DIAGONAL STRUT MODEL FOR MASONRY INFILL SHEAR WALLS IN VARIOUS STANDARDS AND CODES

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ABSTRACT

Masonry walls have been used extensively to fill the frames of concrete and steel structures. Masonry infill walls contribute to resisting lateral loads exerted on framed buildings. Typically, the contribution of these walls to lateral load resistance is ignored in the design and masonry infill walls are rather treated as non-structural elements. Recently, several experimental and numerical investigations showed that masonry infill walls contribute significantly to the lateral load resistance of steel and concrete framed structures. A few of the current design standards and codes have adopted some of the models proposed in these investigations for the design of masonry infill shear walls.

A comparison of the in-plane resistance of masonry infill shear walls computed using the diagonal strut models in the Canadian, New Zealand, and American standards and codes is presented in this paper. Experimental test results from available literature for different types of masonry units and frame materials were used to assess the adequacy of the design expressions. All three design documents failed to provide consistent estimates for the lateral load resistance. Only the American code provided lateral load resistance estimates for masonry infill walls that are less than the measured values. The results of this study clearly demonstrated that much research is still needed to gain better understanding of the behaviour of masonry infilled frames and develop design expressions that are capable of predicting the lateral load resistance of this type of wall with greater accuracy.

KEYWORDS: lateral load resistance, steel/concrete frames, masonry infill shear walls, diagonal strut model, design standards/codes

INTRODUCTION

Most of masonry design standards and codes ignore the contribution of masonry infill shear walls to lateral load resistance. Ignoring the interaction between the masonry infill walls and the structural frames could lead to unsafe and/or uneconomical designs [1]. For example, partial height walls will restrain the frame's columns. This in turn may lead to the development of additional moments in the columns not accounted for during design. A few masonry design standards and codes such as the Canadian standard [2], the New Zealand standard [3] and the American code [4] provide design guidance for masonry infill walls but is limited to solid walls filling the frame completely (no openings) and in full contact with the containing frame. These conditions are difficult to achieve in real construction. Most of masonry infill shear walls would contain a door and/or a window opening and could be of partial height (not filling the frame entirely). Moreover, it is difficult to ensure full contact between the frame and the masonry infill wall. Only the American code considers the possibility of the presence of a small gap (≤ 9.5 mm) between the frame and the infill wall which is deemed closed when lateral load is applied. For this case, the code requires a 50% reduction in the strength and stiffness of the infill wall.

This paper reports on the findings of an analytical study aimed at assessing the adequacy of the design approaches for masonry infill shear walls in the current Canadian standard, New Zealand standard and American code. Design expressions for the other modes of failure were not included due to space limitation.

LITERATURE REVIEW

Available test results from five large investigations were used in the analytical study. These investigations are reviewed in this section to provide necessary background information. Dawe and Seah [5] conducted an experimental investigation on 28 different full-size masonry infilled steel frames with a total height of 2800 mm and length of 3600 mm. The columns and beam of the frame were constructed using W250×58 and W200×46, respectively. The masonry infill walls were constructed using 200 mm hollow concrete masonry units and type S mortar. Dawe and Seah reported that infill walls enhance the capacity of the containing frame even when there is a small gap between the infill and the frame or when there is a window or a door opening within the frame.

El-Dakhakhni [6] tested full-size steel frames 3600 mm long and 3000 high infilled with hollow concrete masonry. The masonry infill wall was constructed using 150 mm hollow concrete masonry and type S mortar. The specimens were subjected to cyclic loading at one end. El-Dakhakhni reported that the infill wall was able to carry more load even though diagonal and shear cracks were developed; failure of the infill wall was ultimately reached through corner crushing. Tasnimi and Mohebkhah [7] studied the performance of 5, two-third-scale steel frames infilled with solid clay brick units. The steel frame had a length of 2400 mm and a height of 1800 mm. The masonry infill was constructed using 219×66×110 mm solid masonry brick units. It was reported that the presence of openings within the infill wall had no significant effect on the initial stiffness of the infilled frame. It was found that walls with deep spandrel (portion of wall above an opening) dissipate more energy than those with shallow ones. Evidence of the formation of diagonal struts in the infill wall around the opening was observed.

