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Strut-and-tie model for shear capacity of corroded reinforced concrete columns

Cao Thanh Ngoc Tran*[1,2], Xuan Huy Nguyen[3a], Huy Cuong Nguyen[3b] and Ngoc Son Vu[4c]

[1]*Department of Civil Engineering, International University, Ho Chi Minh City, Vietnam*
[2]*Vietnam National University, Ho Chi Minh City, Vietnam*
[3]*Faculty of Construction Engineering, University of Transport and Communications, Vietnam*
[4]*Department of Structural Mechanics, National University of Civil Engineering, Vietnam*

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Abstract. An analytical model is developed in this paper to predict the shear capacity of reinforced concrete (RC) columns with corroded transverse reinforcements. The shear strength model for corroded RC columns is proposed based on modifying the existing strut-and-tie model, which considers the deformational compatibility between truss and arch mechanisms. The contributions to the shear strength from both truss and arch mechanisms are incorporated in the proposed model. The effects of corrosion level of transverse reinforcements are considered in the proposed model through the minimum residual cross-sectional area of transverse reinforcements and the reduction of concrete compressive strength for the cover area. The shear strengths calculated from the developed model are compared with the experimental results from Vu's study (2017), which consisted of RC columns with corroded transverse reinforcements showing shear failure under the cyclic loading. The comparison results indicate satisfactory correlations. Parametric studies are conducted based on the developed shear strength model to explore the effects of column axial loading, aspect ratios, transverse reinforcements and the corrosion levels in transverse reinforcements to the shear strength of RC columns with corroded transverse reinforcements.

Keywords: reinforced concrete; column; corrosion; shear strength; seismic

1. Introduction

Corrosion of both transverse and longitudinal reinforcements in reinforced concrete structures has been considered as one of the major causes of degradation in strengths of reinforced concrete structures under the corrosive environments. The direct effects of the corrosion in steel reinforcements include the reduction of the effective reinforcement area in resisting the applied stresses and the increase in the volume of corroded reinforcements leading to cracking and spalling of the concrete at the cover area (Ayinde *et al.* 2019). The decreases in the effective area of reinforcements and effective compressive strength of concrete at the cover area will result in the reduction of flexural and shear capacities of reinforced concrete members, which will affect the durability and safety of reinforced concrete structural members. These adverse effects are especially serious when the structures are in the earthquake prone areas. Cagatay (2005) had found out that the sea sand and chlorides in concrete mix are the causes of the severe corrosion in reinforcements of reinforced concrete structures during the 17th August 1999 Izmit earthquake. Severe bond losses between concrete and reinforcements were found by Cagatay (2005) during this earthquake. This could be one of the major causes in the loss in load-carrying capacities of the structural members during this earthquake. Amongst the structural members of the reinforced concrete buildings, columns play a crucial role to ensure the continuity of forces within the structures. Recent post-earthquake reports (Cagatay 2005, EERI 2017) had found out that the shear failure in the columns had resulted in a collapse of the whole buildings. Hence, it is obvious that more researches should focus on estimating the residual shear strengths of corroded reinforced concrete columns subjected to earthquake loadings.

Comparing the research studies on the effects of corrosion to the behavior of reinforced concrete beams (Malerba *et al.* 2017, Zhang *et al.* 2018, Zhao *et al.* 2018, Li *et al.* 2018, Hosseini *et al.* 2019), the studies conducted on the seismic behavior of corroded reinforced concrete columns are limited. These includes the research studies conducted by Ma *et al.* (2012), Meda *et al.* (2014), Goksu and Ilki (2016), Yang *et al.* (2016), Vu (2017). These studies can be categorized into two main categories, namely the effects of corrosion on the flexural and shear behaviors of reinforced concrete columns subjected to seismic loadings. The very first experimental study on the seismic behavior of corroded reinforced concrete columns was conducted by Ma *et al.* (2012). Fixed-pinned cantilever specimens with a

*Corresponding author, Associate Professor
E-mail: tctngoc@hcmiu.edu.vn
[a]Associate Professor
E-mail: nguyenxuanhuy@utc.edu.vn
[b]Ph.D. Candidate
E-mail: nguyenhuycuong@utc.edu.vn
[c]Lecturer
E-mail: sonvn@nuce.edu.vn

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high aspect ratio were tested to investigate the effects of corrosion in the longitudinal reinforcements on the flexural behavior of these specimens subjected cyclic loadings. Similar experimental research studies were conducted by Meda *et al.* (2014), Goksu and Ilki (2016), Yang *et al.* (2016) to explore the effects of various corrosion levels in the longitudinal reinforcements on the flexural behavior of reinforced concrete columns under seismic loadings. The only experimental study conducted on the effects of corrosion in both transverse and longitudinal reinforcements on the shear strength of reinforced concrete columns subjected to cyclic loadings was conducted by Vu (2017). In Vu (2017)'s experimental study, eight (8) corroded reinforced concrete columns with a short span subjected cyclic loading was tested to explore the effects of corrosion levels in transverse reinforcements and column axial loading on the shear strength of corroded reinforced concrete columns. Four levels of corrosion in transverse reinforcements and two levels of column axial loading were investigated. Based on the results of the experimental study, Vu (2017) concluded that the increase in corrosion levels had resulted in the severe degradation of the shear strength of reinforced concrete columns with a short span. Furthermore, the degradation in the shear strength of the specimens was more significant in the specimens with a higher column axial loading.

