STRENGTH AND DEFORMABILITY FOR AXIALLY LOADED REINFORCED CONCRETE COLUMNS CONFINED WITH WELDED WIRE FABRIC

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ABSTRACT

A comprehensive study on the strength and deformability of confined reinforced concrete columns were investigated based on available experimental data. The aim of this paper is to investigate the applicability of SNI 03-2847 Building Code provisions to reinforced concrete columns confined by welded wire fabric (WWF). In particular, design of columns subjected to axial loads. The results further indicate that the product of the confinement effectiveness coefficient, volumetric ratio and strength of confinement WWF, normalized with respect to concrete strength, can be used as a design parameter.

Keywords: code, columns (supports), confinement, deformation, ductility, reinforced concrete, strength, WWF.

1. INTRODUCTION

Reinforced concrete columns in seismically active regions are required to be confined with properly designed and detailed transverse reinforcement. Parameters of confinement include the amount, spacing, grade, and arrangement of the transverse reinforcement, percentage and distribution of longitudinal reinforcement. A proper combination of these parameters results in strength and ductility enhancements in core concrete, which in turn improves the behavior of the column. Conventional confinement reinforcement used for square and rectangular columns consist of perimeter hoops, overlapping hoops, and crossties with 135 deg bends and bend extensions properly anchored into the core concrete.

The requirements of confinement reinforcement for such columns often result in high volumetric ratios, close spacings, overlapping of hoops, and bends and bend extensions. Although these requirements are necessary for improved behavior of earthquake resistant columns, they may lead to the congestion of the column cage and create constructability problems. Therefore, practical and cost efficient solutions are needed, different from those conventionally used to confine concrete. It is further evident that more research is needed to develop an analytical approach to the behavior of compression reinforcement in concrete columns. Alternative reinforcement, in the form of welded wire fabric (WWF), was considered in this study. The use of WWF as lateral reinforcement appears to have great potential in increasing the strength and ductility of reinforced concrete columns (Holland 1995; Hong 1997; Mau et al. 1998; Lambert and Tabsh 2001). This is because WWF uniformly confines all areas of the concrete core to a greater degree than attainable using conventional ties.

Current SNI 03-2847 code provisions were derived from tests of columns reinforced with conventional bars and ties, are not applicable to columns transversely reinforced with WWF. Therefore, there are question as to whether SNI Code provisions for placement of reinforcement are applicable or necessary for columns reinforced with WWF. A critical examination of the validity of code provision when applied to reinforced concrete columns may lead to the development of more rational provisions as well as a better understanding of the current empirical formula.

The aim of this paper is to investigate the applicability of SNI 03-2847 Building Code provisions to reinforced concrete columns confined with WWF. In particular, design of columns subjected to axial loads. Strength and deformability of columns transversely reinforced with WWF is one area where little design information is available for practicing engineers. The results further indicate that the product of the effectiveness coefficient of confinement reinforcement, volumetric ratio and strength of confinement WWF, normalized with respect to concrete strength, can be used as a design parameter.

2. COLUMN TESTS CONSIDERED

There is a database of reinforced concrete columns with square cross section tested under monotonic and concentric axial loading was used. The database includes tests conducted by three different researcher groups; Lambert-Aikhionbare and Tabsh (2001), Mau et al. (1998), Hong (1997), and Holland (1995). A total of 100 square columns were used in this study. This resulted in 48 reinforced column specimens designs. For Mau's tests, each design were tested three identical specimens. While, Hong's tests, each design were tested two identical specimens for small scale columns. The compressive strength of unconfined concrete ranges from about 44 to 70 MPa and yield strength of WWF ranges from about 288 to 576 MPa. The volumetric ratio ranges from about 0.7% to 5.0%. The other parameters such as the spacing of the WWF sheet, number of layers (sheets) of WWF in each bundle of lateral reinforcement, and WWF grid configuration. Details of reinforcement arrangements and columns considered are included in Table 1. A database includes seven configurations of transverse reinforcement grids shown in Fig. 1. Most of the results reported by researchers here in this study are the averages of two or three identical specimens.

