A Practical Performance Model for Reinforced Concrete Bridge Columns

Marc O. Eberhard and Michael P. Berry
University of Washington, Seattle, WA

ABSTRACT
This paper describes a practical method for estimating the likelihood of spalling of the concrete cover and buckling of the longitudinal reinforcement in a reinforced concrete bridge column. The methodology, which is based on plastic-hinge analysis, was calibrated using the damage observations from cyclic tests described in the Pacific Earthquake Engineering Research center's (PEER) structural performance database (*http://nisee.berkeley.edu/spd/*). For the 33 spiral-reinforced bridge columns most representative of bridge engineering practice, the ratio of the observed displacement to the calculated displacement at spalling of the concrete cover had a mean of 1.05 and a coefficient of variation of 34%. The ratio of the observed displacement to the calculated displacement at the onset of buckling of the longitudinal bars had a mean of 1.01 and a coefficient of variation of 25%. The methodology can be used to evaluate existing columns and to design new ones.

INTRODUCTION
An important aspect of performance-based earthquake engineering is the relationship between the deformation of a structural member and the likelihood that the member will reach various levels of damage. Such relationships are needed for many bridge components and levels of damage, both moderate and severe. For example, potential catastrophic modes of response, such as span unseating and brittle column shear failure, need to be suppressed with high levels of confidence.

This paper focuses on two flexural damage states (column cover spalling and column longitudinal bar buckling) that have less drastic impacts on safety, but have important economic and functional consequences. The onset of cover spalling is often the first level of damage at which significant repairs are needed. Buckling of the longitudinal bars requires expensive repairs and triggers concerns about the safety of the structure, which in turn may lead to the closure of the bridge.

PERFORMANCE METHODOLOGY
A methodology has been developed to estimate the likelihood of concrete spalling (Berry and Eberhard 2004) and longitudinal bar buckling in reinforced concrete columns (Berry and Eberhard 2005). The form of the methodology is based on the results of plastic-hinge analysis. The coefficients were calibrated using 142 observations of cover spalling and 104 observations of longitudinal bar buckling during laboratory tests of spiral-reinforced rectangular-reinforced concrete columns. The tests are described in the PEER Structural Performance Database (Berry et al. 2004).

According to this methodology, the drift ratio at the onset of spalling ($\frac{\Delta_{spall_calc}}{L}$) can be estimated as follows:

$$\frac{\Delta_{spall_calc}}{L}(\%) \cong 1.6\left(1-\frac{P}{A_g f'_c}\right)\left(1+\frac{L}{10D}\right) \quad (1)$$

where P is the column axial load, A_g is the gross area of the cross section, f'_c is the concrete compressive strength, L is the distance from the column base to the point of contraflexure, and D is the column depth. For example, a column with an axial-load ratio ($\frac{P}{A_g f'_c}$) of 0.15 and a shear-span-to-depth ratio ($\frac{L}{D}$) of 3.5 would be expected to begin to spall its cover at a drift ratio of 1.6*0.85*1.35 = 1.8%.

The drift ratio at the onset of buckling ($\frac{\Delta_{bb_calc}}{L}$) of the longitudinal bars can be estimated as follows:

$$\frac{\Delta_{bb_calc}}{L}(\%) = 3.25\left(1+k_{e_bb}\rho_{eff}\frac{d_b}{D}\right)\left(1-\frac{P}{A_g f'_c}\right)\left(1+\frac{L}{10D}\right) \quad (2)$$

where k_{e_bb} = 40 for rectangular-reinforced columns and 150 for spiral-reinforced columns, $\rho_{eff} = \rho_s f_{ys} / f'_c$, ρ_s is the volumetric transverse reinforcement ratio, f_{ys} is the yield stress of the transverse reinforcement, and d_b is the diameter of the longitudinal reinforcing steel. Because little data was available for large values of the transverse reinforcement spacing to the longitudinal bar diameter (s/d_b), k_{e_bb} should be taken as 0.0 for columns in which s/d_b exceeds 6.

Again, consider a column with an axial-load ratio of 0.15, a shear-span-to-depth ratio of 3.5. Assume that the 4-ft diameter column is reinforced longitudinally with #11 bars (d_b = 1.41 in.), which results in D/d_b = 34. The transverse reinforcement ratio is 0.01, f_{ys} is 60 ksi and f'_c = 5 ksi, which results in ρ_{eff} = 0.12. For this column, longitudinal bar buckling would be expected to begin, on average, at a drift ratio of 3.25*1.53*0.85*1.35 = 5.7%.

