EVALUATION OF SHEAR STRENGTH OF REINFORCED CONCRETE STRUCTURAL WALLS OF ACI 318-14 AND EUROCODES

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Abstract - Reinforced concrete structural walls are very effective in resisting lateral loads due to their high strength and stiffness. While Vietnamese Standard TCVN 5574-2012 does not provide detailed provisions for design of structural walls, the shear strength of reinforced concrete structural walls according to various building codes are very different. The paper investigates the design shear strength of reinforced concrete structural walls using provisions from ACI 318-14, Eurocode 2 EN 1992-1:2004, and Eurocode 8 EN 1998-1:2004. The theory used in these building codes to determine wall shear strength is analyzed and numerical comparison is carried out to evaluate the influence of key parameters, including compressive concrete strength, axial load level, and shear span ratio, on the wall shear capacity, for both non-seismic and seismic design.

Key words - reinforced concrete; structural wall; shear wall; shear strength; building code

1. Introduction

Reinforced concrete structural walls are commonly used to resist lateral loads, such as wind or earthquake loads, due to their high strength and stiffness. Although being important structural members, detailed provisions for behavior and design of structural walls are not provided in Vietnamese Standard TCVN 5574-2012 [1]. In fact, the design of reinforced concrete structural walls for shear has become an issue as the shear capacity according to various building codes are very different due to the complex stress redistributions that occur after cracking. Shear transfer mechanisms have been proved to be influenced by various parameters.

Several factors have an influence on the shear capacity of reinforced concrete structural walls. The most influenced parameters are known as wall cross section, concrete strength, axial force and shear span ratio. There has been much research on the shear performance and design of reinforced concrete structural walls according to different building codes [2], [3], [4], [5], [6]... However, no investigation has been done on direct comparison of design provisions from ACI 318 and Eurocodes with respect to specific parameters. This study investigates the design shear strength of reinforced concrete structural walls using provisions from ACI 318-14 [7], Eurocode 2 EN 1992-1:2004 [8], and Eurocode 8 EN 1998-1:2004 [9] for both non-seismic and seismic design.

2. Shear provisions of structural walls in ACI 318-14, Eurocode 2 EN 1992-1:2004, and Eurocode 8 EN 1998-1:2004

2.1. ACI 318-14

In ACI 318-14, design provisions for shear of reinforced concrete structural walls are presented in Sections 11.5.4 and 18.10.4. These two semi-empirical equations are based on the modified truss analogy approach and can be used to predict the peak shear capacity of reinforced concrete walls. According to this modified truss analogy approach, the peak wall shear strength is the summation of two shear forces, one resisted by concrete and the other resisted by horizontal web reinforcement. Both sections assume a diagonal tension failure mechanism with a 45-degree crack and diagonal compression failure is prevented by controlling an upper limit for the wall shear stress. While Section 11.5.4 provides requirements for non-seismic design (NSD) of structural walls, Section 18.10.4 provides provisions for seismic design (SD) of structural walls.

The procedure to predict the shear capacity of reinforced concrete walls in Section 11.5.4 is given by the following equations.

$$V_n = V_c + V_s \le 10\sqrt{f_c^{'}}hd \quad (1)$$

$$V_c = \min[V_{c1}, V_{c2}] \quad (2)$$

$$V_{c1} = 3.3\lambda\sqrt{f_c^{'}}hd + \frac{N_u d}{4l_w} \quad (3)$$

$$V_{c2} = \left[0.6\lambda\sqrt{f_c^{'}} + \frac{l_w\left[1.25\lambda\sqrt{f_c^{'}} + \frac{0.2N_u}{l_w h}\right]}{\frac{M_u}{V_u} - \frac{l_w}{2}}\right]hd \quad (4)$$

$$V_s = \frac{A_v f_{yt} d}{s} \quad (5)$$

where V_n (lb) is the nominal shear strength of the wall; V_c (lb) is the nominal shear strength provided by concrete; V_s (lb) is the nominal shear strength provided by horizontal web reinforcement; λ is the modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normal weight concrete of the same compressive strength, λ=1.0 for normal concrete; f'_c (psi) is the specified compressive strength of concrete; h (in.) is the thickness of the wall; l_w (in.) is the length of the wall; d (in.) is the distance from the extreme compressive fiber to centroid of longitudinal tension reinforcement and assumed to be $0.8l_w$ unless a larger value is determined by a strain compatibility analysis; M_u (lb-in) and V_u (lb) are the factored moment and shear force at the critical section, respectively; N_u (lb) is the factored axial load that is positive in compression and negative in tension; A_v is the area of horizontal web reinforcement within spacing s; f_{yt} is the specified yield strength of horizontal web reinforcement.

