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Analytical prediction of seismic behavior of RC joints and columns under varying axial load

Javad Shayanfar[a], Habib Akbarzadeh Bengar[a,*], Azadeh Parvin[b]

[a] Department of Civil Engineering, The University of Mazandaran, Babolsar, Iran
[b] Department of Civil and Environmental Engineering, The University of Toledo, Toledo, USA

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ABSTRACT

In this study, an analytical model for predicting nonlinear behavior of exterior reinforced concrete (RC) beam-column joints under varying axial load was developed. The main focus was given on the assessment of the effect of axial load variations on the response of RC joints and columns. During seismic actions, overturning moments are produced by lateral loads that are translated as axial loads in the columns. It leads to compressive axial force on one side of the structure along with tensile on the opposite. It can overwhelm nonlinear behavior associated with axial, flexural, shear stresses of RC columns and joints. To simulate and evaluate these nonlinearities, a beam- column joint model consisted of rotational springs were developed. The characteristics of joint spring could be computed using principle tensile stress-joint rotation relation (p_t versus θ_j) in the joint core depending on the type of the beam bar anchorage. Therefore, for the joints with various beam bar anchorage details, p_t versus θ_j relations in the joint core were proposed. A new theoretical methodology was also developed to consider the effect of the axial load variations in determining characteristics of rotational springs. To assess the accuracy and reliability of the analytical model, it was compared through experimental data available in the literature. The results showed that the proposed analytical model could predict the experimental response of poorly detailed RC beam-column joints under varying or constant axial loads with reasonable precision. Furthermore, parametric studies were carried out to highlight the overwhelming effect of axial load variations on RC beam-column joints and columns. The simple analytic procedure would make the model sufficiently suitable for practical applications.

1. Introduction

Beam-column joint elements are of paramount importance in seismic performance of RC structures, especially non-seismically designed ones. Columns tend to transfer vertical forces from roof and stories to foundations, while joints transmit moments and shears of beams into the columns. Due to seismic loads, such as earthquake loading or wind, columns and joints are subjected not only to the effects of gravity loads but also to variable moment, shear and axial loads. Axial load produced by lateral loads into columns causes compressive axial force on one side of the structure along with tensile on the opposite. Accordingly, columns as well as the joint core would experience variable axial load levels during lateral loading.

Significant effects of axial load on inelastic behavior of RC joints were confirmed by experimental studies [1–4]. On the other hand, to assess the seismic performance of RC joints under varying axial loads were experimentally investigated by few researchers [5–13], due to the complexity of implementing a fluctuating axial force during testing. The Experimental results showed that seismic response of RC beam-column joints, especially poor detailed ones, were considerably influenced by axial load variations so that a combination of lateral and varying axial loads resulted in a severe reduction in strength and ductility capacities. To consider the effects of axial load variations in the calculation of the RC beam-column joint response, several analytical studies have been conducted mostly based on hierarchy of strength method [6–13]. In this method, carrying out a bending moments versus axial force (*M-N*) performance domain, consisting of the internal hierarchy of strengths in an RC beam-column joint along with the lateral demand in accordance with axial load variations resulted by lateral loads, the joint response could be evaluated. Although useful information about seismic performance of RC joints can be obtained by this approach, it needs an iterative procedure to develop *M-N* domain. Accordingly, considering the fact that for each stage of rotation, θ_j, *M-N* domain should be determined, the method seems not to be enough practical to model RC

* Corresponding author.
E-mail address: h.akbarzadeh@umz.ac.ir (H.A. Bengar).

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joints under varying axial load. It is well known that to perform a realistic nonlinear analysis, nonlinearities in the joint core should be considered in the modeling simulation. Several analytical and numerical joint models have been provided in the literature [14–32]. In general, these models need large computational efforts or special programs to model elements with various springs. Besides, these models do not consider the effects of axial load variations and work virtually well under constant axial load. Consequently, developing a practical model which considers the effects of the axial load variations would be necessary for accurate and realistic evaluation of RC beam-column joints.

One of the most severe deficiencies in existing RC structures which makes them vulnerable to earthquakes might be inadequate column shear capacity resulting in brittle shear failure, and subsequently, shear-axial failure in such columns ([33–40]). Experimental studies ([33,34,41–44]) proved that the shear capacity of RC columns would significantly be overwhelmed by their inelastic flexural deformations. Accordingly, some models were developed to compute shear capacity of RC columns as a function of ductility demand ([44–52]). However, it should be considered that the models in literature are generally suitable for RC columns with constant axial load. On the other hand, experimental and analytical studies ([34–36,53–64]) on RC columns under varying axial load confirmed that the seismic response of RC columns in terms of strength, deformation capacity and stiffness was noticeably different from those under constant axial load. Therefore, a comprehensive model seems to be necessary to predict their shear and flexural behavior while considers the effects of fluctuation on axial load.

