New Seismic Design Concept for RC Bridge Columns

Lee, Jae Hoon* Son, Hyeok Soo**

ABSTRACT

The purpose of this study is to develop new seismic design concept based on ductility demand for reinforced concrete bridge columns in areas of low to moderate seismicity. In developing the ductility based design approach, relationship between ductility demand and transverse reinforcement demand should be quantitatively developed. To evaluate ductility capacity of reinforced concrete columns, analytical models and a non-linear analysis program, NARCC have been developed. Based on analytical and experimental results, an equation for relationship between curvature ductility and displacement ductility, an equation for designing the transverse confinement reinforcement for ductility demand, and a new seismic design concept of RC bridge columns are presented.

1. INTRODUCTION

The main concept of seismic design stated in most countries is that seismic design shall be performed with the aim to ensure safety during earthquake as well as prevent fatal damage affecting human life and degradation of function of the structure affecting the life and production of inhabitants. It has long been recognized that the bridge columns must be designed to behave in a ductile manner in order to assure that bridges perform well during severe earthquakes. Ductile behaviour can be obtained in reinforced concrete column by providing adequate confinement reinforcement to resist shear forces, to confine the core concrete, and to inhibit premature buckling of the longitudinal steel in plastic hinge regions. Bridge columns for strong earthquake area are to be designed and constructed so that enough ductility should be guaranteed. Therefore large amount of transverse reinforcement is required to confine core concrete of the bridge column by most bridge design specifications. In moderate seismicity regions, however, adopting the full ductility design concept sometimes results in construction problems due to reinforcement congestion. For the moderate seismicity regions, a design based on required ductility and required transverse reinforcement might be a reasonable approach. In developing the ductility based design approach, relationship between ductility demand and transverse reinforcement demand should be quantitatively developed. Determination of ductility demand and prediction of nonlinear seismic response of a bridge column under cyclic loading have become a very important subject for design

* Associate Professor, Ph.D., Dept. of Civil Engineering, Yeungnam University, Korea
** Research Associate, Ph.D., Dept. of Civil Engineering, Yeungnam University, Korea

and assessment of reinforced concrete bridge column. To evaluate ductility capacity of reinforced concrete columns, analytical models and a non-linear analysis program, NARCC (Non-linear Analysis of Reinforced Concrete Columns) have been developed. The developed computer program NARCC was verified by comparison with reliable experimental results. Then, in order to develop relationships between the curvature ductility and the displacement ductility, analysis for total 7,200 columns was carried out as parametric studies. Based on the results from the parametric studies, a correlation equation between the curvature ductility and the displacement ductility was developed. In addition, an equation for calculating the required transverse confinement reinforcement based on ductility demand was developed for seismic design of reinforced concrete bridge columns.

2. NEW SEISMIC DESIGN CONCEPT (DUCTILITY DEMAND BASED DESIGN APPROACH)

The current seismic design criteria of the Korea Design Specifications for Highway Bridge (KDSHB 2000) adopted the seismic design concept and requirements of the AASHTO specifications [1]. In order to obtain full ductile behavior under seismic loads, i.e. when applied seismic force is larger than design flexural strength of column section, a response modification factor (R=3 or 5) is used. Then, the transverse confinement reinforcement should be used as computed by Eq. (1) or Eq. (2).

$$\rho_s = 0.45\left[\frac{A_g}{A_c} - 1\right]\frac{f_{ck}}{f_{yh}} \tag{1}$$

$$\rho_s = 0.12\frac{f_{ck}}{f_{yh}} \tag{2}$$

Even though the applied elastic seismic force is slightly larger than the design flexural strength of column section, large amount of confinement steel calculated by Eq. (1) or Eq. (2) should be designed by adopting full-ductility design concept in the current design specifications. However, it sometimes results in not economical design or construction problems such as difficulties in steel cage manufacturing and concrete placement due to reinforcement congestion. Therefore, new seismic design concept based on ductility demand might be an appropriate approach especially for regions of moderate seismic risk. The procedure of this proposed design approach can be summarized as follows:

Step 1. : Construct acceleration-displacement (or force-displacement) spectrum demand.

