# Improving Column Confinement

## Part 2: Proposed new provisions for the ACI 318 Building Code

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As shown in Part 1 of this article,[1] the confinement provisions specified in ACI 318-08, "Building Code Requirements for Structural Concrete,"[2] do not provide a consistent level of safety against deformation and damage during earthquakes.

In Part 2 of this article, we extend our discussion of detailing requirements and propose new confinement provisions suitable for use in the ACI 318 Building Code. We compare the provisions against existing provisions in the current building codes in the U.S.,[2] Canada,[3] and New Zealand,[4] and evaluate the provisions using test data from 145 columns in the PEER database.[5]

Compared with current ACI requirements, which do not depend on the level of axial load on the column, the equations proposed here would allow reduced confining reinforcement for columns with low axial load and require increased confining reinforcement for columns with higher axial load. Improved requirements related to column core area and the detailing of confining ties are also incorporated into the proposed equations.

## OBJECTIVES

To be practical, economical, and safe, confinement provisions should:

- Provide a consistent degree of safety (deformation capacity) for the range of applicability in practice (for example, small to large columns, low-to-high axial load, normal- to high-strength materials);
- Account for the key parameters that affect the relationship between the amount of confining reinforcement and lateral deformation capacity;
- Be as simple and straightforward as possible (while meeting the previous criteria); and
- Be applicable to building components other than columns (for example, wall boundary elements) that are designed by reference to the confinement provisions.

## DETAILING PROVISIONS

### Current ACI 318-08 requirements

As shown in Table 1, the ACI 318-08 Building Code has numerous provisions that address the function and benefits of transverse reinforcement in columns. In general, the requirements for tie spacing $s$ are related to controlling buckling of longitudinal bars, while the required amount of transverse reinforcement $A_{sh}$ is mainly related to confining the core concrete to achieve higher strain.

Section 7.10.5.3 of ACI 318-08 requires lateral restraint for corner bars and at least every other longitudinal bar. The section also requires longitudinal bars without lateral restraint to be located no further than 6 in. (150 mm) clear from a restrained longitudinal bar, and Section 21.6.4.2 requires the horizontal spacing of hoop legs or crossties $h_x$ to be no greater than 14 in. (350 mm) on center. The ACI definition of a crosstie requires a seismic hook (that is, a hook with a bend angle ≥ 135 degrees) at one end and permits a 90-degree hook at the other end. An extension of at least 3 in. (76 mm) or 6 bar diameters is required for all hooks, and the 90-degree hooks must be alternated end-for-end along the longitudinal bars.

### Confinement effectiveness

While the current 318-08 detailing requirements described in the previous section are generally sufficient to provide adequate confinement, it is intuitive that some details would provide better seismic performance compared to the minimum requirements:

## TABLE 1:
### Selected sections of the ACI 318-08 Building Code that relate to transverse reinforcement requirements for columns

| Section | Topic |
|---|---|
| 2.2 | Definitions of boundary element, crosstie, collector element, design story drift ratio, hoop, moment frames (ordinary, intermediate, and special), spiral reinforcement, and tie |
| 7.10.4 | Requirements for spiral reinforcement, including 3 in. maximum clear spacing |
| 7.10.5 | Requirements for ties, including need for lateral support of at least alternate longitudinal bars |
| 10.9.2 | Requirements for at least six longitudinal bars in columns with spirals and at least four longitudinal bars in columns with circular or rectangular ties |
| 10.9.3 | Required minimum volumetric ratio of spiral reinforcement (can govern over seismic requirements for small columns) |
| Chapter 11 | Shear strength of a cross section |
| Chapter 12 | Allowable reduction of bar development and lap splice lengths in tied members |
| 21.6 | Requirements for columns of special moment frames |
| 21.6.3.2 | Requirement for lap splices to be in the center half of the column height, confined with the full amount of confining reinforcement that is required at member ends |
| 21.6.4 | Requirements for transverse reinforcement, including the length of end regions over which it must be provided, the details of ties, tie spacing, and amount of transverse reinforcement |
| 21.6.4.3 | Minimum spacing requirements for transverse reinforcement |
| 21.6.4.4 | Confinement equations for amount of transverse reinforcement |
| 21.6.5 | Shear strength demands |
| 21.7 | Requirements for beam-column joints of special moment frames |
| 21.9.6.2 | Special boundary elements in walls |
| 21.11.7.5 | Collector elements in floor and roof diaphragms |
| 21.13 | Columns not designated as part of the seismic-force-resisting system (applies to high seismic design categories) |