Flanagan and Bennett [8] studied 8 full-size steel frames filled with hollow clay tile units. The infill wall thickness varied between a single wythe (195 mm thick) and a double wythe (330 mm thick). The size of the steel frame sections as well as the length and height of the infill wall varied to study the effect of frame stiffness on the infill wall behaviour. Flanagan and Bennett reported that all tested specimens failed through corner crushing, and surprisingly failure was relatively insensitive to the frame characteristics.

Mehrabi et al. [9] tested 12 half-scale single storey, single bay, reinforced concrete frames. Hollow and solid concrete masonry units were used to simulate weak and strong infills, respectively. The dimensions of the frame’s columns and beam were 177.8×177.8 mm and 152.4×228.6 mm, respectively. Mehrabi et al. concluded that the presence of masonry infill wall within a concrete frame increases its capacity compared to bare frame and can be used to improve the performance of existing non-ductile concrete frames.

DESIGN OF MASONRY INFILL SHEAR WALLS

There are three main modes for the failure of the infill walls: diagonal cracking due to exceeding masonry tensile strength, sliding along bed joints due to exceeding masonry shear strength, and corner crushing of the compression strut that forms along the diagonal of the infill wall due to exceeding masonry compressive strength. The latter mode is the focus of this study.

The lateral load capacity of masonry infill shear walls in the Canadian standard CSA S304.1-04 [2] is defined as the least value computed from the following failure modes: diagonal tension cracking, sliding shear along bed joints and corner crushing of the diagonal strut. The lateral load resistance based on corner crushing is as given in Equation 1.

$$V_r = (0.85\emptyset_m \chi f'_m w_{eff} t_e)/\left(\sqrt{1+(h_w/l_w)^2}\right) \tag{1-1}$$

$$w_{eff} = \text{smaller of} \begin{cases} \sqrt{\alpha_h^2 + \alpha_l^2}/2 \\ l_d/4 \end{cases} \tag{1-2}$$

$$\alpha_h = (\pi/2)\sqrt[4]{(4 E_f I_c h_w)/(E_m t_e \sin 2\theta)} \tag{1-3}$$

$$\alpha_l = (\pi)\sqrt[4]{(4 E_f I_b l_w)/(E_m t_e \sin 2\theta)} \tag{1-4}$$

$$\theta = \tan^{-1}(h_w/l_w) \tag{1-5}$$

Where, $\emptyset_m$ is the masonry material resistance factor, f'_m is the masonry compressive strength normal to bed joints, χ is a factor that accounts for the direction of the compressive stress in the masonry assembly, w_{eff} is the effective width of the diagonal compression strut, t_e is the effective thickness of the masonry infill wall, α_h and α_l are the vertical and horizontal contact lengths between the frame and the infill wall, l_d is the diagonal length of the compression strut, E_f and E_m are moduli of elasticity for the frame and masonry materials, respectively; I_b and I_c are the moments of inertia for the frame's beam and columns, respectively.

Similar to the Canadian standard, the New Zealand standard NZS 4230-2004 [3] considers the possibility of masonry infill walls to fail due to diagonal tension cracking, sliding shear along bed joints and failure in the compression strut. Unlike the Canadian standard, the width of the compression strut (w_{eff}) is set to a constant value equal to quarter the length of the developed diagonal compression strut. The lateral resistance, V_r, based on compression strut failure is given by Equation 2.

$$V_r = (0.85\ \emptyset\ f'_m\ w_{eff}\ t_e)/\left(\sqrt{1+(h_w/l_w)^2}\right) \tag{2-a}$$

$$w_{eff} = l_d/4 \tag{2-b}$$

Where, $\emptyset$ is a strength reduction factor, f'_m is the compressive strength of masonry, and t_e, h_w and l_w are the effective thickness, height and length of the masonry infill wall, respectively.

