Study of minimum requirements of confinement in concrete columns confined with WRG in moment resisting frames

Benny Kusuma

Department of Civil Engineering, Universitas Kristen Indonesia Paulus, Makassar, Indonesia

*kusumab06@yahoo.com

Abstract. The national concrete standard SNI 2847:2013 which refers to the ACI 318M-11 has not accommodated the influences of the axial load and deformation parameters as performance requirement, where both parameters are very critical to affect the required confining steel of concrete columns. This study presents the test results of reinforced concrete columns confined with WRG which were designed according to ACI standards. The test results were analyzed using several codes such as SNI 2847:2013, ACI 318M-14, CSA A23.3-04, and NZS 3101-06 standards. Furthermore, the minimum confinement equation is proposed for the design of columns confined with WRG, then it is also compared with selected confinement provisions. The study results showed that the equation for confining reinforcement adopted in the SNI 2847:2013 or ACI 318-11 is very conservative compared to other codes when applied to low axial load levels (≤ 0.25 $A_{g}f'$), but relatively less conservative or unsafe if the axial load level is greater than 0.3. From result of evaluation show that CSA A23.3-04 provide most conservative result for confinement design. The additional confinement design equations at ACI 318M-14 has been improve confinement design of ACI Code. Compared with SNI 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 higher axial load. Overall, the proposed equation presents the best correlation to actual drift capacity of columns, and in addition it can be used for columns reinforced with WRG-transverse reinforcement having a yield strength higher than 500 MPa. The study also provides the recommendation for further refinement of SNI 2847 in the future related to the requirement of WRG confinement in concrete columns of Special Moment Frames in highly seismic regions.

1. Introduction

Most areas in Indonesia are grounds with high level of earthquake hazard risk. Based on standard building Code, any building construction to be erected in an area with a high earthquake risk must be designed in accordance with earthquake-resistant building planning rules. This matter is necessary to ensure the safety of buildings and occupants against earthquakes. The most important part in the planning rules for earthquake-resistant reinforced concrete building construction is the provision of adequate reinforcement detailing on structural elements that have the potential to experience damage when an earthquake occurs. One of the important requirements for earthquake resistant buildings...
associated with reinforcement detailing is the use of confinement reinforcement in moment resisting frame. Based on Indonesian Standard Code (SNI 2847:2013) [1] the amount of confinement area depends only on column cross sectional area, strength of confinement reinforcement and concrete strength material. The national concrete standard SNI 2847:2013 [1] which refers to the ACI 318M-11 [2] has not accommodated the influences of the axial load and deformation parameters as performance requirement, where both parameters are very critical to affect the required confining steel of concrete columns.

Several researchers [3]–[13] conducted experimental study and evaluated the ACI 318M-11 confinement provision [2]. The study shown some limitations such as (1) the confinement requirements do not account for effect of axial load level; (2) the deformation parameters is not accounted into confinement demand; (3) the utility of high-strength materials does not take account into confinement provisions. This inadequacy has been addressed in ACI 318M-14 [14] by add one confinement design equations that consider the effect high-strength concrete, confinement effectiveness, deformation demand. However, this additional confinement design equation at ACI 318M-14 [14] has not been assessed through experimental and analytical study.

This paper presents the test results of reinforced concrete columns which were confined according to SNI or ACI standards. The test results were analyzed using several codes such as SNI [1], ACI [14], CSA [15], and NZS [16] standards. Only confinement requirements for rectangular column were evaluated. The deformability of SNI [1] are assessed and compared with ACI [14], CSA [15] and NZS [16] confinement provisions. Furthermore, the minimum confinement equation is proposed for the design of columns confined with WRG, then it is also compared with selected confinement provisions. Compared with SNI 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 higher axial load. The study also provides the recommendation for further refinement of SNI 2847 in the future related to the requirement of WRG confinement in concrete columns of special moment frames in highly seismic regions.

2. Confinement Provisions

Table 1 summarizes four sets [1], [14]–[16] of confinement provisions for rectangular building columns. All of the provisions are intended for the design of structures in regions of high seismicity, and all can be expressed in terms of the confinement reinforcement ratio $A_{sh}/sb_c$ in each transverse direction. With the exception of SNI, the listed provisions were developed by placing limits on a deformation parameter at failure, where failure is defined as a specified reduction in lateral load resistance. The most commonly used deformation parameter is curvature ductility ratio $\mu_\delta$, the quotient of curvature at failure and curvature at first yield. One of the provision in Table 1, however, were developed using the drift ratio $\delta$, the quotient of the interstory drift at failure and the story height.