- Restraining every longitudinal bar instead of every other bar would provide improved confinement and bar-buckling restraint;
- Using a 135-degree hook, or a closed tie with 135-degree hooks, would provide improved confinement and bar-buckling restraint compared to using a 90-degree hook of a crosstie. Testing has shown that 90-degree hooks tend to open and lose effectiveness after concrete cover spalls;[5] and
- With other variables being equal, providing laterally restrained longitudinal bars at a closer spacing around a column perimeter (for example, $h_x$ = 8 in. [200 mm]) will provide more effective confinement for the same $A_{sh}$ than providing such bars at the maximum 14 in. (350 mm) spacing.[6] Equation (21-2) of Section 21.6.4.3 in ACI 318-08 already provides some encouragement for designers to reduce $h_x$ by allowing a larger spacing of transverse reinforcement along the member length as $h_x$ reduces from 14 to 8 in. (350 to 200 mm).

## Recommended factor $k_n$

As discussed in Part 1 of this article,[1] a confinement effectiveness factor $k_n$ along the lines of that used in the Canadian Standards Association (CSA) requirements can encourage good column detailing, both for restraint of bar buckling and concrete confinement. From the considerations given in the previous paragraphs, we recommend modifying the effectiveness factor $k_n$ of the CSA equation to the following

$$k_n = [0.6 + 0.4(n/n_{ls})][(h_x+12)/20] \quad (1)$$

where the term $(h_x+12)/20$ shall not be taken less than 1.0; $n$ is the total number of longitudinal bars in the column cross section; $n_{ls}$ is the number of longitudinal bars in the column cross section that are laterally supported by the corner of hoops or by seismic hooks of crossties that are ≥ 135 degrees; and $h_x$ is (per ACI 318) the center-to-center horizontal spacing of crossties or hoop legs, in inches.

A practical advantage of this formulation, logical and helpful from the engineer's perspective, is that the factor will always be the minimum value of 1.0 if the longitudinal bar spacing is kept to 8 in. (200 mm) or less and all longitudinal bars are laterally restrained. If an engineer follows this detailing practice, she or he will not need to recalculate $k_n$ if the column size or detailing changes. No benefit is given for placing longitudinal bars at less than an 8 in. (200 mm) spacing, because a tighter spacing can lead to congestion at lap splices and intersecting members. The factor will be larger than 1 if less effective details are used, but will typically not exceed 1.4.

## CONFINEMENT EQUATION

### Current ACI 318-08 requirements

The provisions for rectangular columns in ACI 318-08 (Eq. (21-4) and (21-5)) require an amount of transverse reinforcement $A_{sh}$ that complies with

$$A_{sh}/sb_c \geq 0.3\frac{f_c'}{f_{yt}}\left(\frac{A_g}{A_{ch}}-1\right) \leq 0.09\, f_c'/f_{yt} \tag{2}$$

where $b_c$ is the width of the core measured to the outside of the confining bars; $f_c'$ is the specified concrete cylinder strength; $f_{yt}$ is the yield strength of the transverse reinforcement (limited to 100 ksi [689 MPa]); $A_g$ is gross cross-sectional area of the column; and $A_{ch}$ is the area of the confined core.

Compliance with Eq. (2) is required by a number of other provisions of the ACI code, including those for wall boundary elements, beam-column joints, columns not designated as part of the seismic-force-resisting system, and collector elements in floor and roof diaphragms (refer to Table 1).

