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ESTIMATION OF DEFORMATION CAPACITY OF REINFORCED CONCRETE SHEAR WALLS

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Abstract

In regions of high seismicity, reinforced concrete shear walls are commonly used to provide lateral load carrying capacity of structures. Majority of shear wall buildings in the existing building stock have been constructed prior to introduction of modern seismic codes. Field investigations after major earthquakes showed that such buildings were heavily damaged or even collapsed due to poor design and construction, particularly because of inadequate boundary reinforcement and detailing. To ensure sustainability of buildings even after strong ground motions, seismic rehabilitation and retrofit of existing buildings are important. Efficient rehabilitation and retrofitting can better be achieved by analytically modeling expected behavior of existing buildings as close to accurate as possible. Behavior of structural walls under lateral cyclic loading can be best characterized by shear strength and deformation capacity (or ductility). Many studies have been carried out to examine shear strength of reinforced concrete shear walls, which have led to development of shear strength equations to be used in current seismic codes. However, studies that investigate deformation capacity of reinforced concrete shear walls remain relatively limited. This study focuses on assessment of deformation capacity of reinforced concrete structural walls as well as influence of various key parameters (e.g. shear span ratio, axial load, reinforcement ratios) on wall ductility. To achieve these goals, a detailed wall test database consisting of 172 specimens was assembled. Statistical studies and linear regression analyses were carried out on this database to determine parameters that affect ductility of shear walls controlled by different failure modes. Based on statistical studies, mean values of curvature ductility were obtained as about 1.5, 3.5, and 5 for shear-controlled, transition, and flexure-controlled walls, respectively. Results of the regression analyses with single parameter indicated that shear span ratio has the highest correlation for curvature ductility.

Keywords: RC shear walls, Seismic Rehabilitation, Ductility, Deformation capacity

1. Introduction

In seismically active zones, reinforced concrete shear walls are widely used to enhance lateral strength and ductility to resist wind and earthquake loads. A large fraction of the shear wall buildings in the existing building stock were constructed before recent seismic codes were introduced, most of which were observed to experience severe damage/collapse as they were constructed without adequate amount of reinforcement and detailing. To prevent potential damage/collapse in those buildings in the future earthquakes, effective seismic rehabilitation and retrofit is essential, which can be best achieved if the building behavior is analytically modeled as accurate as possible. Two prominent properties that characterize behavior of shear walls under load reversals are shear strength and deformation capacity (ductility). There exist many studies on shear strength of RC shear walls in literature and shear strength equations are provided in building codes, however studies about ductility of shear walls are relatively limited. This study aims to address this gap by assessing deformation capacity of reinforced concrete shear walls and investigating influence of various parameters on deformation capacity using a detailed wall test database.

A comprehensive literature review was conducted to develop the wall test database. There exist several studies in literature that investigate influence of different wall properties on wall deformation capacity. Senel and Kaplan [1] conducted an analytical research to investigate the influence of longitudinal and horizontal boundary reinforcement on shear walls deformation capacity and showed that higher ratio of confinement and longitudinal boundary reinforcement increase wall deformation capacity. Lefas et al. [2] showed that axial load reduces the recorded top lateral displacement values, thus, wall deformation capacity. Another study to investigate the influence of axial load on ductility was carried out by Farvashany et al. [3], which indicates that axial load was found to decrease horizontal displacement of the top of the wall, whereas higher amount of horizontal web reinforcement increased the top lateral displacement.

There exist databases consisting of reinforced concrete wall tests created by various other researchers available in literature, each of which had different points of interest. Shear strength and deformation capacity of high-strength concrete shear walls were studied by Farvashany et al. [3], and Gupta and Rangan [4] by creating databases consisting of 76 and 69 specimens, respectively. Orakcal et al. [5] created a database of 49 specimens to investigate shear strength of lightly reinforced wall piers and spandrels using only lightly reinforced poorly detailed shear walls. Gulec et al. [6] studied on shear strength of squat rectangular reinforced concrete by using a database of 148 specimens. As an analytical research, Sengupta and Li [7] used a database with 100 specimens to study on analytical modeling for hysteresis loops of walls.

