VOL. 12, NO. 9, MAY 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

DEFORMABILITY ASSESMENT 0F SEISMIC DESIGN CONFINEMENT OF REINFORCED CONCRETE COLUMNS

Harun Alrasyid and Munarus Suluch
Department of Civil Engineering, Institut Teknologi of Sepuluh Nopember, Indonesia
E-Mail: harun@ce.its.ac.id

ABSTRACT

This research shows the result of deformability evaluation of confinement design equation of ACI 318-11, ACI 318-14, CSA 3004 and NZS 2006. The database of experimental result of 163 rectangular reinforced concrete columns and moment curvature analysis were used to evaluate these confinement requirements. The result of evaluation show that CSA 2004 provide most conservative result for confinement design. The additional confinement design equations at ACI 318-13 has been improve confinement design of ACI Code. The numerical analysis showed that the provide amount of transverse reinforcement at high axial compression from each code can provide higher nominal moment but still less ductile than column subjected to low axial compression.

Keywords: confinement, seismic, reinforced concrete columns.

1. INTRODUCTION

In reinforced concrete members, transverse reinforcement serves three functions as: (1) prevent members from shear failure; (2) Avoid buckling of longitudinal bar; (3) Confine core concrete of columns. These functions begin when diagonal tension cracks occurred and cover concrete spalled. In this research, the roles of transverse reinforcement as column confinement are discussed. The ACI 318-11[1] confinement design equations based work of Richart, Bradtzaeg [2] which is developed to allow columns still to resist axial compression after cover concrete spalled. This confinement requirement is the ratio of gross area column section to the area of concrete core and the specified concrete compressive strength to the specified yield strength of transverse reinforcement.

Several researchers [3-11] conducted experimental study and evaluated the ACI 318-11 confinement provision [1].The study shown some limitations such as (1) the confinement requirements do not account for effect of axial load level; (2) The deformation parameters in 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 318-14[12] 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 318-14[12] has not been assessed through experimental and analytical study.

In this research the deformability of ACI 318-11 ad ACI 318-14 are assessed and compared with CSA [13] and NZS [14] confinement provisions. The confinement provisions are evaluated using the experimental of 163 rectangular reinforced concrete columns. Numerical study also conducted to provide additional data for comparison. Only confinement requirements for rectangular column were evaluated.

2. CONFINEMENT PROVISIONS

For comparison, the confinement provision of CSA A23.3 [13], NZS 3101 [14] are discussed throughout this study. The Canadian codes [13] for confinement requirement were derived by Paultre and Légeron [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 [13].

Watson, Zahn [11] developed confinement provision of NZS 3101 [14]. Similar with [13] the axial compressive load, high-strength concrete, curvature demand as deformation parameter also accounted in the confinement provisions [14]. 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 [13] and NZS 3101 [14], but this axial load influence is not currently applied by ACI 318-11[1]. The ability of confining steel to maintain core concrete columns and enlarge deformation capacity is related to the configuration of transverse and longitudinal reinforcement. Columns with well distributed and configuration of longitudinal reinforcement can provide confinement effectively than column with wider spacing of longitudinal reinforcement. The confinement effectiveness as parameter to determine the behavior of confined concrete has been counted into CSA code for column confinement design.

The ACI 318-11[1] does not account for confinement effectiveness in determining the required amount of confinement. These deficiencies have been addressed in ACI 318-14, 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%. Table-1 summarizes confinement equations for rectangular reinforced concrete columns. Table-2exhibited the additional parameter that accounted into each confinement provisions. The additional

VOL. 12, NO. 9, MAY 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

parameters are defined parameters beside column gross area (A_g), confined core of columns are (A_{ch}), concrete compressive strength ($f_c^{'}$) and yield strength of transverse reinforcement (f_{yt}). CSA A23.3 [13], NZS 3101 [14] consider all additional parameters. The Canadian and New Zealand confinement provision apply curvature ductility as deformation parameter while ACI 318-14 use drift ratio as deformation demand.

Table-1. Confinement equations for rectangular reinforced concrete columns.

