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Preface

Dear Participants,

A year preparation for The 1st International Conference on Sustainable Civil Engineering Structures and Construction Materials has already been elapsed. Announcement for abstracts and full papers submission has also been delivered through electronic mail to many related domestic and foreign universities as well as public / private institutions in Europe and Asian Countries since the beginning of this year. Up to the closing date of the abstract submission, more than 63 abstracts have been submitted from the USA, the UK, the Germany, the Switzerland, the Japan, the Taiwan, the Singapore, the Thailand, the Pakistan and the Iran.

But unfortunately, for many reasons not all participants submitting their abstracts proceeded with their full papers on the appointed date. For this reason the organizing committee decided to extend the period of the submission. As the number of the submitted full papers was less than we expected, not all reviewers were involved in the review process. The organizing comittee realizes that providing a good quality of papers is not just a matter of writing itself, but a comprehensive knowledge. Therefore, the organizing committee does understand to prospective participants whom are not able to finish writing on the scheduled date. The organizing committee still think that a number of 44 full papers will be reasonably enough to host this International Conference for the first time. The organizing committee do believes that in the next International Conference on SCESCM, the adequate time for preparing full papers can be accommodated by the organizing committee for involvement of more participants.

As the chairperson of scientific committee, anyway, would like to thank for the generousity and help of the reviewers who have reviewed and delivered their comments. I also would like to say sorry to all reviewers for any inconvenience that may happen during this review process.

Prof. Priyosulistyo

Chairperson of Scientific Committee The 1st International Conference on SCESCM

Welcoming Speech

It is my great pleasure, on behalf of the Department of Civil and Environmental Engineering, Universitas Gadjah Mada, to welcome all of you to participate in the 1st International Conference on Sustainable Civil Engineering Structures and Construction Materials.

It is also a great honor for our Department to host this very important conference addressing on the issues of sustainability in Civil Engineering.

This conference is held as result of the close collaboration between Universitas Gadjah Mada, Hokkaido University, and Karlsruhe Institute of Technology. We would like to thank to both universities for the nice collaboration that has been implemented so far.

It is the pleasure of the Department of Civil and Environmental Engineering, Universitas Gadjah Mada, to organize this conference, and I am very confident that the conference will bring the best of the participants and to forester future collaborations among us.

Concept of sustainability has been gradually applied in various aspects of civil engineering structures. The concept as indicated by high efficiency in human and material resources but less in environmental impacts shall be further implemented in design, construction and maintenance of every civil engineering structure. In this regard, potential networking and sharing information on the latest scientific findings and achievements among civil engineers around the globe shall be accommodated through international conferences as what we will have in this conference in our blue campus of Universitas Gadjah Mada, Yogyakarta-Indonesia.

We are glad that we will have opportunities in this conference to learn from our colleagues, to share knowledge and experiences among us, and after it to tackle the challenges on the way in the future.

We would like also to express our hearty welcome to many distinguished professors, academicians, practitioners, industry representatives, as well as students, who have been joining and participating in this conference.

We truly believe that we can advance our profession, both individually and collectively.

September is the best time of the year, and I wish you all pleasant stay in Yogyakarta.

We do hope that this symposium would be successfully held to facilitate all participants in exchanging knowledge, experiences, and ideas for the sake of solving our problems related to sustainability.

Finally, I would like to thanks to the conference organizers for the hard working to prepare this event. Appreciation is also addressed to those who assisted in making the 1st International Conference on

Sustainable Civil Engineering Structures and Construction Materials a reality. I would also to thank all of you for traveling to our beautiful country.

I am confident that you will enjoy your stay and that the conference will be an informative and enjoyable event.

Thank you very much.

Prof. Bambang Suhendro, Ph. D

Head of Civil and Environmental Engineering Department Universitas Gadjah Mada

SCESCM

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Shear Strength of Normal to High Strength Concrete Walls

J. Chandra and S. Teng
Nanyang Technological University, Singapore

Abstract: This paper presents an analytical study on the behavior of normal to high strength concrete walls. Experimental data of concrete walls were collected from available literatures and several building code provisions were evaluated by comparing nominal wall strengths calculated using code formulas with experimental wall strengths. Moreover, behavior of concrete walls as influenced by various parameters was investigated by plotting the normalized experimental wall strengths and average shear stresses against shear span ratio, axial load ratio, web reinforcement ratio, and concrete strength. The analysis results show that most code formulas underestimate wall shear strengths. It is shown that longitudinal web reinforcement also has contribution to the shear strength of concrete walls even though it is not accounted in code formulas. Furthermore, the accuracy of code formulas is also affected by variation in concrete strength. For example, the ACI code considerably underestimates the shear strength of high strength concrete walls due to its limitation on maximum wall shear stress which is quite conservative for high strength concrete walls. Thus, a modification of ACI code formula is proposed to enhance its accuracy. The results show that the modified formula yields better predictions of both normal and high strength concrete wall shear strengths.

Keywords: Shear strength, concrete walls, building code formulas.

1 INTRODUCTION

Concrete structural walls have been used widely in many structures since they provide good resistance to lateral loadings (Fintel 1991). This study presents an analytical review on the behavior of concrete walls having compressive strength varying from normal strength to high strength in excess of 100 MPa. Data from past experiments on concrete walls from different countries were collected and studied.

Data from these experiments were used to calculate nominal wall strengths using several building code formulas, such as those formulas recommended by the American Concrete Institute (ACI 318 2011), Architectural Institute of Japan (AIJ 1994), and Eurocode (EC8 2004). Subsequently, the nominal wall strengths calculated using code formulas were compared with experimental wall strengths. Hence, the accuracy of these building code provisions in determining the nominal wall strengths could then be evaluated. In addition, to investigate further the behavior of concrete walls as influenced by various parameters, normalized experimental wall strengths and normalized average shear stresses were plotted against shear span ratio, axial load ratio, longitudinal and transverse web reinforcement ratios, and concrete strength. The results from this analytical study will be used as a basis for further experimental study on concrete walls as well as further development of analytical model for predicting wall shear strengths.

2 CONCRETE WALL EXPERIMENTS

As mentioned before, previous experiments on concrete walls reported by researchers from different countries were studied (Cardenas and Magura 1972; Cardenas et al. 1980; Chiou et al. 2003; Corley et al. 1981; Deng et al. 2008; Farvashany et al. 2008; Gupta and Rangan 1998; Kabeyasawa and Hiraishi 1998; Lefas et al. 1990; Salonikios et al. 1999; Wood 1991; Yan et al. 2008; Yun et al. 2004; Zhang and Wang 2000). There were a total of 139 specimens studied.

Data from these experiments were collected in terms of concrete compressive strength (f'_c); shear span ratio ($M/[VL_w]$ where M is the applied bending moment in wall, V is the applied shear force in wall, and L_w is the wall length); axial load ratio ($P/[f'_cA_g]$ where P is the applied axial load in wall, and A_g is the gross cross sectional area of the wall); longitudinal and transverse web reinforcement contributions ($\rho_l f_{yl}$ and $\rho_t f_{yt}$ where ρ_l and ρ_t are longitudinal and transverse web reinforcement ratios of wall, f_{yl} and f_{yt} are the yield strengths of longitudinal and transverse web reinforcements); maximum wall strength (in-plane lateral load applied) obtained from experiment (V_{exp}); and average shear stress in wall ($V_{exp}/[A_w\sqrt{f'_c}]$ where A_w is the area of wall web). These data frequency distributions based on several parameters are presented in Figure 1.

