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Axial capacity and ductility of reinforced concrete columns with strip plate steel and conventional stirrup reinforcements

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Abstract. A column is a vertical structural element that transmits loads to the foundation and is required to withstand a variety of loads. The incorporation of reinforcing bars serves to enhance the axial capacity and mitigate the risk of sudden collapse of the column. The potential use of alternative materials for stirrup reinforcement represents a topic of significant interest within the academic community. Prior research has demonstrated that the stirrup reinforcement ratio exerts a significant influence on the strength and ductility of concrete. Specifically, higher ratios have been shown to lead to enhanced performance in both of these attributes. This study examined the behavior of core concrete in reinforced concrete columns with varying types of reinforcing bars, including 3×25 mm, 3×30 mm, 4×25 mm strip plate steel, and 10 mm diameter deformed conventional stirrups. A total of thirteen columns were tested until collapse in order to evaluate a number of factors, including column shortening, peak axial load, column stress, reinforcement and core concrete strain, and a comparison of theoretical and actual confined core concrete compressive strength. The study demonstrated that the incorporation of strip plate stirrups in reinforced concrete columns exerted a marginal influence on the column's axial capacity. The columns reinforced with conventional stirrups exhibited enhanced peak axial load, column stress, and restraint strength, accompanied by a reduction in column shortening. Conversely, the columns with 3×30 mm strip plates demonstrated superior ductility. An elevated stirrup reinforcement ratio was observed to enhance the compressive strength of confined concrete, although a discrepancy was noted between the theoretical calculations and the actual values.

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1. Introduction

Concrete is the most prevalent building material in use today. Conventional concrete is composed of coarse aggregate, fine aggregate, water, and cement [1]. These building materials are utilized extensively in the construction of a multitude of infrastructure projects, including buildings, roads, bridges, and underground structures such as foundations and tunnels [2]. Concrete has a high compressive capacity, is relatively inexpensive to maintain, is readily available in raw form, and can be molded into a variety of shapes, making it a versatile and economical material for a range of construction applications [3]. Nevertheless, concrete has a relatively low tensile strength, which necessitates the use of reinforcing steel to enhance its tensile strength performance [4]. The reinforcement system utilizes reinforcing steel, which is capable of withstanding tensile loads on concrete, thereby preventing cracking and enhancing the ductility of the structure [5]. In this context, the two principal types of reinforcing steel are plain and deformed [6]. The combination of the two materials results in the formation of a composite material that is capable of bearing both compressive and tensile loads. This material is known as reinforced concrete [7].

In a frame structure, columns are vertical structural elements that bear the load of the beams and floor slabs above them [8]. A column is a structural element that serves to compress and reinforce a building's framework. It is responsible for transferring the total building load to the foundation, which includes both dead and live loads, as well as earthquake loads [9]. A column, as a vertical structural element, is required to provide resistance to bending, shear, axial, and torsional collapse due to the aforementioned loads [10]. One of the principal causes of collapse in a column is axial loading. The objective of transverse reinforcement is to enhance the axial capacity of the column [11].

The function of the transverse reinforcement is to maintain the axial capacity of the column by ensuring the stability of the core concrete [12]. The installed transverse reinforcement will serve to resist the lateral forces generated by the axial loads received by the core concrete [13]. The role of transverse reinforcement in columns is of paramount importance, given that collapse can occur abruptly and without warning [14]. Prior research has investigated the impact of transverse reinforcement on the axial capacity of reinforced concrete columns subjected to confinement. This has involved the utilisation of diverse configurations and ratios of transverse reinforcement [15].

The cross-sectional area of the transverse reinforcement is intimately associated with the transverse reinforcement ratio, which exerts a profound influence on the ductility of the confined core concrete. In their research, Imran and Antonius demonstrated that an elevated transverse reinforcement ratio gives rise to a heightened ductility strength of the confined concrete. Nevertheless, if the reinforcement ratio is excessively high, the concrete will succumb to collapse before the transverse reinforcement reaches its yield point [15, 16]. In their research, Saatcioglu and Razvi demonstrated that the strength and ductility of confined concrete increase as the reinforcement ratio increases. Columns with low reinforcement ratios exhibited brittle behavior, displaying a pronounced reduction in strength after reaching the peak load. In contrast, columns with higher reinforcement ratios demonstrated the capacity to undergo significant deformation without a notable reduction in strength [17, 18]. Similarly, research conducted by Cusson and Paultre indicates that an increased transverse reinforcement ratio is associated with enhanced confinement efficiency [19].

The research on the performance and influence of transversal reinforcement has become increasingly diverse over time. This has prompted researchers to seek alternative materials that are stronger and more efficient, such as the use of strip plate steel as transversal reinforcement. Previous studies have demonstrated the efficacy of strip plate steel in increasing the shear capacity of wide concrete beams, enhancing the durability of wide concrete beams after the first shear crack, increasing ductility, and facilitating easier management during the construction process [20]. Furthermore, the use of strip plate steel in the transverse reinforcement of concrete can enhance its shear capacity, particularly in the context of beams. Reinforced concrete beams with the incorporation of strip plate steel exhibit enhanced resistance to maximum loads and exhibit greater stiffness compared to their plain concrete counterparts. However, it is observed that the crack pattern in beams with the aforementioned reinforcement tends to produce cracks with larger inclination angles, a more uniform distribution on the side of the beam, and a greater number of cracks compared to plain concrete beams [21].