A limited number of models had been developed to estimate the shear strength of reinforced concrete columns with corroded transverse reinforcements. Up to date, the only model for the shear strengths of these columns was developed by Vu (2017). In this model, Vu (2017) had modified the existing shear strength equation proposed by ASCE/SEI 41 (2014) by including the effects of corrosion in transverse reinforcements in the proposed formula. The decreases in the effective area of reinforcements and effective compressive strength of concrete at the cover due to different levels of corrosion in the transverse reinforcements were considered in the modified shear strength model. The modified model was then compared with Vu's experimental data (2017) and produced satisfactory results.

Comparing between non-corroded and corroded columns, the developed shear strength model for the corroded reinforced concrete columns is limited. Moreover, there are no research studies to explore the applicability of strut-and-tie approaches in predicting the shear strength of corroded reinforced concrete columns subjected to cyclic loadings. These strut-and-tie approaches had been proved their capability in predicting accurately the shear strengths of reinforced concrete members, especially the reinforced concrete columns with short spans subjected to cyclic loadings. By applying these approaches, several well-known formulae had been developed to estimate the shear strength of reinforced concrete columns. Therefore, it is clear that more researches should focus on applying the strut-and-tie approaches in predicting the shear strength of corroded reinforced concrete columns.

This paper consists of two parts. The experimental observations of Vu's study (2017) are highlighted in the first part as a foundation to develop the proposed strut-and-tie model to predict the shear strength of corroded reinforced concrete columns. The strut-and-tie model with deformational compatibility developed by Pan and Li (2013) is modified in this part to capture the experimental observation of corroded reinforced concrete columns tested by Vu (2017). The model is then compared with the experimental results from Vu's study (2017). In the second part of the paper, a parametric study is conducted to further explore the effects of several important parameters on the shear strength of corroded reinforced concrete columns.

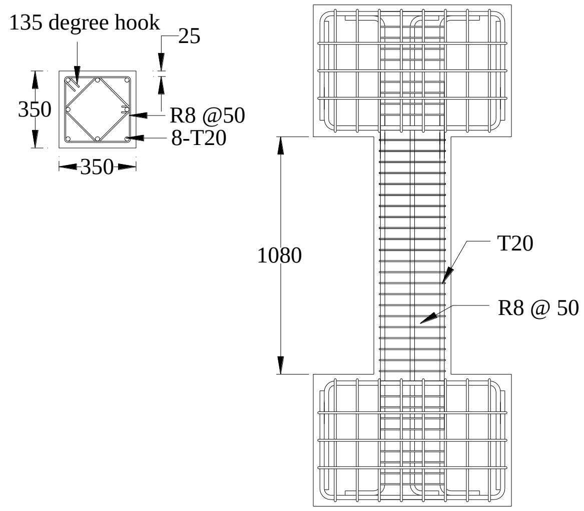


Fig. 1 Details of Vu's shear failure specimens (2017) (in mm)

2. Experimental observations and database for rc columns with corroded transverse reinforcements failed in shear

To accurately develop the model to capture the shear behavior of corroded reinforced concrete columns, experimental studies should be conducted in advance. The observations from the experimental studies are used as a foundation to develop shear strength model. Up to date, the only experimental study conducted on the shear behavior of corroded reinforced concrete columns was carried by Vu (2017). In this study (Vu 2017), reinforced concrete columns with various degrees of corrosion in transverse reinforcements were subjected to cyclic loadings to study the shear behavior. The double-curvature boundary condition was chosen by Vu (2017) to capture the realistic boundary condition for columns in reinforced concrete buildings. Details of these RC columns are shown in Table 1 and Fig. 1. The experimental results indicated a typical shear failure behavior as shown in Fig. 2. As illustrated in Table 1, f'_c is the compressive strength of concrete; P is the applied axial loading; A_g is the cross-sectional area; b is the width of column; a is the shear span; d is the effective depth of column; s is the spacing of transverse reinforcements; E_s is the elastic modulus of reinforcements; f_{yv} is the yield strength of transverse reinforcements; A_{sv} is the total transverse reinforcement area with spacing s; ζ is the softening coefficient and X_{corr} is the corrosion level of transverse reinforcements measured based on minimum

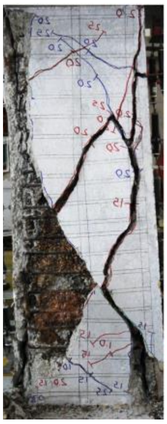


Fig. 2 Typical shear failure in Vu's specimens (2017)

residual cross-sectional area.

Two levels of column axial loadings and four degrees of corrosion in transverse reinforcements were investigated by Vu (2017). The measurement procedure for corrosion levels in Vu (2017)'s study followed ASTM G1-03 standard (2003). Three methods of estimating the levels of corrosion in reinforcements; namely mass loss, average residual cross-sectional area and minimum residual cross-sectional area were reported in Vu's study (2017). Vu (2017) had used these three corrosion level measurements in his proposed model in estimating the shear strength of corroded columns. Based on the validating study of the proposed model, it was concluded that the shear strength using the minimum residual cross-sectional area of transverse reinforcement showed a good correction with the test results. Vu (2017) recommended the use of minimum residual cross-sectional area of transverse reinforcements in estimating the shear strength of corroded columns.

