MINIMUM LATERAL REINFORCEMENT IN REINFORCED CONCRETE COLUMNS

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ABSTRACT

The ACI Building Code (ACI 318-99) requires minimum lateral ties or links of at least 3/8 (#3) inch in diameter and spaced not over 16 bar diameters, 48 ties diameter, or the least dimension of the column. When more than four bars are used, additional ties are to be provided so that longitudinal bar is held firmly in its position and has lateral support equivalent to that provided by a 90 degree corner of a link exempting bars which are located within 6 inches clear on each side along the tie from adequately tied bars. The British Standard BS 8110 also gives requirements for the provision of minimum links in columns. The ties are limited to at least ¼ the size of the largest longitudinal compression bar with a maximum spacing of 12 times the size of the smallest compression bars. Review of other codes of practice also reveal similar limitations in design for ties in reinforced concrete columns.

The aim of the work presented in this paper is to study the significance of minimum link requirements and to determine the effect, if any, on the ultimate capacity of the column and providing a lower amount of lateral reinforcement.

Keywords: columns, stirrups, links, lateral reinforcement, axial load

INTRODUCTION

Stirrups (or links) have traditionally been provided with a view toward reducing the possibility of local buckling of longitudinal reinforcement when the load approaches the ultimate strength of the column. For this reason, all codes of practice (CP110,1972) (BS8110,1985) (ACI,1999) (Egyptian Code, 1995), give requirements for minimum links in columns which are the diameter of the stirrups and the spacing between them.

The above requirements on the stirrups may lead to a high amount of lateral reinforcement. The purpose of the present work is intended to give an indication of the minimum lateral reinforcement required to achieve the full capacity of reinforced concrete axially loaded column. This may lead to an economy resulting from a reduction in the amount of lateral steel used, and elimination or reduction in the amount of internal tie elements, which would lead to several other benefits. The detailing and fixing of the column reinforcement would be simplified, and the placing and compaction of the concrete within the core of the column would be facilitated. This last benefit could result in an increase in the core strength (Larsson, 1975). In addition, tie arrangements involving several interior ties will probably impede the compaction and settlement of the concrete in the core to a considerable extent. Therefore, such tie arrangements may decrease the column strength under practical construction conditions.

In this paper, 24 square tied columns were tested under concentric load to explore the influence of the diameter and spacing of lateral reinforcement on the strength and behavior of reinforced concrete columns.

REVIEW OF PREVIOUS WORK

The provision of links in reinforced concrete columns may increase the capacity of a column in two ways, firstly by preventing buckling of the main longitudinal reinforcement and, secondly, if sufficient lateral reinforcement is provided by restraining the central core of concrete which, being in triaxial compression, can sustain a higher load.

King (1946) presented the first comprehensive investigation into this subject. He demonstrated the importance of links, preventing the buckling of main steel. Tests showed a steady increase in column capacity with increasing number of links. He concluded that, for the particular columns tested, the capacity was related to the amount of longitudinal and lateral steel by the following expression:

$$N = 0.865W + 0.883X + 1.5Y + 0.3Z \qquad (1)$$

where: W = Concrete capacity = $A_c.f_{cu}$
X = Main steel capacity = $A_s.f_y$
Y = Yield load of links / pitch^2 = $A_{sv}.f_{ysv}/S_v^2$
Z = Product of X and Y.

The paper makes no reference to a minimum link requirement nor does it indicate any change in behavior at a particular number links.

Other investigation was carried out by Bunni (1975). He also demonstrated the influence of links, leading to considerable increases in column capacity. He describes this to both containment of the core and also the preventation of buckling of the main steel. However, he concluded that the spacing of the ties is more significant than their size in influencing the ultimate load capacity. Again, no mention is made of minimum stirrup requirements.