Step 2. : Determine column size and longitudinal reinforcement.

Step 3. : Construct acceleration-displacement (or force-displacement) spectrum capacity.

1) Calculate yielding effective stiffness [2].

$$I_{eff} = \left(0.16 + 12\rho_l + 0.3\sqrt{\frac{P}{f_c' A_g}}\right)I_g \tag{3}$$

2) Calculate design lateral force capacity, under axial load.

3) Construct acceleration-displacement (or force-displacement) spectrum capacity.

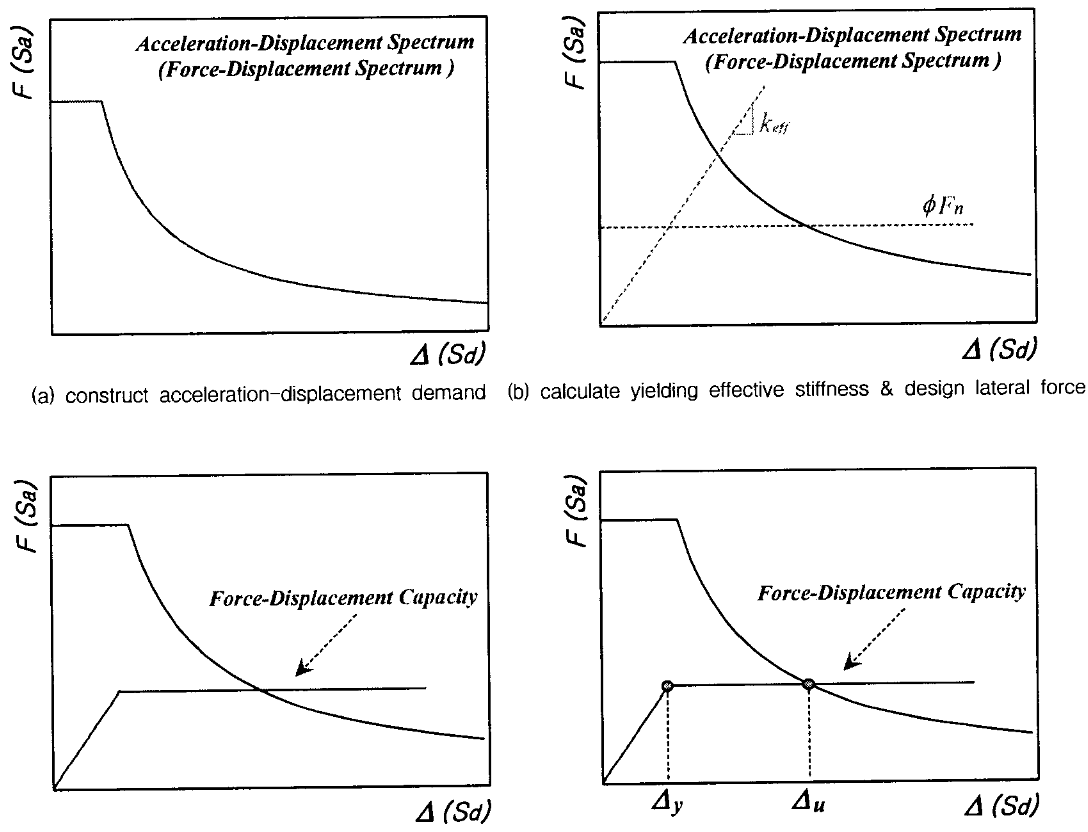
Step 4. : Determine required displacement ductility.

$$req'd \ \ \mu_{\Delta} = \frac{\Delta_u}{\Delta_y} \tag{4}$$

Step 5. : Determine required curvature ductility from required displacement ductility.

Step 6. : Determine required confinement steel ratio.

Step 7. : Design transverse reinforcement.



