13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2531

RELATIONSHIPS BETWEEN DRIFT AND CONFINEMENT IN REINFORCED CONCRETE COLUMNS UNDER CYCLIC LOADING

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SUMMARY

The influence of transverse reinforcement and axial load on the drift limit of rectangular reinforced columns was investigated using test results from 184 specimens subjected to cyclic loading. Columns within the set were selected to have shear span-to-depth ratios exceeding 2.5 so that truss action would be the primary mechanism of shear resistance, and the deformation component related to shear would be small compared with that related to flexure. Expressions relating the limiting drift ratio to the axial load ratio and the amount of confining reinforcement were evaluated. A simple design equation is proposed to calculate the amount of confining reinforcement required to achieve a limiting drift ratio for reinforced concrete columns in regions of moderate and high seismicity.

INTRODUCTION

Previous research on the amount of transverse reinforcement required for adequate performance of reinforced concrete members under cyclic loading has resulted in expressions that relate shear strength to the ductility or lateral drift ratio (Ang [1], Wong [2], Watanabe [3] and Priestley [4]). The drift ratio is defined as the ratio of maximum lateral drift to total height of the specimen. The procedure developed by Priestley [4] relies on the ductility ratio ($\Delta_{ult}/\Delta_{yield}$) to calculate the reduction in shear strength that occurs under cyclic loading and lateral drift increase. Pujol [5] developed a procedure to estimate the limiting drift ratio at which no significant loss of shear capacity occurs in terms of the average shear stresses, the amount of transverse reinforcement, and the shear span-to-depth ratio.

The analysis presented seeks to establish a direct relationship between the limiting drift ratio, and the corresponding material and structural properties of reinforced concrete columns. The study focused on columns with sufficient transverse reinforcement to preclude shear failures prior to yielding of the longitudinal reinforcement, and intermediate shear span-to-depth ratios ($a/d \geq 2.5$). For these columns proper confinement of the concrete, and not shear strength, is the primary consideration for proportioning the amount of transverse reinforcement. The proposed relationships were based on the premise that for intermediate columns the capacity to sustain inelastic deformations, expressed in terms of the drift ratio, is

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approximately proportional to the plastic rotation that the column can sustain, and that the plastic rotation is dependent on the amount of confining reinforcement, the axial stress, and the compressive strength of concrete. The main objectives were to provide a design expression to detail columns for a selected limiting drift ratio, or to estimate the limiting drift ratio of a column based on a given amount of transverse reinforcement.

Column Test Data

The proposed equations were calibrated based on test results from 184 rectangular column specimens. The columns were subjected to cyclic loading under various loading protocols. Data of 135 column specimens were taken from the reinforced concrete column test database provided by the University of Washington (Eberhard [6]). The remaining 49 test data were collected from various sources (Aschheim [7], Wight [8], Azizinamini [9], Lynn [10] and Mo [11]). Details of the column data including dimensions, material properties, and limiting drift ratios are found in Brachmann [12].

The limiting drift ratio of the columns may be defined as the displacement corresponding to 80% of the maximum shear strength (V_{max}) according to previous research performed by Ang [1], Wong [2], Priestley [4], and Matamoros [13]. Tests that did not have significant strength decay due to the imposed drift were not included in the analysis in order to maintain an objective criterion for the definition of failure. Only columns with aspect ratios equal to or exceeding 2.5 were included in the analysis to ensure that the selected specimens exhibited predominantly flexural response, and that the shear span-to-depth ratio had a minor influence on the strength of the members. Corrections in the column displacement and maximum lateral load of the column specimens due to P-Δ effects are described in the analysis by Brachmann [12].

Research Parameters and Limitations of the Study

The parameters considered in the study included concrete compressive strength (f'_c), transverse reinforcement ratio (in terms ρ_{vol} or ρ_{area}), the yield strength of the transverse reinforcement (f_{yh}), and the axial load (P). Table 1 presents the range of properties of the columns included in the database.

TABLE 1 Range of Properties in the Selected Column Database

Parameter	Units	Variable	Minimum	Maximum
Concrete Compressive Strength	MPa	f'_c	22	116
Vol. Transverse Reinforcement Ratio	%	ρ_{vol}	0.17	6.64
Area Transverse Reinforcement Ratio	%	ρ_{area}	0.07	3.05
Yield Strength of the Hoop Reinf.	MPa	f_{yh}	255	1262
Longitudinal Reinforcement Ratio	%	ρ_{long}	0.5	6.0
Yield Strength of Longitudinal Reinf.	MPa	f_{yl}	315	587
Aspect Ratio	-	a/d	2.5	7.64
Axial Load Ratio	%	$P/A_g f'_c$	0	70

A dimensionless parameter c_p was adopted to quantify the amount of confinement in the columns. The confinement parameter was defined as $c_p = \rho \, f_{yh}/f'_c$ (Table 1). A similar parameter is used in Eq. 21-3 and 21-4 of the ACI-318 Building Code [14]. The commentary of the ACI 318 Building Code indicates that the theoretical basis for the confinement requirements in Eq. 21-3 and 21-4 is that sufficient transverse reinforcement must be provided in order to increase the strength of the confined core and compensate for the reduction in cross sectional area that occurs after the concrete cover has spalled off. Although the reasons provided in the commentary are not directly related to the deformation capacity of columns subjected to lateral load reversals, the use of a similar confinement parameter was deemed reasonable because previous research (Roy [15] and Park [16]) demonstrated that transverse reinforcement has the effect of reducing the slope of the descending branch of the stress-strain curve for concrete, and that confinement becomes less effective as compressive strength of concrete increases (Matamoros [13]).