Codes	A_{sh}/sb_c
ACI 318-11[1]	$0.3\frac{f_c^{'}}{f_{yt}}\left(\frac{A_g}{A_{ch}}-1\right) \geq 0.09\, f_c^{'}/f_{yt} \quad f_{yt} \leq 700$ MPa
ACI 318-14[12]	$0.3\frac{f_c^{'}}{f_{yt}}\left(\frac{A_g}{A_{ch}}-1\right) \geq 0.09\, f_c^{'}/f_{yt} \quad 0.2k_f k_n \frac{P}{f_{yt}A_{ch}} \quad f_{yt} \leq$ 700 MPa $k_f = \frac{f_c^{'}}{175}+0.6 \leq 1 \quad k_n = n_l/(n_l-2)$
CSA A23.3-0.4[13]	$0.2k_n k_p \frac{A_g}{A_{ch}}\frac{f_c^{'}}{f_{yt}} \geq 0.09\, f_c^{'}/f_{yt} \quad f_{yt} \leq 500$ MPa $k_n = n_l/(n_l-2)$ and $k_p = P/P_0$
NZS 3101-06[14]	$\left(\frac{1.3-\rho_t m}{33}\frac{A_g}{A_{ch}}\frac{f_c^{'}}{f_{yt}}\frac{P}{\phi f_c^{'} A_g}\right)-0.006$ $\rho_t m \leq 0.4\left(m = f_{yl}/0.85 f_c^{'}\right) \quad A_g/A_{ch} \leq 1.5 \quad \phi = 0.85$ $f_{yt} \leq 800$ MPa
A_{sh} = total cross-sectional of transverse reinforcement within spacing s and perpendicular to b_c ; b_c = cross-sectional member core measured to outside edges of transverse reinforcement composing area A_{sh} ; A_g =gross area of column; A_{ch}= Cross-sectional area of structural members measured out to out of transverse reinforcement; $f_c^{'}$= specified concrete compressive strength; f_{yt} =specified yield strength of transverse reinforcement; f_{yl} =specified yield strength of longitudinal reinforcement; h_x= center-to-center spacing of longitudinal reinforcement laterally supported by corner of hoop or hook of cross tie; m =mechanical reinforcing ratio; n_l =number of longitudinal bars laterally supported by corner of hoop or hook of crosstie; P = axial applied load on column; P_0 =nominal axialload at zero eccentricity ($P_0 = 0.85 f_c^{'}\left(A_g - A_s\right) + A_s f_{yl}$); ρ_l =total area of longitudinal reinforcement divided by A_g ; ϕ= capacity reduction factor.	

Table-2. Additional parameter that considered into confinement equation.

Codes	Axial load ratio	ρ_l	Confinement effectiveness	Deflectionp arameter	High-strength concrete
ACI 318-11	-	-	-	-	
ACI 318-14	*		*	$\delta_u = 3\%$	*
CSA A23.3-0.4	*	*	*	$\mu_\phi = 16$	*
NZS 3101-06	*	*	*	$\mu_\phi = 20$	*
*=parameter that accounted into confinement equation					