The SNI 2847:2013 [1] or ACI 318-11 [2] does not account for confinement effectiveness in determining the required amount of confinement. These deficiencies have been addressed in ACI 318-14 [14], a proposed confinement design equation added by ACI 318 committees to provide the amount of confinement that can be achieved the target drift ratio of 3%. Confinement effectiveness is a key parameter determining the behavior of confined concrete (Mander et al. [17]) and has been incorporated in the CSA A23.3-04 [15] equation for column confinement.

The Canadian codes [15] for confinement requirements were derived by Paultre and Legeron [8]. The curvature demand for ductile earthquake-resistant reinforced concrete columns as were used as deformation parameter. The influences of axial load level, confinement effectiveness, high-strength concrete, and high-strength transverse reinforcement were covered in confinement requirements [15]. Watson and Zahn [11] developed confinement provision of NZS 3101-06 [16]. Similar with [15] the axial compressive load, high-strength concrete, curvature demand as deformation parameter also accounted in the confinement provisions [16]. Both researchers [8], [11] used moment curvature analysis in derive the confinement equations. Although, the requirement of the amount of confinement...
on axial load demand has been established by CSA A23.3 [15] and NZS 3101 [16], but this axial load influence has not been implemented by previous editions of SNI 2847 [1] or ACI 318 [2].

Table 1. Summary Of Confinement Equations For Rectangular Reinforced Concrete Building

| Codes | \( A_{nl}/s_b = \) | Deformation parameter |
|-------|-----------------|----------------------|
| SNI 2847:2013, or ACI 318M-11 | \( \frac{f_c'}{f_yt} \left( \frac{A_g}{A_{ch}} - 1 \right) \geq 0.09 \frac{f_c'}{f_yt}; f_yt \leq 700 \text{ MPa} \) | None |
| ACI 318M-14 | \( \frac{f_c'}{f_yt} \left( \frac{A_g}{A_{ch}} - 1 \right) \geq 0.09 \frac{f_c'}{f_yt}; f_yt \leq 700 \text{ MPa} \) | \( \delta = 3\% \) |
| CSA A23.3-04 | \( \frac{A_g}{A_{ch}} \frac{f_c'}{f_yt} \geq 0.09 \frac{f_c'}{f_yt}; f_yt \leq 500 \text{ MPa} \) | \( \mu_0 = 16 \) |
| NZS 3101-06 | \( 1.3 - \rho_{cm} \frac{A_g}{A_{ch}} \frac{f_c'}{f_yt} \frac{P}{\phi f_yt A_{ch}} \phi(A_g) - 0.006; f_yt \leq 800 \text{ MPa} \) | \( \mu_0 = 20 \) |

\( A_{sh} = \) cross-sectional area of structural member measured out-to-out of transverse reinforcement; \( A_g = \) gross area of column; \( A_{ch} = \) total cross-sectional area of transverse reinforcement (including crosssties) within spacing \( s \) and perpendicular to dimension \( b_s \); \( b_s = \) cross-sectional member core measured to outside edges of transverse reinforcement composing area \( A_{sh} \); \( f_c' = \) specified cylinder strength of concrete; \( f_{sl} = \) specified yield strength of longitudinal reinforcement; \( f_{yl} = \) specified yield strength of transverse reinforcement; \( m = \) mechanical reinforcing ratio (\( m = f_{sl}/0.85 f_c' \)); \( n_l = \) number of longitudinal bars laterally supported by corner of hoop or hook of crosssties; \( P = \) axial compressive force on column; \( P_o = \) nominal axial load strength at zero eccentricity (\( P_o = 0.85 f_{sl} (A_g-A_{sh})+A_{sh} f_{yl} \)); \( s = \) spacing of transverse reinforcement measured along longitudinal axis of member; \( \kappa = \) total area of longitudinal reinforcement divided by \( A_{sh} \); \( \square = \) capacity reduction factor; \( \square \mu = \) curvature ductility ratio; and \( \kappa = \) drift ratio.

3. Proposed Confinement Design Equation

The confining-reinforcement design equation used by SNI [1]. ACI [2, 14], CSA [15] and NZS [16] for conventional confinement steel cannot be directly applicable to WRG-confined columns, as the geometry and configuration grids are significantly different. The objective of this section is to develop simplified design equations directly providing \( A_{sh} \) or \( \rho_s \) for two different levels of ductility, which, in this research, are targeted as (i) moderate ductility level corresponding to a force reduction factor of 2.5 and curvature ductility factor \( \mu_0 \) of at least 8, and (ii) ductile level corresponding to a force reduction factor of 3.5 and curvature ductility factor \( \mu_0 \) of at least 16 (Kusuma [12]).

