

Behavior of RC Columns with Different Internal Ties Configurations Subjected to Axial Load: Numerical Study

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Abstract: Reinforced concrete columns use a lot of ties, particularly inner cross-ties in large columns. The major goal of this work is to create new approaches for horizontal reinforcement in RC columns and evaluate their effect on column behaviour. The suggested V-ties as transverse reinforcement, which would replace the cross-ties features, are cost-effective. They make it possible to complete projects faster and spend less on labour and material. Numerical study is carried out. FE models for sixty (60) specimens were developed. Each specimen is modeled with different cross-sections (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm) at different values of spacing 50 mm, 100 mm, and 200 mm. It was discovered that adopting V-tie techniques instead of traditional ties might increase column axial load capacity, reduce early local buckling of longitudinal reinforcing bars, and enhance the concrete core confined to RC columns.

Keywords: RC columns; Transverse reinforcing; Confined effect; Finite element analysis; Concrete damage plasticity model; Reinforcing buckling.

1. Introduction

Reinforced concrete columns are regarded as one of the most essential structural components in various construction systems. They should thus be investigated in order to improve their behaviour and performance. One of the most critical challenges in the construction of RC columns, particularly those with enormous dimensions, is the organisation of transverse reinforcement, which requires a considerable number of connections, particularly the inner ties. There are instances where the tight spaces of the cross-ties cause the pillars to nest. The type of reinforcement used for ties, its quantity, and the maximum distance between transverse reinforcement are all specified by standard codes, such as the American Concrete Institute's ACI 318-18 [1]. To keep longitudinal reinforcing bars from buckling, middle bars are treated the same way as corner bars.

Six rectangular solid section columns were tested by Kim et al. [2] under cyclic lateral loads and constant axial stresses at the same time. It was determined that for simpler, more dependable, and quicker construction, the suggested triangle reinforcement details might be a great substitute for traditional reinforcement details. In order to make sure that there would be no longitudinal reinforcing buckling failure, the triangular confining reinforcement was also assessed.

In order to determine how well the V-ties contain the concrete core, Yang and Kim [3] tested fourteen reinforcing columns until they failed under a concentric axial stress. It was determined that the V-ties columns had a higher ductility ratio than the cross-ties columns because the descending branch of the axial load-strain curve of the columns declined more quickly in the former than the latter. Even for high-strength concrete columns, no V-ties were removed from the concrete core during testing; instead, 90-degree hooks on cross-ties gradually opened until the columns' ultimate strength was reached. As a result, the longitudinal reinforcement buckling length for V-ties columns was less than that of cross-ties columns.

Five RC columns were evaluated under both eccentric and concentric compression stresses by Hwange et al. [4]. The transverse reinforcement shapes (i.e., traditional cross-ties or U-tie bars) and the U-tie bar anchorage method (i.e., straight bars or 90° hooked bars) were the test criteria. They also evaluated the cyclic load on ten columns made of reinforced concrete. Neutral axis depth of the column section (i.e., symmetric or asymmetric arrangement of longitudinal reinforcing bars), shape (i.e., traditional cross-ties or U-tie bars), anchorage technique for U-tie bars replacing cross-ties (i.e., straight bars, 90° hooked bars, or headed bars), and cyclic loading conditions were the test parameters. During the compression test, the columns with U-tie bars for cross-ties showed similar post-peak behaviour and load-carrying capacity as the column with traditional hoops and cross-

ties. According to this result, U-ties can serve as a suitable substitute for cross-ties in terms of lateral confinement. The application of U-tie bars did not significantly influence the specimen's structural capability, according to the results of the cyclic lateral load test. This result suggested that U-tie bars may take the role of cross-ties once the shear need was achieved.

Elbakry et al. [5] performed an experimental and numerical study to quantify performance measures and examine the developed transverse reinforcement details. The newly developed reinforcement was a stable. It was concluded that all specimens with the proposed V-ties reinforcement details showed almost the same behavior and stiffness compared with cross-ties.

Ketut Sudarsana and Gede Gegiranang Wiryadi [6] used the plastic damage plasticity (CDP) model in Abaqus to do a numerical study of how confinement affects the axial capacity and ductility of thin section columns. It was concluded that the finite element analysis can predict well the behaviors of the tested column specimen in terms of stress on concrete, reinforcement, and the crack pattern. Beyond the effectiveness of confinement, the right hoops configurations to achieve effective confining effects on the concrete core are just as important as larger values of the volumetric ratio of the hoops.

By using bracing reinforcement to connect the longitudinal steel rebars on one side of the square column cross-section with the opposite side in the lower tie, Murtada A. Ismael et al. [7] performed a new method that has been proposed to enhance the structural performance of RC columns. These bracings not only brace the longitudinal reinforcement but also help the ties form reinforcement like a spiral in circular section columns. The number of bracings within the column height, the pattern of bracing reinforcement, and the use of bracing reinforcement under eccentric stress were the three characteristics that were examined. In comparison to columns without bracing reinforcement, it was determined that the suggested technique of using bracing reinforcement is an effective technique for improving the structural performance of RC columns by increasing yield and ultimate loads, as well as increasing stiffness by reducing displacement in all stages of loading and increasing ductility.

Most of the previous studies on the behavior of reinforced concrete columns used deformed high-tensile reinforcement as transverse reinforcement and replaced the cross-ties with different shapes of transverse reinforcement. The commonly considered parameters in the previous studies focused on the effect of anchorage method of different tie bars. For example, cross-ties were replaced with tie bars (straight bars, 90° hooked bars, or headed bars). In this study, some other parameters, which have not been studied by other researchers, are investigated. These parameters include using smooth, mild steel bars as transverse reinforcement for V-ties and the effect of the aspect ratio of cross-section.

This paper's contents are as follows: title page, abstract, introduction, research significance, recommendation for a v-tie setting, numerical programme, numerical analysis, results and discussion, and references sections.

This paper investigates the use of V-ties as an alternative to cross-ties for longitudinal reinforcing bars in order to minimise the amount of transverse reinforcement and allow speedy installation. Additionally, V-ties don't require specialised labour, which helps to save money and time. A numerical investigation is conducted for this reason.

2. Recommendation for a V-tie Setting

Figure 1 by Yang and Kim [3] details the suggested V-tie set, which consists of a V-tie bar and a connector to attach the V-tie to a single longitudinal reinforcing bar. The V-ties are prevented from rotating or losing their effect during casting by using the setting-up technique shown in Figure 1.

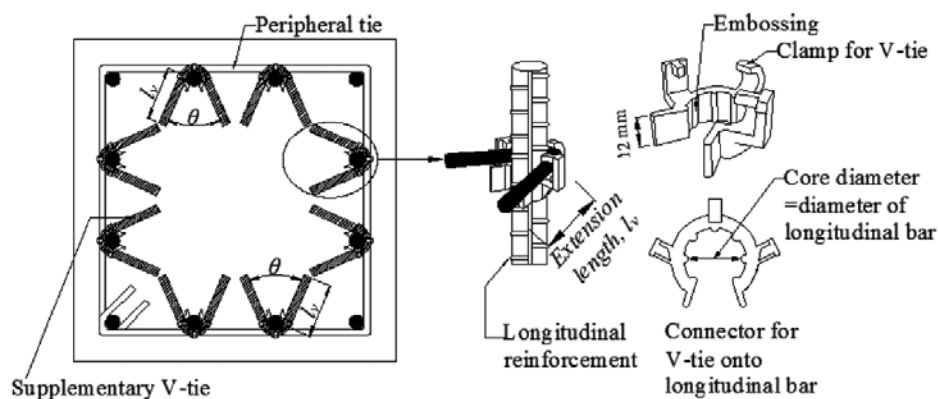


Figure 1. Details of the suggested V-tie arrangement [3].

3. Numerical Program

In the present study, FE models for sixty (60) specimens were developed. Each specimen is modeled with different cross-sections (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm) at different values of spacing 50 mm, 100 mm, and 200 mm. The concrete grade for all specimens is 35 MPa. The longitudinal reinforcing ratio for all specimens is 1.69%. Figures 2 – 6 show the arrangement of transverse reinforcement for all specimens.