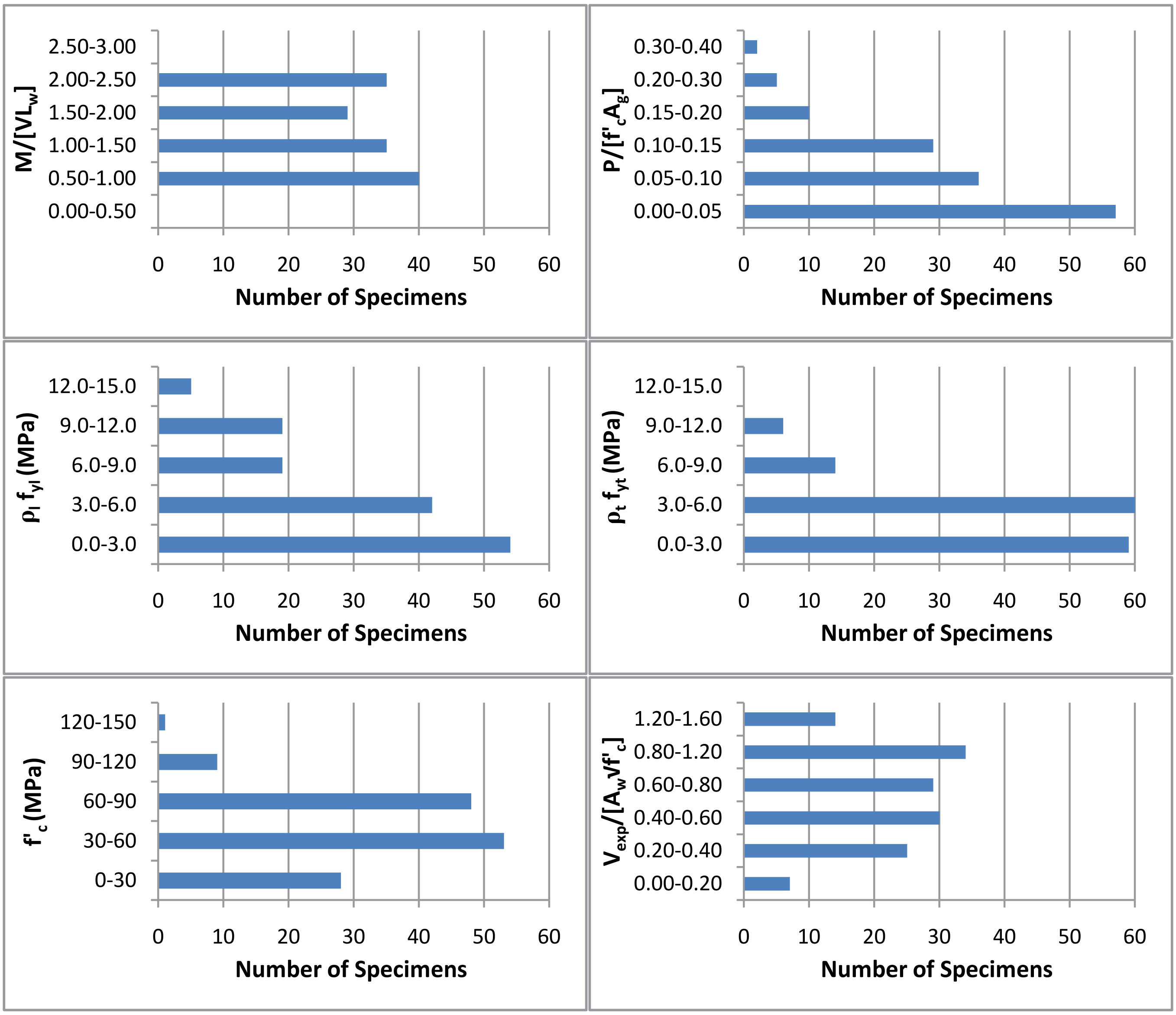

Figure 1. Data frequency distributions based on several parameters.

3 ANALYTICAL STUDY

The nominal wall strengths were then calculated according to the methods of ACI 318 (2011), AIJ (1994), and EC8 (2004). The flexural strength of the walls was calculated based on flexural theory for members subjected to bending moment and axial load as suggested by Paulay and Priestley (1992) whereas the shear strength was calculated using formulas given in the building codes. The smaller value of the flexural strength and the shear strength was then taken as the nominal wall strength. Shear strength formulas according to building codes mentioned above are given as follows.

3.1 ACI 318 (Chapter 21)

According to ACI 318 chapter 21 (2011), the nominal shear strength of special structural walls can be calculated as follow:

$$V_n = A_{cv}\left(\alpha_c \lambda \sqrt{f_c'} + \rho_t f_{yt}\right) \tag{1}$$

where V_n is nominal wall shear strength (N); A_{cv} is gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered (mm^2); α_c is coefficient defining the relative contribution of concrete strength to nominal wall shear strength, which may be taken as 0.25 for $H_w/L_w \leq 1.5$, 0.17 for $H_w/L_w \geq 2.0$, and varies linearly between 0.25 and 0.17 for H_w/L_w between 1.5 and 2.0, where H_w/L_w is the height to length ratio of the wall; λ is modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength.

Furthermore, ACI 318 also limits the maximum shear stress for walls to $0.83\sqrt{f'_c}$.

3.2 AIJ

AIJ guidelines (1994) provide the following equations to calculate the nominal shear strength of structural walls based on plastic theory combining arch and truss shear resistance mechanisms:

$$V_n = t_w L_w \rho_t f_{yt} \cot\theta_{st} + 0.5 \tan\theta_{sa} (1-\beta) t_w L_w \nu_e f_c' \quad (2)$$

$$\tan\theta_{sa} = \sqrt{(H_w/L_w)^2 + 1} - H_w/L_w \quad (3)$$

$$\beta = (1 + \cot^2\theta_{st}) \rho_t f_{yt} (\nu_e f_c')^{-1} \quad (4)$$

$$\nu_e = 0.7 - (f_c'/2000) \quad (5)$$

where V_n is nominal wall shear strength (N); t_w is thickness of wall (mm); cot θ_{st} can be taken as 1.0.

3.3 EC8

The nominal shear strength of structural walls is taken as the minimum shear strength between diagonal tension failure of the web and diagonal compression failure of the web according to EC8 (2004). The formulas are given as follows.

3.3.1 Diagonal compression failure

$$V_n = \alpha_{cw} b z \nu_1 f_c' (\cot\theta_s + \tan\theta_s)^{-1} \quad (6)$$

where V_n is nominal wall shear strength (N), which for the critical region, it may be taken as 40% of the calculated value; α_{cw} is coefficient taking account of the state of the stress in the compression chord, which may be taken as 1.0 for non-prestressed structures, [1 + $P/(f'_c A_g)$] for $0 < P/(f'_c A_g) \leq 0.25$, 1.25 for $0.25 < P/(f'_c A_g) \leq 0.5$, or 2.5 [1 − $P/(f'_c A_g)$] for $0.5 < P/(f'_c A_g) < 1.0$; b is width of web cross section (mm), z is inner lever arm, for a member with constant depth, corresponding to the bending moment in the element under consideration, which may be taken equal to 0.8 L_w; ν_1 is strength reduction factor for concrete cracked in shear, which can be taken as 0.6 (1.0 − f'_c/250); cot θ_s and tan θ_s can be taken as 1.0.

