Lateral Load-Drift Model for Normal and High-Strength Reinforced Concrete Columns

Saim Raza[1], Hing-Ho Tsang[2] and John L.Wilson[3]

1. Corresponding Author. PhD Student, Center for Sustainable Infrastructure, Swinburne University of Technology, VIC 3122, Australia
   Email: sraza@swin.edu.au

2. Senior Lecturer, Center for Sustainable Infrastructure, Swinburne University of Technology, VIC 3122, Australia
   Email: htsang@swin.edu.au

3. Professor and Pro Vice-Chancellor, Swinburne University of Technology, VIC 3122, Australia.
   Email: jwilson@swin.edu.au

Abstract

Generally, structural design engineers are well versed with the strength behaviour of reinforced concrete (RC) columns, whilst there is a lack of understanding of the corresponding drift behaviour of RC columns. For the displacement-based design approach, it is very important to have reliable prediction of the drift behaviour of RC columns in both the elastic and inelastic range. On the other hand, no unified lateral load-drift model exists that could predict the drift capacity of both normal-strength reinforced concrete (NSRC) and high-strength reinforced concrete (HSRC) columns in the inelastic range. This paper presents a detailed lateral load-drift model that has the ability to predict the drift capacity of lightly to moderately reinforced normal-strength and high-strength concrete columns in the elastic as well as inelastic range. The proposed detailed lateral load-drift model provides a simple and direct way for approximating the drift capacity of limited to moderately ductile RC columns at an early design stage with a reasonable accuracy.

Keywords: drift capacity, lateral load-drift model, lateral load failure drift, axial load failure drift

1. Introduction

The confinement requirements in regions of low to moderate seismicity such as Australia are not very stringent, thereby resulting in widely spaced transverse reinforcement and thus a limited ductile column. These limited ductile RC columns prevail in the majority of the building stock in Australia including the organizations with post disaster functions (Wilson et al. 2015). It is commonly believed that such lightly reinforced RC columns have a low drift capacity (FEMA, 2000).

The seismic performance of such columns can be assessed using the capacity spectrum method as shown in Figure 1, in which the structural capacity curve and seismic demand curve are superimposed on each other to get the performance point of the structure. The seismic demand curve is regionally dependent and site-specific and can be derived from the relevant seismic code, e.g. AS1170.4. It is expressed in the form of acceleration-displacement response spectrum (ADRS). On the other hand, the know-how of the relationship between lateral load and drift capacity is required for plotting the structural capacity curve, which is essentially the pushover curve of the column.

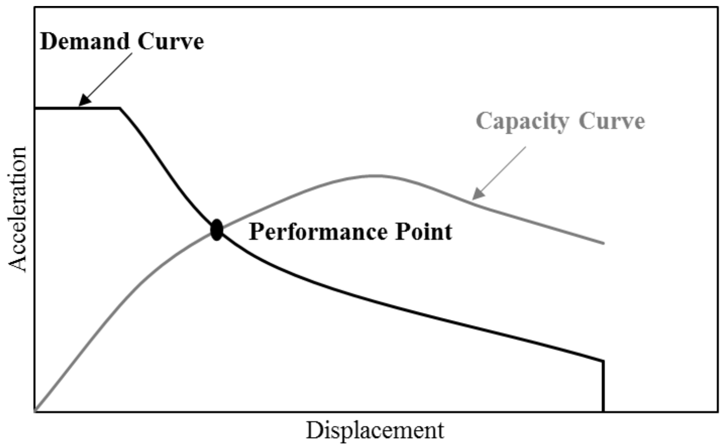

Figure 1: Capacity spectrum method

A survey of literature shows that while detailed lateral load-drift models (pushover curve) have been proposed for limited-ductile NSRC columns, very limited work has been done in this domain on HSRC columns. Moreover, no unified set of post-peak drift capacity models exist that could predict the drift capacity of both NSRC and HSRC columns.

The primary aim of this paper is to present a detailed lateral load-drift model (pushover curve) that possesses the ability to predict the lateral load-drift behaviour of limited to moderately ductile NSRC as well as HSRC columns. The next section summarizes the influence of design parameters on the lateral load-drift behaviour of the RC column. This is followed by detailed lateral load-drift model for both NSRC and HSRC columns. Finally, the last section presents a case study example to demonstrate the application of the proposed model.

