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Behavior of Short Columns Reinforced with Welded Wire Fabric as Transverse Reinforcement under Concentric Loading

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ABSTRACT

The purpose of this study was to investigate the behavior of concrete columns reinforced by Welded Wire Fabric, WWF, as transverse reinforcement under concentric loading and to compare the results with concrete columns reinforced by round bar as tie reinforcement when the volumetric ratio of transverse reinforcement was equal. Additionally, the effect of the spacing of transverse tie reinforcement on strength and ductility of the columns was studied by testing six different types of column specimens. The results indicated that the strength of the column increased slightly when the volumetric ratio was increased. The ductility of the column also had the same trend as the strength. However, the comparison of ductility showed columns reinforced by WWF tie had ductility indexes less than columns reinforced by RB 6 tie bars. This was because the WWF welded joint broke when subjected to lateral pressure from the concrete core, while conventional RB 6 tie showed ductile behavior due to the hook being stretched. Moreover, the test results were compared with the constitutive models proposed by Saatcioglu and Chan. The results showed that Saatcioglu's formula is more practical than Chan's formula for confined concrete columns. However, the mode of failure of transverse reinforcements that affects the ductility of the column should be considered.

Keywords: WWF, Welded Wire Fabric, concrete column, concentric loading

INTRODUCTION

Columns are structural elements used primarily to support compressive loads. The weight of the above structure is supported by columns with or without moments. Therefore, failure of one column in a critical location can cause the progressive collapse of the whole structure. To design reinforced concrete columns against external loads, a structural engineer who is directly concerned with this process, must consider both the strength and ductility of the column. This is especially true in seismic regions where ductility in the concrete column is highly necessary to resist earthquake forces.

For the past 7 decades, there are many researchers attempting to investigate and describe the natural behavior of columns under varying loads. It is well known that confined concrete behaves differently from unconfined concrete due to the effect of lateral pressure. Tests of reinforced concrete columns indicate that the strength and ductility of concrete compression are improved not only by longitudinal reinforcement, but also transverse reinforcement. Transverse steel in reinforced concrete columns serves the 3 major functions of preventing lateral bucking of the longitudinal reinforcing steel, acting as shear reinforcement, and confining the compressed concrete.

Characteristics of confined concrete have been researched extensively during the last 3 decades although early studies date back to the 1920s. Richart and co-workers [1] were among the first to study the confinement of normal-strength concrete. Their research on concrete cylinders, either confined by uniform hydrostatic pressure or spiral reinforcement provided some of the basic information on modeling confined concrete. The results showed that lateral pressure has an effect on the compressive strength of concrete columns and could be calculated by the equation shown below [1-3].

$$f'_{cc} = f'_c + 4.1 f_l \tag{1}$$

$$f_l = \frac{\sum R A_{sh} f_{yh}}{b_c s} \tag{2}$$

where

f'_{cc} is the Strength of the concrete subjected to lateral pressure
f'_c is the Compressive strength of the concrete cylinder
f_l is the Lateral pressure
A_{sh} is the Area of the transverse reinforcement
f_{yh} is the Yield strength of transverse reinforcement
b_c is the Width of the concrete core
s is the Longitudinal spacing of transverse reinforcement
R is 0.5 and 1.0 for tie and spiral reinforcement respectively

For the past 2 decades, cold-drawn steel wire has been used instead of typical transverse reinforcement known as Welded Wire Fabric (WWF). In 1989, Razvi and Saatcioglu were the first researchers who studied WWF for use in concrete columns [4]. Thirty-four reinforced columns with sections 160 mm × 120 mm and 460 mm in height were tested. Columns were wrapped around by conventional ties and WWF, and they were tested by concentric loading. The results showed that it was very favorable but practical difficulties existed in placing WWF in columns, especially when 135° hook ties were used. Furthermore, wrapping WWF around a column would require overlap of WWF, which means more material and more construction labor. They also proposed the confined-concrete model and the expressions to analyze lateral pressure from the concrete core based on the computation of confinement pressure developed from the materials and geometric properties of the column by the following equations [5,6].

$$f'_{cc} = f'_{co} + k_1 k_2 f_l \tag{3}$$

$$f_l = \Sigma \frac{A_{sh} f_{yh}}{s b_c} \tag{4}$$

$$k_1 = 6.7 (k_2 f_l)^{-0.17} \qquad ; f_l \ \text{in MPa} \tag{5}$$

$$k_2 = 0.26 \sqrt{\frac{b_c}{s} \frac{b_c}{s_l} \frac{1}{f_l}} \qquad ; f_l \ \text{in MPa} \tag{6}$$

where

f'_{cc}	is the Confined concrete strength in members
f'_{co}	is the Unconfined concrete strength in members
f_l	is the Average lateral confinement pressure
k_1	are the Coefficients of lateral pressure
k_2	are the Coefficients of confined column
A_{sh}	is the Area of transverse reinforcement
f_{yh}	is the Yield strength of transverse reinforcement
b_c	is the Width of the concrete core
s	is the Longitudinal spacing of transverse reinforcement
s_l	is the Spacing of Longitudinal reinforcement

However, there is limited research concerning WWF in Thailand. This is because of a limitation in welded wire manufacturing and confidence among Thai engineers to use other construction materials without experience or familiarity. Thus, the research at Walailak University is aimed to investigate column behavior reinforced by WWF as transverse reinforcement and to compare with the columns reinforced by conventional ties.