Drift Ratio at Yield

The drift at yield, defined as the lateral displacement at the onset of yielding of the longitudinal reinforcement, is difficult to calculate in a reliable manner. A thorough discussion on this topic is presented by Konwinski, [17]. An approximate method based on the load-deformation curve of the column was used to determine yield displacement. The yield displacement of a column was defined as the intersection of the linearly increasing portion of the curve in the elastic displacement range and the horizontal line at maximum shear load (V_{max}). The slope of the linear portion in the elastic displacement range was determined as the ratio of 75%V_{max} to its corresponding displacement value ($\Delta_{@75\%Vmax}$).

Figure 1 shows the drift ratios at yield versus the volumetric confinement parameter for the selected experimental column data. The data plotted in Fig. 1 is based on the volumetric transverse reinforcement ratio. The data distribution and linear regression trend line indicate that the drift ratio at yield was approximately insensitive to the amount of confinement and had an average value of approximately 1%. This data distribution was to be expected because the amount of transverse reinforcement should have a negligible effect on the behavior of columns until the lateral expansion of concrete is large enough to generate significant stresses in the hoops, which occurs at drift ratios higher than that corresponding to yield.

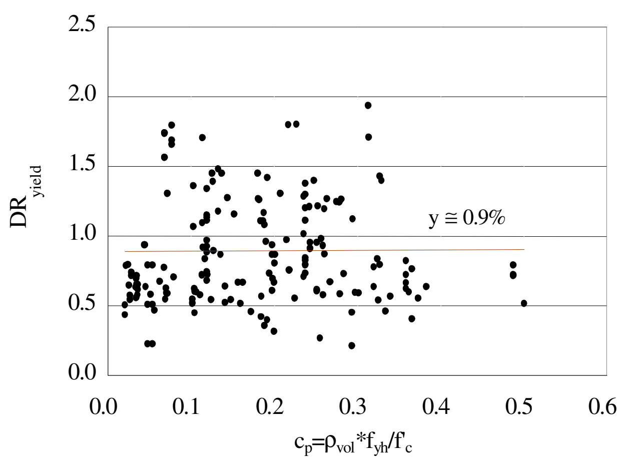

Fig. 1. Drift ratio at yield versus volumetric confinement parameter

Ductility Ratio

The ductility ratio (μ) is commonly used to define the performance of reinforced concrete columns under cyclic loading. The relationship between ductility and limiting drift ratio (DR_{lim}) was explored to facilitate simple comparisons between expressions in terms of these two parameters. A comparison of measured ductility ratios and the corresponding limiting drift ratios is shown in Fig. 3, with a linear regression trend line of the data through the origin. The slope of the trend line showed a value of approximately one, which implies that the ductility ratio was approximately equal to the limiting drift ratio for the set of data considered (Eq. 1).

