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TRUSS MODEL FOR SHEAR STRENGTH OF STRUCTURAL CONCRETE WALLS | 28

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interest includes

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435 – Deflection, and 421 – Design of concrete slabs.

His research interests include behavior of structural concrete walls, shear strength of | 22

slabs,

size effect in shear behavior of concrete members, computational modeling of | 21

concrete structures, and durability of marine concrete structures. ABSTRACT A number of methods for calculating shear strengths of structural walls are available. However, due to the complexity of wall behaviors and possible loading combinations that they may be subjected to, it is quite challenging to derive a method that is reasonably simple but can accommodate various influencing parameters

in order to get more accurate predictions of wall shear strengths. The | 57

authors had earlier tested a series of very

high strength concrete wall specimens (f'c = 100 MPa | 104

(14500 psi))

to investigate the influence on shear strength of several parameters, such as: | 75 height to length ratios, shear

(web) reinforcement ratios in the vertical and horizontal directions, 61

as well as the presence of flanges (boundary elements). The conclusions of the authors' experimental study in the light of other research results reported by other researchers will be summarized here and will be used as a guide for deriving a proposed truss model. The proposed model is based on modern truss analogy principles (softened truss model, compression field theory, etc.) and it has been shown by comparing it with experimental results to be accurate and stable. The design and

analysis procedure based on the proposed 100

truss model will also represent an improvement over existing ACI and Eurocode design procedures. Keywords: building codes; shear strength; shear reinforcement; horizontal reinforcement; vertical reinforcement; structural walls; high strength concrete; truss analogy. INTRODUCTION General wall behavior

Reinforced concrete (RC) walls are commonly used to carry lateral 88

wind or earthquake loads, as well as to carry vertical (gravity) loads from adjacent floors, transfer beams, etc. 2 The overall height of the wall can be single story, double stories or multi-stories up to tall walls. The

height to length ratio (hw/lw) can be less than 2 .0 5

for low-rise (squat) walls or much greater than 2.0 for tall walls in taller buildings. Previous studies by various researchers [1, 2] show that the behavior of structural walls having hw/lw of greater than 3.0 would be governed mainly by their flexural behavior, while those with hw/lw between 2.0 and 3.0 is governed by combined flexural and shear behavior, and those having

hw/lw of less than 2 .0 is governed more by 5

shear behavior. It is generally understood that flexure behavior of walls can be studied reasonably accurately using normal flexural theory [3] and the flexural

strength of walls can be predicted reasonably accurately also using the 89

normal flexural theory as described in various building codes. The shear behavior of walls, however, is more complex than the flexural behavior and

more research is needed to understand the shear behavior of 82

walls as it is affected by

concrete compressive strength (f'c), hw/lw, vertical and 35

horizontal web reinforcement ratios (ρv and ρh), as well as the presence of flanges. So, this paper concentrates on the shear behavior, especially at the ultimate limit state. Note that building code formulas (ACI 318-14 [4]

and Eurocode-8 [5]) for calculating the shear strength of RC walls subjected to seismic loading 40

are mainly empirical and, as such, their applicability may not be as wide as they could be. Based on previous experimental study by the authors [6], it can be concluded that the ACI 318

neglects the contribution of vertical shear (wall) reinforcement while the 23

Eurocode 8, for walls with hw/lw of 2.0 or greater, considers that the shear strength of walls depends only on the horizontal shear 54

reinforcement. Dowel action in walls with flanges plays significant role in determining wall shear strengths, and this dowel action has not been treated accurately by building codes.

The use of very high strength concrete may also introduce inaccuracy in 87

code procedures as those formulas are not intended for very high strength concrete walls. Nevertheless, the authors [6] had also found 3 that ACI 318 has low safety factors for walls with f'c of 60 MPa (8700 psi) or lower. The Eurocode 8, however, is overly conservative for all cases of concrete strengths. These conditions call for more research and new design procedures for structural walls. The rational theory

for predicting shear strength of RC members was developed based on 64

the classical truss analogy in early 1900s and since then it has undergone many major developments to arrive at a better accuracy in

predicting the shear strength of RC members. For RC walls, which 86

can be categorized as membrane elements, numerous research have been conducted in order to predict their shear strengths (see Bazant's micro-plane model [7], Maekawa-Okamura's stress field formulation [8], Collins-Vecchio's

modified compression field theory [9] and Hsu's softened truss model 76

[10]). All those formulations or theories are able to produce complete load-deformation response of a given RC membrane elements, shells, or walls. Those theories, however, require the use of a nonlinear Finite Element procedure in their implementation. Therefore, in order to take advantage of their superior theoretical derivations for engineering design purposes, some simplifications are needed. The proposed truss model is intended to address some of those issues in building code formulas and to improve the predictions of RC wall shear strengths. RESEARCH SIGNIFICANCE Based on the authors' test data on very high strength concrete walls as well as data from literature, the authors attempt to introduce

a new method for calculating the shear strength of RC walls. The method is based on 46

modern field truss analogy principles, such as the

softened truss model and the compression field theory. The new 80

proposed method is intended for the ultimate limit state, and it has been shown to be reasonably accurate and reliable. The authors expect that this paper can highlight useful concepts that may help our understanding of structural wall behavior. 4 CODE AND OTHER METHODS The ACI 318 and the Eurocode 8 are two reference building codes that are adopted in many countries, including in Singapore. As such, those two building codes and two more proposed methods by other researchers [11, 12] are reviewed briefly below and their performance will then be compared with available experimental results, including the authors' test results. ACI 318-14

According to ACI 318- 14 [4], the nominal shear strength (Vn) of 68

RC walls subjected to seismic loading 99

can be calculated as follows: = (√′ +) {ACI 318-14 Eq. (18.10.4.1)} ACI 318-14 also states that the value of Vn shall not exceed 0.83Acw√f'c (in Newton). Even though ACI 318-14 does not directly consider

the contribution of vertical shear reinforcement to shear strength, it does require that 28

structural walls be provided with vertical shear reinforcement of the amount that depends on hw/lw.

Eurocode 8 (EN 1998-1:2004) According to Eurocode 8 92

[5] or EC8, the ultimate shear strength of RC walls subjected to earthquake loads can

be taken as the smaller of the shear strengths or shear resistance 7

calculated from two shear failures of the wall web: (1) diagonal compression failure (,) and (2) diagonal tension failures, either , or (see below). Diagonal compression

failure of the web due to shear For the case of diagonal compression failure, the shear 42

strength (resistance) is given by VRd,max: , = 1/(cot + tan) (1) where:

The recommended value of αcw is as follows: 1. 0 for non-prestressed structures 32

(1a) (1.0 +

σcp/fcd) for 0 < σcp ≤ 0.25 fcd (1b) 1.25 for 0.25 fcd < σcp ≤ 0.5 fcd (1c) 2.5 (1. 0 – σcp/fcd) for 0.5 fcd < σcp < 1.0 fcd 4

(1d) The recommended value for v1 is

0.6 [1. 0 – fck/250] (fck in MPa). 1

EC8 recommends that the values of cot θ and tan θ are taken as 1.0.