Tabel 1. Properties of column specimens

Column number	Researcher	Reinforcement arrangement	f'_c MPa	b_c mm	Longitudinal Reinforcement			Transverse Reinforcement					Number of sheets per bundle	$k_e \rho_s f_{yh}/f'_c$
					Number & Diameter, mm	ρ_l (%)	f_y MPa	Dia. mm	s mm	s' mm	ρ_s (%)	f_{yh} MPa		
CS-1		5	70.0	305.0	4 D 25.4	1.6	441	5.71	76	30	3.5	450	4	0.098
CS-2		6	70.0	305.0	4 D 25.4	1.6	441	5.71	95	49	3.5	450	4	0.092
CS-3		5	70.0	305.0	4 D 25.4	1.6	441	5.71	51	17	4.0	450	3	0.123
CS-4		6	70.0	305.0	4 D 25.4	1.6	441	5.71	63	29	4.0	450	3	0.119
CS-5	Lambert and	5	70.0	305.0	4 D 25.4	1.6	441	5.71	44	10	4.5	450	3	0.142
CS-6	Tabsh (2001)	6	70.0	305.0	4 D 25.4	1.6	441	5.71	57	23	4.5	450	3	0.137
CS-7		5	70.0	305.0	4 D 25.4	1.6	441	5.71	57	11	4.75	450	4	0.143
CS-8		6	70.0	305.0	4 D 25.4	1.6	441	5.71	54	20	4.75	450	3	0.146
CS-9		5	70.0	305.0	4 D 25.4	1.6	441	5.71	54	8	5.0	450	4	0.152
CS-10		6	70.0	305.0	4 D 25.4	1.6	441	5.71	49	15	5.0	450	3	0.156
CS-11		3	46.9	101.6	–	–	–	2	31.8	27.8	0.80	288	1	0.013
CS-12		3	46.9	101.6	–	–	–	2	25.4	21.4	1.00	288	1	0.017
CS-13		3	46.9	101.6	–	–	–	2	19.1	15.1	1.30	288	1	0.024
CS-14		3	46.9	101.6	–	–	–	2	12.7	8.7	1.90	288	1	0.037
CS-15		3	46.9	101.6	–	–	–	2.7	31.8	26.4	1.40	397	1	0.031
CS-16		3	46.9	101.6	–	–	–	2.7	25.4	20	1.80	397	1	0.043
CS-17		3	46.9	101.6	–	–	–	2.7	19.1	13.7	2.20	397	1	0.056
CS-18		3	46.9	101.6	–	–	–	2.7	12.7	7.3	3.40	397	1	0.093
CS-19	Mau et al.	2	46.9	114.3	–	–	–	2.4	31.8	27	0.90	436	1	0.022
CS-20	(1998)	2	46.9	114.3	–	–	–	2.4	25.4	20.6	1.20	436	1	0.032
CS-21	[Holland	2	46.9	114.3	–	–	–	2.4	19.1	14.3	1.60	436	1	0.045
CS-22	(1995)]	2	46.9	114.3	–	–	–	2.4	12.7	7.9	2.40	436	1	0.072