MATERIALS AND METHODS

Test Specimens

The experimental research consisted of 18 square columns with different parameters of confinement; types of transverse reinforcement and volumetric ratio as shown in **Table 1**. Specimens were tested under concentric uniaxial compression by a Tinius Olsen Universal Testing Machine with a capacity of 200 tons until failure. The cross sections of the specimens were 12.5 × 12.5 cm and 60 cm in height. **Figure 1** shows 2 different types of transverse reinforcement.

Table 1 Details of reinforced concrete column specimens.

Specimen	**Type of transverse reinforcement**	**Longitudinal Spacing (cm)**	ρ_{sh} **(%)**	**Number of Samples**
CDR6(2.5)	WWF	2.5	4.13	3
CDR6(5.0)	WWF	5.0	2.06	3
CDR6(7.5)	WWF	7.5	1.38	3
RB6(2.5)	Conventional tie	2.5	4.13	3
RB6(5.0)	Conventional tie	5.0	2.06	3
RB6(7.5)	Conventional tie	7.5	1.38	3

Remark - All specimens used 4-RB9 as longitudinal reinforcement
- ρ_{sh} is a volumetric ratio of transverse reinforcement ($\rho_{sh} = V_{sh} / V_c$)

Figure 1 Two types of transverse reinforcement of column specimens.

Specimen Preparation and Testing Procedure

Round bar diameter 6 mm could be easily bent to the required section, while welded wire fabric could not be bent because it was stiffer than round bar, therefore electrical resistance welding known as spot welding was used to build up the section of transverse reinforcement. Longitudinal and transverse reinforcements were built up depending on the type of transverse reinforcement and longitudinal spacing.

In order to control the failure that might occur at both ends of the column, extra reinforcements were used to protect cracking in corbel due to stress concentration. Then, 3 steel formworks were used to cast each set of specimens. They were cast horizontally with an open surface on the top. Also, 3 standard concrete cylinders were cast at the same time. After concrete setup of about 1 day the formwork was taken off and specimens were covered by moist fabric and left for 28 days. Then, the specimen was set up on the universal testing machine, and steel plate bearings were put at the both ends of the specimen. A dial gauge was attached with a magnetic-base frame to measure overall axial deformation of the column. After the testing set up was ready, a compression force was slowly applied to the specimen at a deformation rate of 0.125 mm/s. Meanwhile, all behaviors were observed at every stage. Eventually, testing was stopped automatically only when the column could not resist the external load from the universal testing machine and this was called the ultimate load.

Mechanical Properties of Materials

The compressive strength of each concrete cylinder was slightly different because of the mixing procedure in the laboratory. Additionally, there were 3 types of steel reinforcement, including round bars RB6 (diameter 6 mm) and RB9 (diameter 9 mm), and cold drawn steel wire CDR6 (diameter 6 mm). The results of the tensile strength test are shown in the **Table 2**.

Table 2 The result of tensile strength test of reinforcements.

Type of Reinforcement	Yield Strength (kg/cm^2)	Ultimate Strength (kg/cm^2)	Elongation (%)
RB6	3471	4716	29.9
RB9	3725	4883	37.3
CDR6	6180	6200	17.1
Concrete	Compressive strength, $f_c^{'} = 310$ kg/cm^2		

RESULTS AND DISCUSSION

Column Behavior

The test results showed that tiny cracks visible at the surface of all columns appeared at about 90 % of the maximum axial force. After the maximum axial force, load capacity began to decrease gradually with more visible signs of cracks and spalled concrete covering as shown in **Figures 2** and **3**. Sometimes, there were loud sounds of fractures.

As a result of using concrete brackets at the top and bottom of all specimens, failure extended in the desired region, at the middle height. All columns failed by buckling of longitudinal reinforcements depending on the spacing of lateral reinforcement and the type of reinforcement. One exception was a column of RB6(2.5) No.2, which failed prematurely due to a vulnerable bracket at the top of the column.

