.1 MSJC Allowable Stress Design (ASD)

The MSJC ASD shear design provisions are specified separately for unreinforced masonry and for reinforced masonry.

2.1.1.1 Unreinforced Masonry

ASD shear design provisions for unreinforced masonry are given in MSJC Section 2.2.5. Shear stresses in unreinforced masonry due to applied service loads are calculated using Equation 2-1.

$$f_v = \frac{VQ}{I_n b} \quad (2-1)$$

For in-plane loading, the calculated shear stresses, f_v , shall not exceed any of the allowable stress limits (a), (b) and the applicable condition of (c) through (f) as listed below.

(a) $1.5\sqrt{f'_m}$

(b) 120 psi

(c) For running bond masonry, not grouted solid:

$$37 \text{ psi} + 0.45 \frac{N_v}{A_n}$$

(d) For stack bond masonry with open end units and grouted solid:

$$37 \text{ psi} + 0.45 \frac{N_v}{A_n}$$

(e) For running bond masonry grouted solid:

$$60 \text{ psi} + 0.45 \frac{N_v}{A_n}$$

(f) For stack bond masonry other than open end units grouted solid:

$$15 \text{ psi}$$

No allowable stress limits are specified in Section 2.2.5 for out-of-plane shear stresses.

2.1.1.2 Reinforced Masonry

ASD shear design provisions for reinforced masonry are given in MSJC Section 2.3.5. Separate provisions for reinforced masonry are provided for members that are subjected to flexural tension and for those without flexural tension.

Reinforced masonry members that are subjected to flexural tension are to be designed in accordance with MSJC Sections 2.3.5.2 and 2.3.5.3. Shear stresses due to service loads are calculated using Equation 2-2.

$$f_v = \frac{V}{bd} \quad (2-2)$$

Note that the area used to calculate the shear stress does not distinguish between fully and partially grouted sections. The calculated shear stresses, f_v , shall not exceed the applicable

allowable stress limit, F_v , given in MSJC Section 2.3.5.2.2 and as listed below. For flexural members (i.e., for beams), F_v is given by Equation 2-3. For shear walls with M/Vd ratios less than 1, F_v is given by Equation 2-4. For shear walls with M/Vd ratios greater than or equal to 1, F_v is given by Equation 2-5.

$$F_v = \sqrt{f'_m} \leq 50 \text{ psi} \quad (2-3)$$

$$F_v = \left(\frac{1}{3}\right) \left[4 - \left(\frac{M}{Vd}\right) \right] \sqrt{f'_m} \leq 80 - 45 \left(\frac{M}{Vd}\right) \text{ psi} \quad (2-4)$$

$$F_v = \sqrt{f'_m} \leq 35 \text{ psi} \quad (2-5)$$

If f_v is less than or equal to the applicable F_v limit, the masonry is assumed to provide the entire shear strength and shear reinforcement is not required. If f_v is greater than the applicable F_v limit, the masonry is assumed to carry no shear and shear reinforcement must be provided in accordance with MSJC Section 2.3.5.3.

For reinforced masonry subjected to flexural tension, and where it has been determined that shear reinforcement is required, the shear reinforcement is to comply with MSJC Section 2.3.5.3. The minimum area of shear reinforcement, A_v , at a spacing, s , shall be determined using Equation 2-6.

$$A_v = \frac{Vs}{F_s d} \quad (2-6)$$

The shear reinforcement is to be provided parallel to the direction of the applied shear force with a spacing not to exceed the lesser of $d/2$ or 48 in. Reinforcement is also required perpendicular to the shear reinforcement with an area equal to at least $1/3A_v$ and with a spacing not to exceed 8 ft.

When shear reinforcement is provided, the shear stress under service loads, f_v , calculated using Equation 2-2, shall not exceed the applicable allowable stress limit, F_v , as given in MSJC Section 2.3.5.2.3 and as listed below. For flexural members (i.e., for beams), F_v is given by Equation 2-7. For shear walls with M/Vd ratios less than 1, F_v is given by Equation 2-8. For shear walls with M/Vd ratios greater than or equal to 1, F_v is given by Equation 2-9. In effect, these limits provided an upper bound on the shear strength permitted in reinforced masonry members, no matter the amount of shear reinforcement that is provided.

$$F_v = 3.0\sqrt{f'_m} \leq 150 \text{ psi} \quad (2-7)$$

$$F_v = \left(\frac{1}{2}\right) \left[4 - \left(\frac{M}{Vd}\right) \right] \sqrt{f'_m} \leq 120 - 45 \left(\frac{M}{Vd}\right) \quad (2-8)$$

$$F_v = 1.5\sqrt{f'_m} \leq 75 \text{ psi} \quad (2-9)$$

Reinforced masonry members that are not subjected to flexural tension are to be designed in accordance with either the requirements of MSJC Section 2.2.5 for unreinforced masonry or with the requirements of MSJC Section 2.3.5.1. This latter section requires that shear reinforcement complying with MSJC Section 2.3.5.3 be provided and that the allowable stress limits of MSJC Section 2.3.5.2.3 be met.

The MSJC ASD provisions for reinforced masonry do not distinguish between in-plane shear and out-of-plane shear.

2.1.2 MSJC Strength Design (SD)

The MSJC SD shear design provisions are specified separately for unreinforced masonry and for reinforced masonry.

2.1.2.1 Unreinforced Masonry

SD shear design provisions for unreinforced masonry are given in MSJC Section 3.2.4. The nominal shear strength, V_n , is specified as the smallest of (a), (b) and the applicable condition of (c) through (f) as listed below:

(a) $3.8A_n\sqrt{f'_m}$

(b) $300A_n$

(c) For running bond masonry not solidly grouted:

$$56A_n + 0.45N_u$$

(d) For stack bond masonry with open end units and grouted solid:

$$56A_n + 0.45N_u$$

e) For running bond masonry grouted solid:

$$90A_n + 0.45N_u$$

(f) For stack bond other than open end units grouted solid:

$$23A_n$$

For design, the factored shear force, V_u , shall not exceed the nominal shear strength, V_n , times the strength- reduction factor, ϕ , for shear of 0.80.

The MSJC SD provisions for unreinforced masonry do not distinguish between in-plane shear and out-of-plane shear.

2.1.2.2 Reinforced Masonry

SD shear design provisions for reinforced masonry are given in MSJC Section 3.3.4. The nominal shear strength, V_n , is given as the sum of the nominal shear strength provided by the

masonry, V_{nm} , and the nominal shear strength provided by the shear reinforcement, V_{ns} , as shown in Equation 2-10.

$$V_n = V_{nm} + V_{ns} \quad (2-10)$$

For design, the factored shear force, V_u , shall not exceed the nominal shear strength, V_n , times a shear strength- reduction factor, ϕ , of 0.80.

The nominal shear strength, V_n , is given by Equation 2-11. The first term in this equation represents the strength contribution from the masonry, and the second term represents the shear strength contribution from the applied axial compressive load. The third term represents the nominal shear strength provided by the shear reinforcement, V_{ns} .

$$V_n = \left[4.0 - 1.75 \left(\frac{M_u}{V_u d_v} \right) \right] A_n \sqrt{f'_m} + 0.25 P_u + 0.5 \left(\frac{A_v}{s} \right) f_y d_v \quad (2-11)$$

The nominal shear strength, V_n , shall not exceed $6.0 A_n \sqrt{f'_m}$ for walls with values of $M_u/V_u d_v$ less than or equal to 0.25. A limit on V_n of $4.0 A_n \sqrt{f'_m}$ applies for values of $M_u/V_u d_v$ greater than or equal to 1.0. For $M_u/V_u d_v$ values between 0.25 and 1.0, the maximum value of V_n is linearly interpolated. Values for $M_u/V_u d_v$ need not be taken greater than 1.0 and shall be taken as a positive number.

The MSJC SD provisions for reinforced masonry do not distinguish between in-plane shear and out-of-plane shear.

2.1.3 MSJC Notation

- A_n = net cross-sectional area of a member
- A_v = cross-sectional area of shear reinforcement
- b = width of section

- d = distance from extreme compression fiber to centroid of tension reinforcement
- d_v = actual depth of a member in direction of shear considered
- F_s = allowable tensile or compressive stress in reinforcement
- F_v = allowable shear stress in masonry
- f'_m = specified compressive strength of masonry
- f_v = calculated shear stress in masonry
- f_y = specified yield strength of steel for reinforcement or anchors
- I_n = moment of inertia of net cross-sectional area of a member
- M = maximum moment at the section under consideration
- M_u = factored moment
- N_u = factored compressive force acting normal to the shear surface that is associated with the V_u loading combination case under consideration
- N_v = compressive force acting normal to the shear surface
- P_u = factored axial load
- Q = first moment about the neutral axis of an area between the extreme fiber and the plane at which the shear stress is being calculated
- s = spacing of reinforcement
- V = shear force
- V_n = nominal shear strength
- V_u = factored shear force
- ϕ = strength-reduction factor

2.2 Uniform Building Code

The Uniform Building Code (UBC) (ICBO, 1997) contains two sets of provisions for shear design. Provisions based on working stress design (WSD), equivalent to ASD, are given in UBC Section 2107, and provisions based on SD are given in UBC Section 2108.

2.2.1 UBC Working Stress Design (WSD)

The UBC WSD shear design provisions are specified separately for unreinforced masonry and for reinforced masonry.

2.2.1.1 Unreinforced Masonry

WSD shear design provisions for unreinforced masonry are given in UBC Section 2107.3. Shear stresses in beams and shear walls due to service loads are calculated using Equation 2-12.

$$f_v = \frac{V}{A_e} \quad (2-12)$$

This shear stress, f_v , shall not exceed the applicable allowable stress limit, F_v , given in UBC Sections 2107.3.6 and 2107.3.7 and as listed below. For flexural members (i.e., for beams), F_v is given by Equation 2-13.

$$F_v = \sqrt{f'_m} \leq 50 \text{ psi} \quad (2-13)$$

For shear walls, F_v is given by the applicable condition of Equations 2-14 through 2-16.

$$\text{Clay units: } F_v = 0.3 \sqrt{f'_m} \leq 80 \text{ psi} \quad (2-14)$$

$$\text{Concrete units, Type M or S mortar: } F_v = 34 \text{ psi} \quad (2-15)$$

$$\text{Concrete units, Type N mortar: } F_v = 23 \text{ psi} \quad (2-16)$$

In addition, the allowable shear stress, F_v , in unreinforced masonry may be increased by 0.2 times the computed compressive stress due to dead load.

The UBC WSD provisions for unreinforced masonry do not distinguish between in-plane shear and out-of-plane shear.

2.2.1.2 Reinforced Masonry

WSD shear design provisions for reinforced masonry are given in UBC Section 2107.2. Shear stresses in beams and shear walls due to service loads are calculated using Equation 2-17.

$$f_v = \frac{V}{bjd} \quad (2-17)$$

For members of T or I section, the width of the web, b' , shall be substitute for the width, b . This shear stress, f_v , shall not exceed the applicable allowable stress limit, F_v , given in UBC Sections 2107.2.8 and 2107.2.9 and as listed below. For flexural members (i.e., for beams), F_v is given by Equation 2-18.

$$F_v = \sqrt{f'_m} \leq 50 \text{ psi} \quad (2-18)$$

For shear walls with M/Vd ratios of less than 1, F_v is given by Equation 2-19. For shear walls with M/Vd ratios greater or equal to 1, F_v is given by Equation 2-20.

$$F_v = \left(\frac{1}{3}\right) \left[4 - \left(\frac{M}{Vd}\right) \right] \sqrt{f'_m} \leq 80 - 45 \left(\frac{M}{Vd}\right) \text{ psi} \quad (2-19)$$

$$F_v = \sqrt{f'_m} \leq 35 \text{ psi} \quad (2-20)$$

If f_v is less than or equal to the applicable F_v limit, the masonry is assumed to provide the entire shear strength and shear reinforcement is not required. If f_v is greater than the applicable F_v

limit, the masonry is assumed to carry no shear and shear reinforcement must be provided in accordance with UBC Section 2107.2.17.

For reinforced masonry sections where it has been determined that shear reinforcement is required, the shear reinforcement is to comply with UBC Section 2107.2.17. The area required for shear reinforcement placed perpendicular to the longitudinal reinforcement is computed by Equation 2-21.

$$A_v = \frac{V_s}{F_s d} \quad (2-21)$$

The shear reinforcement is to be spaced so that every 45-degree line extending from a point at $d/2$ to the longitudinal tension bars shall be crossed by at least one line of web (shear) reinforcement.

When shear reinforcement is provided, the shear stress under service loads, f_v , calculated using Equation 2-17, shall not exceed the applicable allowable stress limit, F_v , as given in UBC Section 2107.2.9 and as listed below. For flexural members (i.e., for beams), F_v is given by Equation 2-22.

$$F_v = 3.0\sqrt{f'_m} \leq 150 \text{ psi} \quad (2-22)$$

For shear walls with M/Vd ratios less than 1, F_v is given by Equation 2-23. For shear walls with M/Vd ratios greater than or equal to 1, F_v is given by Equation 2-24. In effect, these limits provided an upper bound on the shear strength permitted in reinforced masonry members, no matter the amount of shear reinforcement that is provided.

$$F_v = \left(\frac{1}{2}\right) \left[4 - \left(\frac{M}{Vd}\right) \right] \sqrt{f'_m} \leq 120 - 45 \left(\frac{M}{Vd}\right) \quad (2-23)$$

$$F_v = 1.5\sqrt{f'_m} \leq 75 \text{ psi} \quad (2-24)$$

The UBC WSD provisions for reinforced masonry do not distinguish between in-plane shear and out-of-plane shear.

2.2.2 UBC Strength Design (SD)

The UBC SD shear design provisions are given in UBC Section 2108 and apply only to reinforced masonry. The nominal shear strength, V_n , is generally given as the sum of the nominal shear strength provided by the masonry, V_m , and the nominal shear strength provided by the shear reinforcement, V_s , as shown in Equation 2-25.

$$V_n = V_m + V_s \quad (2-25)$$

For design, the factored shear force, V_u , shall not exceed the nominal shear strength, V_n , times the strength-reduction factor, ϕ , for shear of 0.60. However, the value of ϕ may be taken as 0.80 for any shear wall when its nominal shear strength exceeds the shear corresponding to development of its nominal flexural strength for the factored load combination.

The UBC SD shear provisions for beams are given in UBC Section 2108.2.3.6.2, for walls under out-of-plane loads in UBC Section 2108.2.4.5, and for walls under in-plane loads in UBC Section 2108.2.5.5.

For beams, the strength contribution from the masonry, V_m , is given by Equation 2-26. The nominal shear strength coefficient, C_d , is dependent on the M/Vd ratio. When M/Vd is less than or equal to 0.25, then C_d is =2.4. If M/Vd is greater than or equal to 1.00, then C_d is 1.2. For M/Vd values between 0.25 and 1.00, C_d is interpolated. The strength provided by the shear reinforcement, V_s , is given by Equation 2-27. The value of V_n shall not exceed $6.0A_e\sqrt{f'_m} \leq 380 A_e$ for beams with values of M/Vd less than or equal to 0.25, the maximum value of V_n is $4.0A_e\sqrt{f'_m} \leq 250 A_e$ for values of M/Vd greater than or equal to 1.0, and the

maximum value of V_n is linearly interpolated for M/Vd values between 0.25 and 1.0. Additionally, the value of V_m is taken as zero for any beam region subjected to net tension factored loads.

$$V_m = C_d A_e \sqrt{f'_m} \leq 63 C_d A_e \quad (2-26)$$

$$V_s = A_e \rho_n f_y \quad (2-27)$$

Transverse (shear) reinforcement is required in beams when V_u exceeds V_m . When transverse reinforcement is required, the following provisions apply:

- Shear reinforcement shall be a single bar with a 180-degree hook at each end.
- Shear reinforcement shall be hooked around the longitudinal reinforcement.
- The minimum transverse shear reinforcement ratio shall be 0.0007.
- The first transverse bar shall not be more than one fourth of the beam depth from the end of the beam.
- The maximum spacing shall not exceed half the depth of the beam nor 48 in.