$$\mu \cong DR_{lim} \, (DR_{lim} \text{ in } \%) \quad (1)$$

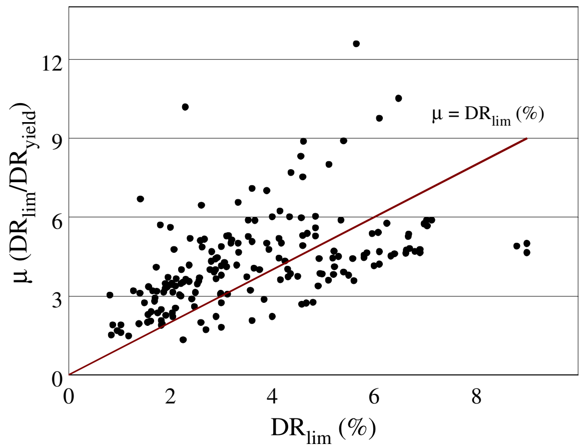

Fig. 2. Ductility ratio versus limiting drift ratio

Effect of Confinement and Axial Load on Limiting Drift Ratio

The primary objective of the study was to define a relationship between the limiting drift ratio of reinforced concrete columns and their material and structural properties. The limiting drift ratio was selected as a measure of the nonlinear deformations for several reasons. For the data set considered the drift ratio at yield was approximately 1% (Fig. 1), and was linearly related to the ductility ratio (Fig. 2). Consequently, the limiting drift ratio is a good indicator of the inelastic deformation sustained by the column members. In addition, the drift ratio is approximately proportional to the average rotation over the plastic hinge length in the inelastic range of response. The third reason is that specimens in the column data set had oversized connections or base blocks proportioned to prevent the loss of bond and subsequent slip of the reinforcement that can occur in actual beam-column connections subjected to cyclic loading. As a result the deflections related to slip of the reinforcement and distortion of the connection were significantly smaller in these specimens than what can be expected in full scale moment resisting frames. The percentage of the total lateral drift attributed to slip and distortion of the connection under these circumstances is significantly higher for the displacement at yield than for the displacement at the failure condition (Matamoros [13]). Consequently, the uncertainty associated with the aforementioned deformation components is significantly less for the limiting drift ratio than it is for the ductility ratio.

The transverse reinforcement ratio ρ in the confinement parameter c_p, can be expressed either in terms of the ratio of steel to concrete area or volume. The area transverse reinforcement ratio is defined as $\rho_{area} = A_v \cdot f_{yh}/(b \cdot s)$, where A_v is the area of shear reinforcement, f_{yh} the yield strength of the transverse reinforcement, b is the width of the specimen, and s is the spacing of the transverse reinforcement. The area transverse ratio is commonly used in expressions for shear design, whereas the volumetric ratio (ρ_{vol}) is used primarily in expressions involving the amount of confining reinforcement (Park [16]).

A statistical analysis of the test results was completed using both forms of reinforcement ratio. The volumetric reinforcement ratio was found to describe a correlation between transverse reinforcement and limiting drift ratio in a more reliable manner. This finding substantiates the premise that confinement was the primary concern for the columns studied in this manuscript ($a/d \geq 2.5$). The analysis of limiting drift ratios using the area transverse reinforcement ratio followed the same general procedure as that of the volumetric ratio, with further details found in Brachmann [12].

Limiting drift ratios for each column test are plotted against the volumetric confinement parameter in Figure 3. The column data was grouped into three axial load ranges, low ($P/A_gf'_c$=0-15%), intermediate ($P/A_gf'_c$=16-30%) and high axial loads ($P/A_gf'_c$=31-70%). For each axial load range trend lines are presented corresponding to linear and square root functions. Several trends are noted from Fig. 3. Columns with low axial loads exhibited higher limiting drift ratios than columns with intermediate or high axial loads having similar confinement. The slopes of the trend lines show that the effect of increasing the amount of confinement was greater as the axial load decreased, indicative of a nonlinear relationship between the confinement parameter and the limiting drift ratio.

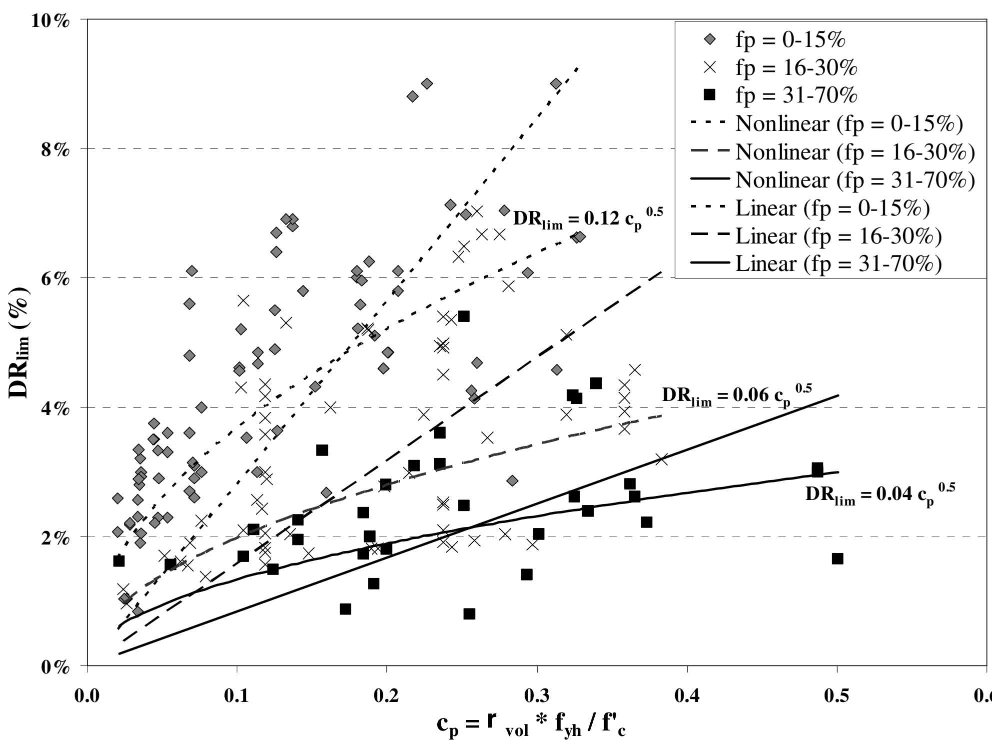

Fig. 3. Limiting drift ratio versus volumetric confinement parameter

The effect of axial load was assessed by comparing the slope of the curve relating limiting drift ratios to the confinement parameter for various axial load ranges. Figure 4 shows that the limiting drift ratio had an approximately linear decreasing trend with respect to the axial load ratio. The linear reduction of the estimated limiting drift ratio ($DR_{lim,est}$) with respect to the axial load was incorporated into linear and nonlinear relationships, resulting in two expressions with a similar format:

Linear relationship $$DR_{\lim,est} = \alpha c_p \left(1 - \beta f_p\right) \qquad (2)$$

Nonlinear relationship $$DR_{\lim,est} = \alpha \sqrt{c_p} \left(1 - \beta f_p\right) \qquad (3)$$

where c_p is the confinement parameter, and f_p is the axial load ratio, $f_p = P/(A_g \cdot f'_c)$. The constants α and β are used to describe the influence of the confinement parameter and axial load ratio, respectively. Both of these relationships imply that the limiting drift ratio increases with the amount of confinement. In the nonlinear relationship the effect of additional transverse reinforcement on the limiting drift ratio decreases as the amount of transverse reinforcement increases, while in the linear expression this effect remains constant. Table 2 summarizes values of the constants α and β obtained through linear regression of the test results (Brachmann [12]).

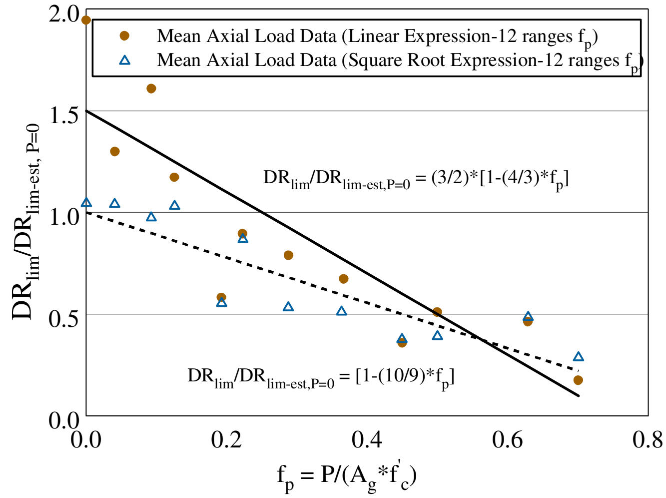

Fig. 4. Ratio of $DR_{lim}/DR_{lim,est}$ for P=0 vs. mean axial load ratios

TABLE 2 Values of α and β for Linear and Nonlinear Expressions

Transverse Reinforcement Ratio, ρ	Expression Type	α	β
ρ_{vol}	Mean Linear Expression, Mean Response	3/7	4/3
	Nonlinear Expression, Mean Response	1/8	10/9
	Nonlinear Expression, Design Upper Bound	1/12	10/9
ρ_{area}	Linear Expression, Mean Response	1	7/5
	Nonlinear Expression, Mean Response	1/5	8/7
	Nonlinear Expression, Design Upper Bound	1/8	8/7

Reliability of the proposed expressions

Figure 5 shows the coefficients of variation for the ratio of measured to estimated limiting drift based on Eq. (2) and (3). Generally, the use of the volumetric reinforcement ratio resulted in a lower coefficient of variation than the area reinforcement ratio. The difference between the two was most significant for Eq. (2) (COV of 88% for the area ratio compared with 53% for volumetric ratio). The linear expression resulted in the highest coefficient of variation for estimates of transverse reinforcement and limiting drift ratio. This trend supports the conclusion that the effectiveness of confinement tended to decrease as the amount of confinement increased.

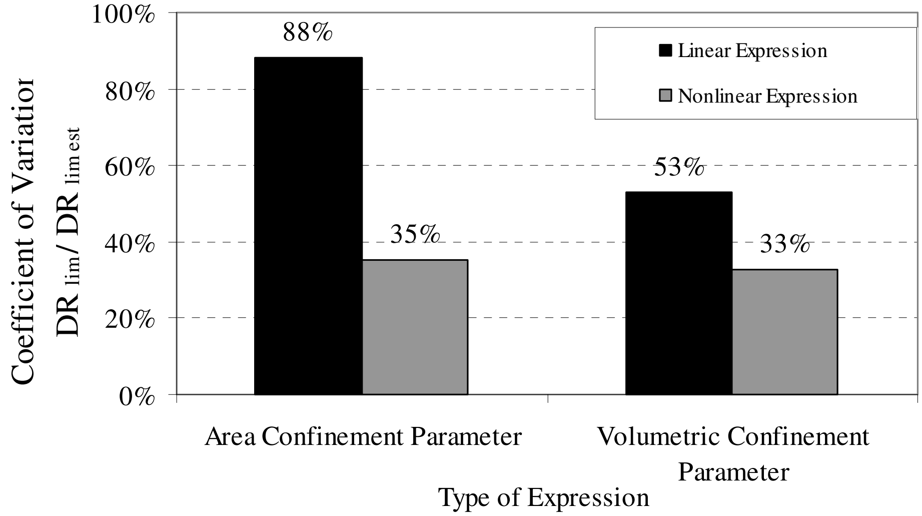

Fig. 5 Coefficient of variation for various estimation procedures and transverse reinforcement ratios

