Modeling aspects concerning the axial behavior of RC columns

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Abstract

This paper is concerned with the axial behavior of the RC columns. Stress-strain relationships of experimentally tested RC columns under concentric loading are compared with the predictions of the Koksal model. Moment-curvature analyses of RC sections are also performed employing the same model in a self-developed moment-curvature program for confined concrete. Results are compared with the output of EXTRACT which uses the Mander concrete model.
Keywords: confinement, reinforced concrete columns, concentric loading, stress–strain relations.

1   Introduction

Confining pressure on RC columns increases the concrete strength. Transverse reinforcements such as steel stirrups, FRP wraps, and steel jackets create a tri-axial compressive stress state producing confinement action around the concrete core. Extensive research on the improvement of concrete confinement has been carried out since the pioneering study of Richart et al. [1]. The constitutive model for confined concrete plays an important role on the accuracy of the moment-curvature curves to perform a reliable pushover analysis of RC frames. There are some frequently cited models (Hognestad [2], Kent and Park [3], Sheikh and Uzumeri [4], Mander et al. [5], Saatcioglu and Razvi [6]) to predict

the peak stress or the stress–strain curve of confined concrete. Köksal has also proposed a failure criterion for concrete under tri-axial compression stress state [7]. In this paper, four square RC columns tested in Yıldız Technical University (Turgay [8], Köksal et al. [9]) are evaluated implementing Koksal model. The flexural behavior of the columns is also simulated and their moment-curvature relations corresponding to different axial load levels are obtained using the same model. Moment-curvature curves are compared with the outputs of EXTRACT.

2 Experimental study

The square specimens in the test program have 200x200 mm cross-section dimensions and 1000 mm height. The columns were tested in the structural laboratory of Yıldız Technical University [8]. Figure 1 shows the details of test setup and instrumentation for the two specimens.
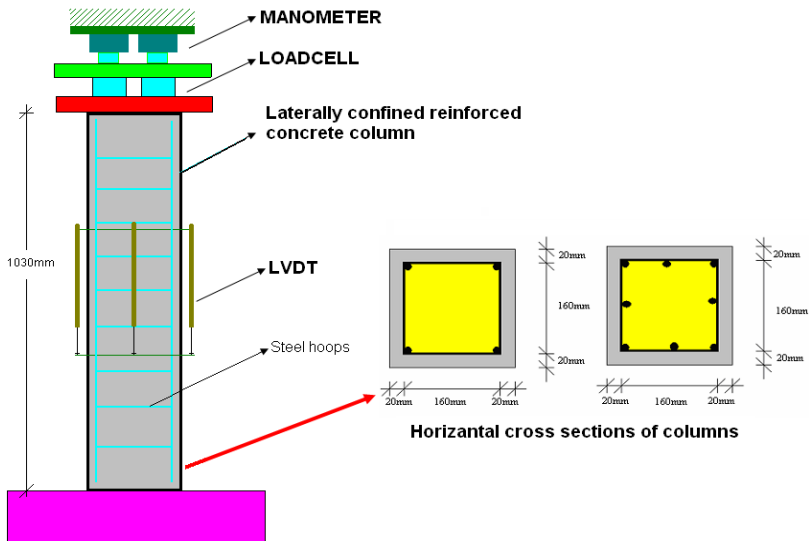

Figure 1:   Test setup and details of test specimens C1L4S8 and C1L8S8 [8].