For out-of-plane loads on walls which have vertical load stresses under unfactored loads greater than $0.04 f'_m$ but less than $0.2 f'_m$, and with a wall slenderness ratio h'/t that does not exceed 30, the nominal shear strength, V_n , is given by Equation 2-28.

$$V_n = 2A_{mv} \sqrt{f'_m} \quad (2-28)$$

For in-plane loads on walls, the nominal shear strength, V_n , is given by Equation 2-29. The first term in this equation represents the strength contribution from the masonry, V_m , and the second term represents the nominal shear strength provided by the shear reinforcement, V_s . The nominal shear strength coefficient, C_d , is 2.4 for M/Vd less than or equal to 0.25, C_d is 1.2 for

M/Vd greater than or equal to 1.00, and C_d is interpolated for M/Vd values between 0.25 and 1.00.

$$V_n = C_d A_{mv} \sqrt{f'_m} + A_{mv} \rho_n f_y \quad (2-29)$$

The value of V_n shall not exceed $6.0 A_e \sqrt{f'_m} \leq 380 A_e$ for walls with values of M/Vd less than or equal to 0.25, the maximum value of V_n is $4.0 A_e \sqrt{f'_m} \leq 250 A_e$ for values of M/Vd greater than or equal to 1.0, and the maximum value of V_n is linearly interpolated for M/Vd values between 0.25 and 1.0.

In the case that a shear wall has a nominal shear strength which exceeds the shear corresponding to the development of its nominal flexural strength, two shear regions exist. For all cross sections within the region defined by the base of the shear wall and a plane at a distance L_w above the base of the shear wall, the shear contribution from the masonry is taken as zero and the nominal shear strength shall be determined by Equation 2-30. The required shear strength for this region shall be calculated at a distance $L_w/2$ above the base of the shear wall, but not to exceed one half story height. For the other region, the nominal shear strength of the wall shall be determined by Equation 2-29.

$$V_n = A_{mv} \rho_n f_y \quad (2-30)$$

2.2.3 Uniform Building Code Notation

- A_e = effective area of masonry
- A_{mv} = net area of masonry section bounded by wall thickness and length of section in direction of shear force considered
- A_v = cross-sectional area of shear reinforcement

- b = effective width of rectangular section or width of flange for T and I sections
- b' = width of web in T or I section
- C_d = nominal shear strength coefficient
- d = distance from compression face of flexural member to centroid of longitudinal tensile reinforcement
- F_s = allowable tensile or compressive stress in reinforcement
- F_v = allowable shear stress in masonry
- f'_m = specified compressive strength of masonry
- f_v = computed shear stress due to design load
- f_y = specified yield strength of steel for reinforcement or anchors
- h' = effective height of wall
- j = ratio or distance between centroid of flexural compressive forces and centroid of tensile forces of depth, d
- M = maximum moment at the section under consideration
- s = spacing of reinforcement
- t = effective thickness of wall
- V = total design shear force
- V_n = nominal shear strength
- V_u = factored shear force
- ρ_n = ratio of distributed shear reinforcement on plane perpendicular to plane A_{mv}
- ϕ = strength-reduction factor

2.3 New Zealand Standard 4230:2004

The New Zealand Standard *Design of Reinforced Concrete Masonry Structures* (NZS, 2004) provisions for shear design are given in Section 10.3. The design shear force from ultimate limit state loads, V^* , shall not exceed the nominal shear strength, V_n , times the strength-reduction factor, ϕ , for shear of 0.75.

The nominal shear strength is given as the specified shear stress, v_n , times the effective area of the section, as given by Equation 2-31. The effective area, $b_w d$, is defined in Figure 2.1 for in-plane and out-of-plane loadings and for full and partial grouting.

$$V_n = v_n b_w d \quad (2-31)$$

The specified shear stress v_n consists of a contribution from the masonry, v_m , a contribution from any axial load, v_p , and a contribution from the shear reinforcement, v_s . The three components are defined by Equations 2-32, 2-33 and 2-34, respectively. The total shear stress, v_n , may not exceed the stress limit, v_g , as defined in Table 2.1.

$$v_m = C_1 + C_2 \gamma_{bm} \quad (2-32)$$

$$v_p = 0.9 \frac{N^*}{b_w d} \tan \alpha \quad (2-33)$$

$$v_s = C_3 \frac{A_v f_y}{b_w s} \quad (2-34)$$

The shear strength coefficient C_1 in the v_m equation accounts for the shear contribution from dowel action of the longitudinal steel and is defined by Equation 2-35 for longitudinal reinforcing ratios greater than 0.07%. The shear coefficient C_2 is a function of the wall aspect ratio. For h_e/L_w less than 0.25, C_2 is equal to 1.5. For h_e/L_w greater than one, C_2 is equal to 1.0. For h_e/L_w greater than or equal to 0.25 and less than or equal to 1.0, C_2 is define by Equation 2-

37. Beams and columns have a C_2 value equal to 1.0. Values for the basic shear stress, v_{bm} , are given in Table 2.1 as a function of observation type and stress condition. Observation type refers to the level of inspection specified during construction (see Table 2.2).

The shear stress contribution from axial load, v_p , must be less than or equal to $0.1f'_m$. In addition, the value of N^* must be less than or equal to $0.1f'_m A_g$. The α term accounts for differences in the effective location of the axial load in walls subjected to single or double bending (see Figure 2.2)

The coefficient C_3 in the v_s equation is defined as 0.8 for walls and 1.0 for beams and columns. The spacing of the shear reinforcement, s , must not exceed $0.5L_w$ for walls and not exceed $0.5d$ nor 600 mm for beams and columns. A minimum area of shear reinforcement, defined by Equation 2-38, must be provided.

$$C_1 = 33\rho_w \frac{f_y}{300} \quad (2-35)$$

$$\rho_w = \frac{A_s + A_{ps}}{b_w d} \quad (2-36)$$

$$C_2 = 0.42 \left[4 - 1.75 \left(\frac{h_e}{L_w} \right) \right] \quad (2-37)$$

$$A_v = \frac{0.15b_w s}{f_y} \quad (2-38)$$

2.3.1 New Zealand Standard Notation

- A_{ps} = area of prestressed reinforcement in flexural tension zone
- A_s = area of nonprestressed reinforcement
- A_v = area of shear reinforcement within a distance, s

- b_w = effective web width
- C_1, C_2, C_3 = shear strength coefficient
- d = distance from extreme compression fibre to centroid of longitudinal tension reinforcement, but needs not be less than $0.8L_w$ for walls and $0.8h$ for prestressed components
- f_y = lower characteristic yield strength of non-prestressed reinforcement
- h_e = effective wall height in the plane of applied loading
- L_w = horizontal length of wall, in direction of applied shear force
- N^* = design axial load in compression at given eccentricity
- s = spacing of shear reinforcement in direction parallel to longitudinal reinforcement
- V^* = design shear force at section
- v_{bm} = basic type-dependent shear strength of masonry
- v_g = maximum permitted type-dependent total shear stress
- V_n = nominal shear strength of section
- v_n = total shear stress corresponding to V_n
- α = angle formed between lines of axial load action and resulting reaction on a component
- ϕ = strength reduction factor
- ρ_w = ratio of longitudinal reinforcement in a wall

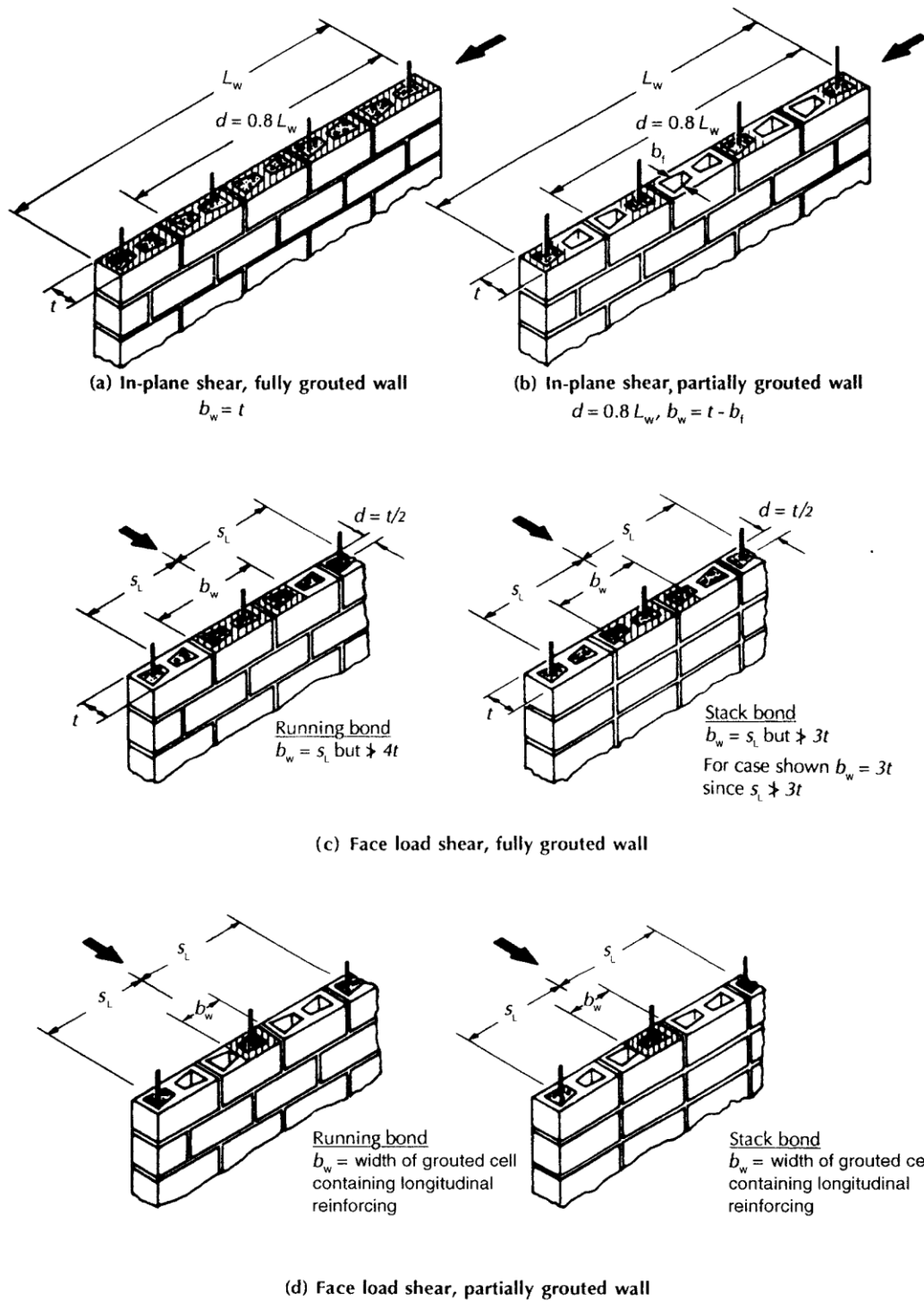


Figure 2.1 Effective Areas for Shear

Table 2.1 Type Dependent Nominal Strengths

Type of stress	Observation type of masonry		
	C	B	A
Compression; f'_m	4	12	12*
Basic shear provided by masonry, General conditions, v_{bm}	0.30	0.70	$0.2\sqrt{f'_m}$
Basic shear provided by masonry in potential plastic hinges of limited ductile structures, v_{bm}	N/A	0.50	$0.15\sqrt{f'_m}$
Basic shear provided by masonry in potential plastic hinges of ductile structures, v_{bm}	N/A	0	0
Maximum total shear, general conditions, v_g	0.80	1.50	$0.45\sqrt{f'_m}$

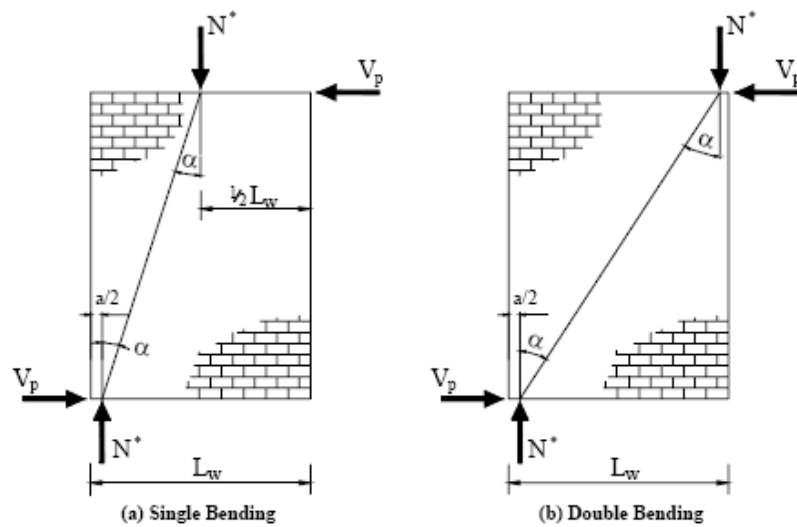


Figure 2.2 Contribution of Axial Load to Wall Shear Strength

Table 2.2 Observation Types, Admissible Use and Nominal Strengths

Observation type	Observation requirement	Admissible use	Maximum design compressive strength of masonry (MPa)
C	May be built without construction observation by a design engineer or a nominated representative thereof.	<ul style="list-style-type: none"> Elastic and nominally ductile structures. Face loaded walls designed for limited ductility. 	4
B	Shall be inspected by a design engineer or by a nominated representative thereof, who may be a mason deemed to comply with the competency requirements of NZS 4210. Such inspection shall establish that the design is being interpreted correctly and that the work is being carried out generally as specified.	Elastic, nominally ductile, limited ductile or ductile structures.	12
A	<p>In addition to the inspection required of Type B, Type A observation of masonry shall require construction supervision at all critical stages by a person approved by a design engineer, having appropriate knowledge/experience of correct masonry trade practices and reporting to a design engineer, such as to ensure that the standards of materials and workmanship applying on the job are of a consistently high quality commensurate with the achievement of superior strengths.</p> <p>Masonry shall be constructed using a mason deemed to comply with the competency requirements of NZS 4210.</p>	Elastic, nominally ductile, limited ductile or ductile structures.	<p>≥12</p> <p>A higher design f'_m may be used if substantiated by testing in accordance with Appendix B.</p>

2.4 Canadian Standards Association S304.1-04

The shear design provisions in the Canadian Standards Association *Design of Masonry Structures* (CSA S304.1, 2004) are given in Section 7.10 and are specified separately for unreinforced masonry and for reinforced masonry.

2.4.1 Unreinforced Masonry

The factored shear resistance, V_r , for unreinforced masonry walls is given by Equation 2-39. The first term defines the shear strength contribution from the masonry, and the second term is the shear strength increase due to axial stress. The strength reduction factor for masonry, ϕ_m , is specified as 0.60. For use in the equation, the ratio $M_f/V_f d_v$ is restricted to be greater than 0.25 and less than 1.0. For fully grouted walls, γ_g is equal to 1.0. For partially grouted walls, γ_g is equal to A_e/A_g but may not be greater than 0.5.

$$V_r = \phi_m \left(0.16 \left(2 - \frac{M_f}{V_f d_v} \right) \sqrt{f'_m} b_w d_v + 0.25 P_d \right) \gamma_g \leq 0.4 \phi_m \sqrt{f'_m} b_w d_v \gamma_g \quad (2-39)$$

For squat walls with aspect ratios, h_w/l_w , between 0.5 and 1.0, the maximum factored shear resistance may be increased to the value defined by Equation 2-40.

$$0.4 \phi_m \sqrt{f'_m} b_w d_v \gamma_g \left[2 - \left(\frac{h_w}{l_w} \right) \right] \quad (2-40)$$

For out-of-plane loading of unreinforced walls and columns, the factored shear resistance is defined by Equation 2-41.

$$V_r = \phi_m \left(0.16 \sqrt{f'_m} A_e + 0.25 P_d \right) \leq 0.4 \phi_m \sqrt{f'_m} A_e \quad (2-41)$$

2.4.2 Reinforced Masonry

The factored shear resistance, V_r , for reinforced masonry walls is given by Equation 2-42. The first two terms in the equation, accounting for the masonry and axial stress contributions to shear strength, are the same as those used for unreinforced masonry. The third term represents the contribution due to shear reinforcement. The strength reduction factor for masonry, ϕ_m , is specified as 0.60, and the strength reduction factor for steel, ϕ_s , is specified as 0.85. For squat walls with aspect ratios of between 0.5 and 1.0, the limit on factored resistance is defined by Equation 2-43. For out-of-plane loading of reinforced walls and columns, the shear resistance is the same as that for unreinforced sections, as defined by Equation 2-41.

$$V_r = \phi_m \left(0.16 \left(2 - \frac{M_f}{V_f d_v} \right) \sqrt{f'_m} b_w d_v + 0.25 P_d \right) \gamma_g + 0.60 \phi_s A_v f_y \frac{d_v}{s} \leq 0.4 \phi_m \sqrt{f'_m} b_w d_v \gamma_g \quad (2-42)$$

$$V_r = \phi_m \left(0.16 \left(2 - \frac{M_f}{V_f d_v} \right) \sqrt{f'_m} b d + 0.25 P_d \right) \leq 0.4 \phi_m \sqrt{f'_m} b d \quad (2-43)$$