Not all of the column tests used to develop equations 1 and 2 were representative of bridge engineering practice. A smaller dataset was created that included only spiral-reinforced concrete columns with an axial-load ratio less than or equal to 0.3, and a longitudinal reinforcement ratio less than or equal to 4%. The screening process reduced the number of relevant tests to 33 for both cover spalling and bar buckling. The ratio of the measured displacement at spalling to the displacement calculated with Equation 1 ($\frac{\Delta_{spall}}{\Delta_{spall_calc}}$) had a mean of 1.05 and a coefficient of variation of 34%. The ratio of the measured displacement at bar buckling to the displacement

calculated with Equation 2 ($\frac{\Delta_{bb}}{\Delta_{bb_calc}}$) had a mean of 1.01 and a coefficient of variation of 25%. These variations are not due entirely to the inaccuracies of equations 1 and 2. Substantial scatter results from the observation subjectivity, and the effect of having cyclic deformation histories that usually impose only a limited number of discrete deformation levels. Figure 1 shows the normal and lognormal cumulative distributions for the ratio of $\frac{\Delta_{bb}}{\Delta_{bb_calc}}$.

APPLICATION TO COLUMN EVALUATION

To apply equations (1) and (2) to the evaluation of existing bridge columns, it was assumed that the accuracy of these equations is the same for columns in the field as in the laboratory. For a given displacement demand, Δ_{demand}, and calculated mean displacement at onset of damage Δ_{calc}, the likelihood of reaching that damage state can be calculated from the ratio $\Delta_{demand}/\Delta_{calc}$ and the statistics of equations 1 and 2.

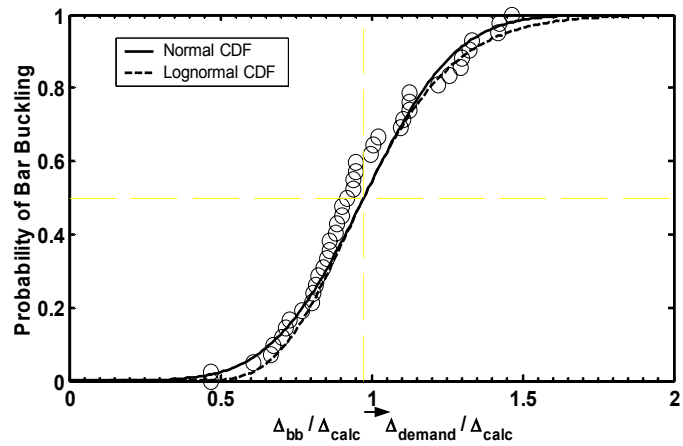

Fig. 1. Fragility Curves for Onset of Bar Buckling in Spiral-Reinforced Columns

For example, assuming that the column described above is subjected to a drift ratio of 2.0%. In this case, $\Delta_{demand}/\Delta_{calc}$ is equal to 2.0/1.8=1.1 for cover spalling, which is 0.17 standard deviations above the mean. For a normal distribution function, the likelihood of cover spalling is 57%. Similarly, $\Delta_{demand}/\Delta_{calc}$ = 2.0/5.7 = 0.35 for bar buckling, which is 2.6 standard deviations below the mean. The likelihood of bar buckling is 0.5%.

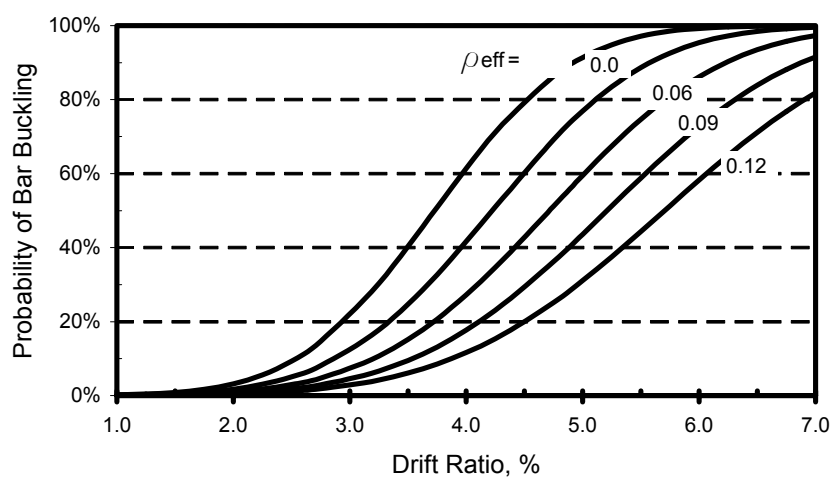

Fig. 2. Effect of Effective Transverse Reinforced Ratio on Likelihood of Bar Buckling (L/D = 3.5, P/f'cAg = 15%, D/db = 34)

The implications of equation (2) to the evaluation of bar buckling in spiral-reinforced concrete columns can be seen in Fig. 2, which was developed for L/D = 3.5, P/f'cAg = 15%, D/db = 34. As expected, the likelihood of bar buckling increases with increasing drift ratio and decreases with increasing amount of transverse reinforcement.