In the present study, an analytical joint model consisting of a rotational spring in the centre of the joint core was proposed in an attempt to practically simulate seismic response of RC beam-columns joints under varying axial load. To consider the remarkable effects of the combination of lateral and varying axial loads, a new theoretical approach was also developed so that the model could be capable of the calculation of the joint response in each level of the axial load variations. The nonlinear characteristics of the joint rotational spring were determined according to principles of mechanics (Mohr circle's theory) and a semi-empirical analytical model. Accordingly, through providing a relatively large database of test specimens, p_t versus θ_j relations depending on the anchorage type of beam bars were proposed. Furthermore, for calculating shear and flexural capacities of RC columns subjected to varying axial load, a simple procedure was also proposed based on moment-curvature analysis. Overall, the analytical beam-column joint model is suitable to be carried out by hand calculations to predict joint shear capacity with no special software program requirement and accordingly, can easily be employed in practical applications.

2. Proposed analytical beam-column joint model

In this section, nonlinear behavior of RC beam-column joint under combined lateral cyclic and varying axial loads is modeled. Fig. 1 illustrates the mechanics of an exterior RC beam-column joint when subjected to lateral loading. L_b and L_c are the distance of the critical section to the point of contra-flexure in beam and storey height, respectively. The other parameters were defined in the figure. During seismic loading, beam-column joints are subjected to axial and shear stresses in the joint core. These stresses would lead to principle tensile and compressive stresses which result in diagonal cracking or concrete crushing in the joint core. To simulate nonlinearities in the beam-columns joints, several analytical and numerical joint models have been provided in the literature [14–32]. In general, these models do not seem to be practical and suitable enough to be used by engineers for predicting nonlinear behavior of RC beam-column joints, while practical models are known to be scarce. One of the main reasons is that these models need large computational efforts or special programs to model elements with various springs. Besides, these models do not consider the effects of axial load variations and work virtually well under constant axial load. In the present study, an analytical beam–column joint model was developed to simulate the joint mechanism under varying axial load (Fig. 2). As can be seen, the model includes a nonlinear rotational spring in the joint core to simulate joint post-cracking shear deformation (Fig. 2(b)). According to a new theoretical approach, the effects of axial load variations were considered in the calculation of the joint rotational spring. Finite dimensions of the joint zone were also taken into account using rigid elements. The relation between p_t and θ_j due to the joint shear deformation as well as slippage of beam/column longitudinal bars was assumed to be converted into a moment-rotation relationship in the joint core, which will be discussed in more details in the following sections. As shown in Fig. 2(c) and (d), to consider beam and column nonlinear behavior, rotational springs, adjacent to the joint core, were also assigned based on lumped plasticity approach [65]. For a comprehensive nonlinear analysis, distinct behavior i.e. shear and flexural behavior of beam and column elements should be taken into account. As in an RC beam/column, the shear capacity tends to reduce when the inelastic flexural deformation increases. Thus, the definition of the interaction between flexural and shear capacities is required to determine the characteristics of beam and column rotational springs. After which, the total response of the beam-column joint, in terms of load versus displacement curve, can be calculated by summing up the displacement contribution of each element for an applied load stage. While the contribution of each element in joint response is evaluated depending on the boundary conditions, other elements are assumed to behave as rigid elements (see Fig. 2).

3. Flexural and shear behavior of beam and column elements

This section addresses the calculation of moment versus rotation relation of beam/column rotational spring. To determine flexural capacity of an RC beam/column, the moment-curvature analysis of cross-section can give useful information. After which, it can be converted into the flexural moment-rotation relation based on the plastic hinge method recommended by Priestley et al. [65] to be assigned to the rotational springs. Accordingly, the rotation, θ_i, corresponding to curvature, φ_i, can be calculated as:

for column element (Fig. 2(c))

$$\theta_i = \frac{\varphi_i L_{eff}}{2} \quad \text{for } \varphi_i \leqslant \varphi_y \tag{1a}$$

$$\theta_i = \theta_y + (\varphi_i - \varphi_y) L_p \quad \text{for } \varphi_i > \varphi_y \tag{1b}$$

for beam element (Fig. 2(d))

$$\theta_i = \frac{\varphi_i L_{eff}}{3} \quad \text{for } \varphi_i \leqslant \varphi_y \tag{2a}$$

$$\theta_i = \theta_y + (\varphi_i - \varphi_y)\left(L_p - \frac{L_p^2}{2L_{eff}}\right) \quad \text{for } \varphi_i > \varphi_y \tag{2b}$$

in which (Paulay and Priestley [66])

$$L_p = 0.08L + 0.022 f_y d_b \geqslant 0.044 f_y d_b \text{ (Paulay and Priestley[66])} \tag{3}$$

$$L_{eff} = L + 0.022 f_y d_b \tag{4}$$

where φ_y, φ_u, θ_y are defined as the yield curvature, ultimate curvature and yield rotation, respectively; L_{sp} and L_p are the strain penetration length and the plastic hinge length, respectively. f_y is the yield stress of longitudinal reinforcement; d_b is the diameter of the longitudinal reinforcements. L is the shear span (distance from maximum moment section to inflection point). Using the aforementioned equations, the flexural characteristics of beam/column rotational springs can be obtained.

One of the most severe deficiencies in existing RC structures which makes them vulnerable to earthquakes might be inadequate column shear capacity resulting in brittle shear failure, and subsequently, shear-