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RELIABILITY OF REINFORCED CONCRETE WALL SHEAR STRENGTH EQUATIONS IN MODERN SEISMIC CODES

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Abstract

Reinforced concrete (RC) shear walls have been widely used in buildings located in seismic regions due to their high ductility and rigidity against earthquake and wind loads. Majority of the reinforced shear wall buildings which were not constructed based on modern seismic codes (e.g. ASCE 7, ACI 318, Turkish Seismic Code 2007, EuroCode 8, and Japanese Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings 2001) have poor material quality, inadequate reinforcement and detailing. Post-earthquake observations have shown that such buildings are more likely to experience a greater degree of damage or even collapse because of considerable influences of insufficient reinforcement detailing and inadequate material quality. Rehabilitation and retrofit of existing buildings has been vital and commonly used to minimize the risk of possible damage/collapse. For better rehabilitation, it is necessary to understand the behavior of RC shear walls to minimize the risk of potential damages that may occur in the future earthquakes. Shear strength is one of the most prominent properties to represent behavior of reinforced concrete structural walls. This paper aims to assess modern seismic code provisions and to investigate reliability and accuracy of code-estimated shear strength using a detailed wall test database consisting of a large number of shear wall tests (a total of 172) conducted around the world. Specimens in the database were classified based on their failure modes and statistical studies were carried out. Mean values of the ratio of experimental strength to the estimated strength according to ACI 318 were 1.11, 0.79, and 0.66 for shear-controlled, transition, and flexure-controlled walls, respectively. Results of the analyses to determine reliability of estimated shear strength showed that equations provided by ACI 318, Turkish Seismic Code, and Japanese Seismic Code 2001 underestimate the shear strength of shear-controlled walls by 11%, 7%, and 3%, respectively. It is also indicated that equation provided by Turkish Seismic Code 2007 is not appropriate for non-rectangular shear walls.

Keywords: RC shear walls, Shear strength, Seismic rehabilitation

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, Turkish Seismic Code 2007 (TSC-2007), and Japanese Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings (JSC-2001)), buildings with structural walls were constructed with several problems [1, 2, 3]. Reinforcement detailing and strength of materials in such buildings were insufficient. According to investigation after past earthquakes, such buildings are likely to experience heavy damages or collapsed. To prevent possible after earthquake damages, seismic rehabilitation and retrofitting of existing buildings is required. Analytical models, that are representative for expected behavior of existing building stock, can lead an effective rehabilitation.

Wall shear strength is one of the most important features that play an important role by identification of actual response of shear walls. Therefore, shear strength should be estimated in analytical models close to its exact values. Shear strength equations given in modern seismic codes are considered while calculating wall shear strength in process for both designing a new shear wall structure and investigation of existing structures. Equations provided in TSC- 2007 and ACI 318-14 to calculate the shear strength of reinforced concrete walls are relatively simple and including less number of parameters, however shear strength equation given in Japanese Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings is more complicated [1, 2, 3]. The equation 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. On the other hand, Eq. 2 shows the shear strength (V_n) equation provided by ACI 318-14, , 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. Finally, Eq. 3 presents shear strength (Q_{su}) equation in JSC-2001, which includes longitudinal reinforcement at the boundary (p_{te}), specified concrete strength (F_c), shear span ratio ($M/(Q*l)$), horizontal web reinforcement (p_{se}), axial stress (σ_{0e}) and ($b_e j_e$) as area of the walls cross section. It is noted that Eq. 3 is given for existing buildings and includes more parameters than equation for design because quality assessment on existing buildings is far difficult then quality control during construction.

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

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

$$Q_{su} = \left\{\frac{0.053{p_{te}}^{0.23}(18+F_c)}{M/(Ql)+0.12} + 0.85\sqrt{p_{se}\sigma_{0e}}\right\}b_e j_e \tag{3}$$

Equations provided by ACI 318-14 and TSC-2007 are relatively less complicated and number of parameters is fewer than the JSC-2001 equation. In equations given in TSC-2007 and ACI 318-14, nominal shear strength is directly proportional to horizontal web reinforcement, whereas ACI 318-14 equation considers influence of aspect ratio on shear strength as well. Tensile and compressive concrete strength were mentioned in TSC-2007 and ACI 318-14, respectively. However, there are research conducted by Orakcal, Wood, and Wallace that focused on influence of axial load, vertical web reinforcement, and boundary confinement, respectively [4, 5, 6], which showed These studies showed that various other parameters that were not mentioned in these equations can affect wall shear strength. Research conducted by Zhang [7] showed that higher amount of confinement increases shear strength. Alarcon [8] studied influence of axial load on wall shear strength and showed that higher axial load ratio causes an increase in shear strength.

