Code requirements for column confinement with a view on drift

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ABSTRACT

Confinement provided by transverse reinforcement plays an essential role in reinforced concrete columns. When proportioned judiciously, confinement provides longitudinal bar restraint, contributes to shear resistance, and can maintain the integrity of the concrete core. Its role is most critical in applications requiring toughness, such as in columns subject to seismic demands. As a result, the New Zealand NZS3101-06 and United States ACI318-19 design provisions for structural concrete specify minimum confinement requirements for earthquake applications. Both design codes intend to provide columns with the toughness to sustain inelastic displacements without a considerable loss in strength. Moreover, United States code provisions explicitly state that design expressions are intended to result in columns capable of sustaining 3% drift without considerable loss in strength. In this investigation, rectangular reinforced concrete column data compiled by ACI committee 369 was used to vet the efficacy of both design provisions from the perspective of drift capacity. The results indicate no clear correlation between expected drift capacity and minimum code confining requirements, contrary to current expectations. In addition, these requirements often lead to inefficient and non-constructible designs. Herein, the authors suggest an urgent revision of current practice regarding minimum confinement requirements. Not doing so may lead to consequential and unintended performance of columns during future earthquakes.

1 INTRODUCTION

1.1 Background

Current design provisions for confinement in reinforced concrete columns required to resist earthquake demands in New Zealand and the United States are quite different. The New Zealand NZS3101-06 code requirements for confinement are based on the work of Watson et al. (1994) proposed required confinement based on a curvature-ductility approach. This method related required confinement to a target level curvature-ductility factor. This factor was expressed as the limiting flexural curvature to the curvature at the

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onset of flexural yielding of the reinforced concrete column. While the objective of providing confinement for both strength and deformability are emphasized, no effort is placed on drift capacity. On the other hand, the United States ACI318-19 code provisions require confinement to ensure spalling of the column shell does not result in large resistance loss. In addition, the work by Elwood et al. (2009) was implemented into the ACI318-19 code with the intent of producing columns capable of exceeding 3% drift ratio without a considerable loss in strength. The different design objectives between the New Zealand and United States code provisions make comparisons difficult. Therefore, the objective of this study is to evaluate code requirements for confinement as it relates to drift capacity, arguably the most critical property for earthquake response of structures.

1.2 Current design expressions

The New Zealand NZS3101-06 requirements are expressed in Equations 1-2 below. Equation 1 is the required confinement reinforcement.

$$A_{sh} = \left[\left(\frac{1.3-\rho_t m}{3.3}\frac{A_g}{A_c}\frac{f'_c}{f_{yt}}\frac{N^*}{f'_c A_g}\right) - 0.006\right] s_h h'' \tag{1}$$

Where, A_{sh}= area of steel required for confinement, s_h= s = spacing of transverse reinforcement, h''= b_c = dimension of concrete core of rectangular section, ρ_t= ratio of longitudinal steel area to concrete core area, m = ratio of $f_{yl}/0.85f'_c$, A_g= cross-section gross area, A_c = cross section core area, f'_c= concrete compressive strength, f_{yl} = specified yield strength of longitudinal reinforcement, f_{yt} = transverse reinforcement yield strength and N^*= compressive axial load.

Equation 2 is the required area of hoop reinforcement required to restrain longitudinal reinforcement against bar buckling.

$$A_{te} = \frac{\sum A_b f_y}{96 f_{yt}}\frac{s_h}{d_b} \tag{2}$$

Where, A_{te}= area of all legs of stirrup-ties, $\sum A_b$ = *sum of area of steel longitudinal bars supported by transverse tie*, f_y= longitudinal bar yield strength, d_b= longitudinal bar diameter, s_h= spacing of transverse reinforcement.

* = For simplicity and comparison sake this was estimated as the total area of longitudinal bars in tension supported by all transverse tie legs.

The United States ACI318-19 confinement requirements for rectilinear hoops are shown in Table 1.

Table 1: ACI318-19 confinement requirements for columns of special moment frames

Transverse Reinf.	Condition		Applicable Expression	
$\frac{A_{sh}}{sb_c}$	$P_u \leq 0.3A_g f'_c$ and $f'_c \leq 69\ MPa$	Greater of (a) and (b)	$0.3\left(\frac{A_g}{A_{ch}}-1\right)\frac{f'_c}{f_{yt}}$	(a)
			$0.09\frac{f'_c}{f_{yt}}$	(b)
	$P_u > 0.3A_g f'_c$ or $f'_c > 69MPa$	Greater of (a), (b) and (c)	$0.2k_f k_n \frac{P_u}{f_{yt}A_{ch}}$	(c)

Where, A_{sh} = total cross-sectional area of rectangular hoop, A_{ch}= RC core area, P_u= Compressive axial load, k_f = concrete strength factor, k_n = confinement effectiveness factor.