Through the experimental study, Vu (2017) found out that the higher corrosion levels had resulted in the more severe degradation of the shear strength of reinforced concrete columns. In addition, the degradation in the shear strength was more significant in the specimens with a higher column axial loading. The reduction in shear strength of corroded columns is attributed to the decrease in the effective area of steel reinforcements and the compressive strength of concrete cover. Vu (2017) suggested the use of the minimum residual area of transverse reinforcements and the measured total crack widths to capture the reduction in shear strength contributions of transverse reinforcements and concrete cover. The proposed strut-and-tie model developed in the next part of the paper will capture these observations from Vu's study (2017) to accurately model the shear behavior of corroded reinforced concrete columns.

The reinforced concrete columns with corroded transverse reinforcements from Vu's study (2017) are used as a database to verify the shear strength model developed based on the strut-and-tie method. All the collected specimens had shown a shear failure behavior when subjected to cyclic loadings. Eight (8) reinforced concrete columns satisfied such requirements had been collected as shown in Table 1. Details of these 8 RC columns are shown in Table 1.

Table 1 Experimental database

Specimen	f'_c MPa	$\frac{P}{f'_c A_g}$	b mm	a mm	d mm	s mm	E_s GPa	f_{yv} MPa	A_{sv} mm^2	ζ	X_{corr} %
Vu (2017)											
UC1	32.2	0.10	350	540	307	50	210	300	163	1.00	0.0
CC1	28.8	0.10	350	540	307	50	210	300	163	0.85	40.2
CC2	32.0	0.10	350	540	307	50	210	300	163	0.84	58.4
CC3	27.8	0.10	350	540	307	50	210	300	163	0.75	60.3
UC2	38.1	0.25	350	540	307	50	210	300	163	1.00	0.0
CC4	34.4	0.25	350	540	307	50	210	300	163	0.87	30.1
CC5	31.3	0.25	350	540	307	50	210	300	163	0.84	44.2
CC6	40.0	0.25	350	540	307	50	210	300	163	0.80	51.2

3. Proposed model

One of the preferable models for the shear strength of reinforced concrete members to the structural engineers is the strut-and-tie model due to its simplicity. Complex knowledge of material behaviors, which might be unfamiliar to the engineers, is not required by this method. Over the years, researchers had tried to propose different strut-and-tie models for the shear strength of reinforced concrete columns, which both are able to capture the real behavior and maintain their simplicity for easy usage. The classic concept of truss and arch mechanisms as shown in Fig. 3 had been successfully applied by Watanabe and Ichinose (1991), Priestley *et al.* (1994) to propose the well-known formulae for shear strength of reinforced concrete columns. To keep the simplicity of proposed models, Watanabe and Ichinose (1991), Priestley *et al.* (1994) had used the superimposition concept of truss and arch mechanisms, which ignored several important realistic behaviors, such as the deformational compatibility between the two mechanisms. Pan and Li (2013) had further developed this method by incorporating the displacement compatibility between truss and arch actions. Their developed model still maintains its simplicity. In this part of the paper, this displacement compatibility model (Pan and Li 2013) is modified to include the effects of corrosion in transverse reinforcement to predict the shear strength of reinforced concrete columns with corroded transverse reinforcements.

3.1 Arch mechanism

Pan and Li (2013) had derived the shear stiffness of the arch mechanism as follows

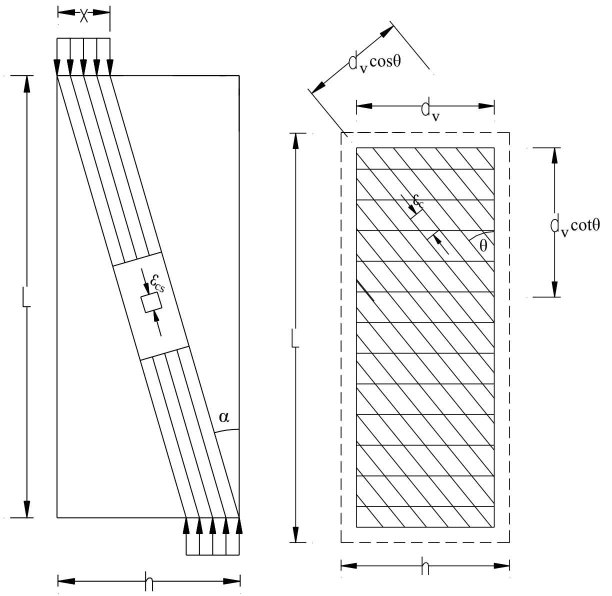
$$K_{strut} = E_c b c_a \sin^2 \alpha \cos^2 \alpha \quad (1)$$

where E_s is the elastic modulus of concrete and c_a is the effective depth of the strut in the arch mechanism.

