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# PROPOSED FORMULA AND COMPARISON OF SHEAR STRENGTHS OF REINFORCED CONCRETE BEAMS UNDER VARIOUS CODES

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**ABSTRACT:** In the paper, the shear strength calculations were carried out in accordance with the SNI 2847:2019, ACI 318M-19, EN 1992-4, NZS 3101.2, and CSA A23.3 to predict the shear strength data from the literature. The number of data used for validation involved 129 experimental concrete beams to generate the predicted shear strengths of the corresponding various beams. After the predicted shear strength results were obtained, the next step was to compare the results of the predicted shear strength using these five available formula codes against the results of the experimental concrete beam test. This study focuses on the investigation of normal-strength and high-strength concrete beams. The comparisons were made to determine the predictive test strength based on which formula has the closest shear strength prediction to the experimental test results. A proposed formula has also been introduced to obtain a more optimal shear strength prediction. The results indicate that NZS 3101.2 provides better results compared to the other five formulations among the codes. In contrast, CSA A23.3 is the most conservative formulation. The newly developed formula is $[0.66\lambda(\rho_w)^{1/3}(f_c')^{0.53}+(N_u/6A_g)]b_wd$, which modifies the ACI formula, to improve the prediction and maintain it on the safe side of the majority, and the proposed formulation improves the prediction compared with others.

*Keywords: ACI 318; Codes; Concrete Beams; Disaster Risk Reduction, EN 1992; NZS 3101.2; Shear Strength; SNI 2847.*

## 1. INTRODUCTION

In the design of structural concrete, members such as beams and columns are required to be designed properly [1], [2]. Otherwise, the lack of design will bring such high consequences, e.g., retrofitting effort, etc. [3] The use of concrete and steel are very popular in the past century and requires better materials and more effective design [4], [5]. Besides flexure, shear is one of the main considerations that is required to be designed accurately [6]–[8]. There are many regulations for designing the shear strength of reinforced concrete beams for building structures, such as ACI 318, EN 1992-4, NZS 3101.2, and CSA A23.3.

Indonesia also has standards for the shear strength of reinforced concrete beams. Indonesian's design regulations for the shear strength of reinforced concrete beams, namely SNI 2847:2019. This standard is an improvement of SNI 2847:2013, which refers to ACI 318M-14. This standard is used in the planning and implementation of concrete structures for buildings or other structures with the same character as the building structure.

Currently, the regulation of SNI 2847 is adopted directly from ACI 318. However, practitioners and academics currently do not know whether the regulations adopted by SNI, namely ACI, are the most appropriate and efficient regulations for designing the shear strength of reinforced concrete beams for building structures in Indonesia. They do not know which regulations are closest to the experimental results and the results of calculations using building design regulations.

Table 1 Samples of Concrete Beams using UHPC

| Beam ID | Dimensions (b × h) | Longitudinal Reinforcement | $f_c'$ (MPa) |
|---|---|---|---|
| B1 | 152 × 152 | 3-D25 | 137 |
| B2 | 152 × 152 | 3-D22 | 137 |
| B3 | 152 × 152 | 3-D25 | 137 |
| B4 | 152 × 152 | 3-D22 | 137 |
| B5 | 152 × 152 | 3-D19 | 137 |
| B21 | 152 × 152 | 3-D20 | 125 |
| B22 | 152 × 152 | 3-D18 | 125 |
| B23 | 152 × 152 | 3-D20 | 125 |
| B24 | 152 × 152 | 3-D18 | 125 |
| B29 | 102 × 203 | 2-D20 | 125 |
| B30 | 102 × 203 | 2-D16 | 125 |
| B35 | 152 × 76 | 3-D14 | 125 |
| B36 | 152 × 76 | 3-D10 | 125 |
| B37 | 152 × 76 | 3-D10 | 125 |

In 2017, Pourbaba and Joghataie [9] conducted research on the shear strength of Ultra-High-Performance Concrete Beams (UHPC). Pourbaba made 14 samples of concrete beams using UHPC with the geometry shown in Table 1.