2 METHODOLOGY

2.1 ACI 369 database

Ghannoum et al. (2012) compiled test data from 326 experiments on reinforced concrete columns with rectangular cross sections for committee ACI369. Columns in this database were subject to monotonic or cyclic loading but this study focused on the latter. This database was used in this study to identify a group of flexural controlled columns to compare the NZS3101-06 and ACI318-19 confinement requirements.

2.2 Column identification

Columns inferred to be likely to fail in shear or bond were eliminated from the database to concentrate on columns dominated by flexure. Three criteria were used to eliminate columns to identify columns not governed by flexure. These criteria are: I) Shear strength less than 85% of the shear demand at flexural yielding, II) unit bond stress greater than the mean unit bond strength from Richter (2012) experimental data from unconfined splices, and III) abrupt decrease in lateral force observed in load-displacement histories. The remaining columns (after applying criteria I, II, and III) are assumed to have failed in flexure.

Criterion I, seen below in Equation 3, was used to eliminate columns from the dataset for which nominal shear strength is smaller than the shear demand associated with flexural yielding. These columns are expected to have been governed by shear.

$$V_n < 0.85V_p \tag{3}$$

Where, V_p = shear demand at flexural yielding, V_n = shear strength.

The shear demand at flexural yielding V_p was taken as the value reported by ACI369. The factor of 0.85 was chosen to reflect uncertainties in calculating shear strength and to ensure no columns which failed in shear were included in the analysis. Shear strength V_n is calculated using two definitions in this study. The first definition of shear strength was calculated in accordance with ACI318-19, as seen below in Equations 4-7 which are all consistent with inch-pound units.

$$\frac{V_n}{bd} = \begin{cases} max\left(2, 8\rho_w^{\frac{1}{3}}\right)\sqrt{f'_c} + \frac{P}{6A_g} + \rho_t f_{yt};\ if\ A_v \geq A_{v,min} \\ 8\lambda_s \rho_w^{\frac{1}{3}}\sqrt{f'_c} + \frac{P}{6A_g} + \rho_t f_{yt};\ if\ A_v < A_{v,min} \end{cases} \tag{4}$$

$$A_v = \rho_t bs \tag{5}$$

$$A_{v,min} = \max\left(50, 0.75\sqrt{f'_c}\right)\frac{d}{f_{yt}}s \tag{6}$$

$$\lambda_s = \sqrt{\frac{2}{1+\frac{d}{10}}} \leq 1 \tag{7}$$

Where, ρ_w= ratio of longitudinal tensile reinforcement to area bd, f'_c = concrete compressive strength, P = axial load, A_g = column gross area, ρ_t = transverse reinforcement ratio, f_{yt} = transverse reinforcement yield strength, A_v = provided area of transverse reinforcement, $A_{v,min}$ = minimum required area of transverse reinforcement, d = effective depth to tensile reinforcement, s = spacing, b = column width, λ_s = size effect modification factor

The second definition of shear strength used is given by Equation 8.

$$V_n = 0.8A_g\left(\frac{6\sqrt{f'_c}}{\frac{M}{Vd}}\sqrt{1+\frac{P}{6A_g\sqrt{f'_c}}}\right) + \rho_t f_{yt} bd \tag{8}$$

Where, $\frac{M}{Vd}$ = largest ratio of moment to shear times effective depth.

All columns with shear strengths using either definition of shear strength (Equation 4 or 8) failing criterion I were eliminated from the dataset. Criterion II involved eliminating columns that may have failed in bond prior to flexural yielding. This involved comparing the mean bond stress to lower bound mean bond strengths measured in unconfined lap-splice tests by (Richter 2012). Unconfined test data were used to make the selection criterion more stringent. Equation 9 and 10 below were used to calculate mean bond stress.

$$f_s = \frac{V_{test}}{V_p} f_y \tag{9}$$

$$\mu_{mean} = \frac{d_b}{4a} f_s \tag{10}$$

Where, μ_{mean} = mean bond stress, d_b = bar diameter, a = shear span which is assumed to equal development length, f_s = tensile stress developed in longitudinal reinforcing bars, f_y= longitudinal bar yield strength, V_{test}= maximum applied lateral load during test, V_p = the shear demand at flexural yielding.