### Proposed confinement design equation

Based on our assessment of key parameters influencing the confinement of the column core in Part 1 of this article,[1] we recommend that:

- The required area of transverse reinforcement $A_{sh}$ should be directly proportional to axial load ratio $P/A_g f_c'$;
- Minimum confinement should be specified by defining a minimum limit on the axial load used in the confinement equation;
- $A_{sh}$ should be directly proportional to $A_g/A_{ch}$, not $(A_g/A_{ch} - 1)$; and
- A confinement effectiveness factor $k_n$ should be included to encourage and give benefit to good transverse reinforcement detailing.

Considering these points and the good agreement between test data and the CSA equation[3] shown in Part 1 of this article,[1] we recommend the following equation, which has the same functional form as the CSA equation:

$$A_{sh}/sb_c \geq 0.25\, k_p k_n (f_c'/f_{yt})(A_g/A_{ch}) \tag{3}$$

In this proposed confinement design equation, $k_n$ is as given in the previous section (Eq. (1)); $k_p = P_u/A_g f_c'$ but taken as not less than 0.2; and $P_u$ is the factored axial force on the column, found using load factors per ACI 318-08. Consistent with ACI 318-08 provisions, we recommend a maximum value of $f_{yt}$ = 100 ksi. We selected the 0.25 coefficient in Eq. (3) and the minimum $k_p$ value to produce an appropriate comparison to the column test data in Reference 1, as will be discussed later in this article. We also compared the resulting transverse reinforcement to that required by existing provisions.

### Comparisons with existing provisions

Figure 1 shows the required confining reinforcement ratio using Eq. (3) and the current ACI, CSA, and Standards Association of New Zealand (NZS) equations for a 24 in. (600 mm) square column with the reinforcement arrangement shown. A comparison shows that:

- For an axial load ratio $P/A_g f_c' < 0.2$, the proposed provisions result in about 70% of the confining reinforcement required by ACI 318-08;
- For $P/A_g f_c'$ of about 0.27, the proposed provisions begin to require more confining reinforcement than ACI—about twice as much if $P/A_g f_c' = 0.6$ (the approximate upper limit of permissible axial load that results from applying the column design requirements of ACI 318-08);
- For columns constructed with normal-strength concrete and reinforcing steel and subjected to high axial loads, the proposed provisions give comparable results to the CSA and NZS equations; and
- For columns constructed with high-strength concrete and reinforcing steel and subjected to high axial loads, the proposed provisions require somewhat less transverse reinforcement than CSA and NZS (although, as we demonstrate in the following section, the test data show the proposed provisions to be appropriate).

Figure 2 illustrates a 42-story residential building designed for a high seismic area. The proposed requirements for confining reinforcement are compared with the current ACI 318 requirements over the building height. As shown in the details, the transverse reinforcement (with $f_{yt}$ = 100 ksi [689 MPa]) comprises closed hoops with longitudinal bars spaced at no more than 8 in. (200 mm), resulting in $k_n$ = 1 in Eq. (3). The figure shows that at the base of the building and at levels where the axial stress is highest (about 0.35 $f_c'$), the proposed equation requires the same or slightly more confining reinforcement than ACI 318. At all other levels, the proposed equation allows less confining reinforcement than ACI 318.