To obtain the shear strength, a test was carried out using 14 beam specimens. Then from the geometry shown in Table 1, the shear strength will be calculated using ACI 318, RILEM, and Iranian Code. Furthermore, the experimental results of the beam samples will be compared with the results of the shear strength estimation using the ACI, RILEM, and Iranian Codes. The research above shows that the ACI and Iranian Codes produce an estimated shear strength that is overly conservative, with a ratio of around 8. While RILEM it produces a ratio of 3.6.

To find out which regulations are the most suitable for the design of the shear strength of reinforced concrete beams for building structures, an experimental test is needed that examines the shear strength of reinforced concrete beams. In this study, the shear strength of concrete beams is used based on experimental results from several studies, compared with the results of analytical calculations using building design regulations from various countries, namely, ACI 318, EN 1992-4, NZS 3101.2, and CSA A23.3.

This study will develop a new shear strength formulation for reinforced concrete beams with some modifications to the concrete compressive strength. It will be verified using experimental beam tests from the literature.

Three regulations give unsafe results, namely SNI, EN1992, and NZS. ACI and CSA provide safe results. ACI gives better results than CSA, which manages to be conservative (avg. Vexp/Vcode is 1.87). The proposed equation is carried out by adjusting the ACI equation. Because among the five formulations, ACI is the regulation that gives the best outcomes but can still be improved to make it more optimal.

The present proposed equation provides more suitable results compared to the ACI equation. Nevertheless, the proposed equation performs well for beams with normal-strength concrete. For high-strength concrete, the proposed equation also delivers better results than the five formulations with an average Vexp/Vcode of 4.35.

## 2. RESEARCH SIGNIFICANCE

The existing reliable equations for predicting the shear strength are lacking. This research provides a simple equation for predicting the shear strength of reinforced concrete beams by modifying the ACI equation. It has been verified using experimental data from numerous beam tests. Through the research, academics and practitioners can better understand that certain equations deliver unsafe shear strength results, while the other equations give under-estimated results which can lead to the design results being inefficient.

## 3. MATERIALS AND METHOD

### 3.1 Specimens and Parameter

In this study, 129 experimental concrete beams tested for shear strength were used.

Since then, many researchers [9-15] have performed concrete beam tests. The experimental beam test used normal-strength and high-strength concrete. Figure 1 illustrates the experimental beam test where the beam is loaded by a load “P”. Table 2 shows the number of experimental beams used in this study. The numbers in brackets indicate the year the beam was tested.

The range of each parameter in the experimental concrete beam is shown in Table 3. From a total of 129 experimental beams, beams with concrete compressive strength of 10-137 MPa were used. The distribution of effective height, beam width, shear span-depth ratio, flexural reinforcement ratio, and shear strength can be seen in Figure 2. In Figure 2(c), it can be seen that 45 beams (34.8%) are beams that have an effective height of 300 mm. The most widely used concrete compressive strength is 25 MPa with 30 beams (23%) (Figure 2(a)). As for the flexural reinforcement with a ratio of 2%, the beam has the highest frequency, which is about 51% (66 beams), shown in Figure 2(b).