ARPN Journal of Engineering and Applied Sciences

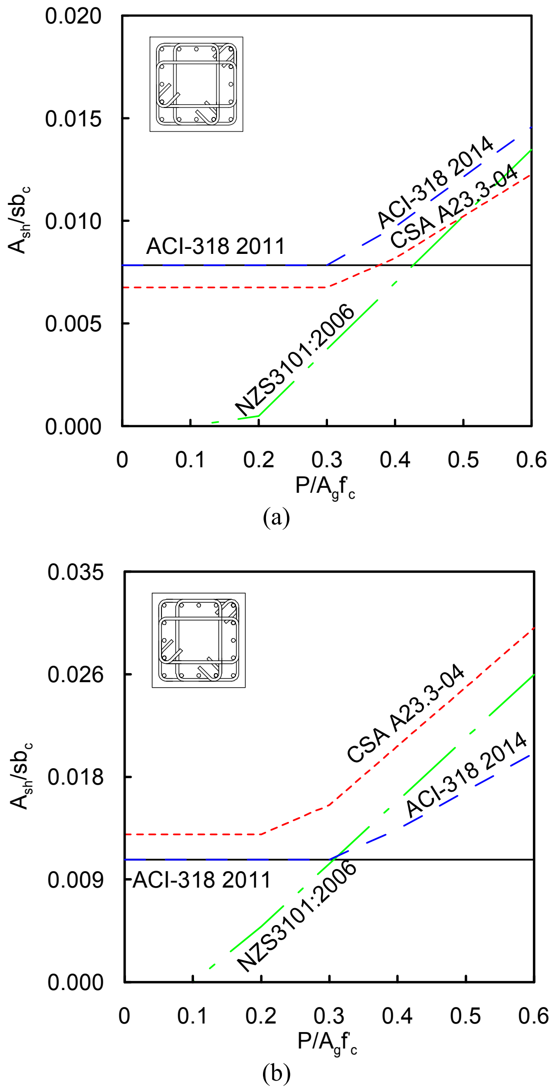


Figure-1. Comparison confinement demand applied to column with gross area of 600x600mm^2 with (a) $f_c^{'}$=30 MPa and $f_{yl} = f_{yt}$ = 400 MPa; (b) $f_c^{'}$=70 MPa, f_{yl} = 500 MPa and f_{yt} =700 MPa.

The comparison of confinement demand from all codes [1,12-14] are compared. The confinement provisions are applied on 600x600mm^2 columns. The ratio of longitudinal reinforcement were 2.18 %. This number of longitudinal reinforcement satisfy the requirement of special moment resisting columns at high risk earthquake area. The normal-strength and high-strength of reinforced concrete were used. The concrete compressive strength $f_c^{'}$ of 30 MPa and the yield strength of longitudinal and transverse reinforcement of 400 MPa are specified for normal strength of reinforced concrete. The specified material for high-strength reinforce concrete are concrete compressive strength of 70 MPa dan the yield strength of longitudinal and transverse reinforcement of 500 MPa and 700 MPa, respectively.

Figure exhibited the confinement demand from each provision in each axial compression load level.Column with normal-strength of reinforced concrete show that for $P / A_g f_c^{'} > 0.3$, confinement requirement at ACI 318 - 14 [12] and CSA [13] increased along with the increasing of axial compression load. New Zealand codes [14] exhibit increment of confinement requirement since $P / A_g f_c^{'} > 0.2$. ACI 318-11 [1] provide consistent amount confinement reinforcement for each axial load level. For columns with normal-strength of reinforced concrete ACI 318-14 [12] requires highest amount of confinement reinforcement than other codes. NZS [14] confinement demand showed the lowest amount of confinement reinforcement until $P / A_g f_c^{'} \leq 0.4$. When $P / A_g f_c^{'} > 0.4$ New Zealand code provide higher amount of confinement reinforcement than ACI 318-11[1]. For columns with high-strength of reinforced concrete CSA [13] requires highest amount of confinement reinforcement than other codes. This due to limitation of yield strength of transverse reinforcement to 500 MPa. NZS [14] confinement demand showed the lowest amount of confinement reinforcement until $P / A_g f_c^{'} \leq 0.3$. When $P / A_g f_c^{'} > 0.3$ New Zealand code provide higher amount of confinement reinforcement than ACI 318-11 [1].

3. DATA AND CRITERION

In this part all confinement requirements for rectangular column were evaluated using 163 column test result database from Elwood [15], Hwang [5], and Ou *et al*[16]. These columns have flexure failure modes or satisfied ACI 318 minimum transverse reinforcement spacing of six longitudinal bar diameters. To evaluate the deformation capacity of column specimens, the measured drift at 80% lateral force in post-peak lateral force resistance was used. Table-3 listed the parameters that exhibit in the rectangular column database that used for this research. Although Table-2 showed two deformation parameters, drift capacity was selected as the performance measure. The drift capacity was selected since this deformation parameter is reported at all test specimens. The drift capacity also not depend on definition of yield displacement or yield curvature. 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. The maximum earthquake demands are 1.5 times design basis demands, where 2% drift limit is specified for buildings with concrete columns. This target performance is also considered in ACI 318-14.

VOL. 12, NO. 9, MAY 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

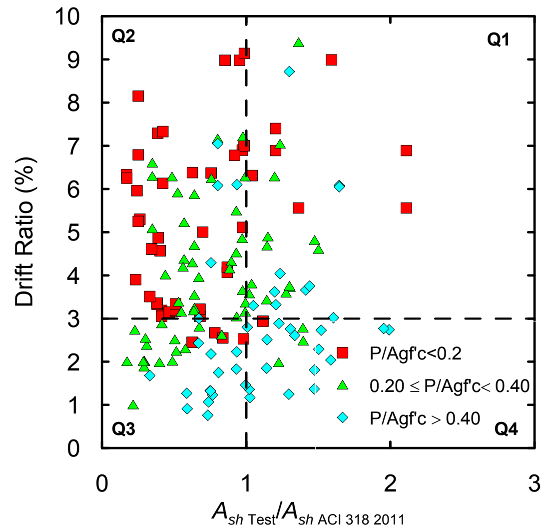
Table-3. Material paramenter range.