Diagonal tension failure of the web due to shear, 58

either VRd,s or VRd:

If αs = MEd/(VEd lw) ≥ 2. 34

0, where MEd is the design bending

moment at the base of the wall and VEd is the design shear force, then the shear strength (resistance) is 30

given by VRd,s: , = cot (2)

If αs = MEd/(VEd lw) < 2. 34

0, the shear strength

(resistance) is given by VRd: = , 14

+ 0.75ℎ,ℎ (3) Hwang-Lee's Method

Hwang and Lee [11] proposed a method based on the 101

strut and tie model for calculating the shear strength of RC walls. In their model, the 29

applied external forces were

assumed to be resisted by combination of **concrete** compression struts **and** 11

steel tension ties as shown in Fig. 1. There are three load paths, i.e. diagonal, vertical, and horizontal components. The diagonal compression force acting on nodal zone, Cd, is calculated from the three components according to their relative stiffness (Rd, Rv, and Rh). Then, the

shear capacity of RC wall **is determined** by **the** nominal capacity **of the** 62

nodal zone as given by Eq.

(4). The nominal **shear strength of** RC **wall** 102

can

be calculated as the horizontal component **of the** diagonal **compression force** that is corresponding **to the** nominal capacity **of the** 7

nodal zone. The softening behavior of cracked concrete has also been taken into account in their method. Thus, the model is called softened strut and tie model. , = ζ′ (4) where: K = strut and tie index, which is defined as follows: = −+ ℎ + −+coℎs(1−sinc2os)+ssiinn(1−cos2 ≥ 1.00 (4a) 2 2) ζ = softening coefficient of cracked diagonal concrete strut, which is approximated as (3.35/√f'c) and should not be taken more than 0.52. Gupta-Rangan's Method Another analytical method considered here

for calculating the shear strength of RC walls 25

is the one developed by Gupta and Rangan [12]. They used the modified compression field theory [9] as the basis for their model. They assumed that the shear force due to external lateral load was primarily resisted by wall panel and the effect of bending stresses

on the shear **behavior of the panel** was negligible. **The** shear stress on **the wall** 19

panel was assumed to be uniform and acted over an effective shear area which was taken as wall thickness (tw) multiplied by the effective depth of the wall (dw). In the stress analysis, they considered equilibrium conditions,

strain compatibility, and stress-strain relationships of concrete and steel. 18

They also take

into account the softening behavior **of cracked concrete** 103

as proposed by Collins et al. [13]. One of the main assumptions in their model is the value of the strut angle 7 that

is assumed to be constant and depended upon **the** effective **depth of the** wall (dw) **and** wall height (hw). **The** 37

strut angle is given by Eq. (5). However, the strut angle (α) as calculated by Eq. (5) does not need to be taken larger than the value calculated for the condition when transverse strain (εt) = 0 and does not need to be taken smaller than the value calculated for the condition when transverse stress (σt) = 0. In other words, these values become lower and upper limits for the strut angle (α). This equation provides the necessary condition to solve the equilibrium and compatibility conditions at each analysis stage. The procedure is started with small strain value and it is repeated with certain strain increment until the force-displacement relationship of the RC wall is obtained. The

nominal shear strength of RC wall **is** then **taken as the maximum shear** 38

force obtained from the force- displacement relationship of the RC wall. tan = (5) ℎ THE NEW PROPOSED

METHOD The minimum requirement for a design procedure is the fulfillment of the equilibrium conditions, and also applicable materials laws. The purpose of the authors' proposed truss model is to estimate shear strength at ultimate stage. Equilibrium conditions Consider a typical RC wall panel

as shown in Fig. 2a. The applied external shear force (V) 22

and the applied external

axial force (P) are assumed to be distributed uniformly throughout the 98

wall panel by means of a rigid top beam or slab. As the external shear force V increases in magnitude, diagonal cracks would occur in the wall panel, forming

a series of concrete diagonal struts with a certain angle (θ) to the 18

horizontal axis. At ultimate stage, as 8 shown in Fig. 2b, the stresses in wall panel are summation of stress in concrete struts and stress in web reinforcement. In this model, the principal stress directions of the

concrete are assumed to coincide with the directions of cracks and the 21

steel bars in the wall panel are

assumed to take only axial stresses, neglecting dowel action 20

of web reinforcement. Note that in addition to the natural coordinate system

in the horizontal and vertical directions or the 96

v-h axes, another coordinate system r-d is needed to describe the principal stress directions. To obtain the three stress components, i.e. σv, σh, and τvh that represent the applied stresses in the vertical and horizontal directions (v-h axes)

in terms of stresses in the r -d directions, 93

consider the wedge A-o-p in Fig. 2c. This wedge is a cut out of the rectangular block ABCD in Fig. 2b and is also an enlarged portion of RC wall panel of Fig. 2a. Let the thickness of the RC wall panel be one unit and the length of the side o-p of wedge A-o-p be one unit as well. Hence, the area of the side o-p is one-unit area and the areas of A-o and A-p sides become (cos θ) and (sin θ), respectively. Fig. 2c also shows a diagram of idealized average stresses acting on wedge A-o-p. By taking the summation of average forces (stress multiplied by area)

in the vertical direction, stress component in the vertical direction, 91

σv, can be obtained as given by Eq. (6). Similarly, Fig. 2d shows a diagram of idealized average stresses acting on wedge B-m-n. Stress component in the horizontal direction, σh, can be obtained from

equilibrium of forces in the horizontal direction, and 24

this is presented in Eq. (7). In order to obtain shear stress, τvh,

equilibrium in the horizontal direction of forces acting on 24

wedge A-o-p in Fig. 2c can be used. The shear stress, τvh, in this case is given in Eq. (8). Hence, the three average stresses in the v-h axes of the RC wall panel in terms of the principal stresses, σd and σr, with τrd being zero or vanished in the principal directions, are represented by Eqs. (6) to (8) as shown below. Average stress equilibriums in wall panel: where: σv σh σd σr τvh ρv ρh fv fh θ = sin2 + cos2 + *h* = cos2 + sin2 + *hh h* = (−) sin cos (6) (7) (8) = applied normal stress in vertical direction (axis),

positive for tension. = applied normal stress in 3 horizontal direction (axis),

positive for tension. = principal **stress** of **concrete in** d-axis, **positive for tension.** = principal **stress** of **concrete in** r-axis, **positive for tension.** = average **shear** stress **in** 3

v-h coordinate system and is due to shear force acting on the wall. = average

vertical web reinforcement ratio. = average **horizontal web reinforcement ratio.** 25

= average stress

in the vertical web reinforcement. = average stress **in the** horizontal **web reinforcement.** 52

= angle of diagonal concrete strut (d-axis) with respect to horizontal axis at ultimate stage. Conditions at ultimate load stage The overall shear strength of RC wall is governed by either web reinforcement yielding or diagonal concrete strut crushing. The procedure to calculate the shear strength can be described as follows. By imposing equilibrium

in the vertical and **horizontal directions of the wall,** 77

Eq. (6) and Eq. (7) can be combined to become Eq. (9). Eq. (9) can also be rearranged into Eq. (10). + *h* = + + + *hh* (9) − = − − *h* + + + *hh* 10 (10) At ultimate load stage, either the diagonal concrete struts or web reinforcements will reach their individual capacities. Therefore, it is necessary to know which failure mode governs the overall shear strength of RC wall. The necessary steps start with Eq. (10) and are as follows. Certain quantities such as σv, σh, and σr can be calculated easily and then substituted into Eq. (10). σv is the applied

normal stress in the vertical **direction** caused by **the applied axial** force (= P/Ag) **and** 66

it is

positive for tension and negative for compression. The σh **is** 14

mostly zero in typical RC wall. σr which

is the principal **tensile stress in concrete** 14

in r-axis can be replaced by the assumed average residual tensile stress in cracked diagonal concrete strut. This tensile stress is also

to take into account the stiffening effect of steel bars in **concrete** 20

in tension. Normally, σr is defined as

a function of the principal strain of **the concrete in the** 44

r- axis (εr) [14, 15]. However, in this proposed model which is intended for the ultimate condition only, the average residual tensile stress in cracked diagonal concrete strut (σr) is estimated as 2 percent of concrete cylinder compressive strength (0.02f'c) as shown in Fig. 3. This assumption is

based on experimental data on **stress-strain** behavior of **concrete in tension** 84