2.4.3 Canadian Standards Notation

- A_e = effective cross-sectional area of masonry
- A_v = cross-sectional area of shear reinforcement
- b_w = overall web width
- d_v = effective depth for shear calculations, which need not be taken as less than 0.8 L_w for walls
- f'_m = compressive strength of masonry normal to bed joint at 28 days
- f_y = yield strength of reinforcement
- h_w = total wall height

- l_w = wall length
- M_f = factored moment
- P_d = axial compressive load on the section under consideration, based on 0.9 times dead load plus any factored axial load arising from bending in coupling beams where applicable
- s = spacing of shear reinforcement measured parallel to the longitudinal axis of the member
- V_f = shear under factored loads
- V_r = factored shear resistance
- γ_g = factor to account for partially grouted walls or columns or ungrouted walls and columns when calculating shear resistance
- ϕ_m = resistance factor for masonry
- ϕ_s = resistance factor for reinforcing bars

2.5 Shing et al.

Shing et al (1990a) developed a shear strength prediction equation based on laboratory tests producing shear failures in masonry walls. Shing's equation, given in Equation 2-44, accounts for the shear contributions from the masonry, axial load and shear reinforcement. In addition, the shear strength contribution from dowel action of vertical reinforcement is accounted for by the $\rho_v f_y$ term in the equation.

$$V_n = 0.0018(\rho_v f_y + \sigma_c) + 2 \bar{A} \sqrt{f'_m} + \left(\frac{L - 2d'}{s} - 1 \right) A_h f_y \quad (2-44)$$

2.5.1 Shing et al. Notation

- A = the net horizontal cross-sectional area
- A_h = area of a horizontal reinforcing bar
- d' = the distance of the extreme vertical steel from the edge of a wall
- f'_m = compressive strength of masonry
- f_y = yield strength of the steel
- L = the horizontal length of a wall
- s = the vertical spacing of the horizontal reinforcement
- V_n = nominal shear strength
- ρ_v = the ratio of the vertical steel
- σ_c = axial compressive stress

2.6 Anderson and Priestley (1992)

Anderson and Priestley developed an empirical equation to predict the ultimate shear strength of masonry walls. Anderson and Priestley's equation, given in Equation 2-45, includes the term b to account for the type of masonry used and the term k to account for strength degradation due to cyclic loading of walls. The b factor is specified as 0.24 for walls constructed out of concrete masonry units and as 0.12 for clay brick walls. The k factor is based on the flexural ductility ratio. For a ductility ratio less than 2.0, k is specified as 1.0, indicating that the wall has not suffered significant shear strength degradation. The k factor linearly decreases from 1.0 to zero as the ductility ratio increases from 2.0 to 4.0. When the flexural ductility ratio has reached a value of 4.0, the masonry has endured significant degradation and the masonry contribution is assumed to be negligible.

$$V_n = kb\sqrt{f'_m}wt + 0.25P + 0.5A_h f_{yh} d/s \quad (2-45)$$

2.6.1 Anderson and Priestley Notation

- A_h = area of a single horizontal reinforcing steel bar
- b = coefficient to account for the type of masonry used in construction
- d = distance from compression face to extreme tension bar
- f'_m = masonry compressive strength
- f_{yh} = yield strength of horizontal reinforcing steel
- k = ductility coefficient
- P = axial load
- s = spacing of horizontal shear reinforcement
- t = wall thickness
- V_n = nominal shear strength
- w = wall width (length)

CHAPTER 3

SHEAR WALL TEST DATA

Available results from laboratory tests of masonry walls failing in shear were collected from researchers from around the world. Much of the data was collected previously by NERHP (2000) and Voon (2007). For the selected data, all walls were fully grouted, subjected to in-plane shear loading, and the failure mode was determined to be shear. The data set include walls constructed of clay masonry and concrete masonry, resulting from tests performed by Shing et al (1990a), Masumura (1987), Sveinsson et al (1985) and Voon and Ingham (2006).

3.1 Shing et al.

Shing et al. (1990a) tested 22 masonry walls with dimensions of 72 in. by 72 in. The walls were subjected to a single bending loading arrangement, shown in Figure 3.1. Ten of the walls failed in shear, and it is the results for those tests that were included in the shear data set for this study. Eight wall specimens were constructed of nominal 6 in. x 8 in. x 16 in. concrete blocks, and the other two wall specimens were constructed of nominal 4 in. x 6 in. x 16 in. clay units. All walls were fully grouted and contained uniformly distributed horizontal and vertical reinforcement. The wall aspect ratio, h_e/L_w , was kept constant at 1.0. The compressive strength of masonry, f'_m , values were between 2,500 psi and 3,800 psi. The horizontal reinforcing ratio, ρ_h , varied from 0.0012 to 0.0022. The vertical reinforcing ratio, ρ_v , ranged from 0.0038 to 0.0074. The axial stresses on the wall specimens varied from 0 psi to 280 psi. The reported displacement ductility at failure, μ , ranged from 2.0 to 4.44. Data from the wall tests by Shing et al are given in Appendix A.

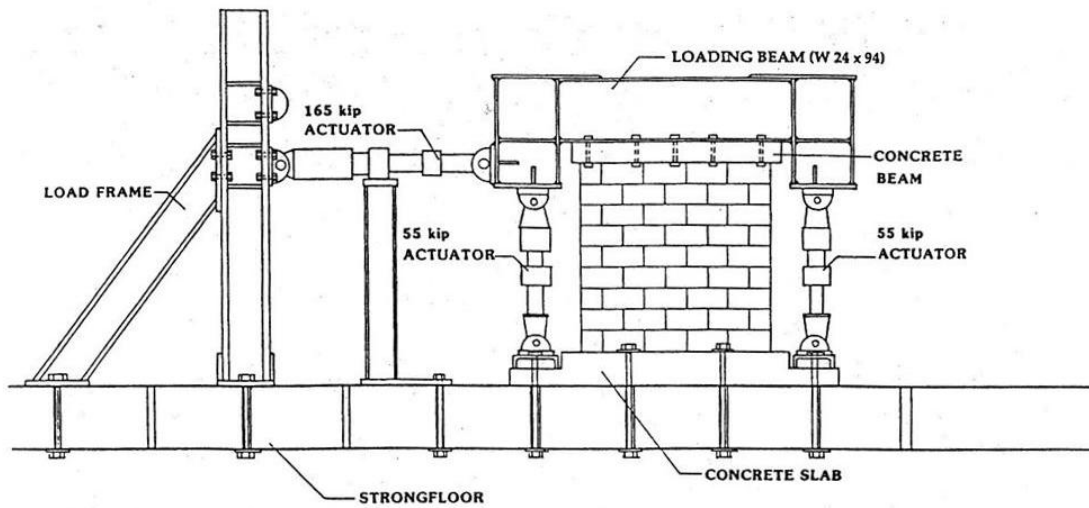


Figure 3.1 Shing et al.- Test Apparatus and Setup

3.2 Matsumura

Matsumura (1987) tested 80 masonry wall specimens, 18 of which failed in shear and were fully grouted. These walls included 14 walls constructed of concrete masonry and 4 walls constructed of clay masonry. The wall heights varied from 1700 mm to 1800 mm (67 in. to 71 in.), and the wall lengths ranged from 790 mm to 1590 mm (31 in. to 63 in.). The wall specimens were tested as cantilevers and subjected to horizontal shear loads. Figure 3.2 illustrates the test apparatus. The aspect ratio, h_e/L_w , varied from 0.57 to 1.14. The masonry compressive strength f'_m , values were between 21.8 MPa to 31.4 MPa (3160 psi to 4550 psi). The horizontal and vertical reinforcing ratios ranged from 0 to 0.0067 and from 0.00057 to 0.0115, respectively. The axial stresses on the wall specimens varied from 0.49 MPa to 1.96 MPa (71 psi to 284 psi). The reported displacement ductility, μ , ranged from 0.95 to 3.36. Data from the wall tests by Matsumura are given in Appendix A.

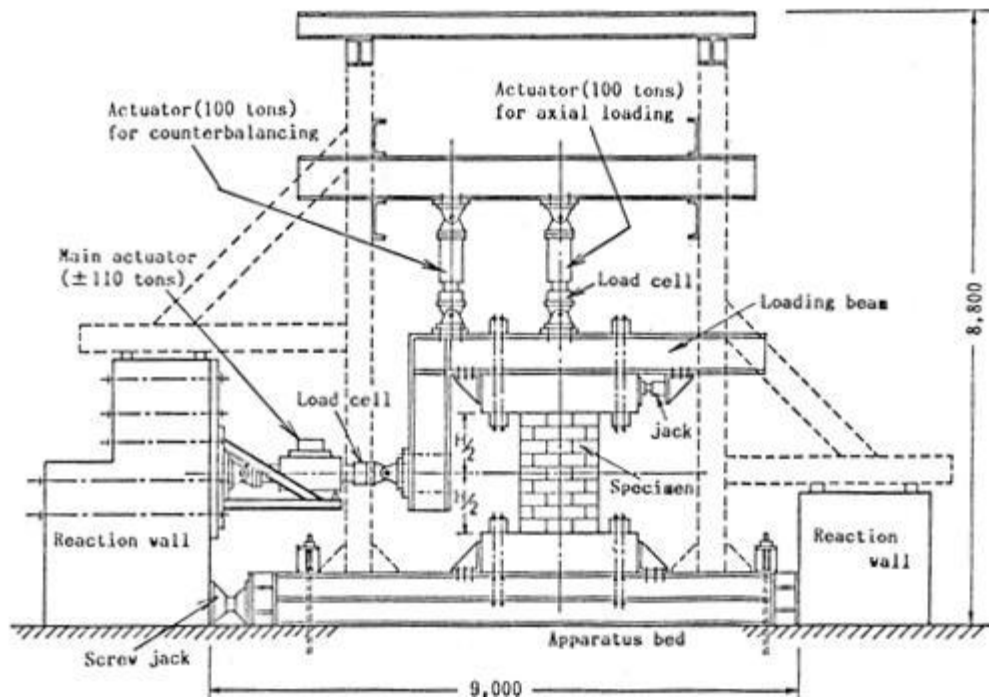


Figure 3.2 Matsumura - Test Apparatus and Setup

3.3 Sveinsson et al.

Sveinsson et al. (1985) tested twenty wall specimens that were all fully grouted and failed in shear. Half of the walls were constructed out of concrete masonry, and the other half were constructed of clay masonry. The wall specimens were loaded in double bending, resulting in an effective wall height, h_e , equal to half of the actual wall height. The wall aspect ratio, h_e/L_w , was kept constant at 0.58. The masonry compressive strength f'_m , values were between 2190 psi and 4000 psi. The horizontal and vertical reinforcing ratios ranged from 0.0008 to 0.0063 and from 0.0015 to 0.0064, respectively. The axial stresses on the wall specimens varied from 272 psi to 437 psi. The reported displacement ductility, μ , ranged from 2.2 to 6.26. Data from the wall tests by Sveinsson et al. are given in Appendix A.

3.4 Voon and Ingham

Voon and Ingham (2003) conducted tests on seven concrete masonry wall specimens. The walls were fully grouted and failed in shear when subjected to a horizontal shear force in single bending. The test setup is shown in Figure 3.3. The masonry compressive strength f'_m values were between 17.0 MPa and 24.3MPa (2470 psi and 3520 psi). The horizontal and vertical reinforcing ratios ranged from 0 to 0.0006 and from 0.0059 to 0.0097, respectively. The axial stresses on the wall specimens varied from 0 MPa to 0.5 MPa (0 psi to 72 psi). The reported displacement ductility, μ , ranged from 1.33 to 2.85. Data from the wall tests by Voon and Ingham are given in Appendix A.

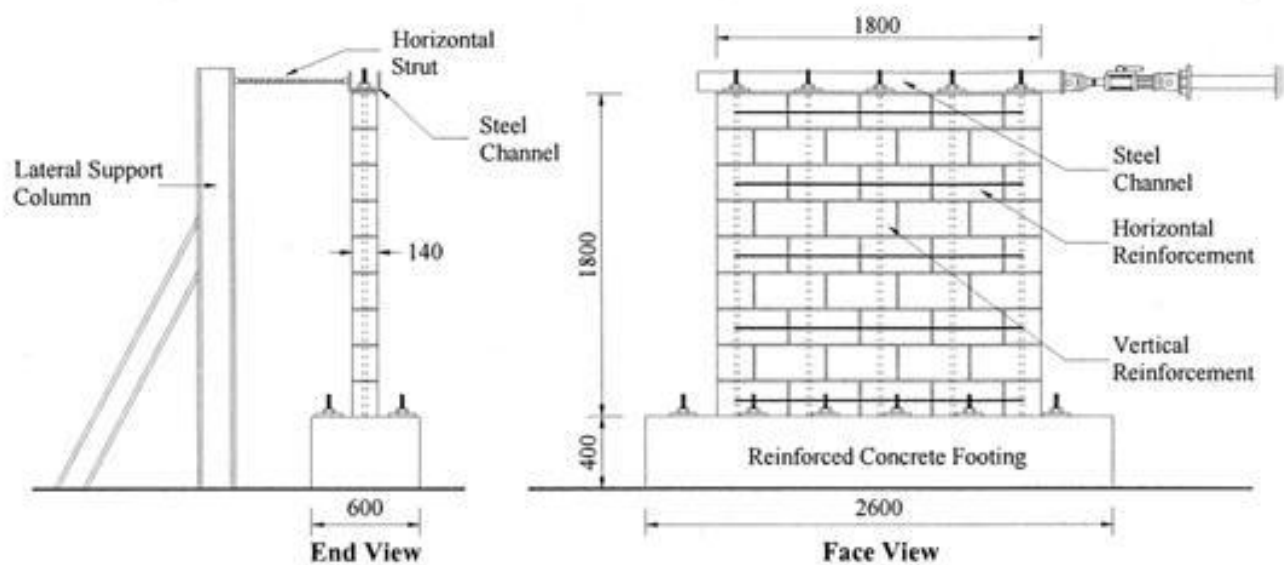


Figure 3.3 Voon and Ingham - Test Apparatus and Setup

CHAPTER 4

ANALYSIS

4.1 Interpretation of Shear Equations

To facilitate the evaluation of the effectiveness of the various code provisions and strength predication equations, consistent definitions of the equation variables were used. In addition, one set of units was also used for performing the comparisons (English units were chosen). In some cases, the original equations were modified to accommodate the consistent definitions of the variables. However, the resulting predicted shear strengths and allowable shear stresses are consistent with those produced by the original equations.

Several modifications were made to the variable definitions used in the MSJC shear provisions. The $M_u/V_u d_v$ term in the MSJC equations was replaced with the ratio of the effective wall height to the wall length, h_e/L_w . The effective wall height takes into account whether the wall is loaded in double bending or single bending. The variable P_u was also replaced with the level of axial stress, σ_n , multiplied by the wall cross-sectional area, A_n , defined as wall thickness, t , times the total wall length, L_w . The area of shear reinforcement, A_v , was relabeled as A_h . The spacing of the shear reinforcement, s , was relabeled as s_h . The yield stress in the shear reinforcement was labeled f_{yh} , rather than f_y . The variable d_v , which is defined by MSJC as the actual depth of a member in the direction of shear considered, was relabeled as the wall length, L_w .

The MSJC ASD shear provisions utilize allowable stresses rather than nominal strengths. The allowable stresses incorporate additional safety factors for application to service loads. In addition, the MSJC ASD provisions specify that, depending upon the level of service loads, either the masonry alone or the shear reinforcement alone must provide the needed shear

capacity. Since design service loads are not applicable to the reported failure loads, the ASD masonry design stress and the shear reinforcement design stress were each determined separately. A corresponding allowable shear force was then calculated by multiplying the specified allowable shear stress, F_v , by the applicable wall cross-sectional area, A_n , and then compared to the reported shear failure loads from the laboratory tests.

The UBC WSD shear provisions are the same as the MSJC ASD shear provisions, and thus these provisions were not considered in the evaluations. Variables in the UBC SD provisions were modified as follows. The variable A_{mv} in the UBC equations is the net area of the wall and was relabeled as A_n . The term in the shear reinforcement contribution, $A_{mv}\rho_n f_y$, was relabeled as $A_h(L_w/s_h)f_{yh}$.