Although Eq. (3) does not include all parameters that can influence the limiting drift of columns, the parameters considered in the study resulted in accuracy that is comparable to that of other design expressions currently used in the ACI Building Code [14]. For example, the coefficient of variation for Eq. (3) (COV = 0.35) is similar to that obtained by Reineck [18] when comparing the results of Eq. 11-2 of the ACI Building Code [14] to results from 361 static shear tests of slender beams (a/d>2.9, COV=0.32).

Equation (3) was originally calibrated to provide an estimate of the mean limiting drift ratio. It was determined that approximately 2/3 of the estimates of limiting drift ratios and required volumetric reinforcement ratios were conservative if the coefficients obtained from the optimal curve fit were employed in Eq. (3). Because a higher confidence level of reaching the desired performance objective is needed for design, a safer estimate was sought by introducing a reduction factor for the limiting drift ratio and establishing a minimum requirement for the amount of transverse reinforcement. The coefficients were adjusted such that proposed equations would provide a safe estimate for the mean plus one standard deviation of the data. The design coefficients presented in Table 2 reflect this correction, reducing the probability of overestimating the limiting drift or underestimating the amount of reinforcement to approximately 16%.

Development of Simple Design Expression

A design procedure to determine the amount of transverse reinforcement required for proper confinement is proposed based on Eq. (3), which relates the limiting drift ratio to the confinement parameter c_p. Equation (3) is solved for the confinement parameter

$$c_p = \left(\frac{DR_{\lim}}{\alpha\left(1-\beta f_p\right)} \right)^2 \qquad (4)$$

The transverse reinforcement ratio is given by

$$\rho = \left(\frac{DR_{\lim}}{\alpha \left(1 - \beta f_p \right)} \right)^2 \frac{f'_c}{f_{yh}} \qquad (5)$$

Table 2 indicates that the coefficient β had values of 1.11 and 1.14 for nonlinear expressions based on the volumetric and area transverse reinforcement ratios respectively, indicating that the effect of axial load was insensitive to the type of confinement parameter adopted. Equation (5) is simple to use because it relies on the ratio of applied load to gross section area of the column. Equations 21-3 and 21-4 of the 2002 ACI Building Code recognize that as cover increases, the amount of confinement must be increased because the axial stress in the core increases. Upon further review of the experimental data it was found that if the axial load ratio was calculated on the basis of the area of the confined core, the coefficient β was approximately 0.8. For that reason, and to further simplify the design expression, Eq. (5) is rewritten as:

$$\rho = \left(\frac{\lambda \, DR_{\lim}}{1 - 0.8 f_{pc}} \right)^2 \frac{f'_c}{f_{yh}} \qquad (6)$$

Suggested values for the dimensionless coefficient λ are presented in Table 3. The suggested values for circular columns are based on the conservative assumption that the confining reinforcement is 75% as effective in rectangular columns than it is circular columns. Tests of confined columns under uniaxial compression have shown that spirals may be as much as twice as effective as rectilinear reinforcement to increase the strength of the confined core (Park et al., 1982 [16]).

When Eq. 6 was used to estimate the limiting drift ratio of the column set based on the volumetric reinforcement ratio, the mean ratio of estimated to calculated drift ratio was approximately 1.5 with a coefficient of variation of 35%. Both the mean and the coefficient of variation were slightly higher when the area reinforcement ratio was used.

TABLE 3. Value of Coefficient λ for Proposed Design Equation

Transverse Reinforcement Ratio, ρ	**Coefficient λ, Circular Columns**	**Coefficient λ, Square and Rectangular Sections**
ρ_{vol}	10	12
ρ_{area}	6	8

Applicability of Proposed Equations to Columns with High Strength Materials

The magnitude of the confinement parameter adopted in this paper is proportional to the product of the volumetric reinforcement ratio and the yield strength of the reinforcement. According to this formulation it is possible to reduce the volume of reinforcement and increase its yield strength without affecting the limiting drift ratio of a column. This raises a concern that if the yield strength of the reinforcement is too high the lateral expansion of the concrete will not be sufficient to cause the transverse reinforcement to develop its full yield capacity.

The database used in the study had specimens with yield strength of the transverse reinforcement ranging between 255 and 1,262 MPa, and volumetric transverse reinforcement ratios ranging from 0.17 to 6.64. Because specimens with transverse reinforcement having a yield strength of 1,200 MPa had significantly lower test/estimate ratios, it is recommended to establish an upper limit of 800 MPa for the yield strength of the transverse reinforcement. This is consistent with the observations by Kato et al. [21] and Saatcioglu et al. [22] that the effective confining pressure decreases and the probability of buckling of the longitudinal reinforcement increases with increasing hoop spacing. Similarly the NZS 3101:1995 design provision [23] establishes an upper limit of 800 MPa for the nominal yield strength of the transverse reinforcement.

