Eleventh East Asia-Pacific Conference on Structural
Engineering & Construction (EASEC-11)
“Building a Sustainable Environment”
November 19-21, 2008, Taipei, TAIWAN

EFFECT OF LONGITUDINAL REINFORCEMENT ON LATERAL STRENGTH OF HIGH STRENGTH CONCERETE COLUMNS UNDER ECCENTRIC COMPRESSION

M. J. KUMAR[1], K. P. THIAGARAJAN[2] and B. V. RANGAN[3]

ABSTRACT : A computer based iterative numerical procedure has been developed to analyze reinforced high strength concrete columns subjected to horizontal wave loads and eccentric compression by taking the material, geometrical and wave load non-linearity into account. The behavior of the column has been assumed, to be represented by Moment-Thrust-Curvature relationship of the column cross-section. The formulated computer program predicts horizontal load versus deflection behavior of a column up to failure. The developed numerical model has been validated with the available experimental results of 36 reinforced rectangular columns and 4 circular columns of various slenderness, structural properties and compressive thrust levels, tested by other researchers. The predicted values are having a better agreement with experimental results. The reinforced concrete columns of different sizes with various compressive strengths of concrete and slenderness ratios under various levels of vertical compressions were analyzed by the formulated numerical procedure for various longitudinal reinforcement ratios of 1%, 2.5% and 4%. The analyzed result shows, the slender columns with higher longitudinal reinforcement ratios are having better resistance to lateral loads under the applied eccentric compression. This paper describes the effect of longitudinal reinforcement on flexural strength, lateral strength and deflection characteristics of high strength concrete columns under various vertical loads. Based on the parametric study carried out, design recommendations are made for reinforced concrete slender columns to resist the lateral loads along with eccentric compression.

KEYWORDS: Concrete column, Wave loads, Eccentric compression, Moment-Thrust-Curvature, longitudinal reinforcements.

1. INTRODUCTION

A computer based iterative numerical procedure has been developed by the authors [2], to analyze reinforced High Strength Concrete Columns subjected to horizontal wave loads and constant vertical load by taking the material, geometrical and wave load non-linearity into account. The behavior of the column has been assumed, to be represented by Moment-Thrust-Curvature relationship of the column cross-section. The formulated computer program predicts horizontal load versus deflection behavior of a column up to failure. In order to use the described procedure to predict the strength and response of columns, it is important that the appropriate stress-strain relationships for concrete and reinforcing steel are used to develop the moment-curvature relationships of the cross section. The stress-strain relationship used in this analysis was proposed by Popovics [5] and subsequently modified by Collins [6] to ensure a steeper descending part for high strength of concrete. The stress-strain relationship of the reinforcing steel is assumed as elastic-perfectly plastic both in tension and compression. The developed Numerical Model has been applied to analyze several column specimens of various

---

[1] Senior Lecturer, Civil Engineering, Curtin University of Technology, Sarawak Campus, Malaysia.
[2] Assoc. Professors School of Mechanical Engineering, University of Western Australia, Australia.
[3] Emeritus Professor, Faculty of Engineering, Curtin University of Technology, Australia.

slenderness, structural properties and axial load ratios, tested by other researchers [7-13]. The predicted values are in very reasonable agreement with experimental results [3].

A simplified user friendly hydrodynamic load model has been developed by the authors [1], based on Morison equation supplemented with a wave slap term to predict the high frequency non-linear impulsive hydrodynamic ringing loads arising from steep waves. Stokes fifth- order wave theory has been applied to obtain the water particle kinematics of near breaking steep waves. A computer program has been formulated based on the model to obtain the wave loads and non-dimensional load coefficients for all discretised nodes, along the length of column from instantaneous free water surface to bottom of the column at mud level. The predicted wave loads vary hyperbolically along the length of the column. The simplified wave impact load model was validated with the published experimental results of Zou and Kim [4]. The predicted results are in good agreement with measured and calculated values by Zou and Kim [4]. The calculated non-dimensional wave load coefficients for all discretised nodes of the column by the authors [3], are used in this parametric study.

In order to conduct a parametric study using the numerical method developed by the authors [3], two reinforced concrete column sections with various grade of concrete and contained different percentage of longitudinal reinforcement were selected. The columns contained lateral reinforcement in the form of closed ties. The columns were assumed to be fixed at bottom and free at the top. Using the results of the parametric study, design recommendations are made for reinforced concrete slender columns primarily to resist the lateral loads along with eccentric compression.