The masonry, axial load and shear reinforcement contributions to shear strength in NZS 4230:2004 are specified in terms of stresses. The nominal shear strength is then obtained by multiplying the total shear stress by the effective wall area, td . The axial load term N^* was relabeled as is the applied axial stress, σ_n , multiplied by the wall cross-sectional area, A_n . Several variables in the shear contribution were relabeled: A_h for A_v , f_{yh} for f_y , and s_h for s . The NZS 4230:2004 is written for SI units. In order to utilize the NZS tables and figures, all calculations were first determined in SI units, and the resulting design strength was then converted into English units.

The shear provisions in CSA S304.1-04 include the term $M_f/V_f d_v$ to account for wall aspect ratio. Similar to the change made for the MSJC, this term was replaced with the ratio of the effective wall height, h_e , to the effective wall depth, d , defined as the distance from the compression face of wall to the extreme vertical reinforcement but not less than $0.8L_w$. The variable b_w is equivalent to t , and d_v was relabeled as d . The axial force P_u was represented as the

applied axial stress, σ_n , multiplied by a nominal area, A_n . The γ_g variable is equal to 1.0 for fully grouted walls, so this variable thus drops out for the walls considered. As before, A_h is equivalent to A_v , and s is equivalent to s_h . The ϕ factors were removed from the equations in order to compare a nominal strength to another nominal strength without application of material resistance factors. Finally, CSA provisions are specified in SI units, and in order to use English units, a $1/0.083$ conversion factor was applied to all terms with $\sqrt{f'_m}$.

The only changes in the shear strength prediction equation developed by Shing et al. were associated with changes in the subscripts of the variables while maintaining the same definition. The yield stress in the reinforcement was taken as f_{yv} for vertical reinforcement and f_{yh} for horizontal reinforcement, instead of f_y used in the original equation. The wall area, A , in Shing's equation is relabeled as A_n , L is relabeled as L_w , and s is relabeled as s_h in the adapted equation.

The wt terms in the Anderson and Priestley equation were replaced with A_n , maintaining the same meaning. The axial load term P , was exchanged with $\sigma_n A_n$. The horizontal spacing was defined with a s_h term rather than s .

The equations used to determine the masonry, axial load, and shear reinforcement contributions as specified by the various code provisions and strength prediction equations are summarized in Table 4.1. The calculated values resulting from the evaluated equations are given in Appendix B.

Table 4.1 Shear Prediction Equations

Source	Masonry	Horizontal Steel	Axial Stress	Equation
MSJC SD	$\left[4.0 - 1.75 \left(\frac{h_e}{L_w} \right) \right] A_n \sqrt{f'_m}$	$0.5 \left(\frac{A_h}{s_h} \right) f_{yh} \frac{L_w}{w}$	$0.25 \sigma_n A_n$	(4-1)
MSJC ASD V_m	$\left(\frac{h_e}{L_w} \right) < 1 \left(\frac{l}{3} \right) \left[4 - \left(\frac{h_e}{0.8 L_w} \right) \right] \sqrt{f'_m}$ $\left(\frac{h_e}{L_w} \right) \geq 1 \quad \sqrt{f'_m}$			(4-2)
MSJC ASD V_s		$\frac{A_h F_s}{s_h t}$		(4-3)
UBC SD	$C_d A_n \sqrt{f'_m}$	$A_h f_{yh} \frac{L_w}{s_h}$		(4-4)
NZ-2004	$C_1 + C_2 \left(\frac{y_{bm}}{t} \right) \left(\frac{0.8 L_w}{d} \right)$	$C_3 A_h f_{yh} \frac{0.8 L_w}{s_h}$	$0.9 \sigma_n A_n \tan \alpha$	(4-5)
CANADIAN STANDARD	$0.16 \left(2 - \frac{h_e}{d} \right) \sqrt{f'_m} t \left(\frac{0.8 L_w}{d} \right)$	$0.60 A_h f_{yh} \frac{0.8 L_w}{s_h}$	$0.25 \sigma_n A_n$	(4-6)
SHING ET AL	$0.0018 \rho_v f_y + 2 \left(\frac{A_n}{s_h} \right) \sqrt{f'_m}$	$\left(\frac{L_w - 2d'}{s_h} - 1 \right) A_h f_{yh}$	$0.0018 \sigma_n A_n \sqrt{f'_m}$	(4-7)
ANDERSON AND PRIESTLEY	$bk \sqrt{f'_m} A_n$	$0.5 A_h f_{yh} \frac{d}{s_h}$	$0.25 \sigma_n A_n$	(4-8)

4.2 Statistical Evaluations

All of the various code and proposed equations were evaluated based on how well they predicted the reported shear capacities of the walls. The first method explored for evaluating the effectiveness of the various equations was a statistical evaluation and comparison. The ratio of test strength to the predicted strength (V_{test}/V_n) was calculated for each of the walls in the

compiled data set. A ratio of one indicates that the equation does a perfect job of predicting the wall shear capacity. A value greater than one means that the equation is conservative, and a ratio less than one indicates that the equation is unconservative. For the MSJC ASD equations, the ratios should be larger than one because they include a factor of safety for application to design using service loads. Table 4.2 lists the mean, standard deviation, coefficient of variation, minimum value, maximum value and 5th percentile value obtained for each of the various code and predicted strength equations. The fifth percentile values were calculated assuming a normally distributed data set.

Table 4.2 Statistical Comparisons of Design Equations

Shear Equation	V_{test}/V_n					
	Mean	Standard Deviation	Coeff. Of Variation	Minimum Value	Maximum Value	5th Percentile
MSJC SD/NEHRP	1.16	0.17	0.15	0.77	1.55	0.88
MSJC ASD V_m	8.51	2.09	0.25	3.83	13.65	5.08
MSJC ASD V_s	9.62	4.59	0.48	3.99	24.71	2.07
UBC	1.51	0.37	0.25	0.86	3.11	0.90
CSA	1.50	0.22	0.15	0.96	1.95	1.16
Shing et al.	1.12	0.24	0.21	0.54	1.66	0.72
NZS	1.38	0.26	0.19	0.85	2.05	1.01
Anderson and Priestley	1.35	0.40	0.30	0.82	2.28	0.69

The mean values from the MSJC SD and Shing equations are the closest to 1.0, indicating that these equations provide the best predictions of mean shear strength. The MSJC ASD mean values exceeded 8.5, which is higher than would be expected even taking into account the additional factor of safety present with allowable stress design. The smallest

standard deviation value, and therefore least varying equation, was the MSJC SD, with the CSA, Shing, and the NZS equations also having low values. The coefficient of variation (COV) was also calculated to quantify the true scatter. The lowest COV values were the MSJC SD and the CSA. The COV values for the MSJC ASD equations were among the largest, indicating significant variation in the accuracy of the ASD equations.

The fifth percentile value is the ratio whereby 95 percent of the walls failed at loads equal to or higher than are predicted by code or proposed equation. The fifth percentile value for the MSJC SD provisions is 0.88, which is above the material resistance factor value of $\phi = 0.8$ specified by the MSJC. The fifth percentile values for the UBC, NZS, and CSA equations also are at or above 0.8.

As an overall assessment of the statistics shown in Table 4.2, the best performance of the various code and proposed equations is obtained using the MSJC SD equation.

4.3 Test Parameter Evaluations

After the statistics were calculated and the general behavior of the equation was better understood, plots were created to isolate the effects of individual specimen parameters. These plots illustrate the relationship between a particular variable and the ratio of test strength to predicted strength by the various code and predictive equations. The parameters evaluated were: masonry compressive strength (f'_m), amount of shear reinforcement ($\rho_h f_{yh}$), level of axial compressive stress (σ_n), amount of vertical reinforcement ($\rho_v f_{yv}$), displacement ductility (μ), and wall aspect ratio (h_e/L_w).

The ideal equation will have data points aligned along the horizontal line of $V_{test}/V_n = 1.0$. This situation is the result of an equation that predicts the test value accurately and handles the

isolated parameter correctly. Data scatter and bias are measures of the effectiveness of the predictive equation for accounting for the effects of the parameter. The more scatter, the less accurate the equation is at predicting strength. A bias, meaning a trend to increase or decrease as the parameter varies, indicates that the equation is not accounting for the variable properly. A negative bias indicates that the equation over-predicts the effects of the parameter, and a positive bias means that the code under-predicts the effects of the parameter. The test parameter evaluations are grouped according to the code or predictive equation being evaluated and are shown in Figures 4.1 through 4.8.