The specimen's notation is COC, COV-7, COV-10.5, and COV-14. Specimen notation includes four parts. The first letter refers to reinforced concrete columns C. The Second letter gives outer ties. The third is used to identify type of internal transverse reinforcement: C for cross-tie and V for V-ties. The fourth is used to identify extension length of V-tie legs. For example, Specimen COV-7 indicates column having a traditional ties as outer transverse reinforcement and V-ties with extension length of V-tie legs $7 \phi_s$ (56 mm) as internal transverse reinforcement for middle bars only. Where ϕ_s is the diameter of the transverse reinforcement (8 mm).

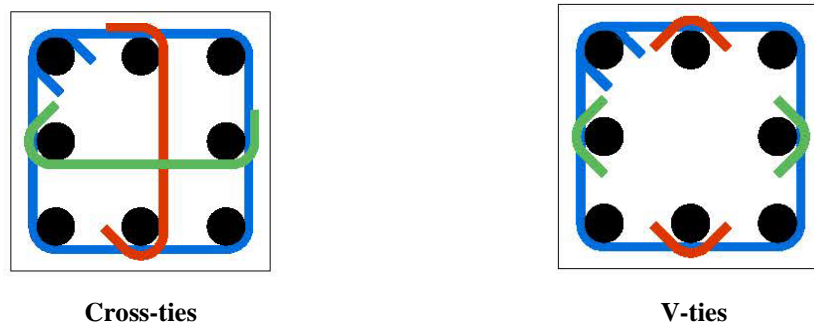


Figure 2. Details of transverse reinforcement for columns with cross-section (250 *250 mm).

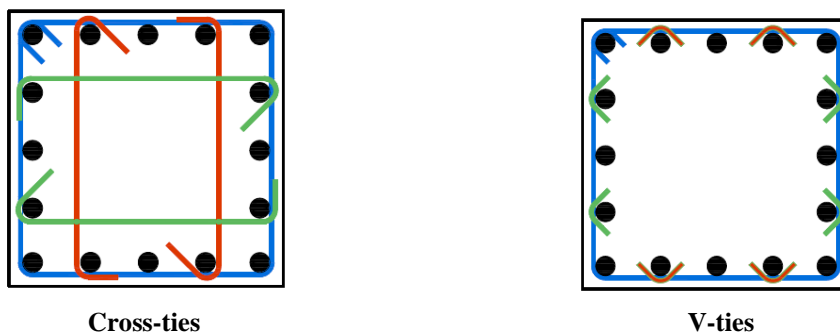


Figure 3. Details of transverse reinforcement for columns with cross-section (500 *500 mm).

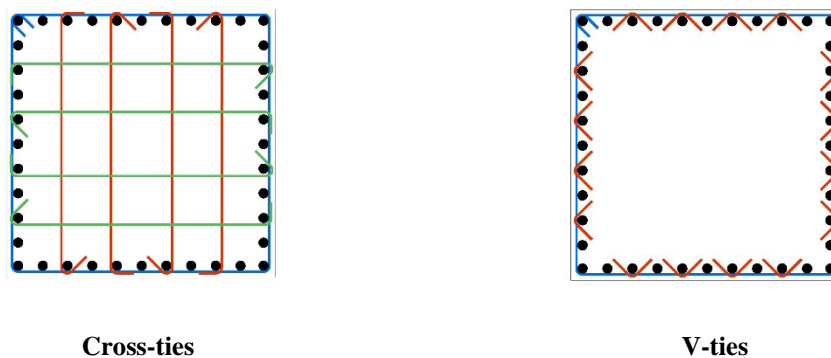


Figure 4. Details of transverse reinforcement for columns with cross-section (1000 *1000 mm).



Figure 5. Details of transverse reinforcement for columns with cross-section (250 * 500 mm).

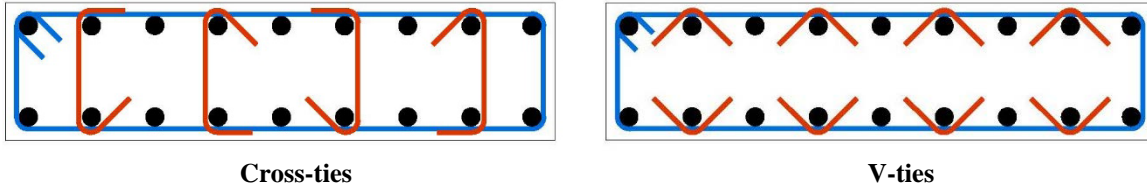


Figure 6. Details of transverse reinforcement for columns with cross-section (250 * 1000 mm).

The transverse reinforcement spacing for specimens with cross-section (250 mm * 250 mm) is depicted in Figure 7 at 50 mm, 100 mm, and 200 mm. Other specimens have the same arrangement for spacing between ties (S). The details of specimens COC, COV-7, COV-10.5, and COV-14 for a column with a 500 mm by 500 mm cross-section are illustrated in Figure 8. Figure 9 shows the extension length of V-tie legs with different values of 7 ϕ s (56 mm), 10.5 ϕ s (85 mm), and 14 ϕ s (112 mm) for all specimens with cross-section 1000 mm * 1000 mm.

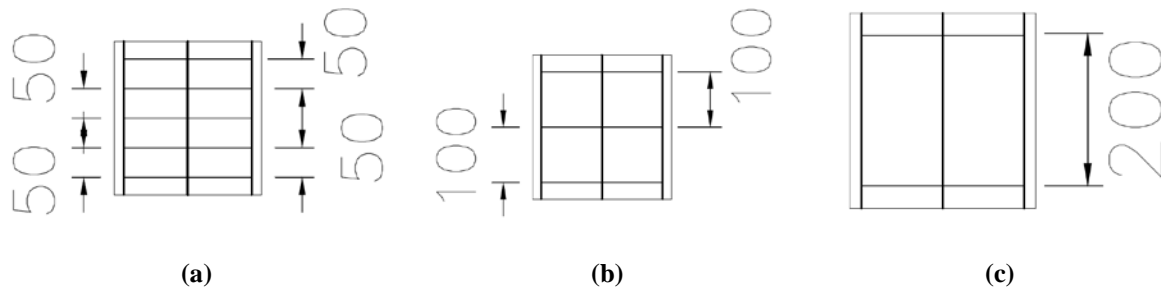


Figure 7. Longitudinal section shows details about the transverse reinforcement spacing for specimens with cross-section (250*250 mm); (a) S = 50 mm; (b) S = 100 mm; (c) S = 200 mm.

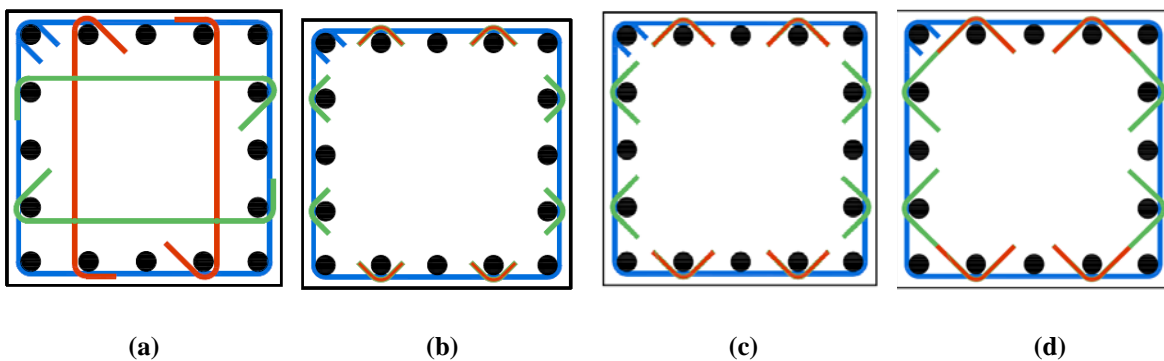


Figure 8. Specifications of transverse reinforcement for all columns with a 500 by 500 mm cross-section; (a) COC; (b) COV-7; (c) COV-10.5; (d) COV-14.