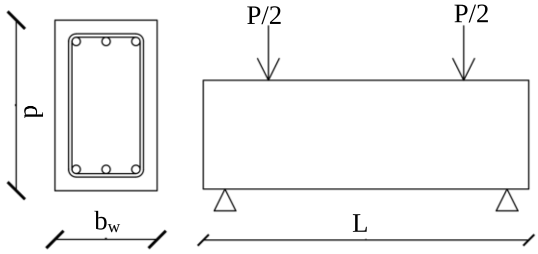


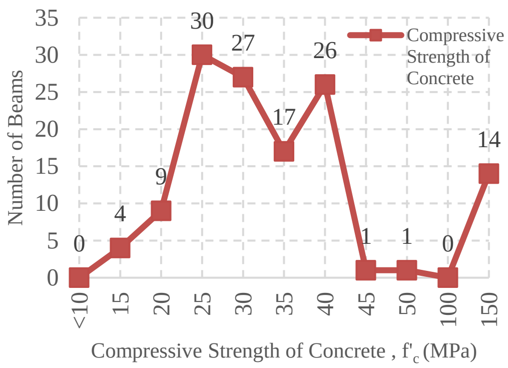

Fig.1 Illustration of Experimental Concrete Beam

Table 2 Experimental Beam Test Data

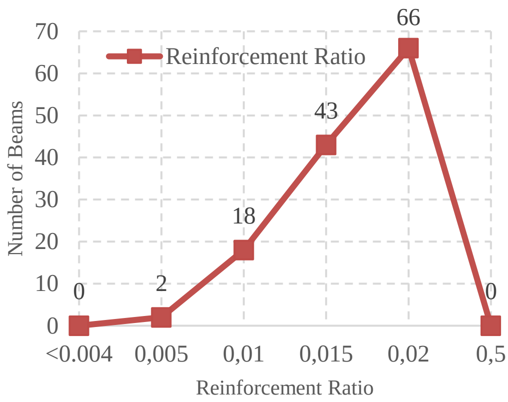
| References/Researchers | Number of Data |
|---|---|
| Moody, Viest, Elstner, dan Hognestad [10] | 17 |
| Diaz de Cossio, Gould, Measor, Johannes Moe, Smoot, Sozen dan Hawkins [11] | 2 |
| Leonhard dan Walther [11] | 13 |
| Mathey dan Watstein [12] | 6 |
| Krefeld dan Thurston [13] | 13 |
| Bhal [11] | 8 |
| Mattock [11] | 2 |
| Taylor [11] | 8 |
| Walraven [11] | 2 |
| Chana [11] | 9 |
| Elzanaty, Nilson dan Slate [14] | 2 |
| Papadakis [11] | 16 |
| Kotsovos dan Pavlovic [11] | 4 |
| Collins dan Kuchma [15] | 9 |
| Angelakos, Bentz, dan Collins [11] | 4 |
| Pourbaba, Joghataie, dan Mirmiran [9] | 14 |

Table 3 Parameter of Experimental Beam Test

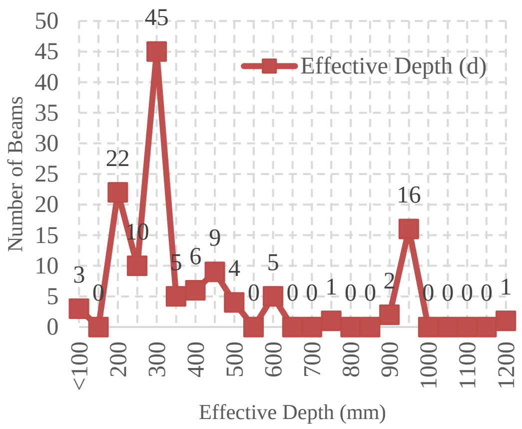
| ρ | $b_w$ (mm) | d (mm) | H (mm) | $f_c$ (MPa) | a/d |
|---|---|---|---|---|---|
| Moody, Viest, Elstner, and Hognestad [10] | | | | | |
| 0.016 to 0.0189 | 152 to 178 | 267 to 272 | 295 to 300 | 15.4 to 41.2 | 2.95 to 3.41 |
| Diaz de Cossio, Gould, Measor, Johannes Moe, Smoot, Sozen, and Hawkins [11] | | | | | |
| 0.0181 to 0.0185 | 501 to 502 | 252 to 253 | 280 | 34.1 to 34.5 | 2.67 |
| Leonhardt and Walther [11] | | | | | |
| 0.0133 to 0.0207 | 150 to 225 | 210 to 600 | 240 to 670 | 28.4 to 37.7 | 3 to 5 |
| Mathey and Watstein [12] | | | | | |
| 0.0047 to 0.0093 | 203 | 403 | 450 to 600 | 23.5 to 30.5 | 2.84 to 3.78 |
| Krefeld and Thurston [13] | | | | | |
| 0.008 to 0.0209 | 152 to 203 | 240 to 483 | 265 to 535 | 12.5 to 34.5 | 2.87 to 4.8 |
| Bhal [11] | | | | | |
| 0.0059 to 0.0129 | 240 | 297 to 1200 | 350 to 1250 | 22.8 to 29.1 | 2.94 to 3.03 |
| Mattock [11] | | | | | |
| 0.0103 to 0.0103 | 152 | 254 | 305 | 17.1 to 46.9 | 2.74 |
| Taylor [11] | | | | | |
| 0.0135 to 0.0135 | 100 to 400 | 232 to 930 | 250 to 1000 | 22.4 to 32.1 | 3.00 |
| Walraven [11] | | | | | |
| 0.0074 to 0.0079 | 200 | 420 to 720 | 450 to 750 | 27.4 to 27.8 | 3.00 |
| Chana [11] | | | | | |
| 0.0173 to 0.0184 | 100 to 203 | 170 to 356 | 200 to 406 | 25.9 to 39.5 | 3.00 |
| Elzanaty, Nilson and Slate [14] | | | | | |
| 0.006 to 0.012 | 178 | 280 | 305 | 20.7 | 4.00 |
| Papadakis [11] | | | | | |
| 0.008 to 0.018 | 140 to 200 | 175 to 350 | 200 to 400 | 10.5 to 29 | 3 to 4 |
| Kotsovos and Pavlovic [11] | | | | | |
| 0.0134 to 0.0162 | 150 to 225 | 280 to 600 | 315 to 670 | 36.1 to 40 | 3.00 |
| Collins and Kuchma [15] | | | | | |
| 0.005 to 0.0209 | 300 | 925 | 1000 | 21 to 39 | 2.00 |
| Angelakos, Bentz, and Collins [11] | | | | | |
| 0.0076 to 0.0101 | 300 | 925 | 1000 | 36 to 39 | 2.00 |
| Pourbaba and Joghataie [9] | | | | | |
| 0.022 to 0.078 | 102 to 152 | 76 to 203 | 559 | 125 to 137 | 0.9 to 2.8 |