APPLICATION TO COLUMN DESIGN

The proposed methodology can also be used to design reinforced concrete columns. Equation (2) can be solved for the effective transverse reinforcement ratio as follows.

$$\rho_{eff} = \left(\frac{D}{k_{e_bb} d_b}\right)\left(\frac{\dfrac{\Delta_{demand}}{L\left(\text{target}\dfrac{\Delta_{demand}}{\Delta_{bb_calc}}\right)}(\%)}{3.25\left(1-\dfrac{P}{A_g f'_c}\right)\left(1+\dfrac{L}{10D}\right)}-1\right) \tag{3}$$

According to this equation, the amount of confinement reinforcement required depends on the displacement demand, Δ_{demand}, and the target Δ_{demand} / Δ_{bb_calc} ratio, which is a function of the target likelihood of bar buckling. For a target likelihood of bar buckling of 1.0%, which corresponds to $\Delta_{demand,}$ / Δ_{bb_calc} = 0.42, and a demand drift ratio of 2.0%, the effective reinforcement ratio that is required for the example column is (34/150)*[(2.0/0.42)/(3.25*0.85*1.35) -1] = 0.06. This ratio is half the spiral confinement required by the American Concrete Institute building code (ACI 2002) and the American Association of State Highway and Transportation Officials (AASHTO 2004).

Fig. 3 shows a design chart that illustrates the implications of implementing equation (3) in design. The chart was developed for L/D = 3.5, D/db = 34, and a probability of buckling of 1% The effective confinement ratio increases with increasing drift ratio and axial-load ratio. For columns

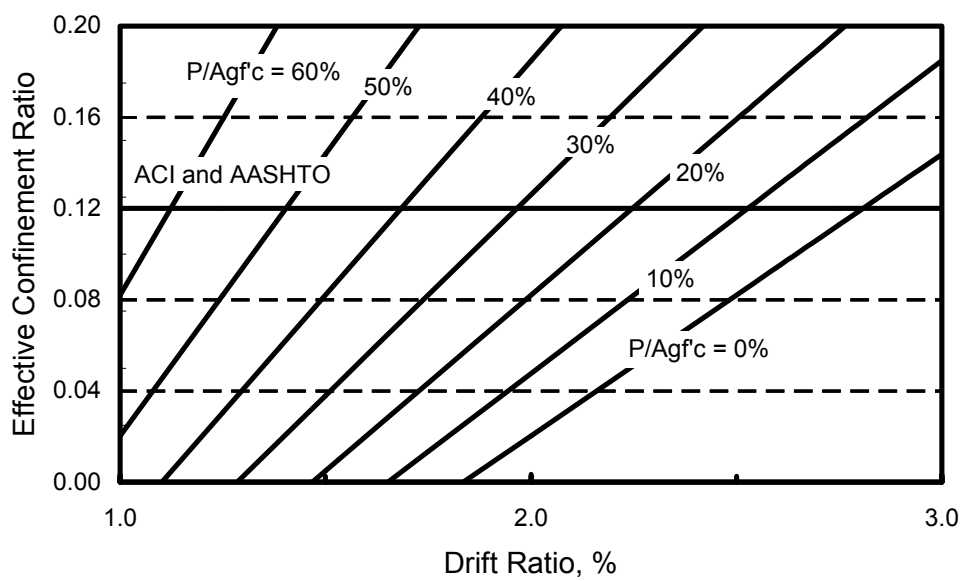

Fig. 3. Effect of Drift Ratio Demand and Axial Load on Transverse Reinforcement Requirements (L/D = 3.5, D/db = 34, Probability of Buckling = 1%)

with axial-load ratios below 15%, such as used typically in bridge columns, the drift ratio demand is approximately 2.5% for columns designed with an effective transverse reinforcement ratio of 0.12. The allowable drift ratio decreases rapidly with increasing axial load.