Previous studies carried out by Tuna [9] have also shown that experimental shear strength measured during experiments is much higher than the calculated shear strength, which may cause over-conservative designs and non-economical rehabilitation. Therefore, alternative equations should be recommended with more detailed statements for shear strength were needed. To investigate reliability of shear strength equations in recent seismic codes and influence of various parameters on wall shear strength, as well as to develop alternative shear strength equations, a detailed wall test database was created using shear wall tests conducted by various researchers.

2. Description of the Database

2.1 Parameters in the database

Wall specimens tested by other researchers was collected to assemble a comprehensive and detailed database. Primary parameters in the database include: parameters related to wall geometry such as 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), and shear span ratio (M/VL_w); axial load ratio ($P/A_{ch}f_c^{'}$), loading type, curvature type, and reported failure mode as additional information about specimen. Mechanical properties of concrete and reinforcing steel, as well as ratio of reinforcement are included in the database.

For mechanical properties of concrete, nominal strength (f_{ck}), cube strength (f_{cw}), cylinder strength ($f_c^{'}$), tensile strength (f_{ct}) and modulus of elasticity (E_c) were used. In case some of these characteristics were not reported, equations (Eq. 4 and Eq. 5), which are given in TSC-2007, were used to calculate missing parameters.

$$f_{ct} = 0.4\sqrt{f_{ck}} \tag{4}$$

$$E_c = 14,000 + 3250\sqrt{f_{ck}} \tag{5}$$

Mechanical properties of reinforcing steel were examined in four sections, namely: longitudinal boundary reinforcement, boundary transverse reinforcement, vertical web reinforcement and horizontal web reinforcement. Nominal yield strength, actual yield strength, and ultimate strength values, as well as reinforcement ratios were included for each section. If actual strength values were not given for reinforcement, these values were assumed by using Eq. 6 – Eq. 8 given in TSC-2007 and ACI 318-14.

$$f_c^{'} = 1.3f_{ck} \tag{6}$$

$$f_y = 1.17f_{yk} \tag{7}$$

$$f_u = 1.3f_y \tag{8}$$

As this study aims to investigate the behavior of non-rehabilitated conventional reinforced concrete shear walls, the following specimens were not included in the database: (i) specimens including diagonal reinforcement (e.g. [10]), (ii) specimens including FRP of GFRP (e.g. [11, 12]), and (iii) specimens made of composite materials. As a result, a wall test database of 265 specimens was created.

2.2 Determination of experimental and theoretical strength for each specimen

Experimental shear strength of each specimen was obtained using lateral load – top displacement curves. Peak lateral load reached in positive and negative loading were obtained, average of which was taken as experimental shear strength (V_{max}) of the specimen. Theoretical shear strength was calculated using equations provided by TSC-2007, ACI 318-14, and JSC-2001 (Eq.1 – Eq.3) by substituting the parameters from the database. It is noted that Eq.1 has a safety factor for practical use. In practice, design tensile strength of concrete (f_{cd}) and design yield strength of horizontal web reinforcement (f_{yd}) are used to calculate theoretical shear strength according to Eq. 1. However, in this study tested material strengths were used in equations given by seismic codes without a safety factor to calculate estimated shear strength. Experimental and theoretical strength values are used to compare and investigate reliability of shear strength equations, as summarized in the following subsections.

2.3 Determination of failure type for each specimen

During the literature review, reported failure modes, cracking patterns, and damages occurred during testing of each specimen were noted and included in the database. Failure modes and damages were generally stated in the reports, while in some cases photographs of specimens showing after failure crack patterns were provided. Diagonal cracks, sliding shear, web cracks, concrete spalling, rebar buckling, concrete crushing, and flexural cracks are most common failure modes. Two of these failure modes, buckling of boundary longitudinal reinforcement and sliding shear failure are presented as an example in Fig. 1.