CS-23		1	46.9	101.6	–	–	–	3	31.8	25.8	1.10	373	1	0.023
CS-24		1	46.9	101.6	–	–	–	3	25.4	19.4	1.40	373	1	0.032
CS-25		1	46.9	101.6	–	–	–	3	19.1	13.1	1.70	373	1	0.041
CS-26		1	46.9	101.6	–	–	–	3	12.7	6.7	2.60	373	1	0.068
CS-27		1	46.9	101.6	–	–	–	4.1	38.1	29.9	1.60	576	1	0.050
CS-28		1	46.9	101.6	–	–	–	4.1	31.8	23.6	2.00	576	1	0.067
CS-29		1	46.9	101.6	–	–	–	4.1	25.4	17.2	2.50	576	1	0.091
CS-30		1	46.9	101.6	–	–	–	4.1	19.1	10.9	3.10	576	1	0.121
CS-31		6	56.0	101.6	4 D 9.5	1.76	455	2	25.4	21.4	1.23	288	1	0.029
CS-32		6	56.0	101.6	4 D 9.5	1.76	455	2	19.1	15.1	1.64	288	1	0.041
CS-33		6	56.0	101.6	4 D 9.5	1.76	455	2	12.7	8.7	2.46	288	1	0.066
CS-34		6	56.0	101.6	4 D 9.5	1.76	455	2.7	25.4	20	2.15	397	1	0.071
CS-35		6	56.0	101.6	4 D 9.5	1.76	455	2.7	19.1	13.7	2.87	397	1	0.101
CS-36		6	56.0	101.6	4 D 9.5	1.76	455	2.7	12.7	7.3	4.30	397	1	0.162
CS-37		5	56.0	114.3	4 D 9.5	1.76	455	2.5	25.4	20.4	1.34	436	1	0.047
CS-38		5	56.0	114.3	4 D 9.5	1.76	455	2.5	19.1	14.1	1.79	436	1	0.067
CS-39	Hong (1997)	5	56.0	114.3	4 D 9.5	1.76	455	2.5	12.7	7.7	2.68	436	1	0.107
CS-40		4	56.0	101.6	4 D 9.5	1.76	455	4.1	31.8	23.6	2.03	496	1	0.079
CS-41		4	56.0	101.6	4 D 9.5	1.76	455	4.1	25.4	17.2	3.04	496	1	0.128
CS-42		4	56.0	101.6	4 D 9.5	1.76	455	4.1	19.1	10.9	4.05	496	1	0.182
CS-43		7	56.6	304.8	4 D 25.4	1.6	441	4.1	25.4	17.2	2.40	496	1	0.109
CS-44		7	55.0	304.8	4 D 25.4	1.6	441	4.1	50.8	34.4	2.40	496	2	0.103
CS-45		7	52.6	304.8	4 D 25.4	1.6	441	4.1	50.8	26.2	3.60	496	3	0.161
CS-46		5	59.4	304.8	4 D 25.4	1.6	441	5.7	25.4	14	2.55	490	1	0.110
CS-47		5	58.6	304.8	4 D 25.4	1.6	441	5.7	50.8	28	2.55	490	2	0.102
CS-48		5	54.9	304.8	4 D 25.4	1.6	441	5.7	50.8	16.6	3.83	490	3	0.164