The lateral load resistance of masonry infill shear walls, $V_{n\ inf}$, is computed in the American code 2011 MSJC [4] as the least value from corner crushing of the compression strut (Equation 3), sliding along bed joints or the horizontal component of the force in the compression strut at a 25 mm displacement. For the latter case, the force in the compression strut is computed from an elastic analysis of the frame braced with a diagonal strut having the width given by Equation 4.

$$V_{n\ inf} = \emptyset\ 150\ t_{net\ inf}\ f'_m \tag{3}$$

$$w_{inf} = 0.3/(\lambda_{strut}\ \cos\theta), \text{ where } \theta = \tan^{-1}(h/l) \tag{4-a}$$

$$\lambda_{strut} = \sqrt[4]{(E_m\ t_{net\ inf}\ \sin 2\theta)/(4\ E_{bc}\ I_{bc}\ h_{inf})} \tag{4-b}$$

Where, 150 is an empirical value in mm for the width of the diagonal strut, $t_{net\ inf}$ is the net mortared area of the masonry unit, w_{inf} is the width of the compression strut, h_{inf} is the height of the infill wall, λ_{strut} is a characteristic stiffness parameter for the masonry infill wall, θ is the angle of inclination of the diagonal strut, h and l are the height and length of the masonry infill wall, respectively, E_m and E_{bc} are moduli of elasticity for the masonry and frame's column, respectively, and I_{bc} is the moment of inertia of the frame's column.

ANALYTICAL STUDY

The Canadian standard [2], New Zealand standard [3], and the American code [4] were examined using experimental results for masonry infilled frames from the five investigations described under the literature review section [5, 6, 7, 8 and 9]. The main objectives of this study are to assess the adequacy of the current design expressions in a) predicting the lateral load resistance of infill walls failing by corner crushing, and b) estimating the width of the theoretical diagonal compression strut. Therefore, only specimens failed by corner crushing of the masonry infill wall were considered in this analysis and Equations 1 to 4 were used to predict the in-plane resistance of masonry infill walls. All material reduction factors were set to unity in resistance calculations. Table 1 summarizes the properties of frames and infill walls of the specimens used.

The American code computes the capacity of the compression strut as the smaller value from Equation 3 and the horizontal component of the force developed in the compression strut at a lateral displacement of 25 mm for the infilled frame. The horizontal component in the diagonal strut was determined from an elastic analysis of the frame braced with a diagonal strut representing the infill wall using SAP 2000 [11].

Only the Canadian standard accounts for the fact that the compressive stresses that develop in the infill wall are not perpendicular to bed joints through the application of a 0.5 factor (χ) to f'_m measured perpendicular to bed joints. El-Dakhakhni [10] proposed Equation 5 to estimate masonry compressive stress at an angle (f'_θ) for infill walls.

$$f'_\theta = f'_{mx} + 0.43\ (f'_{my} - f'_{mx}) \tag{5}$$

Where, f'_θ is the inclined masonry compressive strength acting at an angle to bed joints, f'_{my} is masonry compressive strength perpendicular to the bed joints and f'_{mx} is masonry compressive strength parallel to the bed joints which is typically assumed to be 0.5 the compressive strength perpendicular to bed joints [1]. Substituting into Equation 5 gives a ratio of 0.72 of f'_{my}.

Table 1: Properties of the Frames and Masonry Infill Walls used in the Analytical Study

Ref	Spec	Frame			Masonry Infill Wall				
		Type E (MPa)	I-Column (10^6 mm^4)	I-Beam (10^6 mm^4)	Unit Type & Size (mm)	Thickness (mm)	f'_m (MPa)	l_w (mm)	h_w (mm)
[5]	WA1*	Steel 200,000	18.80	45.40	Concrete block 200×200×400	64.00	27.40	3592	2597
	WA2*						27.70		
	WA3*						26.50		
	WA4						24.40		
	WB1*						23.70		
[6]	D1	Steel 200,000	48.90	48.90	Conc. block 400×200×150	60.00	13.40	3342	2742
[7]	T	Steel 200,000	5.41	5.41	Clay brick 219×110×66	110.00	7.4	2260	1800
[8]	F1	Steel 200,000	0.913	119.00	Clay tile 300×200×300	195.00	5.6	2240	2240
	F2		7.03	119.00	Clay tile 300×200×300	195.00	5.6	2240	2240
	F4		4.04	556.00	Clay tile 300×200/100×300	330.00	2.3	2240	2240
	F5		12.00	295.00	Clay tile 300×200/100×300	330.00	2.3	2240	2240
	F9		71.10	119.00	Clay tile 300×200×300	195.00	5.6	2240	2240
	F17		7.03	1.19	Clay tile 300×200×300	195.00	5.6	3450	2240
	F21		7.03	119.00	Clay tile 300×200×300	195.00	5.6	2840	2240
[9]	M4	Concrete 17,225	83.30	152.00	Conc. block 100×100×200	31.76	10.62	2123	1422
	M7	Concrete 18,603	142.00	152.00	Conc. brick 100×100×200	92.07	13.57	2123	1422
	M8	Concrete 17,225	83.30	152.00	Conc. block 100×100×200	31.76	9.51	2123	1422
	M10	Concrete 20,119	83.30	152.00	Conc. block 100×100×200	31.76	10.61	2963	1422