As shown in Fig. 3(a), the inclination angle of this strut (α) could be determined as

$$\alpha = arctan\left(\frac{h-x}{L}\right) \quad (2)$$

where the depth, width and height of columns are h, b and L, respectively. As guided by Paulay and Priestley (1992), the depths of the compression zones in column, x can be



(a) Arch mechanism (b) Truss mechanism

Fig. 3 Truss and arch mechanisms

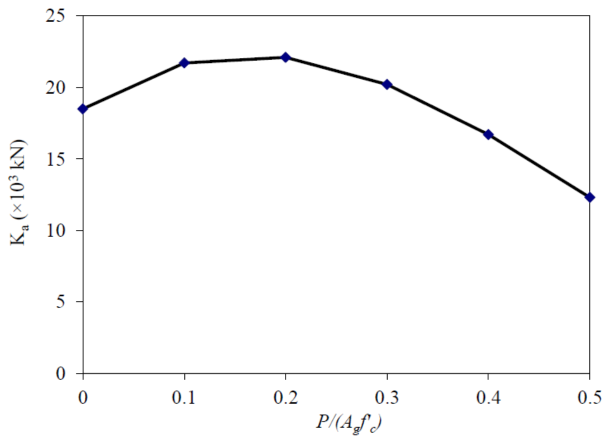


Fig. 4 Effects of column axial loading on the shear stiffness of arch mechanism

estimated as

$$x = \left(0.25 + 0.85 \frac{P}{A_g f_c'}\right) h \tag{3}$$

The concrete cover could spall of at the maximum shear force, therefore c_a is calculated as x-c. Where c is the concrete cover of columns.

It is well-known that the column axial loading significantly affects the shear strength of reinforced concrete columns. A higher shear strength of reinforced concrete columns is expected with a higher column applied axial loading (ACI 318-14 2014, Sezen and Moehle 2004). Pan and Li (2013) had relied on Paulay and Priestley's suggestion (1992) regarding to the depths of the compression zones in column to capture the effects of column axial loading. A parametric study based on Pan and Li's method (2013) regarding to the effects of column axial loading is conducted. Vu's Specimen CC 1 (2017) is used as the sample specimen. As shown in Fig. 4, the change in the column axial loading affects the shear stiffness of the arch mechanisms. A higher column axial loading does not always produce a higher shear stiffness in the arch mechanisms. This is attributed to the facts that a higher column axial load will produce a higher depth of the strut; however, a lower inclination angle. An increase in the column axial loading ratio from 0.2 to 0.3 leads to a decrease in the shear stiffness in the arch mechanism. Therefore, depending on only the depths of the compression zones in column to capture the effects of column axial loading will lead to incorrect results. Hence; in this proposed model, the effects of column axial loading reflect not only on the depths of the compression zones in column but also on the concrete contribution to shear strength of the truss mechanism. This will be discussed in more detail in the next part of this paper.

In Li and Pan's model (2013), the shear strength of reinforced concrete columns is depended on the shear capacity of truss mechanism. The arch mechanism is contributed to the shear strength through the deformational compatibility equation. The contribution from the arch mechanism does not have an upper-limit value. This may not be the true behavior of the column subjected to cyclic loadings. The failure could be happened due to the high axial stress in the strut or the reduction in the compressive strength of the strut due to excessive shear cracks at the maximum shear force. This is the shortcoming of Li and Pan's model (2013). To amend this shortcoming, an upper-limit value of the arch mechanisms is proposed as follows

$$V_{strut} = (f_{strut} \times A_{strut}) \times \sin\alpha \tag{4}$$

where f_{strut} is the effective compressive strength of concrete in the strut defined as $0.6(1-f'_c/250)f'_c$ based on EC2 (2004).

The cracking and spalling of the concrete at the cover area due to the increase in the volume of corroded reinforcements are considered by Vu (2017). Following Vu's suggestion (2017), the effective area of the diagonal strut (A_{strut}) is calculated as

$$A_{strut} = (c_a \times \cos\alpha) \times b_{eff} \tag{5}$$

Considering the spalling of concrete cover due the effects of the corrosion, the effective width of diagonal strut is defined as

$$b_{eff} = b - 2c + 2c \times \zeta \tag{6}$$

where ζ is the softening coefficient. As suggested by Hsu and Mo (2010), this coefficient is calculated as

$$\zeta = \frac{0.9}{\sqrt{1+600\varepsilon_r}} \tag{7}$$

The tensile strain induced by the cracks in concrete cover due to the corrosion in the transverse reinforcements (ε_r) is defined as W_{cr}/p_0. Where p_0 is the perimeter of the specimen and W_{cr} is the total crack width of the specimen which can be easily estimated.

