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Assessment of RC Wall Shear Strength Provisions in Seismic Codes

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ABSTRACT: Reinforced concrete shear walls are used to provide lateral stiffness and strength to resist earthquake and wind loads. Majority of the RC shear wall buildings, particularly those that were constructed before recent seismic codes (e.g. ASCE 7, ACI 318, and Turkish Seismic Code 2007) were adopted, have inadequate reinforcement and detailing. Post-earthquake observations have shown that such buildings experienced a greater extent of damage or even collapsed. Therefore, seismic rehabilitation of existing buildings is well acknowledged to reduce the risk of damage in the future earthquakes. To achieve effective rehabilitation, it is essential that analytical modelling of the systems capture expected responses reasonably close to accurate. This study aims to assess current code provisions, and to enhance the accuracy and reliability of estimated shear strength using a detailed wall test database consisting of a large number of shear wall tests conducted worldwide. Within the scope of the study, influence of various parameters (e.g. wall geometry, reinforcement details, axial load) on wall shear strength were investigated. Alternative relations for shear-controlled walls were recommended depending on expected shear strength statistics, which will allow improved failure assessment, thus rehabilitation, of shear wall buildings.

1 INTRODUCTION

Reinforced concrete structural (shear) walls are commonly used to provide lateral stiffness and strength to resist wind loads and earthquake. Prior to the introduction of modern seismic codes (e.g. ACI 318, ASCE 7, and Turkish Seismic Code 2007), shear wall buildings were mostly designed with inadequate reinforcement and detailing. Reconnaissance after many of the past earthquakes showed that such buildings were heavily damaged and required seismic rehabilitation and retrofit. To achieve effective rehabilitation, behavior and response of the buildings should be well understood and analytical models of existing buildings should adequately represent the expected behavior, as close to accurate as possible.

One critical feature that needs to be reasonably accurate to model the exact behavior of shear walls is wall shear strength. For both design of new buildings, and evaluation of existing buildings, wall shear strength is calculated based on the expressions provided in seismic design codes. Current provisions in Turkish Seismic Code (2007) and ACI 318-14 (2014) for determining the shear strength of reinforced concrete walls are relatively unsophisticated. The expression used in TSC 2007 for wall shear wall strength (V_r) is shown in Eq. 1, where A_{ch} is the wall cross-section area, f_{ct} is the tensile strength of concrete, ρ_{sh} is the horizontal web reinforcement ratio, and f_{ywsh} is the yield strength of horizontal web reinforcement. The shear strength (V_n) equation provided by ACI 318-14, on the other hand, is presented in Eq.2, where A_{cv} is the wall cross section area, α_c is a coefficient to depending on the aspect ratio $(H_w / L_w), H_w$ and L_w are wall height and length, respectively; $f_c^{'}$ is the specified concrete strength; and ρ_t and f_{yt} are the reinforcement ratio and yield strength of the web horizontal reinforcement, respectively.

$$V_r = A_{ch}(0.65 f_{ct} + \rho_{sh} f_{ywsh}) \tag{1}$$

$$V_n = A_{cv}(\alpha_c \sqrt{f_c'} + \rho_t f_{yt}) \tag{2}$$

Both equations indicate that wall nominal shear strength is proportional to amount and yield strength of the web horizontal reinforcement, except wall aspect ratio is also mentioned in ACI 318-14 expression. Tensile and compressive concrete strength were also taken into account in TSC 2007 and ACI 318-14, respectively. However, previous studies have shown that shear strength is influenced by other factors such as axial load (Orakcal et al, 2009), wall vertical reinforcement (Wood, 1990), and the quantity of boundary transverse reinforcement (Wallace, 1998).

Previous studies have also shown that actual shear strength obtained from the test results is much higher than the estimated shear strength (Tuna, 2012). This overestimation of shear strength may cause over-conservative designs. As use of performance-based design approaches, which typically include the use of nonlinear response history analysis, become more common, alternative equations with more comprehensive expressions for shear strength are needed. For this purpose, a comprehensive database consisting of 172 specimens was conducted.