Note: Reinforcement arrangements are illustrated in Fig. 1.

Strength enhancement, as well as ductility ratio obtained from the evaluation of 48 column specimens, are included in Table 2. The analysis of test data indicates that column deformability is a function of parameter related to confinement reinforcement.

Tabel 2. Column test results

Specimens		f'_c MPa	Axial Loads/Strengths		Axial strains			$k_e \rho_s f_{yh} / f'_c$
			P_{test}/P_o	f'_{cc}/f'_c	ε_{co}	$\varepsilon_{cc\,85}$	$\varepsilon_{cc\,85}/\varepsilon_{co}$	
Lambert and Tabsh (2001)	CS-1	70.0	0.97	1.24	0.0020	0.00592	2.96	0.098
	CS-2	70.0	1.01	1.29	0.0020	0.00792	3.96	0.092
	CS-3	70.0	0.96	1.22	0.0020	0.01458	7.29	0.123
	CS-4	70.0	1.03	1.32	0.0020	0.01228	6.14	0.119
	CS-5	70.0	1.03	1.31	0.0020	0.01472	7.36	0.142
	CS-6	70.0	1.06	1.35	0.0020	0.02060	10.30	0.137
	CS-7	70.0	0.96	1.23	0.0020	0.02920	14.60	0.143
	CS-8	70.0	1.12	1.43	0.0020	0.02720	13.60	0.146
	CS-9	70.0	1.06	1.35	0.0020	0.01894	9.47	0.152
	CS-10	70.0	1.07	1.37	0.0020	0.02780	13.90	0.156
Mau et al. (1998) [Holland (1995)]	CS-11	46.9	0.79	1.06	0.0020	0.00657	3.34	0.013
	CS-12	46.9	0.84	1.12	0.0020	0.00460	2.34	0.017
	CS-13	46.9	0.86	1.15	0.0020	0.00653	3.32	0.024
	CS-14	46.9	0.94	1.25	0.0020	0.00800	4.07	0.037
	CS-15	46.9	0.75	1.00	0.0020	0.00670	3.35	0.031
	CS-16	46.9	0.84	1.11	0.0020	0.00670	3.35	0.043
	CS-17	46.9	0.84	1.11	0.0020	0.00443	2.22	0.056
	CS-18	46.9	0.95	1.26	0.0020	0.00843	4.22	0.093
	CS-19	46.9	1.04	1.10	0.0018	0.00497	2.71	0.022
	CS-20	46.9	1.08	1.13	0.0018	0.00610	3.33	0.032
	CS-21	46.9	1.16	1.22	0.0018	0.00513	2.80	0.045
	CS-22	46.9	1.25	1.32	0.0018	0.00890	4.86	0.072
	CS-23	46.9	0.81	1.07	0.0019	0.00607	3.25	0.023
	CS-24	46.9	0.87	1.16	0.0019	0.00497	2.66	0.032
	CS-25	46.9	0.87	1.16	0.0019	0.00760	4.07	0.041
	CS-26	46.9	0.96	1.28	0.0019	0.00820	4.39	0.068
	CS-27	46.9	0.78	1.04	0.0019	0.00737	3.81	0.050
	CS-28	46.9	0.80	1.06	0.0019	0.00690	3.57	0.067
	CS-29	46.9	0.85	1.13	0.0019	0.00800	4.14	0.091
	CS-30	46.9	0.93	1.24	0.0019	0.00673	3.48	0.121
Hong (1997)	CS-31	56.0	0.83	1.26	0.0019	0.00605	3.18	0.029
	CS-32	56.0	0.83	1.26	0.0019	0.00595	3.13	0.041
	CS-33	56.0	0.97	1.48	0.0019	0.00700	3.68	0.066
	CS-34	56.0	0.83	1.27	0.0019	0.00975	5.13	0.071
	CS-35	56.0	0.99	1.51	0.0019	0.01035	5.45	0.101
	CS-36	56.0	1.11	1.69	0.0019	0.02660	14.00	0.162
	CS-37	56.0	0.97	1.17	0.0019	0.00390	2.05	0.047
	CS-38	56.0	1.09	1.32	0.0019	0.00700	3.68	0.067
	CS-39	56.0	1.17	1.41	0.0019	0.01300	6.84	0.107
	CS-40	56.0	0.73	1.12	0.0019	0.00500	2.63	0.079
	CS-41	56.0	0.85	1.30	0.0019	0.00765	4.03	0.128
	CS-42	56.0	1.00	1.53	0.0019	0.02305	12.13	0.182
	CS-43	56.6	1.09	1.42	0.0024	0.01250	5.21	0.109
	CS-44	55.0	1.06	1.39	0.0026	0.01320	5.08	0.103
	CS-45	52.6	1.24	1.64	0.0023	-	-	0.161
	CS-46	59.4	1.07	1.39	0.0026	0.01520	5.85	0.110
	CS-47	58.6	1.04	1.35	0.0024	0.00960	4.00	0.102
	CS-48	54.9	1.15	1.51	0.0024	0.02380	9.92	0.164