2. PARAMETRIC STUDY

The variables used for this study are concrete strength, slenderness ratio, vertical load ratio and longitudinal reinforcement ratio. The two different column cross-sections with different reinforcement ratios were used.

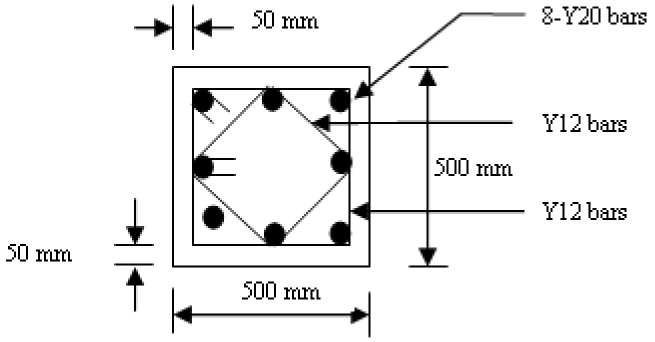
The parameters varied in the range as mentioned below in this study.

N / P_0 = 0.1 to 0.6
L_e / r = 40, 60, 80 and 100.
f_c' = 40, 60, 80 and 100 MPa.
p = 1.0%, 2.5% and 4.0%.

where,

N / P_0 = Vertical load ratio in which N and P_0 are applied vertical load squash load of the column section.
L_e / r = Slenderness ratio in which L_e and r are the effective length and radius of gyration respectively; r is taken as 0.3D for a rectangular sections.
f_c' = Concrete compressive strength and
p= Longitudinal reinforcement ratio = A_s / bD in which A_s is the total area of longitudinal reinforcement.

Since the columns are assumed to be fixed at bottom and free at top, the effective length was considered as twice the actual length of the column in slenderness calculations. The column cross-section of 500x500 mm with reinforcement details are shown in Fig.1.The entire length of the column was discretised into 20 equal segments and each nodes are subjected to the lateral wave loads varied hyperbolically form top to bottom nodes. The lateral wave loads were applied in terms of calculated wave load coefficients [3]. The lateral and vertical loads considered in this study are shown in Fig.2. The lateral loads assumed in terms of wave load coefficients were incremented up to failure for each applied vertical load as the percentage of squash load P_0 of the column section.



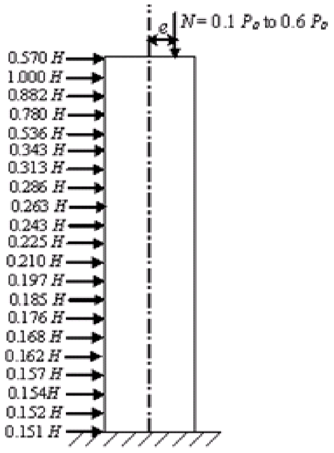


Figure1. Column cross-section 500mm x500mm **Figure 2. Column shows lateral and vertical loads**

For obtaining the best results, the lateral load *H* shown in Fig. 2 incremented as small as 0.000025 H_0. Whereas H_0 is the hypothetical maximum lateral load expected to resist by the column of given material and structural properties with out considered the secondary moments resulting by the vertical load in deflected mode of the column. The results of this study are discussed in the following sections.

3. APPLIED VERTICAL LOADS

For each column sections considered in this study, forty eight columns of different combinations of concrete compressive strengths, longitudinal reinforcement ratios and slenderness ratios were analysed by the developed numerical procedure at various vertical loads ranging from 0.1 to 0.6 P_0 and the column sections were assumed to have the adequate lateral reinforcement of 12 mm diameter bars to confirm the failure only in flexure. From the summary of the results shown elsewhere, results for the columns of 500x500 mm at slenderness ratios of 80, having longitudinal reinforcement ratio p = 1.0, 2.5 and 4.0% with a concrete compressive strength f_c' = 40 and 80 MPa are given in Table 1 to 6. The various comparative graphs of vertical load ratio versus lateral loads, moments and deflections for various longitudinal reinforcement ratios with different concrete compressive strength at selected slenderness ratio of 80, were drawn and shown in Fig. 3 to 6.