Various other researchers have conducted studies to create a database consisting of reinforced concrete walls, each of which had different points of interest. Sengupta and Li (2014) studied on analytical modeling for hysteresis loops of RC walls under monotonic loading using a database of 100 specimens. Shear strength of squat rectangular reinforced concrete walls were studied by Gulec et al. (2008) using a database of 148 wall tests. Farvashany et al. (2008) and Gupta and Rangan (1999) created databases of 76 and 69 specimens, respectively, to study the shear strength and deformation capacity of high-strength concrete shear walls. Orakcal et al. (2009) created a database with 49 specimens to represent the lightly reinforced, poorly detailed buildings and studied shear strength of lightly reinforced wall piers and spandrels. In this study, similar to previous research, a comprehensive literature review was conducted, and a detailed database of 265 specimens was created using experimental results reported by 41 different authors from 18 different countries. Shear walls with diagonal reinforcement (Salonikios et al., 1999), repaired and strengthened specimens (Li and Lim, 2010), and specimens with FRP or GFRP (Mohamed et al., 2013) were excluded from the database. Specimen characteristics and test parameters included in the database are discussed in the following section. Prominent components of the database were 37 specimens from Kabeyasawa et al. (1993), 14 specimens from Oesterle et al. (1979), 13 specimens from Lefas et al. (1990), 13 specimens from Zhang et al., (2007), 6 specimens from Thomsen and Wallace (2004), and 6 specimens from Dazio et al. (2009); while 176 others are not mentioned here due to space limitations.

Test results examined during the development of database showed that the characteristics of the walls affect wall response and behavior. Walls dominated by shear behavior have high demand-to-capacity ratio for strength but low deformation capacity. However walls governed by flexural behavior, have low demand-to-capacity ratio for strength but high deformation capacity. That’s why classification depending on wall characteristics will be needed. Typically, squat walls with low aspect ratios behave as shear-controlled walls and slender walls with high aspect ratios are flexure-controlled walls. However, in this study, classification of the walls based on their responses is made by considering their reported damages, instead of their dimension. For each specimen in the database, reported failure modes were identified and statistical studies were conducted based on various test parameters, for each failure mode. Statistical values such as maximum, minimum, mean values, as well as dispersions were also determined for each type of failure.

2 DESCRIPTION OF THE DATABASE

2.1 Parameters in the database

A comprehensive and detailed database was assembled by collecting wall specimens tested worldwide. Primary database parameters include: length (L_w), thickness (t_w), and height (H_w) of the specimens, dimensions of the boundary region (if exists), wall aspect ratio (H_w / L_w), shear span ratio (M / VL_w), axial load ratio ($P / A_{ch} f_c$), mechanical properties of concrete and reinforcing steel, as well as reported failure mode and shape of the specimens.

Mechanical properties of concrete were included using nominal strength (f_{ck}), cube strength (f_{cw}), cylinder strength (f_c), tensile strength (f_{ct}) and modulus of elasticity (E_c). In case some of these characteristics were not reported, equations (Eq. 3 and Eq.4), which are given in TSC 2007, were used.

$$f_{ct} = 0.4\sqrt{f_{ck}} \tag{3}$$

$$E_c = 14,000 + 3250\sqrt{f_{ck}} \tag{4}$$

Mechanical properties of reinforcing steel were examined in four sections, namely: longitudinal boundary reinforcement, boundary transverse reinforcement, vertical web reinforcement and horizontal web reinforcement. For each type of reinforcement, nominal yield strength, actual yield strength, and ultimate strength values, as well as reinforcement ratios were included. It is noted that expected strength values were assumed based on TSC 2007 and ACI 318-14 as given in Eq. 5 - Eq.7, when actual strength values were not reported.