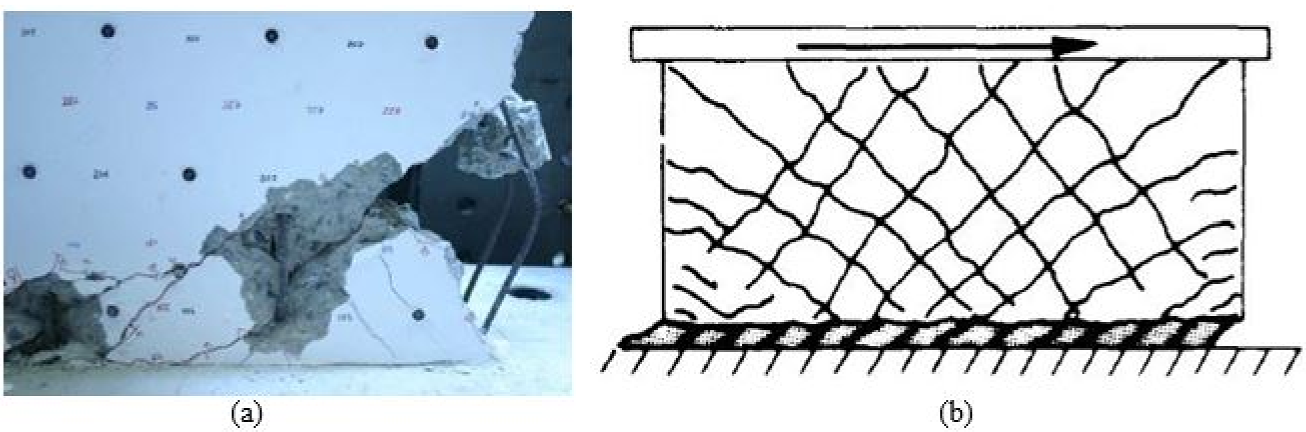

Fig. 1 – (a) Buckling of longitudinal boundary reinforcement [13], (b) Sliding shear failure [14]

3. Statistical Studies

3.1 Classification of the database

Specimens in the database were classified into different bins to allow consistent evaluation of the data, based on three different classification criteria, namely: (i) loading type (monotonic versus cyclic), (ii) cross-section type (rectangular versus barbell/flanged), and (iii) failure type (shear-controlled versus flexure-controlled). The most important classification of all was the latter one, which was completed based on the reported failure modes such that specimens failed by diagonal tension failure, sliding shear or web crushing were considered as shear-controlled walls, whereas the specimens damaged due to concrete spalling, flexural cracks or rebar buckling at the boundary elements were considered as flexure-controlled walls. Shear walls that contain both failure modes were named as shear-flexure interaction, hereinafter transition walls. Statistical values such as maximum, minimum, mean values, as well as dispersions of key parameters in the database were determined for each failure type.

3.2 Filtering of the database

Prior to the statistical analyses, the database was filtered based on the following criteria: (i) experiments conducted under cyclic loading were included only, as this study aims to investigate the behavior of shear walls under earthquake loading, (ii) specimens without horizontal or vertical web reinforcement and those constructed using high strength materials (e. g. [15, 16]) were filtered as they did not represent the existing building stock. Consequently, number of specimens used in statistical studies reduced from 265 to 172, including shear-controlled (35), transition (73), and flexure-controlled (64) walls. 29 of the 35 shear-controlled, 54 of the 73 transition, and 57 of the 64 flexure-controlled walls have rectangular cross section. Minimum, maximum, and mean values of various parameters are summarized for the three failure types in Table 1.

Table 1 – Summary and range of parameters included in the database

PARAMETERS	Shear-Controlled Walls (35 Specimen)			Transition Walls (73 Specimens)			Flexure-Controlled Walls (64 Specimens)		
	Min.	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**
H_w (mm)	690	2150	1394.5	476.25	12000	2775.59	1200	12000	2590.34
l_w (mm)	585	3000	1359.29	450	3048	1382.73	400	2300	1053.16
b_w (mm)	60	152	107.46	45	200	103.54	50	200	107.88
M/VL_w	0.35	2	0.81	0.25	2.89	1.77	1.5	7.38	2.45
$P/A_{ch}f_c'$	0	0.3	0.02	0	0.35	0.10	0	0.5	0.14
f_{cm} (MPa)	15.7	58.3	27.58	17.16	65	37.01	15.4	57	34.61
f_{ctm} (MPa)	1.39	2.77	1.83	1.45	3.55	2.26	1.63	2.83	2.22
f_{ys} (MPa)	321	551.6	423.25	348	610	488.04	289	620	435.51
ρ_s (%)	0	1.13	0.16	0	2.09	0.58	0	2.04	0.55
f_{yb} (MPa)	314	533.1	414.6	353	702	477.48	276	601	442.52
ρ_b (%)	0	12.73	5.52	0	12.56	2.85	0.45	9.42	2.87
f_{ysh} (MPa)	314	607.8	416.83	305	610	520.4	216	608.4	429.45
ρ_{sh} (%)	0.13	1.98	0.43	0.19	1.37	0.59	0.25	1.11	0.51
f_{yver} (MPa)	314	607.8	420.08	305	610	494.76	216	583.7	438.06
ρ_{ver} (%)	0.13	3.29	0.48	0.19	2.39	0.73	0.27	2.47	0.73