Bresler and Gilbert (1961) considered both the buckling mechanism and the restraint of the core concrete after the outer skin of concrete had spelled away. The investigation was largely theoretical with tests on only 4 columns. They concluded that to develop the strength of the core, the tie spacing should not exceed the least lateral dimension of the column. The maximum stirrups spacing of the main reinforcement is related to its yield strength as follows:

For $f_y = 250$ N/mm^2 spacing S = 18.5 Ø
$f_y = 410$ N/mm^2 spacing S = 14.5 Ø
$f_y = 460$ N/mm^2 spacing S = 14 Ø
These are somewhat larger than 12 Ø specified by the code (BS 8110, 1985).

Further tests were carried out by Pfister (1964). He concluded that the primary function of ties is to provide lateral restraint for the concrete, causing the columns to fail in a more gradual way than if no ties were present. He also found that the number of interior ties in columns with larger number of main bars could reasonably be reduced. Columns with ties carried slightly more load than those without but he drew no conclusions about the minimum tie requirements except that the ACI figures were satisfactory.

Buckling of longitudinal steel in columns was also reported by Somerville and Taylor (1972) in their investigation into the influence of reinforcement detailing. However, it would appear that there is no generally agreed explanation for the increase in column capacity with increasing amount of stirrups and its minimum value. The requirements are probably based on the judgment of the drafting committee as to what would be a reasonable diameter and spacing of the stirrups.

TEST SPECIMENS

All test columns were 12 x 12 cm in cross section with an overall length of 56 cm. Each column was reinforced longitudinally by 4 bars, 8 mm diameter. The principal variables considered in the test program were the spacing and the size of the stirrups. The test program was divided into three series each consisted of eight columns, one column had no stirrups and the other seven columns had stirrups spacing ranged between 6.25 cm and 25 cm. Each series had constant stirrups size of 2mm, 4mm and 6mm diameter for series A, B and C respectively.

At both ends of all columns, three stirrups, 6 mm diameter were grouped closely together to prevent end splitting of the column under load. The elevations, sections and distribution of lateral reinforcement along the length of the columns are shown in Figure 1.

TEST DETAILS

The columns are cast in a wooden moulds mounted on a vibrating table, stripped after 24 hours and cured under plastic sheating in the laboratory conditions. Steel plates were used at the ends of the columns to give smooth faces. The ends of the columns were also bedded into layers of plaster during setting up to give an even distribution of load. The columns were tested at 28 days to failure using a testing machine of capacity 100 tons as shown in Figure 2. The rate of testing was controlled which was decreased as the load approached the failure load.

100 mm cubes were also cast with each series and cured in water and with the specimens. Some of the cubes were tested at 7 days (cured in water and with specimens) and the others were tested at the same day as those of the columns. Details of cube tests for all series are shown in Table 1.

TABLE 1
Concrete Cube Strength Details

		Cube Curing			
		With Specimens		In Water	
Series	Age at test (days)	No. of Cubes	Average Cube Strength (kg/cm^2)	No. of Cubes	Average Cube Strength (kg/cm^2)
A	7	2	165	2	175
	28	4	243	4	303
B	7	2	154	2	175
	28	4	294	4	332
C	7	2	140	2	170
	28	4	216	4	234

Steel samples of 40 cm length were taken from the main longitudinal bars (8mm diameter) and from the links (2mm, 4mm and 6mm diameter). These were tested in tension to determine the ultimate strength of steel reinforcement. Details of the steel samples used in the columns are shown in Table 2.

TABLE 2
Steel Reinforcement Details

				Yield Strength Kg/cm^2		Ultimate Strength Kg/cm^2	
Steel Bars	Sample No.	Nominal Diameter (mm)	Actual Diameter (mm)	Individual	Average	Individual	Average
Lateral Reinf.	T12	2	2.017	4100	4125	5100	5126
	T22	2	2.038	4150		5152	
	T41	4	3.994	4300	4265	5347	5227
	T42	4	3.994	4230		5107	
	T61	6	5.924	5225	5238	5552	5562
	T62	6	5.894	5242		5572	
Long. Reinf.	T81	8	7.99	3490	3275	4128	4091
	T82	8	8.003	3360		4055	

A manual strain gauge was used and attached at the middle height of each vertical face of the columns. The gauges were used to monitor the progress of the tests and to ensure that loading was reasonably uniform across the cross section of the column. Unequal loading between one side and the other could be detected at the early stages of the test and corrected by moving the lower end of the column to one side or the other.