*Specimens with truss type joint reinforcement.

In determining the width of the compression strut, the Canadian standard takes into account the relative stiffness between the infill wall and the containing frame (Equation 1-b) and places a limit of ¼ the diagonal length of the wall. The New Zealand standard takes the width of the compression strut to be ¼ the diagonal length of the wall (equation 2-b) and ignores the effect of the relative stiffness between the infill wall and the frame. The American Code considers the stiffness of the frame's columns but not its beam (Equation 4). Another expression to compute the width of the diagonal strut is given by FEMA 356-00 [13], which also considers only the column's stiffness (Equation 6).

$$a = 0.175\ (\lambda_1\ h_{col})^{-0.4}\ r_{inf} \qquad (6\text{-a})$$

$$\lambda_1 = [(E_{me}\ t_{inf}\ \sin 2\theta\ )/(4\ E_{fe}\ I_{col}\ h_{inf})]^{0.25} \qquad (6\text{-b})$$

Where, a is the width of the diagonal strut in inches, h_{col} is the column height between centrelines of the beams in inches, h_{inf} is the height of the infill wall in inch, t_{inf} is the thickness of the infill wall, E_{me} and E_{fe} are the moduli of elasticity for the masonry and frame materials in ksi, respectively; I_{col} is the moment of inertia of column in $inch^4$, r_{inf} is the diagonal length of the infill panel in inch, θ is angle whose tangent is the infill height-to-length ratio in radian.

Diagonal strut width computed from standard and code expressions as well as FEMA's equation was used to estimate the initial stiffness of the frames investigated in this study using 2D SAP 2000 elastic analysis. The frame elements as well as diagonal strut were modelled using beam elements. For the diagonal strut, moment at the beam-column intersection was released to act as link member. The real cross-sectional area of the beam and column are assigned to these elements. The diagonal strut member was given the cross-sectional area equal to the effective width as given by the standards/codes and the effective thickness of the infill wall. The computed initial stiffness values were compared to the initial stiffness values determined from experimental results. This comparison aims to assess the accuracy of the standard/code expressions in estimating the width of the diagonal strut.

RESULTS AND DISCUSSION

A summary of the results for the lateral load resistance of masonry infill shear walls predicted as per the Canadian standard, New Zealand standard, and American code is given in Table 2. The experimental values for resistance reported in Table 2 were computed by subtracting the load resisted by the bare frame from that resisted by the infilled frame at a displacement corresponding to the maximum load resistance. Resistance values reported in Table 2 for the American code are those determined from Equation 3 since values determined from the 25 mm sway of the frame were higher. Figure 1 shows the ratio of lateral load resistance predicted by the three design documents to that determined experimentally.

It is clear from Table 2 and Figure 1 that the Canadian standard overestimates the resistance of masonry infilled steel frames with concrete and clay masonry infills by 26% and 42% on average, respectively. This is likely due to overestimating the width of the diagonal strut. On the other hand, the Canadian standard underestimates the capacity of concrete frames filled with concrete masonry by 51%. While standards and codes are intended to be conservative, significant underestimation of resistance is uneconomical.