3.3 Statistical data for experimental strength

Distribution of the experimental shear strength for different failure types is given in Fig. 2. Mean shear strength values were 473.6 kN (106.5 kips), 460.5 kN (103.5 kips), and 232.7 kN (52.3 kips) for shear-controlled, transition, and flexure-controlled walls, respectively. Higher shear values for shear-controlled walls and lower shear values for flexure-controlled walls were as expected. For each specimen in the database, experimental shear stress values were also calculated by dividing strength values by the entire wall area ($v_{max} = V_{max} / A_{ch}$), distribution of which is presented in Fig. 3 for different failure types. As shown in Fig. 3, mean shear stress values were 2.88 MPa (0.41 ksi), 2.9 MPa (0.42 ksi), and 1.98 MPa (0.29 ksi) for shear-controlled, transition, and flexure-controlled walls, respectively.

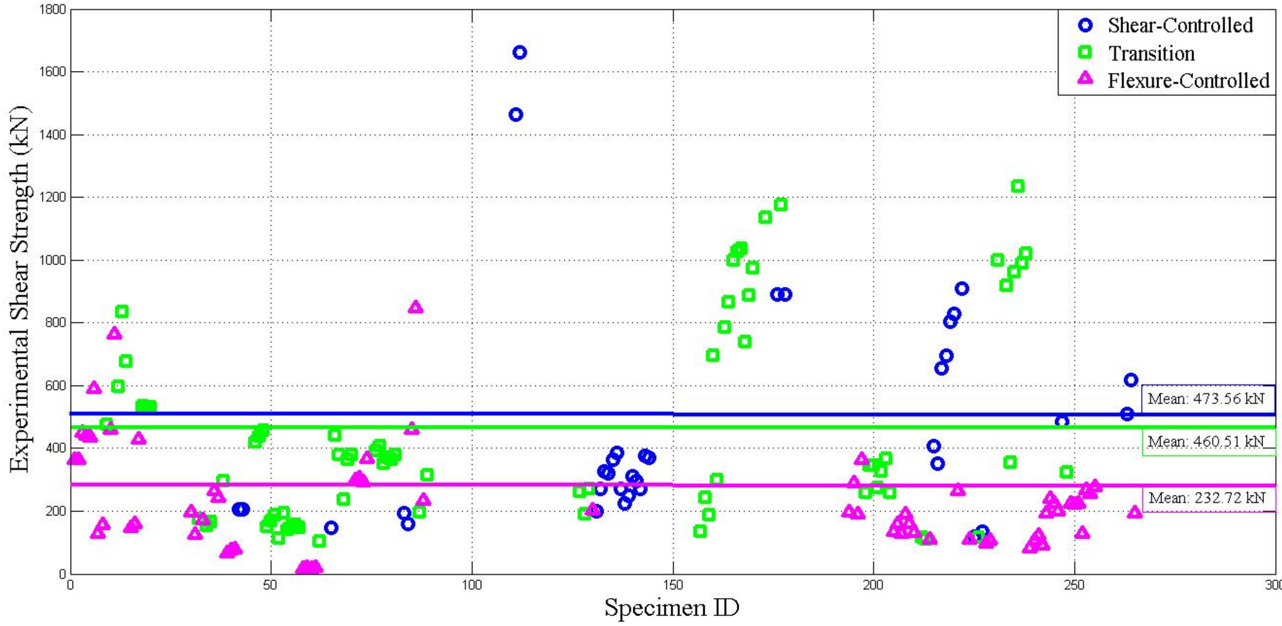

Fig. 2 – Distribution of experimental shear strength (V_{max}) for different failure types