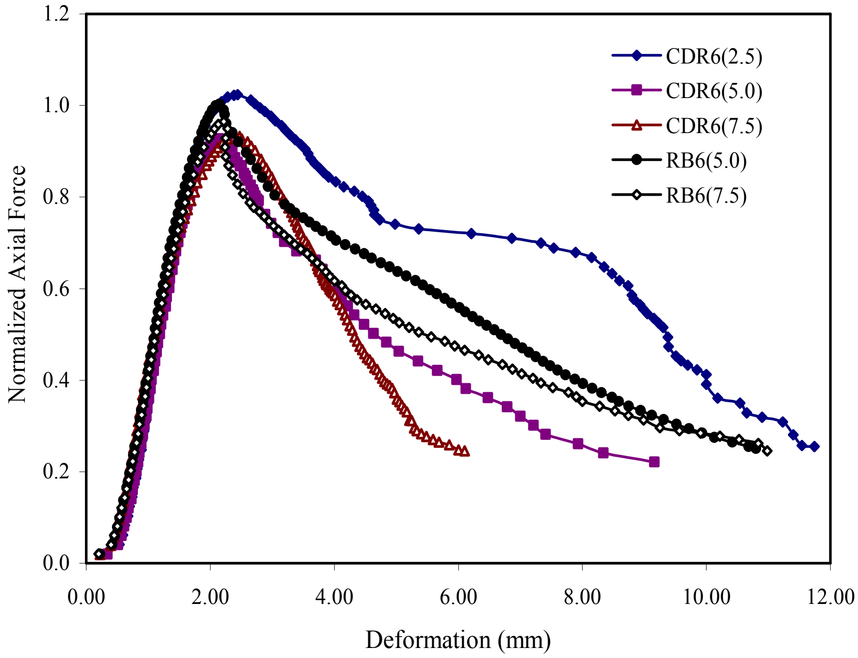

Figure 2 Axial compressive load-deformation curves of column specimens.

Figure 3 Failure in a column specimen.

Columns, reinforced by WWF, were observed to fail as a result of breaking at a welded joint of the WWF which supported the maximum lateral pressure from the concrete core as shown in **Figure 4**. Therefore, at the position of failure of WWF, the effective length of longitudinal reinforcement between supports became more than that with non-deformed WWF. It finally caused lateral buckling in the longitudinal reinforcement. In contrast, columns reinforced by conventional ties shown in **Figure 5**, failed by a mode of extension in the cross tie hook and longitudinal bucking because of high lateral pressure from the concrete core and axial forces. No breaking or yielding in the tie bar was observed.

Figure 4 Breaking at a welded joint of WWF caused failure of specimen CDR 6(2.5).

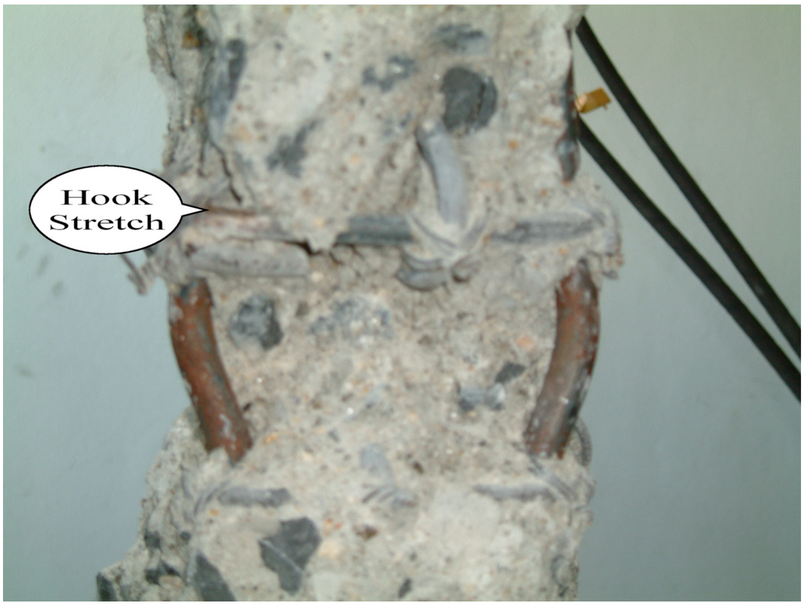

Figure 5 Hook stretch in conventional tie caused failure of specimen RB6(5.0).

Effect of Volumetric Reinforcement Ratio on Column Strength

The results of the compressive strength of concrete cylinders at 28 days were slightly different because of the mixing procedure in the laboratory. The difference will affect the comparison of the strength of the concrete columns with other groups. Therefore, the axial force of the column from the experiments was normalized by dividing the axial forces by the nominal strength (P_0) of reinforced concrete column provided by ACI 318-05.

In the group of columns reinforced by WWF, called the CDR group, the results showed that the average maximum normalized axial force increased slightly when the volumetric reinforcement ratios were increased. For instance, according to **Table 3**, **Figure 6** and **Figure 8**, when the volumetric ratio increased from 2.06 for CDR6(5.0) to 4.13 for CDR(2.5), the average maximum normalized axial force was increased from 0.93 to 0.99.

Table 3 Comparison of the maximum normalized axial force.