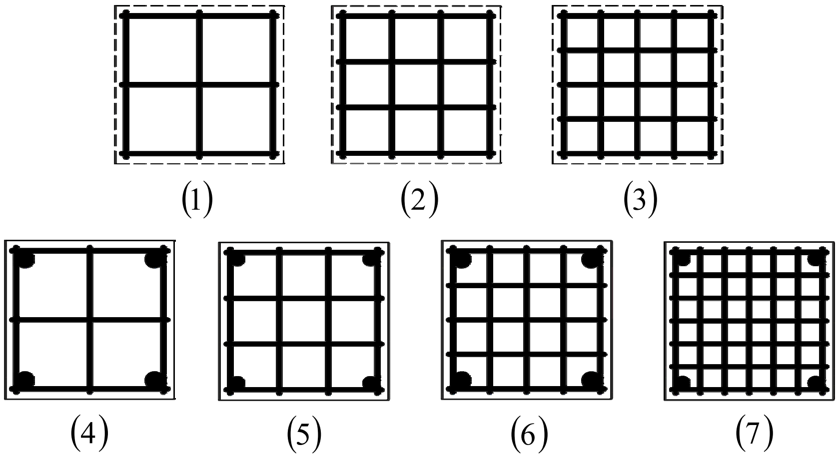

Figure 1. Reinforcement arrangements considered in column tests from researchers

3. EVALUATION OF COLUMN STRENGTH UNDER CONCENTRIC COMPRESSION

The concrete strength used in capacity calculations is the in-place strength of concrete, which is known to be somewhat less than that determined by a standard cylinder test. The difference in strength is usually attributed to differences in size, shape, and concrete casting practice between actual column members and standard cylinders. The in-place strength of column concrete is represented in the SNI Building Code (SNI 03-2847) by $0.85\, f_c'$, where f_c' is the strength of concrete determined by a standard cylinder test. The following expression is used in SNI 03-2847 to compute the concentric capacity P_o of a reinforced concrete column made with normal-strength concrete is given by

$$P_o = 0.85 f_c' \left(A_g - A_s\right) + A_s f_y \tag{1}$$

where A_g is the gross cross-sectional area of the compression member, A_s is the area of the longitudinal reinforcement, and f_y is the yield stress of the longitudinal reinforcement.

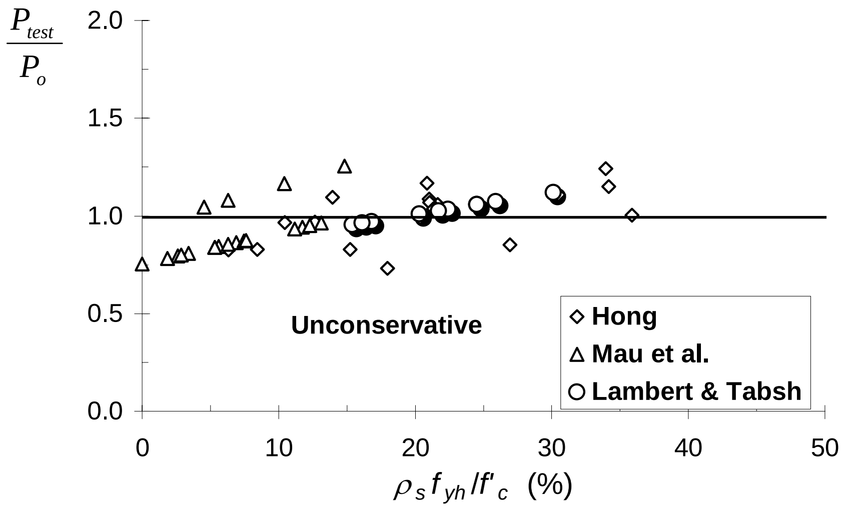

Figure 2. Comparisons of experimental and calculated concentric strengths of columns

Figure 2 shows the relationship between the parameter $\rho_s f_{yh} / f_c'$ and the ratio of experimentally obtained axial load capacity for 48 columns transversely reinforced with WWF to that predicted by Eq. (1). From this plot it could be observed that columns with a low volumetric ratio of transverse reinforcement may not achieve their strength as calculated by SNI 03-2847; however, well-confined columns can result in strength in excess of that calculated by SNI 03-2847. Excess strength of columns with relatively higher amounts of transverse reinforcement is generally obtained after spalling of cover concrete. This strength enhancement comes as a result of an increase in strength of the confined core concrete.

From figure 2 also shows the variability obtained in results of P_{test} / P_o where P_{test} is obtained from tests and P_o is that obtained using SNI 03-2847. Results as high as 1.2 (conservative) and as low as 0.7 (unconservative) were obtained. Columns tested by Holland (1995) which reported by Mau et al. (1998) did not have any cover and longitudinal steel, consistently showed lower capacities than those computed using Eq. (1). Equation (1) may still be applicable to these columns. They showed that $\rho_s f_{yh} / f_c'$ ratio can be used as a design parameter to increase the lateral pressure in proportion to unconfined strength of concrete.