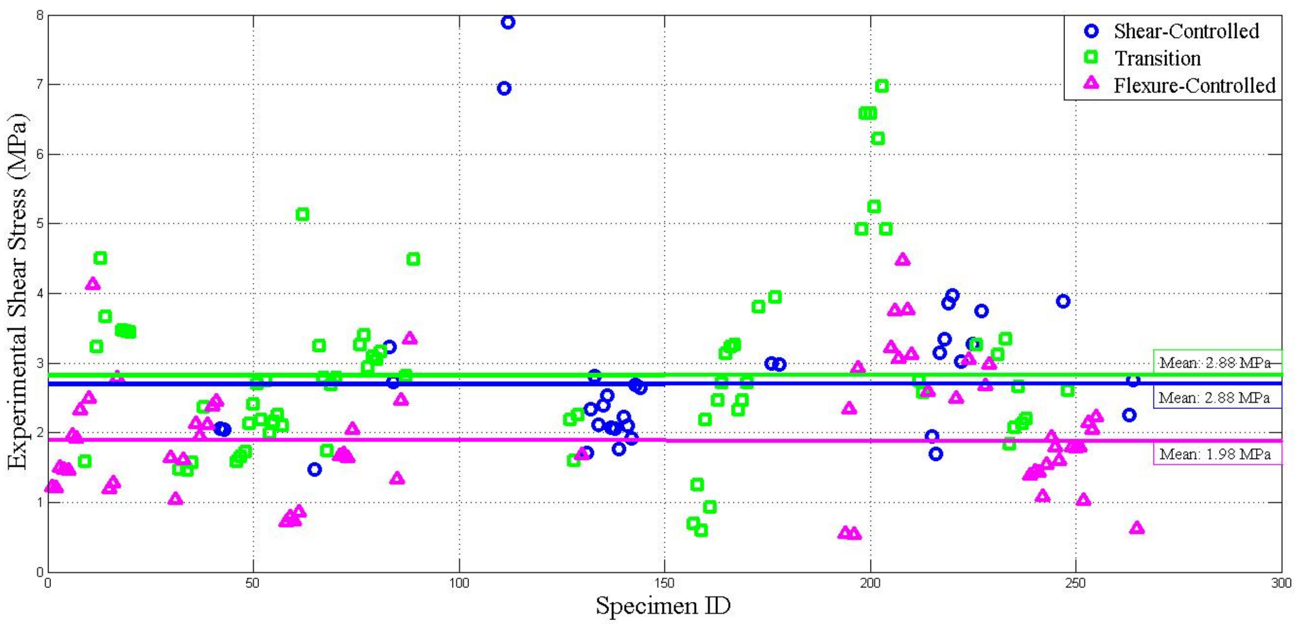

Fig. 3 – Distribution of experimental shear stress (v_{max}) for different failure types

3.4 Comparison of experimental and calculated strength

Reliability of estimated shear strength was investigated by comparing estimated shear strength values (V_r, V_n, Q_{su} based on TSC-2007, ACI 318-14, and JSC-2001, respectively) to the experimental values (V_{max}). Fig. 4 plots experimental shear strength versus theoretical shear strength according to TSC-2007, ACI 318-14, and JSC-2001, along with $V_{max} = V_r$, $V_{max} = V_n$, and $V_{max} = Q_{su}$ lines to allow easier comparison. As shown in Fig. 4, shear-controlled walls are generally above the reference line for both TSC-2007 and ACI 318-14, indicating that experimental strength is higher than the theoretical strength. For JSC-2001, estimated shear strength values were very close to the actual values.