$$f_c = 1.3 f_{ck} \tag{5}$$

$$f_y = 1.17 f_{yk} \tag{6}$$

$$f_u = 1.3 f_y \tag{7}$$

2.2 **Classification of the database**

For more efficient statistical studies on the database, the walls were classified based on their load type and failure mode. Specimens tested with monotonic loading were excluded: experiments performed by Cardenas et al. (1980), Gupta and Rangan (1999), and Farvashany et al. (2008). Another classification was about failure types. The walls, which have damages such as diagonal tension failure, sliding shear and web crushing were considered as shear-controlled walls, whereas the walls which are damaged by concrete spalling and crushing, and/or rebar buckling at the boundary elements were considered by flexure-controlled walls. The specimens that contain both damage types are classified as transition (i.e., shear-flexure interaction). According to this classification, there were 41 shear-controlled, 57 transition, and 74 flexure-controlled walls in the database. For the three failure types; minimum, maximum, and mean values of various parameters were summarized in Table 1.

Table 1. Range of the parameters included in the database

Parameters	Unit	Shear-Controlled			Transition			Flexure-Controlled		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Height	mm	690	4572	2013	476	12,000	2682	750	12,000	2456
Length	mm	585	3000	1440	450	3048	1381	400	2300	1056
Thickness	mm	60	152	107	45	200	102	60	200	108
Shear Span Ratio	-	0.35	2.39	1.14	0.25	3	1.78	1	7.38	2.26
Axial Load Ratio	-	0	0.3	0.03	0	0.35	0.1	0	0.5	0.14
Conc. Comp. Str.	MPa	15.7	58.3	30.8	17.2	65.0	32.3	15.4	57	35.3
Conc. Tensile Str.	MPa	1.4	2.8	1.9	1.5	3.6	2.2	1.7	2.8	2.3
Yield Str. of Bound. Trans. Reinf.	MPa	0	551.6	173.3	0	1115	364.9	0	620	408.6
Bound. Trans. Reinf. Ratio	-	0	1.1	0.2	0	2.1	0.5	0	2.0	0.6

Yield Str. of Bound. Long. Reinf.	MPa	0	533.1	374.1	0	1044	484.5	289	601	458.6
Bound. Long. Reinf. Ratio	-	0	12.7	5.2	0	6.9	2.7	0.5	12.6	2.9
Yield Str. of Web Hor. Reinf.	MPa	314	607.8	428.4	216	610	507.7	262	608.4	453.5
Web Hor. Reinf. Ratio	-	0.1	2.0	0.5	0.2	1.1	0.6	0.3	1.1	0.5
Yield Str. of Web Ver. Reinf.	MPa	314	607.8	430.4	216	610	481.6	289	583.7	456.2
Web Ver. Reinf. Ratio	-	0.1	3.3	0.4	0.2	2.4	0.7	0.2	2.5	0.8