3.2 Truss mechanism

Pan and Li (2013) had derived the shear stiffness of the

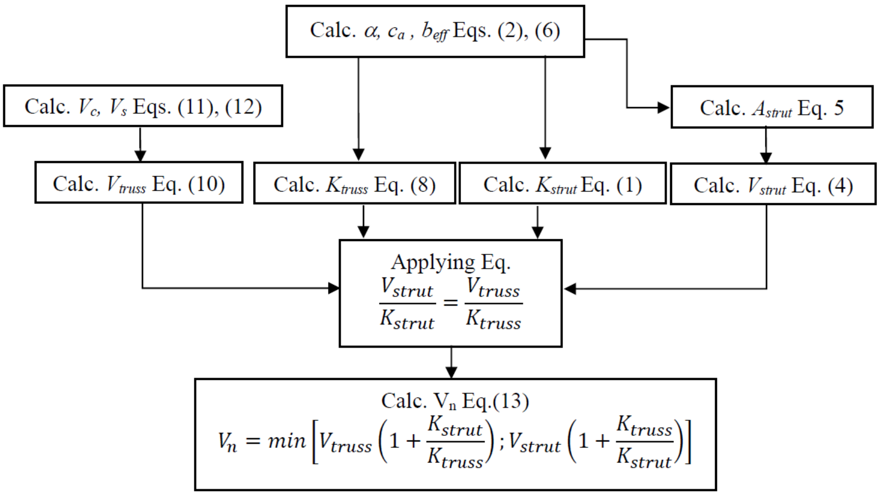


Fig. 5 Flow chart for shear strengths of corroded reinforced concrete columns

truss mechanism as follows

$$K_{truss} = \frac{n\rho_{sv}E_c b d_v \cot^2\theta}{1+n\rho_{sv}\csc^4\theta} \tag{8}$$

As shown in Fig. 3(b), the inclination angle of the strut in the truss mechanism (θ) for the specimens is assumed as 45° degree as suggested by ACI 318.11 (2014).

Where ρ_{sv} are the volumetric ratio of transverse reinforcements to concrete, n is the ratio of E_s/E_c, d_v is the flexural lever arm taken as $0.9d$. Taking into consideration the effects of the corrosion in reducing effective area of steel reinforcements, the volumetric ratio of transverse reinforcement to concrete (ρ_{sv}) is calculated as

$$\rho_{sv} = \frac{A_{vc}}{bs} \tag{9}$$

where the effective area of transverse reinforcements after corrosion, A_{vc} is defined as $(1\text{-}X_{corr})A_{sv}$. As suggested by Vu (2017), the minimum residual area of transverse reinforcements is used as the corrosion level of transverse reinforcements (X_{corr}).

The contribution of the truss mechanism to the shear strength of the columns is from the concrete and transverse reinforcement.

$$V_{truss} = V_c + V_s \tag{10}$$

where V_c and V_s are the shear strengths contributed from concrete and transverse reinforcements, respectively.

In Pan and Li's model (2013), the concrete shear strength as suggested by Bentz *et al.* (2006) is adopted. In this model, the concrete shear strength is related to the longitudinal strain at the mid-depth of the column section. The beneficial effect of column axial loading on the shear strength in Pan and Li's model (2013) was reflected through this longitudinal strain. A higher column axial loading will result in a lower longitudinal strain, leading to a higher concrete shear strength or higher shear strength of the column. However, this longitudinal strain is not available. The value of this strain depends on the calculated shear strength of the specimens. To simplify this problem, the concrete shear strength proposed by ACI 318.11 (2014) is adopted in this proposed model, where the concrete shear strength is as follows

$$V_c = 0.166\sqrt{f_c'}\left(1+\frac{P}{13.8A_g}\right)0.8\left(A_{core}+\sqrt{\zeta}A_{cov\,er}\right) \tag{11}$$

where A_{core} and A_{cover} are the core and cover concrete areas, respectively.

The effects of corrosion in transverse reinforcement are considered in the concrete shear strength through the softening coefficient ζ.

The transverse reinforcement shear strength can be expressed as

$$V_s = \frac{A_{vc} f_{yv}^c d \cot\theta}{s} \tag{12}$$

where the residual yield strength of transverse reinforcements after the corrosion, f_{yv}^c is defined as $(1-\alpha_s X_{corr})f_{yv}$. The yield strength reduction factor, α_s is taken as 0.005 as suggested by Du *et al.* (2005).

3.3 Displacement compatibility

By applying the concept of displacement compatibility as suggested by Pan and Li (2013) and limiting the shear strength of both truss and arch mechanisms. The shear strength of corroded reinforced concrete columns is given as

$$V_n = min\left[V_{truss}\left(1+\frac{K_{strut}}{K_{truss}}\right); V_{strut}\left(1+\frac{K_{truss}}{K_{strut}}\right)\right] \tag{13}$$

The flow chart for the shear strength of corroded reinforced concrete columns is given as Fig. 5.

4. Verification of the proposed model

Eight (8) reinforced concrete columns with corroded transverse reinforcements as shown in Table 1 are used to verify previous developed shear strength model. As shown in Table 2 and Figs. 6 and 7; the average ratio of the experimental shear strengths to the proposed ones of corroded reinforced concrete columns and its standard deviations are 1.00 and 0.12, respectively. The proposed