[16-18]; that

is, the residual tensile strength of concrete is about 20 percent of 13

its peak tensile strength. Hence, assuming its peak tensile strength is normally about 10

percent of its compressive strength, the residual tensile stress of concrete can then be 63

assumed to be 2 percent of its compressive strength. Determination of failure modes By replacing some terms with their known quantities, the number of unknown variables in Eq. (10) is now reduced to three, i.e.: σd, fv, and fh. σd is the compressive strength of cracked diagonal concrete struts (= -ζf'c, with ζ being the softening coefficient) and fv and fh are the stresses in the vertical and horizontal reinforcements at the time the wall fails. The 11 maximum values of fv and fh are taken to be the smaller of 80% of yield strengths of the web reinforcements (0.8fyv and 0.8fyh, respectively) and 500 MPa (72.52 ksi). The authors' experimental results on high strength concrete (HSC) walls [6] show that most of the web reinforcements do not reach yield during testing. Thus, it is reasonable to take their maximum stresses to be 80% of their yield strengths. Moreover, it is also reasonable to assume that the maximum strengths are limited to 500 MPa (72.52 ksi) for typical shear reinforcement as the use of higher strength reinforcement does not necessarily lead to stresses much higher than 500 MPa. If the left hand side of Eq. (10) is larger than the right hand side, it means both web reinforcements reach their maximum strengths and the value of σd will be determined by the total value of the right hand side. This also means that the σd

is less than the compression capacity of the cracked diagonal concrete strut (-ζf 'c). On the 36

other hand, if the left hand side of Eq. (10) is less than the right hand side, it means the diagonal concrete strut fails in compression. In this case, the following assumption is made in order to calculate the stresses in web reinforcements. If the hw/lw is less than 1

.0, it is assumed that only the vertical web reinforcement 90

reaches its yield strength, whereas if hw/lw is equal to or more than 1.0, it is assumed that only the horizontal web reinforcement reaches its yield strength. These assumptions are based on data obtained from past experiment on RC walls [19] and the authors' own experimental study [6]. The remaining stress in the web reinforcement (either fv or fh) can then be calculated. Softening coefficient of concrete struts A number of equations have

been proposed to take into account the softening behavior of concrete 73

under compression (ζ) when subjected to transverse strains [9, 15, 20, 21]. A suitable formula is introduced by Zhang and Hsu [21] as shown in Eq. (11). In this proposed 12 model, the value of εr is approximated as 0.005, which falls within the typical range of εr for RC membrane element subjected to shear [9]. where: ζ f'c εr ζ = (5.8 ≤ 0.9) (1 √1+400) (11) √' = softening coefficient of the concrete in compression. = concrete cylinder compressive strength (in MPa). = principal strain of concrete in r-axis, positive for tension. Determination of angle of strut inclination After all the terms in Eq. (10) are determined, the angle (θ)

of the diagonal concrete struts with respect to the horizontal axis 17

can be calculated by rearranging Eq. (6) to become Eq. (12). Then, the nominal

shear strength of RC wall (Vn) can be calculated by multiplying the 10

average shear stress (τvh) at the ultimate load stage as defined in Eq. (8) by wall web area (Aw). In this proposed model, the wall web area (Aw) is defined as the thickness of wall web (tw) multiplied by the effective depth of wall (dw). The effective depth of wall can

be taken as the distance between center to center of 7

boundary elements or 0.8lw (80% of wall length) in case of walls without boundary elements. where: θ σv σd = sin−1 (√−++) −+ (12) = angle of diagonal concrete strut

(d-axis) with respect to horizontal axis 3 at ultimate stage. = applied normal (vertical) stress,

positive for tension. = principal **stress** of **concrete in** d-axis, **positive for tension** 3

(normally compression). σr = principal

stress of concrete in r-axis, **positive for tension** 95

(normally tension). ρv = average

vertical web reinforcement ratio. fv = average **stress** in **the vertical web reinforcement.** 56

Dowel action from reinforced boundary elements The inclusion of dowel action from reinforced boundary elements is in agreement with experimental findings [22] and is also confirmed by the authors' experimental study [6]. The boundary elements can be in the form of flanges with reinforcement or columns at the ends of the wall with concentrated reinforcement. In this proposed model, the dowel action formula as developed by Baumann and Rusch [23] was adopted and shown in Eq. (13). This equation was also used by He [24] for predicting shear strengths of RC beams. In Eq. (13),

the total area of the vertical reinforcement in 1

one boundary element (Asb) is converted to a single dowel bar with the same area that has an equivalent bar diameter (dbe). Then, the effective width of boundary element (bef) can be calculated by subtracting the overall width of the boundary element (bf) with the equivalent bar diameter (dbe). Here, the overall width of the boundary element (bf) does not need to be taken greater than half of wall height plus wall web thickness (0.5hw+tw) as suggested by ACI 318 Chapter 18 [4]. The dowel force (Du) is then added as an additional component to the

shear strength of RC **walls.** Thus, **the** nominal **shear strength of** RC **walls** 10

(Vn)

according to this proposed model can be expressed 78

by Eq. (14). Note that in this proposed model, the dowel force is considered for one boundary element only (the one in tension) since the dowel force will become active following crack opening. = 1.64 3√′ (13) = (−) sin cos + 1.64 3√′ (14) where: Du bef dbe Vn tw dw = dowel force of vertical reinforcement in one boundary element (in Newton). = effective width of boundary element (in mm). = equivalent bar diameter (in mm). = nominal shear strength of RC wall (in Newton). =

thickness of wall web **(in mm). = effective depth of wall** 5

(in mm). Summary of the new proposed method Overall, the step by step procedure of the proposed method can be summarized as follows: 1) Calculate σr as 0.02f'c and ζ using Eq. (11) assuming εr is equal to 0.005. 2) Check if the web reinforcements reach their yield strengths or if the diagonal concrete struts get crushed (use Eq. (10)). a. If both web reinforcements reach their yield strengths, then calculate the value of σd which should be

less than the compression **capacity of cracked** diagonal **concrete** struts (-ζf **'c).** b. If **the diagonal** 17

concrete struts crushed, then calculate the stresses in the shear reinforcements. For RC wall with hw/lw less than 1.0, assume fv to be the smaller of 0.8fyv and 500 MPa (72.52 ksi), and then calculate fh. Otherwise, assume fh to be the smaller of 0.8fyh and 500 MPa (72.52 ksi), and then calculate fv. 3) Calculate θ using Eq. (12). 4) Calculate Du using Eq. (13). 5) Calculate the ultimate or nominal shear strength Vn using Eq. (14).