DIRECT USE OF PLASTIC-HINGE ANALYSIS

It is also possible to use plastic-hinge analysis directly to develop a performance model for reinforced concrete bridge columns. According to plastic-hinge analysis, the displacement at bar buckling, $\Delta_{_bb}$, is equal to the sum of the yield displacement, Δ_y, and the plastic deformation at bar buckling, Δ_{p_bb}. This plastic deformation is assumed to result from the rigid-body rotation of the member around the center of a plastic-hinge near the base of the column. For simplicity, the curvature in the plastic-hinge is assumed to be constant ($\phi_{p_bb} = \phi - \phi_y$) over an equivalent plastic-hinge length, L_p. The plastic rotation at bar buckling, θ_{p_bb}, can then be expressed as, $\phi_{p_bb} L_p$, and the total deflection at bar buckling is:

$$\Delta_{bb} = \Delta_y + \theta_p \left(L - L_p/2\right) = \Delta_y + \left(\phi_{p_bb} L_p\right) \left(L - L_p/2\right) \tag{4}$$

where L is the distance from the column base to the point of contraflexure. For a known Δ_{bb}, which is obtained from experiments, one can solve Equation (4) for the plastic curvature at bar buckling, ϕ_{p_bb}. The nominal compressive strain in the reinforcing bar at bar buckling can then be calculated with moment-curvature analysis.

The results of such analyses depend greatly on the choice of the plastic-hinge length L_p. For the plastic-hinge length proposed by Priestley et al. (1996), Figure 4 shows the nominal compressive strain in the longitudinal reinforcement for the 33 observations of bar buckling considered earlier. Using the average, nominal compressive strain of 0.026, the estimated displacement at bar buckling can be calculated with Equation (4).

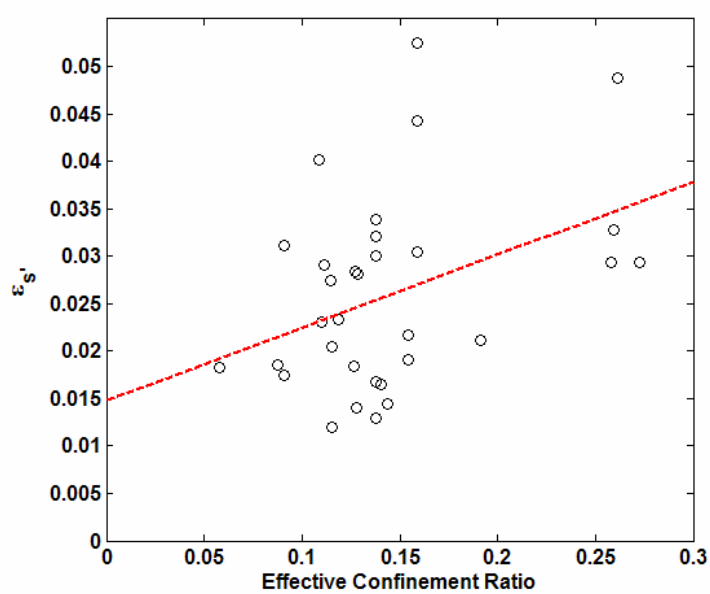

Fig. 4. Nominal Longitudinal Reinforcement Compressive Strain at Bar Buckling

Using this methodology, the ratio of the measured displacement at buckling to the displacement calculated with Equation 4 and the

average strain ($\frac{\Delta_{bb}}{\Delta_{bb_calc}}$) had a mean of 0.99 and a coefficient of variation of 31.8%. Further work is being conducted to develop a plastic-hinge length that makes it possible to more accurately predict the onset of cover spalling and bar buckling using plastic-hinge analysis.

SUMMARY AND CONCLUSIONS

For a known displacement demand, equations (1) and (2) provide a practical means of estimating the likelihood that the concrete cover for a reinforced concrete column will have begun to spall or the columns' longitudinal bars will have begun to buckle. The methodology, which can be used to develop simple charts, can be used both for column evaluation and design of reinforced concrete columns. A plastic-hinge model is being developed to serve as an alternative way of predicting damage in reinforced concrete columns.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO) (2004). "LRFD Bridge Design Specifications."

American Concrete Institute (ACI 318-02). (2002). "Building Code Requirements for Structural Concrete."

Berry, M.P. and Eberhard, M.O. (2004). "Performance Models for Flexural Damage in Reinforced Concrete Columns," Pacific Earthquake Engineering Research Center Report PEER-2003-18, University of California, Berkeley, August 2004, 156 pp.

Berry, M.P., Parrish, M. and Eberhard, M.O. (2004). "PEER Structural Performance Database User's Manual, Version 1.0" Pacific Earthquake Engineering Research Center Report, University of California, Berkeley, 2004 (available at *http://nisee.berkeley.edu/spd/*).

Berry, M.P. and Eberhard, M.O. (2005). "A Practical Performance Model for Bar Buckling," *Journal of Structural Engineering, ASCE*, July, Vol. 131, No. 7, pp 1060-1070.

Priestley, M.J.N., Seible, F., and Calvi, G.M. (1996). *Seismic Design and Retrofit of Bridges*, John Wiley and Sons, Inc., New York, New York.