Minimum Amount of Confinement

A minimum amount of confinement is suggested to provide a threshold level of ductility. Equation 11-15 of ACI 318-02 [14] defines the shear strength provided by the transverse reinforcement based on a truss model with 45° struts as

$$V_s = \frac{n_l \; A_{s,bar} \; f_{yh} \; d_{eff}}{s} \tag{7}$$

where n_l is the number of hoop legs, and $A_{s,bar}$ is the cross-sectional area of the transverse bar. The volumetric reinforcement ratio can be expressed in terms of the area of the bars $A_{s,bar}$, the width and height of the column core (b_c and h_c), and the spacing of the transverse reinforcement, s. Substituting the relationship between volumetric reinforcement ratio and area of the transverse bar into Eq. (7), the shear strength V_s can be expressed in terms of the volumetric reinforcement ratio (ρ_{vol}) as:

$$V_s = \frac{f_{yh} \, d_{eff}}{s} \frac{\rho_{vol} \, b_c \, h_c \, s}{(b_c + h_c)} \tag{8}$$

A symmetrical configuration of the transverse reinforcement (equal number of reinforcement legs in both directions) was assumed, which was consistent with over 95% of the column specimens in the data set. In addition, the dimension of the effective depth for the column was assumed to be approximately equal to the height of concrete core ($d_{eff} \approx h_c$).

The minimum amount of confinement necessary to develop yielding of the column was determined based on the difference between the total shear demand and the shear strength provided by the concrete (V_c):

$$\rho_{vol} \frac{f_{yh}}{f'_c} = \frac{(V_y - V_c)(b_c + h_c)}{b_c h_c^2 f'_c} \tag{9}$$

Two expressions for V_c (ACI Building Code, 11.3.1) were used to determine amount of confinement needed to develop yielding of the columns:

$$V_c = 2\left(1 + \frac{P}{200A_g}\right)\sqrt{f'_c}\,bd_{eff} \tag{10}$$

$$V_c = 2\sqrt{f'_c}\,bd_{eff} \tag{11}$$

Although these are lower bound expressions derived for static loading conditions, it has been shown that the fraction of the total shear carried by the concrete changes as damage to the plastic hinge region increases (Wight [8], Matamoros [13]). Both expressions were deemed adequate to develop a simple recommendation for the minimum amount of reinforcement needed to reach yielding of the columns and provide some level of ductility.

Figure 6 shows the amount of confinement required to reach yielding of the column specimens plotted with respect to the corresponding axial load ratio. The magnitude of the confinement parameter obtained with Eq. (11) for V_c did not exceed a value of 0.10, and for the less conservative Eq. (10) a majority of the data was below 0.12. As a result, a lower limit of 0.12 is recommended for the volumetric confinement parameter. Equations 21-3 and 21-4 of the ACI-318 [14] recommend minimum confinement of 0.12 and 0.18 for spiral and rectangular columns respectively.

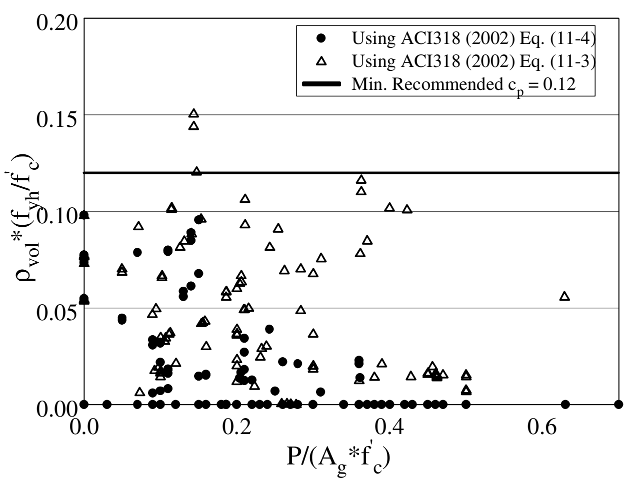

Fig. 6. Required volumetric c_p for developing M_y versus f_p, V_c calculated using Eq. (10) and (11)

Estimates of required volumetric transverse reinforcement ratios in terms of a given limiting drift ratio must incorporate the minimum limit for the volumetric confinement described above. When both the reduction factor and the lower limit for the confinement parameter were applied, the probability of failure was reduced to be less than 10% for the limiting drift and transverse reinforcement estimates.