The objective of this study is to conduct a more thorough investigation into the effect of using strip plate steel as a stirrup reinforcement in columns on the axial capacity of columns and the ductility of columns subjected to concentric axial loads. Strip plate steel is used as an alternative to deformed steel. The utilization of strip plate steel is predicated on the assumption that strip plate steel is more readily manipulable than deformed steel. Additionally, strip plate steel possesses a more substantial cross-sectional area than deformed steel, which allows for more effective confinement of the core concrete. Further research will be conducted on the behavior of reinforced concrete columns using strip plate steel reinforcement. The axial load that can be achieved, the strain that occurs in stirrup reinforcement, longitudinal reinforcement, and core concrete, as well as the amount of shortening that occurs in the column, will be reviewed. This research is expected to corroborate the preceding research hypothesis, namely that the axial capacity of reinforced concrete columns can be enhanced.

2. Materials and Method

This study focused on a particular type of column, characterized by conventional stirrup reinforcement and strip plates. The conventional transverse reinforcement measures 10 mm in diameter, while the strip plate steel has dimensions of 3×25 mm, 3×30 mm, and 4×25 mm. The design of concrete mixtures is guided by the Indonesian Standard SNI 7656:2012. Subsequently, the concrete cylinders were subjected to testing in accordance with the standards set forth in SNI 1974:2011. The steel utilized in this investigation was evaluated for tensile strength in accordance with the standards set forth in SNI 8389:2017. The particular attributes of the concrete and reinforcing steel used are set forth in Tables 1 and 2, respectively.

Table 1. Concrete properties.

	Average Values
Slump	100 mm
Compressive Strength	23.9 MPa

Table 2. Steel reinforcements properties.

Type of Steels	Cross-Sectional Area (mm^2)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
D10	57.13	346.20	460.65	10.84
3×25 mm	63.42	366.10	541.58	6.56
3×30 mm	80.96	392.39	543.96	8.78
4×25 mm	84.75	383.86	524.60	9.37

A total of thirteen column specimens were subjected to axial loading until collapse occurred. Column specimens bearing the initials D10 represent reinforced concrete columns using conventional transverse reinforcement, whereas column specimens bearing the initials 3×25, 3×30, and 4×25 represent reinforced concrete columns using strip plate steel transverse reinforcement. The test area was situated between two simple pedestals, with both ends of the columns attached to the compression tester. In all columns, the longitudinal reinforcement comprised four pieces of 6 mm diameter plain reinforcement, which served as a tie for the transverse reinforcement.

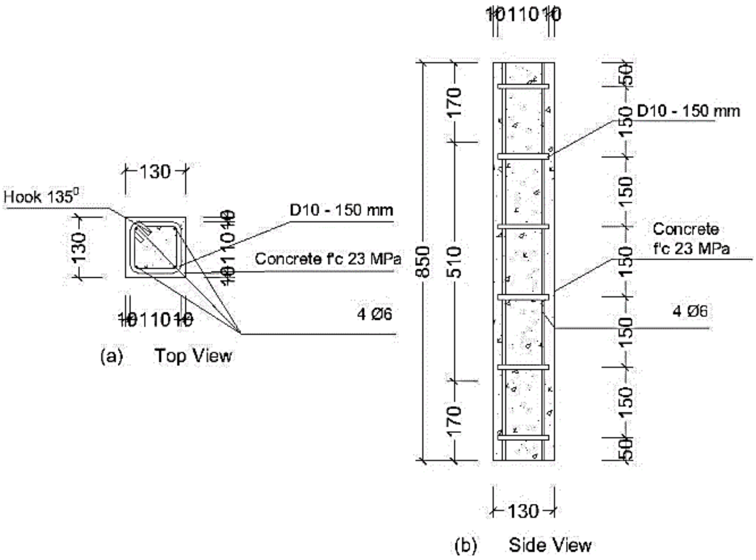


Figure 1. Schematic of conventional stirrup reinforcement installation on columns.

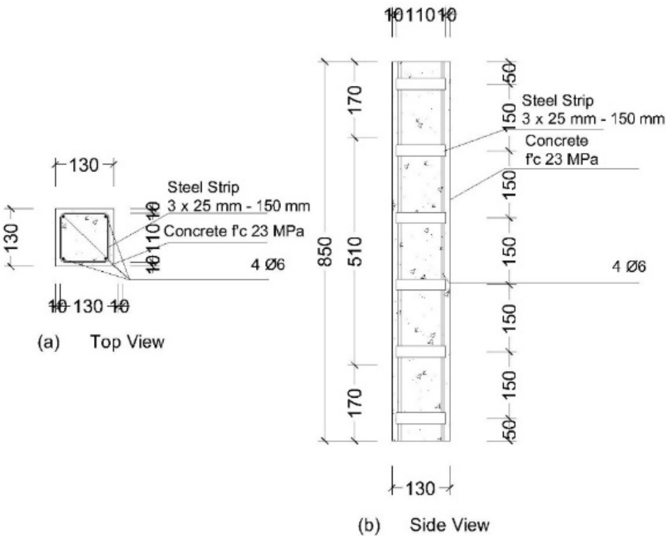


Figure 2. Schematic installation of 3×25 mm strip plate reinforcement on columns.