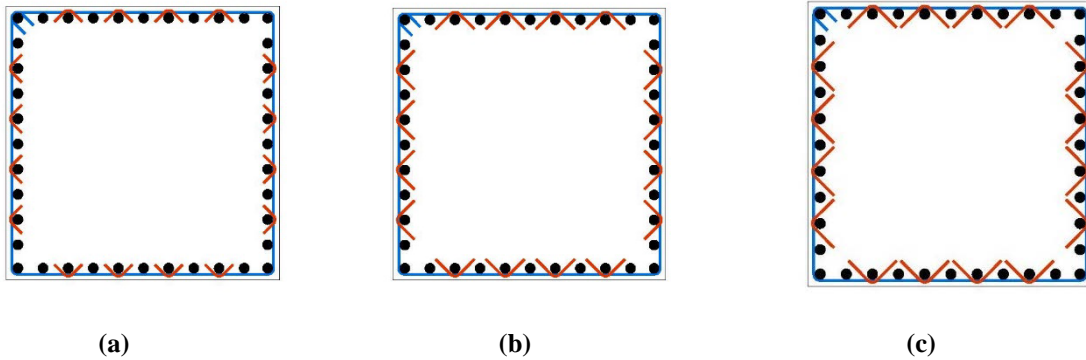


Figure 9. Details of V-tie legs with different values for specimens with cross-section (1000 * 1000 mm) ; (a) COV-7 ; (b) COV-10.5 ; (c) COV-14 .

4. Numerical Analysis

The commercially available finite element analysis tool Abaqus/standard [8] was used to perform a nonlinear finite element (FE) study. The primary goal of the numerical research was to use a FE model to forecast the overall behaviour of reinforcing columns under concentric axial stress while accounting for the impact of transverse reinforcement. The constitutive models that were employed are briefly explained below.

4.1 Material properties and constitutive models

The four-node linear tetrahedron solid element (C3D4) with three displacement degrees of freedom for each node was used to model the concrete in the current work. Using 3-D, 2-node truss components with three degrees of freedom at each node, steel reinforcing bars were simulated. It was believed that there would be a perfect connection between the concrete and the steel reinforcing bars. Two steel plates are selected and given an elastic-plastic behaviour in order to replicate the test setting. In order to ensure that the axially applied load is distributed uniformly, the RC column has stiff plates at both ends. The local collapse of concrete caused by stress concentration at the column ends can be avoided with such a rigid plate. For determining the column capacity and post-cracking behaviour of the RC columns, the load control approach is used. In order to find the ideal size for the FEM modelling, various mesh sizes were tested for this study. Mesh convergence progresses from fine meshes to a coarse mesh. Mesh element sizes of 25 mm, 30 mm, 50 mm, and 100 mm were taken into consideration. According to the data, 30 mm was the optimal size, outperforming all other sizes and experimental results by Elbakry et al. [5]. FE model setup system is displayed in Figure 10 for specimen COV-10.5 with cross-section (250* 250mm) and 100 mm spacing between ties.

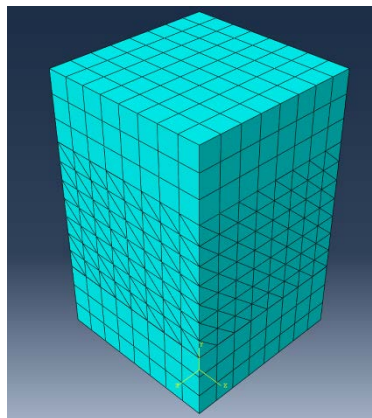


Figure 10. FE simulation (3D model) of specimen COV-10.5 for cross-section (250* 250mm) and S=100 mm.

4.2 Concrete material

The behaviour of the concrete was modelled in the current study using the Concrete Damage Plasticity Model (CDP). Separate strain rates, yield strengths, and damage factors in tension and compression are supported by CDP. The concrete grade for all specimens is 35 MPa.

Elastic modulus, E_c , and tensile strength, f_{ct} , are the elastic parameters needed to create the tension stress-strain curve. As per ACI 318-18 [1], the calculations of E_c and f_{ct} were done using:

$$E_c = 4700 \sqrt{f'_c} \tag{1}$$

$$f_{ct} = 0.33 \sqrt{f'_c} \tag{2}$$

where cylinder compressive strength of concrete is represented by f'_c .

For the concrete model, five primary parameters were taken into account: the dilation angle ψ , the stress ratio σ_{bo}/σ_{co} , the eccentricity ϵ , the yield surface shape K_c , and the viscosity regularisation ν . The Drucker-Prager hyperbolic flow potential function $G(\sigma)$, which is not associated, is taken into account by the CDP model, as shown in [1, 8-13], as illustrated in Figure 11. The ratio of the tension meridian to the compression meridian in the deviatoric cross section is represented by the parameter K_c , which is displayed in Figure 11. According to [8, 14; 15], K_c has a default value of 0.667. The function $G(r)$ approaches at a certain rate, denoted by a small positive dimensionless value. It is suggested by ABAQUS [8] that ϵ be set to 0.1 by default.

The parameter σ_{bo}/σ_{co} , which represents the ratio of the uniaxial compressive strength σ_{bo} to the equal biaxial compressive strength σ_{co} (i.e., $\sigma_{co}=f_c$), is taken into account by the CDP model. 1.16 is the default value for σ_{bo}/σ_{co} that is advised in ABAQUS [8]. According to ABAQUS [8], a default value of 0 is advised for the viscosity ν . To calibrate the dilation angle ψ parameter, numerous experimental and numerical investigations were gathered from the literature. As per the findings of Ali et al. [16], the optimal dilation angle was 38° . With the exception of the dilation angle, which was derived from the data published, Table 1 presents the values of the CDP model parameters taken into account as default values in ABAQUS [8].

Table 1. Values of CDP model parameters

Item	ψ	ϵ	K_c	σ_{bo}/σ_{co}	ν
Parameter value	38°	0.1	0.667	1.16	0.0

* ψ = the dilation angle, ϵ = the eccentricity, K_c = yield surface shape, σ_{bo}/σ_{co} = the stress ratio, ν = the viscosity regularization

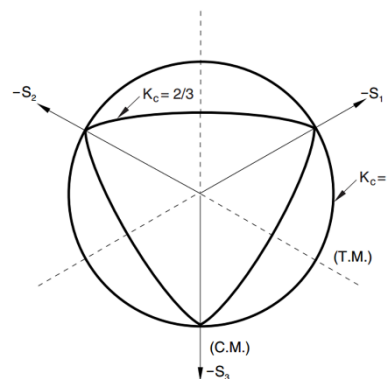


Figure 11. Yield surfaces in the deviatoric plane, corresponding to different values of K_c [8].

There are various models for tension stiffening; for the purposes of this investigation, the model created by Wahathantri et al. [17] was chosen since it is suitable for the reinforced concrete member. This approach also shows similarities to the tension stiffening model required for the concrete damaged plasticity model CDP. Originally, the homogenised stress-strain relationship that Nayal and Rasheed [18] established to account for tension softening served as the foundation for this tension stiffening model. The updated tension stiffening model for ABAQUS [8] is displayed in Figure 12.

The uniaxial compressive stress-strain curve for the concrete was created using the stress-strain relationship suggested by Saenz [19] for the compression stress-strain curve. The concrete uniaxial compressive stress-strain curve was created using equations (3) through (6). Figure 13 shows a typical compressive stress-strain relationship along with damage terms and characteristics.

$$\sigma_c = \frac{E_c \epsilon_c}{1+(R+R_E-2)\left(\frac{\epsilon_c}{\epsilon_0}\right)-(2R-1)\left(\frac{\epsilon_c}{\epsilon_0}\right)^2+R\left(\frac{\epsilon_c}{\epsilon_0}\right)^3} \tag{3}$$

Where ϵ_0 is the strain at the ultimate stress, and σ_c is the effective strain at any given ϵ_c .

$$R = \frac{R_E(R_\sigma - 1)}{(R_E - 1)^2} - \frac{1}{R_E} \tag{4}$$

$$R_E = \frac{E_c}{E_o} \tag{5}$$

$$E_o = \frac{f_c}{\epsilon_o} \tag{6}$$

According to Hsuam [20], where R is the material parameter based on the shape of the stress-strain curve, E_o is the material's initial undamaged elastic stiffness, (f_c) is the cylinder compressive strength, and R = 4. For concrete, a Poisson's ratio of 0.20 was assumed.