The value for M_u/V_u is evaluated at the critical section above the base of the wall, and the location of that section is described in Figure 1.

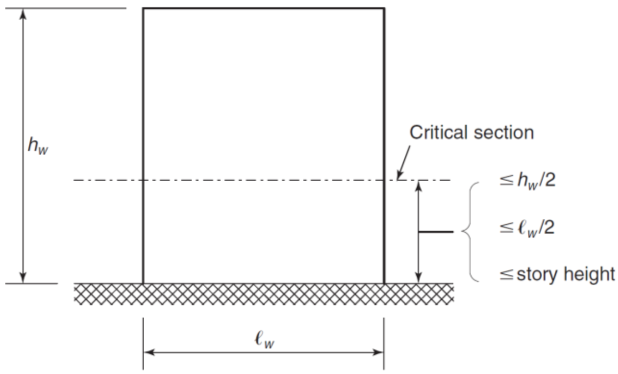

Figure 1. *Location of critical section for checking flexural-shear strength [10]*

Equation (4) does not apply if:

$$\frac{M_u}{V_u} - \frac{l_w}{2} \leq 0 \tag{6}$$

In order to avoid diagonal compression failure, the wall shear stress is limited to $10\sqrt{f_c^{'}}$. The horizontal web reinforcement has the minimum ratio of 0.25%:

$$\rho_t \geq 0.0025 \tag{7}$$

The minimum vertical web reinforcement ratio is given by:

$$\rho_l \geq 0.0025 + 0.5\left(2.5 - \frac{h_w}{l_w}\right)\left(\rho_t - 0.0025\right) \tag{8}$$

In SI units, the three equations (1), (3), (4) are replaced by the three following equations (9), (10), (11), respectively,

$$V_n = V_c + V_s \leq 0.83\sqrt{f_c^{'}}hd \tag{9}$$

$$V_{c1} = 2.7\lambda\sqrt{f_c^{'}}hd + \frac{N_u d}{4l_w} \tag{10}$$

$$V_{c2} = \left[0.05\lambda\sqrt{f_c^{'}} + \frac{l_w\left[0.1\lambda\sqrt{f_c^{'}} + \dfrac{0.2N_u}{l_w h}\right]}{\dfrac{M_u}{V_u} - \dfrac{l_w}{2}}\right]hd \tag{11}$$

where f'c is (MPa), h (mm), l_w (mm), d (mm), M_u (Nm), V_u (N), and N_u (N).

The nominal shear strength of reinforced concrete structural walls per Section 18.10.4 is given as follows.

$$V_n = \left(\alpha_c\lambda\sqrt{f_c^{'}} + \rho_t f_{yt}\right)A_{cv} \leq 10\sqrt{f_c^{'}}A_{cv} \tag{12}$$

where V_n (lb) is the nominal shear strength of the wall; α_c is a function of wall aspect ratio, equal to 2.0 for $\frac{h_w}{l_w} \geq 2.0$, 3.0 for $\frac{h_w}{l_w} \leq 1.5$ and varies linearly for $1.5 \leq \frac{h_w}{l_w} \leq 2.0$; f'c (psi) is the specified compressive strength of concrete; ρ_t is the horizontal web reinforcement ratio; f_{yt} (psi) is the yield stress of the horizontal web reinforcement; A_{cv} (in^2) is the gross area of the wall bounded by the web thickness and the wall length; h_w (in) and l_w (in) are the height and length of the wall, respectively.