The parameters investigated in deriving the design formula include section area ratio \( (A_g/A_{sh}) \), axial load level \( (P/A_{sh} f_{c}') \), confinement effectiveness factor \( (k_e) \), and curvature ductility factor \( (\mu_0 = \phi_0/\phi_1) \) was the performance criterion selected. Considering these points and the good agreement between test data and the CSA and ITG equations (CSA A23.3-04 [15], ITG 4.3R-07 [18]), following empirical expression is proposed to estimate the amount of lateral steel \( A_{sh} \) for WRG-confined columns.

For \( P \leq 0.25 A_g f_{c}' \):
\[
\frac{A_{sh}}{sb_c} = 0.06k_x \frac{f'_{c}}{f_{yt}} \frac{A_x}{A_{sh}}
\]

For \( P > 0.25A_{g}f'_{c} \):

\[
\frac{A_{sh}}{sb_c} = 0.15k_x \frac{1}{(k_w)^{1/3}} \frac{f'_{c}}{f_{yt}} \frac{A_x}{A_{sh}} A_{g} f'_{c}
\]

where, \( f_{yt} \) is the specified yield strength of the transverse reinforcement (limited to 700 MPa, per ACI 318 [14]; \( A_x/A_{sh} \) is the ratio of the gross concrete area to the core area (the core area is measured to the outside of peripheral tie reinforcement according to NZS 3101 [16] and ACI 318 [14]; \( k_w \) is a confinement effectiveness factor according to ITG 4.3R [18]; and \( k_x \) is section performance factor suggested by Sheikh and Khoury [10] and Bayrak and Sheikh [3] is adopted with different coefficients.

\[
A_x/A_{sh} \leq 1.5
\]

\[
k_{ve} = \frac{0.15b}{\sqrt{sh_c}} \leq 1.0
\]

\[
k_{y} = \frac{(\mu_y)^{\gamma}}{\beta}
\]

if, \( P \leq 0.25A_{g}f'_{c} \) : \( \beta = 17.5 \), \( \gamma = 1.0 \)

\( P > 0.25A_{g}f'_{c} \) : \( \beta = 1649 \), \( \gamma = 2.5 \)

4. Comparisons with Existing Provisions

The comparison of confinement demand from all codes [1], [2], [14]–[16] and equations proposed by the author [12] are compared. The confinement provisions and propose are applied on 600×600 mm² columns. The ratio of longitudinal reinforcement was 1.1% and the yield strength of longitudinal reinforcement of 420 MPa are specified for normal-strength (\( f'_{c} = 28 \) MPa) and high-strength (\( f'_{c} = 70 \) MPa) of reinforced concrete. Concrete cover is 40 mm. The confining-WRG reinforcement has a diameter of 12.5 mm, with a yield stress (\( f_{yt} \)) of 420 MPa.

Figure 1 shows the required confining reinforcement ratio (\( A_{sh}/sb_{c} \)) using the proposed equation from Kusuma [12] (Eq. 1-2) and the current SNI, ACI, CSA, and NZS equations for square column with the reinforcement arrangement shown. Column with normal- and high-strength of reinforced concrete show that for an axial load ratio \( P/A_{g}f'_{c} \leq 0.25 \), the proposed provisions result in about 70% of the confining reinforcement required by SNI 2847:2013 [1] or ACI 318-11 [2]. For the axial load ratio \( P/A_{g}f'_{c} \) of about 0.30, the proposed provisions begin to require more confining reinforcement than SNI 2847:2013 [1] or ACI 318-11 [2] about 1.9 times 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 318-11 [2]).

For columns constructed with normal- and high-strength concrete and subjected to high axial loads, the proposed provisions require somewhat less transverse reinforcement than ACI 318-14 [14], CSA A23.3 [15] and NZS 3101 [16] equations. SNI 2847:2013 [1] and ACI 318-11 [2] provide consistent amount confinement reinforcement for each axial load level. For columns with high-strength of reinforced concrete NZS 3101 [16] requires highest amount of confinement reinforcement than other codes and proposed provisions. When \( P/A_{g}f'_{c} \leq 0.30 \) NZS 3101 [16] showed the lowest amount of confinement reinforcement.
Figure 1. Comparison of confinement demand applied to the 600×600 mm² column with (a) $f'_c = 28$ MPa and $f_{yl} = f_{yt} = 420$ MPa; (b) $f'_c = 70$ MPa and $f_{yl} = f_{yt} = 420$ MPa