2. Lateral Load-Drift Behaviour

The post-peak drift behaviour of the column was studied using a database of 190 RC columns (111 NSRC and 79 HSRC) from the literature (Raza et al. 2017). The influence of six design parameters, namely, aspect ratio (*a/h*), longitudinal reinforcement ratio

(ρ_v), transverse reinforcement ratio (ρ_h), transverse reinforcement yield strength (f_{yh}), concrete compressive strength (f_c') and axial load ratio (n) on the drift capacity of the RC column is described as follows:

- *Aspect Ratio:* It was observed that aspect ratio is the main controlling parameter that shifts the mode of failure from flexure to shear. The post-peak drift of shear-critical columns increased with the increase of aspect ratio. However, aspect ratio had no significant influence on the post-peak drift of flexure-critical columns.
- *Longitudinal Reinforcement Ratio:* Post-peak drift showed both increasing and decreasing trends with the increase of longitudinal reinforcement ratio. Hence, no direct correlation could be delineated between the two parameters.
- *Transverse Reinforcement Ratio:* A definite increasing correlation was observed between the drift and the transverse reinforcement ratio for both NSRC and HSRC columns. However, the rate of increase in drift had some dependency on other parameters.
- *Transverse Reinforcement Yield Strength*(f_{yh})*:* There was a very slight increase in lateral load failure drift (drift at 20% degradation of lateral strength) with the increasing transverse reinforcement yield strength. However, axial load failure drift (collapse drift) showed more substantial increase with the increase of transverse reinforcement yield strength.
- *Concrete Compressive Strength:* It was noticed that with the increase of concrete compressive strength the post-peak failure drift reduced for HSRC columns. However, the rate of reduction had some interdependency with other design parameters.
- *Axial Load Ratio:* Among all the design parameters, axial load ratio had the most significant impact on the post-peak failure drift. A substantial reduction in failure drift was observed with the increase in axial load ratio for both NSRC and HSRC columns.

3. Detailed Column Lateral Load-Drift Model

The detailed column lateral load-drift model can be defined by five points, namely, cracking strength, yield strength, ultimate strength, lateral load failure (20% lateral strength degradation) and axial load failure (50% lateral strength degradation) as shown in Figure 2. The model presented in this paper is an extension of the model presented in Wilson et al. (2015) and includes the expressions for post-peak failure drift that are applicable to both NSRC and HSRC columns.

- *Point A (Cracking Strength):* The principles of basic mechanics are used to determine the lateral strength at cracking point and the corresponding drift.

$$F_{cr}=\frac{M_{cr}}{L} \tag{1a}$$

$$M_{cr}=(f_t-\frac{P}{A_g})\frac{I_g}{y} \tag{1b}$$

$$\delta_{cr}=\frac{M_{cr}L}{3E_cI_g} \tag{1c}$$

where F_{cr}= cracking strength, M_{cr}= cracking moment, δ_{cr}= drift at cracking,

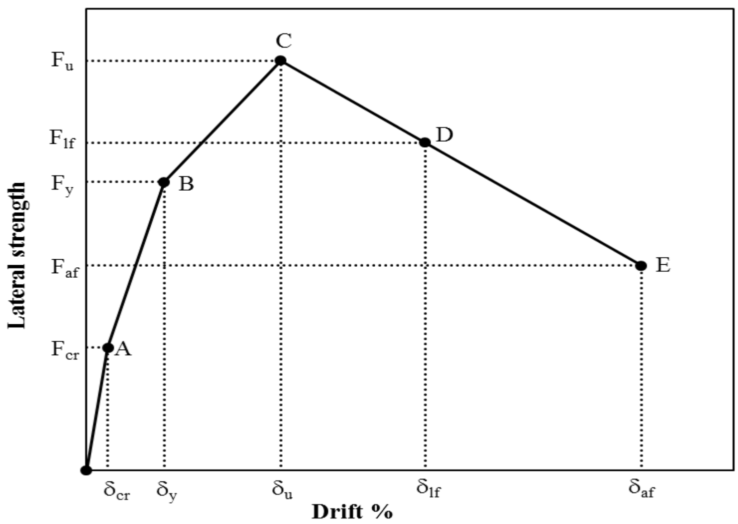

Figure 2: Detailed column lateral load-drift model

A_g= gross area of column , flexural tensile strength of concrete $= f_t = 0.6\sqrt{f_c'}$ (AS 3600-2009), P= axial load, L=shear span of the column, E_c=elastic modulus of concrete, y = distance to the neutral axis and I_g= gross moment of inertia of column cross-section.