Table 2 Experimental verification

Specimen	a/d	$\frac{P}{f'_c A_g}$	ρ_{sv} %	X_{corr} %	V_{exp} (kN)	V_{Vu} (kN)	$V_{proposed}$ (kN)	V_{Vu}/V_{Exp}	$V_{Proposed}/V_{Exp}$
					Vu (2017)				
UC1	1.76	0.10	0.93	0.0	411.2	484.6	488.9	1.18	1.19
CC1	1.76	0.10	0.93	40.2	358.9	316.7	326.4	0.88	0.91
CC2	1.76	0.10	0.93	58.4	327.8	284.6	287.8	0.87	0.88
CC3	1.76	0.10	0.93	60.3	293.8	263	251.5	0.9	0.86
UC2	1.76	0.25	0.93	0.0	513.2	601.8	575.3	1.17	1.12
CC4	1.76	0.25	0.93	30.1	426.6	449.2	427.7	1.05	1.00
CC5	1.76	0.25	0.93	44.2	368.8	368.0	368.9	1.00	1.00
CC6	1.76	0.25	0.93	51.2	397.5	421.7	413.2	1.06	1.04
							Average	1.01	1.00
							SV	0.12	0.12

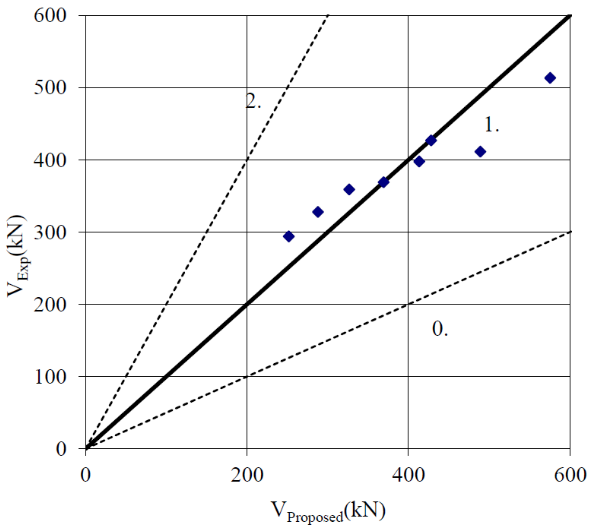


Fig. 6 Correlation of experimental and predicted shear strength based on the proposed model

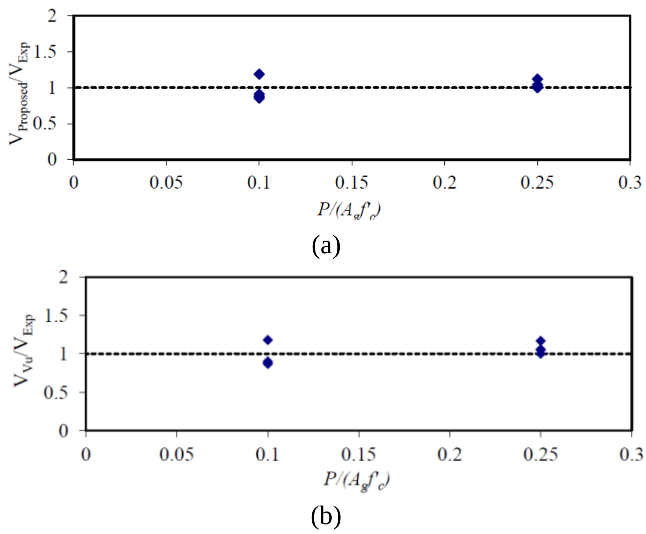


Fig. 7 Variation of experimental to proposed shear strength ratio as a function of column axial ratio

strut-and-tie model for the corroded reinforced concrete columns has showed good correlations with the experimental results.

The proposed model is also compared with Vu's shear strength model (2017) modified from ASCE/SEI 41-23 guidelines (2014). The recommended shear strength model as proposed by Vu (2017) is as follows

$$V_n = \frac{0.5\sqrt{f'_c}}{\frac{M}{Vd}}\left(1+\frac{P}{0.5\sqrt{f'_c}\left(A_{core}+\sqrt{\zeta}A_{cov\,er}\right)}\right) 0.8\left(A_{core}+\sqrt{\zeta}A_{cov\,er}\right)+\frac{A_{vc}f^C_{yv}d}{s} \quad (14)$$

The average ratio of the experimental shear strengths to the ones proposed by Vu (2017) of corroded reinforced concrete columns and its standard deviations are 1.01 and 0.12, respectively. The comparison indicates that both Vu's modified model (2017) and the proposed one produce reliable shear strengths of reinforced concrete columns with corroded transverse reinforcements. Slightly better statistical correlations (mean and standard deviation) are obtained by the proposed strut-and-tie model than Vu's modified model (2017). Both Vu's modified model (2017) and the proposed strut-and-tie model in this paper could be used as reliable tools to find out the shear strength of corroded reinforced concrete columns. As shown in Table 2 and Fig. 7, it is to be noted that both Vu's (2017) and proposed models underestimate and overestimate the shear strengths of corroded reinforced concrete columns with the axial loading levels of 0.1 and 0.25, respectively. Further experimental studies regarding to the effects of column axial loadings on the shear strengths of corroded reinforced concrete columns should be conducted to examine the trend of these shear strength models.