Specimen	ρ_{sh} (%)	Maximum Normalized Axial Force			Average
		No.1	No.2	No.3	
CDR6(2.5)	4.13	0.94	1.02	1.01	0.99
CDR6(5.0)	2.06	0.94	0.93	0.93	0.93
CDR6(7.5)	1.38	0.93	0.89	0.88	0.90
RB6(2.5)	4.13	1.01	1.02	1.03	1.02
RB6(5.0)	2.06	0.99	1.00	1.00	1.00
RB6(7.5)	1.38	0.95	0.98	0.97	0.97

Remark $P_0 = 0.85f'_c(A_g\text{-}A_{st})+f_yA_{st}$

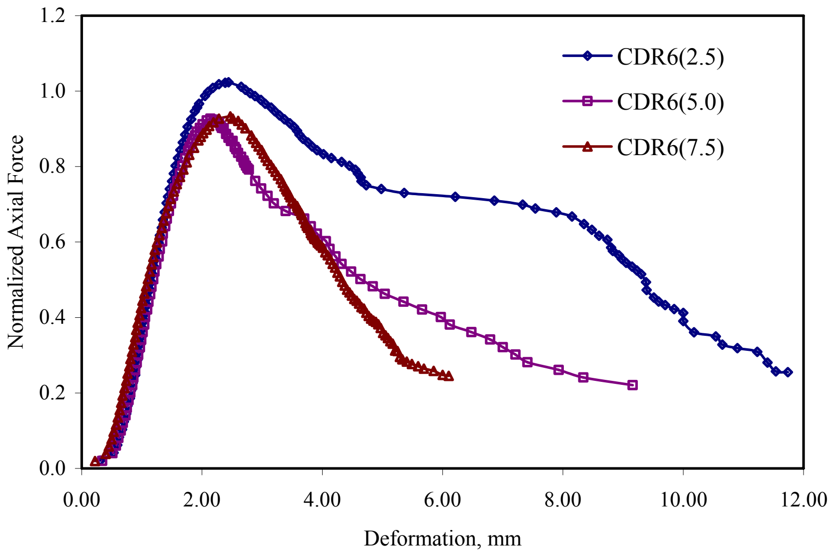

Figure 6 Uniaxial compressive load-deformation curves of column specimens by using Welded Wire Fabric (CDR group).

Columns reinforced by conventional ties, called the RB group, had the same trend as the CDR group. That is the average normalized axial force increased slightly when the volumetric reinforcement ratios were increased. From **Table 3**, **Figure 7** and **Figure 8**, the average maximum normalized axial force increased from 1.00 to 1.02 when the volumetric ratio was increased from 2.06 to 4.13 for RB(5.0) and RB(2.5), respectively.

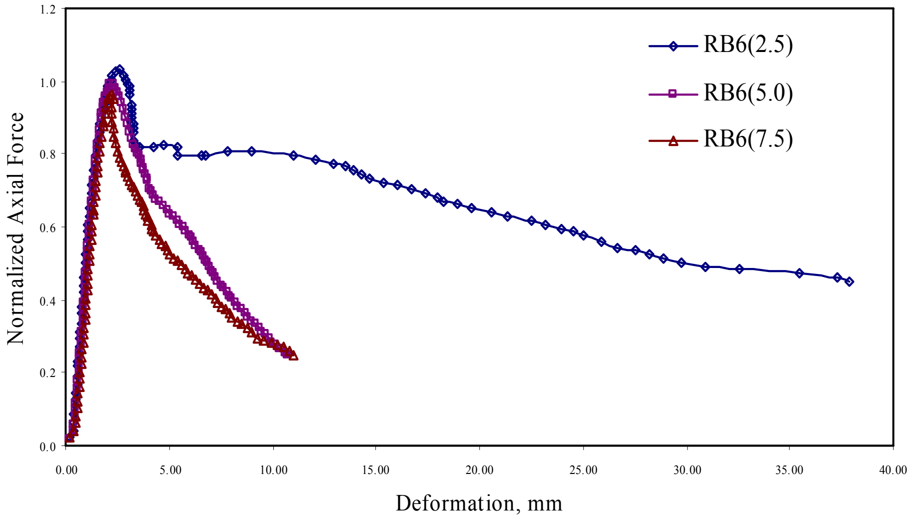

Figure 7 Uniaxial compressive load-deformation curves of column specimens by using conventional ties (RB group).