The result of the comparison indicates that for minimum confining-reinforcement WRG for moderate axial load levels of 0.2 to 0.3, the SNI and ACI are very conservative. However, for higher axial load levels, the provisions from SNI 2847 [1] and ACI 318-11 [2] for the confinement provisions are below than the ACI 318-14 [14], CSA A23.3 [15], NZS 3101 [16] and proposed provisions [12]. These findings implicate that the SNI 2847 [1] and ACI 318-11 [2] standards are less profitable for low to moderate axial load levels.
5. Comparisons with Test Data
We compared the proposed equation with other confinement provisions using drift ratio capacity plots, as shown in Figure 2. In this section all confinement requirements for square column were evaluated using 20 column test result from Kusuma [12] and Saatcioglu and Griba [19]. To evaluate the deformation capacity of column specimens, the measured drift at 80% lateral force in post-peak lateral force resistance was used. In this research, 3% drift are used as target performance in order to assess confinement provision to test data. This is relating to the maximum allowed earthquake drift demand by ASCE/SEI 7-05 [20]. The maximum earthquake demands are 1.5 times design basis demands, were 2% drift limit is specified for buildings with concrete columns. This target performance is also considered in ACI 318-14 [14].

Although the provisions in Table 1 were developed based on different deformation parameters, a consistent performance measure is required to enable all to be compared against each other. Drift capacity was selected for several reasons: (1) this quantity is routinely reported for all test specimens, while the curvature ductility capacity is not; (2) it does not depend on the definition of yield displacement or yield curvature; and (3) the drift capacity can be directly related to drift limits specified in building codes.
Figure 2. Drift ratio capacity versus confinement requirements for square columns: (a) SNI; (b) ACI; (c) CSA; (d) NZS; and (e) proposed (refer to Eq. (1) and (2)).

The performance target is shown as a horizontal dotted line at a 3% drift ratio. The vertical dotted line corresponds to the limit between compliance and noncompliance to the amount of confinement reinforcement recommended in the specific code or proposed equations. For an ideal confinement provision, all of the data would appear in the upper-right quadrant (Quadrant 1) and in the lower-left quadrant (Quadrant 4). Data in Quadrant 1 represent columns with confinement reinforcing exceeding that required by the considered provision but with drift capacities equal to or greater than the performance target. Data in Quadrant 4 represent columns with less confinement reinforcing than that required by the considered provision but with drift capacities less than the performance target.

Data appearing in the upper-left quadrant (Quadrant 3) represent columns with less confinement reinforcing than that required by the provision but exhibiting a drift capacity exceeding the target, thus indicating that the provisions may be considered overly conservative in such cases. In contrast, data in the bottom-right quadrant (Quadrant 2) represent columns with more confinement reinforcing than required by the provision but exhibiting drift capacity below the target, thus indicating that the provisions may be considered unconservative for these cases.

The drift ratio capacity plots for SNI, ACI, CSA, NZS and proposed equation are shown in Figure 2 (a), (b), (c), (d) and (e) respectively. As illustrated by the data in Figure 2, the proposed equation (Eq. (1) and (2)) provides substantial improvement in terms of safety over the current confinement provisions in SNI and produces about the same or better agreement with the test data as the ACI 318-14, CSA and NZS equations. Table 2 exhibited the number of data point in each quadrant from each code. The SNI showed the highest data point in Q2 it means that this provision less conservative compared to other codes and proposed equation. This due to SNI do not account for the effect of axial compression load. In Figure 2(a) shows that most data point of columns with $0.2 < P/Ag'c \leq 0.4$ are placed in Q2. With new additional confinement equation at ACI 318-14 [14] the number of column in Q2 are reduced. The CSA and ACI codes are the most conservative for confinement requirement. These provision provides the smallest number of columns data point in Q2.

Overall, the proposed equations (Eq. (1) and (2)) present the best correlation to actual drift capacity of columns, and in addition it can be used for columns reinforced with WRG-transverse reinforcement having a yield strength higher than 500 MPa.
6. Conclusion

This article proposes provisions suitable for use in both SNI 2847 and ACI 318 Building Code for design of welded reinforcement grid as transverse reinforcement in columns and other elements. Compared with the SNI 2847:2013 or ACI 318-11 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.

From the result of the studies as discussed, the following conclusions can be drawn:

1. The equation for confining reinforcement adopted in the SNI 2847:2013 and ACI 318-11 is very conservative compared to other codes when applied to low axial load levels ($\leq 0.25 A_{gf}'$), but relatively less conservative or unsafe if the axial load level is greater than 0.3.