4. DESIGN IMPLICATIONS

SNI 03-2847 Building Code (2002) requirements for column confinement are based on an arbitrary performance criterion where the loss in concentric capacity associated with cover spalling, is made up by the increase in concrete strength due to confinement. Therefore, cover-to-core area ratio also becomes a parameter in expressing the required amount of confinement steel. As the cover concrete in a section decreases, the strength loss due to cover spalling would also decrease. Therefore, columns with small cover-to-core area ratios require lower volumetric ratios of confinement reinforcement. Equation 2 gives the current SNI 03-2847 requirement for the volumetric ratio of spiral reinforcement needed in a circular column.

$$\rho_s = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f_c'}{f_{yh}} \tag{2}$$

For large columns, where the cover-to-core ratio can be very small, a lower limit is placed on the volumetric ratio requirement. This is done by placing an upper limit of 1.25 on the A_g / A_c ratio. This translates into Eq. (3).

$$\rho_s = 0.12\frac{f_c'}{f_{yh}} \tag{3}$$

The volumetric steel ratio requirement for rectilinear columns is obtained from Eq. (2) and (3), with the premise that the efficiency of rectilinear reinforcement is not as high as that of spirals, and therefore approximately 1/3 more steel is needed to attain the same level of confinement. For square columns with equal transverse reinforcement in two directions, and with an upper limit of 1.30 for A_g / A_c, this translates into Eq. (4) and (5).

$$\rho_s = 0.6\left(\frac{A_g}{A_c} - 1\right)\frac{f_c'}{f_{yh}} \tag{4}$$

$$\rho_s = 0.18\frac{f_c'}{f_{yh}} \tag{5}$$

where A_g = gross cross-sectional areas; A_c = concrete core area measured to outside diameter of spiral or circular hoop reinforcement; and f_{yh} = transverse reinforcement yield strength.

The above equations indicate that, for the cover-to-core area ratio considered in the experimental program presented in this paper, with $\left(A_g / A_c - 1\right)$ = 0.18, the SNI provisions require $\rho_s f_{yh} / f_c'$ ratios of 5% to 38% for all columns.

The previously mentioned requirements of the SNI 03-2847 are compared with the experimental values of concentrically tested colomn, obtained by Lambert and Tabsh (2001), Mau et al. (1998), Hong (1997), and Holland (1995), in terms of lateral pressure $\rho_s f_{yh}$ and the resulting strength enhancement. The comparison, shown in Figure 3, indicates that Eq. (4) does not provide a good correlation with experimental data, producing under-conservative quantities of transverse reinforcement. It is clear from the comparisons shown in Fig. 3 that the code expressions do not provide adequate representation of experimental data observations for the performance criterion for which they were developed.