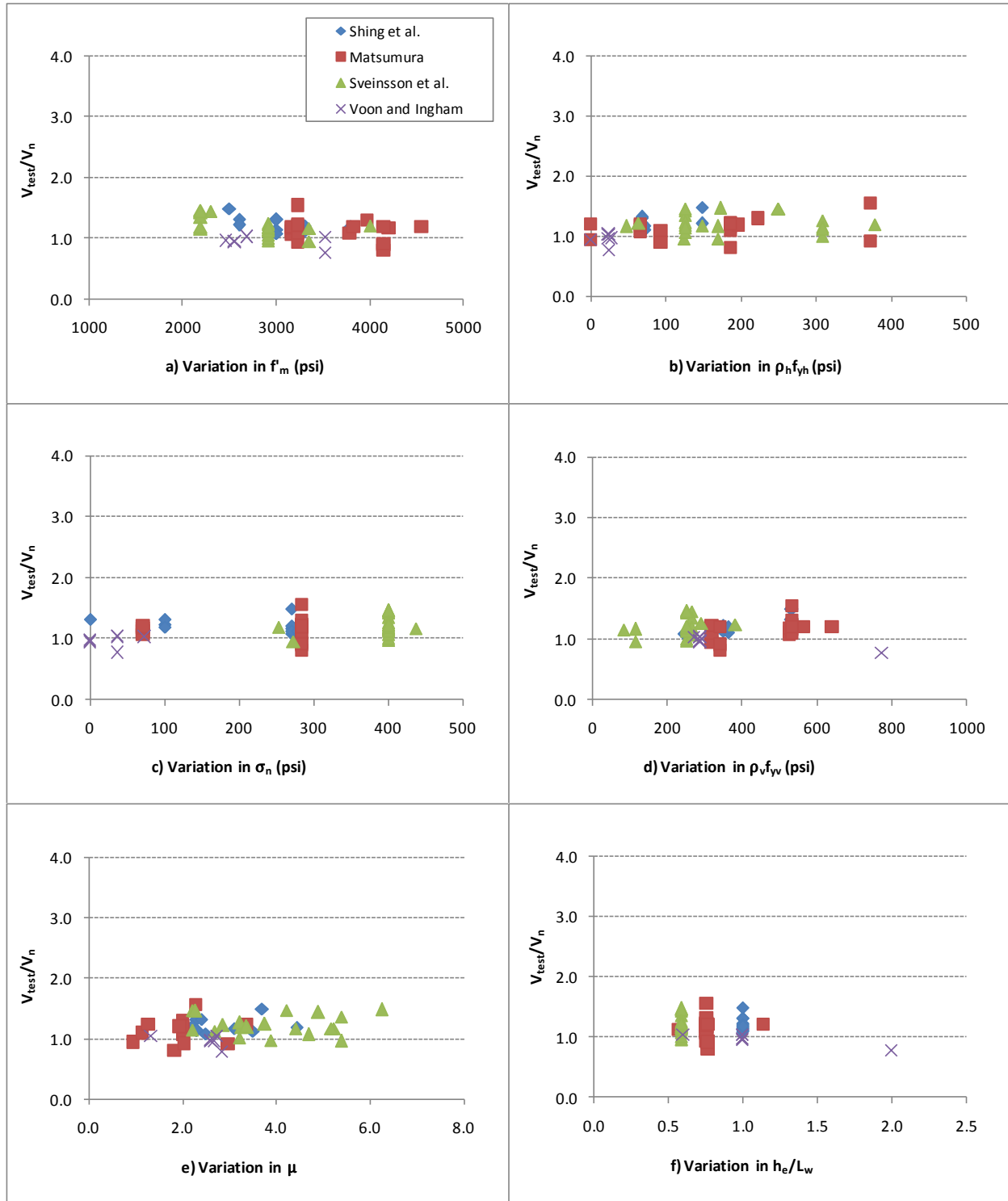


Figure 4.1 Effectiveness of MSJC SD Shear Provisions

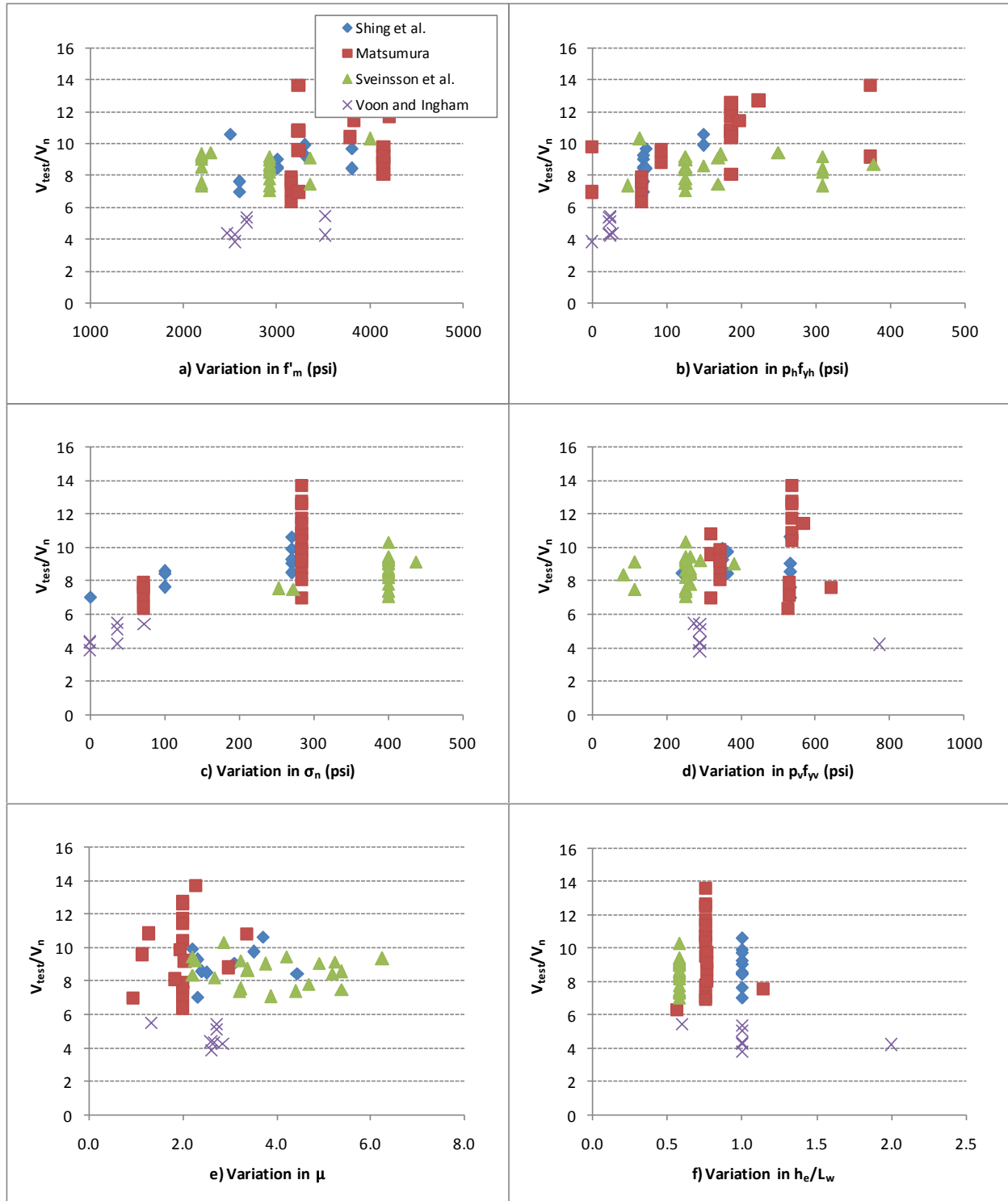


Figure 4.2 Effectiveness of MSJC ASD V_m Shear Provisions

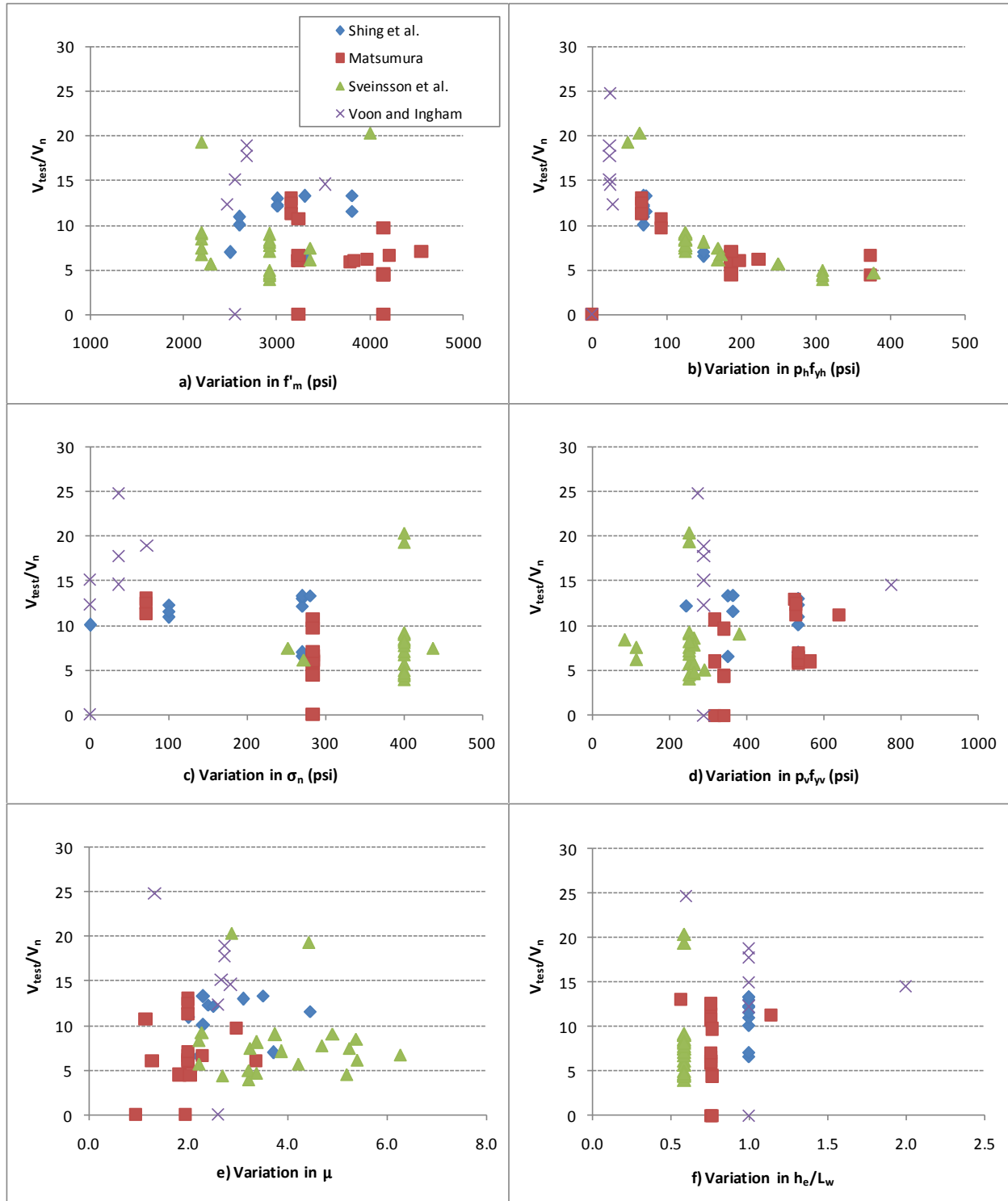


Figure 4.3 Effectiveness of MSJC ASD V_s Shear Provisions

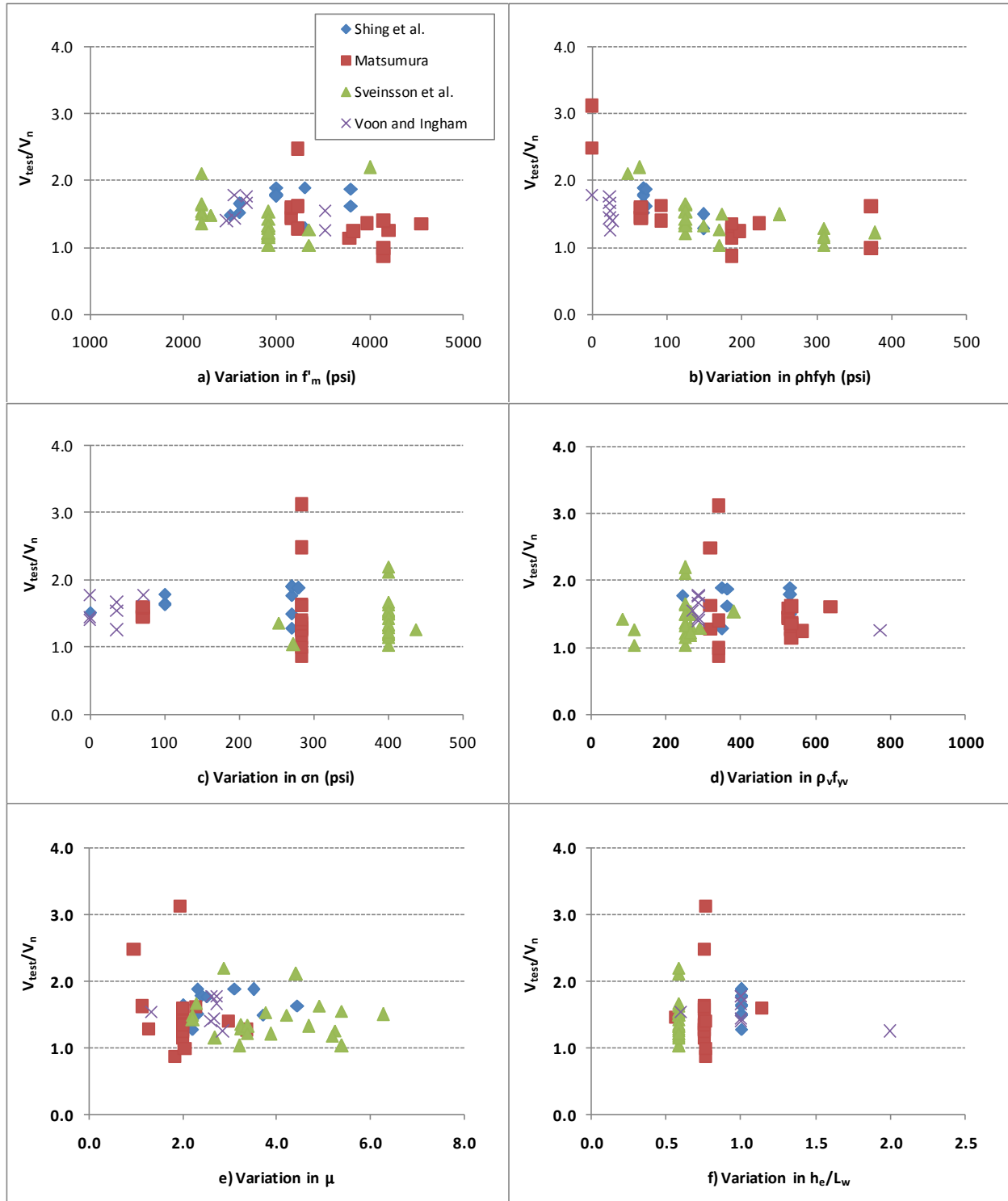


Figure 4.4 Effectiveness of UBC SD Shear Provisions

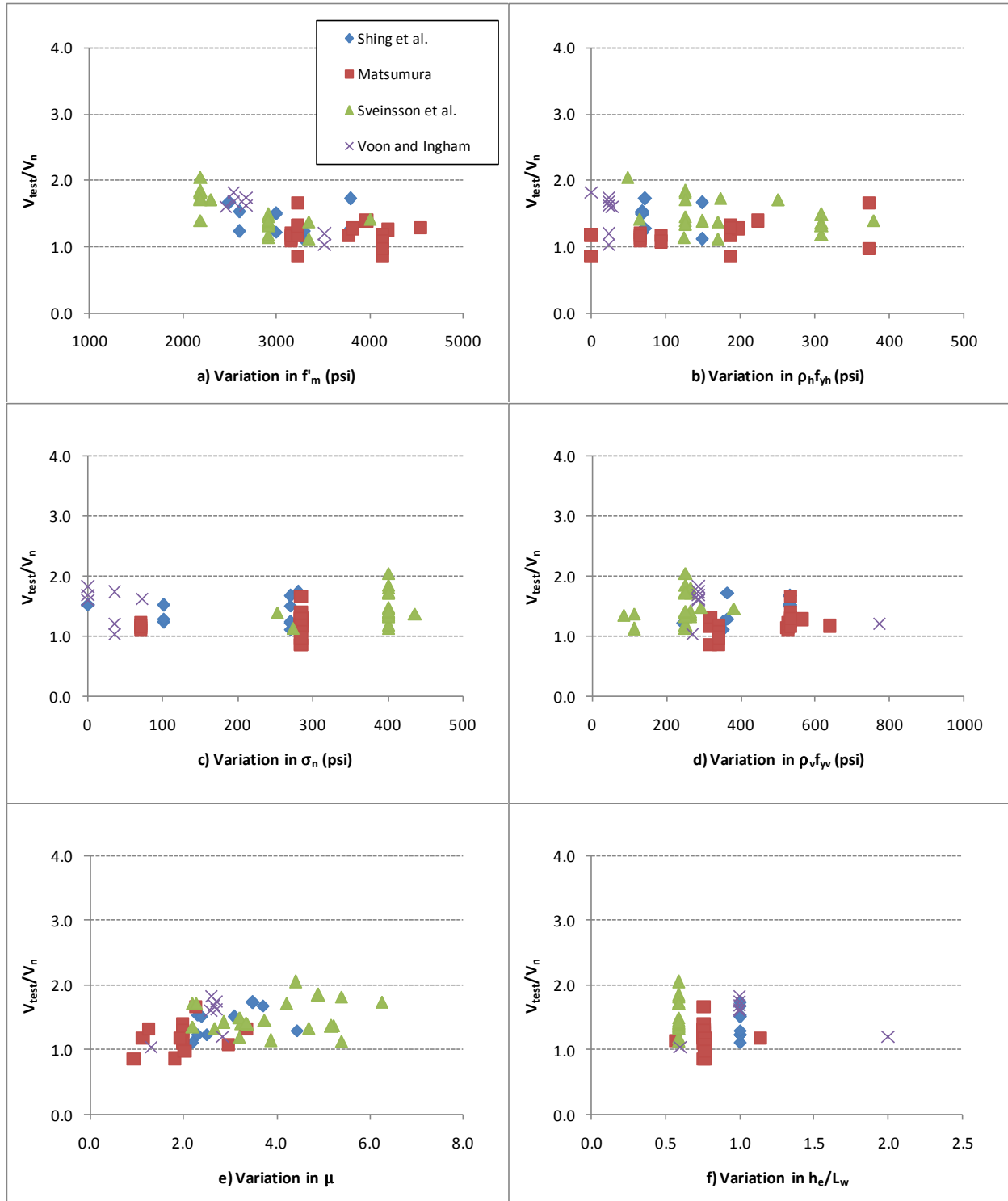


Figure 4.5 Effectiveness of NZS Shear Provisions

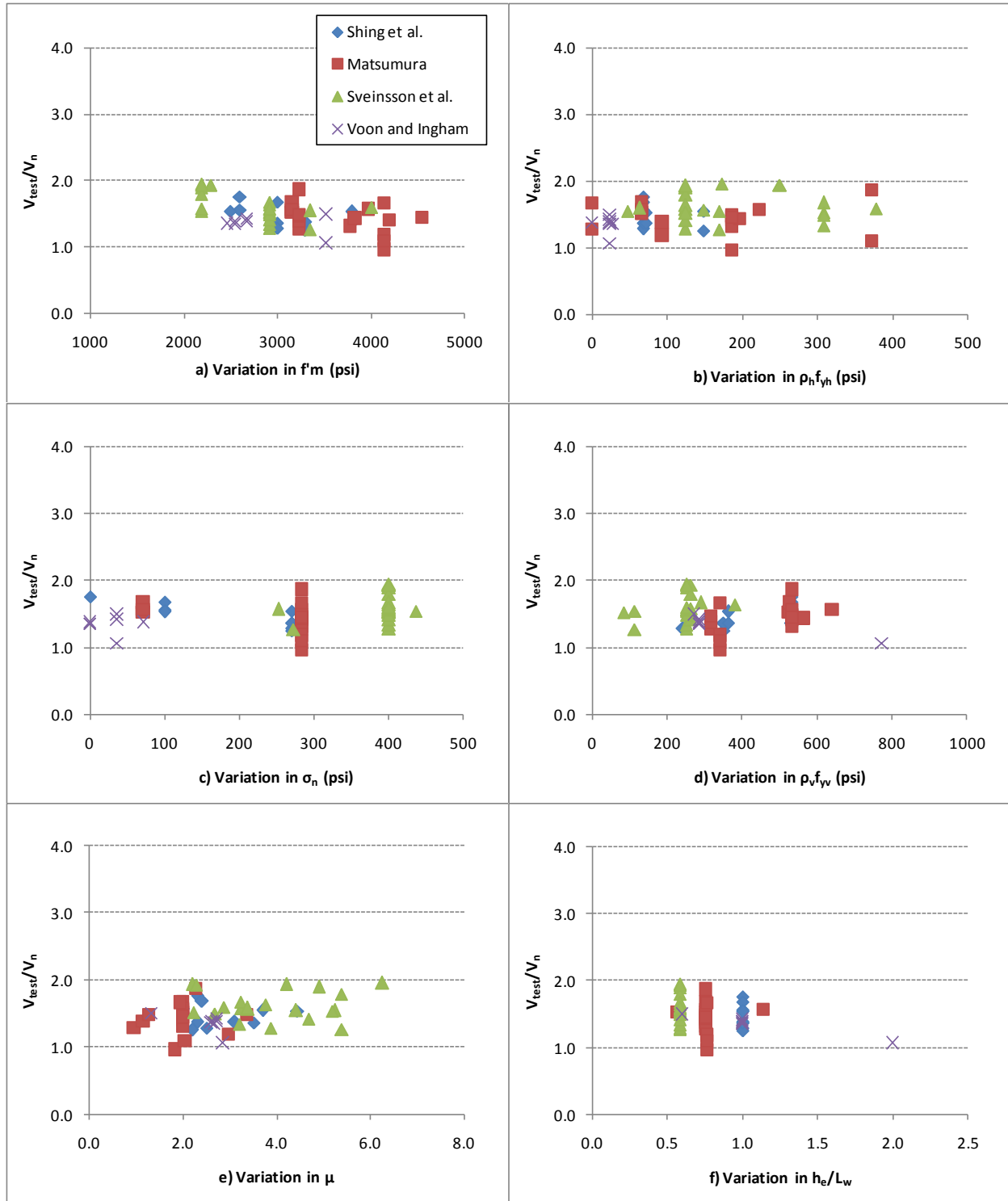


Figure 4.6 Effectiveness of CSA Shear Provisions

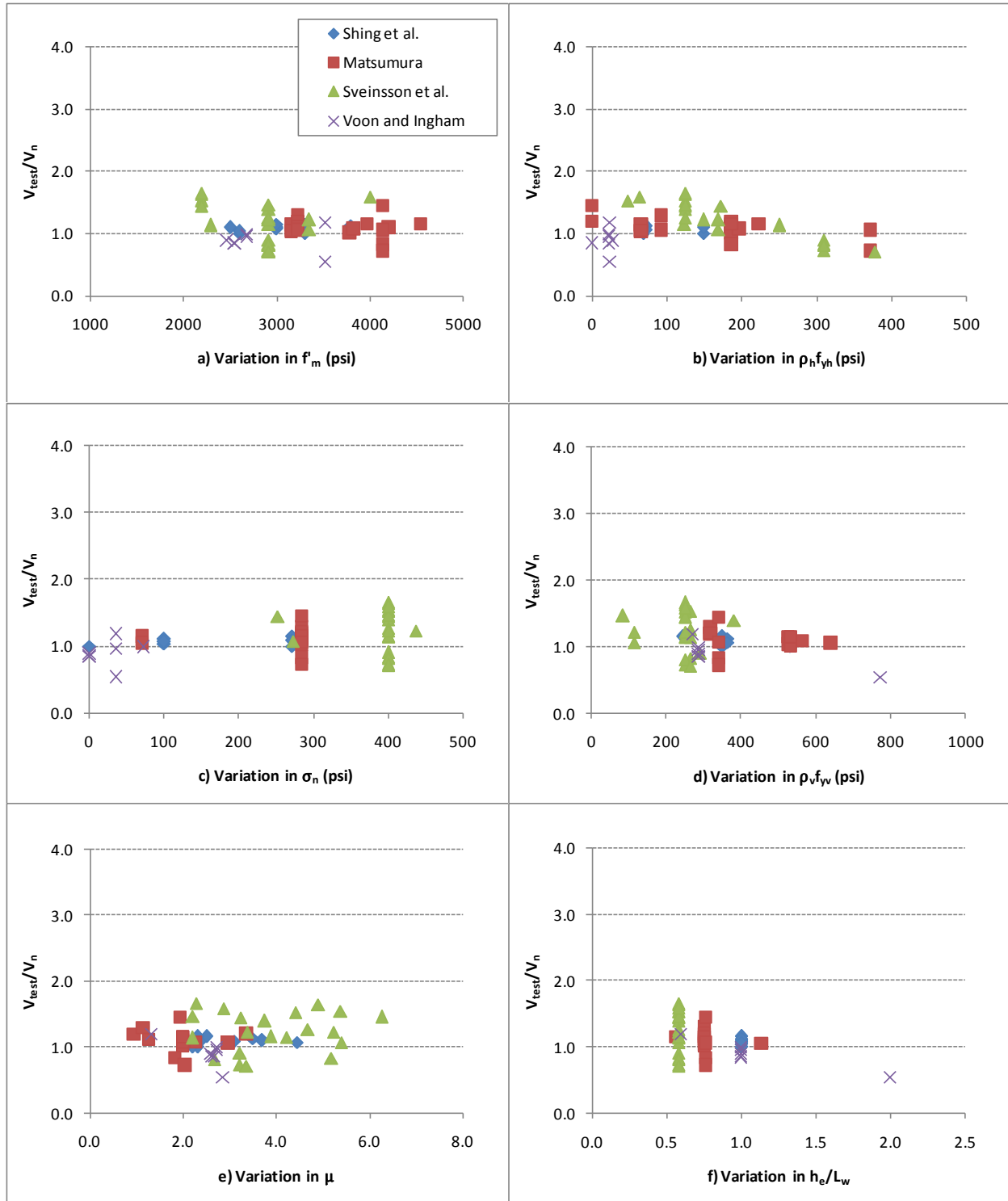


Figure 4.7 Effectiveness of Shing Shear Prediction Equation

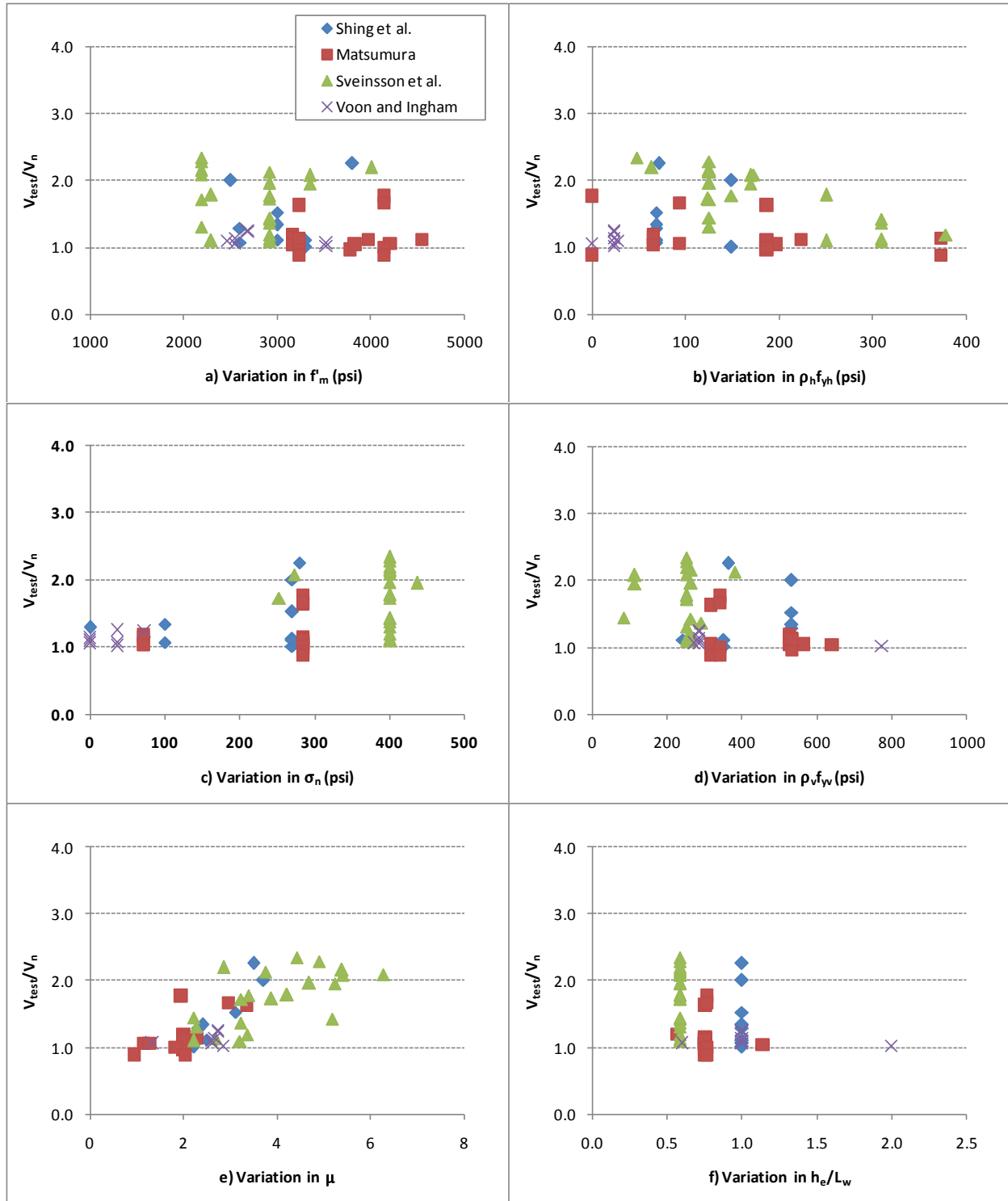


Figure 4.8 Effectiveness of Anderson and Priestley Predictive Equations

The best code and predictive equations at accounting for the effects of varying values of f'_m on shear strength are obtained using the MSJC SD provisions and the Shing predictive equation. Both equations produce the least scatter and the smallest bias. The MSJC SD, Shing, NZS and the CSA equations all reasonably account for the effects of varying amounts of shear reinforcement on shear capacity. The MSJC SD and Shing equations provide the best at accounting for the effects of axial loading on shear strength. The MSJC SD is the most accurate equation for predicting for the effects of varying vertical reinforcement, even though the MSJC SD equation does not have a vertical reinforcement term in the equation. Further, the performance of the NZS and Shing equations are less favorable despite explicitly including the contribution of vertical steel. The best equations for predicting the effects of displacement ductility level were the MSJC SD and Shing equations, both of which do not incorporate a μ value. The Anderson and Priestly and the NZS equations include a μ term and yet displayed significant bias. The NZS equation is the best at accounting for wall aspect ratio on shear strength, exhibiting virtually no bias and small scatter. The MSJC SD and the UBC equations were also successful in accounting for the effects of wall aspect ratio; however the UBC had a slight positive bias, and the MSJC SD had a slight negative bias.

The MSJC SD equation is the best predictor of shear strength for four of the six variables examined. It also was one of the top predictive equations for the other two variables considered. Overall, it demonstrated the best performance of the code and predictive equations evaluated for accounting for the effects of the various parameters considered in the evaluation.

The MSJC ASD equation considering only V_m , given in Figure 4.2, has a significant positive slope as the parameter $\rho_h f_{yh}$ is increased, with resulting ratios of $V_{test}/V_{predicted}$ reaching 12 and higher. This trend reflects that this equation is increasingly conservative when additional

shear steel is added. The MSJC ASD equation considering only V_s , given in Figure 4.3, has a significant negative slope as the parameter $\rho_h f_{yh}$ is increased. For small amounts of reinforcement, the resulting ratios of $V_{test}/V_{predicted}$ reach 20 and higher. These observations indicate that it is more accurate to add the masonry and shear reinforcement contributions together rather than choosing one or the other.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This research investigated the effectiveness of eight different code provisions and proposed design equations for predicting the strengths of masonry walls failing in shear under in-plane loading. Shear data used in this research was collected previously by NEHRP (2000) and by Voon (2007) and consisted of fifty six walls constructed of either concrete or clay masonry, all of which were fully grouted. Variables encompassed by the specimens included different masonry compressive strengths, reinforcement ratios, axial loads, displacement ductility and wall aspect ratios. These six variables were isolated and evaluated to determine which equations best accounted for the selected parameters. The ratios of test strength to predicted strength were analyzed statistically for each provision or equation. The mean, standard deviation, coefficient of variation, minimum value, maximum value, and fifth percentile were determined and compared. The ability of each equation to account for the effects of the various wall test parameters was also evaluated in terms of scatter and bias. Based on the performance of each equation in the statistical analysis as well as in the test parameter analysis, the most accurate equation was selected. Recommendations were then made for improving the effectiveness of the existing MSJC shear design provisions.

5.2 Conclusions

Results from this study of the effects of the various wall parameters indicate that it is appropriate to combine the shear contribution from the masonry with that resulting from the

shear reinforcement. Considering only one component at a time, as is specified by the current MSJC ASD provisions, results in inaccuracy and is overly conservative.

The wall parameter evaluation showed that several of the design equations performed well for a particular parameter despite not explicitly incorporating that parameter in the equation. The MSJC SD provisions performed well with respect to the displacement ductility level and amount of vertical reinforcement, even though these parameters are not included in these provisions. Further, the performance of other equations which included these parameters did not perform as well as the MSJC SD provisions.

Results from this study show that the MSJC ASD provisions produce more conservative predictions of performance when compared to the results of the strength-based provisions. Some of this is due to the safety factor incorporated for performing service load design. However, even considering this additional safety factor, the results obtained using the MSJC ASD are clearly overly conservative.