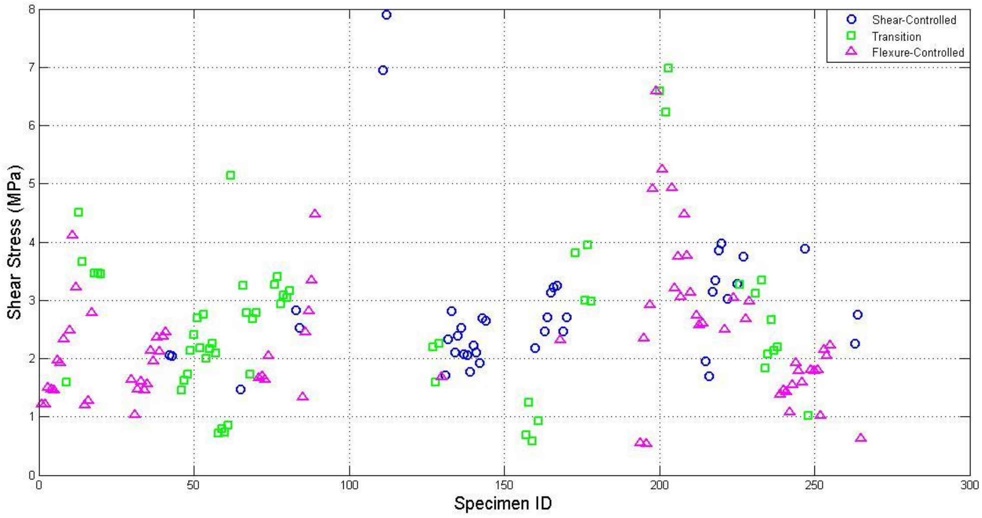

Figure 1. Shear stress distribution of the specimens in the database.

For each specimen in the database, ultimate shear values ($V_{\max}$) were extracted from test reports. Figure 1 shows peak shear stress values for each specimen, where shear stress was calculated as $v_{\max} = V_{\max} / A_{ch}$. Peak shear stress values were checked with strength limits $v_{\max} / f_c \leq 0.22$ provided by TSC 2007 and $v_{\max} / \sqrt{f_c} \leq 8$ ksi and $v_{\max} / \sqrt{f_c} \leq 10$ ksi given by ACI 318-14, as shown in Figure 2. Mean values for the three failure modes are presented in Table 2. Results indicate that $v_{\max} / f_c$ values for all failure modes are under the limit of 0.22 given in TSC 2007. However, for several specimens $v_{\max} / \sqrt{f_c}$ ratio was exceeding the limits given in ACI 318-14, although mean ½values were remaining under that limit.

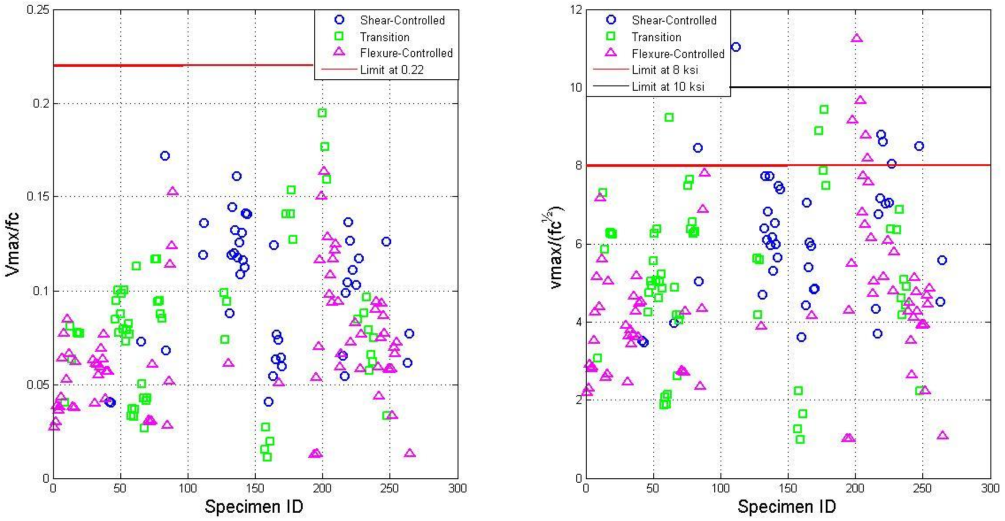

Figure 2. Distribution of (a) $v_{\max} / f_c$ according to TSC 2007, (b) $v_{\max} / \sqrt{f_c}$ according to ACI 318-14

Table 2. Shear stress limit check based on TSC 2007 and ACI 318-14

	$v_{\max} / f_c$ **(in MPa)**			$v_{\max} / \sqrt{f_c}$ **(in ksi)**		
	Shear	**Tran.**	**Flexure**	**Shear**	**Tran.**	**Flexure**
Max.	0.17	0.2	0.16	12.56	13.73	12.07
Min.	0.04	0.01	0.01	3.48	0.98	1.01
Mean	0.10	0.08	0.07	6.36	5.51	4.76