3.3.2 Diagonal tension failure

If $M/(VL_w) \geq 2.0$:

$$V_n = bd\left[C_{Rd,c} k (100\rho_l f_c')^{1/3} + k_1 \sigma_{cp}\right] + zb\rho_t f_{yt} \cot\theta_s \quad (7)$$

If $M/(VL_w) < 2.0$:

$$V_n = bd\left[C_{Rd,c} k (100\rho_l f_c')^{1/3} + k_1 \sigma_{cp}\right] + 0.75 b\rho_t f_{yt} M/V \quad (8)$$

where V_n is nominal wall shear strength (N); b is width of web cross section (mm); d is effective depth of cross section (mm); $C_{Rd,c}$ can be taken as $0.18/\gamma_c$, which γ_c is taken as 1.0 for nominal strength without reduction factor for material; k can be taken as $1 + \sqrt{(200/d)} \leq 2.0$; k_1 is 0.15; σ_{cp} is equal to $P/A_g < 0.2$ f'_c (MPa); z can be taken as 0.8 L_w; cot θ_s can be taken as 1.0; M is applied bending moment in wall; V is applied shear force in wall.

4 ANALYSIS RESULTS

The analysis results are presented in terms of experimental wall strengths, V_{exp}, normalized by nominal wall strengths calculated from building code formulas, V_n. This is done with purpose of evaluating building code provisions. Furthermore, average shear stresses (shear force divided by wall web area, A_w) normalized by the square root of concrete strength are plotted against key parameters such as shear span ratio, axial load ratio, longitudinal and transverse web reinforcement contributions, and concrete strength. This is done to see the relationship between normalized wall strengths and these parameters. The analysis results can be seen in Figures 2 and 3.

As observed from Figure 2, ACI code and Eurocode generally underestimate the wall strengths. It is understood that most building codes tend to give lower predictions of actual strength so that the design formulas are safe enough to be used for practical design. Thus, even though in average the Japanese code is the most accurate one with average ratio of V_{exp}/V_n closest to 1.00 and has the lowest covariance, it may not provide safe design for some cases since it may overestimate the wall strengths. On the other hand, Eurocode is the most conservative one with average ratio V_{exp}/V_n of 1.47 and covariance of 0.33.

Moreover, from Figure 2, it can be seen that for walls with high shear span ratio (i.e. flexure behavior dominates), the building code predictions are quite accurate with ratio of V_{exp}/V_n closer to 1.00. It means that the flexure strength of walls can be well predicted using flexural theory for members subjected to axial force and bending moment. On the other hand, for walls with low shear span ratio (i.e. shear behavior dominates), ACI code and Eurocode underestimate the wall strengths while the opposite is true for AIJ. This implies that building code formulas are not accurate enough to predict the wall shear strengths.

Furthermore, from Figure 2, it can be observed that the accuracy of building code predictions is also affected by variation in concrete strength. ACI code and Eurocode considerably underestimate the wall strengths for walls with higher concrete compressive strength (>60 MPa) while AIJ slightly overestimates the wall strengths. Further investigation shows that in most cases, this happens for walls with low shear span ratio (i.e. shear behavior dominates). Hence, it can be concluded that building code formulas are less accurate in predicting the shear strength of high strength concrete walls than that of normal strength concrete walls.

Figure 3 shows the behavior of concrete walls with varying parameters such as shear span ratio, axial load ratio, web reinforcement contributions, and concrete strength. As can be seen, the normalized average shear stresses decrease as shear span ratio increases. This means that flexure behavior is more dominant for walls with high shear span ratio while shear behavior is more dominant for walls with low shear span ratio. The figure also shows that the normalized average shear stresses increase with increment in axial load ratio. This implies that walls subjected to higher axial load have higher shear strength.

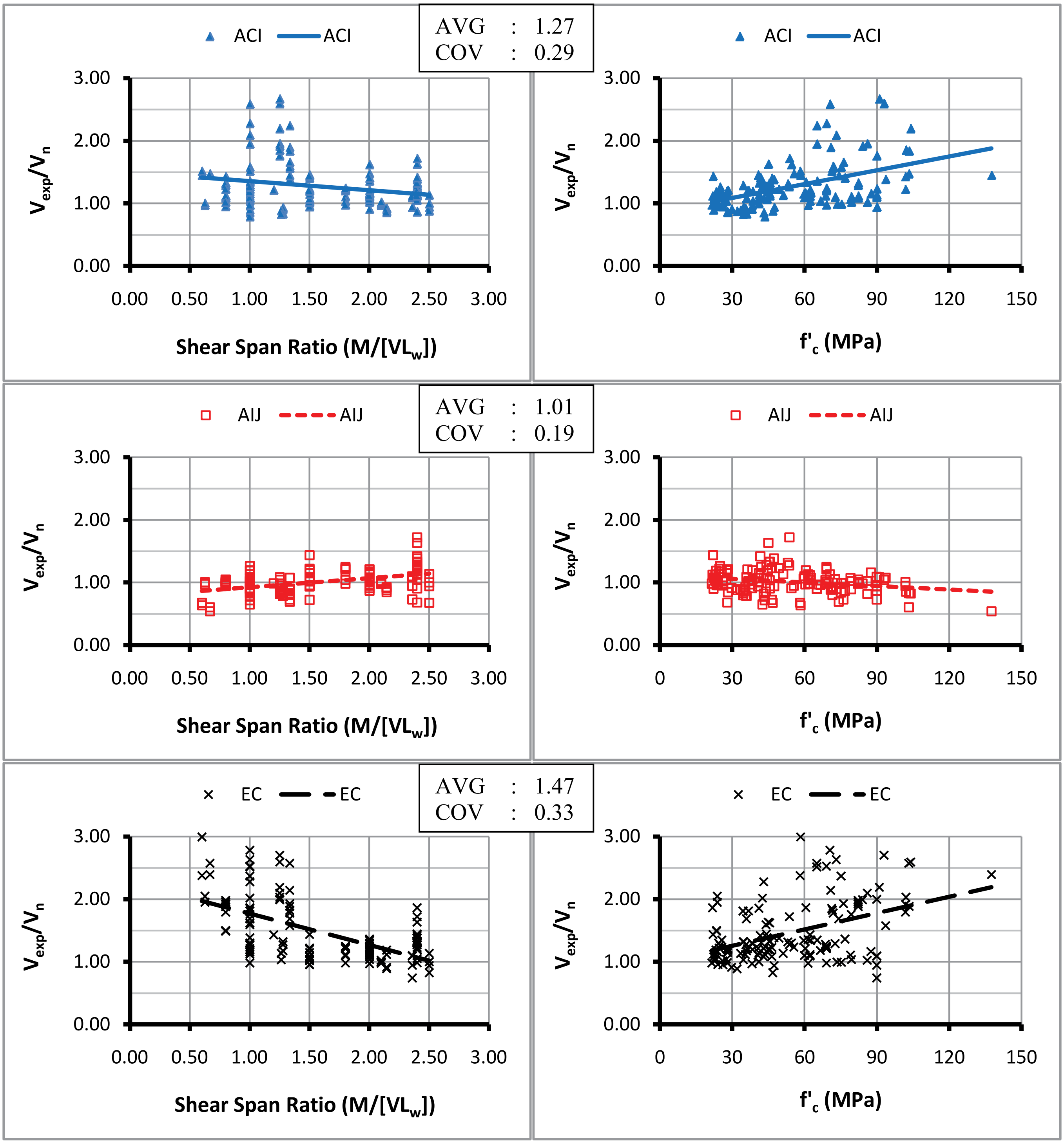

Figure 2. Normalized experimental wall strengths over nominal wall strengths plotted against shear span ratio and concrete strength.