The experimental study was limited to one type of concrete mix design typically. C1 type columns are tested at 30 days. All longitudinal bars are 10mm in diameter and L4 and L8 shows the number of the bars in the cross-section of a column. The tie spacing is 100mm and the S8 represents diameter of stirrups. For measurement of axial strains, four linear variable displacement transducers (LVDTs) are placed over the central 400mm gage length at each side of a column in a similar way used to assess any eccentricity of the applied load as recommended in the study of Shrive et al. [10]. Although the LVDT readings were provided very close to each other, next to the maximum axial load there can be a significant variation between the minimum and maximum values of shortening reaching very high values [9]. Figure 2 shows the axial load-axial

shortening curve for C1L8S8 for which almost perfectly homogeneous strains were obtained. However, for other columns the differences between LVDT readings are somewhat greater indicating a localized damage zone at one specific region of the specimen.
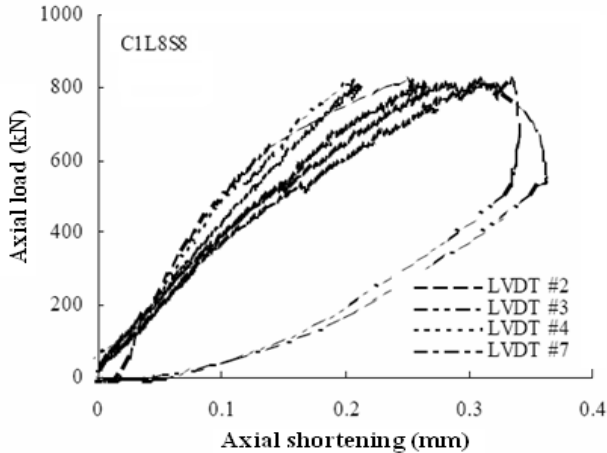

Figure 2:   Four separate LVDT readings of axial load-shortening curves for C1L8S8 [9].

3   Simulation of flexural behavior and moment curvature relations

The limit state design procedure of reinforced concrete elements has undergone major revision by most of the international codes in harmony with the performance-based design engineering approach. In this approach, moment-curvature behavior of flexural members is needed to define the deflection demand and to simulate the behavior of the reinforced concrete members under lateral loads such as earthquake actions. Moment-curvature plots readily illustrate stiffness, strength, and cross-sectional ductility, and allow the calculation of deflections after materials become nonlinear. In a flexural member the shear reinforcement or any other confinement mechanism applies pressure to the concrete in the compression zone and affects energy dissipation capacity directly. Therefore, to predict the moment-curvature behavior of a flexural member, the stress–strain behavior of confined concrete under axial compression is vital. With the development of performance-based design methods, there is an increasing need for simplified but reliable analytical models capable of predicting the flexural behavior of reinforced concrete members. The flexural behavior of reinforced confined concrete sections is introduced by Koksal model [7]. The failure criterion proposed by Koksal is given as:

$$f = 1.1317\xi^{0.7645} + \rho - \sqrt{2}\,k(\sigma_1, \sigma_2, \sigma_3) = 0 \qquad (1)$$

where $k = k\left(f_l, f_c'\right)$, ρ and ξ are deviatoric and hydrostatic lengths, respectively. In this equation k, as a function of the lateral confinement pressure, f_l, and the cylinder compressive strength of concrete, f_c' can be expressed as [7] :

$$k = \left(4.07\frac{f_l}{f_c'} - 0.89\left(\frac{f_l}{f_c'}\right)^2 + 0.807\right)f_c' \qquad (2)$$

The theoretical confining pressure, f_l, can be found in usual way as [11] :

$$f_{l,x} = k_e\,\rho_{sx}\,f_{yh} \qquad \text{or} \qquad f_{l,y} = k_e\,\rho_{sy}\,f_{yh} \qquad (3)$$

In this relation, ρ_{sx} and ρ_{sy} are the confinement proportion both x and y direction respectively, k_e is the confinement effectiveness coefficient, and f_{yh} is the yield strength of transverse reinforcing steel. The Saenz's equation [12] is adopted for describing the monotonic stress-strain relationship for confined concrete:

$$\sigma_1 = \frac{\varepsilon_1 E_0}{1 + \left(\dfrac{E_0}{E_s} - 2\right)\left(\dfrac{\varepsilon_1}{\varepsilon_{cc}}\right) + \left(\dfrac{\varepsilon_1}{\varepsilon_{cc}}\right)^2} \qquad (4)$$