(a) construct acceleration-displacement demand (b) calculate yielding effective stiffness & design lateral force

(c) construct force-displacement capacity (d) determine required displacement ductility

Fig. 1 New seismic design concept based on ductility demand

3. NON-LINEAR ANALYSIS OF RC COLUMNS FOR DUCTILITY CAPACITY

To evaluate ductility capacity of reinforced concrete columns, analytical models and a non-linear analysis program, NARCC (Non-linear Analysis of Reinforced Concrete Columns) has been developed, which is applicable to the RC columns subjected to seismic loading. The computer program NARCC provides moment-curvature relationship and lateral load-displacement curve for reinforced concrete columns. The lateral displacement of a reinforced concrete cantilever element includes flexure, bond slip, and shear components. The constitutive stress-strain model for concrete under compression proposed by Mander et al. [3] was selected for moment-curvature analysis. Under cyclic loading, the characteristic stress-strain curves of steel for monotonic loading may not form an accurate envelope for the inelastic response [4]. Therefore, the stress-strain curve proposed by Shima et al. [5] for monotonic loading was modified to Eq. (5) for cyclic loading. The constitutive equation of stress-strain model for cyclic loading was taken as

$$f_s = f_y + (f_{su} - f_y)[1 - e^{(\varepsilon_y - \varepsilon_s)/k}] \qquad \text{for} \qquad \varepsilon_y \le \varepsilon_s \tag{5}$$

where, f_y, f_{su}, ε_s, and ε_y are the yield stress, maximum stress, strain and yield strain of the steel, and k is the the coefficient dependent on the yield strength of the steel. The coefficient, k, is 0.02 for $f_y = 300$ MPa, and 0.01 for $f_y = 400$ MPa, respectively.

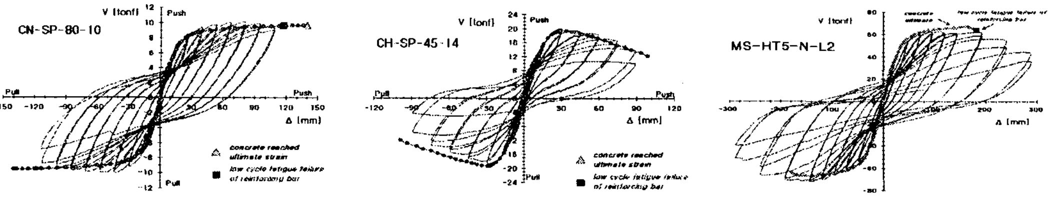
4. COMPARISON OF ANALYSIS AND TEST RESULTS

The validity and efficiency of the program NARCC developed by the authors were verified by comparison to experimental results of reinforced concrete columns with spirals or circular hoops. The analytical results of lateral force-displacement relationships are compared with the measured lateral force-displacement hysteresis loops in Fig. 2. The analytical results by using computer program NARCC are in good agreement with the test results.

Table 1 Characteristics of the test specimens

Specimen	D [cm]	$\frac{L}{D}$	f_{ck} [kgf/cm^2]	f_y [kgf/cm^2]	f_{yh} [kgf/cm^2]	ρ_l [%]	ρ_s [%]	s [cm]	$\frac{P}{f_{ck}A_g}$ [%]	Transverse steel
CN-SP-80-10	40	4.25	280	3,569	3,712	1.26	0.99	8.0	9.9	spiral
CH-SP-45-14	40	3.50	612	4,334	4,201	1.26	0.80	4.5	14.1	spiral
MS-HT5-N-L2	120	4.0	253	3,385	3,763	1.01	0.39	11.5	6.6	circular hoop

Note : D = diameter of the section, $\frac{L}{D}$ = aspect ratio, f_{ck} = concrete compressive strength, f_y = yield strength of the longitudinal steel, f_{yh} = yield strength of the transverse steel, ρ_l = longitudinal reinforcement ratio, ρ_s = volumetric ratio ot the transverse steel, s = vertical spacing of the transverse steel, $\frac{P}{f_{ck}A_g}$ = axial force ratio.