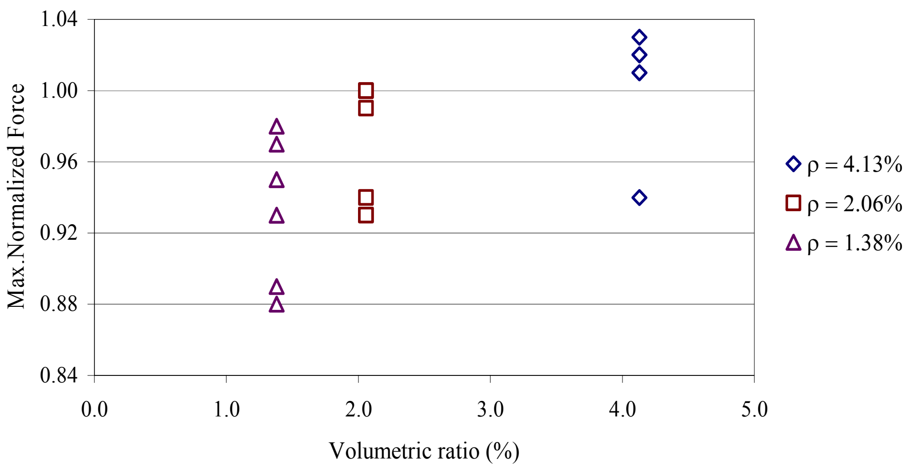

Figure 8 Relationship between maximum normalized force and volumetric ratio.

Effect of Volumetric Reinforcement Ratio on Column Ductility

Ductility is a very important factor especially for seismic design. According to the maximum axial load and failure load obtained from the relationship between load and deformation, this research provided a ductility index that illustrated the ratio between deformation at failure and deformation at maximum load shown in **Table 4** and **Figure 9**.

The results of columns reinforced by WWF, the CDR group, showed that the average ductility index increases when the volumetric reinforcement ratios were increased. **Table 4** and **Figure 6**, show that when the volumetric ratio was increased from 1.38 for CDR6(7.5) to 4.13 for CDR(2.5), the average ductility indices increased from 2.62 to 4.85.

The results of columns reinforced by conventional ties, the RB group, showed that the average ductility indices increased from 5.07 to 14.51 when the volumetric ratios increased from 2.06 for RB6(5.0) to 4.13 for RB6(2.5).

Moreover, the results showed that deformation at maximum load for all columns was found between 1.82 and 3.28, while deformation at failure load of all columns varied in a wide range between 6.10 and 42.35. This indicated that the effect of confining pressure from lateral reinforcements was influential in the concrete core after the maximum axial force was applied. This is referred to as the post peak effect.

Table 4 Comparison of deformation and ductility index.

Specimen	ρ_{sh} (%)	Deformation (mm) at						Average Ductility Index, Δ_f/Δ_p
		Maximum load, Δ_p			Failure load, Δ_f			
		No.1	No.2	No.3	No.1	No.2	No.3	
CDR6(2.5)	4.13	3.28	2.44	2.22	14.80	11.74	11.60	4.85
CDR6(5.0)	2.06	2.08	2.37	2.14	8.66	9.69	9.16	4.18
CDR6(7.5)	1.38	2.47	2.51	2.23	6.10	6.36	6.40	2.62
RB6(2.5)	4.13	2.97	2.02	2.57	42.35	-	37.92	14.51
RB6(5.0)	2.06	2.34	2.58	2.15	10.69	14.50	10.80	5.07
RB6(7.5)	1.38	1.82	2.25	2.22	10.10	12.10	10.98	5.29

<u>Remark</u> Δ_f of column RB6(2.5) No. 2 failed prematurely due to Bracket failure

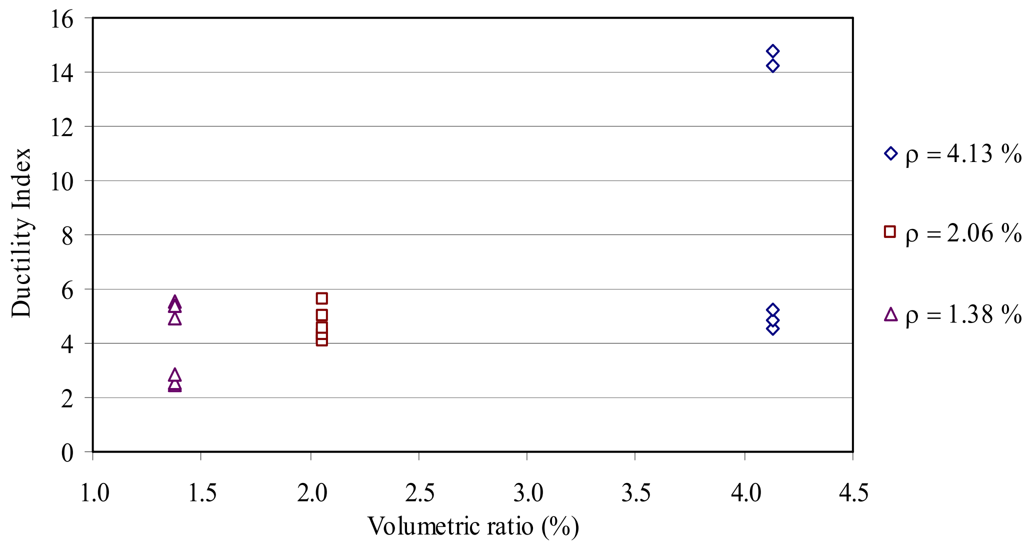

Figure 9 Relationship between ductility index and volumetric ratio.