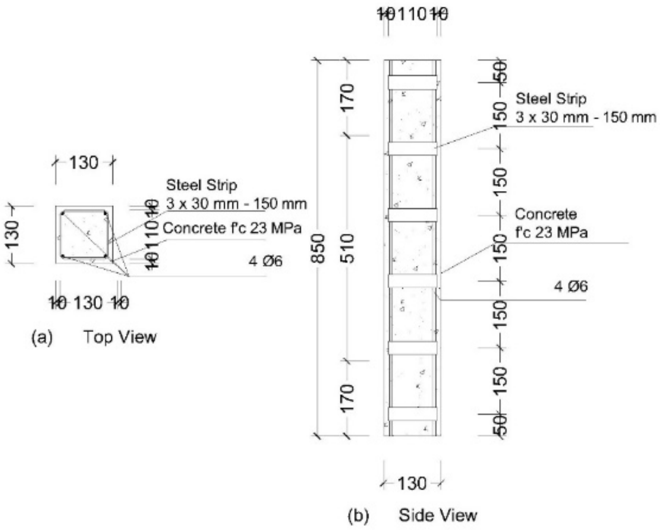


Figure 3. Schematic installation of 3×30 mm strip plate reinforcement on columns.

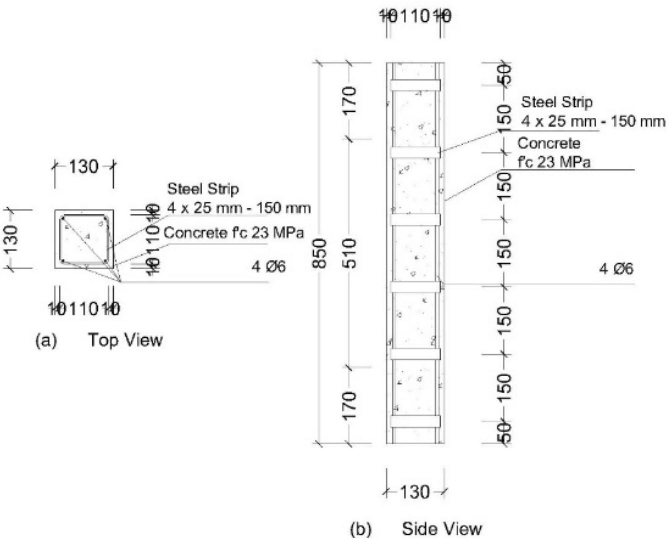


Figure 4. Schematic installation of 4×25 mm strip plate reinforcement on columns.

The experiments were conducted in the structural laboratory of the Civil Engineering Department at Sebelas Maret University. The loading frame is equipped with hydraulic jacks for loading, with a capacity of 500 kN. Furthermore, the hydraulic jack is equipped with a load cell with a capacity of 100,000 pounds (453 kN), which serves to measure the load applied to the column. To quantify the shortening of the specimen, a linear vertical displacement transducer was utilized and installed centrally within the span of the column specimen. The observed shortening of the specimen spanned the range from a load of 0 kN to the peak load tolerated by the column.

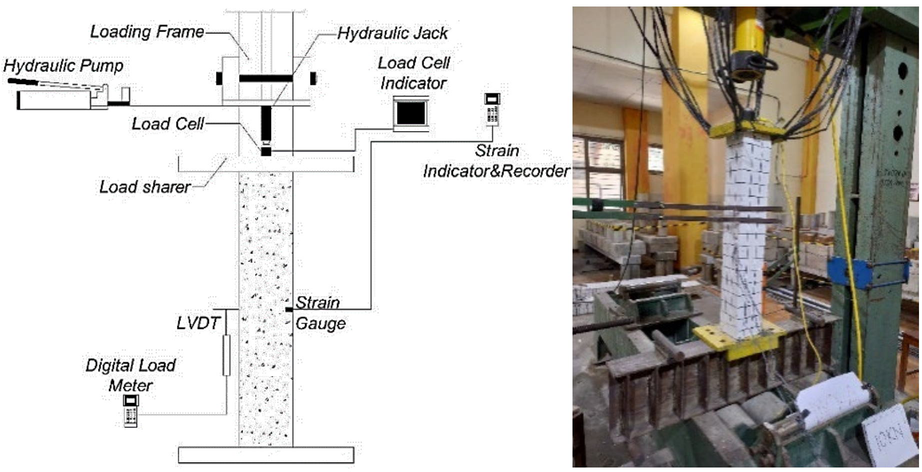


Figure 5. Testing equipment installation scheme and test program setup.

3. Results and Discussion

This test identifies the relationship between the applied axial load and the shortening of the column, as well as the strain occurring in the transverse reinforcement, longitudinal reinforcement, and core concrete. Strain gauges were installed on the stirrup reinforcement, longitudinal reinforcement, and core concrete at the center, with the gauges connected to a strain indicator to obtain the amount of strain at each loading interval. Column shortening was measured using an LVDT attached to the midpoint of the column and connected to a digital load meter. The axial load applied to the column was measured using a load cell connected to a load cell indicator. The objective of this study is to examine the axial load on the column, the strain on stirrup reinforcement, longitudinal reinforcement, and core concrete, and the shortening of the column. Axial load-shortening curves and axial load-strain curves are plotted up to the point of failure, which is indicated by the column reaching its peak load.