Criterion III involved investigating the force-displacement plots of the remaining columns by manually reviewing the load versus displacement test data. This was done to: 1) ensure no column specimens showing signs of brittle failure were included in the selected dataset (that may have passed the first two criteria) and 2) eliminate columns that did not appear to have been tested to failure.

3 RESULTS

After filtering, 66 columns remained. These columns were used to compare the effects of axial load, required confinement, and provided confinement on drift capacity. Of this entire dataset, column axial load ratios P_u/f'_cA_g ranged from 0-70%. The provided confinement and the confinement required by the codes in consideration are defined by Equation 11 and 12.

$$\rho = \frac{A_{tr}}{b_c s} \tag{11}$$

$$\rho_{req} = \frac{A_{tr\_req}}{b_c s} \tag{12}$$

Where, A_{tr}= area of transverse steel provided in column, A_{tr_req}= area of transverse steel required by code in consideration, b_c= h$''$ = column core width, s= s_h = spacing of transverse reinforcement.

3.1 Drift capacity versus ρ/ρ_{ACI} for (ACI318-19)

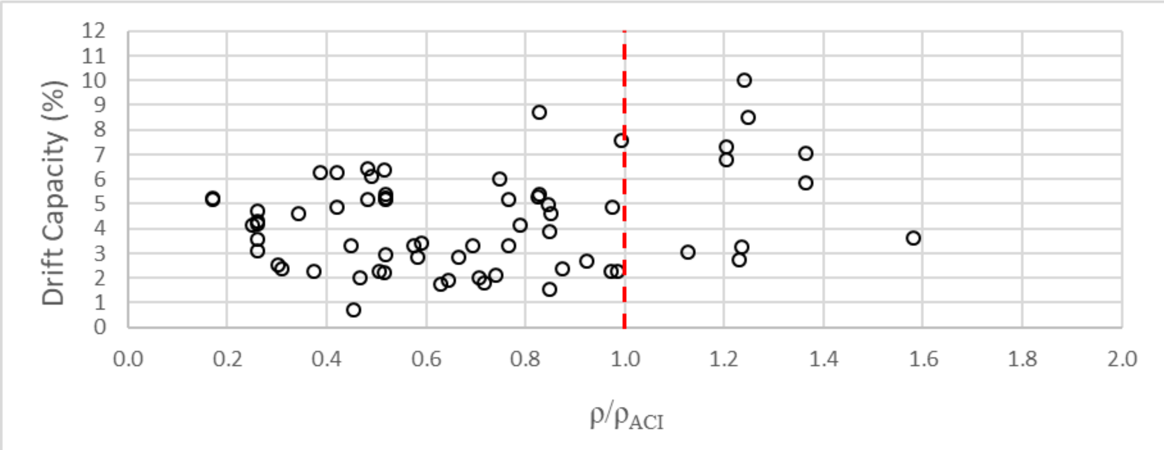

Figure 1: Drift capacity vs. provided confinement / required confinement by ACI318-19