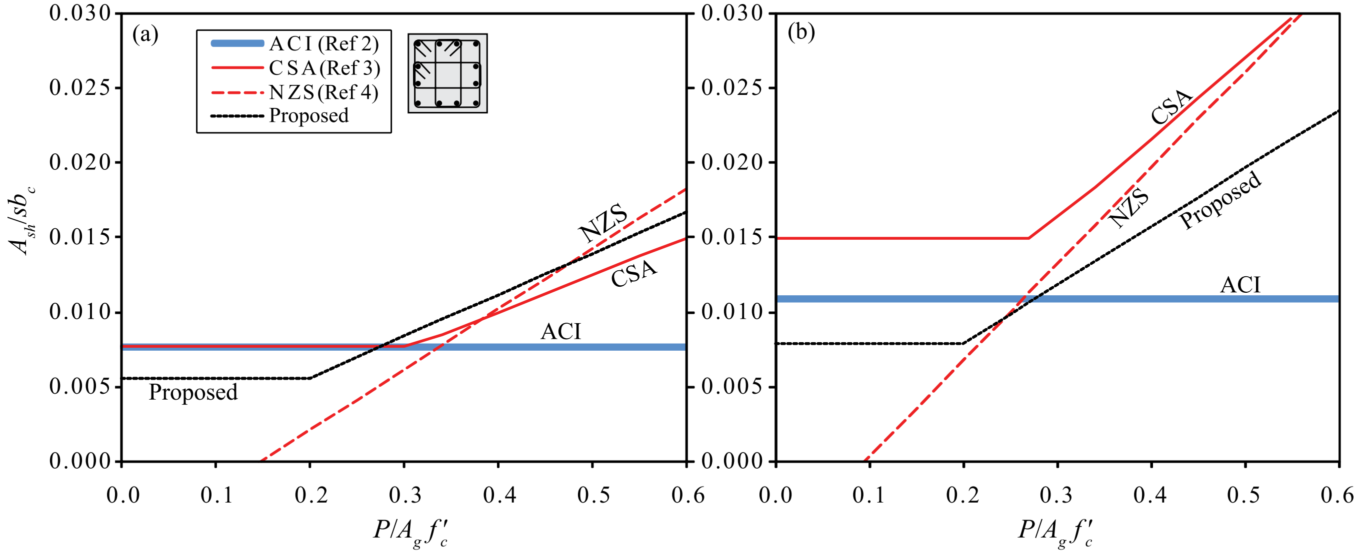


**Fig. 1: Comparison of confinement provisions (per References 2, 3, and 4 and Eq. (3)) applied to a 24 x 24 in. (600 x 600 mm) column with $A_g/A_{ch}$ = 1.3 and 12 No. 9 (No. 30M) bars: (a) $f_c'$ = 5 ksi and $f_{yt}$ = $f_{yl}$ = 60 ksi; (b) $f_c'$ = 12 ksi, $f_{yt}$ = 100 ksi, and $f_{yl}$ = 75 ksi (1 ksi = 6.89 MPa)**