Available databases in the literature focus on behavior of specific walls such as only lightly reinforced or only squat walls. Since these databases do not represent the entire building stock, a detailed database of 265 specimens was created using experimental results reported by 41 different authors from 18 different countries in this research. Several test specimens were not included in the database such as specimens with FRP or GFRP [8] or repaired and strengthened specimens [9], shear walls with diagonal reinforcement [10], and those constructed with composite materials. 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. [11], 14 specimens from Oesterle et al. [12], 13 specimens from Lefas et al. [2], 13 specimens from Zhang [13], 6 specimens from Thomsen and Wallace [14], and 6 specimens from Dazio et al. [15].

2. Description of the Database

After a comprehensive literature review, a detailed wall test database was created. All parameters that can have influence on wall behavior were included in database, namely: wall geometry – length (L_w), thickness (t_w), and height (H_w) of the specimens, dimensions of the confined boundary region (if exists), aspect ratio (H_w / L_w), and shear span ratio (M / VL_w); test setup – axial load ratio ($P / A_{ch} f_c^{'}$), loading type (monotonic versus cyclic), curvature type (single versus double), and reported failure mode; mechanical properties of concrete – nominal and tested/expected cylinder strength of concrete (f_{ck}, $f_c^{'}$), tensile strength of concrete (f_{ct}) and modulus of elasticity of concrete (E_c); mechanical properties of reinforcement – nominal yield strength (f_{yk}), actual yield strength (f_{ym}), ultimate strength (f_u), as well as reinforcement ratios of longitudinal boundary reinforcement, boundary transverse reinforcement, vertical web reinforcement, and horizontal web reinforcement.

In case some of these characteristics were not reported, equations (Eq. 1 to Eq. 5), based on TSC-2007 [16] and ACI 318-14 [17], were used.

$$f_{ct} = 0.4\sqrt{f_{ck}} \tag{1}$$

$$E_c = 14,000 + 3250\sqrt{f_{ck}} \tag{2}$$

$$f_c = 1.3 f_{ck} \tag{3}$$

$$f_y = 1.17 f_{yk} \tag{4}$$

$$f_u = 1.3 f_y \tag{5}$$

Specimens in the database were classified into several bins based on following criteria to allow more efficient discussion on statistical studies:

- Loading types of test specimens: monotonic or cyclic
- Geometric properties of the specimens: rectangular, barbell or flanged walls
- Curvature types of the specimens: single curvature or double curvature
- Failure types of the specimens: reported failure modes were examined and a failure type was chosen for each specimen. Specimens damaged by sliding shear, shear cracks or diagonal web cracks were considered as shear-controlled walls. Specimens damaged by flexural cracks, boundary crushing or cover spalling were considered as flexure-controlled walls. Walls that contain both crack patterns were named as transition walls or shear-flexure interaction.

It is noted that the classifications on curvature type and failure type were particularly important because curvature type of a wall affects calculation of ductility directly, and failure type of a wall affects demand-to-capacity ratio for strength and caused differences in behavior of wall.

3. Statistical Studies

Prior to statistical studies, the database was filtered based on following criteria:

- Specimens tested under monotonic loading (e.g. [3], [4], and [18]) were eliminated as they do not represent walls under ground motion excitation.
- Majority of the buildings in the existing building stock were constructed with poor material qualities. Therefore, specimens constructed with high strength materials (larger than 50 MPa for compressive strength of concrete and 600 MPa for yielding strength of reinforcing steel) were filtered.
- Specimens constructed without vertical or horizontal web reinforcement (e.g. [19]) were eliminated.
- Specimens lacking lateral load – displacement loops were not included in this study as this feature was required for ductility calculations.