- *Point B (Yield Strength):* Classical working stress method is used to determine the yield strength. The corresponding yield drift can be calculated using Equation (2b) that employs classical curvature methods or Equation (2c) that uses elastic drift approach and an effective second moment of area as described in FEMA356 (FEMA, 2000) or Paulay and Priestley (1992):

$$F_y = \frac{M_y}{L} \tag{2a}$$

$$\delta_y = \frac{1}{3} \emptyset_y L \tag{2b}$$

$$\delta_y = \frac{M_y L}{3 E_c I_{eff}} \tag{2c}$$

where F_y= yield strength, M_y= yield moment, δ_y= drift at yield, $\emptyset_y$= yield curvature and I_{eff} = effective second moment of area given by:

(a) FEMA356 (2000)

$I_{eff} = 0.7 I_g$ for axial load ratio $n \geq 0.5$

$= 0.5 I_g$ for axial load ratio $n \leq 0.3$

For $0.3 \leq n < 0.5$, the value of I_{eff} should be interpolated.

(b) Paulay and Priestley (1992)

$$I_{eff} = \left(\frac{100}{f_y} + n\right) I_g \tag{2d}$$

- *Point C (Ultimate Strength):* Ultimate strength design method is used to determine the ultimate flexural strength in the lateral load-drift model. The ultimate drift is calculated as the sum of elastic and plastic drift. The elastic drift is the yield drift whereas the plastic drift is calculated using ultimate curvature and plastic hinge length (Wilson et al. 2015).

$$F_u = \frac{M_u}{L} \tag{3a}$$

$$\delta_u = \delta_y + \delta_{pl} \tag{3b}$$

$$\delta_{pl} = (\emptyset_u - \emptyset_y) L_p \tag{3c}$$

$$\delta_y = \frac{1}{3} \emptyset_y L \tag{3d}$$

where F_u= ultimate strength, M_u= ultimate moment, δ_u= ultimate drift, δ_{pl}= plastic drift, $\emptyset_u$= ultimate curvature from ultimate strength analysis, L_p= plastic hinge length= 0.5*D*, *D*= column width and

Point D (Lateral Load Failure): Lateral load failure point corresponds to 20% degradation in peak lateral strength of the RC column. The drift at lateral load failure of flexure-critical NSRC and HSRC columns can be predicted using the following recently developed empirical expressions (Raza et al. 2017):

$$(\delta_{lf})_{\text{flexure}} = 3(1-2n) + \left(\rho_h \sqrt{\frac{f_{yh}}{f_c'}}\right) \tag{4a}$$

$$(\delta_{lf})_{\text{flexure}} = 3(1-2n) + 0.5\left(\rho_s \sqrt{\frac{f_{yh}}{f_c'}}\right) \tag{4b}$$

where $(\delta_{lf})_{\text{flexure}}$= drift at lateral load failure for flexure-critical columns (in %), n=axial load ratio, ρ_h= transverse reinforcement ratio by area (in %), f_{yh}= transverse reinforcement yield strength (MPa), f_c'= concrete compressive strength (MPa), ρ_s= transverse reinforcement ratio by volume (in %)

The proposed empirical expressions are applicable within the following range of parameters: $12.1 \leq f_c' \leq 104.3$ MPa, $0.07\% \leq \rho_h \leq 1.0\%$, $0.15\% \leq \rho_s \leq 2.47\%$, $f_{yh} \leq$ 500 MPa and $0.027 \leq n \leq 0.5$

- *Point E (Axial Load Failure):* The strength at axial load failure is conservatively taken as 50% of the peak lateral strength of the RC column whereas axial load failure drift of NSRC and HSRC columns can be predicted using the following recently developed empirical expressions:

$$\delta_{af} = 5(1-2n) + \left(\rho_h \sqrt{\frac{f_{yh}}{f_c'}}\right) \tag{5a}$$

$$\delta_{af} = 5(1-2n) + 0.5\left(\rho_s \sqrt{\frac{f_{yh}}{f_c'}}\right) \tag{5b}$$

where δ_{af}= drift at axial load failure (in %), n=axial load ratio, ρ_h= transverse reinforcement ratio by area (in %), f_{yh}= transverse reinforcement yield strength

(MPa), f_c'= concrete compressive strength (MPa), ρ_s= transverse reinforcement ratio by volume (in %)

The proposed empirical expressions are applicable within the following range of parameters: $13.5 \leq f_c' \leq 104.3$ MPa, $0.07\% \leq \rho_h \leq 0.92\%$, $0.15\% \leq \rho_s \leq 2.65\%$, $240 \leq f_{yh} \leq 1360$ MPa and $0.05 \leq n \leq 0.5$

Equations (4a), (4b), (5a) and (5b) have been developed and calibrated using an extensive database of NSRC and HSRC columns from the literature. These expressions fit the experimental data very well and relate the post-peak drift capacity with the following design parameters: axial load ratio, transverse reinforcement ratio, transverse reinforcement yield strength and concrete compressive strength.