Figure 6. Strain indicator, digital load meter, and load cell indicator.

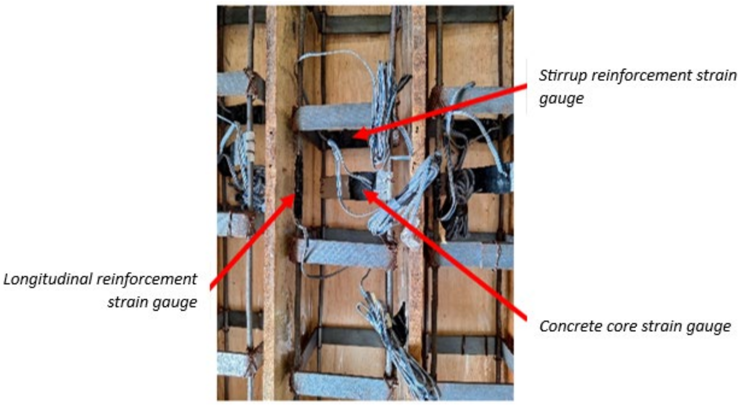


Figure 7. Installation location of strain gauge.

3.1. Column Shortening

The response of reinforced concrete columns with conventional transverse reinforcement and strip plate steel stirrups is linear elastic prior to the formation of the first crack. The shortening of reinforced concrete columns with conventional transversal reinforcement commences at a load of 75 kN, whereas the shortening of reinforced concrete columns with strip plate steel stirrups begins at a load of 45 kN for 3×25 columns, 30 kN for 3×30 columns, and 15 kN for 4×25 columns. As the load increases, the formation of additional cracks causes the shortening curve to become linear. The shortening at maximum axial load in reinforced concrete columns with conventional transversal reinforcement is less than that observed in columns with strip plate steel stirrups. The discrepancies in shortening at maximum axial load are 26.29 % for the 3×25 columns, 78.32 % for the 3×30 columns, and 52.90 % for the 4×25 columns. Columns with conventional reinforcement demonstrate enhanced bearing capacity. It is observed that the shortening of the columns is less pronounced in comparison to columns utilising strip plate stirrups, and they are capable of withstanding greater axial loads before significant shortening occurs. This outcome may be attributed to the fact that conventional stirrups possess a greater cross-sectional thickness in comparison to strip plate stirrups. This allows for a more robust confinement of the concrete core, which ultimately results in the smallest column shortening in comparison to columns with strip plate stirrups, despite the latter exhibiting the lowest tensile strength. However, columns with 3×30 mm strip plate stirrups display greater ductility than other columns. This is demonstrated by the larger shortening of the column in comparison to the other columns, despite the relatively minor differences in load. The relationship between the mean column shortening and the peak axial load at the time of column failure is illustrated in Fig. 8.

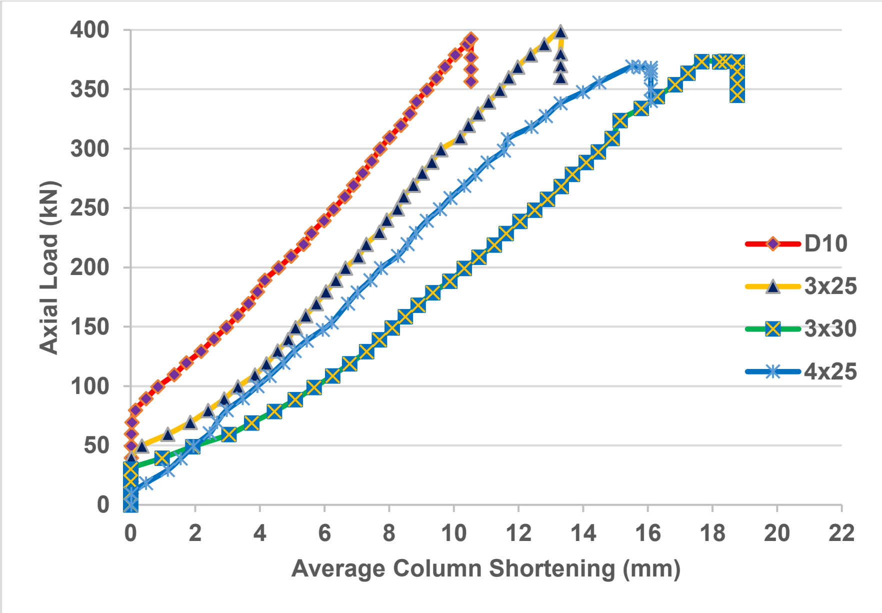


Figure 8. Maximum axial load-shortening curve of column specimen.