The New Zealand standard overestimates the resistance of concrete block and clay brick walls filling steel frames by almost two multiples. This may be attributed to the higher values of the diagonal strut width and the absence of any reduction factor to account for the fact that compressive stresses act at an angle to bed joints. Conversely, the predicted resistances for concrete frames filled with concrete masonry walls are in good agreement with the measured values. If a stress factor of 0.5 is applied to the New Zealand standard's expression, estimated resistances would be comparable to those computed using the Canadian standard.

Table 2: Predicted vs Experimental Lateral Load Resistance of Masonry Infill Walls

Frame	Infill	Ref	Spec #	V_{Exp} (kN/m)	CSA S304.1-04 [2]		NZS 4230-04 [3]		2011 MSJC [4]	
					V_{CSA} (kN/m)	$\frac{V_{CSA}}{V_{Exp}}$	V_{NZS} (kN/m)	$\frac{V_{NZS}}{V_{Exp}}$	V_{MSJC} (kN/m)	$\frac{V_{MSJC}}{V_{Exp}}$
Steel	Concrete units	[5]	WA1	418.8	557.3	1.33	1338.5	3.20	263.0	0.63
			WA2	387.8	561.9	1.45	1353.2	3.49	265.9	0.69
			WA3	410.8	543.6	1.32	1294.6	3.15	254.4	0.62
			WA4	423.8	510.9	1.21	1192.0	2.81	234.2	0.55
			WB1	422.9	499.9	1.18	1157.8	2.74	227.5	0.54
		[6]	D1	246.6	285.5	1.16	571.0	2.32	120.6	0.49
			Average			1.26		2.95		0.59
			COV (%)			8.56		12.7		11.33
	Clay units	[7]	T	153.1	163.1	1.07	390.9	2.55	122.1	0.80
		[8]	F1	164.0	259.9	1.58	519.8	3.17	163.8	1.00
			F2	173.0	259.9	1.50	519.8	3.00	163.8	0.95
			F4	213.0	180.6	0.85	361.3	1.70	113.9	0.53
			F5	172.0	180.6	1.05	361.3	2.10	113.9	0.66
			F9	179.0	259.9	1.45	519.8	2.90	163.8	0.92
			F17	193.0	400.3	2.07	800.6	4.15	163.8	0.85
			F21	181.0	329.5	1.82	659.0	3.64	163.8	0.90
			Average			1.42		2.90		0.83
			COV (%)			27.20		25.55		17.97
Concrete	Concrete units	[9]	M4	162.4	74.5	0.46	149.1	0.92	49.6	0.31
			M7	489.5	281.9	0.58	563.8	1.15	187.5	0.38
			M8	190.0	66.8	0.35	133.6	0.70	44.4	0.23
			M10	189.6	104.0	0.55	208.1	1.10	49.6	0.26
			Average			0.49		0.97		0.30
			COV (%)			18.47		18.25		19.25

The code predicted the resistance of masonry infilled shear walls better than both the Canadian and New Zealand standards as its estimates were consistently below the measured values. The code's best prediction with an average of 83% of measured resistance is for steel frames filled with clay masonry. The average predicted resistance for concrete masonry infilled steel frames is 59% of the measured resistance. However, the American code greatly underestimated the resistance of concrete frames filled with concrete masonry, only 30% of the measured resistance on average.

Table 3 summarizes the initial stiffness results for all masonry infilled frames investigated compared to the initial stiffness values determined from the experimental results. The diagonal strut width values computed according to the Canadian and New Zealand standards and used in the elastic analysis resulted in much higher initial stiffness values than measured for infilled steel frames. The stiffness of the concrete masonry infilled steel frames was overestimated by 174% and 203% on average by the Canadian standard and the New Zealand standard, respectively. The estimated initial stiffness was even higher (570% app.) for steel frames filled with clay masonry. The Canadian and New Zealand standards underestimated the initial stiffness of concrete frames filled with concrete masonry by 48%.