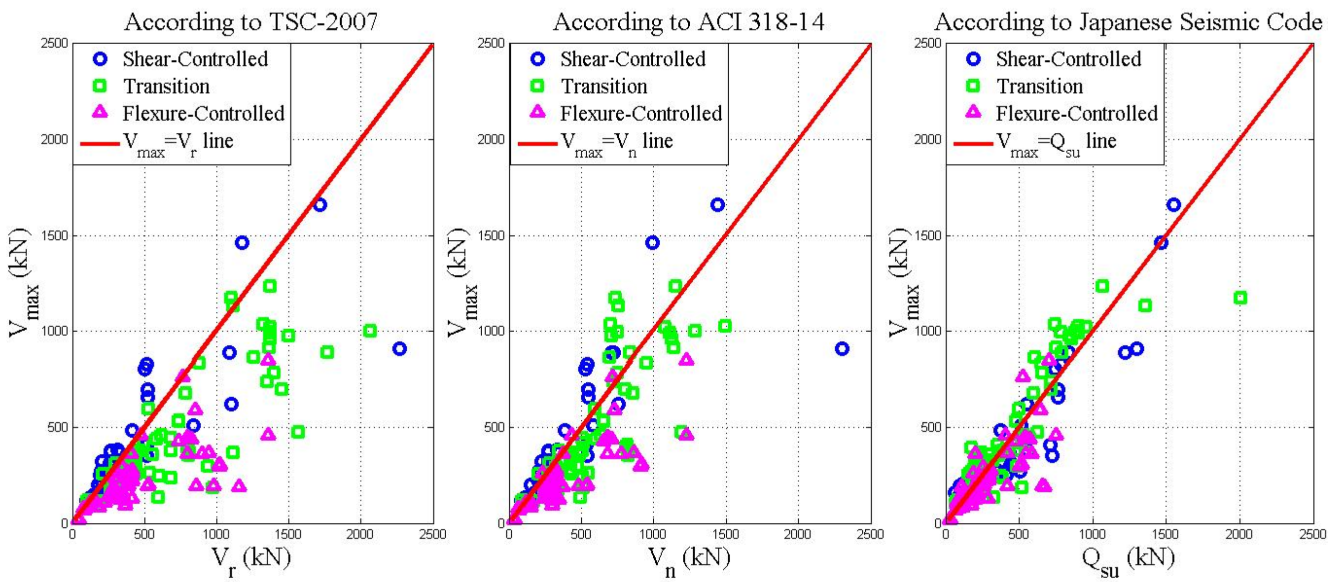

Fig. 4 – Comparison of experimental and calculated shear strength values according to different seismic codes

The ratio of experimental strength to the estimated strength was calculated for the three seismic codes for each failure mode and also showed in Fig. 5.

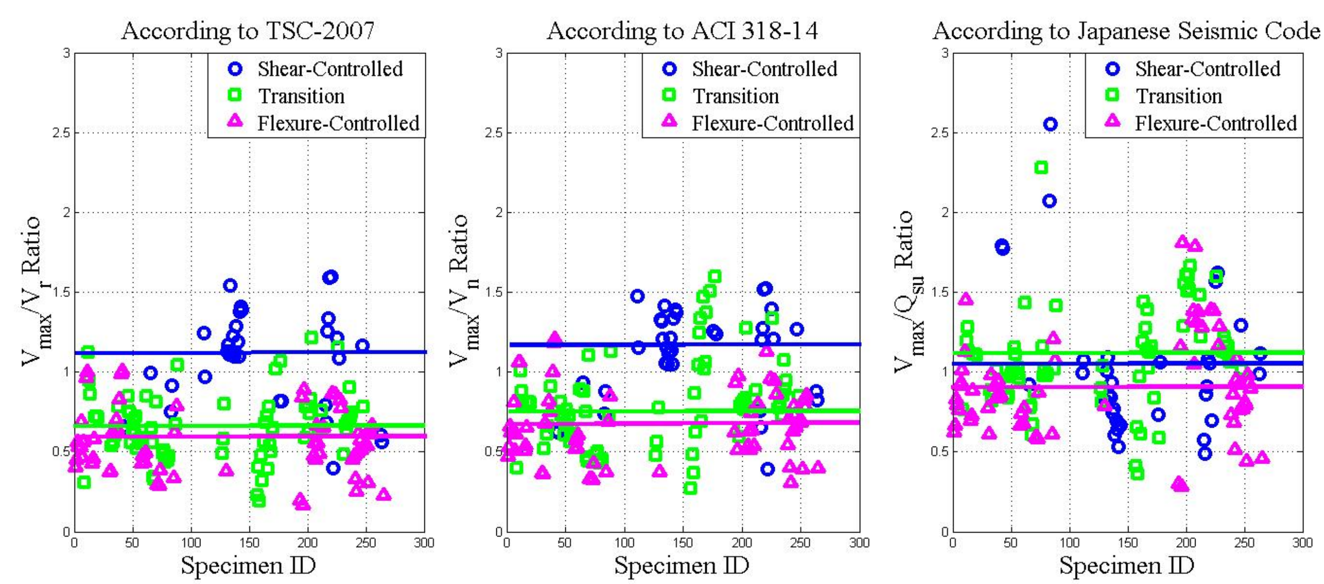

Fig. 5 – Distribution of ($V_{max}/V_{calc.}$) ratio for different failure types and three seismic codes