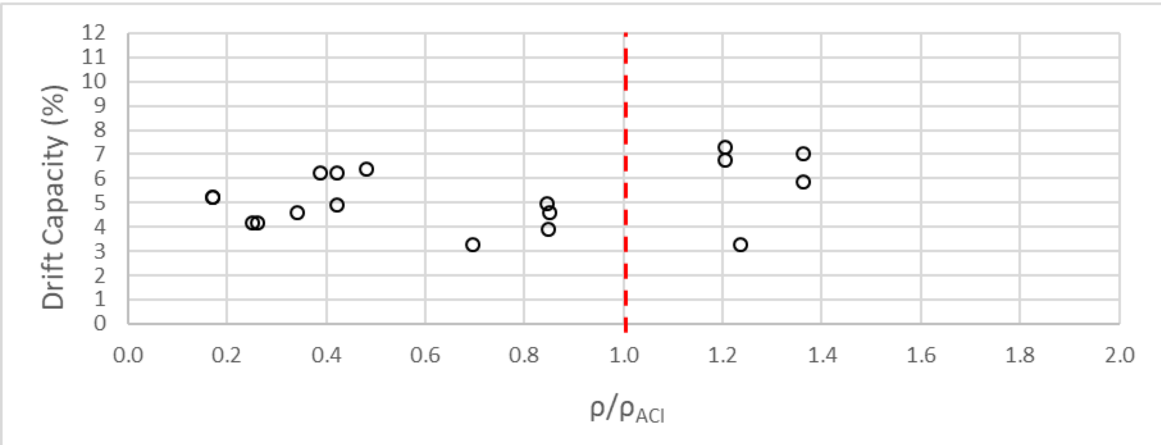

Figure 2: Drift capacity vs. provided confinement / required confinement by ACI318-19 for axial load ratios ranging from 0 – 20%

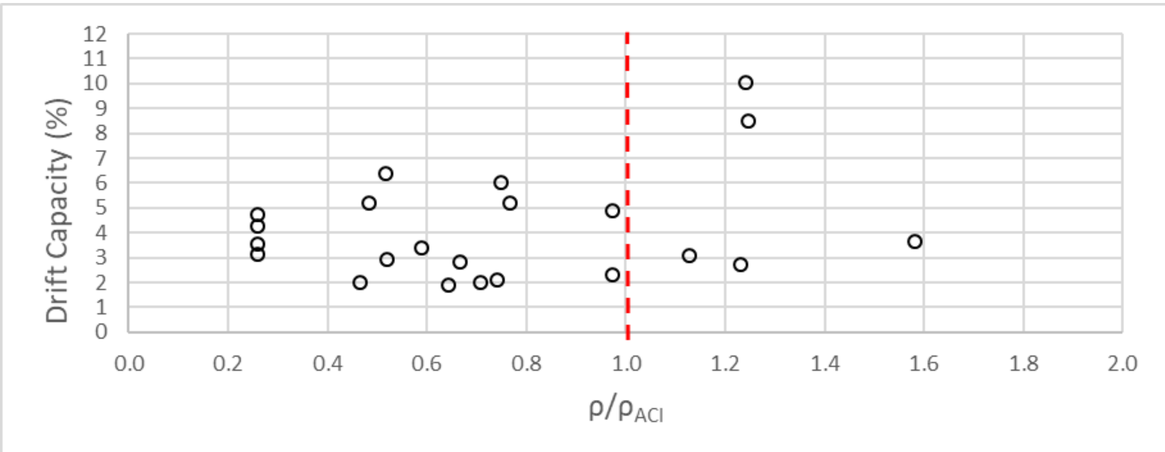

Figure 3: Drift capacity vs. provided confinement / required confinement by ACI318-19 for axial load ratios ranging from 20% – 50%

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3.2 Drift capacity versus ρ/ρ_{NZS} for (NZS3101-06)

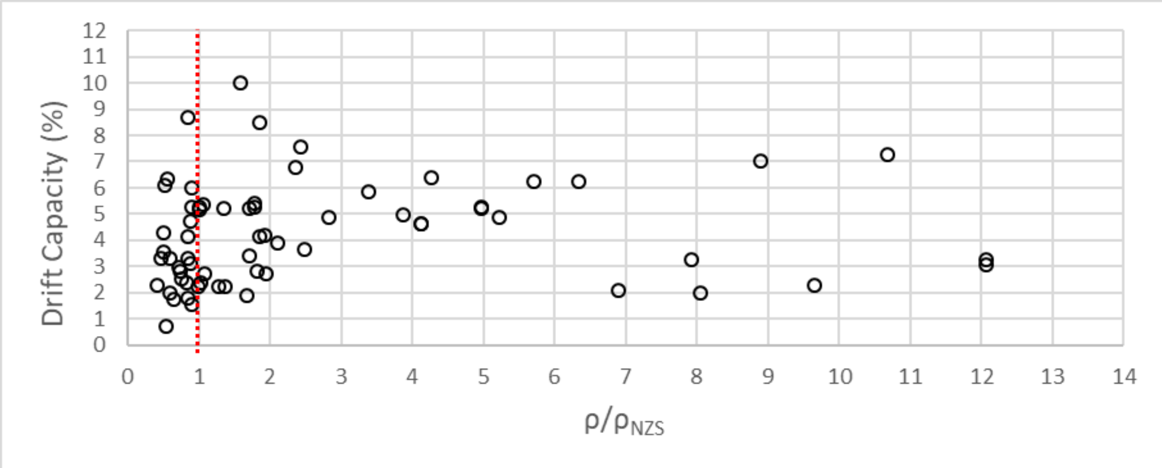

Figure 4: Drift capacity vs. provided confinement / required confinement by NZS3101-06