Of the code and predictive equations considered in this study, the MSJC SD provisions provided the best results. The MSJC SD provisions produced one of the lowest mean values as well as the lowest standard deviation and best coefficient of variation compared to the other equations. The MSJC SD provisions also produced the least amount of scatter and smallest bias in terms of accounting for the effects of the wall variables on shear strength.

5.3 Recommendations

Among the code and proposed shear design equations evaluated in this study, the MSJC SD provisions were shown to be the most accurate. However, there are aspects of these provisions in which improvement can be made.

The current MSJC SD equation for the nominal shear strength is shown in Equation 5-1.

$$V_n = \left[4.0 - 1.75 \left(\frac{M_u}{V_u d_v} \right) \right] A_n \sqrt{f'_m} + 0.25 P_u + 0.5 \left(\frac{A_v}{s} \right) f_y d_v \quad (5-1)$$

The current MSJC provisions do not take into account the loss of masonry shear strength in plastic hinging regions. It is proposed that Equation 5.1 be modified to include an α factor applied to the first term in the equation (associated with the shear strength of the masonry) to account for strength degradation in plastic hinging regions. The proposed α factor has a value of 1.0 for wall ductility ratios of 2.0 or less, and it decreases linearly to zero as the ductility ratio increases from 2.0 to 4.0, as shown in Figure 5.1. The definition of α and the approach for accounting for strength degradation in plastic hinging regions is the same as that used by Anderson and Priestley (1992). The proposed nominal shear strength equation is given as Equation 5-2.

$$V_n = \alpha \left[4.0 - 1.75 \left(\frac{M_u}{V_u d_v} \right) \right] A_n \sqrt{f'_m} + 0.25 P_u + 0.5 \left(\frac{A_v}{s} \right) f_y d_v \quad (5-2)$$

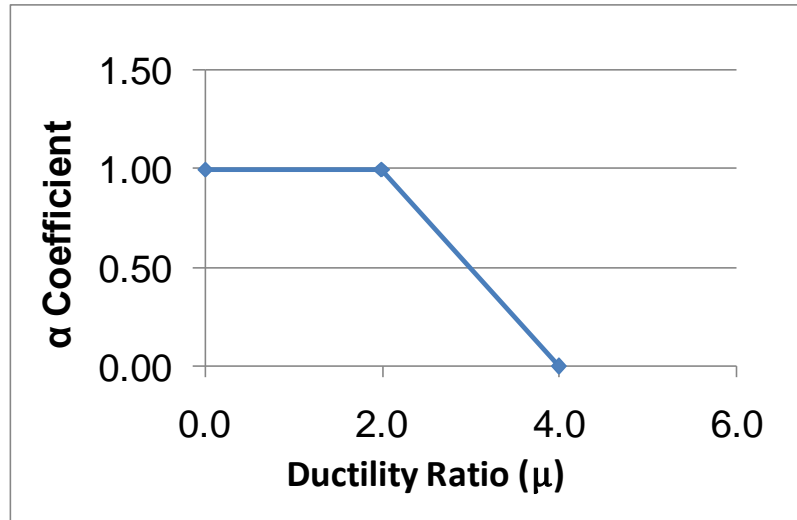


Figure 5.1 Ductility Reduction Factor α

As in the current MSJC provisions, the nominal shear strength by the proposed Equation 5-2 shall not exceed the limits given by Equation 5-3 for $M_u/V_u d_v$ ratios of less than or equal to 0.25 and by Equation 5-4 for $M_u/V_u d_v$ ratios greater than or equal to 1.0. The limit shall be interpolated for ratios between 0.25 and 1.0.

$$V_n \leq 6 A_n \sqrt{f' m} \quad (5-3)$$

$$V_n \leq 4 A_n \sqrt{f' m} \quad (5-4)$$

In the existing MSJC SD provisions, the contribution to nominal shear strength from horizontal shear reinforcement present in a wall is given by Equation 5-5.

$$V_s = 0.5 A_v f_y \left(\frac{d_v}{s} \right) \quad (5-5)$$

This equation incorporates a d_v/s term that represents the number of shear reinforcement bars engaged by an assumed 45-degree shear crack. However, for walls with aspect ratios less than unity (i.e., walls with lengths exceeding the height), the actual crack angle will be less than 45 degrees, and use of the d_v/s term in the design equation will result in a larger amount of shear reinforcement required for the walls than would be obtained based on a 45-degree shear crack angle. However, for uniformity of design approach and because of potentially greater degradation in the masonry contribution for squat walls because of sliding, it is recommended that d_v be used regardless of aspect ratio. This rationale for advocating for the continued use of the d_v/s term in the shear contribution equation is the same as that given by Paulay and Priestley (1992).

Based on the results obtained in this study, it is recommended that the current MSJC ASD provisions be modified. Specifically, it is proposed that the ASD shear provisions be based

on the proposed SD provisions but with a factor of safety to reflect allowable stress design using service loads. Based on the load and resistance factors specified for shear design in the current MSJC SD provisions, a factor of safety of 2.0 is proposed in addition to the safety factor associated with utilizing allowable steel stresses in the reinforcement. An additional change proposed for the MSJC ASD provisions is to modify the area term used to calculate shear stresses to account for partially grouted walls. Rather than using the gross area (bd), the net area (A_n) shall be used, as given in Equation 5-6. The proposed allowable shear stress is given by Equation 5-7, which includes contributions from the masonry and the shear reinforcement, rather than the existing condition of using either the masonry or the shear reinforcement contribution. The allowable shear stress provided by the masonry, F_{vm} , is computed using Equation 5-8. The masonry term also includes the axial load contribution which is not present in current MSJC ASD provisions. The $\frac{1}{2}$ factor in the equation provides the factor of safety of 2.0 proposed for allowable stress design. The contribution to the allowable shear stress provided by the horizontal shear reinforcement, F_{vs} , is computed using Equation 5-9. This equation incorporates the specified allowable stress in for the reinforcement (F_s), which provides the safety factor for allowable stress design associated with the steel contribution.

$$f_v = \frac{V}{A_n} \quad (5-6)$$

$$F_v = F_{vm} + F_{vs} \quad (5-7)$$

$$F_{vm} = \frac{1}{2} \left[\alpha \left(4.0 - 1.75 \left(\frac{M}{Vd_v} \right) \right) \sqrt{f'_m} + 0.25 \frac{P}{A_n} \right] \quad (5-8)$$

$$F_{vs} = 0.5 \left(\frac{A_v F_s}{b_w s} \right) \quad (5-9)$$

The F_v value from Equation 5-7 shall not exceed the limits given by Equation 5-10 for M/Vd_v ratios of less than or equal to 0.25 and by Equation 5-11 for M/Vd_v ratios greater than or equal to 1.0. The limit shall be interpolated for ratios between 0.25 and 1.0. These limits mimic the strength design limits with two changes: the limits are in terms of stress, and a safety factor of 2.0 has been incorporated.

$$F_v \leq 3\sqrt{f'_m} \quad (5-10)$$

$$F_v \leq 2\sqrt{f'_m} \quad (5-11)$$

5.4 Future Work

The scope of this research involved fully grouted masonry walls subjected to in-plane loading. Additional research on partially grouted walls would substantially enrich the current findings. In addition, exploration into the shear behavior of walls subjected to out-of-plane loading is needed. Finally, shear design provisions for masonry beams as well as unreinforced masonry walls should also be evaluated.