COMPARISON WITH EXPERIMENTAL RESULTS To verify the accuracy of the proposed 39 model, data from past experiments on RC walls failing in shear [2, 12, 19, 22, 25-30] as well as those from the experiment conducted by the authors [6] were used. The data are presented in Table 1. A total of 84 specimens were collected. The predictions of wall shear strengths using the proposed model were then

compared with predictions from ACI 318, Eurocode 8, Hwang and 27

Lee's method [11], as well as Gupta and Rangan's method [12]. The

ratios of the experimental shear strengths to calculated shear strengths 67

(Vexp/Vn) was plotted against height to length ratios of walls (hw/lw), concrete

compressive strength (f'c), and vertical reinforcement ratio in the 9

boundary element (pb) in order to see the variation of predictions as influenced by these parameters. The analysis results are presented in Table 2 and Figs. 4 to 6. In Figs. 4 to 6, only Vexp/Vn values from ACI 318 and the authors' proposed model are plotted while the other methods are represented by their trend lines that show the average values of Vexp/Vn within certain ranges of the parameters. From the experimental comparisons (Table 2), it can be seen

that the authors' proposed model is more accurate than the 19

other four methods. This is shown by the average value of Vexp/Vn of 1.36, with the lowest coefficient of variation (COV) of 0.20.

It should be noted, however, that the predictions of the authors' proposed model 55

mostly are quite conservative (Vexp/Vn greater than 2.00) for shorter walls with hw/lw less than 0.5, as tested by Barda et al. [19]. On the other hand, for taller walls with hw/lw more than 2.0, as tested by Corley et al. [22], the predictions of the authors' proposed model are not conservative enough for some cases (Vexp/Vn less than 1.00). As can be seen in Table 2 that Hwang-Lee's model [11] is reasonably accurate (Vexp/Vn = 1.29 and COV = 0.33), but it overestimates the shear strengths of many walls while the authors' proposed model only overestimates six walls out of 84 specimens. Eurocode 8 [5] is the most conservative one with an average value of Vexp/Vn of 16 2.13 and minimum value of 1.21 with COV of 0.35. Gupta-Rangan's model [12] has the highest coefficient of variation of 0.75 while their average value of Vexp/Vn is 1.59. From Figs. 4 to 6,

it can be seen that the predictions of the authors' proposed model are uniformly accurate 43

(average values are quite consistent) for Vexp/Vn versus various ranges of parameters and they are less scattered compared to predictions by other methods. From Fig. 4, it can be seen that for walls with hw/lw more than 2.0, the predictions of the authors' proposed model are less conservative while Gupta-Rangan's model [12] are overly conservative.

From Fig. 5, it can be seen that as the concrete compressive strength increases, 16

predictions by other methods become less accurate whereas the authors' proposed model are quite consistent even for high strength concrete walls.

From Fig. 6, it can be seen that as the ratio 16

of vertical reinforcement in boundary element increases, the predictions by other methods become less accurate while the authors' proposed model are quite consistent because it takes into account the dowel action from the reinforced boundary elements. This clearly shows that inclusion of dowel action is quite important in order to predict more accurately RC wall shear strengths. CONCLUSIONS The authors have presented an analytical model

based on the principles of truss analogy to calculate the shear strengths of 51 high strength as well as normal strength concrete walls. The 53

following conclusions can be made: 1. The effective contributions of the vertical and horizontal 83

shear reinforcements to the overall shear strengths of walls are dependent on

wall height to length ratio (hw/lw). As the 5

hw/lw becomes higher than 1.0, the horizontal web reinforcement becomes more effective than the vertical web

reinforcement. This is represented correctly in the authors' model. 2. The contribution of dowel action from the 23

reinforced boundary elements is significant and it has been confirmed by various researchers [22] as well as by the authors [6]. The presence of

boundary elements or flanges increases the shear strength significantly beyond the additional area of the 47

flanges. 3. The proposed model was verified with a total of 84 RC wall specimens failing in shear that were selected from available literature [2, 12, 19, 22, 25-30] as well as from the authors' own experimental study [6], and it is confirmed to be reasonably accurate. 4. Compared to the methods by Hwang-Lee and Gupta-Rangan [11, 12], as well as the methods in the ACI 318 and Eurocode 8, the predictions of the authors' proposed model are more accurate in the sense that it has the average value of Vexp/Vn of 1.36

with the lowest coefficient of variation of 0. 20. The proposed 69

method is also

able to predict the shear strength of RC walls with 11

consistent accuracy for wide ranges of wall height to length ratios, concrete compressive strengths, and percentage of reinforcements in the boundary elements. ACKNOWLEDGMENTS This research is part of the Competitive Research Program "Underwater Infrastructure and Underwater City of the Future" funded by the National Research Foundation (NRF) of Singapore. The authors are grateful for the funding. Support by

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is also very much appreciated. NOTATION:

Acv = gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered. Acw = area of concrete section of the individual vertical wall segment 2

considered. Ag = wall gross cross section area. Asb =

total area of vertical reinforcement in 11

one boundary element. Astr = area of diagonal

concrete strut. Asw = cross sectional area of shear reinforcement. 72

Aw = wall web area. bef = effective width of

boundary element. bf = width of boundary element. bw = minimum width (thickness) of wall 49

between tension and compression chords. bwo = width of wall web. Cd = diagonal

compression force acting on nodal zone. Cd ,n = nominal capacity of the 85

nodal zone. D = compression force in the diagonal strut. dbe = equivalent bar diameter. Du = dowel force of vertical reinforcement in one boundary element. dw =

effective depth of wall. f'c = concrete cylinder compressive strength. 27

fcd = design value of concrete compressive strength. fck = characteristic compressive cylinder strength of concrete at 28 days. fcr = cracking stress of concrete. 4

fh = average stress in the horizontal web reinforcement. Fh =

tension force in the horizontal tie. fv = average stress in the 31

vertical web reinforcement. Fv =

tension force in the vertical tie. fy = specified yield strength of 31

reinforcement. 19 fyb fyd,h fyh fyv fywd hw K lw MEd P s tf tw V VEd Vexp Vn VRd VRd,c VRd,max VRd,s z α = yield strength of

vertical reinforcement in boundary element. = design value of the 97

yield strength of horizontal web reinforcement. = yield strength of horizontal shear reinforcement. = yield strength of vertical shear reinforcement. = design yield strength of shear reinforcement. = height of 1

wall. = strut and tie index. = wall length. = design bending

moment at the base of the wall. = axial load applied at top of wall. 48

=

spacing of horizontal shear (web) reinforcement. = thickness of 35

boundary element. = thickness of wall web. = applied external shear force. =

design shear force. = experimental wall shear strength. = nominal shear strength 74

of RC wall. =

shear resistance of a member with shear reinforcement. 1

=

design shear resistance of a member without shear reinforcement. = 15 design value of the maximum shear force which can be sustained by the member. = design value of

shear force which can be sustained by the yielding shear reinforcement. 41

= inner lever arm, which is taken as 0.8 lw (lw is wall length). = average strut angle with respect to longitudinal (vertical) axis.