3.2. Relationship between Peak Axial Load and Longitudinal Reinforcement Strain

Each column exhibits the same amount of longitudinal reinforcement and the same steel tensile strength. The findings of the research indicate that as the axial load applied to the column increases, there is an accompanying increase in the strain in the longitudinal reinforcement. From the initial to the final stages of loading, the relationship between axial load and longitudinal reinforcement strain is proportional, indicating an increase in longitudinal reinforcement strain for each incremental increase in axial load. The ratio of transversal reinforcement used affects the peak. While there are differences in the strain magnitude occurring in the longitudinal reinforcement, they are not significant. The 3×30 column has the highest strain value in the longitudinal reinforcement compared to the other columns, suggesting that the longitudinal reinforcement in 3×30 mm strip plate columns is more ductile than that observed in columns with alternative stirrup reinforcement. Fig. 9 illustrates the relationship between the average longitudinal reinforcement strain and the peak axial load at the point of column failure.

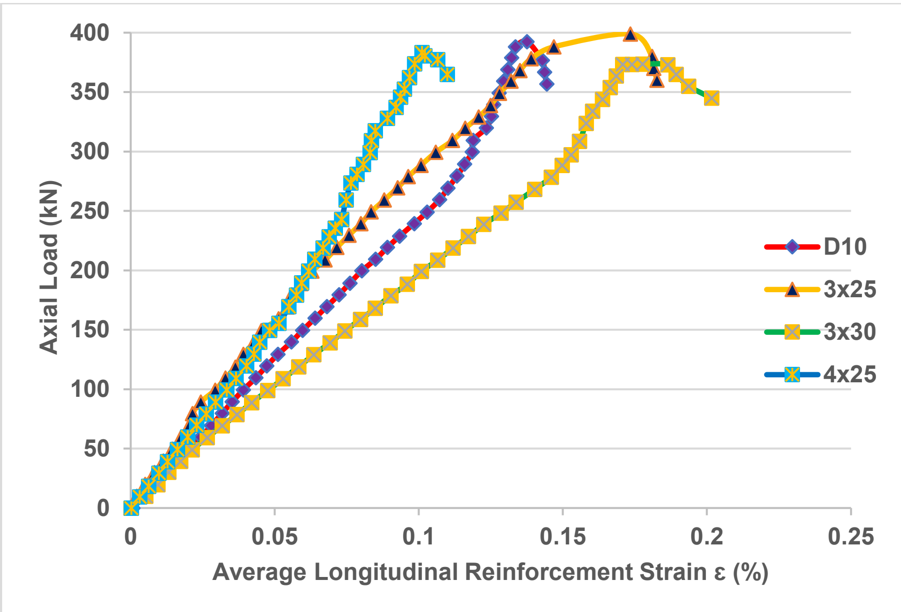


Figure 9. Load-strain curve of longitudinal reinforcement of column specimen.

3.3. Relationship between Peak Axial Load and Transverse Reinforcement Strain

Each column exhibits the same form of transversal reinforcement, yet exhibits differences in tensile strength of steel, cross-sectional area, and transversal reinforcement ratio. The test results demonstrate that the strain in the transverse reinforcement increases in conjunction with the application of an increasing axial load to the column. From the outset to the conclusion of the loading process, the relationship between axial load and the strain in the transversal reinforcement demonstrates a proportional increase in strain for each incremental increase in axial load. The ratio of the transversal reinforcement affects the maximum axial load that can be sustained until the column reaches its failure point. The degree of strain in the transversal reinforcement exhibits variability, but it is not statistically significant. Column D10 shows the higher level of strain in the transversal reinforcement in comparison to the other columns. These findings indicate that the stirrup reinforcement in conventional columns exhibits the greatest confinement strength, the most ductility, and the most effective performance when compared to columns with alternative stirrup reinforcement. The 10 mm diameter deformed stirrups utilized in column D10 are more readily manipulable than alternative forms of transversal reinforcement, as they do not necessitate the use of specialized tools for the bending of steel into stirrup shapes. The relationship between the average transversal reinforcement strain and the peak axial load at the point of column failure is illustrated in Fig. 10.

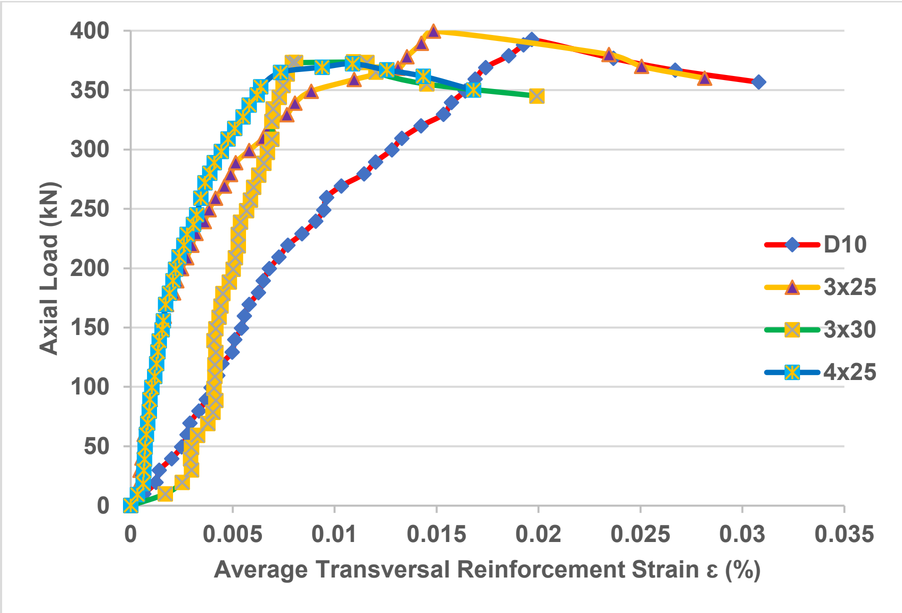


Figure 10. Load-strain curve of trasnsversal reinforcement of column specimen.