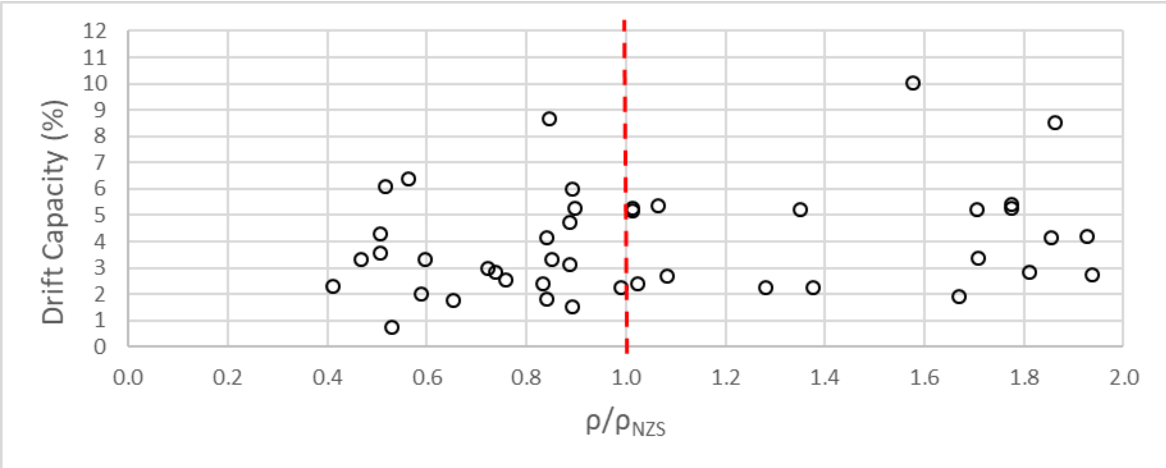

Figure 5: Drift capacity vs. provided confinement / required confinement by NZS3101-06 (Reduced scale)

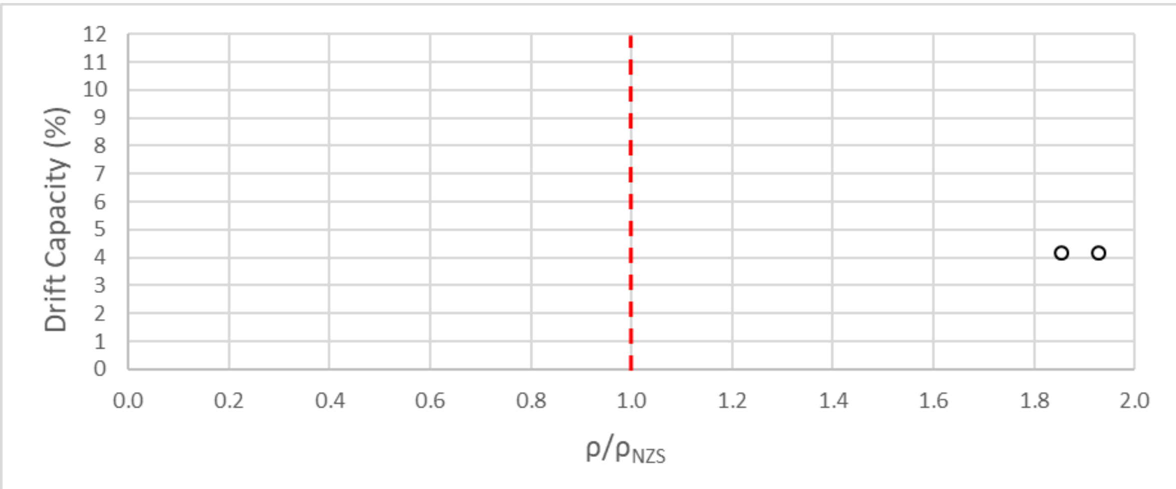

Figure 6: Drift capacity vs. provided confinement / required confinement by NZS3101-06 for axial load ratios ranging from 0 – 20%