5. Parametric studies

As indicated in the previous research regarding to the shear behavior of reinforced concrete columns; column axial loading, transverse reinforcement ratios and aspect ratios strongly affect the shear strength of columns. For corroded reinforced concrete columns, besides these factors, the corrosion levels in the transverse reinforcements also significantly affects the shear strength of columns. To further explore the effects of these factors to the shear

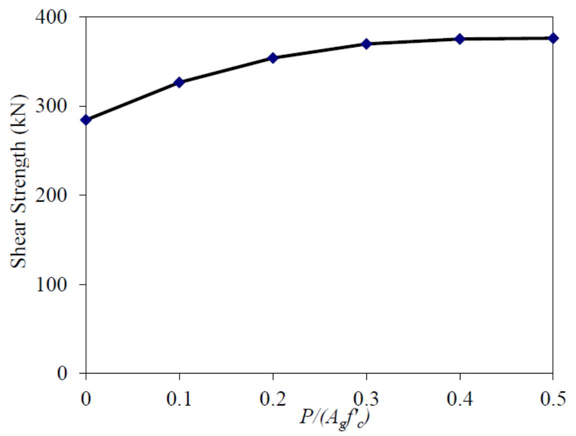


Fig. 8 Effects of column axial loading

strength of corroded reinforced concrete columns, specifically column axial loading ($P/f_c'A_g$), transverse reinforcement ratios (ρ_{sv}), aspect ratios (*a/d*) and corrosion level in transverse reinforcements (X_{corr}); parametric studies are conducted in this part of the paper. Specimen CC1 in Vu's study (2017) is chosen as the reference specimen in the parametric studies.

5.1 The effects of column axial loading ($P/f_c'A_g$)

The analyses as shown in Fig. 8 was conducted to assess the effects of column axial loading on the shear strength of corroded reinforced concrete columns. The reference specimen has a corrosion level of 40.2%. Six levels of column axial loading ($P/f_c'A_g$) of 0, 0.1, 0.2, 0.3, 0.4 and 0.5 were investigated to study the effects of column axial loading to the shear strength of Specimen CC1. Fig. 8 shows that with an increase in the ratio of column axial loading from 0 to 0.1, 0.2, 0.3, 0.4 and 0.5; shear strength of corroded columns increased by approximately 14.8%, 24.5%, 30.0%, 31.9% and 32.0%; respectively. As shown in Fig. 8, the column axial loading significantly affects the shear strength of the corroded column up to the ratio of 0.3. The increases in the column axial loading ratio from 0.3 to 0.4 and 0.5 slightly enhance the shear strengths of the column.

5.2 The effects of corrosion in transverse reinforcements (X_{corr})

The effects of corrosion levels in transverse reinforcements on shear strengths of corroded reinforced concrete columns are presented in Fig. 9. Seven corrosion levels in transverse reinforcements ranging from 0 to 60% were considered. As shown in Fig. 9, the shear strengths of corroded beams were observed to reduce linearly with an increase in the level of corrosion in transverse reinforcements. An increase in the level of corrosion from 0 to 10%, 20%, 30%, 40%, 50% and 60% had resulted in a decrease in the shear strength of corroded columns of 6.4%, 14.2%, 21.8%, 28.5%, 34.7% and 42.6% respectively. This showed the significant influences of the level of corrosion on the shear strength of corroded columns. The

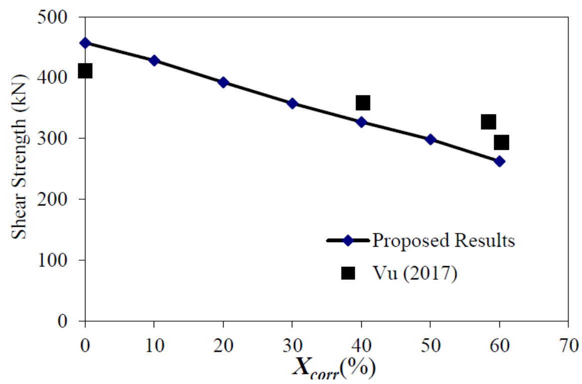


Fig. 9 Effects of corrosion in transverse reinforcements

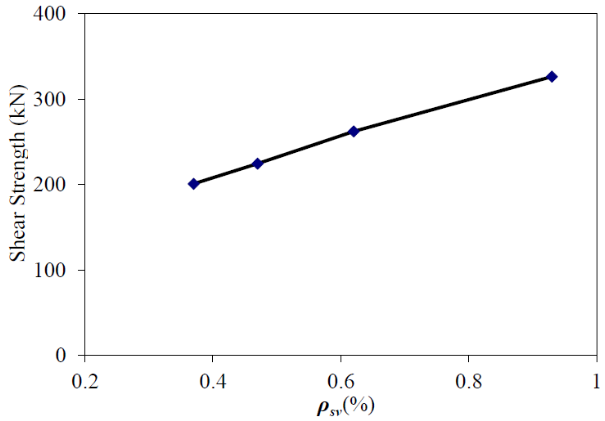


Fig. 10 Effects of transverse reinforcement ratios

experimental results from Vu's study (2017) are shown in Fig. 9, the overall trend of the experimental results showed that the shear strength of corroded columns reduced by increasing the level of corrosion in transverse reinforcements. It is to be noted that, the proposed model had overestimated the effect of corrosion to the shear strength of corroded specimens. A lower shear strength was produced by the proposed model as comparing with the experimental result's one at the same level of corrosion.