The reported shear strength values ($V_{\max}$) were compared with calculated shear strength according to TSC 2007 (V_r, Eq. 1) and ACI 318-14 (V_n, Eq. 2), as tabulated in Table 3. Results show that TSC 2007 underestimates the shear strength by about 5% for the shear-controlled walls, whereas the peak shear stress values for transition and flexure-controlled walls were overestimated about 35% and 40%, respectively. Similar results were obtained according to ACI 318-14. Shear strength is underestimated by 11% for the shear-controlled walls, whereas peak shear stress values for transition and flexure-controlled walls are overestimated 25% and 30%, respectively.

It is noted that the shear strength equation provided in TSC 2007 significantly overestimates the shear strength for non-rectangular (barbell- or T- shaped) walls, primarily because contribution of web reinforcement is overestimated in flanged walls. The stress component due to web reinforcement, calculated by multiplication of yield strength of web horizontal reinforcement (f_{ywsh}) by web horizontal reinforcement ratio (ρ_{sh}), is efficient only in the web zone. However, multiplication of this stress by the entire wall area (including flange zone) causes overestimation of shear strength. Therefore, specimens in the database were also classified based on their cross-sections, which consequently changed mean values for the ratio of measured to calculated shear strength. For example, mean shear strength for shear-controlled rectangular walls was obtained as 1.11 (versus 1.04 for all shear-controlled walls). Studies about cross section-based classification are not discussed in detail in this paper due to space limitations, and results in the following sections consider all wall cross-section types in the same bin.

Table 3. Comparisons of measured shear strength to calculated shear strength values

	$V_{\max}/V_r$ (TSC 2007)			$V_{\max}/V_n$ (ACI 318-14)		
	Shear	**Tran.**	**Flexure**	**Shear**	**Tran.**	**Flexure**
Max.	1.6	1.41	1.21	1.52	1.6	1.28
Min.	0.4	0.23	0.26	0.4	0.27	0.3
Mean	1.04	0.66	0.61	1.11	0.73	0.70

Figure 3 compares theoretical shear strength based on TSC 2007 versus experimental shear strength for the three failure modes, along with a $V_{\max}=V_r$ line to allow an easier comparison. As shown in Figure 4, shear-controlled walls are mainly above the $V_{\max}=V_r$ line, indicating that the measured shear strength values were higher than the calculated values; whereas other walls were generally distributed around the $V_{\max}=V_r$ line.

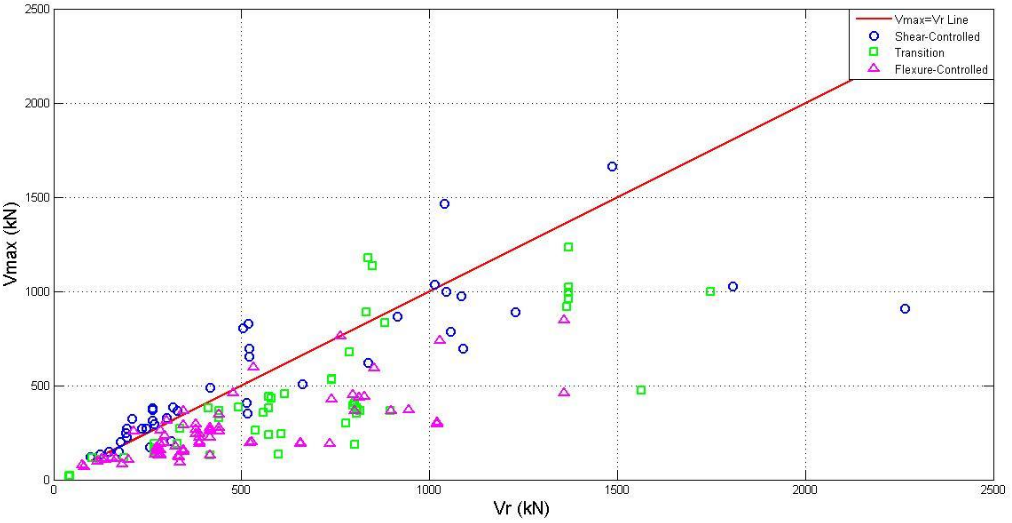

Figure 3. Comparison of measured ($V_{\max}$) and calculated (V_r) shear strength based on TSC 2007