(a) specimen CN-SP-80-10 (b) specimen CH-SP-45-14 (c) specimen MS-HT5-N-L2

Fig. 2 Comparison of analytical results to test results (1 tonf = 9.8 kN)

5. PROPOSED EQUATIONS FOR ADOPTING NEW SEISMIC DESIGN CONCEPT

In order to develop relationships between the curvature ductility and the displacement ductility, analysis using the computer program NARCC has been carried out for total 7,200 column models as a parametric study. The main variables of a parametric study are diameter of the section, aspect ratio, concrete compressive strength, yield strength of longitudinal and transverse steel, longitudinal reinforcement ratio, axial force ratio, and volumetric ratio of transverse reinforcement. Based on the results from the parametric study, a correlation equation between the curvature ductility and the displacement ductility was developed as follows:

$$\mu_\Delta = 0.13\left(1.1 + \frac{D}{L}\right)\mu_\phi + 0.5\left\{0.7 + 0.75\left(\frac{D}{L}\right)\right\} \tag{6}$$

where μ_Δ, μ_ϕ, D, and L are the displacement ductility, curvature ductility, diameter of the section, and length of column between locations of maximum moment and zero moment. Also, from the results of the parametric study, an equation for calculating the required transverse confinement reinforcement was developed for seismic design of RC bridge columns as shown in Eq.(7) through Eq.(10). The proposed equation considers variables, such as curvature ductility(μ_ϕ), axial force ratio($P/f_{ck}A_g$), concrete compressive strength(f_{ck}), yield strength of longitudinal and confinement reinforcement(f_y, f_{yh}), longitudinal reinforcement ratio(ρ_l), and dimensions of section (A_g/A_c). The right term of the Eq. (7) is to limit the vertical spacing of the transverse reinforcement.

$$\rho_s = 0.014\frac{f_{ck}}{f_{yh}}\left\{\frac{A_g}{A_c} - 0.6\right\} \cdot \alpha \cdot \beta + \gamma \geq \frac{1}{1.5}\frac{A_{sp}}{d_b D_{sp}} \tag{7}$$

$$\alpha = \left[3(\mu_\phi + 1)\frac{P}{f_{ck}A_g} + 0.8\mu_\phi - 3.5\right] \tag{8}$$

$$\beta = \left\{\frac{f_y}{3,500} - 0.12\right\} \tag{9}$$

$$\gamma = 0.1(\rho_l - 0.01) \tag{10}$$

6. CONCLUSIONS

The procedure of new seismic design concept based on ductility demand was proposed. To evaluate ductility capacity of reinforced concrete columns, analytical models and a non-linear analysis program, NARCC was developed. The analytical results of lateral force-displacement relationships are compared with the test results and show good agreement. Based on the results from the parametric studies, a correlation equation between the curvature ductility and the displacement ductility was developed and proposed. An equation for calculating the required transverse confinement reinforcement based on ductility demand was developed and proposed for new seismic design concept of reinforced concrete bridge columns.

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REFERENCES

1. AASHTO, Standard Specifications for Highway Bridges, American Association of State Highway and Transportation Officials. 16-th edition, Washington, D.C. 1995.
2. Sung-Yong Bae, Stiffness and Ductility of Spirally Reinforced Concrete Columns subjected to Seismic Loading, Ph.D. dissertation, Department of Civil Engineering, Yeungnam University, KOREA, December, 2000.
3. Mander, J. B., Priestley M. J. N. and Park R., Theoretical Stress-Strain Model for Confined Concrete, Journal of Structural Engineering, ASCE, V. 114, No. 8, August, 1988, pp. 1804-1826.
4. Priestley et al., Seismic Design and Retrofit of Bridges, John Wiley & Sons, Inc, New York, 1996.
5. Shima, H., Chou, L., and Okamura, H., Micro and Macro Models for Bond behavior in Reinforced Concrete, Journal of the Engineering, University of Tokyo(B), Vol. 39, No. 2, 1987, pp. 133~194.
6. Nagi A. Abo-Shadi, M. Saiid Saiidi, and David H. Sanders, Performance-Based Design of Confinement Reinforcement Concrete Bridge Pier Walls for Out-of-Plane Seismic Loads, ACI Structural Journal, Vol. 98, No. 1, January-February, 2001, pp. 3-15.
7. Hyeok-Soo Son, A study on Seismic Design Methodology based on Transverse Reinforcement Demand for RC Bridge Columns, Ph.D. dissertation, Department of Civil Engineering, Yeungnam University, KOREA, June, 2002.
8. Park, R. and Paulay T., Reinforced Concrete Structures, John Wiley & Sons, New York, USA, 1975.