Comparison Between Conventional Tie and WWF as Transverse Reinforcement

The comparison of the maximum normalized axial force between columns reinforced by WWF and conventional ties are shown in **Table 6** which indicates that the maximum normalized axial forces in the RB group were slightly greater than those in the CDR group. The results shown in **Table 5** and **Figures 10** to **12** indicate that columns reinforced by Welded Wire Fabric have ductility indices less than columns reinforced by conventional ties.

Table 5 Comparison of maximum normalized axial force and ductility index between WWF and conventional ties.

Specimen	ρ_{sh} (%)	Maximum Normalized Axial Force	Ductility Index, Δ_f/Δ_p
CDR6(2.5)	4.13	0.99	4.85
CDR6(5.0)	2.06	0.93	4.18
CDR6(7.5)	1.38	0.90	2.62
RB6(2.5)	4.13	1.02	14.51
RB6(5.0)	2.06	1.00	5.07
RB6(7.5)	1.38	0.97	5.29

Table 6 Comparison of maximum normalized axial force between theoretical and experimental results.

Specimen	ρ_{sh} (%)	f'_{cc}/f'_{co}			Percentage difference (%) compared with	
		Chan	Saatcioglu	Experiment	Chan	Saatcioglu
CDR6(2.5)	4.13	2.78	1.60	1.69	–39.2	+5.6
CDR6(5.0)	2.06	1.86	1.33	1.56	–16.1	+17.3
CDR6(7.5)	1.38	1.55	1.22	1.50	–3.2	+23.0
RB6(2.5)	4.13	1.91	1.43	1.75	–8.4	+22.4
RB6(5.0)	2.06	1.47	1.25	1.70	+15.6	+36.0
RB6(7.5)	1.38	1.33	1.19	1.63	+22.6	+37.0
		Average			–4.8	+23.5

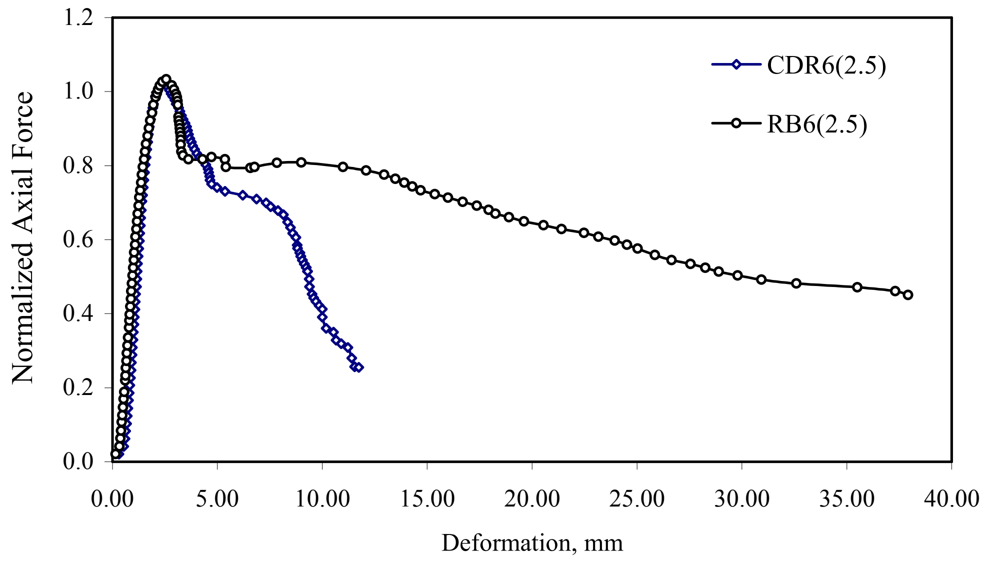

Figure 10 Load-Deformation relationship between CDR6(2.5) and RB6(2.5).