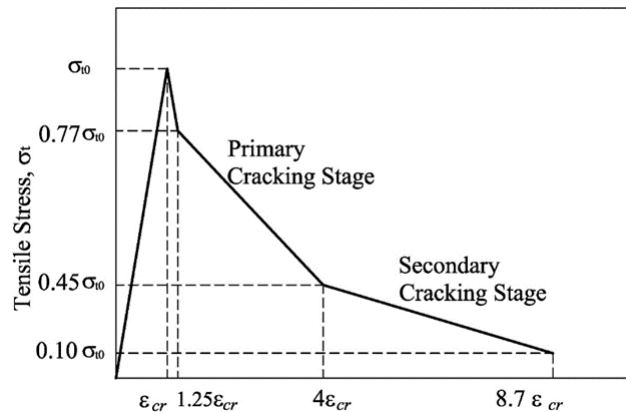


Figure 12. Alternate Tension Stiffening Model for ABAQUS [8].

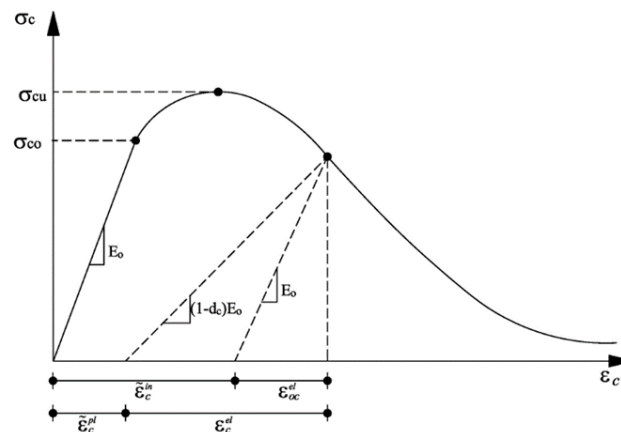


Figure 13. Abaqus Manual [8] terms for the compressive stress-strain relationship in concrete.

4.3 Steel reinforcement

In both tension and compression, reinforcing steel bars were supposed to behave as a bilinear elastic-plastic material. Young's modulus of plastic was taken to be 0.1 E. Table 2 displays the yield stress σ_y, the ultimate stress σ_u, and the elastic modulus E_s. Poisson's ratio for the steel reinforcing bars was 0.3. The used longitudinal reinforcing bars have an average nominal yield stress of 480 MPa and a diameter of 18 mm. The 8 mm diameter, smooth mild steel bars used to make the stirrups have an average nominal yield stress of 320 MPa.

Table 2. Mechanical properties of steel bars

Diameter of steel bar, mm	Type	Average yield stress, MPa	Average tensile strength, MPa	Average modulus of elasticity, GPa	Elongation, %
18	Deformed high tensile steel	480	601	203	25
8	Smooth mild steel	320	472	201	30.4

5. Results and discussion

All columns had been tested up to complete failure. Table 3 summarizes the numerical results for all tested columns. In addition, further discussion on the ultimate axial load and the axial strain for all tested columns are presented and compared here in below.

5.1 The effect of spacing between ties

Figures 14 - 18 show the influence of spacing between ties on the ultimate axial load of RC columns for all specimens at different values of cross-section. It could be noted that the ultimate axial loads of RC columns increase by decreasing the spacing between ties.

Table 3. Ultimate axial loads for all specimens

Cross-section, (mm)	S,mm	P _u (kN)			
		COC	COV-7	COV-10.5	COV-14
250*250	50	3937.3	3811.0	3704.6	3612.5
	100	3428.1	3375.3	3297.9	3235.7
	200	2986.3	2975.2	2963.2	2956.3
500*500	50	14529.4	14185.7	13857.2	14715.1
	100	13183.9	13001.6	12822.6	13250.8
	200	12220.3	12117.7	12063.4	12302.0
1000*1000	50	54779.0	53111.2	51532.8	59760.8
	100	51048.7	50323.6	49771.5	53531.6
	200	48741.1	48351.5	48076.6	49898.7
250*500	50	8799.7	8458.6	8219.3	8610.3
	100	7607.9	7457.8	7357.5	7554.8
	200	6871.8	6817.8	6816.3	6902.6
250*1000	50	12002.7	11075.2	10583.0	11911.4
	100	10707.6	10118.1	9822.1	10677.0
	200	9700.4	9237.4	9023.8	9690.8

5.1.1 The effect of spacing between ties at cross-section (250*250 mm)

Figure 14 shows the effect of spacing between ties on the ultimate axial load for specimens COC, COV-7, COV-10.5, and COV-14. It can be seen that the ultimate axial loads of RC columns increase by decreasing the spacing between ties.

Specimen COV-7 achieves an increase in ultimate axial load of 11.30% and 25% as the spacing between ties is decreased from 200 mm to 100 and 50 mm, respectively. It is observed that specimen COV-7 achieves an increase in ultimate axial load by 12.33% when decreasing spacing between ties from 100 mm to 50 mm. This means that when decreasing the spacing between ties, the effectiveness of V-ties on the ultimate axial load becomes clearer. It is found that specimen COV-7 achieves an increase in ultimate axial load by 2.55%, 1.92% and 0.23% at spacing between ties 50 mm, 100 and 200 mm, respectively, compared to specimen COC. This means that the effectiveness of V-ties is more visible compared with cross-ties by decreasing the spacing between ties.

In specimen COV-10.5, it is found that specimen COV-10.5 achieves an increase in ultimate axial load by 2.87%, 2.34% and 0.4% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. It this means that by increasing V-ties leg, the ultimate axial load of RC columns increases. It is observed that specimen COV-10.5 achieves an increase in ultimate axial load by 5.5%, 4.31% and 0.64% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effective-ness of V-ties is more evident by decreasing spacing between ties and increasing V-ties leg.

It is found that specimen COV-14 achieves an increase in ultimate axial load by 3.3%, 1.57% and 0.37% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-10.5. It is observed that specimen COV-14 achieves an increase in ultimate axial load by 6.3%, 3.95% and 0.78% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that the effectiveness of V-ties on the ultimate axial load is more obvious when decreasing the spacing between ties and increasing V-ties leg. It is observed that specimen COV-14 achieves an increase in ultimate axial load by 9%, 5.95% and 1.02% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of V-ties is more visible compared with cross-ties by decreasing spacing between ties and increasing the V-ties leg.

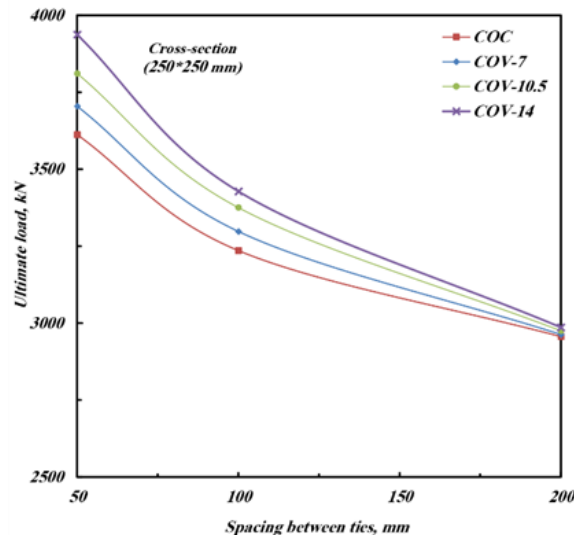


Figure 14. Influence of spacing between ties on the ultimate axial load of RC columns at cross-section (250*250 mm).

5.1.2 The effect of spacing between ties at cross-section (500*500 mm)

Figure 15 shows the effect of spacing between ties on the ultimate axial load for specimens COC, COV-7, COV-10.5, and COV-14. It can be seen that; the ultimate axial loads of RC columns increase by decreasing the spacing between ties.

It is found that specimen COV-7 achieves a decrease in the ultimate axial load by 6.2%, 3.3% and 1.9% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of cross-ties is more visible compared with V-ties by decreasing spacing between ties at cross-section (500*500 mm).

It is found that specimen COV-10.5 achieves an increase in the ultimate axial load by 2.4%, 1.4% and 0.45% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that by increasing V-ties leg, the ultimate axial load of RC columns increases. It is observed that specimen COV-10.5 achieves a decrease in the ultimate axial load by 3.7%, 1.92% and 1.52% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of V-ties is clearer by decreasing the spacing between ties and increasing V-ties leg.