2.3 Filtering of the database

Prior to statistical analyses, the database was filtered based on the following criteria, which reduced the number of specimens from 265 to 172. Based on the filtering criteria, specimens without horizontal and/or vertical web reinforcement (e.g. Hidalgo et al., 2002), and those constructed using high-strength materials were eliminated as they were not representative of existing building stock. As the main focus of this study is to assess shear strength provisions in high seismic zones, only experiments conducted under cyclic loading were included, i.e., specimens tested under monotonic loading were eliminated. In addition, specimens missing hysteresis loops of force-displacement or moment-curvature relations were also eliminated, as these features will be needed in calculation of ductility in future studies.

3 STATISTICAL STUDIES

3.1 Regression analysis with single parameter

Detailed regression analyses were carried out to investigate influence of the key parameters on shear strength for each failure mode. Results of the regression analysis are summarized in Table 4. Correlation coefficient (ρ) shows the linear relationship between two variables. It becomes 0 for a parameter which is not correlated with shear stress and 1.0 for a parameter that correlates with shear stress perfectly. Parameters that showed higher correlation with stress were horizontal web reinforcement ratio (ρ_{sh}) and compressive strength of concrete (f_c) for the shear controlled walls, whereas for other walls (transition and flexure-controlled), both horizontal web reinforcement ratio (ρ_{sh}) and vertical web reinforcement ratio (ρ_{ver}) showed relatively higher correlation with measured shear stress.

Table 4. Correlation coefficients with respect to unit shear stress

Parameter	Unit	Correlation Coefficient		
		Shear-Controlled	Shear-flexure interaction	Flexure-Controlled
Height (H_w)	mm	0.1	0.24	0.47
Length (L_w)	mm	0.31	0.18	0.42
Thickness (T_w)	mm	0.16	0.05	0.39
Shear Span Ratio (M / VL_w)	-	0.01	0.53	0.42
Axial Load Ratio ($P / A_{ch} f_c$)	-	0.35	0.29	0.13
Concrete Comp. Str. (f_c)	MPa	0.51	0.22	0.14
Concrete Tensile Str. (f_{ct})	MPa	0.51	0.28	0.37
Yield Str. of Trans. Bound. Reinf. (f_{ywcon})	MPa	0.32	0.31	0.14
Trans. Bound. Reinf. Ratio (ρ_{con})	-	0.18	0.18	0.02
Yield Str. of Long. Bound. Reinf. (f_{yb})	MPa	0.14	0.34	0.32
Long. Bound. Reinf. Ratio (ρ_b)	-	0.04	0.23	0.38
Yield Str. of Hor. Web Reinf. (f_{ywsh})	MPa	0.19	0.35	0.36
Hor. Web Reinf. Ratio(ρ_{sh})	-	0.68	0.72	0.48
Yield Str. of Ver. Web Reinf. (f_{ywver})	MPa	0.16	0.39	0.27
Ver. Web Reinf. Ratio(ρ_{ver})	-	0.49	0.74	0.71