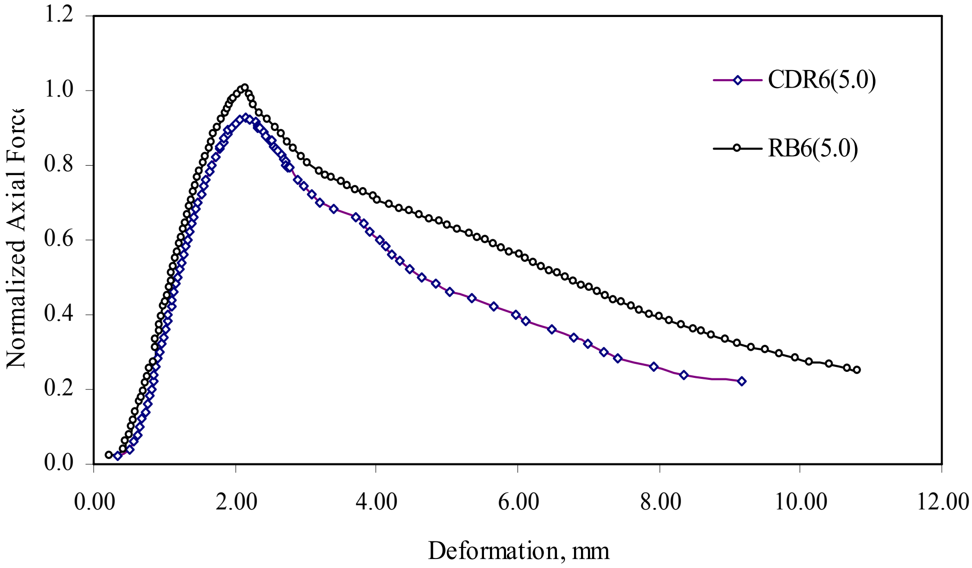

Figure 11 Load-Deformation relationship between CDR6(5.0) and RB6(5.0).

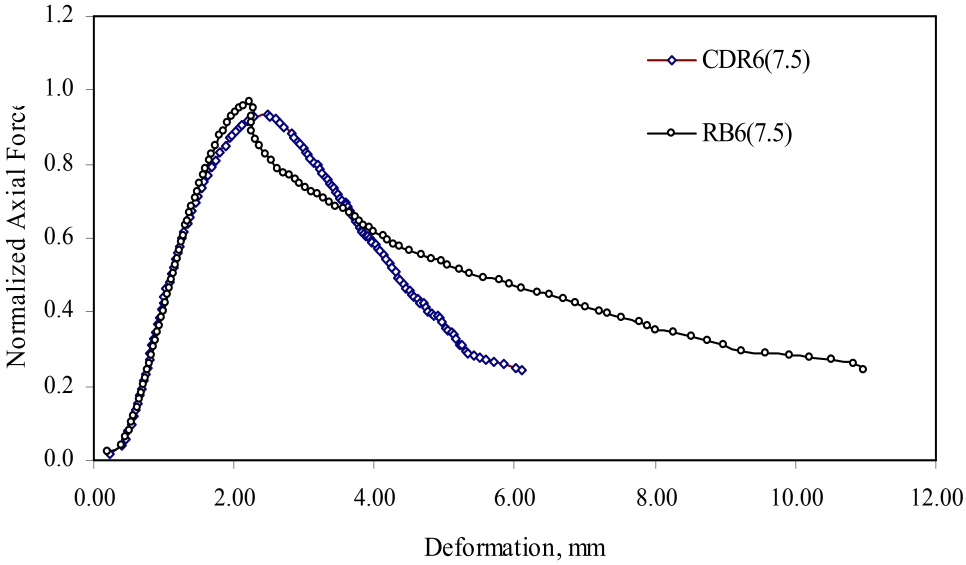

Figure 12 Load-Deformation relationship between CDR6(7.5) and RB6(7.5).

The columns with 7.5 cm longitudinal spacing, CDR6(7.5) and RB6(7.5), have a ductility index of 2.62 and 5.29, respectively. On the other hand CDR6(5.0) and RB6(5.0) have a ductility index of 4.18 and 5.07, respectively. This suggests that columns reinforced by conventional ties have a slightly better ductile efficiency than columns reinforced by WWF. In the group of columns with 2.5 cm longitudinal spacing, their ductility indices are distinctly different. Thus the ductility index of RB6(2.5) is 14.51, while CDR6(2.5) is only 4.85. This is because the characteristic lateral reinforcements have different modes of failure. Conventional ties can withstand lateral pressure from the concrete core to a larger extent than WWF due to hook stretching, while the welded joint of WWF brakes and therefore cannot restrain the lateral buckling that occurs in longitudinal steel. Therefore, it can be concluded that columns reinforced by conventional ties have more ductility than columns reinforced by WWF when the volumetric ratios are equal.

Comparison of Theoretical and Experimental Results

In this research, the results from the experiment can be compared with 2 previous constitutive models provided by Chan [3] and Saatcioglu [5] as shown in **Table 6**.

The ratio f'_{cc}/f'_{co} is the relationship between maximum compressive stress of the column confined by transverse reinforcement and an unconfined concrete column. The difference between experimental and theoretical results are shown in **Table 6** and can be described as follows.

The experimental results compared with Chan's formula have a range of difference percentage between −39.2 and +22.6. If we consider the 2 groups (the CDR group and RB group) separately, we found that the CDR group is on average about 19.5 % lower than the theoretical results, while the RB group is 9.9 % higher than the theoretical results.

Chan [3] proposed his confined concrete model based on the formula of confined concrete under hydrostatic pressure provided by Richart and co-workers [1] in which the effect of configuration and welding of transverse reinforcement was not taken into account. Therefore, it could be concluded that Chan's formula is appropriate for conventional ties, the RB group, rather than the WWF group.