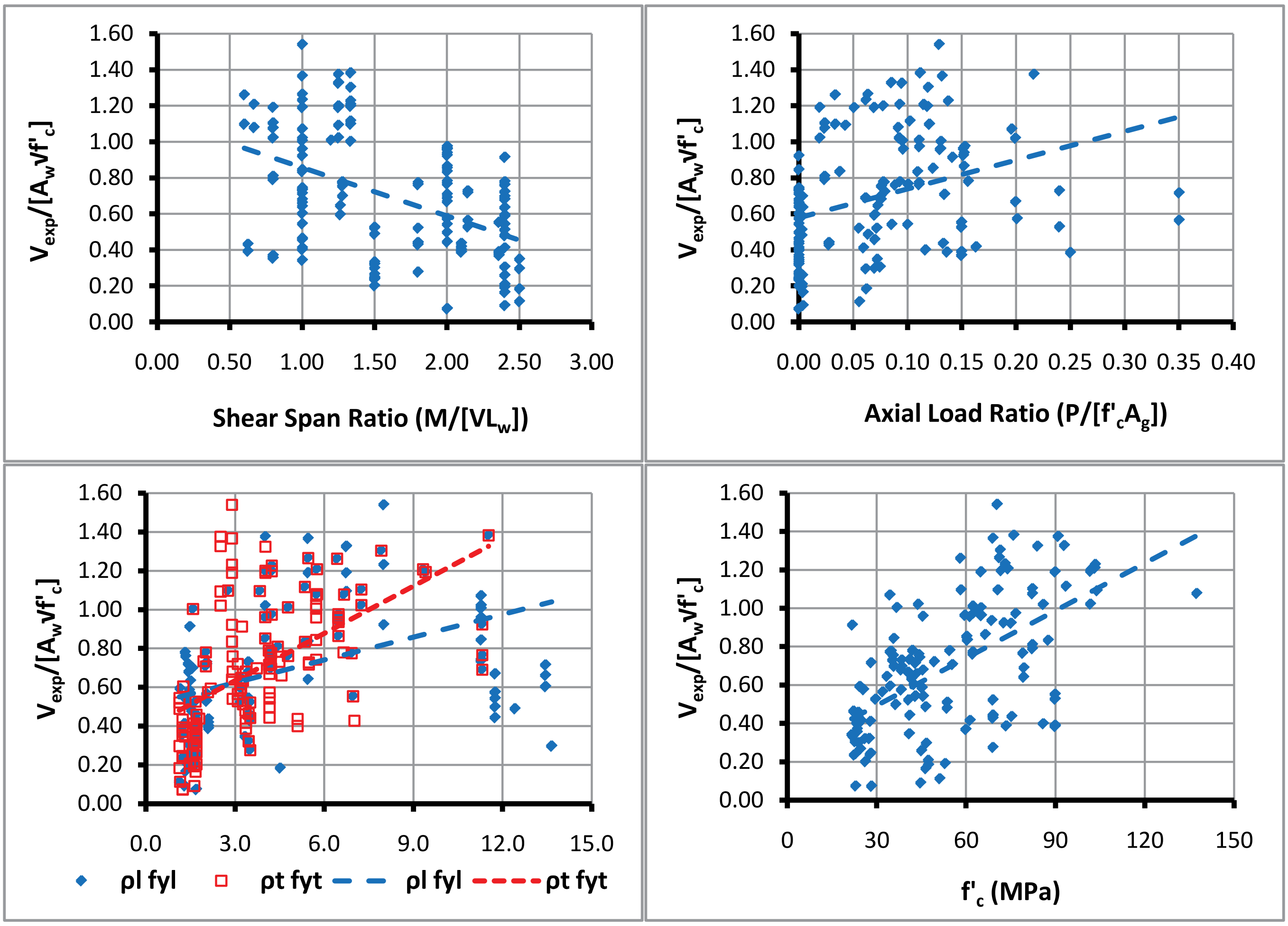

Figure 3. Normalized average shear stresses plotted against several parameters.

For web reinforcement contributions ($\rho_l f_{yl}$ and $\rho_t f_{yt}$), it can be seen from Figure 3 that the normalized average shear stresses increase with the increment of longitudinal and transverse web reinforcement contributions. This implies that both longitudinal and transverse web reinforcement have contributions to the wall shear strengths. However, this phenomenon is not taken into account in building code formulas for calculating wall shear strengths. The code formulas only take into account the contribution from transverse web reinforcement while neglecting the longitudinal web reinforcement contribution. Thus, it may result in underestimation of wall shear strengths for some building codes.

For concrete strength, Figure 3 shows that the normalized average shear stresses increase with increment in concrete strength. It implies that walls with higher concrete compressive strength can resist higher level of shear stress. Nevertheless, building code provisions do not differentiate between normal strength concrete walls and high strength concrete walls. For example, in ACI code, the limit of maximum shear stress for walls is $0.83\sqrt{f'_c}$ regardless of concrete strength. Based on data as presented in Figure 3, for normal strength concrete walls with compressive strength up to 60 MPa, most of specimens have average shear stresses less than $0.83\sqrt{f'_c}$ which fall below ACI code limit. On the other hand, for high strength concrete walls with compressive strength above 60 MPa, many specimens have average shear stresses more than $0.83\sqrt{f'_c}$ which exceed the limit given by ACI code. As a result, ACI code may underestimate the shear strength of high strength concrete walls by assigning the same limit as in the case of normal strength concrete walls.

Therefore, in this study, the issues of longitudinal web reinforcement contribution and maximum shear stress limit for high strength concrete walls are addressed. A modification of ACI 318 formula is proposed and presented in the subsequent section.

5 PROPOSED MODIFICATION OF ACI 318 FORMULA

In this section, a simple modification of ACI 318 formula is proposed to address the issues mentioned previously. It is therefore expected that the modified formula can yield better predictions of concrete wall shear strengths. The modification is described below.

As in the case of original ACI 318 formula, in the proposed formula, the nominal wall shear strength (V_n) is the sum of concrete contribution (V_c) and steel reinforcement contribution (V_s) as shown in equation (9). The concrete contribution, V_c, is calculated using the formulas given in ACI 318 chapter 11 (2011). These formulas are given in equations (10) and (11).

Moreover, for steel contribution (V_s), the contribution of the longitudinal web reinforcement is added. Nevertheless, this addition should not be straight forward assuming both longitudinal and transverse web reinforcements are fully effective in contributing to wall shear strength. Based on previous concrete wall experiments which studied the effectiveness of longitudinal and transverse web reinforcements to the wall shear strength (Barda et al. 1977; Cardenas et al. 1980), it is concluded that the effectiveness of web reinforcements depends on the shear span ratio of walls. For walls with shear span ratio of 1.00, both longitudinal and transverse web reinforcements are effective in contributing to wall shear strength (Cardenas et al. 1980). For walls with shear span ratio less than or equal to 0.50, longitudinal web reinforcement is more effective than transverse web reinforcement in contributing to wall shear strength (Barda et al. 1977). As shear span ratio increases, longitudinal web reinforcement becomes less effective. In other words, longitudinal web reinforcement contribution to wall shear strength is more dominant than that of transverse web reinforcement for walls with shear span ratio less than 1.00 whereas the opposite is true for walls with shear span ratio more than 1.00. Thus, in this study, the effectiveness of web reinforcement contributions is presented as a function of wall shear span ratio. The formulas for calculating overall steel web reinforcement contributions to wall shear strength are presented in equations (12) and (13).