2. The additional confinement equation at ACI 318-14 has been improving the deformability and safety design than previous version. However, from evaluation in column experimental data showed that CSA confinement requirement are the most conservative, since this code limit the yield strength of transverse reinforcement up to 500 MPa.

3. The proposed equation presents the best correlation to actual drift capacity of columns, and in addition it can be used for columns reinforced with WRG-transverse reinforcement having a yield strength higher than 500 MPa.

References

[1] Indonesian National Standard, “Requirements of Structural Concrete for Building,” SNI 2847:2013 (in Indonesian), 2013.
[2] ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318M-11) and Commentary 2011” American Concrete Institute, Farmington Hills, Mich., p. 473, 2011.
[3] O. Bayrak and S. A. Sheikh, “Confinement Reinforcement Design Considerations for Ductile HSC Columns,” ASCE Journal of Structural Engineering, vol. 124, no. 9, pp. 999–1010, 1998.
[4] K. J. Elwood et al., “Improving Column Confinement, part 1: Assessment of Design Provisions,” Concrete International, vol. 31, no. 11, pp. 32–39, 2009.
[5] S. J. Hwang et al., “Design of Seismic Confinement of Reinforced Concrete Columns Using High Strength Materials, in Reinforced Concrete Columns with High Strength Concrete and Steel Reinforcement,” ACI SP-293, American Concrete Institute, Toronto, Canada, 2013.
[6] Li B. and R. Park, “Confining Reinforcement for High-Strength Concrete Columns,” ACI Structural Journal, vol. 101, no. 3, pp. 314-324, 2004.
[7] T. Paulay and M. J. N. Priestley, “Seismic Design of Reinforced Concrete and Masonry Buildings,” John Wiley and Sons Inc, New York, 1992.
[8] P. Paultre and F. Legeron, “Confinement Reinforcement Design for Reinforced Concrete Columns,” ASCE J Journal of Structural Engineering, vol. 134, no. 5, pp. 738-749, 2008.
[9] Razvi S. and M. Saatcioglu, “Strength and Deformability of Confined High-Strength Concrete Columns,” ACI Structural Journal, vol. 91, no. 6, pp. 678-687, 1994.
[10] S. A. Sheikh and S. S. Khoury, “A Performance-Based Approach for the Design of Confining Steel in Tied Columns,” ACI Structural Journal, vol. 94, no. 4, pp. 421-431, 1997.
[11] S. Watson, F. A. Zahn, and R. Park, “Confining Reinforcement for Concrete Columns,” ASCE Journal of Structural Engineering, vol. 120, no. 6, pp. 1798-1824, 1994.
[12] B. Kusuma, “Behavior of Reinforced Concrete Columns Confined with Welded Reinforcement Grid Under Axial Compression and Combined Axial Compression and Reversed Cyclic Loading,” Doctoral Dissertation, Program Pascasarjana, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia, 2015.

[13] B. Kusuma, Tavio, and P. Suprobo, “Behavior of Concentrically Loaded Welded Wire Fabric Reinforced Concrete Columns with Varying Reinforcement Grids and Ratios,” International Journal of ICT-aided Architecture and Civil Engineering (IJIAICE), SERSC, Australia, vol. 2, no. 1, pp. 1–15, 2015.

[14] ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318M-14) and Commentary 2014” American Concrete Institute, Farmington Hills, MI, 2014.

[15] CSA Committee A23.3, “Design of Concrete Structures (CSA A23.3-04),” Canadian Standards Association, Ontario, Canada, p. 214, 2004.

[16] NZS Committee P 3101, “Concrete Structures Standard - The Design of Concrete Structures (NZS3101 Part 1),” Standards New Zealand, Wellington, New Zealand, p. 256, 2006.

[17] J. B. Mander et al., “Theoretical Stress-Strain Model for Confined Concrete,” Journal of Structural Engineering, vol. 114, no. 8, pp. 1804-1825, 1988.

[18] ACI Innovation Task Group 4, “Report on Structural Design and Detailing for High-Strength Concrete in Moderate to High Seismic Applications (ITG-4.3R-07),” American Concrete Institute, Farmington Hills, MI, 66 pp., 2007.

[19] M. Saatcioglu and M. Grira, “Confinement of Reinforced Concrete Columns with Welded Reinforcement Grids,” ACI Structural Journal, vol. 96, no. 1, pp. 29-39, 1999.

[20] ASCE/SEI 7-05, “Minimum Design Loads for Buildings and Other Structures,” ASCE/SEI 7-05, American Society of Civil Engineers, Reston, VA, 388 pp., 2006.