In SI units, Equation (12) is rewritten as the following equation.

$$V_n = \left(\alpha_c\lambda\sqrt{f_c^{'}} + \rho_t f_{yt}\right)A_{cv} \leq 0.83\sqrt{f_c^{'}}A_{cv} \tag{13}$$

where V_n (N); α_c is equal to 0.17 for $\frac{h_w}{l_w} \geq 2.0$, 0.25 for $\frac{h_w}{l_w} \leq 1.5$ and varies linearly for $1.5 \leq \frac{h_w}{l_w} \leq 2.0$; f'c (MPa); f_{yt} (MPa); A_{cv} (mm^2); h_w (mm) and l_w (mm).

The major difference between sections 11.5.4 and 18.10.4 is the calculation of wall shear strength provided by concrete. In Section 11.5.4, the two values of the concrete contribution corresponding to different cracking conditions are determined. Equation (3) corresponds to the occurrence of web shear cracking at a principal tensile stress of approximately $4\lambda\sqrt{f_c^{'}}$ at the centroid of the shear wall cross section. Equation (4) corresponds approximately to the occurrence of flexure-shear cracking at a flexural tensile stress of $6\lambda\sqrt{f_c^{'}}$ at a section $\frac{l_w}{2}$ above the section being investigated. In Section 18.10.4, the concrete contribution is determined using an empirical factor α_c that is a function of wall aspect ratio.

The design shear strength of reinforced concrete structural walls is ϕV_n, where ϕ is the strength reduction factor for shear.

2.2. Eurocode 2 EN 1992-1:2004

The non-seismic design provisions for shear of reinforced concrete structural walls in Eurocode 2 EN 1992-1:2004 (EC2 (2004)) are presented in Section 6.2. According to EC2 (2004), horizontal shear reinforcement of structural walls is calculated on the basis of a variable inclination truss model, which is similar to the theory applied to beams. It should be noted that in this model, all shear is resisted by the provision of links with no direct contribution from the shear capacity of the concrete itself. The shear resistance V_{Rd} in Section 6.2 is determined as follows.

$$V_{Rd} = \min\left[V_{Rd,s}; V_{Rd,\max}\right] \tag{14}$$

$$V_{Rd,s} = \frac{A_{sw} f_{ywd} z}{s}\cot\theta \tag{15}$$

$$V_{Rd,\max} = \frac{\alpha_{cw} f_{cd} b_w z v_1}{\cot\theta + \tan\theta} \tag{16}$$

where $V_{Rd,s}$ is the shear resistance of the links which are horizontal web reinforcement; $V_{Rd,\max}$ is the maximum design value of the shear which can be resisted by the concrete strut; A_{sw} is the cross-sectional area of the shear reinforcement; s is the spacing of horizontal web reinforcement; f_{ywd} is the design yield strength of the horizontal web reinforcement, $f_{ywd} = \frac{f_{yk}}{1.15}$; f_{yk} is the ultimate design yield strength of the horizontal web reinforcement; z is lever arm between the upper and lower chord members of the analogous truss, which can be taken as $0.8l_w$; θ is the angle between the diagonal concrete compression struts to the wall axis perpendicular to the shear force; α_{cw} is a coefficient taking account of the state of the stress in the compression chord, which is taken as 1 for non-prestressed structures; f_{cd} is the design concrete compressive strength, $f_{cd} = \frac{f_{ck}}{1.5}$; f_{ck} is the ultimate design concrete compressive strength; v_1 is a strength reduction factor for concrete cracked in shear $v_1 = 0.6\left[1 - \frac{f_{ck}}{250}\right]$.

In EC2 (2004), the angle θ has a value between 21.8 and 45 degrees, or:

$$1.0 \le \cot\theta \le 2.5 \tag{17}$$

2.3. Eurocode 8 EN 1998-1:2004

The seismic design provisions for ductile reinforced concrete structural walls in Eurocode 8 EN 1998-1:2004 (EC8 (2004)) are presented in Section 5.5. The following provisions are required to prevent diagonal tension failure of the wall web due to shear.

If the shear span ratio $\alpha_s = \frac{M_{Ed}}{V_{Ed} l_w} \ge 2.0$, the previous provisions in EC2 (2004) are applied with the angle θ taken as 45 degrees.