where σ_1 and ε_1 are axial compressive stress and strain of concrete, respectively; E_0 is the initial tangent modulus of elasticity in MPa and can be calculated as $E_0 = 4750\sqrt{f_{co}'}$; E_s is the secant modulus at the point of maximum compressive stress f_{cc}' which can be determined using Equation 1. The strain ε_{cc} corresponding to the maximum compressive stress f_{cc}' can be found employing the recommended relations of Richart et al. [1] :

$$\varepsilon_{cc} = \varepsilon'_c\left(1 + k_2\frac{f_l}{f'_c}\right) \qquad (5)$$

where ε_c' is the peak strain at the strength of plain concrete cylinders. In this equation, k_2 is taken as $5k_1$.

Figure 4 aims to compare experimental axial stress-strain curves of the four column specimens with those predicted from Eqs (1)-(4).

In this study, a simple program is written in FORTRAN to produce moment-curvature plots for confined column section under bending and axial compression. The cross section is divided into 1mm thickness slices. For a given depth of natural axis, the strain at the extreme slice in compression is found by iterative procedure. For each slices, the stress and strain are calculated using force equilibrium and compatibility requirements respectively. Stress acting on the core concrete (cover concrete is neglected) calculated using Koksal's model. Koksal's model has also been utilized through the 3D finite element analysis of RC and FRP-confined concrete columns [11, 13] successively. Figure 3(a)

demonstrates the typical axial stress-strain curves recommended by Saenz for a concrete member [12]. Finite concrete forces for unconfined and confined core of each slice are found by multiplying stress by corresponding areas. Stress at the reinforcement bars is found by entering a simple bi-linear stress-strain curve in Figure 3(b) with the strain value found from compatibility requirements at each load level. Finite forces on steel can be found by multiplying stress by the area of the reinforcement.
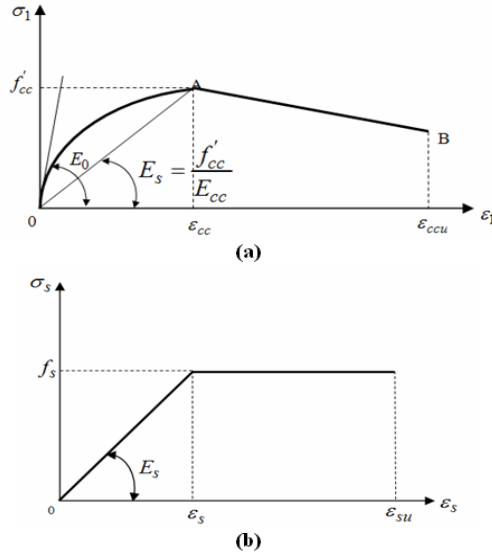

Figure 3:   (a) Saenz curve for uniaxial behavior of concrete; (b) stress-strain relation for steel.
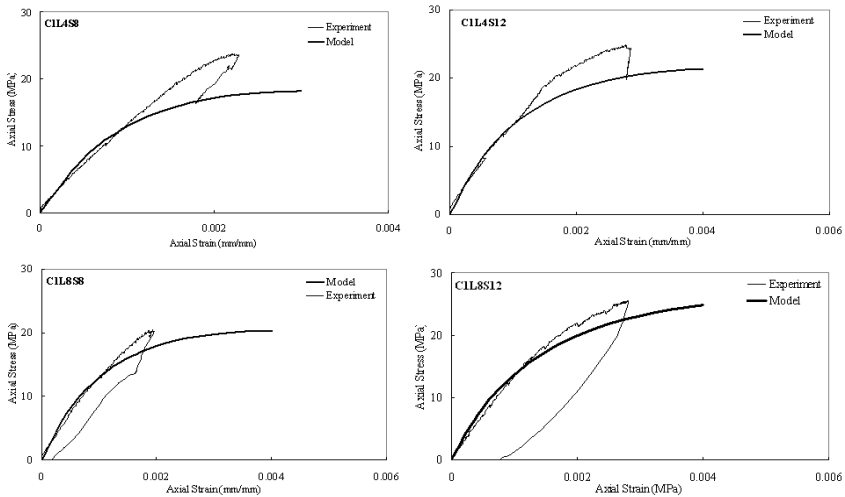

Figure 4:   Experimental and predicted stress-strain curves for the specimens.