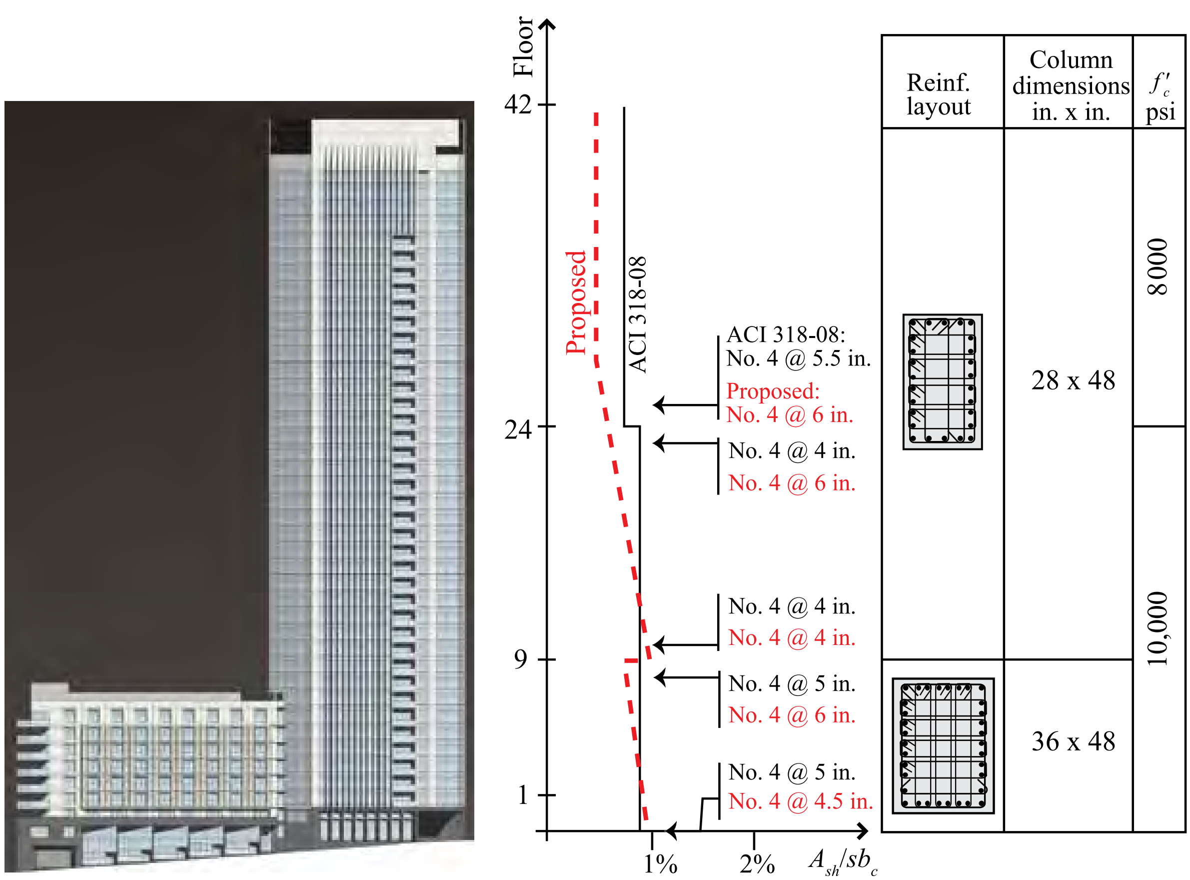


**Fig. 2: Required confinement reinforcing based on ACI 318-08 and the proposed provisions for a moment frame column in a 42-story building with $f_{yt}$ = 100 ksi (*Building design information courtesy of Magnusson Klemencic Associates*) (1 in. = 25.4 mm; No. 4 bar = No. 13M bar; 1000 psi = 6.89 MPa)**

We also compared the confinement reinforcement required for a gravity column in the same building. The example gravity column has higher axial load than the moment frame column; and, in this, case the proposed equation requires—for several levels in the bottom half of the building—up to 1.3 times the confining reinforcement required by ACI.[1] It should be noted, however, that if it can be shown that the gravity columns do not yield (that is, do not reach their moment strength under the design earthquake displacement), then by Section 21.13 of ACI 318-08, the confinement equation need not be applied.

## Comparison with test data

We compared the proposed equation with other confinement provisions using drift ratio capacity plots, as shown in Fig. 3. As discussed in Part 1 of this article,[1] an ideal confinement equation would have zero data points in Quadrant Q2 of the drift ratio capacity plot and only a limited number of data points in Quadrant Q3 to achieve