Table 1 Column 500x500 mm, L_e / r =80, f_c'=40 MPa, p=1.0%

Vertical load Ratio(N/P_o)	Max Lateral Load (kN)	Failure Lateral Load (kN)	Max Moment (kN-m)	Max Deflection (mm)
0.1	7.71	7.67	450.00	132.52
0.2	8.72	8.37	575.00	115.77
0.3	8.91	8.65	664.00	103.90
0.4	8.61	8.09	688.00	90.10
0.5	7.60	7.18	677.00	77.87
0.6	5.71	5.38	642.00	71.83

Table 2 Column 500x500 mm, L_e / r =80, f_c'=40 MPa, p=2.5%

Vertical load Ratio (N/P_o)	Max Lateral Load (kN)	Failure Lateral Load (kN)	Max Moment (kN-m)	Max Deflection (mm)
0.1	15.50	15.49	811.00	140.69
0.2	15.07	15.04	910.00	122.21
0.3	13.54	13.50	990.00	121.70
0.4	11.45	11.18	933.00	101.71
0.5	9.33	8.81	871.00	87.90
0.6	6.51	5.90	791.00	79.54

Table 3 Column 500x500 mm, L_e / r =80, f_c'=40 MPa, p=4.0%

Vertical load Ratio(N/P_o)	Max Lateral Load (kN)	Failure Lateral Load (kN)	Max Moment (kN-m)	Max Deflection (mm)
0.1	20.99	20.99	1070.00	144.80
0.2	18.93	18.90	1140.00	134.91
0.3	15.88	15.87	1150.00	124.21
0.4	12.65	12.43	1070.00	104.96
0.5	9.72	9.25	974.00	90.27
0.6	6.17	5.39	873.00	83.09

Table 4 Column 500x500 mm, L_e / r =80, f_c'=80 MPa, p=1.0%

Vertical load Ratio (N/P_o)	Max Lateral Load (kN)	Failure Lateral Load (kN)	Max Moment (kN-m)	Max Deflection (mm)
0.1	9.26	8.60	598.00	147.29
0.2	11.22	9.50	857.00	142.44
0.3	11.84	10.40	1040.00	123.99
0.4	11.36	9.82	1140.00	112.59
0.5	9.63	8.59	1160.00	99.71
0.6	6.63	5.76	1140.00	93.49

Table 5 Column 500x500 mm, L_e / r =80, f_c'=80 MPa, p=2.5%

Vertical load Ratio (N/P_o)	Max Lateral Load (kN)	Failure Lateral Load (kN)	Max Moment (kN-m)	Max Deflection (mm)
0.1	17.08	17.07	991.00	154.30
0.2	17.46	16.96	1220.00	141.82
0.3	16.35	16.22	1380.00	131.53
0.4	14.23	13.73	1410.00	117.53
0.5	11.75	11.04	1380.00	103.46
0.6	8.06	7.43	1320.00	94.63

Table 6 Column 500x500 mm, L_e / r =80, f_c'=80 MPa, p=4.0%

Vertical load Ratio (N/P_o)	Max Lateral Load (kN)	Failure Lateral Load (kN)	Max Moment (kN-m)	Max Deflection (mm)
0.1	23.07	23.07	1260.00	151.03
0.2	21.87	21.74	1470.00	145.37
0.3	19.25	19.22	1600.00	136.81
0.4	15.83	15.44	1560.00	118.52
0.5	12.44	11.95	1500.00	103.50
0.6	8.13	7.49	1420.00	95.55

4. EFFECT ON FLEXURAL STRENGTH

It can be seen from a general observation from the summary of data, flexural strength of the column sections are increased with increasing the vertical load approximately up to 0.3P_0 to 0.4 P_0 depending upon the structural properties of the section and then the flexural strength of the sections are decreased for further increase in vertical load on the column. The flexural strength of the columns are increased with increasing vertical thrust up to certain level due to the resulting direct compressive stress in concrete which will counter acts with the expected bending tensile stress induced by the external moments. The further increase in vertical thrust reduces the flexural strength of the columns due to increase in direct compressive stresses in concrete and steel. The limit of compressive strain of the extreme concrete fibre from the neutral axis is controlled by the equilibrium condition of forces, that is the total internal forces due to concrete and reinforcing steel should be the same as applied vertical thrust. The maximum flexural strength of the columns at various applied vertical compression for the columns of slenderness ratio 80, concrete compressive strength 40 and 80 MPa with longitudinal reinforcement ratio 1%, 2.5% and 4% were plotted and shown in Fig 3 and 4. It shows that flexural strengths are very significantly increased while increasing the percentage of steel *p* from 1% to 2.5% than further increasing from 2.5% to 4%. The steel bars in under reinforced column sections reached its yield values at flexure much before the concrete will reach its full capacity, particularly for high strength concrete. Over reinforced concrete columns will have a concrete failure first and then followed by steel failure for further increase in lateral loads.