αc = coefficient defining the relative contribution of concrete strength to nominal wall shear strength 2

which may be taken as 0.25 for hw/lw ≤ 1.5,

0.17 for hw/lw ≥ 2.0, and varies linearly between 0.25 and 0.17 for hw/lw between 1.5 and 2.0; where hw/lw is the height to length ratio of 8

the wall. αcw =

a coefficient taking account of the state of the stress in the compression chord. 1

εcr = cracking strain of concrete. εr = principal strain of concrete in r-axis,

positive for tension. εt = average strain of 33

the wall panel in transverse direction,

positive for tension. ζ = softening coefficient of the concrete in 33

compression. θ =

angle between concrete compression strut and wall axis perpendicular to shear force (Eurocode 8). θ = angle of inclination of the 13

diagonal compression strut with respect to the horizontal axis 10

(Hwang-Lee's method). θ = angle of diagonal concrete strut

(d-axis) with respect to horizontal axis 3

at ultimate

λ = modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength. 12

v1 =

strength reduction factor for concrete cracked in shear. ρb = ratio of 1

vertical reinforcement in boundary element. ρh = average horizontal web reinforcement ratio.

ρt = ratio of area of distributed transverse (horizontal) shear reinforcement to gross 2

ρ_v = average vertical web reinforcement ratio. σ_{cp} =

mean compressive stress, measured positive, in the concrete due to the design axial force. 1

21 σ_d =

principal stress of concrete in d- axis, **positive for tension.** 65

σ_h = applied normal stress in horizontal axis, positive for tension. σ_r = principal

stress of concrete in r **-axis,** positive for tension. **σ_t = normal stress in** 71

transverse

direction, positive for tension. σ_v = applied **normal stress in** 3

vertical axis, positive for tension.

τ_{vh} = average shear stress in v-h coordinate system 6

and is due to shear force acting on the wall. REFERENCES 1. Cardenas, A.E. and Magura, D.D., “Strength of High-Rise Shear Walls - Rectangular Cross Section,” ACI Special Publication – SP 36, 1972, p. 119-150. 2. Cardenas, A.E., Russell, H.G., and Corley, W.G., “Strength of Low-Rise Structural Walls,” ACI Special Publication – SP 63, 1980, p. 221-242. 3. Park, R. and Paulay, T., “Reinforced Concrete Structures,” John Wiley & Sons, Inc., 4. ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary,” American Concrete Institute, Farmington Hills, MI, 2014, 520 pp. 5. Comite Europeen de Normalisation, “Eurocode 8: Design of Structures for Earthquake Resistance Part 1: General Rules, Seismic Actions and Rules for Buildings (EN 1998- 1),” Comite Europeen de Normalisation (CEN), Brussel, 2004. 6. Teng, S. and Chandra, J., “Cyclic Shear Behavior of High Strength Concrete Structural Walls,” ACI Structural Journal, 113(6), 2016, p. 1335-1345. 7. 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Burgueno, R., Liu, X., and Hines, E.M., “Web Crushing Capacity of High-Strength Concrete Structural Walls: Experimental Study,” ACI Structural Journal, 111(1), 2014, p. 37-48. APPENDIX An example of calculations of RC wall shear strength using the authors’ proposed model is given here. A specimen from the authors’ experiment [6] is used, i.e. specimen J5. The procedure is given as follows (in SI unit): Specimen J5 data: Concrete compressive strength, f’c = 103.3 MPa Wall gross cross section area, Ag = 196000 mm2 Axial load applied at top of wall, P = 1012 kN (compression) Wall height, hw = 2000 mm Wall length, lw = 1000 mm Thickness of wall web, tw = 100 mm Width of boundary element, bf = 500 mm Thickness of boundary element, tf = 120 mm Ratio of vertical reinforcement in boundary element, ρb = 0.0388 Yield strength of vertical reinforcement in boundary element, fyb = 630 MPa

Ratio of vertical shear **(web)** reinforcement **in wall,** 6

ρv = 0.0028

Yield strength of vertical shear **reinforcement, fyv** 6

= 610 MPa Ratio of horizontal shear (web) reinforcement in wall, ρh = 0.0028 Yield strength of horizontal shear reinforcement, fyh = 610 MPa 25 Experimental wall shear strength, Vexp = 595.76 kN Calculation of nominal shear strength (Vn) according to the proposed model: 1. Calculate σr as 0.02f’c and ζ using Eq. (11) assuming εr equal to 0.005. = 0.02′ = 0.02 × 103.3 = 2.07 MPa ζ = (5.8 1 √′ ≤ 0.9) (√1 + 400) ζ = (5.8 1 √103.3 ≤ 0.9) (√1 + 400 × 0.005) ζ = 0.33 2. Check whether both web reinforcements reach their yield strengths or diagonal concrete strut crushes using Eq. (10). − > − − ℎ + + + ℎℎ −(−ζ′) > − (−) − 0 + + 0.8 + ℎ0.8ℎ (0.33×103.3) > (5.16) − 0 + 2.07 + 0.0028 × 488 + 0.0028 × 488 34.09 > 9.96 → both web reinforcements reach yield strengths = −9.96 MPa 3. Calculate θ using Eq. (12). = sin−1 (√− + +) − + = sin−1 (√ 5.16 + 2.07 + 0.0028 × 488 9.96 + 2.07) = 57.71° 26 4. Calculate Du using Eq. (13). bf = 500 mm < 0.5 hw + tw = 1100 mm (OK) = × × = 0.0388 × 500 × 120 = 2328 mm2 = √0.25 = √0.25 2328 = 54.44 mm = 1.64 3√′ = 1.64 × (500 − 54.44) × 54.44 × 3√103.3 = 186.65 kN 5. Calculate Vn using Eq. (14). = (−) sin cos + 1.64 3√′ [(2.07 + 9.96) sin 57.71° cos 57.71° × 100 × 880] = 1000 + 186.65 = 478.07 + 186.65 = 664.72 kN Thus, Vexp/Vn = 595.76/664.72 = 0.90

TABLES AND FIGURES List of Tables: Table 1 – Experimental data **of** 70

RC walls failing in shear Table 2 – Experimental and calculated wall shear strengths List of Figures: Fig. 1 –