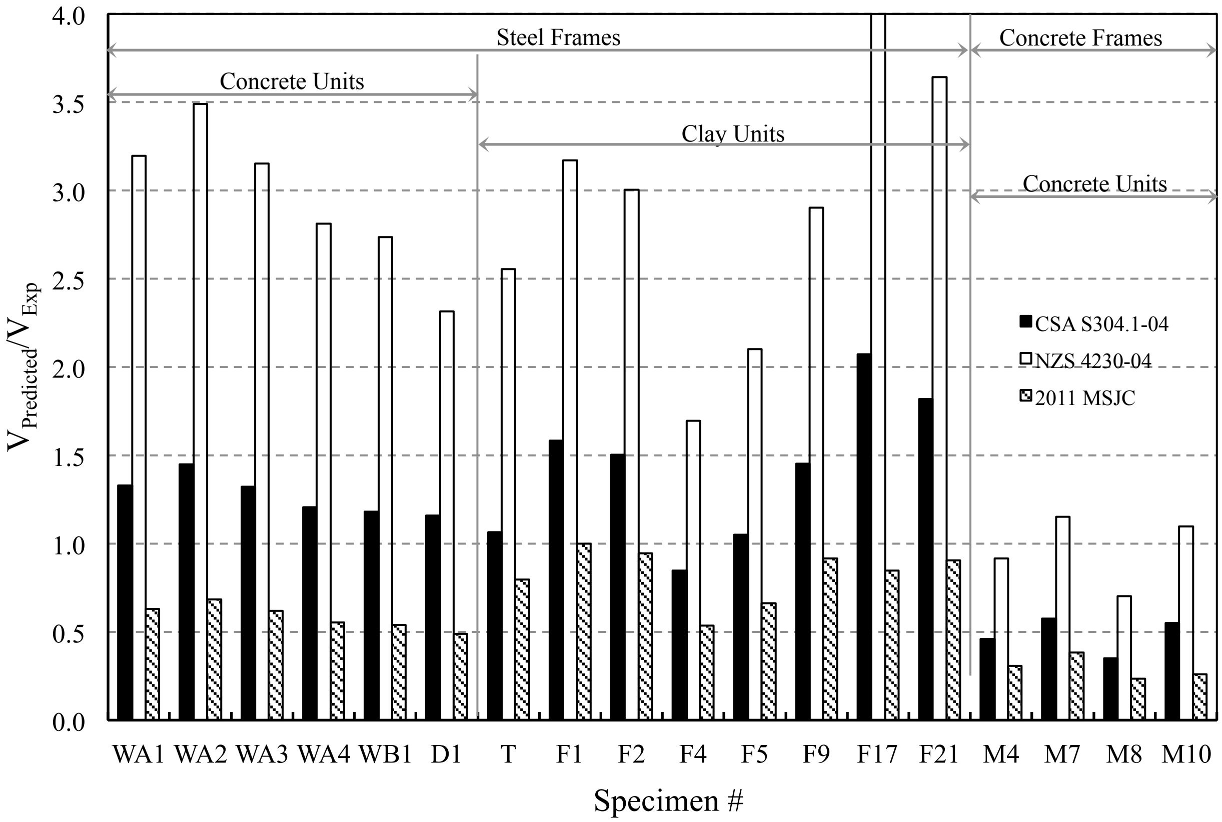

Figure 1: Diagonal Compression Strut Resistance Predicted by Different Standards/Codes

The American code overestimated the initial stiffness of clay masonry infilled steel frames by 63% on average. It underestimated the initial stiffness for steel frames filled with concrete masonry by 35%. Initial stiffness values predicted using FEMA's expression (Equation 6) were comparable to the measured values for concrete masonry infilled steel frames. However, FEMA's expression overestimated the initial stiffness for steel frames filled with clay masonry by 182% on average. Both the American code and FEMA's expression exceptionally underestimated the stiffness of concrete frames filled with concrete masonry walls by 80% and 71% of the measured values, respectively.

Further analysis of the estimate of the diagonal strut width was carried out using Equation 3 of the American code since it is the only expression among the three design documents considered in this investigation that yielded conservative predictions for the resistance of all masonry infill walls. The 150 mm fixed width of the diagonal strut in Equation 3 was replaced by the width determined from MSJC's Equation 4 and FEMA's Equation 6 and lateral load resistance values were recomputed. The predicted values were compared to the resistance determined experimentally as shown in Table 4.