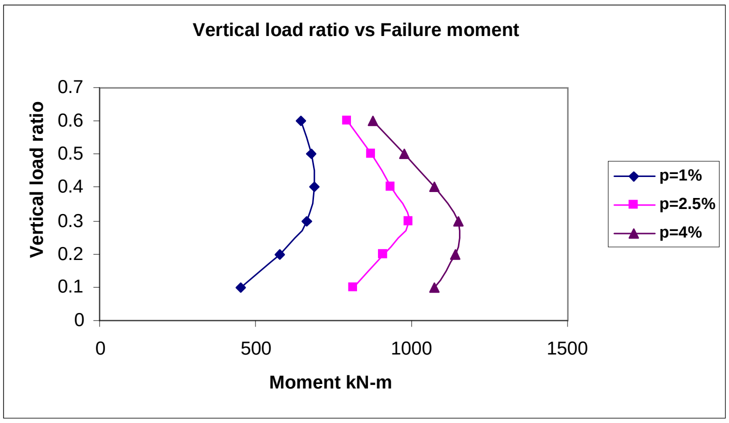


Figure 3. ***N/Po*** **vs Failure moment-Column 500x500,** ***Le/r=80, ,*** f_c' ***= 40MPa***

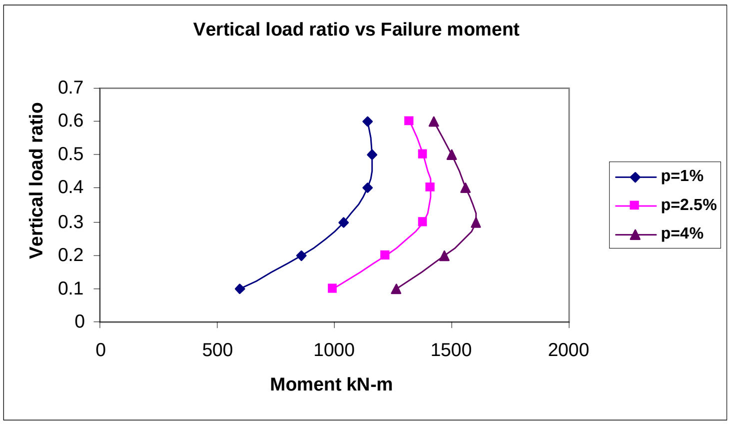


Figure 4. ***N/Po*** **vs Failure moment-Column 500x500,** ***Le/r=80,*** f_c' ***= 80MPa***

5. EFFECT ON DEFLECTION

In general the results indicate that flexural strengths as well as failure deflections of the columns are increasing for the increase in compressive strength of the concrete and percentage of steel. The failure deflections at various vertical compressions for the columns having *p* = 1%, 2.5% and 45 were plotted and shown in Fig. 5 and 6. It shows that for all the grades of concrete failure deflections are reduced for increase in applied vertical thrust level on the column. At higher vertical loads, ductility of the column is reduced due to high direct compressive stresses. The deflections were decreased while increasing the applied vertical load on the column sections having percentage of longitudinal reinforcement ratios were 2.5% and 4.0% whereas for the column section having the longitudinal reinforcement ratio of 1.0%, the deflections were increased up to certain level of increasing the vertical load and then decreased for further increasing the applied vertical load on the columns. The increase in longitudinal steel has very less significant effect on failure deflections for the column of high compressive strength of 80 MPa than the columns of compressive strength of 40 MPa, particularly at high vertical loads. Increasing the steel above 2.5% is not having any considerable effect on failure deflections at high vertical loads because columns are loosing its ductility at higher vertical loads even though for the high percentage of longitudinal steel.