Strut and tie mechanisms **proposed by Hwang and Lee** 26

[11]. Fig. 2 – State of stresses in a typical RC wall panel. Fig. 3 –

Average stress-strain curve **of concrete in tension. Fig. 4** 60

– Vexp/Vn plotted against height to length ratio (hw/lw). Fig. 5 – Vexp/Vn plotted against concrete compressive strength (f’c). Fig. 6 – Vexp/Vn plotted against ratio of vertical reinforcement in boundary element (?b). 1 Table 1–Experimental data of RC walls failing in shear No. Specimen ID f’c (MPa) Ag (mm2) P (kN) hw (mm) lw (mm) tw (mm) bf tf (mm) (mm) ρb fyb (MPa) ρv fyv (MPa) ρh fyh (MPa) Vexp (kN) Loading Type Barda et al. [19] 1 B1-1 29 296774 0 876 1905 102 610 102 0.0180 525 0.0050 543 0.0050 496 1218 M 2 B2-1 16 296774 0 876 1905 102 610 102 0.0640 487 0.0050 552 0.0050 499 978 M 3 B3-2 27 296774 0 876 1905 102 610 102 0.0410 414 0.0050 545 0.0050 513 1108 C 4 B6-4 21 296774 0 876 1905 102 610 102 0.0410 529 0.0025 496 0.0050 496 876 C 5 B7-5 26 296774 0 400 1905 102 610 102 0.0410 539 0.0050 531 0.0050 501 1140 C 6 B8-5 23 296774 0 1829 1905 102 610 102 0.0410 489 0.0050 527 0.0050 496 886 C Cardenas et al. [2] 7 SW-7 43 145161 0 1905 1905 76 76 191 0.0767 448 0.0077 448 0.0027 414 519 M 8 SW-8 42 145161 0 1905 1905 76 76 191 0.0300 448 0.0300 448 0.0027 465 570 M Corley et al. [22] 9 B2 54 317419 49 4572 1905 102 305 305 0.0367 410 0.0029 532 0.0063 532 680 C 10 B5 45 317419 49 4572 1905 102 305 305 0.0367 444 0.0029 502 0.0063 502 762 C 11 B6 22 317419 979 4572 1905 102 305 305 0.0367 441 0.0029 512 0.0063 512 825 C 12 B7 49 317419 1241 4572 1905 102 305 305 0.0367 458 0.0029 490 0.0063 490 980 C 13 B8 42 317419 1241 4572 1905 102 305 305 0.0367 447 0.0029 454 0.0138 482 978 C 14 B9 44 317419 1241 4572 1905 102 305 305 0.0367 430 0.0029 461 0.0063 461 977 C 15 B10 46 317419 1241 4572 1905 102 305 305 0.0197 443 0.0029 464 0.0063 464 707 C 16 F1 38 358709 49 4572 1905 102 914 102 0.0389 445 0.0030 525 0.0071 525 836 C 17 F2 46 358709 1241 4572 1905 102 914 102 0.0435 430 0.0031 464 0.0063 464 887 C Maeda [25] 18 MAE03 58 210400 412 1200 2180 80 180 180 0.0781 389 0.0119 321 0.0119 321 1460 C 19 MAE07 58 210400 412 1200 2180 80 180 180 0.0781 389 0.0200 321 0.0200 321 1676 C Okamoto [26] 20 W48M6 82 369600 725 1280 1720 120 800 120 0.0089 560 0.0079 560 0.0079 560 1516 C 21 W48M4 82 369600 725 1280 1720 120 800 120 0.0119 347 0.0119 347 0.0119 347 1479 C 22 W72M8 82 369600 725 1280 1720 120 800 120 0.0089 792 0.0091 792 0.0091 792 2066 C 23 W72M6 82 369600 725 1280 1720 120 800 120 0.0119 560 0.0119 560 0.0119 560 2015 C 1 Table 1–Experimental data of RC walls failing in shear (continued) No. Specimen ID f’c (MPa) Ag (mm2) P (kN) hw (mm) lw (mm) tw (mm) bf tf (mm) (mm) ρb fyb

(MPa) ρv fyv (MPa) ρh fyh (MPa) Vexp (kN) Loading Type 24 W72M8 102 369600 725 1280 1720 120 800 120 0.0089 792 0.0091 792 0.0091 792 2128 C 25 W96M8 102 369600 725 1280 1720 120 800 120 0.0119 792 0.0119 792 0.0119 792 2483 C Mo and Chan [27] 26 HN4-1 32 76200 0 500 860 70 170 80 0.0210 302 0.0073 302 0.0081 302 205 C 27 HN4-2 32 76200 0 500 860 70 170 80 0.0210 302 0.0073 302 0.0081 302 247 C 28 HN4-3 32 76200 0 500 860 70 170 80 0.0210 302 0.0073 302 0.0081 302 202 C 29 HN6-1 30 76200 0 500 860 70 170 80 0.0210 443 0.0073 443 0.0081 443 255 C 30 HN6-2 30 76200 0 500 860 70 170 80 0.0210 443 0.0073 443 0.0081 443 204 C 31 HN6-3 31 76200 0 500 860 70 170 80 0.0210 443 0.0073 443 0.0081 443 205 C 32 HM4-1 38 76200 0 500 860 70 170 80 0.0210 302 0.0073 302 0.0081 302 223 C 33 HM4-2 38 76200 0 500 860 70 170 80 0.0210 302 0.0073 302 0.0081 302 231 C 34 HM4-3 40 76200 0 500 860 70 170 80 0.0210 302 0.0073 302 0.0081 302 250 C 35 LN4-1 18 76200 0 500 860 70 170 80 0.0210 302 0.0058 302 0.0081 302 193 C 36 LN4-2 18 76200 0 500 860 70 170 80 0.0210 302 0.0058 302 0.0081 302 217 C 37 LN4-3 30 76200 0 500 860 70 170 80 0.0210 302 0.0058 302 0.0081 302 203 C 38 LN6-1 31 76200 0 500 860 70 170 80 0.0210 443 0.0058 443 0.0081 443 246 C 39 LN6-2 30 76200 0 500 860 70 170 80 0.0210 443 0.0058 443 0.0081 443 200 C 40 LN6-3 30 76200 0 500 860 70 170 80 0.0210 443 0.0058 443 0.0081 443 210 C 41 LM6-1 39 76200 0 500 860 70 170 80 0.0210 443 0.0058 443 0.0081 443 219 C 42 LM6-2 37 76200 0 500 860 70 170 80 0.0210 443 0.0058 443 0.0081 443 205 C 43 LM6-3 35 76200 0 500 860 70 170 80 0.0210 443 0.0058 443 0.0081 443 210 C 44 LM4-2 66 76200 0 500 860 70 170 80 0.0210 302 0.0058 302 0.0081 302 250 C 45 LM4-3 66 76200 0 500 860 70 170 80 0.0210 302 0.0058 302 0.0081 302 227 C Gupta and Rangan [12] 46 S-1 79 135000 0 1000 1000 75 375 100 0.0210 535 0.0100 545 0.0050 578 428 M 47 S-2 65 135000 610 1000 1000 75 375 100 0.0304 535 0.0100 545 0.0050 578 720 M 48 S-3 69 135000 1230 1000 1000 75 375 100 0.0387 535 0.0100 545 0.0050 578 851 M 49 S-4 75 135000 0 1000 1000 75 375 100 0.0315 535 0.0150 533 0.0050 578 600 M 1 Table 1–Experimental data of RC walls failing in shear (continued) No. Specimen ID f'c (MPa) Ag (mm2) P (kN) hw (mm) lw (mm) tw bf tf (mm) (mm) (mm) ρb fyb (MPa) ρv fyv (MPa) ρh fyh (MPa) Vexp (kN) Loading Type 50 S-5 73 135000 610 1000 1000 75 375 100 0.0399 535 0.0150 533 0.0050 578 790 M 51 S-6 71 135000 1230 1000 1000 75 375 100 0.0446 535 0.0150 533 0.0050 578 970 M 52 S-7 71 135000 610 1000 1000 75 375 100 0.0304 535 0.0100 545 0.0100 545 800 M Kabeyasawa and Hiraishi [28] 53 W-08 103 184000 1764 2000 1700 80 200 200 0.0214 761 0.0053 1079 0.0053 1079 1670 C 54 W-12 138 184000 2313 2000 1700 80 200 200 0.0214 761 0.0053 1079 0.0053 1079 1719 C 55 No. 1 65 184000 1568 2000 1700 80 200 200 0.0508 1009 0.0020 792 0.0020 792 1101 C 56 No. 2 71 184000 1568 2000 1700 80 200 200 0.0508 1009 0.0035 792 0.0035 792 1255 C 57 No. 3 72 184000 1568 2000 1700 80 200 200 0.0508 1009 0.0053 792 0.0053 792 1379 C 58 No. 4 103 184000 2617 2000 1700 80 200 200 0.0508 1009 0.0053 792 0.0053 792 1697 C 59 No. 5 77 184000 1568 3000 1700 80 200 200 0.0508 1009 0.0053 792 0.0053 792 1159 C 60 No. 6 74 184000 1568 2000 1700 80 200 200 0.0508 1009 0.0066 1420 0.0066 1420 1412 C 61 No. 7 72 184000 1568 2000 1700 80 200 200 0.0508 1009 0.0100 792 0.0100 792 1499 C 62 No. 8 76 184000 1568 2000 1700 80 200 200 0.0508 1009 0.0145 792 0.0145 792 1639 C Farvashany et al. [29] 63 HSCW1 104 120000 540 1100 880 75 375 90 0.0400 670 0.0126 535 0.0047 535 735 M 64 HSCW2 93 120000 954 1100 880 75 375 90 0.0400 670 0.0126 535 0.0047 535 845 M 65 HSCW3 86 120000 953 1100 880 75 375 90 0.0400 670 0.0075 535 0.0047 535 625 M 66 HSCW4 91 120000 2364 1100 880 75 375 90 0.0400 670 0.0075 535 0.0047 535 866 M 67 HSCW5 84 120000 955 1100 880 75 375 90 0.0400 670 0.0126 535 0.0075 535 801 M 68 HSCW6 90 120000 550 1100 880 75 375 90 0.0400 670 0.0126 535 0.0075 535 745 M 69 HSCW7 102 120000 952 1100 880 75 375 90 0.0400 670 0.0075 535 0.0075 535 800 M Burgueno et al. [30] 70 M05C 46 167640 579 2286 1016 76 254 254 0.0556 491 0.0147 445 0.0183 445 803 C 71 M05M 39 167640 579 2286 1016 76 254 254 0.0556 491 0.0147 445 0.0183 445 855 M 72 M10C 56 167640 579 2286 1016 76 254 254 0.0556 457 0.0147 476 0.0183 476 751 C 73 M10M 84 167640 579 2286 1016 76 254 254 0.0556 457 0.0147 476 0.0183 476 900 M 74 M15C 102 167640 579 2286 1016 76 254 254 0.0528 439 0.0147 481 0.0183 481 819 C 1 Table 1–Experimental data of RC walls failing in shear (continued) No. Specimen ID f'c (MPa) Ag (mm2) P (kN) hw (mm) lw (mm) tw bf tf (mm) (mm) (mm) ρb fyb (MPa) ρv fyv (MPa) ρh fyh (MPa) Vexp (kN) Loading Type 75 M15M 111 167640 579 2286 1016 76 254 254 0.0556 514 0.0147 478 0.0183 478 934 M 76 M20C 131 167640 579 2286 1016 76 254 254 0.0556 449 0.0147 438 0.0244 438 815 C 77 M20M 115 167640 579 2286 1016 76 254 254 0.0556 449 0.0147 438 0.0244 438 923 M Teng and Chandra [6] 78 J1 103 196000 1012 1000 1000 100 500 120 0.0388 630 0.0028 610 0.0028 610 1210 C 79 J2 97 196000 949 1000 1000 100 500 120 0.0388 630 0.0075 578 0.0028 610 1271 C 80 J3 111 196000 1085 1000 1000 100 500 120 0.0388 630 0.0028 610 0.0075 578 1459 C 81 J4 94 111200 520 1000 1000 100 120 280 0.0693 630 0.0028 610 0.0028 610 811 C 82 J5 103 196000 1012 2000 1000 100 500 120 0.0388 630 0.0028 610 0.0028 610 596 C 83 J6 97 196000 949 2000 1000 100 500 120 0.0388 630 0.0075 578 0.0028 610 724 C 84 J7 111 196000 1085 2000 1000 100 500 120 0.0388 630 0.0028 610 0.0075 578 895 C 2