After filtering, certain specimens were eliminated due to their loading type (29), material qualities (43), inadequate web reinforcement (16), and lack of load – displacement curves (5). Statistical studies were therefore carried out with 172 of 265 specimens.

3.1 Estimation of displacement and curvature ductility

As it is essential to predict the failure mechanism of reinforced concrete shear walls as close to accurate as possible, estimation of deformation capacity becomes very important. It is generally assumed that walls that are expected to have brittle failure modes fail by losing their strength and axial load capacity rapidly when maximum lateral load is reached. However, if such walls have a little amount of nonlinear deformation capacity, design of new shear wall buildings and rehabilitation of existing shear wall buildings can be more cost-effective by taking this deformation capacity into account. Therefore, determining deformation capacity not only for flexure-controlled walls, but shear-controlled walls is critical.

Current building codes do not provide any equations to estimate deformation capacity. Therefore, one of the main goals of this research is to obtain relations for deformation capacity of shear walls. To achieve this goal, ductility of each specimen was calculated and statistical studies on ductility were conducted. Displacement ductility for each specimen in the database was calculated by dividing the displacement value corresponding to the failure point to the displacement value at yielding point.

Results of the study conducted by Oesterle et al. [7] have shown that reinforced concrete walls can reach a certain level of displacement without losing their horizontal load-carrying capacity; however, at the point they reach their maximum displacement, their load carrying capacity becomes much less than their maximum shear strength level. Park et al. [20] calculated ductility of quasi-static cyclic test specimens based on the displacement value at the level where the specimen lost 20% of its load carrying capacity. In this paper, statistical values for deformation capacity were calculated based on the same assumption, i.e., displacement corresponding to 80% of maximum shear strength was referred as failure displacement and used to define deformation capacity. Since backbone curves for each specimen were drawn by using line segments as shown in Fig. 1, the displacement value corresponding to the 80% of lateral load was calculated by interpolation method between maximum lateral load point and maximum top displacement point.