Proposed design equations

Equation (6) was found to provide reliable estimates of drift limits based on the transverse reinforcement ratio. The required amount of confining reinforcement calculated using Eq. (6) for various levels of drift and axial load are shown in Figures 7 and 8. The limiting drift ratios range from 1 to 3% and are plotted in

0.5% increments, for varying axial load ratios and volumetric confinement parameters. The vertical lines on the graph indicate the minimum transverse reinforcement ratio required in the ACI 318 Building Code. Because the ACI Building Code establishes confinement requirements for circular columns in terms of the volumetric confinement ratio and rectangular columns in terms of the area reinforcement ratio, these two cases are presented for comparison. Given the reduction factors for the axial capacity of columns in the ACI Building Code, the maximum axial load ratio possible for the confined core is approximately 0.65.

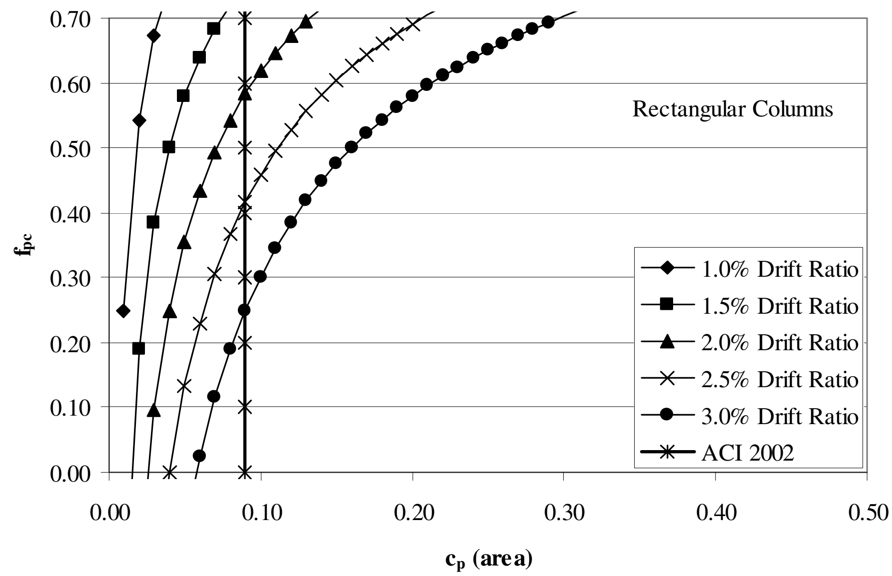

Fig. 7. Interaction between c_p and f_{cp} for rectangular columns with various limiting drift ratios

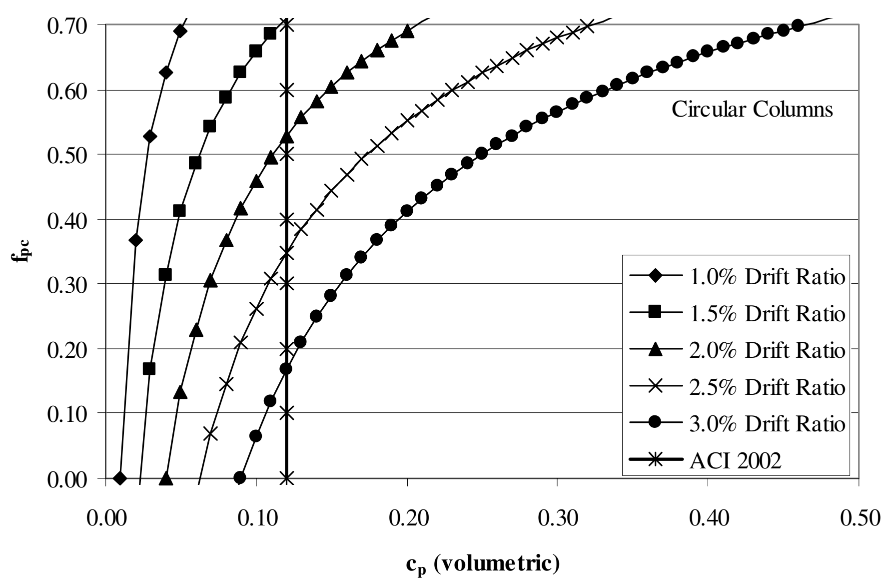

Fig. 8. Interaction between c_p and f_{pc} for circular columns with various limiting drift ratios.

Figures 7 and 8 show that current confinement requirements established in the ACI 318 Building Code are adequate for limiting drift ratios of up to 2% for the range of axial loads allowed by the code. The primary advantages of Eq. (6) are that it allows engineers to determine the amount of confinement needed for more restrictive performance objectives and that it allows the use of lesser amounts of reinforcement in cases where the current provisions are overly conservative. The significance of reducing the amount of confinement when less is needed is that congestion in plastic hinge regions can be reduced, which is a particularly serious problem in the case of high-strength concrete.

Prescriptive confinement requirements for regions of moderate and high seismicity can be established by conservatively assuming limiting drift ratios of 1.5% and 2.5%. The resulting design expression is

$$\rho = \left(\frac{\gamma}{1 - 0.8 f_{pc}} \right)^2 \frac{f'_c}{f_{yh}} \qquad (12)$$

where the values of γ are given in Table 4.