Note: 1 MPa = 145. 04 **psi.** 3 1 **mm = 0.** 04 **in.** 9

4 1 kN = 0.22 kips. 5 Loading type: M = Monotonic 6 C = Cyclic 7 1 Table 2–Experimental and calculated wall shear strengths No. Specimen ID f'c (MPa) hw/lw ACI 318 Eurocode 8 Vexp/Vn Hwang- Lee [11] Gupta- Rangan [12] Proposed Model Barda et al. [19] 1 B1-1 29 0.46 1.65 3.94 1.23 0.98 2.11 2 B2-1 16 0.46 1.51 3.45 1.72 1.17 1.70 3 B3-2 27 0.46 1.48 3.23 1.18 0.91 1.80 4 B6-4 21 0.46 1.25 2.72 1.39 1.50 1.92 5 B7-5 26 0.21 1.56 4.64 1.09 1.16 2.18 6 B8-5 23 0.96 1.24 2.24 1.82 1.66 1.46 Cardenas et al. [2] 7 SW-7 43 1.00 1.30 2.06 0.88 1.11 1.54 8 SW-8 42 1.00 1.36 2.02 0.97 0.37 0.93 Corley et al. [22] 9 B2 54 2.40 0.76 1.31 1.04 5.73 1.15 10 B5 45 2.40 0.91 1.56 1.27 6.77 1.41 11 B6 22 2.40 1.10 1.96 1.56 2.58 1.21 12 B7 49 2.40 1.18 2.05 1.11 2.65 1.17 13 B8 42 2.40 0.94 1.38 1.13 2.69 0.92 14 B9 44 2.40 1.25 2.17 1.12 2.68 1.23 15 B10 46 2.40 0.90 1.56 0.81 1.94 0.90 16 F1 38 2.40 0.90 1.45 1.41 6.19 0.99 17 F2 46 2.40 1.13 1.96 0.91 2.31 0.79 Maed a [25] 18 MAE03 58 0.55 1.46 2.82 1.02 0.81 1.69 19 MAE07 58 0.55 1.52 2.38 1.10 0.68 1.40 Okamoto [26] 20 W48M6 82 0.74 1.10 1.99 0.88 0.88 1.13 21 W48M4 82