TEST RESULTS

The columns tested failed in one of the following modes:

1. Combined compression and / or yielding failure: columns failed in this mode as a result of buckling of the longitudinal reinforcement either between the stirrups or at the position of the stirrups which was followed by yielding of the stirrups. In both cases, the concrete shell spalled off and the core failed immediately in compression. Examples of such failure, are columns of series A, columns B1, B2, B3 and B4 and columns C1 and C2.
2. Combined compression and buckling failure: this mode of failure is characterized by buckling of longitudinal reinforcement and failure of the concrete shell. As a result, the stiffness of the section was greatly reduced resulting in buckling of the column as a whole, followed by failure of the core in compression. This mode occurred in columns with high amount of lateral reinforcement. Examples of such failure are columns B5, B6, B7 and B8 and columns C4, C5, C6, C7, C8. A typical failure is shown in Figure 3.

The ultimate loads carried by the columns are given in Table 3. They depended on the diameter and spacing of the stirrups and were between 30.1 tons and 33.5 tons for series A, between 34.5 tons and 38.7 tons for series B and between 25.9 tons and 29 tons for series C. That is a maximum percentage change of 13%. However, the cube strength of the concrete varied from series to series and to remove the effect of this variability, the failure loads were divided by the appropriate cube strength, giving factors that varied between 99.34 and 121.12. The failure loads were also compared with the ultimate loads calculated from the following equation (Handbook – BSI 8110, 1985):

$$N_{cal} = 0.67A_c f_{cu} + A_s f_y \qquad (2)$$

where: f_{cu} = Cube compression strength measured on 100mm cubes
A_c = Concrete cross sectional area
f_y = Yield strength of longitudinal steel
A_s = Cross sectional area of longitudinal steel

It can be seen from Table 3 that, for all columns, the actual ultimate strength measured in the tests was within 13 percent of the calculated ultimate strength. N_{test}/N_{cal} varied between 0.84 and 1.002. In series A, the ultimate load increased as the spacing decreased and even for the smallest spacing of the stirrups, N_{test}/N_{cal} = 0.935. In series B, the ultimate load increased as the stirrups spacing decreased until a certain value (S = 12.5 cm) which is equivalent to a ratio of the stirrups area / (spacing x column dimension) $A_{sv}/(S_v.b) \cong 0.1\%$ and the volume of the stirrups / volume of concrete $V_{st} / V_c \cong 0.29\%$. Thereafter, the ultimate

TABLE 3
Test Results

	Stirrups Details									
Col. No.	Size of Stirrups (mm)	Spacing (cm)	No. of Stirrups	$A_{sv}/(S_v.b)$ x 10^{-3}	V_{st}/V_c x 10^{-2}	Test Values N_{test} (tons)	Calc. Values N_{cal} (tons)	N_{test}/f_{cu}	N_{test}/N_{cal}	% Increase in Load
A1	2.027	-	0	0	0	30.1	35.812	99.34	0.84	0
A2	2.027	25	1	0.1075	0.0376	31.22	35.812	103.03	0.871	3.72
A3	2.027	16.5	2	0.1629	0.057	31.73	35.812	104.72	0.886	5.415
A4	2.027	12.5	3	0.215	0.0753	32.17	35.812	106.17	0,898	6.877
A5	2.027	10	4	0.269	0.0941	32.56	35.812	107.45	0.909	8.172
A6	2.027	8.3	5	0.324	0.1134	32.93	35.812	108.68	0.919	9.402
A7	2.027	7.1	6	0.3788	0.1326	33.25	35.812	109.73	0.928	10.465
A8	2.027	6.25	7	0.4304	0.1506	33.5	35.812	110.56	0.935	11.295
B1	3.994	-	0	0	0	34.5	38.614	103.91	0.893	0
B2	3.994	25	1	0.4175	0.1461	37.1	38.614	111.74	0.960	7.536
B3	3.994	16.5	2	0.6326	0.2214	37.96	38.614	114.33	0.983	10.028
B4	3.994	12.5	3	0.835	0.2923	38.4	38.614	115.66	0.994	11.304
B5	3.994	10	4	1.044	0.3654	38.6	38.614	116.26	0.999	11.884
B6	3.994	8.3	5	1.2578	0.4402	38.4	38.614	115.66	0.994	11.304
B7	3.994	7.1	6	1.4704	0.5146	38.5	38.614	115.96	0.997	11.594
B8	3.994	6.25	7	1.67	0.5846	38.7	38.614	116.56	1.002	12.174
C1	5.909	-	0	0	0	25.9	29.45	109.28	0.879	0
C2	5.909	25	1	0.914	0.3199	28.9	29.45	121.94	0.981	11.583
C3	5.909	16.5	2	1.385	0.4847	29.3	29.45	123.62	0.995	13.127
C4	5.909	12.5	3	1.828	0.6398	29.4	29.45	124.05	0.998	13.513
C5	5.909	10	4	2.285	0.7998	29.25	29.45	123.417	0.993	12.934
C6	5.909	8.3	5	2.753	0.9636	29.15	29.45	122.99	0.989	12.548
C7	5.909	7.1	6	3.218	1.1265	29	29.45	122.36	0.984	11.970
C8	5.909	6.25	7	3.656	1.2797	29.2	29.45	123.21	0.991	12.741