Parameter	Minimum	Maximum	Average
f_{yt} , MPa	255	1200	550
$f_c^{'}$,MPa	20.2	118	60.4
s mm	25.4	229	77.5
A_{sh}/sb_c ,%	0.11	3.43	1.15
$P/A_g\ f_c^{'}$	0.00	0.80	0.28

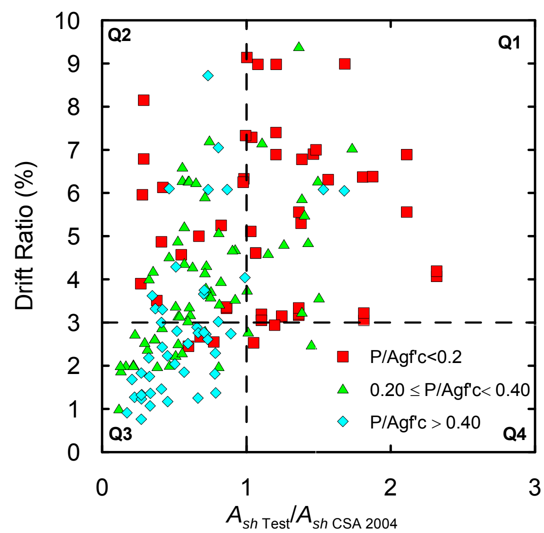
4. DRIFT RATIO CAPACITY PLOT

The columns drift ratio versus the ratio of applied confinement to confinement specified by codes were exhibited in Figure-3. The performance demand at 3% drift ratio is shown as a horizontal line. Data points in quadrant 1 (Q1) show that columns with applied confinement reinforcing exceed that specify by codes, and column drift capacities are equal or greater than performance demand. Quadrant 3 (Q3) represent data points of the applied confinement in columns test that less than required by provision, and the drift capacities are less than the performance demand. The ideal of confinement code will make all data points occur in quadrant 1 and 3. The data point in quadrant 4 (Q4) represent column with applied confinement reinforcement that higher than specify in codes with drift capacity are less than performance demand. More data point appears in this quadrant indicate that the confinement provisions are unconservative for these cases. The quadrant 2 (Q2) shows column with applied confinement reinforcement that less than required by code and columns drift capacity equal or exceed target performance. Data point that appear in Q2 indicate that the codes may be too conservative in such cases.

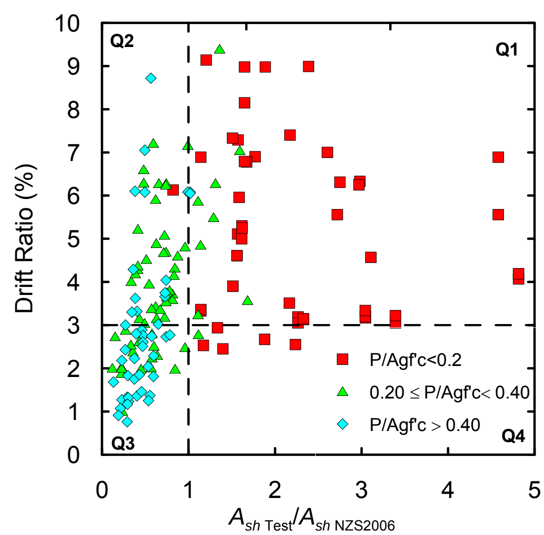
The drift ratio capacity plots for ACI 318-11, CSA, NZS dan ACI 318-14 are shown in Figure-3(a),(b),(c) and (d) respectively. To avoid an unrealistically low confinement requirement for NZS, ACI minimum confinement requirement $\left(A_{sh\min} = 0.09\ f_c^{'}/f_{yt}\right)$ are applied in Figure-3(c). Table-4 exhibited the number of data point in each quadrant from each code. The ACI 318-11 showed the highest data point in Q4 it means that this provision less conservative compare to other codes. This due to ACI 318-11 do not account for the effect of axial compression load. In Figure-3(a) exhibited that most data point of columns with $0.2 < P/A_g f_c^{'} < 0.4$ and $P/A_g f_c^{'} > 0.4$ are placed in Q4. With new additional confinement equation at ACI 318-14 the number of column in Q4 are reduced. However, this code is still less conservative than NZS and CSA code. The CSA code are the most conservative code for confinement requirement. This code provides the smallest number of columns data point in Q4 but more data point in Q4. This due to the limitation of yield strength of shear reinforcement up to 500 MPa.