It is found that specimen COV-14 achieves an increase in the ultimate axial load by 2.4%, 1.4% and 0.85% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-10.5. It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 4.85%, 2.82% and 1.3% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that the effectiveness of V-ties on the ultimate axial load is clearer when decreasing the spacing between ties and increasing V-ties leg. It is observed that specimen COV-14 achieves a decrease in the ultimate axial load by 1.27%, 0.51% and 0.66% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that using V-ties instead of cross-ties has a slight effect on the ultimate axial load of RC columns at cross-section (500*500 mm).

5.1.3 The effect of spacing between ties at cross-section (1000*1000 mm)

Figure 16 shows the influence of spacing between ties on the ultimate axial load for specimens COC, COV-7, COV-10.5, and COV-14. It can be seen that the ultimate axial loads of RC columns increase by decreasing the spacing between ties.

It is found that specimen COV-7 achieves a decrease in the ultimate axial load by 16%, 7.6% and 3.8% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of cross-ties is more visible compared with V-ties by decreasing spacing between ties at cross-section (1000*1000 mm).

It is observed that specimen COV-10.5 achieves a decrease in ultimate axial load by 12.5%, 6.4% and 3.2% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of V-ties is more obvious by decreasing the spacing between ties and increasing V-ties leg.

It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 6.3%, 2.6% and 1.38% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that the effectiveness of V-ties on the ultimate axial load is clearer when decreasing the spacing between ties and increasing

V-ties leg. It is observed that specimen COV-14 achieves a decrease in the ultimate axial load by 9.1%, 4.9% and 2.4% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that using V-ties instead of cross-ties has a slight effect on the ultimate axial load of RC columns at cross-section (1000*1000 mm).

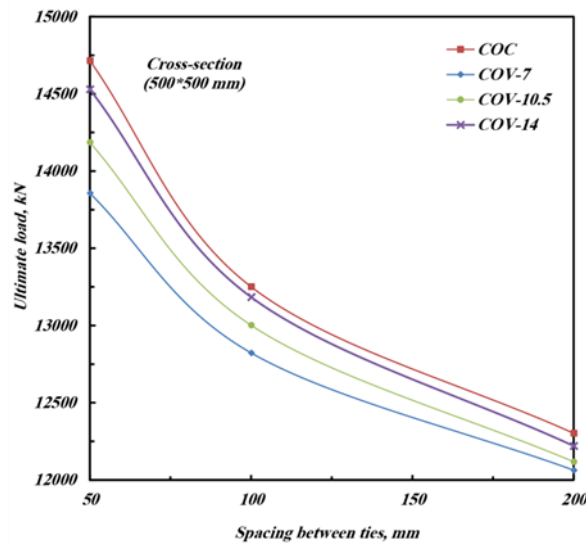


Figure 15. Influence of spacing between ties on the ultimate axial load of RC columns at cross-section (500*500 mm).

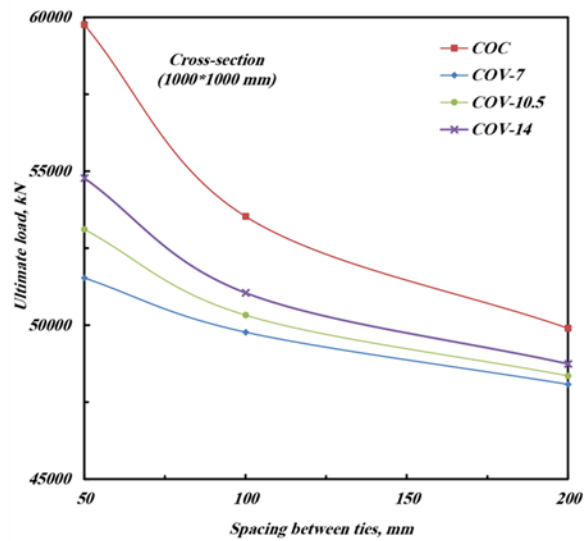


Figure 16. Influence of spacing between ties on the ultimate axial load of RC columns at cross-section (1000*1000 mm).

5.1.4 The effect of spacing between ties at cross-section (250*500 mm)

Figure 17 shows the effect of spacing between ties on the ultimate axial load for specimens COC, COV-7, COV-10.5, and COV-14. It can be seen that the ultimate axial loads of RC columns increase by decreasing the spacing between ties.

It is found that specimen COV-7 achieves a decrease in the ultimate axial load by 4.8%, 2.7% and 1.6% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that using V-ties instead of cross-ties is appropriate.

It is found that specimen COV-10.5 achieves an increase in the ultimate axial load by 2.9%, 1.36% and 0.02% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that by increasing V-ties leg, the ultimate axial load of RC columns increases. It is observed that specimen COV-10.5 achieves a decrease in the ultimate axial load by 1.8%, 1.3% and 1.2% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that using V-ties instead of cross-ties is appropriate.

It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 7.1%, 3.4% and 0.8% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that the ultimate axial load of RC columns improves by decreasing the spacing between ties and increasing V-ties leg. It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 2.2%, 0.7% at spacing between ties 50 and 100, respectively compared to specimen COC. It is observed that specimen COV-14 achieves a decrease in the ultimate axial load by 0.45% at spacing between ties 200 mm compared to specimen COC. This means that the effectiveness of V-ties is more visible compared with cross-ties by decreasing the spacing between ties and increasing V-ties leg.

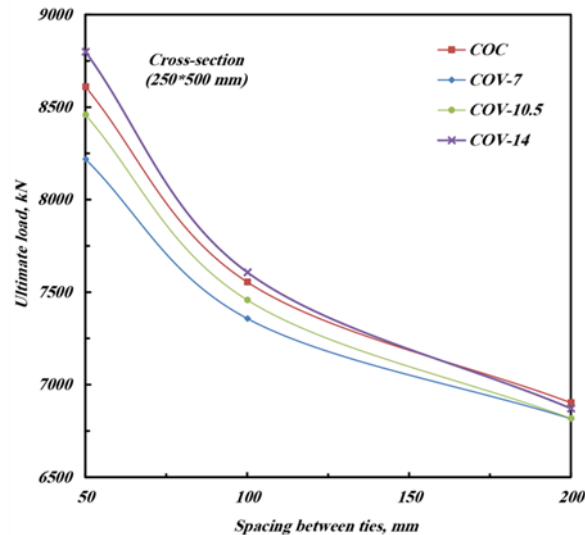


Figure 17. Influence of spacing between ties on the ultimate axial load of RC columns at cross-section (250*500 mm).

5.1.5 The effect of spacing between ties at cross-section (250*1000 mm)

Figure 18 shows the influence of spacing between ties on the ultimate axial load for specimens COC, COV-7, COV-10.5, and COV-14. It can be seen that; the ultimate axial loads of RC columns increase by decreasing the spacing between ties.

It is found that specimen COV-7 achieves a decrease in ultimate axial load by 12.6%, 8.7% and 7.4% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that using V-ties instead of cross-ties is appropriate. In other words, the effectiveness of cross-ties is more visible compared with V-ties by decreasing spacing between ties at cross-section (250*1000 mm).

In specimen COV-10.5, it is found that specimen COV-10.5 achieves an increase in the ultimate axial load by 4.65%, 3% and 2.4% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that by increasing V-ties leg, the ultimate axial load of RC columns increases. It is observed that specimen COV-10.5 achieves a decrease in the ultimate axial load by 7.5%, 5.5% and 4.9% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of cross-ties is more obvious compared with V-ties by decreasing the spacing between ties at cross-section (250*1000 mm).

Specimen COV-14 achieves an increase in the ultimate axial load by 8.4%, 5.8% and 5% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-10.5. It is observed that specimen COV-14 achieves an increase in ultimate axial load by 13.4%, 9% and 7.5% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COV-7. This means that the ultimate axial load of RC columns improves by decreasing the spacing between ties and increasing V-ties leg. It is observed that specimen COV-14 achieves a decrease in the ultimate axial load by 0.77%, 0.28% and 0.1% at spacing between ties 50 mm, 100 and 200 mm, respectively compared to specimen COC. This means that the effectiveness of V-ties is more detectable compared with cross-ties by decreasing the spacing between ties and increasing V-ties leg.