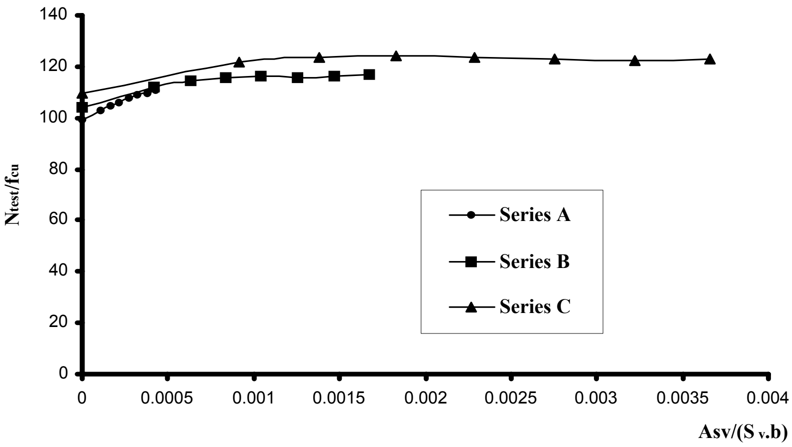
strength of the columns remained approximatly constant and the ratio of the test values to the calculated values approaches to 1. Whereas, in series C, the ultimate strength of the column increased significantly at spacing S = 25 cm. For the column with spacing S = 16.5 cm, the ultimate strength increased only slightly. Thereafter, the ultimate strength remained approximately constant indicating a limiting value of $A_{sv}/(S_v.b) \cong 0.12\%$ and $V_{st}/V_c \cong 0.38\%$. Figures 4 and 5 show the variations of the ultimate capacity with $A_{sv}/(S_v.b)$ and V_{st}/V_c for all columns which indicated that full strength of the columns were achieved when $A_{sv}/(S_v.b) \cong 0.1\%$ and $V_{st}/V_c \cong 0.3\%$.

It can also be seen that the percentage increase in the ultimate strength of the columns varies significantly for columns with one stirrups only. That is, 3.72% for series A, 7.53% for series B and 11.58% for series C. Figure 6 shows such variations with $A_{sv}/(S_v.b)$ and V_{st}/V_c for all columns with maximum value of 13%. It is also indicated that the rate of increase in load decreased as the spacing is reduced.