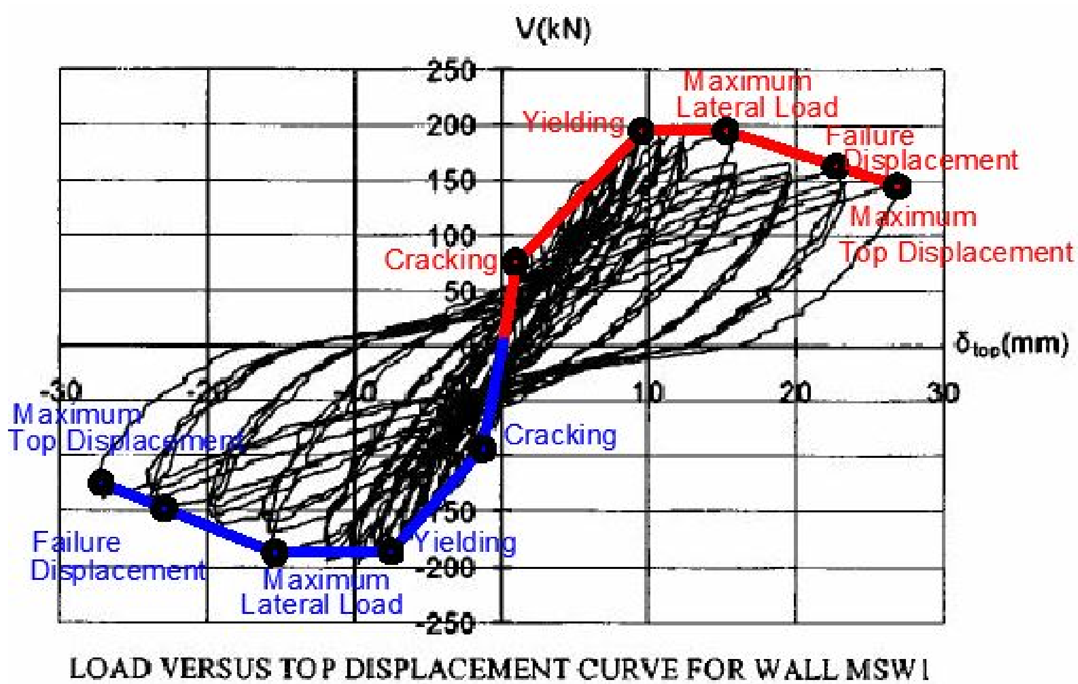

Fig. 1 – Backbone curves for specimen MSW1 [10]

Curvature ductility for each specimen was also calculated, which is particularly important for flexure-controlled walls. Primary advantages of using curvature ductility are that effect of wall height is normalized and curvature types of specimens are taken into account. Curvature ductility of each specimen was obtained by dividing maximum curvature capacity (ϕ_u) by its curvature capacity at yielding point (ϕ_y). Maximum curvature capacity of a reinforced concrete shear wall is related to its deformation capacity (Δ_u), length (L_w), and height (H_w) as shown in Eq. 6.

$$\phi_u = \frac{2\Delta_u}{L_w H_w} \tag{6}$$

Yield curvature of specimens is also affected by curvature type of the wall. For single curvature walls curvature capacity at yielding point was calculated with Eq. 7, whereas curvature capacity at yielding point of a double curvature wall was calculated by the Eq. 8.

$$\phi_y = \frac{3\Delta_y}{H_w^{\ 2}} \tag{7}$$

$$\phi_y = \frac{6\Delta_y}{H_w^{\ 2}} \tag{8}$$

3.2 Estimation of statistical values for ductility

Statistical values for displacement and curvature ductility are shown by providing their distribution for different failure types are shown in Fig. 2 and Fig. 3, respectively.