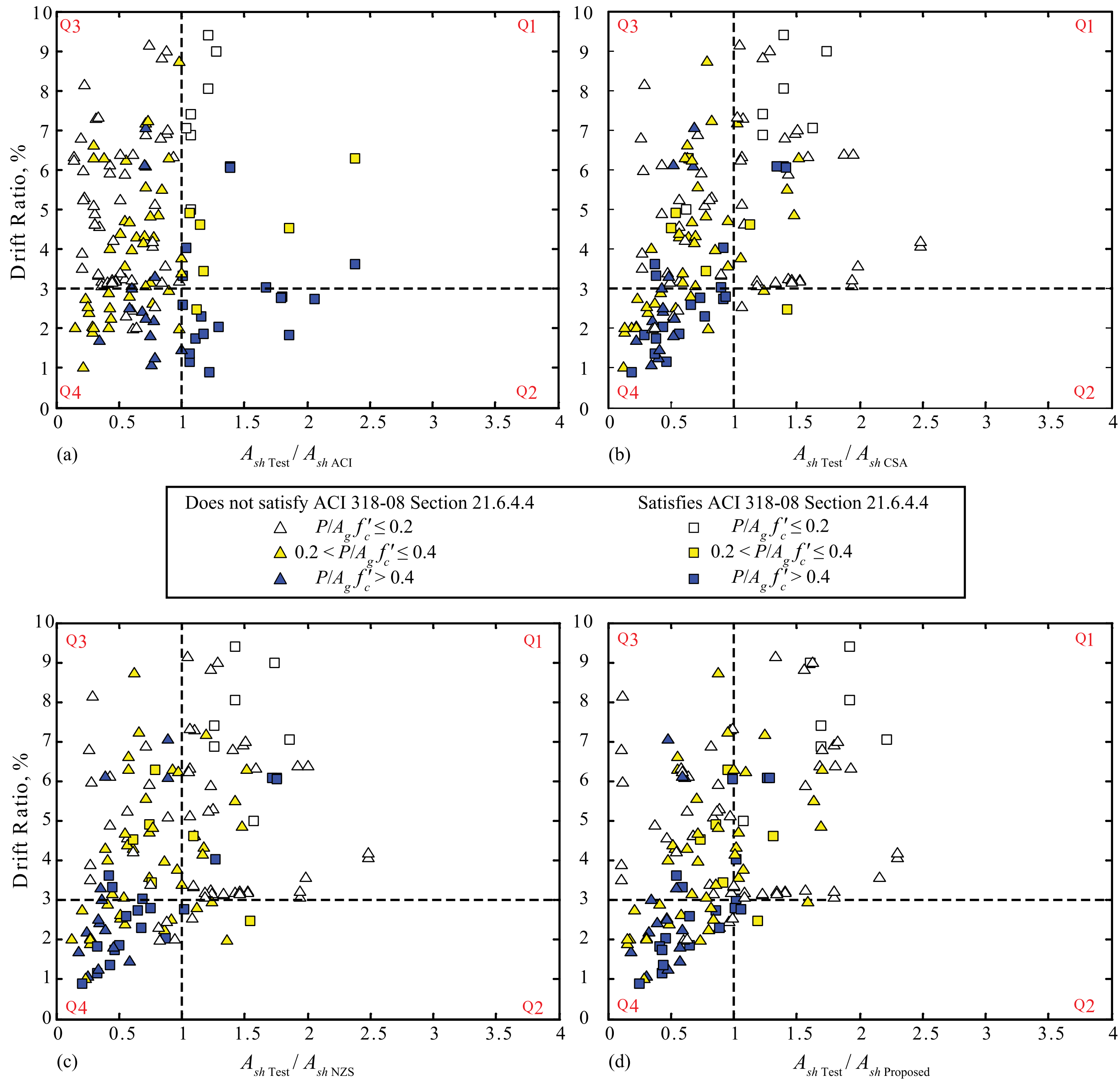


**Fig. 3: Drift ratio capacity versus confinement requirements for rectangular columns: (a) ACI; (b) CSA; (c) NZS; and (d) proposed (refer to Eq. (3))**