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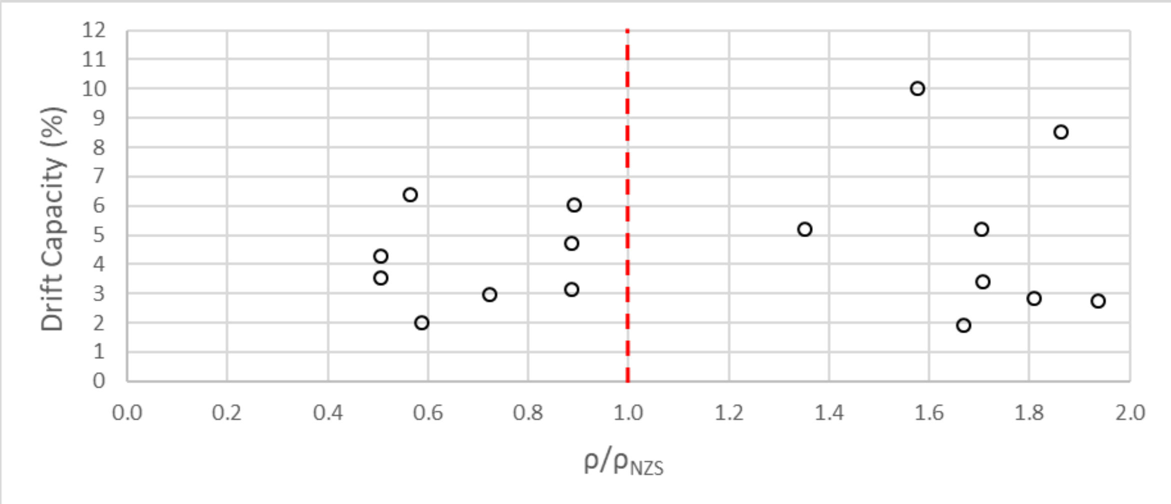

Figure 7: Drift capacity vs. provided confinement / required confinement by NZS3101-06 for axial load ratios ranging from 20 – 50%

4 DISCUSSION OF RESULTS

4.1 ACI318-19

Figure 1 shows drift capacity versus ratio of provided confinement to confinement required by ACI318-19. Columns with confinement provided near or exceeding the required confinement appear to exceed drifts of approximately 3% as suggested by Elwood et al. (2009). Nevertheless, a large number of columns with ratios of ρ/ρ_{ACI} as low as 0.2 to 0.4 performed similar to or better than code conforming columns. No apparent trend relating of ρ/ρ_{ACI} to drift capacity is observed. Figures 2 and 3 show the effects of axial load on drift capacity. While it may appear that larger axial load ratios diminish drift capacity for similar values of ρ/ρ_{ACI}, here again, no definitive trend can be made given the scatter in the data.

4.2 NZS3101-06

At first glance Figure 4 appears to have a trend for ρ/ρ_{NZS} ratios less than 2. However, when ρ/ρ_{NZS} ratios less than 2 are examined more closely in Figure 5 the trend ceases to exist. Similar to the ACI318-19 expression, a number of columns with ρ/ρ_{NZS} ratios as low as 0.5 perform similar to or better than code conforming columns. No apparent trend relating ρ/ρ_{NZS} to drift capacity is observed. The NZS3101-06 data also suggests that confinement could be lightened up by a factor of 12 in some instances and still satisfy NZS3101-06 requirements. The test results in Figure 4 suggest this reduction in provided confinement should not exist or at least not to this extent.

5 CONCLUDING REMARKS

The New Zealand NZS3101-06 and the United States ACI318-19 design codes are used as references throughout the world for the design of reinforced concrete buildings, especially for those built to resist seismic demands. Designers rely on expressions in such codes to be robust and produce reasonable results. The requirements for RC column confinement in both codes were examined against test data quantifying the deformability of RC columns controlled by flexure (i.e. not susceptible to shear and bond failures before flexural yielding). Within the ranges of the parameters listed in Figures 1-7, no clear trend was observed between drift capacity and the ratio of confinement provided (by rectilinear ties) to confinement required by the NZS3101-06 and ACI318-19 provisions. A number of columns with more confinement than required were observed to have drift capacities smaller than 2%. This observation and the mentioned lack of correlation between drift capacity and required confinement suggest urgent revision of current confinement requirements in the US and NZ should be considered. This revision should start with new efforts to identify the most critical parameters affecting the deformation capacity of columns not susceptible to shear and bond failure.

6 REFERENCES

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