Figure 5 show the moment-curvature relations for C1L4S8 and C1L8S8 at various load levels. Increasing the axial load from 200kN to 400kN always results an increase in the moment carrying capacity. But when a load near to the axial load capacity is considered, moment carrying capacity does not increase any more. Also decrease in the curvature is very obvious when the axial load increases as expected.
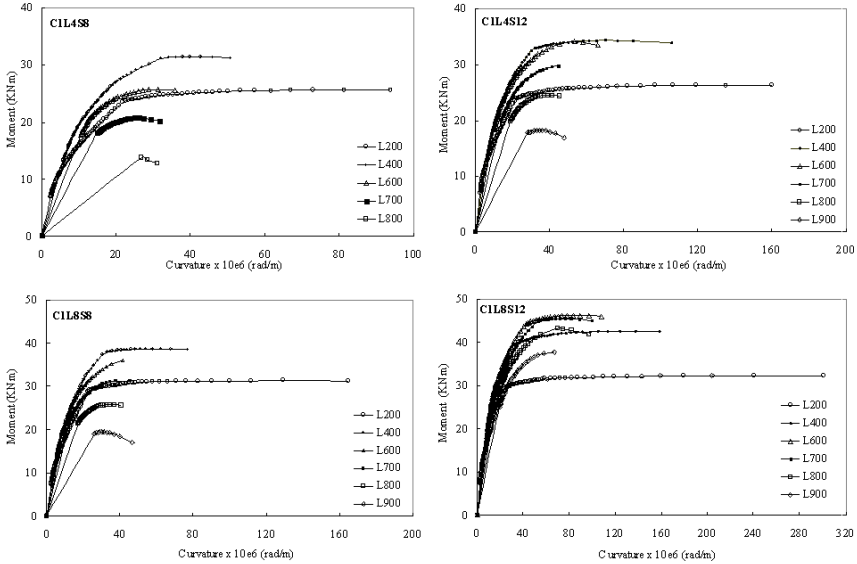

Figure 5:   Moment-curvature diagrams for the four columns at various axial load levels.
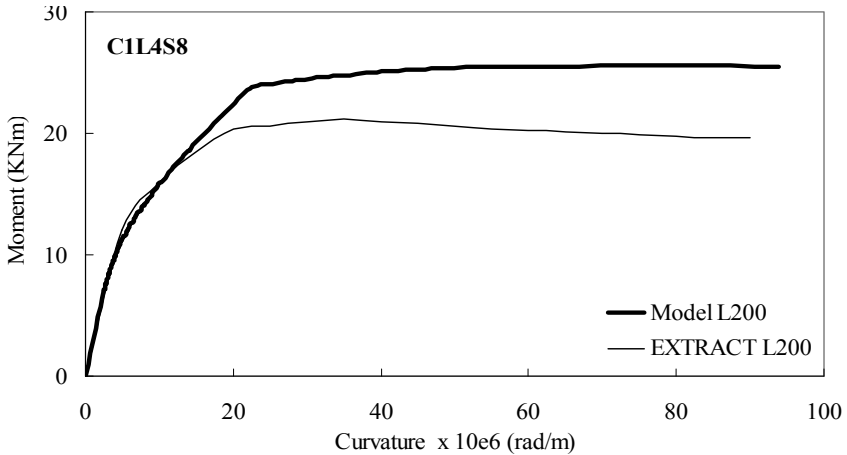

Figure 6:   Output of EXTRACT program and the proposed model for moment-curvature diagrams for C1L4S8 at the axial load level of 200kN.