If the shear span ratio $\alpha_s < 2.0$, the shear resistance V_{Rd} is determined as follows.

$$V_{Rd,s} = V_{Rd,c} + 0.75\rho_h f_{yd,h} b_{wo} \alpha_s l_w \tag{18}$$

where $V_{Rd,c}$ is the design value of shear resistance for members without shear reinforcement, ρ_h is the reinforcement ratio of horizontal web bars, $\rho_h = \frac{A_b}{b_{wo} s_h}$; $f_{yd,h}$ is the design yield strength of the horizontal web reinforcement; b_{wo} is the thickness of the wall.

The design value $V_{Rd,c}$ of shear resistance for members without shear reinforcement is given by:

$$V_c = \left[C_{Rd,c} k (100\rho_1 f_{ck})^{1/3} + k_1 \rho_{cp}\right] b_w d \ge V_{c,\min} \tag{19}$$

The shear resistance V_c is not less than:

$$V_{c,\min} = (v_{\min} + k_1 \rho_{cp}) b_w d \tag{20}$$

where f_{ck} (MPa) is the characteristic compressive cylinder strength of concrete at 28 days;

$$k = \left(1 + \sqrt{\frac{200}{d}}\right) \le 2,0 \tag{21}$$

with d (mm); ρ_1 is the longirtudinal tension with d (mm)

$$\rho_1 = \frac{A_{s1}}{b_w d} \le 0.02 \qquad 22)$$

A_{sl} is the area of longitudinal tension reinforcement, which extends ≥ (l_{bd}+d) beyond the section considered; k_1 is 0.15; σ_{cp} (MPa) is the compressive stress in the concrete from axial load,

$$\sigma_{cp} = \frac{N_{Ed}}{A_c} \le 0.2 f_{cd} \tag{23}$$

N_{Ed} (N) is the axial force in the cross-section due to loading; to be taken as positive for compression and negative for tension; A_c (mm^2) is the area of the concrete cross section; f_{cd} (MPa) is the design value of concrete compressive strength; b_w (mm) is the smallest width of the cross-section in the tensile area; d (mm) is the distance from the extreme compressive fiber to centroid of longitudinal tension reinforcement, v_{min} is determined as:

$$v_{\min} = 0.035 k^{3/2} f_{ck}^{1/2} \tag{24}$$

3. Comparison of design code provisions

The shear resistance of a reinforced concrete shear wall is investigated based on the following building code provisions: ACI 318-14 (NSD), ACI 318-14 (SD), EC2 (2004) and EC8 (2004), where NSD and SD stand for non-seismic design and seismic design, respectively. The structural wall has the rectangular cross section of 25×300cm and is subjected to a concentrated force at the top of the wall. Horizontal web reinforcement consists of two layers of 14mm-diameter bars at spacing of 200mm, and has the design yield strength of 280MPa.