TABLE 3. Value of Coefficient γ for Eq. (12)

Type of Seismic Demand	Transverse Reinforcement Ratio, ρ	Coefficient γ, Circular Columns	Coefficient γ, Square and Rectangular Sections
Moderate Seismicity	ρ_{vol}	0.15	0.18
	ρ_{area}	0.09	0.12
High Seismicity	ρ_{vol}	0.25	0.30
	ρ_{area}	0.15	0.20

CONCLUSIONS

This study evaluated two expressions that relate the limiting drift ratio of columns to the amount of confinement. The proposed expressions may be used to estimate the limiting drift ratio of columns for a given amount of confinement or to select the amount of confining reinforcement needed to reach a specified limiting drift ratio.

It was observed that the limiting drift ratio was primarily a function of the amount of transverse reinforcement, the yield strength of the hoops, the compressive strength of the concrete, and the axial load ratio. A linear relationship between the confinement parameter and the limiting drift ratio resulted in the least reliable estimates of the two expressions that were evaluated. Trends observed in the data indicate that the effect of confinement decreased as the amount of confinement, compressive strength of concrete, and the axial load ratio increased. Because the yield strength of the transverse reinforcement of the columns in the data set ranged between 255 and 1262 MPa (37 ksi and 183 ksi), the study showed that high-strength reinforcement may be used effectively to reduce the area of confining reinforcement required to reach a given drift limit, and thereby reduce congestion within plastic hinge regions. Whereas the proposed equations provided safe estimates of the limiting drift of columns with compressive strengths up to 116 MPa (16.8 ksi), it is recommended that these equations not be used when the yield strength of the reinforcement exceeds 830 MPa (120 ksi). The study showed that the effect of confinement decreased as the amount of confinement increased.

Design expressions were presented in Eq. (6) and (12). Figures 7 and 8 show the influence of the axial load ratio and confinement on the limiting drift ratio of reinforced concrete columns. The proposed design equations provided conservative estimates of the amount of confinement needed to attain a limiting drift ratio for approximately 90% of the columns considered in the study.

Acknowledgements

Support provided by the National Science Foundation, NSF Grant #9904090, is gratefully acknowledged. The authors also are grateful for the information, comments, and suggestions provided by Marc Eberhard during the development of the project.

List of Notation

A_g	=	gross cross-sectional area
A_v	=	area of shear reinforcement
$A_{s,bar}$	=	cross sectional area of the transverse bar
$l_{col} = a$	=	length of the structural member
h	=	height of the column specimen
$d_{eff} \approx h_c$	=	effective depth is approximately equal to height of concrete core
b , b_c	=	width of the column specimen, of the concrete core
a/d	=	shear span-to-depth ratio (aspect ratio)
C.O.V	=	coefficient of variation
c_p	=	$\rho \cdot f_{yh}/f'_c$ = confinement parameter (in terms of either ρ_{area} or ρ_{vol})
$c_{max,p}$, $c_{max,p=0}$	=	volumetric confinement parameter at $DR_{max,p}$, at $DR_{max,p=0}$
$DR_{lim} = (\Delta_{max}/l_{col})$	=	measured limiting drift ratio
$DR_{lim,est}$	=	estimated limiting drift ratio
$DR_{max,p}$, $DR_{max,p=0}$	=	maximum limiting drift ratio for an axial load P, for axial load P=0
$DR_{yield} = (\Delta_{yield}/l_{col})$	=	drift ratio at yield
$DR_{yield,est.}$	=	estimated drift ratio at yield
f'_c	=	concrete compressive strength
$f_p = P/A_g f'_c$	=	axial load ratio
f_{yh} , f_{yl}	=	yield strength of the transverse reinforcement, of the longitudinal bar
n_l	=	number of hoop legs
P	=	axial load acting on column
s	=	spacing of transverse reinforcement
V_{max}	=	maximum shear load
V_c , V_s	=	shear strength provided by the concrete, provided by the steel
V_y	=	shear strength to develop yielding of the column
α, α_0	=	slope for the confinement parameter c_p , the confinement parameter $c_{p=0}$
α_p	=	interception at zero axial loading (Fig. 9)

β = slope for the axial load reduction
β_{cp} , β_{DR} = slope for the axial load reduction for estimating $c_{max,p}$, for estimating $DR_{max,p}$
γ = reciprocal of DR_{max}
$\Delta_{@75\%Vmax}$ = displacement at 75% V_{max}
Δ_{yield} , Δ_{ult} = displacement at yield, at ultimate
μ = $(\Delta_{ult}/\Delta_{yield})$ = displacement ductility factor (ductility ratio)
ρ_{vol} , ρ_{area} = volumetric transverse reinforcement ratio, area transverse reinforcement ratio
ρ_{long} = longitudinal reinforcement ratio
$\rho_{vol,est}$ = estimate of the volumetric transverse reinforcement ratio
$\rho_{vol,design}$ = design estimate of the volumetric transverse reinforcement ratio

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