Table 3: Initial Stiffness based on Different Standards/Codes using a Diagonal Strut Model

Frame	Infill	Ref	Spec #	K_{EXP} (kN/mm)	CSA S304.1-04 [2]		NZS 4230-04 [3]		2011 MSJC [4]		FEMA 356 [11]	
					K_{CSA} (kN/mm)	$\frac{K_{CSA}}{K_{Exp}}$	K_{NZS} (kN/mm)	$\frac{K_{NZS}}{K_{Exp}}$	K_{MSJC} (kN/mm)	$\frac{K_{MSJC}}{K_{Exp}}$	K_{FEMA} (kN/mm)	$\frac{K_{FEMA}}{K_{Exp}}$
Steel	Concrete units	[5]	WA1	73.00	167.20	2.29	193.89	2.66	33.93	0.46	75.33	1.03
			WA2	82.00	167.20	2.04	193.89	2.36	33.93	0.41	75.33	0.92
			WA3	74.00	167.20	2.26	193.89	2.62	33.93	0.46	75.33	1.02
			WA4	63.00	170.94	2.71	193.89	3.08	34.83	0.55	75.88	1.20
			WB1	72.00	171.96	2.39	193.89	2.69	35.00	0.49	76.24	1.06
		[6]	D1	19.60	93.00	4.74	93.00	4.74	29.43	1.50	44.57	2.27
			Average			2.74		3.03		0.65		1.25
			COV (%)			33.49		26.29		59.64		37.08
	Clay units	[7]	T	22.24	69.81	3.14	79.53	3.58	20.71	0.93	36.21	1.63
		[8]	F1	13.19	79.15	6.00	79.15	6.00	14.23	1.08	30.48	2.31
			F2	14.37	105.42	7.34	105.42	7.34	26.36	1.83	42.66	2.97
			F4	20.19	142.18	7.04	142.18	7.04	36.36	1.80	60.52	3.00
			F5	25.75	161.89	6.29	161.89	6.29	50.32	1.95	72.62	2.82
			F9	30.33	118.96	3.92	118.96	3.92	58.37	1.92	66.86	2.20
			F17	17.27	160.50	9.29	160.50	9.29	25.49	1.48	61.37	3.55
			F21	12.94	135.80	10.49	135.80	10.49	26.33	2.03	53.07	4.10
			Average			6.69		6.74		1.63		2.82
			COV (%)			34.52		33.03		24.10		25.93
Concrete	Concrete units	[9]	M4	75.30	32.60	0.43	32.60	0.43	14.16	0.19	18.87	0.25
			M7	255.70	140.88	0.55	140.88	0.55	40.56	0.16	67.48	0.26
			M8	57.80	35.17	0.61	35.17	0.61	14.97	0.26	20.13	0.35
			M10	69.20	34.35	0.50	34.35	0.50	13.63	0.20	20.07	0.29
			Average			0.52		0.52		0.20		0.29
			COV (%)			12.65		12.65		17.93		13.56

The results in Table 4 show that the 150 mm fixed width of the diagonal strut chosen by the American code is very close to the average of the values computed from Equation 4. Except for specimen F9, which has a very strong frame relative to the infill wall, resistance values predicted using the diagonal strut width as determined from Equation 4 were conservative and comparable to the values computed using w = 150 mm (Equation 3). The results suggest that Equation 4, which is based on a more rational approach, could be used to estimate the width of the diagonal strut with a lower limit of 150 mm. Equation 6 (FEMA's expression) yielded diagonal strut width values that are approximately as double as much those computed using Equation 4. This in turn resulted in double the resistance values. Except for concrete frames filled with concrete masonry, Equation 6 resulted in resistance values that are 50% higher than the measured resistance on average. All three equations underestimated the resistance of concrete masonry infilled concrete frames.