Figures 6–8 show the output of EXTRACT program [14] for C1L4S8 subjected to the axial load levels of 200kN, 400kN and 600kN respectively. EXTRACT program employs the Mander model for confined concrete. There are not significant differences if one compares the curvature values for both programs.
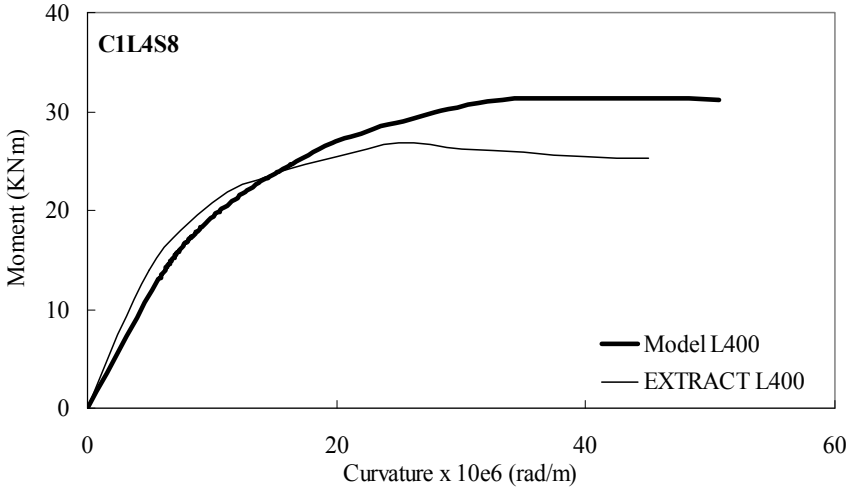

Figure 7: Output of EXTRACT program and the proposed model for moment-curvature diagrams for C1L4S8 at the axial load level of 400kN.
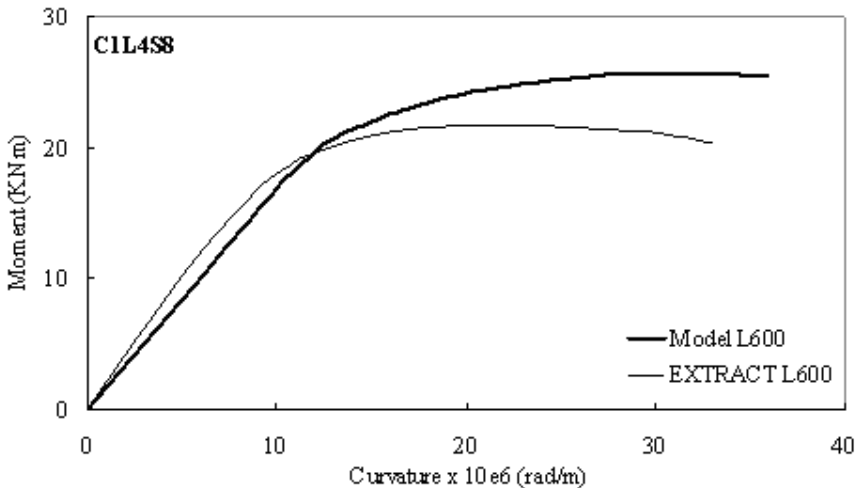

Figure 8: Output of EXTRACT program and the proposed model for moment-curvature diagrams for C1L4S8 at the axial load level of 600kN.

4   Conclusion

This paper has been primarily concerned with the modeling aspects for the axial behavior of RC columns. Experimental axial stress-strain curves of the four column specimens are predicted employing Koksal model. Furthermore, a spreadsheet-based program is constructed to produce moment-curvature plots for the performance-based design engineering approach. The following conclusions can be drawn based on the results of the analyses:

1. As can be seen in Figure 5, Koksal model successively predicts the axial behavior of the four RC column specimens tested under concentric loading.

2. It can be easily observed that Koksal model results into somewhat higher values for the moment carrying capacities than the outputs of EXTRACT program which employs Mander model in Figure 6–8, but the general trend of the curves are the same. The developed program gives 27kNm and 38kNm for moment carrying capacities at the axial load levels of 400kN and 600kN while EXTRACT program results are between 22kNm and 27kNm.

Acknowledgement

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