0.74 1.12 1.97 0.86 0.90 1.13 22 W72M8 82 0.74 1.33 1.89 1.20 0.83 1.35 23 W72M6 82 0.74 1.30 1.93 1.17 0.86 1.18 24 W72M8 102 0.74 1.23 1.93 1.14 0.86 1.31 25 W96M8 102 0.74 1.44 2.04 1.33 0.81 1.30 Mo and Chan [27] 26 HN4-1 32 0.58 0.88 1.58 0.87 0.91 1.35 27 HN4-2 32 0.58 1.06 1.90 1.05 1.10 1.63 28 HN4-3 32 0.58 0.87 1.56 0.86 0.90 1.33 29 HN6-1 30 0.58 0.94 1.70 1.18 0.77 1.30 30 HN6-2 30 0.58 0.75 1.36 0.95 0.62 1.04 31 HN6-3 31 0.58 0.74 1.31 0.90 0.62 1.04 32 HM4-1 38 0.58 0.93 1.69 0.81 1.00 1.41 33 HM4-2 38 0.58 0.96 1.75 0.84 1.04 1.46 34 HM4-3 40 0.58 1.03 1.88 0.86 1.12 1.55 35 LN4-1 18 0.58 0.91 2.00 1.47 1.04 1.57 36 LN4-2 18 0.58 1.02 2.25 1.65 1.17 1.76 37 LN4-3 30 0.58 0.88 1.59 0.93 1.12 1.47 1 Table 2–Experimental and calculated wall shear strengths (continued) No. Specimen ID f'c (MPa) Vexp/Vn hw/lw ACI 318 Eurocode Hwang- 8 Lee [11] Gupta- Rangan [12] Proposed Model 38 LN6-1 31 0.58 0.89 1.58 1.10 0.93 1.35 39 LN6-2 30 0.58 0.73 1.30 0.91 0.76 1.10 40 LN6-3 30 0.58 0.76 1.37 0.95 0.80 1.16 41 LM6-1 39 0.58 0.70 1.28 0.76 0.84 1.14 42 LM6-2 37 0.58 0.67 1.21 0.76 0.78 1.08 43 LM6-3 35 0.58 0.72 1.24 0.83 0.80 1.12 44 LM4-2 66 0.58 0.92 1.78 0.69 1.40 1.37 45 LM4-3 66 0.58 0.84 1.62 0.63 1.27 1.24 Gupta and Rangan [12] 46 S-1 79 1.00 1.11 1.58 0.99 1.12 1.07 47 S-2 65 1.00 1.96 2.24 1.32 1.03 1.46 48 S-3 69 1.00 2.28 2.28 1.23 0.88 1.43 49 S-4 75 1.00 1.58 2.16 1.43 1.07 1.30 50 S-5 73 1.00 2.10 2.43 1.42 0.90 1.41 51 S-6 71 1.00 2.59 2.60 1.40 0.94 1.52 52 S-7 71 1.00 1.52 2.05 1.41 1.15 1.32 Kabeyasawa and Hiraishi [28] 53 W-08 103 1.18 1.48 1.93 1.35 1.10 1.62 54 W-12 138 1.18 1.46 1.95 1.21 0.95 1.40 55 No. 1 65 1.18 2.25 2.19 1.11 1.04 1.70 56 No. 2 71 1.18 1.90 1.93 1.18 1.06 1.61 57 No. 3 72 1.18 1.60 1.84 1.23 1.03 1.51 58 No. 4 103 1.18 1.84 1.88 1.22 0.94 1.42 59 No. 5 77 1.76 1.41 1.50 1.07 1.31 1.25 60 No. 6 74 1.18 1.45 1.86 1.26 1.01 1.40 61 No. 7 72 1.18 1.57 2.01 1.34 1.00 1.22 62 No. 8 76 1.18 1.66 2.13 1.45 1.01 1.07 Farvashany et al. [29] 63 HSCW1 104 1.25 2.20 2.36 1.56 1.34 1.41 64 HSCW2 93 1.25 2.60 2.48 1.60 1.18 1.52 65 HSCW3 86 1.25 1.96 1.85 1.19 1.07 1.22 66 HSCW4 91 1.25 2.68 1.99 1.13 0.84 1.28 67 HSCW5 84 1.25 1.93 2.07 1.42 1.12 1.32 68 HSCW6 90 1.25 1.77 1.94 1.49 1.35 1.34 69 HSCW7 102 1.25 1.85 1.94 1.39 1.37 1.34 Burgueno et al. [30] 70 M05C 46 2.25 1.85 2.68 2.46 3.05 1.43 71 M05M 39 2.25 2.14 3.23 2.76 3.46 1.55 72 M10C 56 2.25 1.56 2.19 2.22 2.73 1.24 73 M10M 84 2.25 1.53 2.09 2.43 3.27 1.39 74 M15C 102 2.25 1.27 1.77 2.09 2.96 1.21 75 M15M 111 2.25 1.38 1.98 2.33 3.39 1.35 76 M20C 131 2.25 1.11 1.72 1.92 3.13 1.08 1 Table 2–Experimental and calculated wall shear strengths (continued) No. Specimen ID f'c (MPa) hw/lw ACI 318 Eurocode 8 Vexp/Vn Hwang- Lee [11] Gupta- Rangan [12] Proposed Model 77 M20M 115 2.25 1.34 1.95 2.27 3.55 1.26 Teng and Chandra [6] 78 J1 103 1.00 2.85 3.25 1.62 1.93 1.82 79 J2 97 1.00 3.05 3.48 1.75 1.52 1.83 80 J3 111 1.00 2.09 2.36 1.71 2.21 1.77 81 J4 94 1.00 1.97 2.35 1.44 1.71 2.07 82 J5 103 2.00 1.73 4.36 1.07 1.92 0.90 83 J6 97 2.00 2.14 5.30 1.33 1.75 1.04 84 J7 111 2.00 1.46 2.58 1.23 2.74 1.09 Statistical parameters Minimum value 0.67 1.21 0.63 0.37 0.79 Maximum value 3.05 5.30 2.76 6.77 2.18 Average value 1.43 2.13 1.29 1.59 1.36 Standard deviation 0.54 0.74 0.43 1.19 0.28 Coefficient of variation 0.38 0.35 0.33 0.75 0.20 2 Note: 1 MPa = 145.04 psi. 3 4 5 Vv Vv (vertical force) 6 concrete strut Fv = Rv Vv 7 (vertical component) Vh Vh (horizontal force) 8 -D = Rd Cd (diagonal component) 9 10 11 steel tension ties 12 Cd Fh = Rh Vh (horizontal component) -D + Fh / cos θ + Fv / sin θ = Cd θ 13

(a) Disturbed stress field (b) Strut and tie idealization 6

14 Fig. 1

–Strut and tie mechanisms **proposed by Hwang and Lee** 26

[11]. 15 Fig. 2–State of stresses in a typical RC wall panel. 3 1 Fig. 3

–Average stress-strain curve of concrete in tension. 81

3 4.00 3.00 V exp/Vn 2.00 1.00 0.00 ACI 318 ACI 318 EC 8 Hwang-Lee Gupta-Rangan 0.00 0.50 1.00 1.50 2.00 2.50 hw/lw Proposed Model Proposed Model 4.00 3.00 V exp/Vn 2.00 1.00 0.00 0.00 0.50 1.00 1.50 2.00 2.50 2 hw/lw Fig. 4–Vexp/Vn plotted against height to length ratio (hw/lw). ACI 318 ACI 318 EC 8 Hwang-Lee Gupta-Rangan 4.00 3.00 V exp/Vn 2.00 1.00 0.00 0 30 60 120 150 90 f'c (MPa) Proposed Model Proposed Model 4.00 3.00 V exp/Vn 2.00 1.00 0.00 0 30 60 90 120 150 2 f'c (MPa) Fig. 5–Vexp/Vn plotted against concrete compressive strength (f'c). Note: 1 MPa = 145.04 psi. 5 ACI 318 ACI 318 EC 8 Hwang-Lee Gupta-Rangan 4.00 3.00 V exp/Vn 2.00 1.00 0.00 0.00 0.02 0.04 ρb 0.06 0.08 Proposed Model Proposed Model 4.00 3.00 V exp/Vn 2.00 1.00 0.00 0.00 0.02 0.04 0.06 0.08 2 ρb Fig. 6–Vexp/Vn plotted against ratio of vertical reinforcement in boundary element (?b). Note: ?b = Asb / (bf x tf). 5 6 7 8 9 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3

4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
20 21 22 23 24 25 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 1 2 3 4 5 6 7 8 9 10 11 12 13 14
15 16 17 18 19 20 21 22 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 1 2 2 1 3
4 1 3 4 1 3 4 1 5 6 9 13 14 15 17 18 20 22 23 24 27 28 29 30 31 32 33 34 35 36 37 38 39 40