5.2 The effect of cross-section

In the present study, the influence of cross-section is investigated by developing FE models for sixty (60) specimens. Each specimen is modeled with different cross-sections (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm) at different values of spacing 50 mm, 100 mm, and 200 mm. Figures

19 - 21 show the influence of cross-section on the ultimate axial load of RC columns for all specimens at different values of spacing between ties.

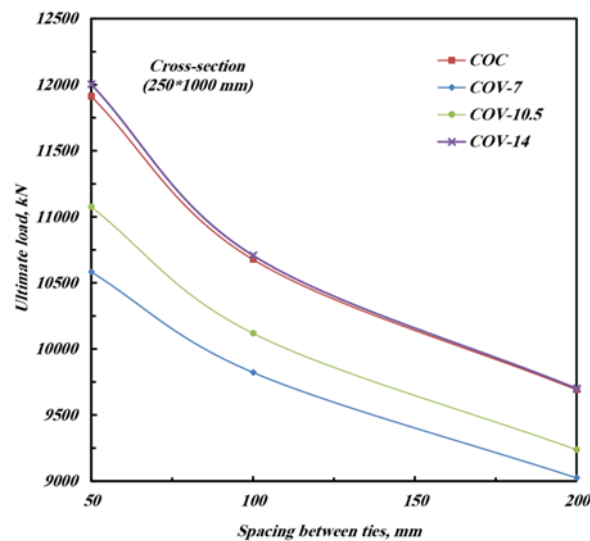


Figure 18. Influence of spacing between ties on the ultimate axial load of RC columns at cross-section (250*1000 mm).

5.2.1 The effect of cross-section at spacing between ties 200 mm

Figure 19 shows the influence of cross-section on the ultimate axial load for all specimens at spacing between tie 200 mm. Specimen COV-7 achieves an increase in the ultimate axial load of 2.3% when compared with specimen COC at cross-section (250*250 mm). It is observed that specimen COV-7 achieves a decrease in the ultimate axial load by 1.94% when compared with specimen COC at cross-section (500*500 mm). It is found that specimen COV-7 achieves a decrease in the ultimate axial load by 3.65%, 1.3% and 6.9 % at cross-section (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively compared to specimen COC. This means that using V-ties with 56 mm V-ties leg instead of cross-ties is appropriate with cross-section (250*250 mm) and (250*500 mm). In other words, increasing cross-section to (500*500 mm), (1000*1000 mm), and (250*1000 mm) using V-ties with 56 mm V-ties leg instead of cross-ties is not appropriate.

In specimen COV-10.5, it is observed that the ultimate axial load increases by 0.64% when compared with specimen COC at cross-section (250*250mm). It is found that specimen COV-10.5 achieves a decrease in the ultimate axial load by 1.5%, 3.1%, 1.2% and 4.7 % at cross-section (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively compared to specimen COC. This means that using V-ties instead of cross-ties is appropriate for cross-sections (250*250 mm), (500*500 mm) and (250*500 mm). A clear difference can be seen as cross-section is increased to (1000*1000 mm) and (250*1000 mm) using V-ties with 85 mm length of V-tie leg when compared with cross-ties. This means that by increasing V-ties leg, the ultimate axial load of RC columns increases. It is found that specimen COV-10.5 achieves an increase in the ultimate axial load by 0.4%, 0.45%, 0.57%, 0.02% and 2.37% when compared with specimen COV-7 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. This means that the effectiveness of V-ties on the ultimate axial load is more evident when V-ties leg is increased.

Specimen COV-14 achieves an increase in the ultimate axial load of 1% and 0.1% when compared with specimen COC at cross-sections (250*250 mm) and (250*1000 mm), respectively. It is observed that specimen COV-14 achieves a decrease in the ultimate axial load by 0.66%, 2.3% and 0.44% when compared with specimen COC at cross-sections (500*500 mm), (1000*1000 mm) and (250*500 mm), respectively. This means that using V-ties instead of cross-ties is appropriate for all RC columns in group 2. It is found that specimen COV-14 achieves an increase in the ultimate axial load by 0.4%, 0.85%, 0.81%, 0.8% and 5% when compared with specimen COV-10.5 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. This means that the effectiveness of V-ties on the ultimate axial load is clearer when increasing V-ties leg. It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 0.78%, 1.3%, 1.4%, 0.8% and 7.5% when compared with specimen COV-7 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. In other words, the ultimate axial load of RC columns improves by increasing V-ties leg.

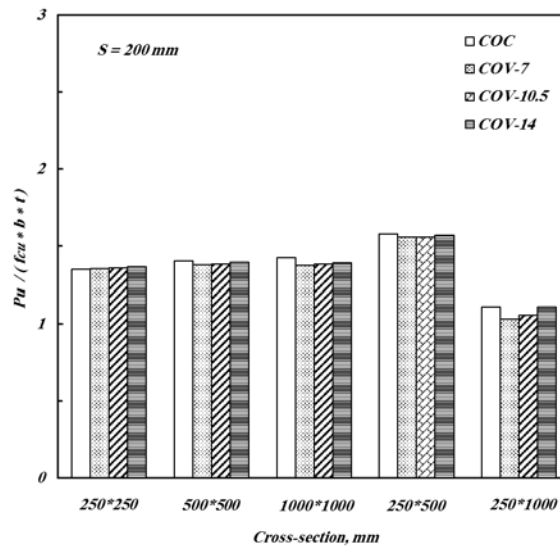


Figure 19. Influence of cross-section on the ultimate axial load of RC columns at S = 200 mm.

5.2.2 The effect of cross-section at spacing between ties 100 mm

Figure 20 shows the influence of cross-section on the ultimate axial load for all specimens at spacing between tie 100 mm. Specimen COV-7 achieves an increase in ultimate axial load of 1.9% when compared with specimen COC at cross-section (250*250 mm). It is found that specimen COV-7 achieves a decrease in the ultimate axial load by 3.2%, 7%, 2.6% and 8% at cross-sections (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively when compared to specimen COC. This means that using V-ties with 56 mm V-ties leg instead of cross-ties is appropriate with cross-section (250*250 mm) and (250*500 mm). In other words, increasing cross-section to (500*500 mm), (1000*1000 mm), and (250*1000 mm) using V-ties with 56 mm V-ties leg instead of cross-ties is not appropriate.

In specimen COV-10.5, it is observed that the ultimate axial load increases by 4.3% if compared with specimen COC at cross-section (250*250mm). It is found that specimen COV-10.5 achieves a decrease in the ultimate axial load by 1.8%, 6%, 1.3% and 5.2% at cross-section (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively when compared to specimen COC. This means that using V-ties instead of cross-ties is appropriate for cross-sections (250*250 mm), (500*500 mm) and (250*500 mm). A clear difference can be seen when increasing cross-section to (1000*1000 mm) and (250*1000 mm) using V-ties with 85 mm length of V-tie leg when compared with cross-ties. This means that by increasing V-ties leg, the ultimate axial load of RC columns increases. It is found that specimen COV-10.5 achieves an increase in the ultimate axial load by 2.3%, 1.4%, 1.1%, 1.36% and 3% when compared with specimen COV-7 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. This means that the effectiveness of V-ties on the ultimate axial load is clearer when V-ties leg is increased.

Specimen COV-14 achieves an increase in the ultimate axial load of 5.9%, 0.7% and 0.3% when compared with specimen COC at cross-sections (250*250 mm), (250*500) and (250*1000 mm), respectively. It is observed that specimen COV-14 achieves a decrease in the ultimate axial load by 0.5% and 4.6% when compared with specimen COC at cross-sections (500*500 mm) and (1000*1000 mm), respectively. This means that using V-ties instead of cross-ties is appropriate for all RC columns. It is found that specimen COV-14 achieves an increase in the ultimate axial load by 1.5%, 1.4%, 1.4%, 2% and 5.8% when compared with specimen COV-10.5 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 3.9%, 2.8%, 2.6%, 3.4% and 9% when compared with specimen COV-7 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. This means that the ultimate axial load of RC columns improves by increasing V-ties leg.