(a)




(b)




(c)

Fig.2 Number of beams against various parameters

### 3.2 Review of Various Codes

1) SNI 2847:2019

SNI 2847:2019 states that the shear strength provided by concrete for non-prestressed structural members must be calculated by $0.17\lambda\sqrt{f'_c}b_wd$. More detailed calculations are given in Table 4.

Table 4 Shear Strength Equation per SNI 2847:2019

| $V_c$ | | |
|---|---|---|
| Least of a), b), and c) | $\left[0.16\lambda\sqrt{f'_c}+17\rho_w\frac{V_ud}{M_u}\right]b_wd$ | a) |
| | $\left[0.16\lambda\sqrt{f'_c}+17\rho_w\right]b_wd$ | b) |
| | $\left[0.29\lambda\sqrt{f'_c}\right]b_wd$ | c) |

Equation a) in Table 4 contains three variables, $\lambda$, $\sqrt{f'_c}$ as the tensile strength of concrete, $\rho_w$ dan $V_{ud}/M_u$, which affect the shear strength. Test results from Joint ACI-ASCE Committee 326 1962 indicate that the shear strength decreases as the component height increases [16].

2) ACI 318-19

$V_c$ is the contribution of the shear strength due to the concrete, which can be seen in the formula below:

$$V_c=\left[0.17\lambda\sqrt{f'_c}+\frac{N_u}{6A_g}\right]b_wd \quad (1a)$$

$$V_c=\left[0.66\lambda\left(\rho_w\right)^{1/3}\sqrt{f'_c}+\frac{N_u}{6A_g}\right]b_wd \quad (1b)$$

$$V_c=\left[0.66\lambda_s\lambda\left(\rho_w\right)^{1/3}\sqrt{f'_c}+\frac{N_u}{6A_g}\right]b_wd \quad (1c)$$

The use of Equations (1a), (1b), and (1c), based on the amount of shear reinforcement $A_v$ and flexural reinforcement $A_s$. Structural components with a value of $A_v$ more than $A_{v,min}$, $V_c$ can be calculated using Eq. (1a) or Eq. (1b). However, if $A_v$ is not more than $A_{v\ min}$, $V_c$ can be calculated using Eq. (1c) [17].