3.4. Relationship between Peak Axial Load and Core Concrete Strain

The columns are of identical dimensions with respect to both core concrete and concrete cover, and are constructed using the same concrete mixture. The test results demonstrate that the strain in confined core concrete increases in conjunction with the rise in axial load and stress on the column. From the outset to the conclusion of the loading process, the relationship between the axial load applied to the column and the strain in the confined core concrete demonstrates a proportional increase in core concrete strain for each incremental increase in axial load and concrete stress. The ratio of transverse reinforcement exerts a significant influence on the peak axial load that can be sustained until column failure and the magnitude of concrete stress that occurs in the column. The strain in the core concrete varies among the different column types, but it is not significant. The 3×25 column exhibits the highest strain in the core concrete and peak axial load compared to the other columns. This suggests that the core concrete in columns with 3×25 mm strip plate steel stirrups is more ductile than in columns with alternative stirrups. The relationship between the average strain of confined core concrete and the peak axial load at the point of column failure is illustrated in Fig. 11.

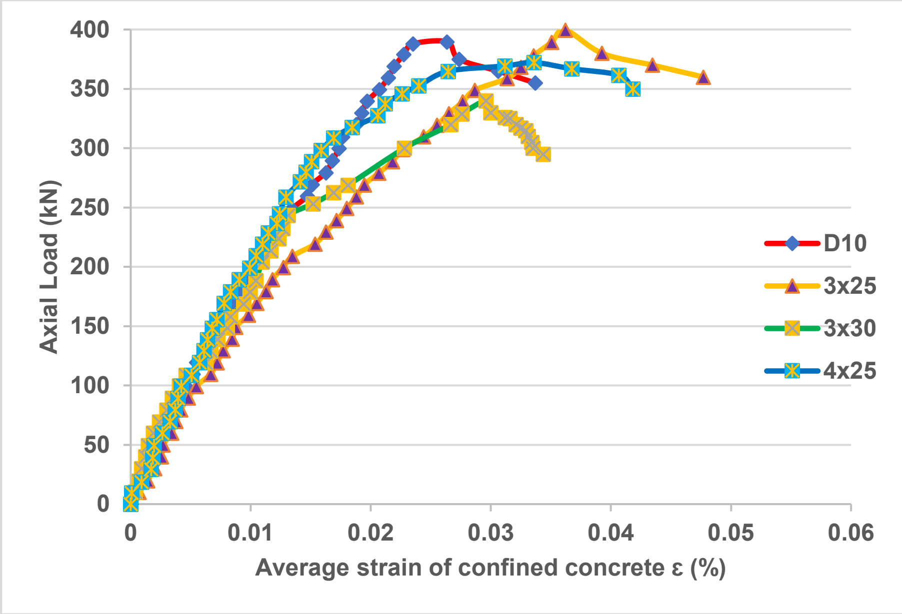


Figure 11. Maximum axial load-strain curve of confined core concrete.

3.5. Actual and Estimated Compressive Strength of Confined Concrete Cores

The estimated confined core concrete compressive strength is expressed in Equation 1. In this study, the equation proposed by Mander et al. is used to estimate the confined core concrete compressive strength observed in column test specimens [22–24]. The predicted results are then compared with the actual confined core concrete compressive strength, as stated in Equation 2.

$$f'_{cc} = f'_{c0}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f_l}{f'_{c0}}} - 2\frac{f_l}{f'_{c0}}\right); \tag{1}$$

$$f'_{cc\cdot test} = \frac{P}{A}; \tag{2}$$

$$\rho_s = \frac{\sum_{i=1}^{n}\left(A_{sx}\right)_i}{bc_y s} + \frac{\sum_{i=1}^{n}\left(A_{sy}\right)_j}{bc_x s}. \tag{3}$$

Furthermore, the equation proposed by Attard and Setunge is used to estimate the confined concrete compressive strength as demonstrated in Equation 4 [25–27].

$$\frac{f_o}{f'_c} = \left(\frac{f_r}{f_t}\right)^k; \tag{4}$$

$$k = 1.25\left[1 + 0.062\frac{f_r}{f'_c}\right]\left(f'_c\right)^{-0.21}; \tag{5}$$

$$f_t = 0.56\sqrt{f'_c}. \tag{6}$$

Table 3 shows the confined concrete compressive strength of reinforced concrete columns with various types of stirrups. In the calculation of $f'_{cc\cdot cal}$ actual, it is observed that as the dimensions of transversal reinforcement increase, the confined concrete compressive strength also increases. However, the test results indicate that the actual confined concrete compressive strength does not differ significantly. Based on the ratio $f'_{cc\cdot test}/f'_{cc\cdot cal}$ using the equation from Mander et al., it is evident that the actual value is higher than the predicted confined concrete compressive strength. On the other hand, when compared with the estimated value according to the equation from Attard and Setunge, the actual value is lower than the estimated value. The results from both equations indicate that the estimated confined concrete compressive strength values do not accurately represent the actual values due to the differences obtained.