Addressing the issue of maximum shear stress limit for high strength concrete walls with compressive strength more than 60 MPa, in this study the limit is taken as $1.25\sqrt{f'_c}$ instead of $0.83\sqrt{f'_c}$. This number is originated from the upper bound value (mean value plus standard deviation) of normalized average shear stresses of high strength concrete wall specimens studied previously (Chandra et al. 2011). In this case, the mean value of average shear stresses is 0.91 with standard deviation of 0.32. The upper bound value is then 0.91+0.32 = 1.23 which is rounded becomes 1.25. Thus, the maximum shear stress limit for high strength concrete walls with compressive strength more than 60 MPa is taken as $1.25\sqrt{f'_c}$. The complete modified formulas are presented as follows.

The nominal wall shear strength (V_n) can be calculated as:

$$V_n = V_c + V_s \tag{9}$$

The concrete contribution (V_c) shall be taken the lesser of:

$$V_{c1} = 0.27\lambda hd\sqrt{f'_c} + Pd/(4L_w) \tag{10}$$

$$V_{c2} = hd\left[0.05\lambda\sqrt{f'_c} + \frac{L_w\left(0.1\lambda\sqrt{f'_c}+0.2\frac{P}{hL_w}\right)}{\frac{M}{V}-\frac{L_w}{2}}\right] \tag{11}$$

The steel reinforcement contribution (V_s) shall be taken as:

$$V_s = A_{st}f_{yt}\sin\varphi + A_{sl}f_{yl}\cos\varphi \tag{12}$$

$$\tan\varphi = \frac{M}{VL_w} \tag{13}$$

In any cases, V_n shall not be taken greater than:

$$V_{n,max} = 0.83hL_w\sqrt{f'_c};\ \text{for } f'_c \leq 60\text{ MPa} \tag{14}$$

$$V_{n,max} = 1.25hL_w\sqrt{f'_c};\ \text{for } f'_c > 60\text{ MPa} \tag{15}$$

where λ is modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength; h is the thickness of wall; d is the effective depth of wall; L_w is the wall length; P is the applied axial force in wall; M is the applied bending moment in wall; V is the applied shear force in wall; A_{sl} and A_{st} are the total area of longitudinal and transverse web reinforcements, respectively. In case of ($M/V - L_w/2$) is negative, equation (11) shall not apply.

The normalized experimental wall strengths to nominal wall strengths (V_{exp}/V_n) for modified ACI 318 formula (ACI*) are presented in Figure 4. Furthermore, comparison of statistical parameters of V_{exp}/V_n such as minimum value, maximum value, mean value, standard deviation, and covariance between building code formulas and the modified ACI 318 formula is presented on Table 1.

From Figure 4, it can be concluded that the modified ACI 318 formula can yield better predictions of concrete wall strengths as compared to the original ACI 318 formula. While the original ACI 318 formula underestimates wall strengths for those failing in shear (low shear span ratio), the modified formula can predict the wall shear strengths as accurate as the flexure strengths. The trend line of the modified formula is nearly flat regardless variation in shear span ratio and the predictions are less scattered as compared to predictions from the original ACI 318 formula. Moreover, while the original ACI 318 formula considerably underestimates the shear strengths of high strength concrete walls, the modified formula is able to predict them more accurately. Hence, the trend line of the modified formula is also flat regardless variation in concrete strength and the predictions are less scattered as compared to predictions from the original formula. However, in some cases, the predictions from the modified formula may be less conservative than those of the original formula.

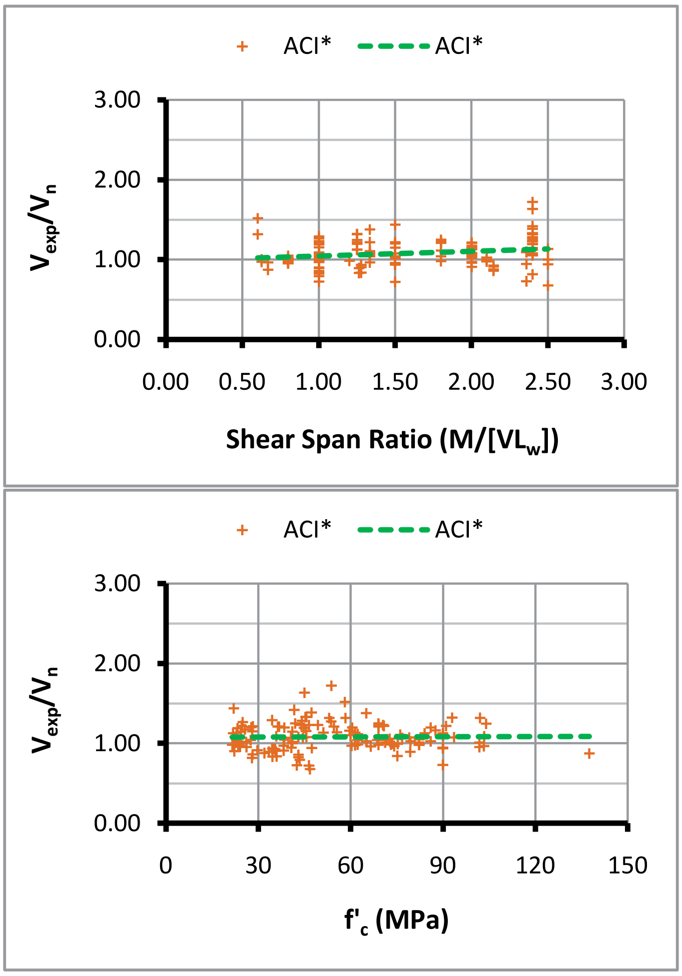

Figure 4. Normalized experimental wall strengths over nominal wall strengths of the modified ACI 318 formula (ACI*) plotted against shear span ratio and concrete strength.

From Table 1, it can be concluded that predictions from the modified ACI 318 formula are close enough to the actual wall strengths with average ratio V_{exp}/V_n of 1.08. Even though AIJ predictions are the closest to the actual wall strengths with average ratio V_{exp}/V_n of 1.01, the modified ACI 318 formula offers more conservative predictions. Furthermore, the proposed formula also has the least scattered data with covariance of 0.16 which is the lowest among other building code predictions.

Table 1. Comparison of statistical parameters of normalized experimental wall strengths over nominal wall strengths

Statistical Parameters	V_{exp}/V_n			
	ACI	AIJ	EC	ACI*
Minimum Value	0.80	0.54	0.74	0.68
Maximum Value	2.68	1.72	3.00	1.72
Mean Value	1.27	1.01	1.47	1.08
Standard Deviation	0.36	0.19	0.48	0.17
Covariance	0.29	0.19	0.33	0.16

6 CONCLUSIONS

This study presents an analytical review on the behavior of concrete walls having compressive strength ranging from normal strength to high strength in excess of 100 MPa. Several conclusions are drawn as follows.