(a)



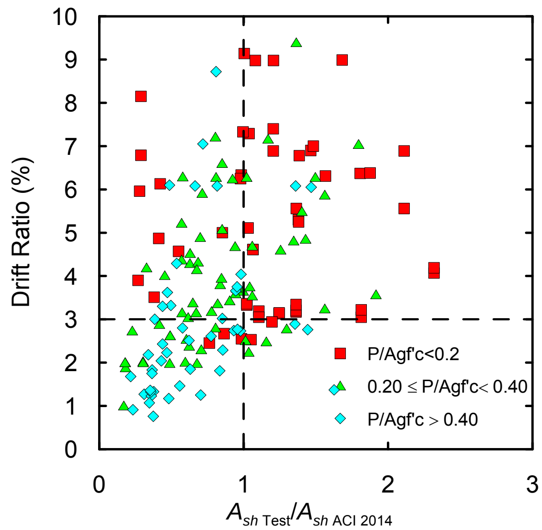
(b)



(c)

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com



(d)

Figure-2. Drint ratio versus confinement requirement for rectangular column from (a) ACI 318-11; (b) CSA; (c) NZS; and (d)ACI (2014).

Table-4. Comparison data point in each quadrant.

Codes	Q1	Q2	Q3	Q4
ACI 318-11	32	76	34	21
CSA 2004	48	60	51	4
NZS 2006	54	54	49	6
ACI 318 -14	55	53	45	10

5. NUMERICAL ANALYSIS

In other to evaluate deformability of each confinement code, moment curvature analyses are conducted. In this analysis columns with dimension of 600x600 mm^2 are used. The concrete compressive strength, the yield stress of longitudinal and transverse reinforcement is 70MPa, 400MPa, and 400 MPa. These properties of columns are representing the actual dimension of columns in high rise buildings. The axial compression load of 0.1 $f_c^{'}A_g$ and 0.4 $f_c^{'}A_g$. The confinement requirements for each axial compression load from each code are listed in table 5. For axial compression load of 0.1 $f_c^{'}A_g$, the CSA code require lowest amount of transverse reinforcement, while ACI 318-11, NZS 2006 and ACI 318-14 provide same amount of confinement. Under axial compression load of 0.4 $f_c^{'}A_g$ ACI 318-14 require highest amount of transverse reinforcement compare to other code. The unconfined and confined concrete models of Razvi are applied in cover and core of column. The concrete confining stresses from the provided transverse reinforcement are listed in Table-6. The amount of confinement can increased concrete compression stress around 23% to 36% from the specify concrete compressive stress (30 MPa). The Mander *et al* [17] stress-strain model for reinforcement rebar are used in modelling longitudinal reinforcement with considered strain hardening. The moment curvature analysis is performed in X-Tract.

Table-5. The confinement requirement for each axial compression for each codes.

Codes	ACI 318 2011	CSA 2004	NZS 2006	ACI 318 2014
0.1 $f_c^{'}A_g$	0.78%	0.68%	0.78%	0.78%
0.4 $f_c^{'}A_g$	0.78%	0.82%	0.78%	0.97%

Table-6. Concrete confining stress $f_{cc}^{'}$ of column (MPa).

Codes	ACI 318 2011	CSA 2004	NZS 2006	ACI 318 2014
0.1 $f_c^{'}A_g$	38.35	36.98	38.35	38.35
0.4 $f_c^{'}A_g$	38.35	38.76	38.35	40.89

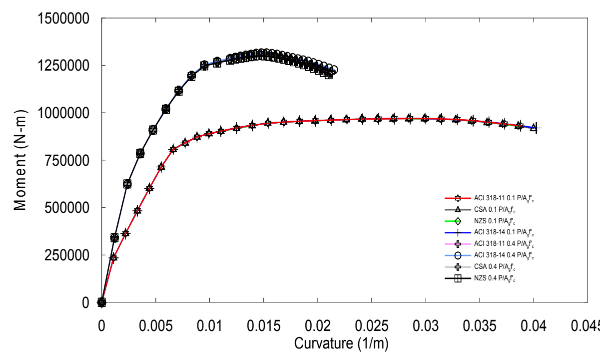


Figure-3. Comparison moment curvature relationship from each code with axial compression load of 0.1 and 0.4 $f_c^{'}A_g$