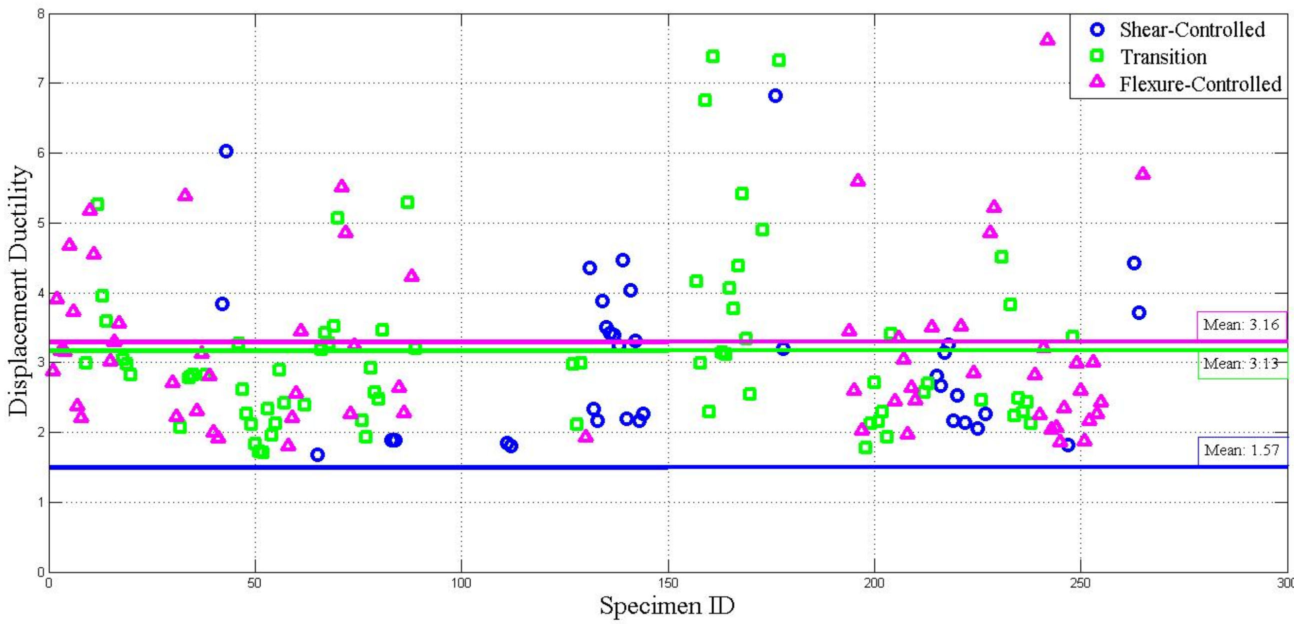

Fig. 2 – Distribution of displacement ductility for different failure types

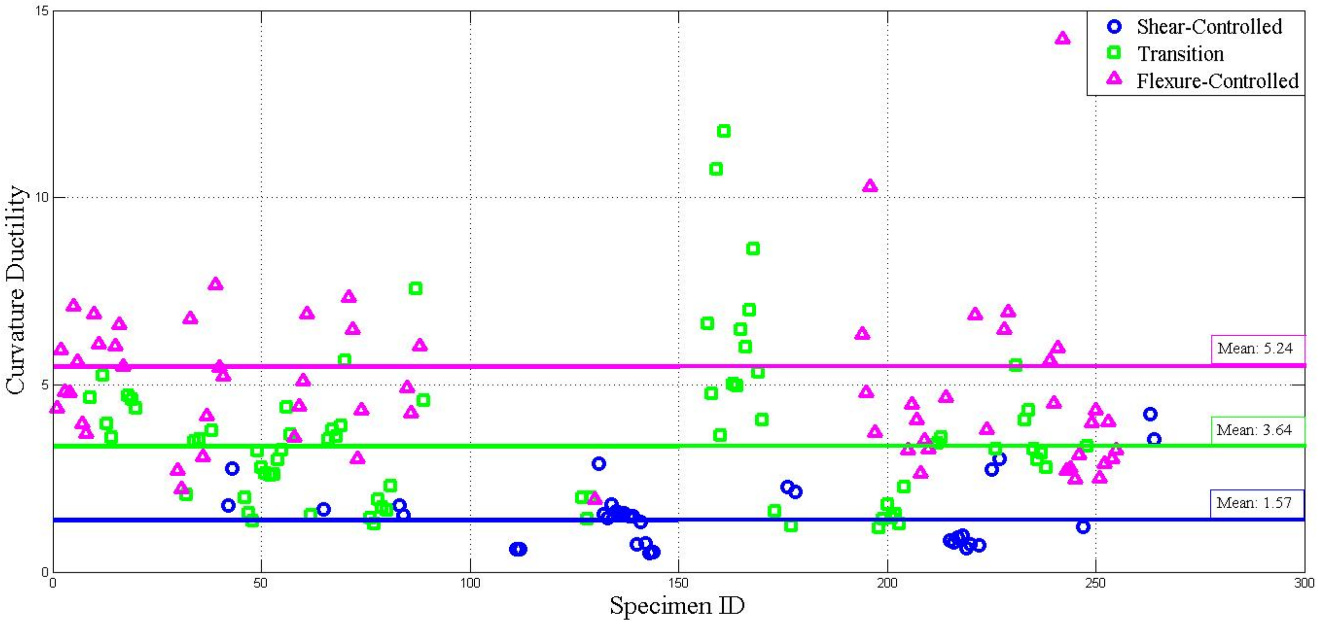

Fig. 3 – Distribution of curvature ductility for different failure types

Mean values for displacement ductility were calculated as 3.05, 3.13, and 3.16 for shear-controlled, transition, and flexure-controlled walls, respectively (Fig. 2). Displacement ductility values were very close to each other, whereas the difference between different failure types becomes more obvious for curvature ductility (Fig. 3). Mean values of curvature ductility for shear-controlled, transition, and flexure-controlled walls were 1.57, 3.64, and 5.24, respectively. Results indicate that curvature ductility for shear-controlled walls were lower than that of flexure-controlled walls, as expected due to their slenderness.