5.2.3 The effect of cross-section at spacing between ties 50 mm

Figure 21 shows the influence of cross-section on the ultimate axial load for all specimens at spacing between tie 50 mm. Specimen COV-7 achieves an increase in the ultimate axial load of 2.5% when compared with specimen COC at cross-section (250*250 mm). It is found that specimen COV-7 achieves a decrease in the ultimate axial load by 5.8%, 13.7%, 4.5% and 11.2% at cross-sections (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively when compared to specimen COC. This means that using V-ties with 56 mm V-ties

leg instead of cross-ties is appropriate with cross-section (250*250 mm). In other words, it is not appropriate to increase cross-section to (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm) using V-ties with 56 mm V-ties leg instead of cross-ties.

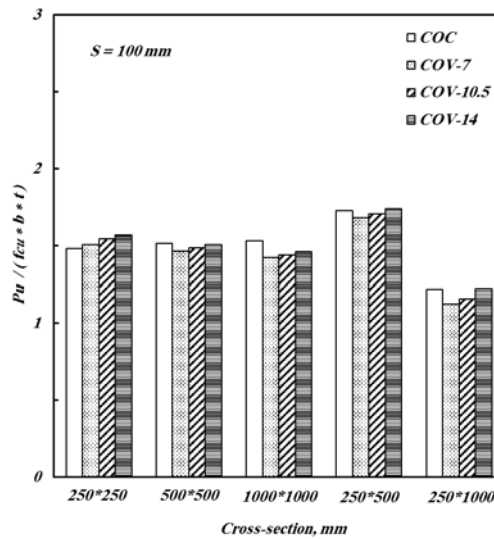


Figure 20. Influence of cross-section on the ultimate axial load of RC columns at S = 100 mm.

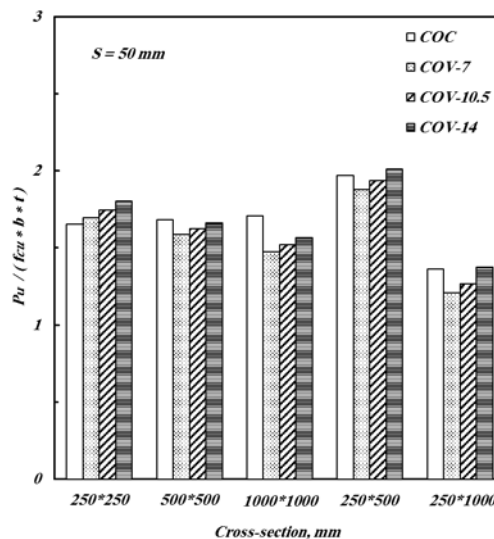


Figure 21. Influence of cross-section on the ultimate axial load of RC columns at S = 50 mm.

In specimen COV-10.5, it is observed that the ultimate axial load increases by 5.5% when compared with specimen COC at cross-section (250*250mm). It is found that specimen COV-10.5 achieves a decrease in ultimate axial load by 3.6%, 11%, 1.7% and 7 % at cross-section (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively when compared to specimen COC. This means that using V-ties instead of cross-ties is appropriate for cross-sections (250*250 mm), (500*500 mm) and (250*500 mm). A clear difference can be seen as cross-section is increased to (1000*1000 mm) and (250*1000 mm) using V-ties with 85 mm length of V-tie leg when compared with cross-ties. It is found that specimen COV-10.5 achieves an increase in the ultimate axial load by 2.8%, 2.4%, 3.1%, 2.9% and 4.7% when compared with specimen COV-7 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. This means that the effectiveness of V-ties on the ultimate axial load is more noticeable when V-ties leg is increased. Specimen COV-14 achieves an increase in the ultimate axial load of 9%, 2.2% and 0.77% when compared with specimen COC at cross-sections (250*250 mm), (250*500) and (250*1000 mm), respectively. It is observed that specimen COV-14 achieves a decrease in ultimate axial load by 1.26% and 8% when compared with specimen COC at cross-sections (500*500 mm) and (1000*1000 mm), respectively. This means that using V-ties instead of cross-ties is appropriate for all RC columns except cross-section (1000*1000 mm). It is found that specimen COV-14 achieves an increase in the ultimate axial load by 3.3%, 2.4%, 3.1%, 4% and 8.4% when compared with

specimen COV-10.5 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. It is observed that specimen COV-14 achieves an increase in the ultimate axial load by 6.3%, 4.9%, 6.3%, 7.1% and 13.4% when compared with specimen COV-7 at cross-section (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm), respectively. Thus, the effectiveness of V-ties on the ultimate axial load becomes clearer when V-ties leg is increased.

5.3 Axial Strains

In the present study, the influence of spacing between ties and cross-section is investigated by developing FE models for sixty (60) specimens. Each specimen is modeled with different cross-sections (250*250 mm), (500*500 mm), (1000*1000 mm), (250*500 mm) and (250*1000 mm) at different values of spacing 50 mm, 100 mm, and 200 mm. Figures 22 - 24 show the relationships between the acting axial load and the axial strain for specimens with cross-section (500*500 mm) at different values of spacing between ties. For other specimens have almost the same behavior. The axial strains are calculated as the strain obtained on the mid-height of corner longitudinal reinforcing bars.

5.3.1 Cross-Section (500*500 mm)

Figures 22 - 24 show the relationships between the acting axial load and the axial strain for specimens COC, COV-7, COV-10.5 and COV-14 at spacing between ties 50 mm, 100 and 200 mm, respectively. It could be observed that all specimens have almost the same stiffness through the early phases of the analysis. This showed that the effect of ties on the initial stiffness of the tested specimens is insignificant.

Figure 22 shows the relationships between the acting axial load and the axial strain for specimens COC, COV-7, COV-10.5 and COV-14 at spacing between ties 50 mm. Early in the analysis, it was possible to see that the stiffness of all specimens is almost the same. This shown that ties have no impact on the initial stiffness of the tested specimens. It is observed that specimens COC, COV-7 and COV-10.5 have approximately the same behavior from the beginning of the test to the failure. This means that using V-ties instead of cross-ties gives the same stiffness of RC columns. It is observed that specimen COV-14 achieves a slight higher stiffness when compared to specimens COC, COV-7 and COV-10.5. Additionally, it might be stated that using V-ties gives the same behavior as RC columns and is more economically and practically possible than using cross-ties.

As seen in Figure 22, it has been found that RC columns have greater ductility when V-ties are used in place of cross-ties. By decreasing the spacing between V-ties, the effect of V-tie legs on ductility was more effective, as shown in Figure 22.

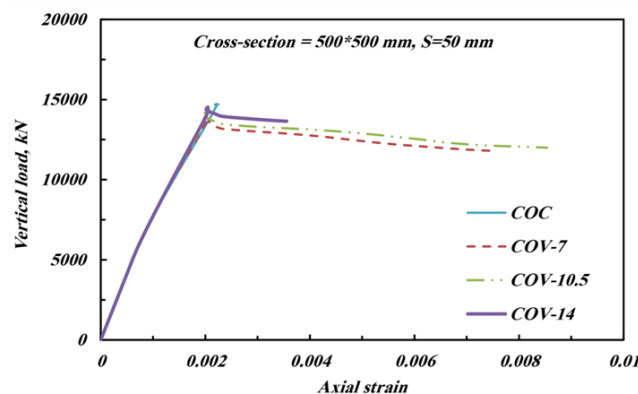


Figure 22. Axial loads and axial strain relationships for columns with cross-section (500*500 mm) at S = 50 mm.

The relationships between the acting axial load and the axial strain for the specimens COC, COV-7, COV-10.5, and COV-14 at a 100 mm spacing between ties are shown in Figure 23. It could be observed that all specimens have almost the same stiffness through the early phases of the analysis. This showed that the effect of ties on the initial stiffness of the tested specimens is insignificant. It is observed that specimens COC, COV-7 and COV-10.5 have almost the same stiffness from the beginning of the analysis to the failure. This means that using V-ties instead of cross-ties gives the same behavior of RC columns. It is observed that specimen COV-14 achieves a relatively slight higher stiffness when compared to specimens COC, COV-7 and COV-10.5. This indicates that using V-ties is more practical and cost-effective than using cross-ties. It was noted that specimens COC, COV-7, and COV-10.5 all show nearly identical ductility; in addition, specimen COV-14 has greater ductility than the other specimens. When V-ties were spaced 100 mm apart, there was very little impact of the legs on ductility.