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APPENDIX A

Table A-1: Original Wall Test Data

Number	Label	h (in)	Lw (in)	t (in)	d (in)	s _h (in)	ρ_h ($\times 10^{-3}$)	f _{yh} (psi)	ρ_v ($\times 10^{-3}$)	f _{vy} (psi)	f _m (psi)	σ_n (psi)	V _{max} (kips)	μ_{vmax}
1	1-Shing	72.00	72.00	5.63	68.00	16.00	1.22	56000	7.40	72000	3000	270.00	102.50	3.10
2	2-Shing	72.00	72.00	5.63	68.00	16.00	1.22	56000	7.40	72000	2600	0.00	79.50	2.30
3	3-Shing	72.00	72.00	5.63	68.00	16.00	1.22	56000	7.40	72000	2600	100.00	86.50	2.00
4	4-Shing	72.00	72.00	5.63	68.00	16.00	1.22	56000	7.40	72000	3000	100.00	97.00	2.40
5	5-Shing	72.00	72.00	5.63	68.00	16.00	1.22	56000	3.80	64000	3000	270.00	96.00	2.50
6	6-Shing	72.00	72.00	5.63	68.00	16.00	2.22	67000	5.40	65000	3300	270.00	112.50	2.20
7	7-Shing	72.00	72.00	5.63	68.00	16.00	1.22	56000	5.40	65000	3300	270.00	105.00	2.30
8	8-Shing	72.00	72.00	5.63	68.00	16.00	2.22	67000	7.40	72000	2500	270.00	120.50	3.70
9	9-Shing	72.00	72.00	5.38	68.00	16.00	1.28	56000	5.60	65000	3800	280.00	105.50	3.50
10	10-Shing	72.00	72.00	5.38	68.00	16.00	1.28	56000	5.60	65000	3800	100.00	91.50	4.44
11	1-Matsumura	70.87	62.60	5.91	59.06	15.75	1.18	55840	9.43	55840	3162	71.07	90.61	2.00
12	2-Matsumura	70.87	46.85	5.91	43.31	15.75	1.18	55840	9.46	55840	3162	71.07	59.19	2.00
13	3-Matsumura	70.87	46.85	5.91	43.31	15.75	1.18	55840	9.46	55840	3162	71.07	65.21	2.00
14	4-Matsumura	70.87	31.10	5.91	27.56	15.75	1.18	55840	11.48	55840	3162	71.07	39.03	2.00
15	5-Matsumura	70.87	46.85	7.48	43.11	15.75	0.00	55840	5.71	55840	3234	284.27	73.19	0.95
16	6-Matsumura	70.87	46.85	7.48	43.11	15.75	1.67	55840	5.71	55840	3234	284.27	100.64	1.14
17	7-Matsumura	70.87	46.85	7.48	43.11	15.75	3.34	55840	5.71	55840	3234	284.27	113.09	3.36
18	8-Matsumura	70.87	46.85	7.48	43.11	15.75	3.34	55840	9.59	55840	3234	284.27	113.60	1.27
19	9-Matsumura	70.87	46.85	7.48	43.11	15.75	6.68	55840	9.59	55840	3234	284.27	143.34	2.28
20	10-Matsumura	70.87	46.85	7.48	43.11	15.75	3.34	55840	9.59	55840	4206	284.27	123.26	2.00
21	11-Matsumura	70.87	46.85	7.48	43.11	15.75	3.34	55840	9.59	55840	3785	284.27	109.28	2.00
22	12-Matsumura	70.87	46.85	7.48	43.11	15.75	4.00	55840	9.59	55840	3974	284.27	133.43	2.00
23	13-Matsumura	70.87	46.85	7.48	43.11	15.75	3.53	55840	10.13	55840	3829	284.27	119.96	2.00
24	14-Matsumura	70.87	46.85	7.48	43.11	15.75	3.34	55840	9.59	55840	4554	284.27	131.90	2.00
25	15-Matsumura	66.93	43.70	7.48	39.57	14.88	0.00	55840	6.12	55840	4148	284.27	94.82	1.94
26	16-Matsumura	66.93	43.70	7.48	39.57	14.88	1.67	55840	6.12	55840	4148	284.27	84.87	2.97
27	17-Matsumura	66.93	43.70	7.48	39.57	14.88	3.34	55840	6.12	55840	4148	284.27	77.99	1.83
28	18-Matsumura	66.93	43.70	7.48	39.57	14.88	6.68	55840	6.12	55840	4148	284.27	88.66	2.04

* Specimens with gray shading were constructed with Clay Masonry Units

Table A-1: Original Wall Test Data

Number	Label	h (in)	Lw (in)	t (in)	d (in)	s _h (in)	ρ_h ($\times 10^{-3}$)	f _{yh} (psi)	ρ_v ($\times 10^{-3}$)	f _{yv} (psi)	f _m (psi)	σ_n (psi)	V _{max} (kips)	μ_{max}
29	1-Sveinsson	55.98	47.99	7.64	45.00	11.18	2.87	58958	1.69	67457	3350	272.67	103.67	5.39
30	2-Sveinsson	55.98	47.99	7.64	45.00	11.18	2.87	58958	1.69	67457	3350	436.56	126.53	5.23
31	3-Sveinsson	55.98	47.99	5.63	45.00	11.18	3.94	63454	4.44	56666	2292	400.30	96.40	4.21
32	4-Sveinsson	55.98	47.99	5.63	45.00	11.18	3.94	63454	4.44	59466	2292	400.30	96.40	2.20
33	5-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	4.44	56666	2190	400.30	92.48	4.90
34	6-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	4.44	59466	2190	400.30	87.39	5.38
35	7-Sveinsson	55.98	47.99	5.63	45.00	7.99	0.75	63454	4.44	56666	2190	400.30	75.24	4.41
36	8-Sveinsson	55.98	47.99	5.63	45.00	15.71	2.72	63454	4.44	56666	2190	400.30	95.23	6.26
37	9-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	4.44	56666	2190	252.37	76.81	3.23
38	10-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	4.44	56666	2190	400.30	94.05	2.27
39	11-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.95	63454	4.44	56666	2915	400.30	72.11	3.87
40	12-Sveinsson	55.98	47.99	5.63	45.00	9.33	4.87	63454	4.44	56666	2915	400.30	75.24	3.20
41	13-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	6.74	56666	2915	400.30	92.09	3.75
42	14-Sveinsson	55.98	47.99	5.63	45.00	9.33	4.87	63454	4.59	63454	2915	400.30	94.05	3.22
43	15-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	4.44	59466	2915	400.30	79.55	4.68
44	16-Sveinsson	55.98	47.99	5.63	45.00	9.33	4.87	63454	4.44	59466	2915	400.30	86.21	5.18
45	17-Sveinsson	55.98	47.99	5.63	45.00	18.66	1.97	63454	1.48	56666	2915	400.30	85.43	2.21
46	18-Sveinsson	55.98	47.99	5.63	45.00	9.33	4.87	63454	4.44	56666	2915	400.30	83.86	2.68
47	19-Sveinsson	55.98	47.99	5.63	45.00	11.18	2.50	59466	4.44	56666	2915	400.30	88.17	3.38
48	20-Sveinsson	55.98	47.99	5.63	45.00	5.08	6.25	60466	4.44	59466	2915	400.30	88.96	3.36
49	21-Sveinsson	55.98	47.99	5.63	45.00	7.99	1.00	63454	4.44	56666	4003	400.30	105.42	2.86
50	1-Voon/Ingham	70.87	70.87	5.51	66.93	15.75	0.50	47137	6.23	46122	2553	0.00	47.02	2.67
51	2-Voon/Ingham	70.87	70.87	5.51	66.93	70.87	0.00	47137	6.23	46122	2553	0.00	41.92	2.61
52	3-Voon/Ingham	70.87	70.87	5.51	66.93	31.50	0.62	44962	6.23	46122	2466	0.00	47.59	2.60
53	4-Voon/Ingham	70.87	70.87	5.51	66.93	15.75	0.50	47137	6.23	46122	2683	72.52	58.92	2.73
54	5-Voon/Ingham	70.87	70.87	5.51	66.93	15.75	0.50	47137	6.23	46122	2683	36.26	55.52	2.73
55	6-Voon/Ingham	141.73	70.87	5.51	66.93	15.75	0.51	47137	9.70	79771	3524	36.26	46.45	2.85
56	7-Voon/Ingham	70.87	118.11	5.51	114.17	15.75	0.51	47137	5.90	46122	3524	36.26	131.24	1.33

* Specimens with gray shading were constructed with Clay Masonry Units

APPENDIX B

Number	Label	V _m							
		MSJC SD	MSJC ASD V _m	MSJC ASD V _s	UBC	NZS	CSA	Shing	Anderson and Priestley
1	1-Shing	49911	11340	0	26619	19500	34210	65640	28864
2	2-Shing	46465	11340	0	24781	34290	31847	61107	50757
3	3-Shing	46465	11340	0	24781	40341	31847	61107	59714
4	4-Shing	49911	11340	0	26619	34667	34210	65640	51314
5	5-Shing	49911	11340	0	26619	27209	34210	54076	48107
6	6-Shing	52347	11340	0	27919	36723	35879	61230	60546
7	7-Shing	52347	11340	0	27919	34683	35879	61230	57183
8	8-Shing	45563	11340	0	24300	5934	31229	59921	8783
9	9-Shing	53677	10836	0	28628	10545	36790	63343	8623
10	10-Shing	53677	10836	0	28628	40863	36790	63343	0
11	1-Matsumura	62557	14243	0	38248	50065	41432	61276	60107
12	2-Matsumura	41639	8291	0	23195	34348	25303	45907	44985
13	3-Matsumura	41639	8291	0	23195	34348	25303	45907	44985
14	4-Matsumura	23238	5143	0	12394	22226	15928	32573	29864
15	5-Matsumura	53344	10502	0	29596	52488	32416	51300	57631
16	6-Matsumura	53344	10502	0	29596	52488	32416	51300	57631
17	7-Matsumura	53344	10502	0	29596	12615	32416	51300	18442
18	8-Matsumura	53344	10502	0	29596	58412	32416	59073	57631
19	9-Matsumura	53344	10502	0	29596	37980	32416	59073	49563
20	10-Matsumura	60832	10502	0	33750	50362	36966	67365	65721
21	11-Matsumura	57711	10502	0	32018	47778	35069	63908	62348
22	12-Matsumura	59130	10502	0	32806	48953	35932	65480	63882
23	13-Matsumura	58041	10502	0	32202	48770	35270	65451	62706
24	14-Matsumura	63299	10502	0	35119	52405	38465	70097	68386
25	15-Matsumura	56001	9657	0	30460	43072	33858	55059	30439
26	16-Matsumura	56001	9657	0	30460	21609	33858	55059	15676
27	17-Matsumura	56001	9657	0	30460	45112	33858	55059	30439
28	18-Matsumura	56001	9657	0	30460	41120	33858	55059	29831
29	1-Sveinsson	63211	13838	0	38291	0	41585	46788	0
30	2-Sveinsson	63211	13838	0	38291	0	41585	46788	0
31	3-Sveinsson	38535	10201	0	23343	0	25351	31726	0
32	4-Sveinsson	38535	10201	0	23343	24467	25351	32015	33660
33	5-Sveinsson	37671	10201	0	22820	0	24783	31015	0
34	6-Sveinsson	37671	10201	0	22820	0	24783	31298	0
35	7-Sveinsson	37671	10201	0	22820	0	24783	31015	0
36	8-Sveinsson	37671	10201	0	22820	0	24783	31015	0
37	9-Sveinsson	37671	10201	0	22820	10166	24783	31015	14076
38	10-Sveinsson	37671	10201	0	22820	22839	24783	31015	31626
39	11-Sveinsson	43463	10201	0	26328	1980	28593	35784	1371
40	12-Sveinsson	43463	10201	0	26328	12185	28593	35784	8437
41	13-Sveinsson	43463	10201	0	26328	4069	28593	39206	2636
42	14-Sveinsson	43463	10201	0	26328	12129	28593	36825	8226
43	15-Sveinsson	43463	10201	0	26328	0	28593	36110	0
44	16-Sveinsson	43463	10201	0	26328	0	28593	36110	0
45	17-Sveinsson	43463	10201	0	26328	24860	28593	31379	18877
46	18-Sveinsson	43463	10201	0	26328	20106	28593	35784	13921
47	19-Sveinsson	43463	10201	0	26328	9444	28593	35784	6538
48	20-Sveinsson	43463	10201	0	26328	9812	28593	36110	6749
49	21-Sveinsson	50931	10201	0	30852	20347	33505	41932	14088
50	1-Voon/Ingham	44403	10937	0	23682	22099	30434	49676	37948
51	2-Voon/Ingham	44403	10937	0	23682	23096	30434	49676	39659
52	3-Voon/Ingham	43639	10937	0	23274	22862	29911	48822	39258
53	4-Voon/Ingham	45524	10937	0	24279	21635	31203	50931	37151
54	5-Voon/Ingham	45524	10937	0	24279	21635	31203	50931	37151
55	6-Voon/Ingham	52174	10937	0	27826	30637	35761	78674	38555
56	7-Voon/Ingham	114011	24087	0	69832	104839	74502	96226	111753

Number	Label	V _p							
		MSJC SD	MSJC ASD V _m	MSJC ASD V _s	UBC	NZS	CSA	Shing	Anderson and Priestley
1	1-Shing	27338	0	0	0	31015	27338	10787	27338
2	2-Shing	0	0	0	0	0	0	0	0
3	3-Shing	10125	0	0	0	12218	10125	3719	10125
4	4-Shing	10125	0	0	0	11748	10125	3995	10125
5	5-Shing	27338	0	0	0	33365	27338	10787	27338
6	6-Shing	27338	0	0	0	32895	27338	11314	27338
7	7-Shing	27338	0	0	0	32895	27338	11314	27338
8	8-Shing	27338	0	0	0	27725	27338	9848	27338
9	9-Shing	27090	0	0	0	32780	27090	12031	27090
10	10-Shing	9675	0	0	0	12573	9675	4297	9675
11	1-Matsumura	6568	0	0	0	14155	6568	2661	6568
12	2-Matsumura	4916	0	0	0	8026	4916	1991	4916
13	3-Matsumura	4916	0	0	0	8026	4916	1991	4916
14	4-Matsumura	3263	0	0	0	3410	3263	1322	3263
15	5-Matsumura	24906	0	0	0	40257	24906	10205	24906
16	6-Matsumura	24906	0	0	0	40257	24906	10205	24906
17	7-Matsumura	24906	0	0	0	40257	24906	10205	24906
18	8-Matsumura	24906	0	0	0	39850	24906	10205	24906
19	9-Matsumura	24906	0	0	0	39850	24906	10205	24906
20	10-Matsumura	24906	0	0	0	39443	24906	11637	24906
21	11-Matsumura	24906	0	0	0	38630	24906	11040	24906
22	12-Matsumura	24906	0	0	0	39037	24906	11312	24906
23	13-Matsumura	24906	0	0	0	38630	24906	11103	24906
24	14-Matsumura	24906	0	0	0	39850	24906	12109	24906
25	15-Matsumura	23232	0	0	0	37930	23232	10780	23232
26	16-Matsumura	23232	0	0	0	37930	23232	10780	23232
27	17-Matsumura	23232	0	0	0	37930	23232	10780	23232
28	18-Matsumura	23232	0	0	0	37930	23232	10780	23232
29	1-Sveinsson	24987	0	0	0	55291	24987	10420	24987
30	2-Sveinsson	40006	0	0	0	63797	40006	16683	40006
31	3-Sveinsson	27040	0	0	0	30410	27040	9325	27040
32	4-Sveinsson	27040	0	0	0	28529	27040	9325	27040
33	5-Sveinsson	27040	0	0	0	28529	27040	9117	27040
34	6-Sveinsson	27040	0	0	0	26648	27040	9117	27040
35	7-Sveinsson	27040	0	0	0	28529	27040	9117	27040
36	8-Sveinsson	27040	0	0	0	28529	27040	9117	27040
37	9-Sveinsson	17047	0	0	0	31037	17047	5747	17047
38	10-Sveinsson	27040	0	0	0	28529	27040	9117	27040
39	11-Sveinsson	27040	0	0	0	40442	27040	10518	27040
40	12-Sveinsson	27040	0	0	0	40442	27040	10518	27040
41	13-Sveinsson	27040	0	0	0	38874	27040	10518	27040
42	14-Sveinsson	27040	0	0	0	38561	27040	10518	27040
43	15-Sveinsson	27040	0	0	0	37934	27040	10518	27040
44	16-Sveinsson	27040	0	0	0	37934	27040	10518	27040
45	17-Sveinsson	27040	0	0	0	40442	27040	10518	27040
46	18-Sveinsson	27040	0	0	0	40442	27040	10518	27040
47	19-Sveinsson	27040	0	0	0	40442	27040	10518	27040
48	20-Sveinsson	27040	0	0	0	40442	27040	10518	27040
49	21-Sveinsson	27040	0	0	0	58312	27040	12325	27040
50	1-Voon/Ingham	0	0	0	0	0	0	0	0
51	2-Voon/Ingham	0	0	0	0	0	0	0	0
52	3-Voon/Ingham	0	0	0	0	0	0	0	0
53	4-Voon/Ingham	7081	0	0	0	9064	7081	2643	7081
54	5-Voon/Ingham	3541	0	0	0	4532	3541	1321	3541
55	6-Voon/Ingham	3541	0	0	0	2266	3541	1514	3541
56	7-Voon/Ingham	5901	0	0	0	12841	5901	2524	5901