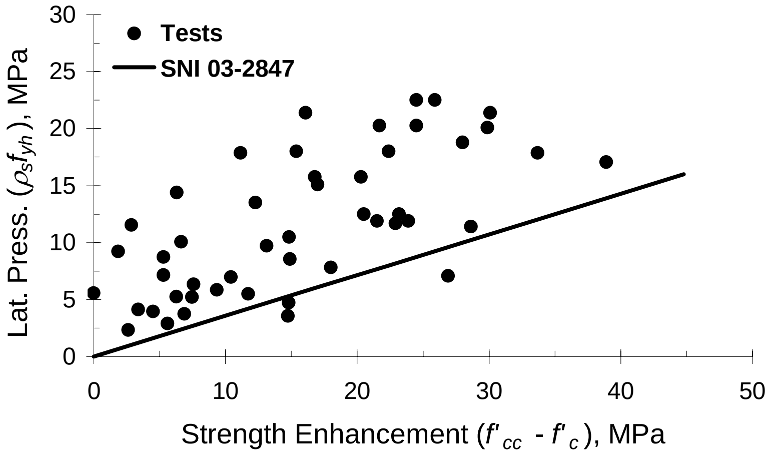

Figure 3. Comparisons of experimental data with SNI 03-2847 requirements

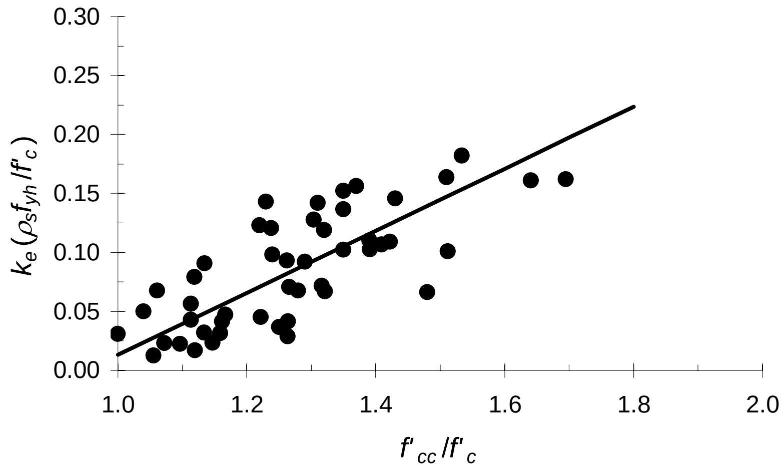

Figure 4. Relationship between strength enhancement and $k_e \rho_s f_{yh} / f_c'$ ratio

The test data reported in this paper concern columns transversely reinforced with WWF subjected to concentric compression were evaluated in terms of strength and deformability. Therefore, they cannot be used to address the shortcomings of SNI design procedure related to the performance criterion adopted, and the lack of lateral load effects. However, the test data can be used to assess the suitability of current SNI design provisions to columns transversely reinforced with WWF. They can also be used to introduce the efficiency of confinement reinforcement in the design process.

It was shown earlier that a trade-off existed between the volumetric ratio and the grade of lateral reinforcement. Furthermore, the effects of the arrangement and spacing of transverse reinforcement could be introduced through coefficient k_e. Therefore, $k_e\rho_s f_{yh}/f'_c$ ratio appears to be a proper design quantity for column confinement. The k_e for tie confined square columns was computed using the procedure suggested by Mander et al. (1988). The computed values of effective confinement index $k_e\rho_s f_{yh}/f'_c$ for various confined specimens are given in Table 1 and 2. The variation of experimentally obtained strength enhancement values with $k_e\rho_s f_{yh}/f'_c$ ratio is illustrated in Figure 4. The figure indicates that the strength enhancement increases approximately linearly with $k_e\rho_s f_{yh}/f'_c$ ratio.