Minimum, maximum, and mean values, as well as standard deviation of displacement and curvature ductility for specimens of each failure type are summarized in Table 1.

Table 1 – Statistical values for displacement and curvature ductility for different failure types

	Shear-Controlled Walls (35 Specimens)				**Transition Walls (73 Specimens)**				**Flexure-Controlled Walls (64 Specimens)**			
	Max.	**Min.**	**Mean**	**Std. Dev.**	**Max.**	**Min.**	**Mean**	**Std. Dev.**	**Max.**	**Min.**	**Mean**	**Std. Dev.**
Displacement Ductility	6.82	1.68	3.05	1.91	7.37	1.70	3.13	1.22	7.62	1.80	3.16	1.20
Curvature Ductility	4.23	0.51	1.57	0.91	11.77	1.19	3.64	2.09	28	1.94	5.24	3.53

Table 1 shows that the dominant behavior of walls affects both displacement ductility and curvature ductility. Since shear-controlled walls are expected to have brittle failure modes, main part of total displacement occurs before yielding. So that ratio of failure displacement to yielding displacement for shear-controlled walls decreases. On the other hand, most of the total displacement in flexure-controlled walls occurs after the yielding of reinforcement. Therefore, it can be assumed that the ratio of failure displacement to yielding displacement for flexure-controlled walls is relatively greater.

In the previous sections, it has been mentioned that the cross-section of wall can affect the behavior of wall. For this reason, the statistical values related to displacement and curvature ductility for different cross-section types in each failure types are summarized in Table 2.

Table 2 – Mean values of displacement and curvature ductility for different failure and cross section types

	Shear-Controlled Walls (35 Specimens)		**Transition Walls (73 Specimens)**		**Flexure-Controlled Walls (64 Specimens)**	
	Rectangle	Barbell - Flanged	Rectangle	Barbell - Flanged	Rectangle	Barbell - Flanged
Displacement Ductility	2.93	3.63	2.72	4.29	3.16	3.59
Curvature Ductility	1.43	2.23	3.02	5.40	4.75	9.26

Results presented in Table 2 shows that mean values of curvature and displacement ductility of barbell-flanged walls are higher than that of rectangular walls for each failure type. Most of the rectangular walls in the database was constructed without any confined boundary region. Ratio of transverse and longitudinal reinforcement was higher for barbell flanged walls. For this reason, boundary regions of non-rectangular walls have higher displacement and curvature ductility levels due to their high confinement reinforcement ratio.

As wall height is normalized in curvature ductility, the results were more meaningful when different failure types were considered. Therefore, influence of various parameters on deformation capacity was investigated and presented only in terms of curvature ductility in the following subsection.

3.3 Regression analyses

Regression analyses were carried out using MATLAB [21] to investigate influence of the key parameters on curvature ductility for each failure type. Highest possible correlation was aimed to be obtained by generating a linear equation for each parameter.

Correlation coefficients of key parameters along with standard deviations were determined and the results were summarized in Table 3 for each failure mode. Correlation coefficient (ρ) shows the linear relationship between a parameter with ductility such that $\rho=0$ indicates that the parameter is not correlated with curvature ductility, $\rho=1$ means that the parameter is directly proportional to curvature ductility, whereas $\rho=-1$ indicates inverse proportion. As shown in Table 3, shear span ratio (M/VL_w) showed the highest correlation with curvature ductility for all failure types. Correlation coefficients of shear span ratio with curvature ductility were calculated as 0.72, 0.62, and 0.76 for shear-controlled, transition, and flexure-controlled walls, respectively. Shear span ratio has a significant influence on slenderness of shear walls and behavior of slender walls with high shear span ratios are governed by flexure. As mentioned above, flexure-controlled walls have higher displacement and curvature ductility as shown in Table 1. Due to its influence on slenderness and expected wall behavior shear span ratio highly correlated with curvature ductility.