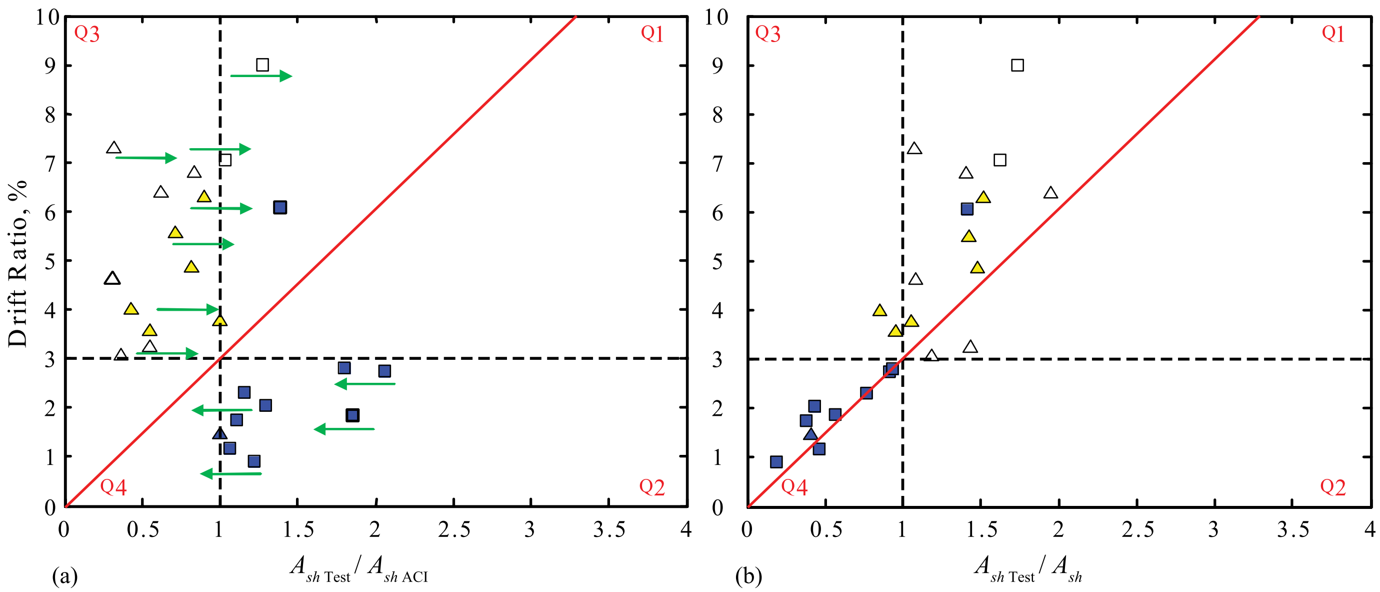


**Fig. 4: Desired movement of data points on plots of drift ratio capacity versus confinement requirements**

an appropriate level of conservatism. The ACI equation produced 13 data points in Quadrant Q2 and 82 in Quadrant Q3 (Fig. 3(a)). Therefore, an equation that demonstrates an improved performance over the ACI equation will display movement of data points from Quadrant Q2 to Quadrant Q4 and from Quadrant Q3 to Quadrant Q1 when compared with the ACI drift ratio capacity plot.

Figure 4 illustrates an example of this movement for a few selected data points. Figure 4(a) shows the location of some of the data points on the ACI drift ratio capacity plot and the desired movement of the data in Quadrants Q2 and Q3. Figure 4(b) shows how the same data would plot using a confinement equation with improved performance. The figure also demonstrates a desired trend, in which data points are aligned in a manner demonstrating a proportional increase in drift capacity with increased confining steel relative to the amount suggested by the provisions (that is, the data align along the diagonal red line). This relationship is particularly meaningful at lower confinement levels. As the amount of confinement provided approaches the amount required by the equation, the drift capacity should approach the performance target.

As illustrated by the data in Fig. 3, the proposed equation (Eq. (3)) provides substantial improvement in terms of safety over the current confinement provisions in ACI and produces about the same or better agreement with the test data as the NZS and CSA equations. Consistent with the discussed desired trends, Eq. (3) demonstrates a proportional increase in drift capacity with a relative increase in confining steel relative to the amount required by Eq. (1).

## ADDITIONAL RECOMMENDATIONS

### Application to wall boundary elements

ACI 318 requires special boundary elements where the wall neutral axis depth $c$ exceeds $l_w/600(\delta_u/h_w)$, where $l_w$ is the wall length, $\delta_u$ is the design displacement demand, and $h_w$ is the wall height. When such elements are required, ACI 318 requires that they contain transverse reinforcement according to the column confinement equations. For the proposed equation, one must define the term $k_p$, and for wall boundary elements, $k_p$ should not depend on the wall axial load but, instead, on the expected strain demand in the wall. This can be related to the ratios $c/l_w$ and $\delta_u/h_w$. We propose that for ties in special wall boundary elements, $k_p$ in Eq. (2) is defined as

$$k_p = 120(c/l_w)(\delta_u/h_w) \tag{4}$$

This corresponds logically to the proposed requirements for columns, because when $c$ in a wall is just large enough to trigger special boundary elements, the resulting $k_p$ will equal 0.2 and result in the same minimum confinement level as for columns. As neutral axis depth or displacement demand increases for a wall, indicating larger compressive strain demands, the $k_p$ value will correspondingly increase. An upper limit on $k_p$ may be appropriate for this application to avoid over-congestion of ties.