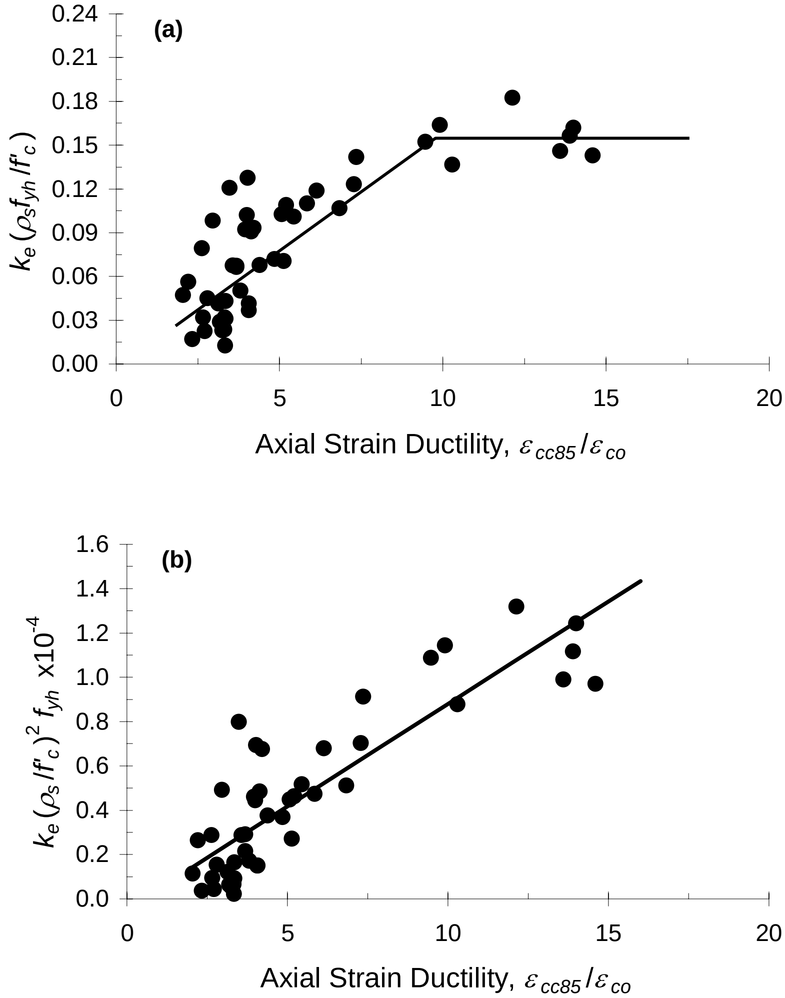

Figure 5. Relationship between axial strain ductility and $k_e\rho_s f_{yh}/f'_c$ ratio

The test data further indicate that if the SNI 03-2847 performance criterion is maintained, that is, strength enhancement in core concrete makes up for the spalling of cover concrete, the following design recommendations can be made for 30 percent strength enhancements in core concrete

$$\left(\frac{k_e\rho_s f_{yh}}{f'_c}\right) \geq 0.092 \tag{6}$$

While the 30 percent strength enhancement may be viewed as the minimum confinement requirement corresponding to cover-to-core area ratio of 0.4. The linear trend observed in Fig. 4, between the confinement parameter $k_e\rho_s f_{yh}/f'_c$ and the strength enhancement.

A number of past studies (Sheikh & Uzumeri 1980; Mander et al. 1988; Razvi & Saatcioglu 1994; Foster & Attard 2001) have indicated that ductility is a function of effective confinement index $k_e \rho_s f_{yh} / f'_c$, where k_e is a confinement effectiveness parameter, which accounts for configuration of lateral steel and resulting longitudinal steel distribution. However, the coefficient k_e has been ignored by the present seismic code requirements as indicated by the following relevant expression of SNI 03-2847 code for rectilinearly confined columns in equation (4) and (5).

In Figure 5(a), the axial strain ratios $(\varepsilon_{cc85} / \varepsilon_{co})$ for all the specimens is plotted against the effective confinement parameter $k_e \rho_s f_{yh} / f'_c$. This plot indicates a linear trend only up to a strain ductility ratio of approximately 10.0. However, when the (ρ_s / f'_c) term is squared and used as $k_e (\rho_s / f'_c)^2 f_{yh}$, implying that the volumetric ratio of steel plays a more dominant role on ductility than steel yield strength, the linearity of the relationship continues beyond the strain ductility ratio of 10.0. It may be concluded from this observation that while both volumetric ratio and yield strength play equally important roles on strength enhancement and the resulting increase in initial inelastic strains, the volumetric ratio plays a more dominant role in strain ductility in the larger strain range. On the other hand, the limiting strain ductility ratio of 10.0 in Fig. 5(a) corresponds to a compressive strain of approximately 2.0% for columns transversely reinforced with WWF.

5. CONCLUSIONS

Strength and deformability of columns transversely reinforced with WWF are discussed. The following conclusions can be drawn based on the research data highlighted in the paper:

1. A conservative estimate of column concentric axial load capacity can be obtained if the core area of concrete is used in capacity calculations with proper in-place strength of column transversely reinforced with WWF.
2. The confinement effectiveness parameter $k_e \rho_s f_{yh} / f'_c$ can be used as a design parameter to increase the lateral pressure in proportion to unconfined strength of concrete, reflect the quantity of ties grids needed to obtain a ductile response.
3. Strength and ductility enhancements in square columns, with up to 70 MPa concrete strength, show approximately linear variation with $k_e \rho_s f_{yh} / f'_c$ when confined by WWF. This trend was observed up to strength enhancement of 30 percent corresponding to column with an average cover-to-core area ratio of 0.4 (Eq. (6)) and strain ductility ratio of approximately 10.0. This level of ductility corresponds to a compressive strain of approximately 2 percent.

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