$N_u$ is the axial load on the beam; $A_g$ is the gross area of the beam; $\rho_w = A_s / b_wd$; and $\lambda_s$ is the size-effect factor. While $\lambda_s$ can be defined as:

$$\lambda_s=\sqrt{\frac{2}{1+\frac{d}{10}}}\leq 1 \quad (2)$$

3) CSA A23[1].3-04

Canadian Standard CSA A23[1].3-04 recommends a method for calculating shear strength based on the Modified Compression Field Theory (MCFT).

$V_c$ is the contribution of the shear strength of the concrete, and $V_s$ is the contribution due to the flexural reinforcement of the concrete beam. The determination of $V_c$ is explained in Article 11.3.4. $V_c$ can be expressed as Eq. (3).

$$V_c=\phi_c\lambda\beta\sqrt{f'_c}b_wd_v \quad (3)$$

The calculation of $\beta$ for a section without shear reinforcement based on the Simplified Method is as follows:

If the cross-section has no shear reinforcement, and the maximum aggregate dimensions are more than 20 mm, then $\beta$ is expressed as:

$$\beta=\frac{230}{(1000+d_v)} \quad (4)$$

If the section does not have shear reinforcement, the value of β can be determined for all dimensions of the aggregate by changing the $d_v$ parameter in Eq. (4) to the equivalent spacing parameter $s_{ze}$

$$s_{ze} = \frac{35 s_z}{15+a_g} \quad (5)$$

However, $s_{ze}$ should not be taken at less than $0.85s_z$. The crack spacing parameter $s_z$ must be taken as equal to $d_v$, or equal to the maximum value of the distance between layers of longitudinal reinforcement [18].

4) NZS 3101.1.2006

The nominal shear strength, $V_c$ at NZS 3101.1.2006 is expressed as Eq. (6).

$$V_c = v_c.A_{cv} \quad (6)$$

While $v_c$ is the shear force resisted by the concrete which can be expressed per Eq. (7).

$$v_c = k_d.k_a.v_b \quad (7)$$

Value of $v_b$ must be taken at least between $\left(0.07+10\rho_w\right)\sqrt{f'_c}$ and $0.2\sqrt{f'_c}$, but cannot be less than $0.08\sqrt{f'_c}$. The value of the $k_a$ factor, in Eq. (7), is a factor that is influenced by the maximum size of aggregate on shear strength. The maximum size of aggregate for concrete of more than or equal to 20 mm, the value of $k_a$ can be taken as 1.0. However, if the maximum size of the aggregate is less than 10 mm, then the value of $k_a$ is taken as 0.85.

The value of the $k_d$ factor is a factor that influences the effective height of the beam. If the beam has an effective height $d \leq 400$ mm, then the value of $k_d$ can be taken as 1.0. Meanwhile, if the effective height $d \geq 400$ mm, the value of $k_d$ can be taken as $(400/d)^{0.25}$.

Exceptions for the beam with an effective height of less than 200 mm, the value of $v_c$ must be the greatest of $0.17k_a\sqrt{f'_c}$ or the value obtained from Eq. (7). For beams with an effective height of $200 \leq d \leq 400$ mm, the value of $v_c$ can be interpolated from the two values of $v_c$ above [19].

5) EN 1992:2004

In EN 1992:2004, the shear strength in beams without transverse reinforcement considers the compressive strength of the concrete, the effective height of the beam, and the ratio of flexural reinforcement. The shear strength in EN 1992:2004 is stated in section 6.2.2, which is stated as:

$$V_{Rd,c} = [C_{Rd,c}.k.(100\rho_1 f_{ck})^{1/3} + k_1.\sigma_{cp}].b_w.d \quad (8)$$

In Eq. (8), $f_{ck}$ is the compressive strength of cylindrical concrete with units of MPa, d is the effective height of the beam in mm, $\rho_1$ is the ratio of flexural reinforcement, which has the formula $A_s/bd$, $b_w$ is the width of the beam in mm [20].