3.1. Shear strength versus concrete compressive strength level

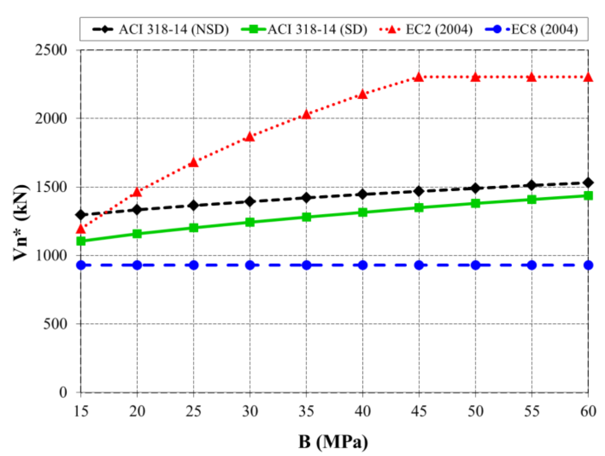

Figure 2. *Comparison of V_n^* versus B for walls with the axial load of 2400kN*

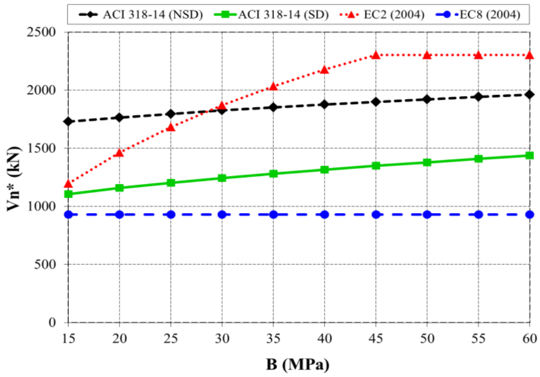

Figure 3. *Comparison of* V_n^* *versus B for walls with the axial load of 6000kN*

Figures 2 and 3 present the relation between the design shear resistance V_n^* and concrete strength grade B mentioned in TCVN 5574-2012. V_n^* stands for ϕV_n in ACI 318-14 and V_{Rd} in Eurocodes. The structural wall has aspect ratio of 2.0. The axial load acting on the wall is kept constant as 2400kN and 6000kN, which is equal to $0.2 f_c^{'} A_{cv}$ and $0.5 f_c^{'} A_{cv}$ for B15 concrete, in Figures 2 and 3, respectively.

As can be seen from the figures, V_n^* calculated for non-seismic wall design is significantly larger than that for seismic design in Eurocodes, especially with high concrete compressive strength. That is because $V_{Rd,\max}$ is proportional to f_{cd}, leading to that $V_{Rd,\max} > V_{Rd.s}$ with high concrete compressive strength for all $\theta = 21.8 \div 45$ degrees. At B45 or above, V_n^* of EC8 (2004) is 2.5 times larger than that of EC2 (2004). This difference in wall shear strength is also obvious between ACI 318-14 (NSD) and ACI 318-14 (SD), especially with high axial load.

In EC8 (2004), as the angle θ is set constant as 45 degrees and $V_{Rd,s}(\theta = 45) < V_{Rd.\max}$, the design shear resistance does not change with varied concrete strength. V_n^* based on ACI 318-14 (SD) and EC8 (2004) are quite closed together for walls with low concrete compressive strength, EC8 (2008) always gives more conservative shear strength compared with ACI 318-14 (SD).

3.2. Shear strength versus axial load ratio

Figures 4 and 5 show the relation between the design shear resistance V_n^* and axial load ratio $\dfrac{N}{f_c^{'} A_{cv}}$. The structural wall also has aspect ratio of 2.0. The concrete strength grade is B20 and B50 in Figures 4 and 5, respectively. Of these building code provisions, only the design shear resistance calculated in ACI 318-14 (NSD) depends on the axial load. V_n^* in ACI 318-14 (NSD) increases much more significantly with higher concrete compressive strength. For walls using B20 concrete, V_n^* at $0.5\dfrac{N}{f_c^{'} A_{cv}}$ is 1.7 times larger than that at $0.2\dfrac{N}{f_c^{'} A_{cv}}$. This difference increases up to 2.5 times for walls using B50 concrete.