Most building code formulas underestimate the wall shear strengths while they can predict relatively accurate for the flexure strengths. The underestimation can be caused by a few inaccuracies in the shear strength formulas, but two factors are especially important. One is the neglected contribution of longitudinal web reinforcement to wall shear strength. Another one is the limitation on the maximum shear strength values, which seems to be quite conservative for high strength concrete walls.

A simple modification of ACI 318 formula is proposed to address these issues and the analysis results show that the modified formula can yield better predictions of concrete wall shear strengths.

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Shear Strength of Normal to High Strength Concrete Walls J. Chandra and S. Teng 2

Nanyang Technological University, Singapore

Abstract: This paper presents an analytical study on the behavior of 5

normal to high strength concrete walls. Experimental data of concrete walls were collected from available literatures and several building code provisions were evaluated by comparing nominal wall strengths calculated using code formulas with experimental wall strengths. Moreover, behavior of concrete walls as influenced by various parameters was investigated by plotting the normalized experimental wall strengths and average shear stresses against

shear span ratio, axial load ratio, web reinforcement ratio, and concrete strength. The analysis results 14

show that most code formulas underestimate wall shear strengths. It is shown that longitudinal web reinforcement also has contribution

to the shear strength of concrete walls 43

even though it is not accounted in code formulas. Furthermore, the accuracy of code formulas is also affected by variation in concrete strength. For example, the ACI code considerably underestimates

the shear strength of high strength concrete walls due to its 34

limitation on maximum wall shear stress which is quite conservative for high strength concrete walls. Thus, a modification of ACI code formula is proposed to enhance its accuracy. The results show that the modified formula yields better predictions of both normal and high strength concrete wall shear strengths. Keywords: Shear strength, concrete walls, building code formulas. 1 INTRODUCTION Concrete structural walls have been used widely in many structures since they provide good resistance to lateral loadings (Fintel 1991). This study

presents an analytical review on the behavior of concrete walls 5 having compressive strength varying from normal strength to high strength in excess of 100 MPa. Data from past experiments on concrete walls from different countries were collected and studied. Data from these experiments were used to calculate nominal wall strengths using several building code formulas, such as those formulas recommended by the American Concrete Institute (ACI 318 2011), Architectural Institute of Japan (AIJ 1994), and Eurocode (EC8 2004). Subsequently, the nominal wall strengths calculated using code

formulas were compared with experimental **wall strengths.** Hence, **the** accuracy of **these** 5

building code provisions in determining the nominal wall strengths could then be evaluated. In addition,

to investigate further **the behavior of concrete walls** as influenced **by** 37

various parameters, normalized experimental wall strengths and normalized average shear stresses were plotted against

shear span ratio, axial load ratio, longitudinal and **transverse** web **reinforcement** ratios, **and** 26

concrete strength. The results from this analytical study will be used as a basis for further experimental study on concrete walls as well as further development of analytical model for predicting wall shear strengths. 2 CONCRETE WALL EXPERIMENTS As mentioned before, previous experiments on concrete walls reported by researchers from different countries were studied (Cardenas and Magura 1972;

Cardenas et al. 1980; Chiou **et al.** 2003; Corley **et al.** 1981; Deng **et al.** 2008; Farvashany **et al.** 8

2008; Gupta and Rangan 1998; Kabeyasawa and Hiraishi 1998; Lefas

et al. 1990; **Salonikios et al. 1999;** Wood 1991; Yan **et al.** 2008; Yun **et al.** 8

2004; Zhang and Wang 2000). There were a total of 139 specimens studied. Data from these experiments were collected in terms of

concrete compressive strength (f’c); shear span ratio (M/[VLw] where **M** 23

is the applied **bending moment** in wall, **V is the** applied **shear force** 27

in wall,

and Lw is the **wall length); axial load** 40

ratio (P/[f’cAg]

where P is the applied **axial load** in wall, **and** Ag **is the** gross **cross sectional area of the** 17

wall); longitudinal l fyl t fyt l t are

longitudinal and transverse web reinforcement ratios 44

of wall, fyl and fyt

are the yield strengths of longitudinal and transverse **web reinforcements);** 30

maximum wall strength (in- plane lateral load applied) obtained from experiment (Vexp); and average shear stress in wall (Vexp/[Aw c] where Aw is the area of wall web). These data frequency distributions based on several parameters are presented in Figure 1. 2.50-3.00 M/[VLw] 2.00-2.50 1.50-2.00 1.00-1.50 0.50-1.00 0.00-0.50 0 10 20 30 40 50 Number of Specimens 60 0.30-0.40

P/[f'cAg] 0. 20 **-0.** 30 **0.** 15 **-0.** 20 **0.** 10 **-0.** 3

15 0.05-0.10 0.00-0.05 0 10 20 30 40 50 Number of Specimens 60 l fyl (MPa) 12.0-15.0 9.0-12.0 6.0-9.0 3.0-6.0 0.0-3.0 0 10 20 30 40 50 Number of Specimens 60 12.0-15.0 t fyt (MPa) 9.0-12.0 6.0-9.0 3.0-6.0 0.0-3.0 0 10 20 30 40 50 Number of Specimens 60 f'c (MPa) 120-150 90-120 60-90 30-60 0-30 0 10 20 30 40 50 Number of Specimens 60 1.20-1.60 Vexp/[Aw c] 0.80-1.20 0.60-0.80 0.40-0.60 0.20-0.40 0.00-0.20 0 10 20 30 40 50 Number of Specimens 60 Figure 1. Data frequency distributions based on several parameters. 3 ANALYTICAL STUDY The nominal wall

strengths were then **calculated according to the** methods of **ACI 318** (2011), AIJ (1994), **and EC8** 20

(2004). The flexural

strength of the walls was calculated based on 36

flexural theory

for members subjected to bending moment and **axial load as** suggested **by** 7

Paulay and Priestley (1992) whereas the shear strength was calculated using formulas given in the building codes.

The smaller value of the flexural strength **and** the **shear strength** 22

was then taken as the nominal wall strength. Shear strength formulas according to building codes mentioned above are given as follows. 3.1 ACI 318

(Chapter 21) According **to ACI** 318 **chapter 21** 7

(2011), the nominal

shear strength of special structural **walls can be** 7

calculated as follow: = + (1) where Vn is nominal wall shear strength (N); Acv is gross

area of concrete section bounded by web thickness and length of section in the direction of shear force considered (mm2); **c is** coefficient defining **the** relative contribution **of concrete** 6

strength to nominal wall shear strength, which may be taken as 0.25 for Hw/Lw Hw/Lw

linearly between 0.25 and 0.17 for Hw **/Lw between 1.5 and 2.0,** where Hw/Lw **is the height** 13

to length ratio of the wall; is

modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength. 4

Furthermore, ACI 318 also limits the maximum shear stress for walls to 0.83 c. 3.2 AIJ f’c (MPa); z can be taken as 0.8 Lw s can be AIJ guidelines (1994) provide the following equations taken as 1.0; M is applied bending moment in wall; V