`

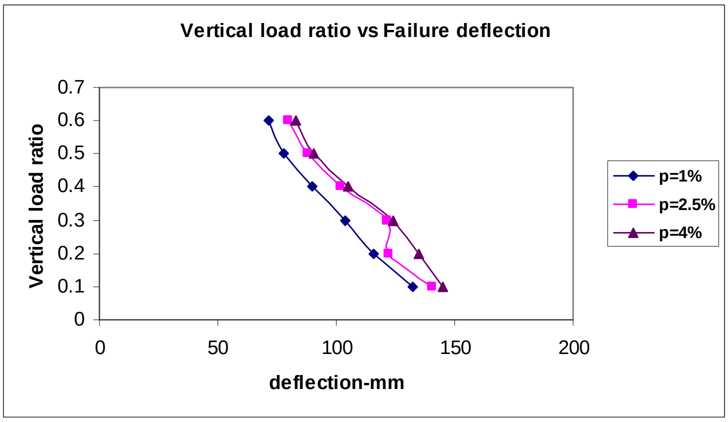


Figure 5. *N/Po* vs Failure deflection-Column 500x500, *Le/r=80,* $f_c' = 40MPa$

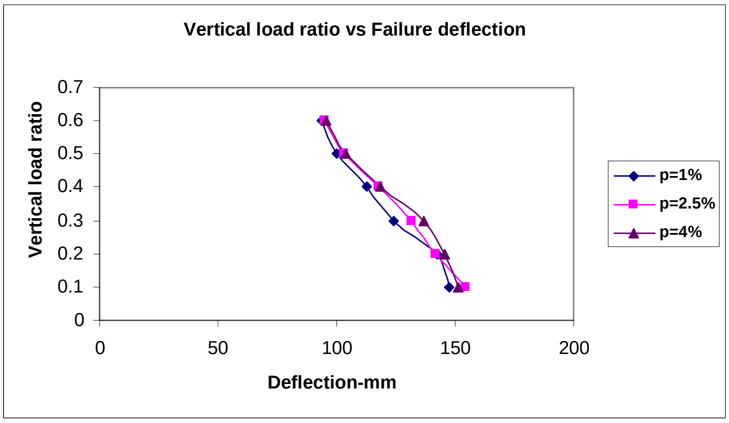


Figure 6. *N/Po* vs Failure deflection-Column 500x500, *Le/r=80,* $f_c' = 80MPa$

6. EFFECT ON LATERAL STRENGTH

The lateral strength at failure under various applied vertical compression for the columns of slenderness ratio 80, concrete compressive strength 40 and 80 MPa with longitudinal reinforcement ratio 1%, 2.5% and 4% were plotted and shown in Fig 7 and 8. It shows that lateral strengths are very significantly increased while increasing the percentage of steel p from 1% to 2.5% than further increasing from 2.5% to 4%.The very slender columns with high strength concrete and low percentage steel, show very poor performances in vertical as well as lateral load resistance. Particularly the slender columns of high strength concrete should have minimum percentage of steel required for balanced failure at flexure to produce a better lateral load resistance. Lateral load resistances are very substantially increased while increasing the percentage of steel p for the columns under less vertical compressions. This parametric study shows that the failure lateral loads were decreased from the maximum value by nearly 99.07% for the column of slenderness ratio 100, concrete compressive strength of 100MPa and percentage of steel 1% at applied vertical load of $0.2P_0$. This clearly indicates that column with less longitudinal steel is at virtue of failure due to applied vertical load itself and doesn't have any strength to resist lateral loads.

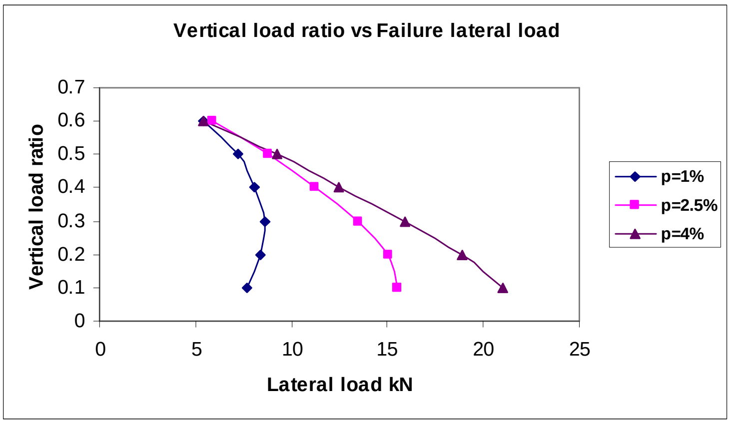


Figure 7. ***N/Po*** **vs Lateral load-Column 500x500,** ***Le/r=80, f_c' = 40MPa***