Table 3 – Correlation coefficients with respect to curvature ductility

Parameters	Shear-Controlled Walls		Transition Walls		Flexure-Controlled Walls	
	Corr. Coef.	Std. Dev.	Corr. Coef.	Std. Dev.	Corr. Coef.	Std. Dev.
H_w (mm)	0.36	0.84	0.31	1.97	0.66	2.62
L_w (mm)	0.37	0.84	0.22	2.03	0.15	3.46
b_w (mm)	0.27	0.87	0.21	2.03	0.03	3.50
M/VL_w	**0.72**	0.63	**0.62**	1.64	**0.76**	2.28
$P/A_{ch}f_c'$	0.23	0.88	0.05	2.08	0.09	3.49
P/A_{ch} (MPa)	0.25	0.87	0.01	2.07	0.01	3.50
f_{cm} (MPa)	0.07	0.90	0.39	1.91	0.30	3.34
f_{ctm} (MPa)	0.07	0.90	0.32	1.97	0.29	3.50
$\sqrt{f_{cm}}$ (MPa)	0.09	0.90	0.40	1.90	0.03	3.35
f_{ys} (MPa)	0.47	0.80	0.17	2.05	0.06	3.49
ρ_s (%)	0.24	0.87	0.07	2.07	0.10	3.48
f_{yb} (MPa)	0.07	0.90	0.19	2.04	0.07	3.49
ρ_b (%)	0.11	0.89	0.10	2.07	0.04	3.50
f_{ysh} (MPa)	0.43	0.81	0.37	1.93	0.13	3.47
ρ_{sh} (%)	0.12	0.89	0.21	2.03	0.05	3.50
f_{yver} (MPa)	0.49	0.78	0.28	1.99	0.08	3.49
ρ_{ver} (%)	0.01	0.90	0.42	1.88	0.13	3.47

4. Summary and Conclusions

Deformation capacity and shear strength are important characteristics to understand and model the behavior of reinforced concrete shear walls. Wall shear strength has been widely studied and shear strength equations are provided in the current code provisions (TSC-2007, ACI 318-14 and JSC-2001); however, studies on shear wall ductility have been relatively limited. In this study, deformation capacity of reinforced concrete shear walls was examined using a detailed wall test database consisting of 265 specimens tested worldwide. Specimens in the database were classified into different groups based on their curvature type, reported failure modes, and cross section types. For each group, deformation capacities were calculated based on test results in terms of displacement ductility and curvature ductility. Mean values of displacement ductility were calculated as 3.05, 3.13, and 3.16 for shear-controlled, transition, and flexure-controlled walls, respectively, whereas mean values of curvature ductility were calculated as 1.57, 3.64, and 5.24 for the same categories respectively. Results showed that mean values of both displacement and curvature ductility were highest for flexure-controlled walls; as such walls are the most slender. Previous research on wall deformation capacity have revealed that some wall properties such as confinement, longitudinal boundary reinforcement, axial load, and shear span ratio have significant influence on deformation capacity of shear walls. Therefore, influence of various key parameters on deformation capacity was also investigated. Results of the regression analyses revealed that for all walls shear span ratio (M/VL_w) showed the highest correlation with curvature ductility.

Future studies include development of equations to estimate deformation capacity by conducting regression analyses and using various combinations of key parameters. Key parameters will be selected based on results of the single-parameter regression analyses as well as findings of other researchers. Proposed equations will be expected to be able to capture the wall behavior as close to accurate as possible based on mean values of the test results. The new equations aim to help the profession to obtain better assessments of failure, therefore more reliable and cost – effective designs for new buildings and seismic rehabilitation of existing buildings.

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