4. Case Study Example

The application of detailed column lateral load-drift model is demonstrated in this section using a case study example. The model is used to plot pushover curve for a cantilever column of 500×500 mm cross-section, having an aspect ratio of 4.0 and

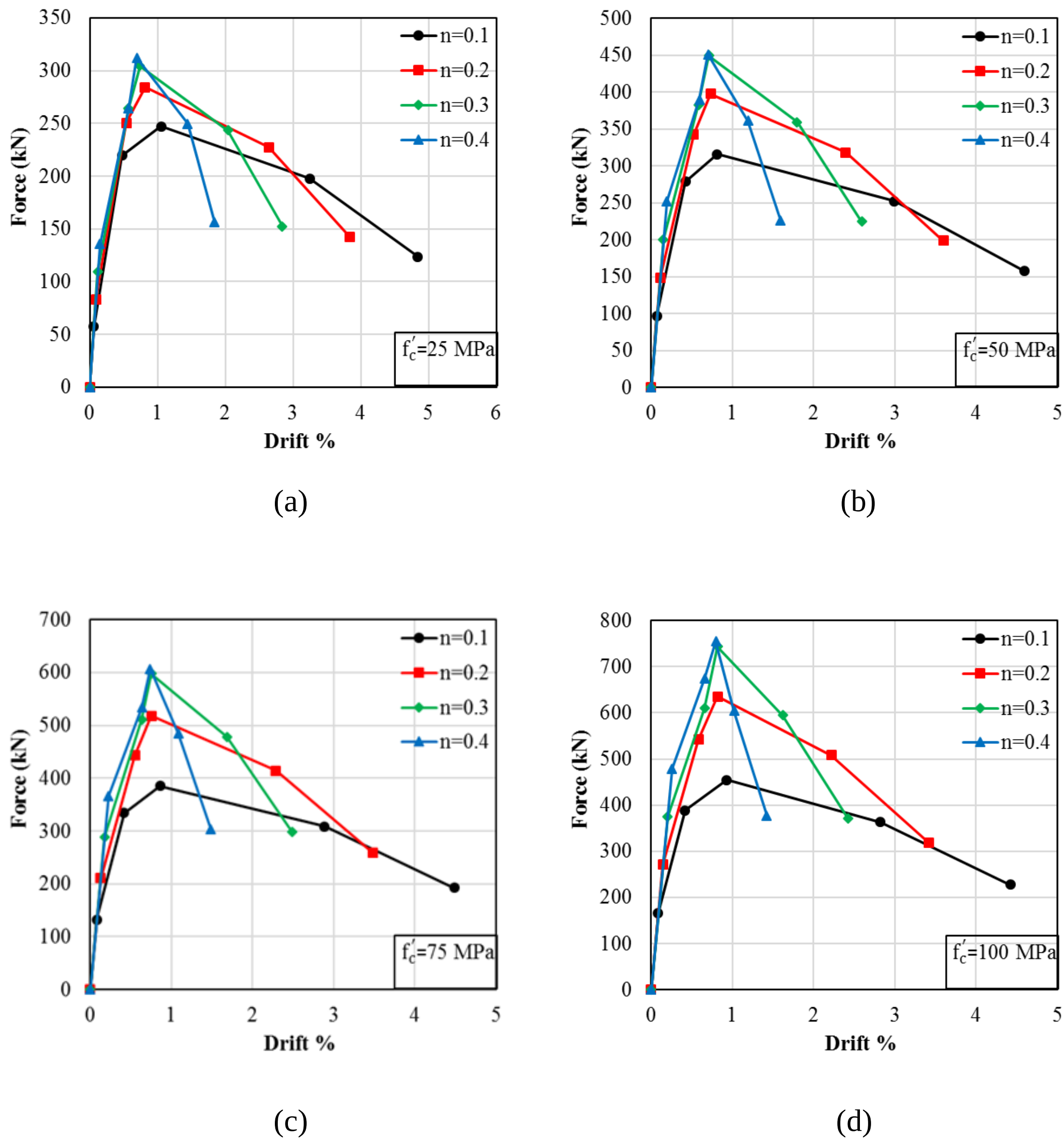

Figure 3: Lateral load-drift curves for case study example

reinforced with 8N24 longitudinal bars (ρ_v=1.45%). The 3-legged N10 ligatures with a transverse reinforcement yield strength of f_{yh} =500 MPa are spaced at 250 mm to give a transverse reinforcement ratio by area of ρ_h=0.19%. The variable parameters for this case study are concrete compressive strength: f_c'=25 to f_c'=100 MPa and axial load ratio: n=0.1 to n=0.4.