Furthermore, the calculations derived from both equations illustrate the impact of the transversal reinforcement ratio. A larger ratio is associated with an elevated estimated confined concrete compressive strength. Column D10 exhibits a relatively lower transversal reinforcement ratio compared to the 3×25 column by 23.59 %, the 3×30 column by 57.98 %, and the 4×25 column by 66.56 %. This indicates that the ratio of transversal reinforcement to the cross-sectional area of the core concrete has a significant impact on the confined concrete compressive strength that can be achieved.

Table 3. Confined concrete compressive strength column specimens

Test Specimen	$f'_{cc\ test}$ (MPa)	$f'_{cc\ cal\ Mander}$ (MPa)	$f'_{cc\ test}/f'_{cc\ cal}$ Mander	$f'_{cc\ cal\ Attard}$ (MPa)	$f'_{cc\ test}/f'_{cc\ cal}$ Attard	ρ_s
D10	31.96	24.70	1.29	35.00	0.91	1.27 %
3×25	33.06	25.57	1.29	38.06	0.87	1.58 %
3×30	31.24	26.41	1.18	42.66	0.73	2.01 %
4×25	32.62	26.23	1.24	43.17	0.76	2.12 %

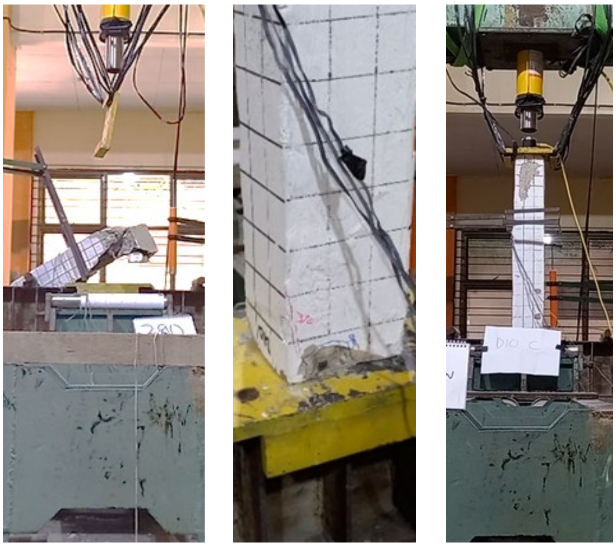
3.6. Crack Pattern

All columns were subjected to concentric axial loads until collapse occurred, which was limited by the capacity of the load cell, which reached 400 kN. All columns exhibited the initial cracking at the top or bottom, with the most prevalent type of cracking being compressive. A compressive crack is a fracture caused by a load exceeding the structural capacity of the material. As the axial load is increased, the cracks lengthen and widen, and the number of cracks caused by compressive axial load increases until the column collapses. The axial load at the first crack and the load at collapse can be seen in Table 4. The columns that have been tested with axial load until collapse can be seen in Figs. 12–16.

Table 4. Axial load at first crack and collapse.

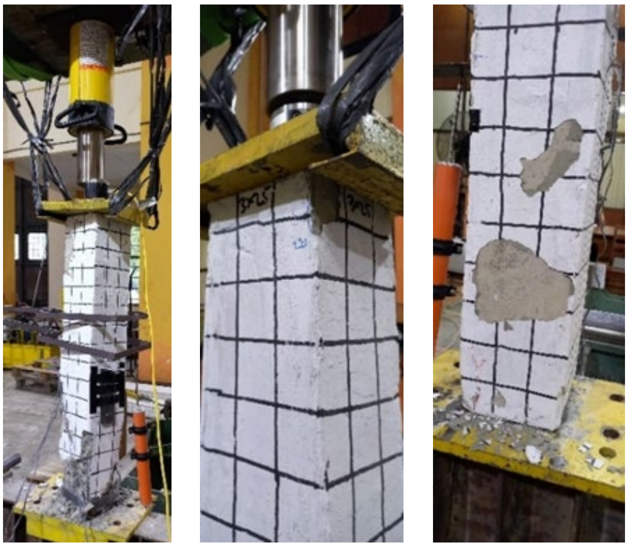
Specimen	Axial load at first crack (kN)	Axial load at collapse (kN)
K	100	370.13
D10 A	230	386.74
D10 B	240	Not Collapsed Yet
D10 C	–	Not Collapsed Yet
3×25 A	300	399.99
3×25 B	220	Not Collapsed Yet
3×25 C	300	Not Collapsed Yet
3×30 A	160	280.00
3×30 B	210	377.96
3×30 C	180	Not Collapsed Yet
4×25 A	80	394.74
4×25 B	230	370.26
4×25 C	290	380.08

Figure 12. Column K after testing under axial load.



(A) (B) (C)

Figure 13. D10 column after testing under axial load.



(A) (B) (C)

Figure 14. 3×25 column after testing under axial load.

(A) (B) (C)

Figure 15. 3×30 column after testing under axial load.