Figure 3 exhibited moment-curvature relationship of each code with axial compression load of of 0.1 and 0.4 $f_c^{'}A_g$. Columns with axial compression load of 0.4 $f_c^{'}A_g$ provide higher moment capacity but less ductile that column with axial compression load of 0.1 $f_c^{'}A_g$. For each axial compression load, all codes provide similar moment-curvature relationship behavior. This is due to the confining stress that provided almost similar.

6. CONCLUSIONS

This study evaluated the deformability of seismic design code. Important conclusions are summarizing as follows:

a) 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 database showed that CSA confinement requirement are the most

ARPN Journal of Engineering and Applied Sciences

conservative, since this code limit the yield strength of transverse reinforcement up to 500 MPa

b) The numerical analysis show that the the increase of amount of transverse reinforcement at column under high axial compression can provide higher moment capacity. However column under low axial compression are more ductile than column under high axial compression.

ACKNOWLEDGEMENTS

This research was funded by Penelitian Doktor Baru Dana PNBP Institut Teknologi Sepuluh Nopember. The authors thank Julio Cesar for assistance in arrange columns data during this research.

REFERENCES

[1] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318M-11) and Commentary2011, American Concrete Institute: Farmington Hills, Mich. p. 473.

[2] Richart F.E., A. Brandtzaeg and R.L. Brown. A Study of The Failure of Concrete under Combined Compressive Stresses.in Bulletin No 1851928, University of Illionis: Urbana.

[3] Bayrak O. and S.A. Sheikh. 1998.Confinement Reinforcement Design Considerations For Ductile HSC Columns. ASCE Journal of Structural Engineering. 124(9): 999-1010.

[4] Elwood K.J., *et al.* 2009.Improving Column Confinement, part 1: Assessment of design provisions. Concrete International. 31(11): 32-39.

[5] Hwang S.-J., *et al*. 2013.Design of Seismic Confinement of Reinforced Concrete Columns Using High Strength Materials, in Reinforced Concrete Columns with High Strength Concrete and Steel Reinforcement (SP-293)2013, American Concrete Institute: Toronto, Canada.

[6] Li B. and R. Park. 2004.Confining Reinforcement for High-Strength Concrete Columns. ACI Structural Journal. 101(3): 314-324.

[7] Paulay T. and M.J.N. Priestley. Seismic Design of Reinforced Concrete and Masonry Buildings1992: John Wiley and Sons Inc, New York.

[8] Paultre P. and F. Légeron. 2008.Confinement Reinforcement Design for Reinforced Concrete Columns. ASCE Journal of Structural Engineering. 134(5): 738-749.

[9] Razvi, S. and M. Saatcioglu. 1994. Strength and Deformability of Confined High-Strength Concrete Columns. ACI Structural Journal. 91(6): 678-687.

[10] Sheikh S.A. and S.S. Khoury. 1997.A Performance-Based Approach for the Design of Confining Steel in Tied Columns. ACI Structural Journal. 94(4): 421-431.

[11] Watson S., F.A. Zahn and R. Park. 1994.Confining Reinforcement For Concrete Columns. ASCE Journal of Structural Engineering. 120(6): 1798-1824.

[12] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary2014, American Concrete Institute: Farmington Hills, Mich. p. 667.

[13] CSA Committee A23.3, Design of Concrete Structures (CSA A23.3-04), 2004, Canadian Standard Association: Mississauga, Canada. p. 214.

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

[15] Elwood K.J., *et al*. 2009.Improving Column Confinement Part 2: Proposed new provisions for the ACI 318 Building Code. Concrete International. 31(12): 41-48.

[16] Ou Y.-C., *et al*. 2015.Cyclic Behavior of Precast High-Strength Reinforced Concrete Columns. ACI Structural Journal. 112(6):839-850.

[17] Mander J.B., M.J.N. Priestley and R. Park. 1988.Theoritical Stress-Strain Model for Confined Concrete. ASCE Journal of Structural Engineering. 114(8): 1804-1826.