to calculate the nominal shear strength of structural **is** applied **shear** 7

force in wall. walls based on plastic theory combining arch and truss shear resistance mechanisms: 4 ANALYSIS RESULTS = cot + 0.5 tan (1) (2) The analysis results are presented in terms of experimental wall strengths, Vexp, normalized by tan = (/)2 + 1 / (3) nominal wall strengths calculated from building code formulas, Vn. This is done with purpose of evaluating = (1 + cot2) ( )1 (4) building code provisions. Furthermore, average shear stresses (shear force divided by wall web area, Aw) = 0.7 (/2000) (5)

normalized by the square root of concrete strength 33

are plotted against key parameters such as shear span where Vn is nominal wall shear strength (N); tw is ratio, axial load ratio, longitudinal and transverse web thickness of wall (mm); st can be taken as 1.0. reinforcement contributions, and concrete strength. This is done to see the relationship between 3.3 EC8 normalized wall strengths and these parameters. The The nominal shear strength of structural walls is taken analysis results can be seen in Figures 2 and 3. as the minimum shear strength between diagonal tension failure of the web and diagonal compression As observed from Figure 2, ACI code and Eurocode failure of the web according to EC8 (2004). The generally underestimate the wall strengths. It is formulas are given as follows. understood that most building codes tend to give lower predictions of actual strength so that the design 3.3.1 Diagonal compression failure formulas are safe enough to be used for practical = 1 (cot + tan) 1 (6) design. Thus, even though in average the Japanese code is the most accurate one with average ratio of where Vn is nominal wall shear strength (N), which V exp/Vn closest to 1.00 and has the lowest covariance, for the critical region, it may be taken as 40% of the it may not provide safe design for some cases since it cw is coefficient taking account of may overestimate the wall strengths. On the other the

state of the **stress in the compression chord,** which hand, Eurocode **is the** 29

most conservative one with may be taken as 1.0 for non-prestressed structures, [1 average ratio Vexp/Vn of 1.47 and covariance of 0.33. + P/(f’cAg)] for 0 < P/(f’cAg P

/(f’ c A g – P **/(f’ c A g**)] for **0.** 24

5 < Moreover, from Figure 2, it can be seen that for walls P/(f'cAg) < 1.0; b is width of web cross section (mm), with high shear span ratio (i.e. flexure behavior z is

inner lever arm, for a member with constant depth, dominates), **the** 11

building code predictions are quite

corresponding to the bending moment in the element 11

accurate with ratio of Vexp/Vn closer to 1.00. It means under consideration, which may be taken equal to 0.8

that the flexure strength **of walls can be** well **predicted** 39

L w 1 is strength reduction factor for concrete using flexural theory for members subjected to axial cracked in shear, which can be taken as 0.6 (1.0 –

force and bending moment. On the 45

other hand, for f'c s s can be taken as 1.0. walls with low shear span ratio (i.e. shear behavior dominates), ACI code and Eurocode underestimate 3.3.2 Diagonal tension failure the wall strengths while the opposite is true for AIJ. If M/(VLw) This implies that building code formulas are not accurate enough to predict the wall shear strengths. = , (100)1/3 + 1 + cot (7) Furthermore, from Figure 2, it can be observed that If M/(VLw) < 2.0: the accuracy of building code predictions is also affected by variation in concrete strength. ACI code = , (100)1/3 + 1 + 0.75 / (8) and Eurocode considerably underestimate the wall strengths for walls with higher concrete compressive where Vn is nominal wall shear strength (N); b is strength (>60 MPa) while AIJ slightly overestimates width of web cross section (mm); d is effective depth the wall strengths. Further investigation shows that in of cross section (mm); CRd,c c, most cases, this happens for walls with low shear span c is taken as 1.0 for nominal strength without ratio (i.e. shear behavior dominates). Hence, it can be reduction factor for material; k can be taken as 1 + concluded that building code formulas are less d k1 cp is equal to P/Ag < 0.2 accurate in predicting the shear strength

of high strength concrete walls **than** that **of normal strength concrete** 28

walls. Figure 3 shows the behavior of concrete walls with varying

parameters such as shear span ratio, axial load ratio, 10

web reinforcement contributions, and concrete strength. As can be seen, the normalized average shear stresses decrease as

shear span ratio increases. This means that 14

flexure behavior is more dominant

for walls with high shear span ratio 3

while shear behavior is more dominant

for walls with low shear span ratio. The 3

figure also shows that the normalized average shear stresses increase with increment in axial load ratio. This implies that walls subjected to higher axial load have higher shear strength. Vexp/Vn 3.00 2.00 1.00 0.00 0.00 ACI ACI AVG : 1.27 COV : 0.29 Vexp/Vn 0.50 1.00 1.50 2.00 2.50 3.00 Shear Span Ratio (M/[VLw]) 3.00 2.00 1.00 0.00 0 30 ACI ACI 60 90 f'c (MPa) 120 150 Vexp/Vn 3.00 2.00 1.00 0.00 0.00 AIJ AIJ AVG : 1.01 COV : 0.19 Vexp/Vn 0.50 1.00 1.50 2.00 2.50 3.00 Shear Span Ratio (M/[VLw]) 3.00 2.00 1.00 0.00 0 30 AIJ AIJ 60 90 f'c (MPa) 120 150 Vexp/Vn 3.00 2.00 1.00 0.00 0.00 EC EC AVG : 1.47 COV : 0.33 Vexp/Vn 0.50 1.00 1.50 2.00 2.50 3.00 Shear Span Ratio (M/[VLw]) 3.00 2.00 1.00 0.00 0 30 EC EC 60 90 f'c (MPa) 120 150 Figure 2. Normalized experimental wall strengths over nominal wall strengths plotted against shear span ratio and concrete strength. Vexp/[Aw c] 1.60 1.40 1.20 1.00 0.80 0.60 0.40 0.20 0.00 0.00 0.50 1.00 1.50 2.00 2.50 3.00 Shear Span Ratio (M/[VLw]) Vexp/[Aw c] 1.60 1.40 1.20 1.00 0.80 0.60 0.40 0.20 0.00 0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 Axial Load Ratio (P/[f'cAg]) 1.60 1.60 1.40 1.40] 1.20 c Vexp/[Aw 1.00 0.80 0.60 0.40 Vexp/[Aw c] 1.20 1.00 0.80 0.60 0.40 0.20 0.20 0.00 0.00 0.0 3.0 6.0 9.0 12.0 15.0 0 30 60 90 120 150 f'c (MPa) Figure 3. Normalized average shear stresses plotted against several parameters. For web reinforcement contributions (l fyl t fyt),

it can be seen from Figure 3 that the normalized average shear 31

stresses increase with the increment of longitudinal and transverse web reinforcement contributions. This implies that both longitudinal and transverse web reinforcement have contributions to the wall shear strengths. However, this phenomenon is not taken into account in building code formulas for calculating wall shear strengths. The code formulas only take into account the contribution from transverse web reinforcement while neglecting the longitudinal web reinforcement contribution. Thus, it may result in underestimation of wall shear strengths for some building codes. For concrete strength, Figure 3 shows that the normalized average shear stresses increase with increment in concrete strength. It implies that walls with higher concrete compressive strength can resist higher level of shear stress. Nevertheless, building code provisions do not differentiate between

normal strength concrete walls and high strength concrete walls. For 25 example, **in** ACI code, **the**

limit of maximum shear stress for walls is 0.83 c regardless of concrete strength. Based on data as presented in Figure 3, for normal strength concrete walls with compressive strength up to 60 MPa, most of specimens have average shear stresses less than 0.83 c which fall below ACI code limit. On the other hand, for high strength concrete walls with compressive strength above 60 MPa, many specimens have average shear stresses more than 0.83 c which exceed the limit given by ACI code. As a result, ACI code may underestimate the shear strength of