6) Proposed Equation

This proposed equation comes from the modification of the formulation of ACI 318-19. The ACI equation provides no overestimated results so that all beams developed using ACI are safe and can still be optimized and not underestimated. Moreover, all the equations of the five regulations, of course, have considered all aspects of suitability before being proposed. So, the author uses this cause and makes efforts to enhance the results of the prediction's accuracy. However, the ACI formulation can be optimized by modifying the f'$_c$ value. The proposed formulation is shown below:

$$V_c = \left[0.66\lambda\left(\rho_w\right)^{1/3} f'_c{}^{0.53} + \frac{N_u}{6A_g}\right] b_w d \quad (9)$$

$V_c$ is a function consisting of three factors, namely $f'_c{}^{0.53}$, $\rho_w$, and the area of the reinforced concrete beam $b_w d$. The compressive strength of concrete strongly influences the shear strength of reinforced concrete beams. If the compressive strength of concrete decreases, the shear strength also decreases.

## 4. RESULT AND DISCUSSION

The shear strength equation based on SNI is not conservative for a small value of longitudinal reinforcement ratio. For ρ that has a value of less than 0.01, the shear strength result is not conservative, with an average value of $V_{exp}/V_{SNI}$ 0.86. As for the value of ρ greater than 0.01, the result is quite conservative, with an average value of $V_{exp}/V_{SNI}$ 1.15. It can be seen in Figure A1, that a beam with a reinforcement ratio of 0.005 to 0.01 is a beam with an unsafe SNI prediction of shear strength.

Forty-nine beams (43%) are not safe if designed using SNI's equation, as shown in Figure A1. The size effect influences this. Beams with an effective height of 200 mm < d < 400 mm do not have a significant size effect. For d > 500 mm, it starts to show the size effect. This is also revealed in a study by Christianto et al. [21,22]. They concluded that a beam with a height of 3 times the width of the beam produces a shear strength of 70.95% smaller than a beam that has the same height and width [21,22]. The same study also concluded that the size effect impacts beams with larger dimensions [21,22].

Figure 3 shows that the results of the shear strength analysis using SNI are below the threshold line, which indicates that the beam is not conservative.

For beams with a reinforcement ratio of less than 1%, if designed using the equation of EN1992, it obtains unsafe results. As for the reinforcement ratio greater than 1%, the resulting shear strength tends to be conservative. It is shown in Figure A.4. In Figure A.16 for the effective height of the beam with d > 800 mm, the beam calculated using the equation of EN1992 is in a dangerous position. In contrast, the resulting shear strength is very conservative for a small effective height. This also occurs in the equation of SNI. There are 12 (10%) experimental beams that are not safe if designed using the shear equation from EN1992.

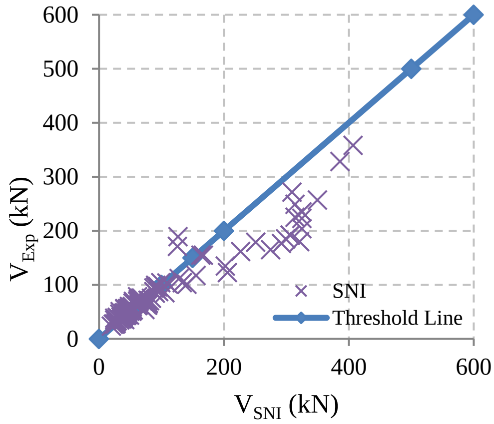



Fig.3 Experimental versus predicted shear strength (SNI)

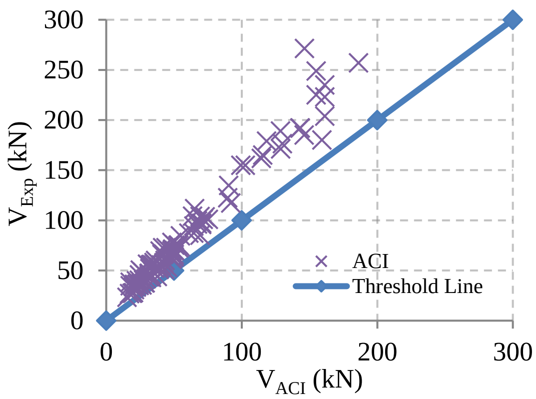



Fig.4 Experimental versus predicted shear strength (ACI)