3.2 Multi linear regression analysis

As presented in Table 3, current code provisions underestimate shear strength by 4% and 11% in TSC 2007 and ACI 318-14, respectively. To obtain equations that calculates the shear strength closer to accurate, multi-linear regression analyses were conducted and alternative equations for shear strength were derived for the shear-controlled walls. Different combinations of various key parameters were tried until the best correlation between the equation and the test results were obtained. During this process, results of single parameter regression analysis were helpful to prioritize the parameters to be used in the equation. Table 5 summarizes alternative equations derived for shear strength using linear regression analyses. The first equation (Eq.8) was obtained using only the same parameters used in Eq. 1, namely: tension strength of concrete (f_{ct}) and yield strength of horizontal web reinforcement multiplied by horizontal web reinforcement ratio ($f_{ywsh}\rho_{sh}$). The second equation (Eq.9) was obtained in the same way, except only the parameters used in Eq. 2 were included: concrete compressive strength ($\sqrt{f_c'}$), and reinforcing ratio times yield strength of the transverse steel in the web ($\rho_t f_{yt}$). Regression analyses were repeated with a total of six parameters namely: yield strength of longitudinal web reinforcement (f_{yb}), longitudinal web reinforcement ratio (ρ_b), concrete compressive strength (f_c), shear span ratio (M/VL_w), yield strength of horizontal web reinforcement (f_{ywsh}), horizontal web reinforcement ratio (ρ_{sh}), and axial stress (P/A_{ch}) to achieve the level of correlation as high as possible. Finally, the third equation (Eq.10) gives physically the most meaningful equation with a correlation coefficient as high as possible. Same procedure was repeated for the walls in other bins, however, results are not presented here due to page limitations.

Table 5. Summary of the unit shear stress equations with corresponding correlation coefficients and standard deviations

Failure Type	Corr. Coef.	Std. Dev.	Equation	
Shear-Controlled	0.60	0.97	$v = 0.75 + 0.75 f_{ct} + 0.0031 f_{ywsh} \rho_{sh}$	Eq.8
	0.60	0.97	$v = 0.64 + 0.29\sqrt{f_c'} + 0.032 f_{ywsh} \rho_{sh}$	Eq.9
	0.90	0.53	$v = -1.1 + 0.00038 f_{yb} \rho_b + 0.03 \dfrac{f_c}{(M/VL_w)} + 0.13\sqrt{f_{ywsh} \rho_{sh}} + 0.29 \dfrac{P}{A_{ch}}$	Eq.10

4 SUMMARY AND CONCLUSIONS

Shear strength equations in the current code provisions (TSC 2007 and ACI 318-14) were assessed by creating a detailed database consisting of 172 specimens tested worldwide, along with important test parameters. Previous research have shown that shear walls have different behavior and responses depending on their properties, particularly aspect ratio or shear span ratio. In this study, shear walls were classified based on their reported failure mode, and correlation of theoretical shear strength (calculated according to current codes) to the measured shear strength was investigated for each wall type separately. Results of the statistical studies showed that the equation provided in TSC 2007 underestimates shear strength about 5% (11% for only rectangular walls), whereas ACI 318-14 equation calculates shear strength about 10% lower than measured values, for shear-dominant walls. Influence of various parameters on wall shear strength was investigated. Results revealed that shear strength of the shear-dominant walls was mostly sensitive to horizontal web reinforcement ratio (ρ_{sh}) and compressive strength of concrete (f_c). Alternative equations were developed by conducting regression analysis, using various combinations of key parameters. These equations were found to be able to capture expected response (shear strength) closer to accurate, based on mean values of the test results. These equations aim to help the profession to obtain better assessments of failure, therefore more reliable and economical designs for seismic rehabilitation.

Future studies will include another important aspect of this study, aiming to determine median values and dispersions of wall deformation capacity associated with different wall failure modes. Deformation capacities of each wall will be calculated by using backbone curves, which were drawn based on the hysteretic lateral force-top displacement relations of test specimens. Deformation capacity will be mathematically formularized, which will be valuable in that they can be used by engineers to provide more reliable designs by assessing demand-to-capacity ratios for ductility. The new relations will also allow improved damage and failure assessment of buildings utilizing structural walls for lateral load resistance.

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