Mean values of the ratios are summarized in Table 2 for different failure and cross section types. Results show that TSC-2007 underestimates the peak shear stress values by about 7% for the shear-controlled walls, whereas the shear strength for transition and flexure-controlled walls is overestimated about 35% and 45%, respectively. Results were similar for ACI 318-14, such that peak shear stress values are underestimated by 11%

for the shear-controlled walls, whereas shear strength for transition and flexure-controlled walls is overestimated about 20% and 35%, respectively. Since the equation given in JSC-2001 is more complex, its reliability was better than the other two equations. According to equation provided by JSC-2001, peak shear stress values are underestimated by about 3% and 8% for shear-controlled and transition walls, respectively, whereas shear strength for flexure controlled walls is overestimated by 9%.

Table 2 – Mean values of ($V_{max}/V_{calc.}$) according to recent seismic codes

Mean values of $V_{max}/V_{calc.}$	**TSC-2007** V_{max}/V_r			**ACI 318-14** V_{max}/V_n			**JSC-2001** V_{max}/Q_{su}		
	All	Rect	Barbell/ Flanged	All	Rect	Barbell/ Flanged	All	Rect	Barbell/ Flanged
Shear-Controlled	1.07	1.12	0.84	1.11	1.11	1.14	1.03	1.04	0.99
Transition	0.66	0.68	0.58	0.79	0.73	0.98	1.08	1.13	0.94
Flexure-Controlled	0.56	0.56	0.52	0.66	0.65	0.76	0.91	0.91	0.89

Table 2 also indicates that shear strength equation estimated by TSC-2007 significantly overestimates the shear strength for non-rectangular shear-controlled walls. The reason for this overestimation is overestimating contribution of web reinforcement in flanged walls. The stress component due to web reinforcement is calculated by multiplication of yield strength of web horizontal reinforcement (f_{ywsh}) by web horizontal reinforcement ratio (ρ_{sh}). Horizontal web reinforcement in a flanged wall is efficient only in the web zone. However, multiplication of this stress by (A_{ch}) which is described in the Turkish Seismic Code as the entire wall area (including flange zone) causes overestimation of shear strength.

4. Summary and Conclusions

Reliability and accuracy of reinforced concrete wall shear strength equations given in current seismic codes (TSC-2007, ACI 318-14, and JSC-2001) were investigated using a detailed wall test database that includes 172 specimens tested worldwide. Previous studies on behavior of RC walls have shown that some wall parameters (e.g. axial load ratio, boundary reinforcement) have significant influence on behavior and response of shear walls. However, current code equations (except JSC-2001) do not include these parameters. To investigate effects of key parameters on different types of shear walls and assess accuracy of the available code equations, the database was divided into different groups in terms of reported failure modes and cross section types of the specimens. Correlation of theoretical shear strength (calculated based on the seismic codes) to the experimental shear strength was investigated for each cross section and for each failure type. Results of statistical analyses have revealed that shear strength equations given in recent seismic codes generally underestimate shear strength by different ratios for shear-controlled walls. TSC-2007 underestimates shear strength about 7% (12% underestimation for only rectangular walls whereas 16% overestimation for barbell or flanged walls), whereas ACI 318-14 calculates shear strength about 11% lower than actual strength. JSC-2001 provides the most complicated equation which underestimates shear strength only about 3%. It is noted that JSC-2001 is applicable for existing buildings; therefore, the high correlation is as expected.

Future studies include investigating influence of different key parameters (e.g. horizontal web reinforcement ratio (ρ_{sh}), compressive strength of concrete (f_c)) on wall shear strength. Future research will also include development of alternative equations for shear strength to estimate shear strength as accurate as possible. Various combinations of parameters that have influence on shear strength will be implemented in regression analyses to obtain new equations. These equations aim to better predict expected behavior and response of shear walls and to help the profession achieve better failure assessment, thus, more reliable and costeffective seismic rehabilitation. It is noted that building codes focus on technical preciseness as well as usefulness in practice. The proposed equations will also aim the same important aspects.

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