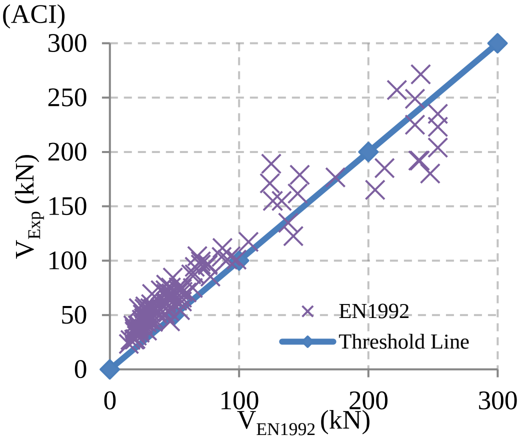



Fig.5 Experimental versus predicted shear strength (EN 1992)

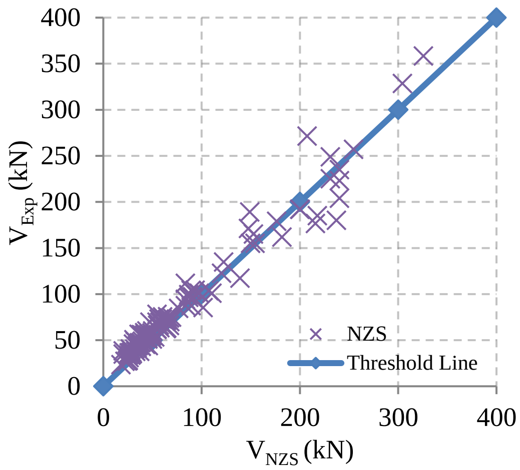



Fig.6 Experimental versus predicted shear strength (NZS)

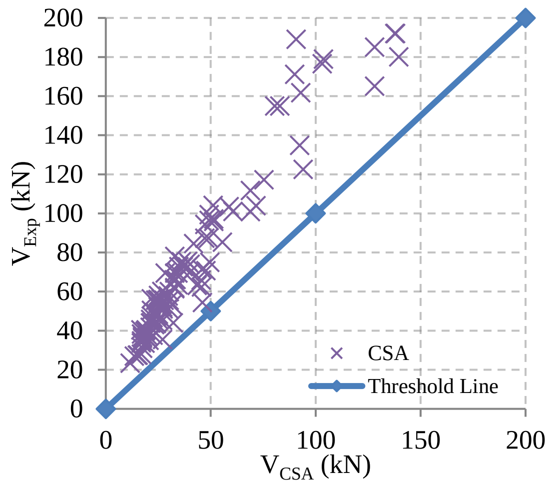



Fig.7 Experimental versus predicted shear strength (CSA)

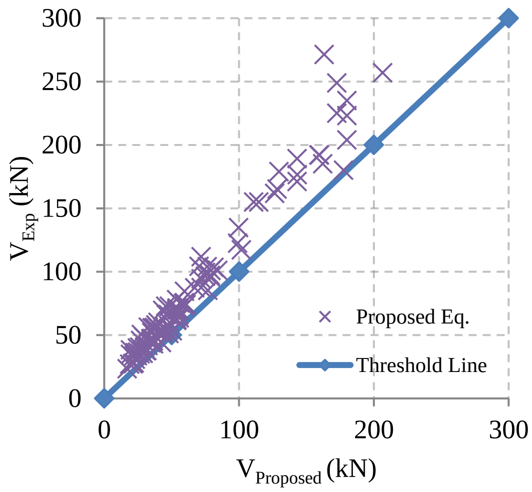



Fig.8 Experimental versus predicted shear strength (Proposed Eq.)