### Application to other elements

As noted previously, in the ACI code, the confinement equations are referenced for design of structural element types other than columns, including:

- Columns not designated as part of the seismic-force-resisting system; and
- Collector elements in floor and roof diaphragms.

Typically, for these applications, we recommend that the $k_p$ factor be computed based on $P_u$ in the element as governed by the applicable load combination specified in ACI 318 or ASCE 7.[7]

This code load combination can underestimate actual earthquake axial forces on columns (such as is predicted from nonlinear response-history analysis), particularly for outside columns of moment frames or outrigger frames.[8] In some cases, load factors on gravity loads compensate for this underestimation. The potential that column axial loads could be higher than estimated using code requirements further emphasizes the importance of providing increased confinement in cases of high axial load.

For beam-column joints, ACI 318-08 uses the column confinement equation to provide transverse steel to resist joint shear. This study has not considered the impact of axial load on beam column joint design; a different formulation or minimum limit for the $k_p$ factor may be appropriate to maintain levels of transverse joint steel consistent with the current requirements. Alternatively, for beam-column joints, $k_p$ could potentially be formulated based on the level of joint shear demand. Further study is required in this regard.

## Confinement for circular columns

Although there are fewer test data for circular columns subjected to high axial loads than for rectangular columns, an assessment of the data suggests that the ACI confinement provisions for spiral or circular tie reinforcement may not provide sufficient deformation capacity for columns with high axial loads.[9] Following the same reasoning and approach as for rectangular ties, we recommend a confinement equation for spiral or circular tie reinforcement, to replace Eq. (21-3) of ACI 318-08, as follows

$$\rho_s = 0.35\, k_p (f_c'/f_{yt})(A_g/A_{ch}) \qquad (5)$$

where $\rho_s$ is the volumetric ratio of transverse reinforcement, and, as for rectangular ties, $k_p = P_u/A_g f_c'$ (but taken as not less than 0.2). Note that a $k_n$ term is not needed for Eq. (5), because it is expected that spiral or circular tie reinforcement can provide effective confinement without additional crosstie or spacing limits for longitudinal bars. (ACI 318 requires columns with spiral reinforcement to have a minimum of six longitudinal bars.) Testing of large circular columns under high axial load is needed to determine if there is a limit on the size of the column above which crossties may be required to achieve effective confinement and further validate the proposed equation.

The proposed equation (Eq. (5)) for circular columns is similar to the confinement equation provided in CSA A23.3-04,[3] except that the CSA equation uses a factor of 0.4 where the proposed equation uses a factor of $0.35A_g/A_{ch}$. We include the $A_g/A_{ch}$ term to address the effect of strength loss from the spalling of the unconfined cover concrete, as described in Reference 1. This effect occurs for columns with spiral and circular ties in the same way as for columns with rectangular ties. In the case of a square column with a circular reinforcement cage (to which Eq. (5) would apply), the effect can be significant because of the relatively large area of unconfined cover concrete.

## CONCLUSIONS

This article proposes provisions suitable for use in the ACI 318 Building Code for design of transverse reinforcement in columns and other elements. Compared with the current ACI code provisions, the proposed provisions will provide a more consistent degree of safety for the range of properties used in practice. The equations encourage (through reduction in required confinement steel) better detailing practices for the reinforcement of columns and are straightforward for engineers to implement.

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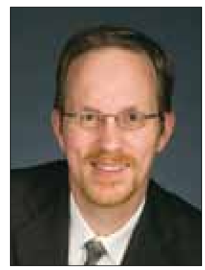

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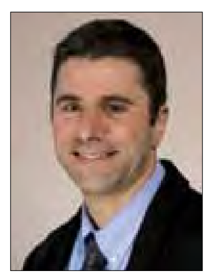

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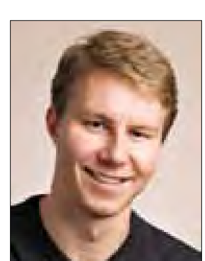

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