Table 4: Effect of the Compressive Strut Width on Resistance Computed as per MSJC [4]

Frame	Infill	Ref	Spec #	V_{Exp} (kN)	w_{inf} = 150 mm		w_{inf} = Equation 4			w_{inf} = Equation 6		
					$V_{W_{150}}$ (kN)	$\frac{V_{W_{150}}}{V_{Exp}}$	w_{Eq4} (mm)	$V_{W_{Eq4}}$ (kN)	$\frac{V_{W_{Eq4}}}{V_{Exp}}$	w_{FEMA}	$V_{W_{FEMA}}$	$\frac{V_{W_{FEMA}}}{V_{Exp}}$
Steel	Concrete units	[5]	WA1	418.8	263.0	0.63	148.7	260.8	0.62	367.7	644.8	1.54
			WA2	387.8	265.9	0.69	148.3	263.0	0.68	367.3	651.2	1.68
			WA3	410.8	254.4	0.62	150.0	254.4	0.62	368.9	625.7	1.52
			WA4	423.8	234.2	0.55	153.1	239.1	0.56	372	580.9	1.37
			WB1	422.9	227.5	0.54	154.2	233.9	0.55	373.1	565.9	1.34
		[6]	D1	246.6	120.6	0.49	242.0	194.5	0.79	418.2	336.2	1.36
			Average			0.59	166.1		0.64	377.9		1.47
			COV (%)			11.34	22.4		12.72	5.3		8.36
	Clay units	[7]	T	153.1	122.1	0.80	132.0	107.4	0.70	260.9	212.3	1.39
		[8]	F1	164.0	163.8	1.00	91.3	99.7	0.61	217.2	237.1	1.45
			F2	173.0	163.8	0.95	152.0	166.0	0.96	266.3	290.8	1.68
			F4	213.0	113.9	0.53	145.0	110.0	0.52	261.3	198.3	0.93
			F5	172.0	113.9	0.66	190.3	144.4	0.84	291.4	221.1	1.29
			F9	179.0	163.8	0.92	271.1	296.0	1.65	335.7	366.5	2.05
			F17	193.0	163.8	0.85	131.1	143.2	0.74	349.0	381.1	1.97
			F21	181.0	163.8	0.90	137.9	150.5	0.83	304.9	333.0	1.84
			Average			0.83	156.3		0.86	258.8		1.58
			COV (%)			17.97	34.4		38.14	15.2		22.56
Concrete	Concrete units	[9]	M4	162.4	49.6	0.31	149.9	49.5	0.30	272.7	90.1	0.55
			M7	489.5	187.5	0.38	125.2	156.5	0.32	254.3	317.8	0.65
			M8	190.0	44.4	0.23	154.1	45.6	0.24	275.7	81.6	0.43
			M10	189.6	49.6	0.26	149.8	49.5	0.26	360.6	119.1	0.63
			Average			0.30	144.7		0.28	290.8		0.57
			COV (%)			19.25	9.1		11.29	16.3		15.30

CONCLUSION

The adequacy of the diagonal strut design equations for masonry infill shear walls in the Canadian standard, the New Zealand standard, and the American code was investigated using available experimental results. All three design documents failed to provide consistent estimate for the lateral load resistance. Based on the findings of this study, the following conclusions can be drawn:

- The design expression for masonry infill walls failing due to corner crushing in the current Canadian masonry standard S304.1-04 overestimates the in-plane lateral resistance of infill walls bounded by steel frames by a wide range from 5% to 100%, with an average of one-third.
- The New Zealand masonry design standard NZS 4230-2004 grossly overestimates the resistance of masonry walls filling steel frames and failing by corner crushing. It is recommended that a reduction factor of 0.5 be applied to masonry compressive strength, similar to the Canadian standard, to account for the inclined direction of the compressive stresses that develop in the compression strut.
- The New Zealand standard was the only design document that yielded resistance values that are comparable to the measured resistance for concrete masonry infilled concrete frames.

- The American code (2011 MSJC) consistently provided lateral load resistance estimates for masonry infill walls that are less than the measured values. However, it extremely underestimated the resistance of concrete masonry infill walls contained by concrete frames which could result in uneconomical designs.
- The results of this study clearly demonstrated that much research is still needed to gain better understanding of the behaviour of masonry infilled frames and develop design expressions that are capable of predicting the lateral load resistance of this type of wall with greater accuracy.

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