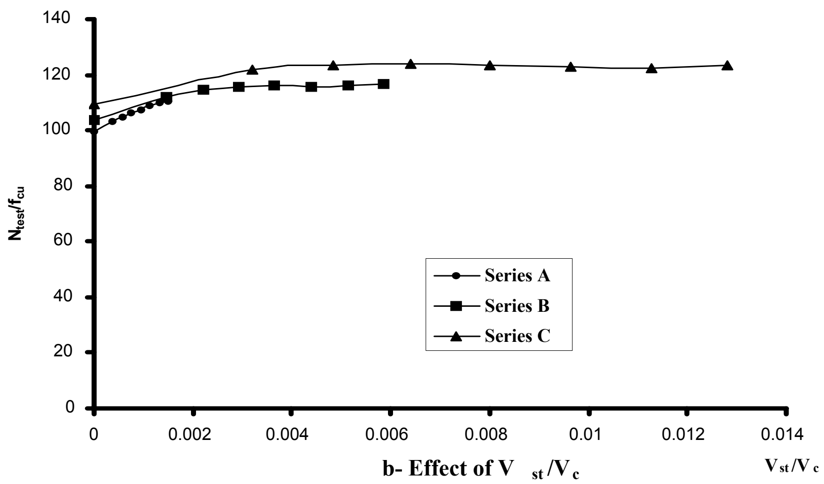
CONCLUSIONS AND RECOMMENDATIONS

Based on the limited model column tests and the varibles (only one size of longitudinal reinforcent and one layer of transversal reinforcement) considered in the test program, it can be concluded that :

1. The primary function of the stirrups in an axially loaded column is to provide lateral restraint for the concrete.
2. The lateral restraint causes the column to fail in a more gradual manner than could be the case if stirrups were not provided.
3. The concrete achieved its full strength when the amount of lateral reinforcement reached a certain value. This value depends on the diameter of the stirrups and the spacing between them. From the experimental work carried out in this study, it seems reasonable to limit the lateral reinforcement which are represented by the ratio $A_{sv}/(S_v.b)$ and V_{st}/V_c, to the larger of 0.1% and 0.3% respectively. These limits showed that full capacities of the test columns are achieved.
4. The test columns behave differently when they have a large percentage of lateral reinforcement specially towards their ultimate load. Their mode of failure changes from buckling of longitudinal steel between the stirrups or at the position of the stirrups to buckling of the column as a whole resulting in crushing of the concrete core in compression.
5. The limited test results indicated that the area of transversal reinforcement given by the codes of practice in reinforced concrete columns could be reduced provided that the above limitations on the stirrups are achieved.