Table 5 Statistical Result of Code Predictions on Normal Strength Concrete Beams

| No. | Code | Statistical Result $V_{exp}/V_{code}$ | | |
|---|---|---|---|---|
| | | Avg | SD | CoV (%) |
| 1 | SNI [16] | 1.01 | 0.21 | 20.65 |
| 2 | ACI [17] | 1.48 | 0.18 | 12.31 |
| 3 | EN1992 [20] | 1.43 | 0.34 | 23.65 |
| 4 | CSA [18] | 1.87 | 0.28 | 15.17 |
| 5 | NZS [19] | 1.16 | 0.19 | 16.00 |
| 6 | Proposed Equation | 1.34 | 0.17 | 12.70 |

Table 6 Statistical Result of Code Predictions on High-Strength Concrete Beams

| No. | Code | Statistical Result $V_{exp}/V_{code}$ | | |
|---|---|---|---|---|
| | | Avg | SD | CoV (%) |
| 1 | SNI [16] | 5.66 | 1.59 | 28.15 |
| 2 | ACI [17] | 5.54 | 1.59 | 28.76 |
| 3 | EN1992 [20] | 5.15 | 1.36 | 26.31 |
| 4 | CSA [18] | 11.80 | 3.12 | 26.46 |
| 5 | NZS [19] | 7.92 | 1.96 | 24.78 |
| 6 | Proposed Equation | 4.35 | 1.25 | 28.76 |

Canadian Standard (CSA) is the most conservative method of all equations. CSA produces an average shear strength ratio of 1.87 and CoV of 15.17%. This shows that this equation is very conservative. For concrete beams with a compressive strength of more than 70 MPa, the average shear strength ratio is 11.80, the CoV is 26.46, and CSA gives conservative results even in high-strength concrete (Table 6).

For NSC beams. SNI, Eurocode, and NZS have resulted in excessive shear strength for beams 49, 12, and 19. SNI overestimates the results of shear strength by up to 18%. On the other hand, the overestimated results of Eurocode and NZS are, respectively, up to 14% and 9%.

Beams that are overestimated are beams with an effective height of more than 500 mm. Figures A.19 and Figure A.20 show the relationship between the shear strength ratio and the a/d ratio of the SNI equation and the proposed equation. For a/d > 2.5, the average ratios of SNI and the proposed equation are respectively 1.066 and 1.34. This comparison shows that SNI and the proposed equation work reasonably well at high a/d ratios. For beams with a/d ratios < 2.5, SNI and the proposed equation are 6.376 and 4.35, respectively. This shows that this equation gives a better result on a low a/d ratio (Table 5).

Three regulations provide unsafe results, namely SNI with the amount of 43% beams (49 beams), EN1992 10% (12 beams), and NZS 17% (19 beams). ACI and CSA give safe results. ACI is not too underestimated, but CSA tends to be conservative. (Avg. $V_{exp}/V_{code}$ respectively 1.48 and 1.87). Thus, from the five codes, there are three overestimated codes. Among the five codes that give the underestimated result is only CSA.

ACI gives the best results in estimating shear strength. However, after modifying the ACI formulation as stated in Chapter 3, the proposed equation provides better results. All beams designed using the proposed equation are safe with an average $V_{exp}/V_{proposed}$ is 1.34 (CV 12.70%)

## 5. CONCLUSION

Based on the discussion of the test results above, the following conclusions can be drawn:

1. The SNI regulations used in this study tend to be unsafe for the value of $\rho < 1\%$.
2. SNI overestimates 49 beams, of which 49 beams have an effective height of > 500 mm
3. For the value of $\rho < 1\%$, the Canadian Standard is the most conservative formula.
4. The regulations that give reasonably good results are the New Zealand Standard and EN 1992, with the average value of $V_{exp}/V_{code}$ for 1.16 and 1.43
5. For normal-strength concrete, CSA gives the most conservative results with an average ratio of 1.87
6. All formulations do not give optimal results on high-strength concrete beams, whereas Eurocode is the best method for designing high-strength concrete beams.
7. New Zealand Standard gives the best result among the five rules.
8. All methods give similar behavior to the effect of the effective height of the beam. The shear strength will decrease if the beam has an effective beam height d > 500 mm.
9. The proposed formulation $\left[0.66\lambda(\rho_w)^{1/3}f'_c{}^{0.53}+\frac{N_u}{6A_g}\right]b_w d$ obtained from the modification of ACI improves the prediction compared with others. This study focuses on normal and high-strength concrete, future research is needed to further develop the equations for UHPC.

## 6. ACKNOWLEDGMENTS

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