(A) **(B)** **(C)**

Figure 16. 4×25 column after testing under axial load.

The initial cracks are predominantly observed in the concrete blanket and typically initiate at the support area, both above and below. As the axial load increases, the number and size of the cracks also increase, extending into the core of the column. By the time the ultimate axial load was reached, the majority of the concrete material had cracked, and visible cracks were present in all areas of the column at the support area. Additionally, cracks were observed in the concrete blanket and column core [28–30].

It can be observed that all columns exhibiting the initial signs of deterioration present compressive cracks at either the top or bottom. A compressive crack is defined as a fracture that occurs as a result of a load exceeding the structural capacity of the material in question. In general, the stirrups were unable to confine the core concrete due to the open bond of the stirrups. This ultimately results in the longitudinal reinforcement being unable to maintain the integrity of the core concrete, which subsequently buckles. Therefore, the concrete failed in a collapse. As the load was applied to the test specimen, the cracks exhibited an increase in length and width, accompanied by the formation of additional cracks due to the compressive load until the column reached its failure point. With respect to the number of cracks, columns with strip plate stirrups, particularly those with dimensions of 3×30 mm and 4×25 mm, exhibited a greater number of cracks than columns with conventional stirrups. This is due to the larger dimensions of the stirrup reinforcement, which enables columns with 3×30 mm and 4×25 mm strip plate stirrups to distribute the load more evenly than columns with 3×25 mm deformed and strip plate stirrups. The additional reinforcement provided by the strip plate stirrups on the sides of the column reduces the surface area of the column that is only reinforced with concrete.

Columns without reinforcement demonstrate a proclivity to undergo load transfer when subjected to loading, with the transfer occurring predominantly in the column support area, both above and below. This is substantiated by the vertical cracks that emerge in the column support area. When the cracks commenced to propagate beyond the support area, the column collapsed as a consequence of the absence of reinforcement on the sides of the column.

4. Conclusion

The experimental testing results obtained in the laboratory led to the following conclusions:

1. Conventional columns are typically more robust in terms of load acceptance but may exhibit brittle behavior. It can be observed that the shortening of the column is less pronounced and the peak axial load that can be achieved is greater. This is attributed to the relatively small cross-sectional area of the stirrups. However, columns with 3×30 mm strip plate steel stirrups exhibit enhanced ductility as indicated by the larger column shortening with a peak axial load that is not significantly different from conventional columns.
2. Columns with 3×30 mm strip plate steel stirrups exhibit the greatest longitudinal reinforcement strains, suggesting that the longitudinal reinforcement in the column displays enhanced ductility due to the 3×30 mm strip plate stirrups. The stirrup reinforcement ratio exerts a notable influence on both the peak load that can be attained and the strain on the longitudinal reinforcement, although the observed difference is not substantial.

3. It can be observed that conventional columns experience the greatest strain on the stirrup reinforcement in comparison to other types of columns. Conventional stirrup reinforcement exhibits the greatest confining strength, the greatest ductility, and the most effective performance compared to columns with alternative stirrup reinforcement. With the same shape of stirrup reinforcement, conventional stirrup reinforcement is more readily workable because it does not necessitate the use of specialized tools to bend the reinforcement. The stirrup reinforcement ratio affects the achievable peak load and the strain in the stirrup reinforcement, although the impact is not significantly different.
4. Columns with 3×25 mm strip plate steel stirrups exhibited the highest core concrete strain and peak load compared to the other columns. This suggests that the core concrete of the column is more ductile due to the 3×25 mm strip plate stirrups. The stirrup reinforcement ratio affects the achievable peak load and strain in the core concrete, although the difference is not statistically significant.
5. Columns with larger ratios of stirrup reinforcement exhibit enhanced compressive strength of confined core concrete, a finding that aligns with the theoretical predictions put forth by Mander et al. [22] and Attard and Setunge [25]. However, the observed compressive strength values did not fully align with the predicted values.
6. Columns with strip plate stirrups, particularly those with dimensions of 3x30 mm and 4×25 mm, exhibited a higher incidence of cracking. The larger dimensions of stirrup reinforcement impart greater ductility to the column, enabling more even load distribution. The strip plate stirrups provide supplementary reinforcement at the sides of the column, thereby reducing the surface area of the column reinforced with concrete only.
7. Columns with strip plate stirrup reinforcement can be substituted for columns with conventional reinforcement due to the fact that both types of reinforcement have the capacity to withstand axial loads that tend to be similar. However, it should be noted that strip plate stirrup reinforcement has the advantage of being more ductile than conventional stirrup reinforcement. These columns have been determined to be suitable for use in residential buildings. The test specimens employed in this study exhibited dimensions equivalent to those of standard residential columns. Further investigation is necessary to assess the performance of larger specimens.

The application of strip plate stirrup reinforcement in reinforced concrete columns has a notable impact on the axial capacity of these structures. However, this influence is not particularly pronounced as evidenced by the comparable peak axial loads observed in the tested columns. Furthermore, the strains experienced in the longitudinal reinforcement, stirrups, and confined core concrete exhibit minor discrepancies, yet these differences are not statistically significant. Similarly, the compressive strength of the confined core concrete does not exhibit a considerable variation.

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