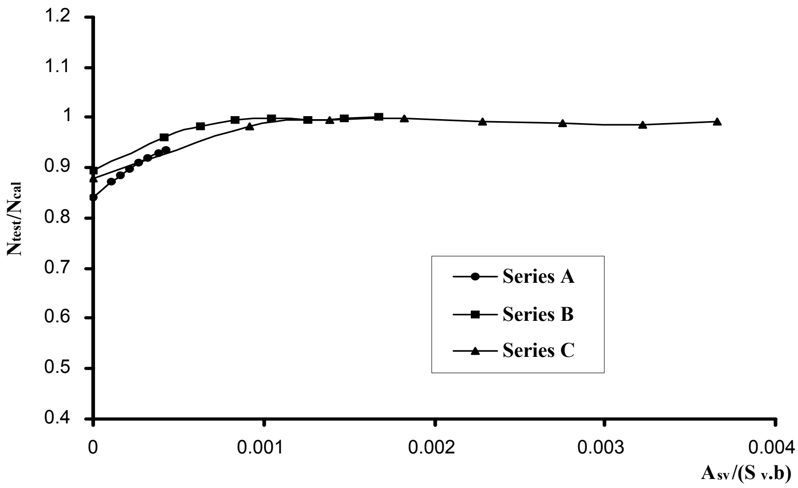


a- Effect of $A_{sv}/(S_v.b)$

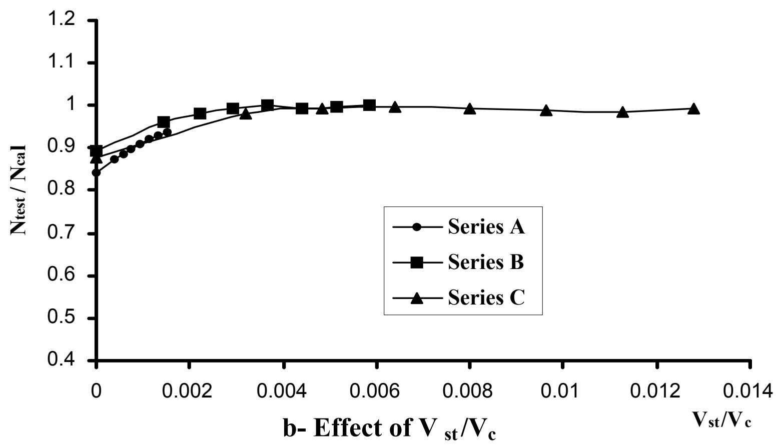


b- Effect of V_{st}/V_c

Figure 4- Effect of Stirrups size and spacing

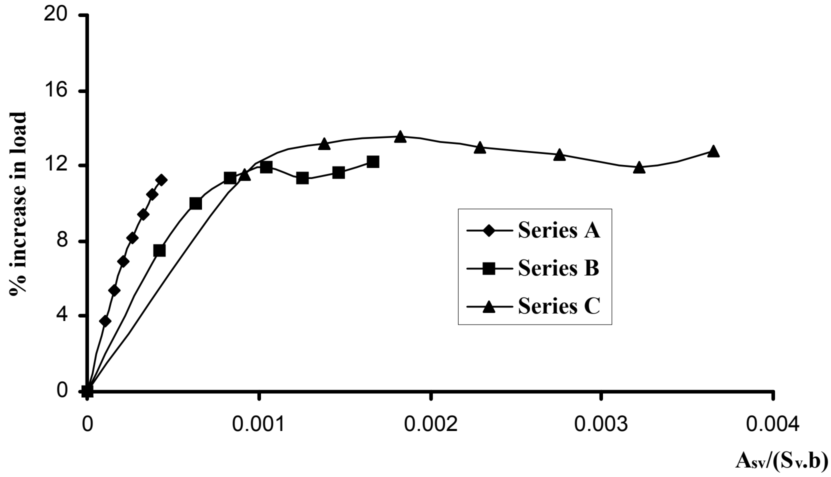


a- Effect of $A_{sv}/(S_v.b)$

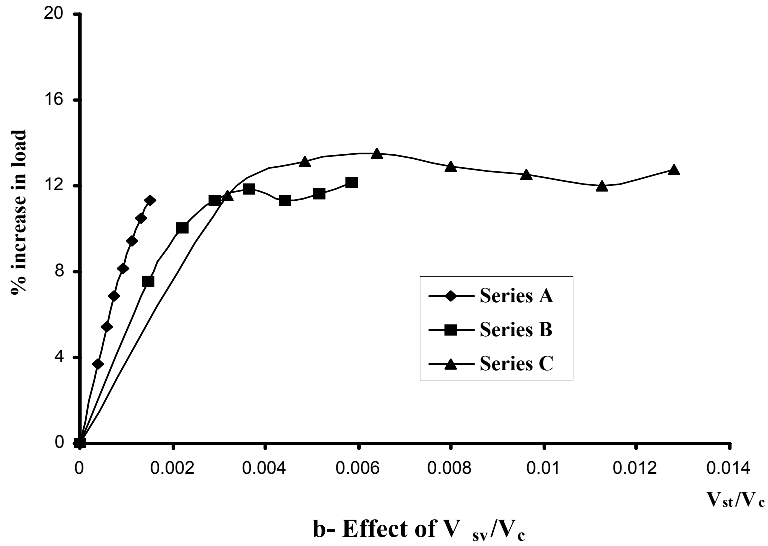


b- Effect of V_{st}/V_c

Figure 5- Comparison between the test values and equation 2



a- Effect of $A_{sv}/(S_v.b)$



b- Effect of V_{sv}/V_c

Figure 6- Percentage increase in load

For further work, tests are required on columns using different yield strengths for longitudinal reinforcement so that a relation between the yield strength of the steel bars, its diameter and the spacing between the stirrups may be obtained. However, realizing the idealization made in this study and the limited scope of the testing program described in this paper, the authors consider further a multi-phase experimental program covering a much larger column scale and variables is highly desirable.

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