high strength concrete walls by assigning **the** **42**

same limit as in the case of

normal strength concrete walls. Therefore, **in this** study, **the** issues **of** **35**

longitudinal web reinforcement contribution and maximum shear stress limit for high strength concrete walls are addressed. A modification of ACI 318 formula is proposed and presented in the subsequent section. 5 PROPOSED MODIFICATION OF ACI 318 FORMULA In this section, a simple modification of ACI 318 formula is proposed to address the issues mentioned previously. It is therefore expected that the modified formula can yield better predictions of concrete wall shear strengths. The modification is described below. As in the case of original ACI 318 formula, in the proposed formula, the nominal wall shear strength (Vn) is the

sum of concrete contribution (Vc) and steel **reinforcement contribution (Vs)** **6**

as shown in equation (9). The concrete contribution, Vc, is calculated using the formulas given in ACI 318 chapter 11 (2011). These formulas are given in equations (10) and (11). Moreover, for steel contribution (Vs), the contribution of the longitudinal web reinforcement is added. Nevertheless, this addition should not be straight forward assuming both longitudinal and transverse web reinforcements are fully effective in contributing to wall shear strength. Based on previous concrete wall experiments which studied the effectiveness of longitudinal and transverse web reinforcements to the wall shear strength

(Barda et al. 1977; Cardenas et al. 1980), **12**

it is concluded that the effectiveness of web reinforcements depends on the shear span ratio of walls. For

walls with shear span ratio of 1. 00, both longitudinal **and** **32**

transverse

web reinforcements are **effective in contributing to** wall **shear strength** 38

(Cardenas et al. 1980).

For walls with shear span ratio less than **or equal to** 3

0.50, longitudinal web reinforcement is more effective than transverse web reinforcement in contributing to wall shear strength (Barda et al. 1977). As shear span ratio increases, longitudinal web reinforcement becomes less effective. In other words, longitudinal web reinforcement contribution to wall shear strength is more dominant than that of transverse web reinforcement for walls

with shear span ratio less than 1. 41

00 whereas

the opposite is **true for walls with shear span ratio** 10

more than 1.00. Thus, in this study, the effectiveness of web reinforcement contributions is presented

as a function **of** wall **shear span ratio.** The formulas **for** 3

calculating overall steel web reinforcement contributions to wall shear strength are presented in equations (12) and (13). Addressing the issue of maximum shear stress limit

for high strength concrete walls **with** compressive **strength more than** 60 **MPa,** in this study **the** 9

limit is taken as 1.25 c instead of 0.83 c. This number is originated from the upper bound value (mean value plus standard deviation) of normalized average shear stresses of high strength concrete wall specimens studied previously (Chandra et al. 2011). In this case, the mean value of average shear stresses is 0.91 with standard deviation of 0.32. The upper bound value is then 0.91+0.32 = 1.23 which is rounded becomes 1.25. Thus, the maximum shear stress limit

for high strength concrete walls **with** compressive **strength more than** 60 **MPa** 9 is taken as 1.25 c. The complete modified formulas are presented as follows. The nominal wall shear strength (Vn) can be calculated as: = + (9) The concrete contribution (Vc) shall be taken the lesser of: 1 = 0.27 + /(4) (10) 0.1 +0.2 2 = 0.05 + (11) 2 The steel reinforcement contribution (Vs) shall be taken as: = sin + cos (12) tan = (13) In any cases, Vn

shall not be taken greater than: , = 0. 83 , = 1.25 ; **for** **15**

f'c (14) ; for f'c > 60 MPa (15) where

mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength; **4**

h

is the thickness **of** wall; **d is the effective depth of** wall; Lw is **the** **21**

wall length; P

is the applied **axial force** in wall; **M is the** applied **bending moment** in wall; V **is the** **19**

applied shear force in wall; Asl and Ast are the total area of longitudinal and transverse web reinforcements, respectively. In case of (M/V –

Lw/2) is negative, equation **(11) shall not apply.** **15**

The normalized experimental wall strengths to nominal wall strengths (Vexp/Vn) for modified ACI 318 formula (ACI*) are presented in Figure 4. Furthermore, comparison of statistical parameters of Vexp/Vn such as minimum value, maximum value, mean value, standard deviation, and covariance between building code formulas and the modified ACI 318 formula is presented on Table 1. From Figure 4, it can be concluded that the modified ACI 318 formula can yield better predictions of concrete wall strengths as compared to the original ACI 318 formula. While the original ACI 318 formula underestimates wall strengths for those failing in shear (low shear span ratio), the modified formula can predict the wall shear strengths as accurate as the flexure strengths. The trend line of the modified formula is nearly flat regardless variation in shear span ratio and the predictions are less scattered as compared to predictions from the original ACI 318 formula. Moreover, while the original ACI 318 formula considerably underestimates the shear strengths of high strength concrete walls, the modified formula is able to predict them more accurately. Hence, the trend line of the modified formula is also flat regardless variation in concrete strength and the predictions are less scattered as compared to predictions from the original formula. However, in some cases, the predictions from the modified formula may be less conservative than those of the original formula. ACI* ACI* 3.00 Vexp/Vn 1.00 2.00 0.00 0.00 0.50 1.00 1.50 2.00 2.50 3.00 Shear Span Ratio (M/[VLw]) 3.00 ACI* ACI* Vexp/Vn 1.00 0.00 2.00 0 30 60 90 120 150 f'c (MPa) Figure 4. Normalized experimental wall strengths over nominal wall strengths of the modified ACI 318 formula (ACI*) plotted against shear span ratio and concrete strength. From Table 1, it can be concluded that predictions from the modified ACI 318 formula are close enough to the actual wall strengths with average ratio Vexp/Vn of 1.08. Even though AIJ predictions are the closest to the actual wall strengths with average ratio Vexp/Vn of 1.01, the modified ACI 318 formula offers more conservative predictions. Furthermore, the proposed formula also has the least scattered data with covariance of 0.16 which is the lowest among other building code predictions. Table 1. Comparison of statistical parameters of normalized experimental wall strengths over nominal wall strengths Statistical Parameters ACI AIJ Vexp/Vn EC ACI* Minimum Value 0.80 0.54 0.74 0.68 Maximum Value 2.68 1.72 3.00 1.72 Mean Value 1.27 1.01 1.47 1.08 Standard Deviation 0.36 0.19 0.48 0.17 Covariance 0.29 0.19 0.33 0.16 6 CONCLUSIONS This study

presents an analytical review **on the behavior of concrete walls** 5

having compressive strength ranging from normal strength to high strength in excess of 100 MPa. Several conclusions are drawn as follows. Most building code formulas underestimate the wall shear strengths while they can predict relatively accurate for the flexure strengths. The underestimation can be caused by a few inaccuracies in the shear strength formulas, but two factors are especially important. One is the neglected

contribution of longitudinal **web reinforcement to wall shear strength.** 12

Another one is **the**

limitation on the maximum shear strength values, which seems to be quite conservative for high strength concrete walls. A simple modification of ACI 318 formula is proposed to address these issues and the analysis results show that the modified formula can yield better predictions of concrete wall shear strengths. ACKNOWLEDGMENTS The authors appreciate very much

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