Unlike Chan's formula, the experimental results compared with Saatcioglu's formula showed only a positive percentage difference from +5.6 to +37.0, while Chan's formula showed both positive and negative differences when compared with the experiments. The CDR group is on average 15.3 % higher than the theoretical results, while the RB group is 31.8 % higher than the theoretical results. This is because Saatcioglu's formula took the effect of configuration and welding of transverse reinforcement into account. Additionally, he proposed that his formula could be used for WWF as well as conventional ties. So, the experiments showed clearly a positive sign when they were compared with Saatcioglu's formula.

However, both formulae did not consider the effect of hook stretching and broken welded joints into account. This might be a reason why the experimental results and the theoretical results were different. This was because during the experiment in the laboratory that modes of failure between the 2 groups of column specimens were different.

CONCLUSIONS

From the beginning of the uniaxial testing, all columns confined by transverse reinforcement distinctly showed a linear elastic relationship between the axial force and axial deformation. Until at about 90 % of maximum load, column specimens showed tiny cracks at the middle height of the column and some fracture sounds were noted. A minute later, the axial force and deformation curve decreased rapidly after it reached a maximum axial force. Then 1 or more surfaces of the column showed clear signs of covering failures. However the column still carried more load due to the effect of confinement. Eventually, column failure was reached when 1 or both the concrete core and transverse reinforcement failed.

The most important factor in the strength and ductility of the confined column was the volumetric ratio of transverse reinforcement. The strength of the column increased slightly when the volumetric ratio increased. Also, the ductility of the column had the same trend as the strength of column. However, the difference between the strength and ductility was that the increase in the ductility was clearer than the strength, when comparing columns reinforced by low and high volumetric reinforcement.

Comparison of Welded Wire Fabric (WWF) and conventional tie bars as transverse reinforcement with equal sizing and longitudinal spacing indicated that the maximum strength capacity of the column reinforced by WWF and conventional ties were able to withstand the same uniaxial load. The comparison of ductility showed that columns reinforced by WWF had ductility indices less than columns reinforced by conventional ties. This was because WWF showed brittle behavior in which welded joints suddenly failed when subjected to lateral pressure from the concrete core, while conventional ties showed ductile behavior due to hooks being stretched.

The experimental results of all specimens were about 4.8 % less than the theoretical results proposed by Chan. However, the experimental results are 23.5 % greater than that predicted by Saatcioglu's formula. Therefore, it can be concluded that Saatcioglu's formula is more practical than Chan's formula for confined concrete columns. This is because Saatcioglu's formula considers the size of the rebar, longitudinal spacing of the transverse reinforcement, column shapes and reinforcement configurations in his constitutive model of confinement, while Chan's formula takes only size and longitudinal spacing into account.

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บทคัดย่อ

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พฤติกรรมเสาสั้นคอนกรีตเสริมเหล็กโดยใช้ตะแกรงลวดเชื่อมเป็นเหล็กเสริมตามขวางภายใต้แรงกระทำตรงศูนย์

งานวิจัยนี้ศึกษาพฤติกรรมเสาคอนกรีตเสริมเหล็กซึ่งใช้ตะแกรงลวดเชื่อม WWF เป็นเหล็กเสริมตามขวางภายใต้แรงกระทำตรงศูนย์ เพื่อนำไปเปรียบเทียบกับเสาคอนกรีตเสริมเหล็กซึ่งใช้เหล็กเส้นกลมเป็นเหล็กเสริมตามขวาง โดยเสาทั้งสองชนิดมีอัตราส่วนเหล็กเสริมตามขวางเท่ากัน นอกจากนี้ได้ศึกษาผลของระยะห่างตามยาวของเหล็กเสริมตามขวางต่อกำลังและความเหนียวของเสา โดยทำการศึกษาเสาตัวอย่าง 6 ตัวอย่าง ผลการทดลองแสดงให้เห็นว่ากำลังและความเหนียวของเสาเพิ่มขึ้นเมื่ออัตราส่วนเหล็กเสริมตามขวางเพิ่มขึ้น อย่างไรก็ตามดัชนีความเหนียวของเสาซึ่งเสริมด้วย WWF มีค่าน้อยกว่าเสาซึ่งเสริมด้วยเหล็กเส้นกลม ทั้งนี้เนื่องจาก WWF เกิดการวิบัติบริเวณรอยเชื่อม ทำให้ไม่สามารถต้านทานแรงดันทางด้านข้างจากแกนเสา ในขณะที่ตะขอของเหล็กเส้นกลมสามารถยืดตัวได้ทำให้สามารถต้านทานแรงดันด้านข้างจากแกนเสาได้ดีกว่า นอกจากนี้ได้ทำการเปรียบเทียบผลการทดลองกับแบบจำลองที่เสนอโดย Saatcioglu และ Chan พบว่าแบบจำลองที่เสนอโดย Saatcioglu เหมาะสมสำหรับเสาที่บีบรัดแกนมากกว่าแบบจำลองของ Chan แต่ทั้งนี้ควรคำนึงถึงลักษณะการวิบัติของเหล็กเสริมตามขวางซึ่งมีผลต่อความเหนียวของเสา

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