Figure 24 shows the relationships between the acting axial load and the axial strain for specimens COC, COV-7, COV-10.5 and COV-14 at spacing between ties 200 mm. Early in the analysis, it was possible to see that the stiffness of each specimen was extremely similar. This shows that ties have no impact on the initial stiffness of the tested specimens. When compared to specimen COC, it is noted that specimens COV-7, COV-10.5 and COV-14 reach a comparatively high stiffness. It is observed that specimen COV-10.5 achieves a relatively large stiffness when compared to specimen COC and a slight higher stiffness when compared to specimen COV-7. It is observed that specimen COV-14 achieves a relatively large stiffness when compared to specimen COC and a slight higher stiffness when compared to specimen COV-7 and COV-10.5. Hence, using V-ties is more feasible and cost-effective than using cross-ties. As demonstrated in Figure 24, It was observed that the ductility of specimens COC, COV-7, and COV-10.5 is almost the same; additionally, specimen COV-14 exhibits more ductility than the other specimens. The effect of the legs on ductility was negligible when the V-ties were 200 mm apart.

Figure 25 shows mode of failure of specimen COV-10.5 for cross-section (250*250 mm) at spacing 100 mm between ties.

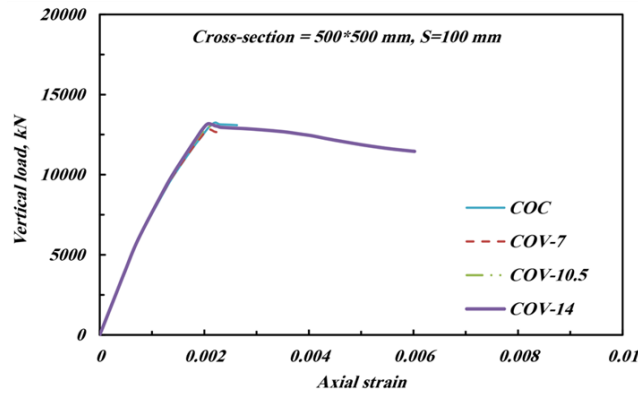


Figure 23. Axial loads and axial strain relationships for columns with cross-section (500*500 mm) at S = 100 mm.

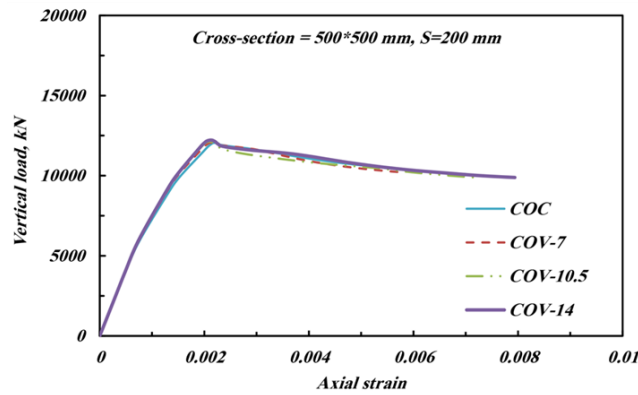


Figure 24. Axial loads and axial strain relationships for columns with cross-section (500*500 mm) at S = 200 mm.

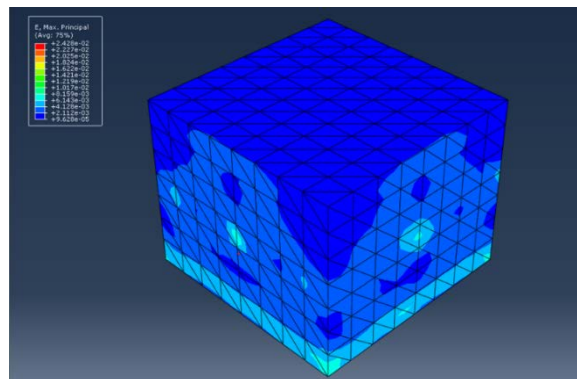


Figure 25. Failure mode of specimen COV-10.5 for cross-section (250* 250mm) and S=100 mm.

5.4 Cost–benefit analysis

The quantities of just the transverse reinforcement are taken into consideration and compared after completing a cost-benefit analysis. For all forms of reinforcement, the formation and operating costs are taken to be constant. Figure 26 additionally illustrates the weight of a single tie for each of the configurations that were taken into consideration for all specimens.

1) Cross-Section (250*250 mm)

It is found that specimens COV-7 and COV-10.5 record a cost decrease of ties of 15.1% and 2.2% compared to specimen COC. It is observed that COV-14 achieves an increase in the cost of tie by 11.9% when compared with specimen COC. This shows that V-ties are more efficient than cross-ties. This shows that the use of V-ties with 56 mm of V-ties leg instead of cross-ties is economically feasible.

2) Cross-Section (500*500 mm)

Specimens COV-7, COV-10.5 and COV-14 record a cost decrease of ties of 33.1%, 23.2% and 11.8% compared to specimen COC. This shows that V-ties are generally effective and could be more economical than cross-ties.

3) Cross-Section (1000*1000 mm)

It is found that specimens COV-7, COV-10.5 and COV-14 record a cost decrease of ties of 52.7%, 45.7% and 37.6% compared to specimen COC. This shows that V-ties are generally effective and could be more economical than cross-ties.

4) Cross-Section (250*500 mm)

Specimens COV-7 and COV-10.5 record a cost decrease of ties of 11.7% and 1.7% compared to specimen COC. It is observed that COV-14 achieves an increased cost of tie by 9.5% when compared with specimen COC. This shows that V-ties are more efficient than cross-ties. Thus, the use of V-ties with 56 and 85 mm of V-ties leg instead of cross-ties is economically feasible.

5) Cross-Section (250*1000 mm)

It is found that specimens COV-7 and COV-10.5 record a cost decrease of ties of 13.1% and 1.9% compared to specimen COC. It is observed that COV-14 achieves an increased cost of tie by 10.7% when compared with specimen COC. This shows that V-ties are more efficient than cross-ties. Thus, the use of V-ties with 56 and 85 mm of V-ties leg instead of cross-ties is economically feasible.

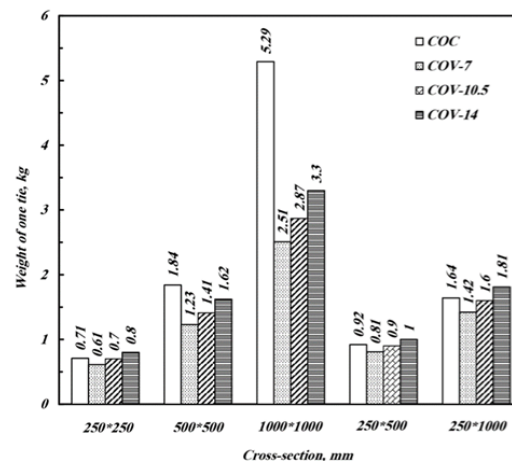


Figure 26. Weight of one tie for all specimens.

6. Conclusions

A new internal transverse reinforcement arrangement for RC columns under axial compression has been developed and put into practice in the current paper. By contrasting RC columns strengthened with traditional ties and those using V-tie procedures, it was demonstrated that the performance of the V-tie columns was enhanced. Both conventional ties and V-ties' load-axial strain responses were contrasted. The following conclusions might be made based on the numerical investigation results and the accepted concrete size, material qualities, longitudinal reinforcing ratio, and tie configurations:

1) The parametric study's findings demonstrate that by reducing the tie spacing, V-ties provide a greater boost in the ultimate axial load of RC columns than cross-ties do.

2) According to the parametric study results, increasing the V-ties leg increases the ultimate axial stress of RC columns.

3) It is economically feasible to use V-ties rather than cross-ties to provide numerical results for all tested columns.

4) The strength increase to weight ratios of the transverse reinforcement demonstrated the economic competitiveness of using V-ties.

5) It was found that the cost difference between specimens with V-ties and those with cross-ties was as much as 52.7%.

6) The study's findings demonstrated how important it is that V-ties' impact as transverse reinforcement for RC columns be taken into account by design codes.

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