		V _s							
Number	Label	MSJC SD	MSJC ASD V _m	MSJC ASD V _s	UBC	NZS	CSA	Shing	Anderson and Priestley
1	1-Shing	13835	0	7906	27670	17709	13281	18446	11068
2	2-Shing	13835	0	7906	27670	17709	13281	18446	11068
3	3-Shing	13835	0	7906	27670	17709	13281	18446	11068
4	4-Shing	13835	0	7906	27670	17709	13281	18446	11068
5	5-Shing	13835	0	7906	27670	17709	13281	18446	11068
6	6-Shing	30120	0	17263	60240	38553	28915	40160	24096
7	7-Shing	13835	0	7906	27670	17709	13281	18446	11068
8	8-Shing	30120	0	17263	60240	38553	28915	40160	24096
9	9-Shing	13870	0	7926	27740	17754	13315	18493	11096
10	10-Shing	13870	0	7926	27740	17754	13315	18493	11096
11	1-Matsumura	12179	0	6979	24358	15589	11692	15473	9743
12	2-Matsumura	9115	0	5224	18230	11667	8751	9345	7292
13	3-Matsumura	9115	0	5224	18230	11667	8751	9345	7292
14	4-Matsumura	6051	0	3468	12102	7746	5809	3217	4841
15	5-Matsumura	0	0	0	0	0	0	0	0
16	6-Matsumura	16340	0	9364	32681	20916	15687	16478	13072
17	7-Matsumura	32681	0	18728	65361	41831	31373	32955	26145
18	8-Matsumura	32681	0	18728	65361	41831	31373	32955	26145
19	9-Matsumura	65361	0	37457	130723	83662	62747	65911	52289
20	10-Matsumura	32681	0	18728	65361	41831	31373	32955	26145
21	11-Matsumura	32681	0	18728	65361	41831	31373	32955	26145
22	12-Matsumura	39138	0	22429	78277	50097	37573	39467	31311
23	13-Matsumura	34540	0	19794	69079	44211	33158	34830	27632
24	14-Matsumura	32681	0	18728	65361	41831	31373	32955	26145
25	15-Matsumura	0	0	0	0	0	0	0	0
26	16-Matsumura	15242	0	8735	30484	19510	14632	14336	12193
27	17-Matsumura	30484	0	17469	60967	39019	29264	28671	24387
28	18-Matsumura	60967	0	34938	121934	78038	58529	57342	48774
29	1-Sveinsson	31012	0	16832	62024	39695	29772	39840	24810
30	2-Sveinsson	31012	0	16832	62024	39695	29772	39840	24810
31	3-Sveinsson	33775	0	20439	67550	43232	32424	43390	27020
32	4-Sveinsson	33775	0	20439	67550	43232	32424	43390	27020
33	5-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
34	6-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
35	7-Sveinsson	6429	0	3891	12859	8229	6172	9114	5143
36	8-Sveinsson	23317	0	14110	46634	29846	22384	25555	18653
37	9-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
38	10-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
39	11-Sveinsson	16716	0	10116	33432	21397	16047	16264	13373
40	12-Sveinsson	41747	0	25264	83495	53437	40078	56850	33398
41	13-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
42	14-Sveinsson	41747	0	25264	83495	53437	40078	56850	33398
43	15-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
44	16-Sveinsson	41747	0	25264	83495	53437	40078	56850	33398
45	17-Sveinsson	16888	0	10220	33775	21616	16212	16430	13510
46	18-Sveinsson	41747	0	25264	83495	53437	40078	56850	33398
47	19-Sveinsson	20084	0	10808	40168	25707	19280	25801	16067
48	20-Sveinsson	51055	0	32423	102109	65350	49012	78571	40844
49	21-Sveinsson	8572	0	5188	17145	10973	8229	12152	6858
50	1-Voon/Ingham	4603	0	3125	9206	5892	4419	6137	3682
51	2-Voon/Ingham	0	0	0	0	0	0	0	0
52	3-Voon/Ingham	5444	0	3875	10888	6969	5226	4839	4355
53	4-Voon/Ingham	4603	0	3125	9206	5892	4419	6137	3682
54	5-Voon/Ingham	4603	0	3125	9206	5892	4419	6137	3682
55	6-Voon/Ingham	4695	0	3187	9390	6010	4507	6260	3756
56	7-Voon/Ingham	7825	0	5312	15650	10016	7512	12520	6260

Number	Label	V _n							
		MSJC SD	MSJC ASD V _m	MSJC ASD V _s	UBC	NZS	CSA	Shing	Anderson and Priestley
1	1-Shing	88731	11340	7906	54289	68224	74828	94873	67270
2	2-Shing	60300	11340	7906	52451	51999	45129	79554	61825
3	3-Shing	70425	11340	7906	52451	70268	55254	83273	80907
4	4-Shing	73871	11340	7906	54289	64123	57616	88081	72507
5	5-Shing	88731	11340	7906	54289	78282	74828	83310	86513
6	6-Shing	93062	11340	17263	88158	100911	89698	112704	111980
7	7-Shing	93062	11340	7906	55588	85286	76498	90990	95588
8	8-Shing	81000	11340	17263	81000	72213	78072	109928	60217
9	9-Shing	94637	10836	7926	56368	61079	77196	93868	46809
10	10-Shing	77222	10836	7926	56368	71189	59781	86133	20771
11	1-Matsumura	81304	14243	6979	62606	79809	59692	79409	76418
12	2-Matsumura	55670	8291	5224	41425	54041	38969	57244	57193
13	3-Matsumura	55670	8291	5224	41425	54041	38969	57244	57193
14	4-Matsumura	32553	5143	3468	24496	33381	25000	37112	37969
15	5-Matsumura	78251	10502	0	29596	86447	57322	61505	82538
16	6-Matsumura	92743	10502	9364	62277	86447	73009	77983	95610
17	7-Matsumura	92743	10502	18728	89200	86447	76842	94460	69493
18	8-Matsumura	92743	10502	18728	89200	86447	76842	102233	108682
19	9-Matsumura	92743	10502	21716	89200	86447	76842	135188	126758
20	10-Matsumura	105761	10502	18728	98431	98582	87628	111958	116772
21	11-Matsumura	100334	10502	18728	96501	93523	83131	107903	113399
22	12-Matsumura	102802	10502	21716	98431	95823	85176	116259	120099
23	13-Matsumura	100909	10502	19794	97054	94059	83608	111385	115244
24	14-Matsumura	110051	10502	18728	98431	102580	91182	115162	119437
25	15-Matsumura	79233	9657	0	30460	81002	57090	65838	53671
26	16-Matsumura	94475	9657	8735	60944	79048	71722	80174	51102
27	17-Matsumura	97439	9657	17469	90462	91318	81171	94509	78058
28	18-Matsumura	97439	9657	20117	90462	91318	81171	123180	101836
29	1-Sveinsson	108493	13838	16832	100315	92025	81800	97048	49797
30	2-Sveinsson	108493	13838	16832	100315	92025	81800	103310	64816
31	3-Sveinsson	66139	10201	16923	64789	56100	49867	84441	54060
32	4-Sveinsson	66139	10201	16923	64789	56100	49867	84730	87720
33	5-Sveinsson	64658	10201	10220	56595	50145	48750	56562	40550
34	6-Sveinsson	64658	10201	10220	56595	48264	48750	56845	40550
35	7-Sveinsson	64658	10201	3891	35678	36758	48750	49246	32183
36	8-Sveinsson	64658	10201	14110	63338	54843	48750	65687	45693
37	9-Sveinsson	64658	10201	10220	56595	54843	48750	53193	44633
38	10-Sveinsson	64658	10201	10220	56595	54843	48750	56562	72176
39	11-Sveinsson	74598	10201	10116	59760	63275	56245	62565	41784
40	12-Sveinsson	74598	10201	18847	73076	63275	56245	103152	68874
41	13-Sveinsson	74598	10201	10220	60103	63275	56245	66155	43186
42	14-Sveinsson	74598	10201	18847	73076	63275	56245	104194	68663
43	15-Sveinsson	74598	10201	10220	60103	59550	56245	63059	40550
44	16-Sveinsson	74598	10201	18847	73076	63275	56245	103479	60438
45	17-Sveinsson	74598	10201	10220	60103	63275	56245	58328	59427
46	18-Sveinsson	74598	10201	18847	73076	63275	56245	103152	74358
47	19-Sveinsson	74598	10201	10808	66496	63275	56245	72103	49645
48	20-Sveinsson	74598	10201	18847	73076	63275	56245	125199	74633
49	21-Sveinsson	86543	10201	5188	47996	74146	65908	66409	47985
50	1-Voon/Ingham	49006	10937	3125	32887	27991	34853	55813	41630
51	2-Voon/Ingham	44403	10937	0	23682	23096	30434	49676	39659
52	3-Voon/Ingham	49084	10937	3875	34163	29831	35137	53661	43613
53	4-Voon/Ingham	57208	10937	3125	33485	36591	42703	59710	47914
54	5-Voon/Ingham	53668	10937	3125	33485	32059	39162	58389	44374
55	6-Voon/Ingham	60410	10937	3187	37216	38913	43809	86449	45851
56	7-Voon/Ingham	127737	24087	5312	85483	127697	87915	111270	123914

Number	Label	V_{test}/V_n							
		MSJC SD	MSJC ASD V_m	MSJC ASD V_s	UBC	NZS	CSA	Shing	Anderson and Priestley
1	1-Shing	1.16	9.04	12.97	1.89	1.50	1.37	1.08	1.52
2	2-Shing	1.32	7.01	10.06	1.52	1.53	1.76	1.00	1.29
3	3-Shing	1.23	7.63	10.94	1.65	1.23	1.57	1.04	1.07
4	4-Shing	1.31	8.55	12.27	1.79	1.51	1.68	1.10	1.34
5	5-Shing	1.08	8.47	12.14	1.77	1.23	1.28	1.15	1.11
6	6-Shing	1.21	9.92	6.52	1.28	1.11	1.25	1.00	1.00
7	7-Shing	1.13	9.26	13.28	1.89	1.23	1.37	1.15	1.10
8	8-Shing	1.49	10.63	6.98	1.49	1.67	1.54	1.10	2.00
9	9-Shing	1.11	9.74	13.31	1.87	1.73	1.37	1.12	2.25
10	10-Shing	1.18	8.44	11.54	1.62	1.29	1.53	1.06	4.41
11	1-Matsumura	1.11	6.36	12.98	1.45	1.14	1.52	1.14	1.19
12	2-Matsumura	1.06	7.14	11.33	1.43	1.10	1.52	1.03	1.03
13	3-Matsumura	1.17	7.87	12.48	1.57	1.21	1.67	1.14	1.14
14	4-Matsumura	1.20	7.59	11.25	1.59	1.17	1.56	1.05	1.03
15	5-Matsumura	0.94	6.97	Undefined	2.47	0.85	1.28	1.19	0.89
16	6-Matsumura	1.09	9.58	10.75	1.62	1.16	1.38	1.29	1.05
17	7-Matsumura	1.22	10.77	6.04	1.27	1.31	1.47	1.20	1.63
18	8-Matsumura	1.22	10.82	6.07	1.27	1.31	1.48	1.11	1.05
19	9-Matsumura	1.55	13.65	6.60	1.61	1.66	1.87	1.06	1.13
20	10-Matsumura	1.17	11.74	6.58	1.25	1.25	1.41	1.10	1.06
21	11-Matsumura	1.09	10.41	5.84	1.13	1.17	1.31	1.01	0.96
22	12-Matsumura	1.30	12.71	6.14	1.36	1.39	1.57	1.15	1.11
23	13-Matsumura	1.19	11.42	6.06	1.24	1.28	1.43	1.08	1.04
24	14-Matsumura	1.20	12.56	7.04	1.34	1.29	1.45	1.15	1.10
25	15-Matsumura	1.20	9.82	Undefined	3.11	1.17	1.66	1.44	1.77
26	16-Matsumura	0.90	8.79	9.72	1.39	1.07	1.18	1.06	1.66
27	17-Matsumura	0.80	8.08	4.46	0.86	0.85	0.96	0.83	1.00
28	18-Matsumura	0.91	9.18	4.41	0.98	0.97	1.09	0.72	0.87
29	1-Sveinsson	0.96	7.49	6.16	1.03	1.13	1.27	1.07	2.08
30	2-Sveinsson	1.17	9.14	7.52	1.26	1.37	1.55	1.22	1.95
31	3-Sveinsson	1.46	9.45	5.70	1.49	1.72	1.93	1.14	1.78
32	4-Sveinsson	1.46	9.45	5.70	1.49	1.72	1.93	1.14	1.10
33	5-Sveinsson	1.43	9.07	9.05	1.63	1.84	1.90	1.64	2.28
34	6-Sveinsson	1.35	8.57	8.55	1.54	1.81	1.79	1.54	2.16
35	7-Sveinsson	1.16	7.38	19.34	2.11	2.05	1.54	1.53	2.34
36	8-Sveinsson	1.47	9.34	6.75	1.50	1.74	1.95	1.45	2.08
37	9-Sveinsson	1.19	7.53	7.52	1.36	1.40	1.58	1.44	1.72
38	10-Sveinsson	1.45	9.22	9.20	1.66	1.71	1.93	1.66	1.30
39	11-Sveinsson	0.97	7.07	7.13	1.21	1.14	1.28	1.15	1.73
40	12-Sveinsson	1.01	7.38	3.99	1.03	1.19	1.34	0.73	1.09
41	13-Sveinsson	1.23	9.03	9.01	1.53	1.46	1.64	1.39	2.13
42	14-Sveinsson	1.26	9.22	4.99	1.29	1.49	1.67	0.90	1.37
43	15-Sveinsson	1.07	7.80	7.78	1.32	1.34	1.41	1.26	1.96
44	16-Sveinsson	1.16	8.45	4.57	1.18	1.36	1.53	0.83	1.43
45	17-Sveinsson	1.15	8.38	8.36	1.42	1.35	1.52	1.46	1.44
46	18-Sveinsson	1.12	8.22	4.45	1.15	1.33	1.49	0.81	1.13
47	19-Sveinsson	1.18	8.64	8.16	1.33	1.39	1.57	1.22	1.78
48	20-Sveinsson	1.19	8.72	4.72	1.22	1.41	1.58	0.71	1.19
49	21-Sveinsson	1.22	10.33	20.32	2.20	1.42	1.60	1.59	2.20
50	1-Voon/Ingham	0.96	4.30	15.05	1.43	1.68	1.35	0.84	1.13
51	2-Voon/Ingham	0.94	3.83	Undefined	1.77	1.82	1.38	0.84	1.06
52	3-Voon/Ingham	0.97	4.35	12.28	1.39	1.60	1.35	0.89	1.09
53	4-Voon/Ingham	1.03	5.39	18.85	1.76	1.61	1.38	0.99	1.23
54	5-Voon/Ingham	1.03	5.08	17.77	1.66	1.73	1.42	0.95	1.25
55	6-Voon/Ingham	0.77	4.25	14.57	1.25	1.19	1.06	0.54	1.01
56	7-Voon/Ingham	1.03	5.45	24.71	1.54	1.03	1.49	1.18	1.06