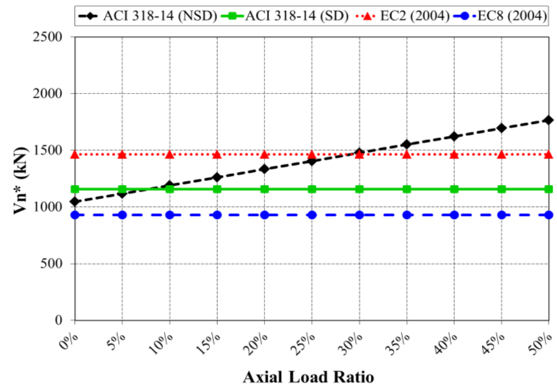

Figure 4. *Comparison of* V_n^* *versus axial load ratio for concrete B20*

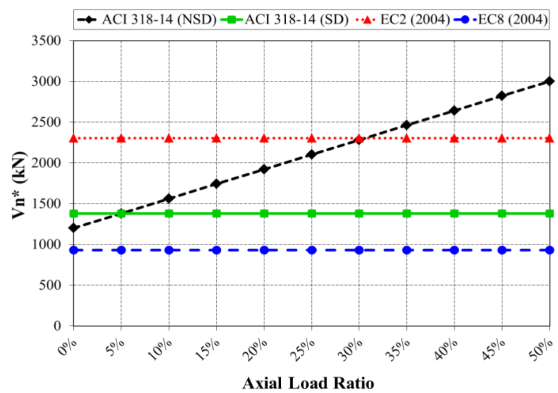

Figure 5. *Comparison of* V_n^* *versus axial load ratio for concrete B50*

3.3. Shear strength versus shear span ratio

When the wall shear span ratio increases from 2.0, the shear strength based on ACI 318-14 (NSD) decreases, while that based on the other building code provisions remains the same. Figure 6 presents the relation between the design shear resistance V_n^* from ACI 318-14 (NSD) and concrete strength grade B, corresponding to the shear span ratio of 2.0, 3.0, and 4.0. The figure indicates that V_n^* decreases when the shear span ratio increases. However, V_n^* decreases substantially at low shear span ratio and decreases slightly at high shear span ratio.

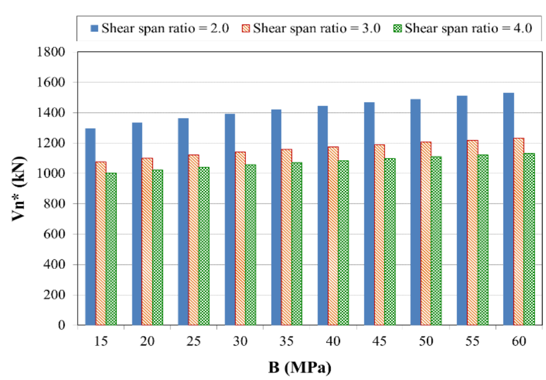

Figure 6. *Comparison of* V_n^* *versus B at shear span ratio ranging from 2.0 to 4.0*

4. Conclusion

The study is carried out to investigate the influence of various parameters on the shear resistance of structural walls in the following building codes: ACI 318-14, Eurocode 2 EN 1992-1:2004, and Eurocode 8 EN 1998-1:2004. The structural wall has the rectangular cross section of 25×300cm and is subjected to a concentrated force at the top of the wall. Horizontal web reinforcement consists of two layers of 14mm-diameter bars at spacing of 200mm, and has the design yield strength of 280MPa. From the study, the following conclusions can be drawn.

- ACI 318-14 provides semi-empirical equations to determine the wall shear strength which are based on the modified truss analogy approach. The peak wall shear strength is the summation of two shear forces, one resisted by concrete and the other resisted by horizontal web reinforcement. ACI 318-14 assumes a diagonal tension failure mechanism with a 45-degree crack.

- According to EC2 (2004) and EC8 (2004), the wall shear strength is calculated on the basis of a variable inclination truss model, in which all shear is resisted by the provision of horizontal web reinforcement with no direct contribution from the shear capacity of the concrete. The angle θ between the diagonal concrete compression struts to the wall axis perpendicular to the shear force varies from 21.8 to 45 degrees in EC2 (2004), while it is set constant as 45 degrees in EC8 (2004).

- Generally, the wall shear resistance increases with concrete compressive strength, except for that calculated from EC8 (2004). In EC8 (2004), as the angle θ is set constant as 45 degrees and $V_{Rd,s}(\theta = 45) < V_{Rd.\max}$, the design shear resistance does not change with varied concrete strength.

- EC8 (2008) provides more conservative wall shear strength compared with ACI 318-14 (SD). Shear strength calculated from ACI 318-14 (SD) is almost 1.5 times larger than that from EC8 (2008) for walls with shear span ratio of 2.0 and B60 concrete.

- Of these building code provisions, only the design shear resistance calculated in ACI 318-14 (NSD) depends on the axial load. V_n^* in ACI 318-14 (NSD) increases much more significantly with higher concrete compressive strength.

- The shear strength based on ACI 318-14 (NSD) decreases when the wall shear span ratio increases from 2.0, while that based on the other building code provisions remains the same. The shear strength decreases more slightly at higher shear span ratio.

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