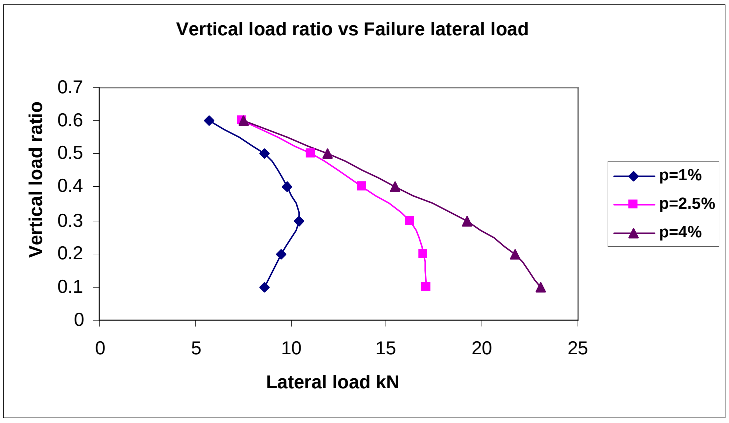


Figure 8. ***N/Po*** **vs Lateral load-Column 500x500,** ***Le/r=80, f_c' = 80MPa***

7. CONCLUSIONS

For a better lateral load resistance, the high strength concrete columns should have a minimum percentage of steel required to develop the balanced failure sections at flexure. Increasing the percentage of longitudinal steel upto certain limit results the substantial increase in flexural strength, failure deflection and lateral strength of the columns. Higher percentage of steel more than 4% of the column sections leads to failure of concrete first in flexure and have the issue of space constrains for concrte placement and compaction.

REFERENCES

1. Kumar, M.J., Thiagarajan, K.P. and Rangan, B.V. (2001), "Hydrodynamic Load Models for Ringing on Offshore Structures" *International Conference in Ocean Engineering*, December 11-14, IIT, Madras, India, pp. 201-206.

2. Kumar, M.J., Thiagarajan, K.P. and Rangan, B.V. (2003), “Effect of Slenderness in High Strength Concrete Columns under Wave Impact Loads” *The Ninth East-Pacific Conference on Structural Engineering and Construction,* December 16-18, Bali, Indonesia, pp. CPM 57-62.
3. Kumar, M.J., Thiagarajan, K.P. and Rangan, B.V. (2004), “Response of High Strength Concrete Columns/Piles under Wave Impact Loads” *The International Conference on Structural and Foundation Failures,* August 2-4, Singapore, pp. 201-209.
4. Zou, J. and Kim, C.H. (1995), “Extreme Wave Kinematics and Impact Loads on Fixed Truncated Circular Cylinder” *Proceedings of Fifth International Offshore and Polar Engineering Conference,* The Hague, The Netherlands, June 11-16, pp.216-225.
5. Popovics, S. (1973), “A Numerical Approach to the Complete Stress-Strain Curve of Concrete”, *Cement and Concrete Research,* Vol. 3, No. 5, May, pp. 538 – 599.
6. Collins, M. P. (1992), “Stress-Strain Relationship of High Strength Concrete for Structural Design”, *Network on Excellence of High Performance Concrete,* Montreal, April 26 – 28.
7. Azizinamini, A., Kuska, S.S.B.,Brungardt, P. and Hatfield, E. (1994), “Seismic Behavior of square High Strength Concrete Columns”, *ACI Structural Journal,* Vol. 91, No. 3, May – June, pp. 336-345.
8. Bayrak, O. and Sheikh, S. A. (1997), “High Strength Concrete Columns under Simulated Earthquakes Loadings”, *ACI Structural Journal*, Vol. 94, No. 6, November – December, pp. 708 – 722.
9. Budek, A. M., Priestly, M. J. N. and Chin Ok Lee (2002), “Seismic Design of Columns with High-Strength Wire and Stand as Spiral Reinforcement”, *ACI Structural Journal,* Vol. 99, No. 5, September – October, pp. 660 – 670.
10. Thomsen IV, J. H. and Wallace, J.W. (1994), “Lateral Load Behavior of Reinforced Concrete Columns Constructed using High-Strength Materials”, *ACI Structural Journal,* Vol. 91, No. 5, September-October, pp. 605-615.
11. Ozcebe, G. and Saatcioglu, M. (1987), “Confinement of Concrete Columns for Seismic Loading”, *ACI Structural Journal*, July – August, pp. 308 – 315.
12. Xiao, Y. and Yun, H.W. (2002), “Experimental Studies on Full-Scale High Strength Concrete Columns”, *ACI Structural Journal,* Vol. 99, No. 2, March – April, pp. 199-207.
13. Youakim, S.A. and Ghali, A. (2002), “Ductility of Concrete Columns with Double Head Studs”, *ACI Structural Journal,* Vol. 99, No. 4, July - August, pp. 480-487.