Figure 3 presents the pushover curves for this case study example. It can be seen that axial load ratio has a very significant impact on the post-peak drift capacity of the RC column. There is a substantial reduction in the drift capacity when the axial load ratio increases from n=0.1 to n=0.4 for both NSRC and HSRC columns. This provides an important insight from the design perspective i.e. the higher the axial load a column is designed to support, the lesser is its collapse drift capacity. Similarly, it can also be seen that there is a reduction in the drift capacity of the column when concrete compressive strength increases from f_c'=25 to f_c'=100 MPa.

5. Conclusion

This paper presented a detailed column lateral load-drift model for both NSRC and HSRC columns. The proposed model uses recently developed empirical expressions to predict post-peak drift capacity of the RC column at lateral load failure and axial load failure. The proposed expressions relate the column drift capacity with the following design parameters: axial load ratio, transverse reinforcement ratio, transverse reinforcement yield strength and concrete compressive strength and thus provides a simple and direct way of estimating drift capacity of the RC column at an early design stage. The application of these models on a case study example shows that axial load ratio is the most influential parameter affecting the drift capacity of the RC column i.e. the higher the axial load ratio, the lesser the drift capacity of the column. This implies that compression dominated columns designed to support high axial loads have a very low collapse drift capacity. Similarly, the models also demonstrate that high-strength RC columns have a low drift capacity as compared to normal-strength RC columns.

References

Applied Technology Council (1996). ATC-40: Seismic evaluation and retrofit of concrete buildings 1&2. California, USA.

AS 3600-2011 Concrete Structures. Standards Australia.

Elwood, K. J. and Moehle, J. P. (2005). Axial capacity model for shear-damaged columns. ACI Structural Journal, 102**,** 578-587.

FEMA 356 (2000). NEHRP Guidelines for the seismic rehabilitation of buildings. Federal Emergency Management Agency, Washington DC, USA.

Ghannoum, W. and Moehle, J. Shear failure model for flexure-shear critical reinforced concrete columns. 14th World Conference on Earthquake Engineering, Beijing, China, 2008.

Ho, J. C. M. and Pam, H. J. (2010). Deformability evaluation of high-strength reinforced concrete columns. Magazine of Concrete Research, 62**,** 569-583.

Ousalem, H., Kabeyasawa, T. and Tasai, A. Evaluation of ultimate deformation capacity at axial load collapse of reinforced concrete columns. Proceedings of 13th World Conference on Earthquake Engineering, 2004.

Park, R. and Paulay, T. (1975). Reinforced Concrete Structures, John Wiley & Sons, New York.

Paulay, T., Priestley, M. 1992, 'Seismic design of reinforced concrete and masonry structures', John Wiley and Sons, New York, USA.

Priestley, M., Calvi, Gm and Kowalsky, Mj. (2007). Displacement-Based Seismic Design of Structures. IUSS Press, Pavia, Italy.
Raza, S., Tsang, H.H., Wilson, J.L. (2017). Unified Models for Post-Peak Failure Drifts of Normal- and High-Strength RC Columns. Submitted for Review. Magazine of Concrete Research.
Sasani, M. (2007). Life-safety and near-collapse capacity models for seismic shear behavior of reinforced concrete columns. ACI Structural Journal, 104**,** 30-38.
Tran, C. T. N. and Li, B. (2013). Ultimate Displacement of Reinforced Concrete Columns with Light Transverse Reinforcement. Journal of Earthquake Engineering, 17**,** 282-300.
Wibowo, A., Wilson, J. L., Lam, N. T. K. and Gad, E. F. (2014b). Drift performance of lightly reinforced concrete columns. Engineering Structures, 59**,** 522-535.
Wilson, J. L., Lam, N. T. K. and Gad, E. F. Hazard Identification and Behaviour of Reinforced Concrete Framed Buildings in Regions of Lower Seismicity. Proceedings of the Tenth Pacific Conference on Earthquake Engineering, 2015, Sydney, Australia.
Wilson, J. L., Lam, N. T. K. and Rodsin, K. (2009). Collapse modelling of soft-storey buildings. Australian Journal of Structural Engineering, 10**,** 11-23.
Wilson, J. L., Wibowo, A., Lam, N. T. K. and Gad, E. F. (2015). Drift behaviour of lightly reinforced concrete columns and structural walls for design applications. Australian Journal of Structural Engineering, 16**,** 62-73.
Zhu, L., Elwood, K. J. & Haukaas, T. (2007). Classification and seismic safety evaluation of existing reinforced concrete columns. Journal of Structural Engineering-ASCE, 133**,** 1316-1330.