5.3 The effects of transverse reinforcement ratios (ρ_{sv})

Four levels of transverse reinforcement ratios (ρ_{sv}) of 0.93%, 0.62%, 0.47%, and 0.37%, which corresponds to the transverse reinforcement of ϕ8 at 50mm, 75mm, 100mm and 125mm; respectively were investigated. With a decrease in the transverse reinforcement ratios, the shear strengths of corroded reinforced concrete columns reduce as expected. Fig. 10 shows that with a decrease in the transverse reinforcement ratios from 0.93% to 0.62%, 0.47%, and 0.37%; shear strength of corroded reinforced concrete columns reduced by 19.7%, 31.3% and 38.5%, respectively.

5.4 The effects of aspect ratios (a/d)

Four levels of aspect ratios *a/d* of 1.75, 2.0, 2.25, and 2.5 were investigated. With an increase in the aspect ratios, the shear strengths of corroded reinforced concrete columns

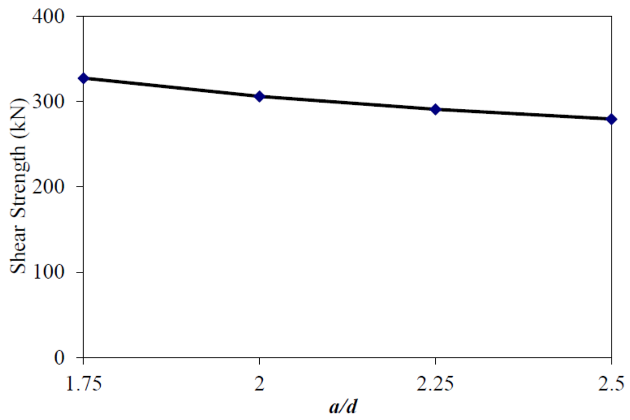


Fig. 11 Effects of aspect ratios

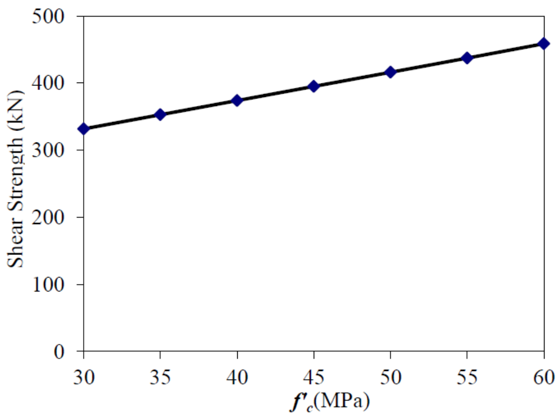


Fig. 12 Effects of concrete compressive strength

reduce as expected. Fig. 11 shows that with a decrease in aspect ratio from 2.5 to 2.25, 2.0 and 1.75; shear strength of corroded reinforced concrete columns increased by 4.0%, 9.5% and 17.2%, respectively.

5.5 The effects of concrete compressive strength (f_c')

Seven levels of concrete compressive strengths (f_c') ranging from 30 MPa to 60 MPa were investigated. With an increase in the concrete compressive strength, the shear strengths of corroded reinforced concrete columns increase linearly as shown in Fig. 12.

6. Limitations of the proposed model

Based on the findings of the current study, the applicability of the proposed model in predicting the shear strength of reinforced concrete columns with corroded transverse reinforcements can be improved in two aspects. Firstly, the proposed model was verified with the limited data; further extension of the available database of reinforced concrete columns with corroded transverse reinforcements failed in shear is necessary to confirm the accuracy of the proposed model. Secondly, the upper limit value of the arch mechanisms is based on EC2's recommendation (2004), which is only related to compressive strength of concrete. This simplification may not be true, the upper limit value of the arch mechanisms is complicated; this value depends on various variables such as column axial loadings, transverse reinforcement ratios and corrosion levels.

7. Conclusions

The paper has presented an analytical model based on the strut-and-tie method to estimate the shear strength of corroded reinforced concrete columns. Specific conclusions can be drawn as follows:

The displacement compatibility model proposed by Pan and Li (2013) is modified to include the effects of corrosion in transverse reinforcements. The developed model is compared with the experimental results conducted by Vu (2017). The average ratio of the experimental to predicted shear strength of corroded reinforced concrete columns by the analytical model is 1.00. This showed a reliable correlation between the analytical model and the experimental results. The improved performance of the proposed model is identified by comparison with Vu's model (2017). The comparison indicates that the developed model in this paper produces slightly better statistical correlations than Vu's model (2017). Both Vu's and the proposed model could provide suitable tools to calculate the shear strength of corroded reinforced concrete columns.

The effects of column axial loading ($P/f_c'A_g$), transverse reinforcement ratios (ρ_{sv}), aspect ratios (*a/d*) and corrosion level in transverse reinforcements (X_{corr}) on the shear strength of corroded reinforced concrete columns had been investigated in the parametric studies. The increases in the column axial loading, and transverse reinforcement ratios enhance the shear strengths of corroded reinforced concrete columns; whereas the rises in corrosion levels in transverse reinforcements and aspect ratios reduce the shear strengths of corroded reinforced concrete columns.

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