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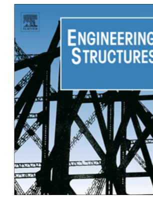

Performance of reinforced concrete columns under bi-axial lateral force/displacement and axial load

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ABSTRACT

Accurate and realistic assessment of the performance of columns in general and those in critical locations that may cause progressive failure of the entire structure, in particular, is significantly important. This performance is affected by the load history, pattern and intensity. Current design code does not consider the effect of load pattern on the load and displacement capacity of columns. In the study reported here, monotonic material models, cyclic rule, and plastic hinge models have been utilized in a fiber-based analytical procedure, validated against experimental data. Comparison of the analytical predictions and experimental data, through moment–curvature and force–deflection analyses, confirmed the accuracy and validity of the analytical algorithm and models. The analytical model was then used in a parametric study considering the effects of axial load variation and lateral force/displacement paths on the flexural strength and energy dissipation capacity of reinforced concrete columns.

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1. Introduction

Columns are structural elements transmitting beam and slab loads to lower floors and foundation of buildings. Because column failure in critical locations causes progressive failure of the floor and, eventually, the entire structure, significant care must be taken to design and construct columns [1]. The behavior of reinforced concrete (RC) columns under seismic loading is considered a significantly important research topic for structures located in earthquake-prone regions [1,2]. During an earthquake, structures are subjected to vertical P-waves bumped from below, sideways shearing motions caused by S-waves, and rolling surface waves. Therefore, earthquake motion is comprised of two horizontal perpendicular components and one vertical component. The columns located at the corners of slabs experience axial force and cyclic bi-axial lateral forces, even by assuming seismic motion in only one principle direction.

Many experimental and analytical studies have been conducted to capture RC columns behavior under cyclic loadings. However, a majority of these studies have focused on the behavior of RC columns under reversed cyclic uniaxial lateral force/displacement [3–10], and only a few studies have taken bi-axial lateral forces into account [11–18]. As reported by Rodrigues et al. in Ref. [2], during the last thirty years, 453 columns were tested under cyclic loadings, but only 12% of them were tested under bi-axial cyclic loading conditions, let alone the independent variation of axial load that has its prominent effect on the flexural performance. Almost all previous experimental results have confirmed that degradation of capacity and flexibility is higher in columns under cyclic bi-axial lateral loadings condition compared to those under uniaxial lateral loading.

RC columns performance under seismic loads depends on the level of axial force, lateral and longitudinal reinforcement characteristics, geometry of cross section, material properties of concrete and steel, and loading or displacement pattern. Since, the empirical assessment of these parameters is expensive, analytical modeling of cyclic behavior of concrete, if reasonably accurate, can be an alternative to assess the behavior of RC columns.

The primary objective of this study was to develop a simple, yet reasonably accurate analytical tool to predict the nonlinear monotonic and cyclic response of RC columns under independently variable bi-axial and uniaxial lateral forces/displacements and axial load. Accuracy of the analytical procedure was validated against experimental data through uniaxial moment–curvature, uniaxial force–deflection, and bi-axial force–deflection analyses. Using the validated analytical model, a parametric study was conducted on the effect of loading path (curvature/displacement) and axial force level on the flexural strength, ductility, and energy dissipation capacity of RC columns.

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2. Fiber-based model

To assess the performance of RC columns behavior under various loading scenarios, a computer application was developed for nonlinear analysis of RC columns under uniaxial lateral forces/displacements and axial loading. Functionalities of this computer application have been explained in detail in Ref. [19]. The analytical procedure and related program reported here, expands the capabilities of aforesaid program to include independent variation of bi-axial force or displacement under any pattern of axial load.

A typical RC column was simulated using nonlinear fiber-based model in which a cross section of an RC column is divided into a number of fibers, including confined concrete fibers located at the section core enclosed by the lateral reinforcement, plain concrete fibers located at the section cover, and longitudinal steel fibers. The fiber-based model has been effectively used by other researchers to simulate the flexural behavior of RC columns [9,20]. Fig. 1 is an example of fiber representation of a square cross section, with triangular mesh [21].

For columns with conventional geometry, the deformation compatibility is considered by the classical Bernoulli–Euler rule of plane sections remaining plane after deformation. Each fiber is assigned to the proper monotonic stress–strain model in which the confining effects are considered when applicable, as well as the cyclic rules for hysteretic performance.

In the present study, Mander et al.'s model [22] was employed to model uniaxial behavior of concrete fibers confined by tie in compression. This model can be used to model normal-weight concrete in circular and rectangular sections confined by spiral, circular, or rectangular tie with or without cross ties. The uniaxial monotonic behavior of unconfined (plain) concrete fibers was modeled using Mander et al.'s model [22]. The equation related to the first part of this model for plain concrete is identical to the equation used for confined concrete by assuming zero lateral pressure; the second part is a line connecting strengths corresponding to a strain of $2 \times \varepsilon_{c0}$ (ε_{c0} is axial strain in unconfined concrete corresponding to maximum compressive stress of plain concrete) and the point of concrete spalling (ε_{csp}) with zero strength. The tensile behavior of confined and unconfined concrete fibers was modeled by a linear stress–strain relationship with a slope equal to the modulus of elasticity of the plain concrete. A fiber will lose its tensile or compressive strength after the first failure in tension or compression. Note that the tensile strength of concrete is generally less than 20% of the compressive strength and it can be obtained experimentally using a tension test or a split-cylinder test. In addition, a bending test of a plain concrete beam can be used to obtain the tensile strength of concrete, known as the modulus of rupture. When experimental data is not available, the tensile strength of concrete is commonly calculated using the equation $f_r = 0.7\sqrt{f'_{c0}}$ (MPa), proposed by American Concrete Institute (ACI) [23]. It has been a common practice to consider the tensile strength of plain concrete, for which there is no direct experimental value, around 10% of the standard compressive strength. Cyclic behavior of confined and unconfined concrete fibers was assumed to be linear with a slope equal to the modulus of elasticity of the plain concrete. The effect of lateral reinforcement was taken into account by using the proper stress–strain model for concrete confined by the lateral reinforcement, namely stirrups. Monotonic and hysteretic stress–strain relationships of confined and plain concrete fibers are shown in Fig. 2.

To model uniaxial monotonic behavior of longitudinal steel bars, four models were assessed: idealized bi-linear model, Menegotto–Pinto's model [24], Esmaeily's model [9,25] and Mander et al.'s model [24] (Fig. 3). These models were selected because of their widespread usage and numerical stability.

The initial line in the idealized bi-linear curve has a slope equal to the steel modulus of elasticity (E_s), followed by the second line with a specific slope in which it is calculated considering fracture strength (f_{sf}) and fracture strain (ε_{sf}) of steel material. The Menegotto–Pinto model [24] has a bi-linear backbone curve, and

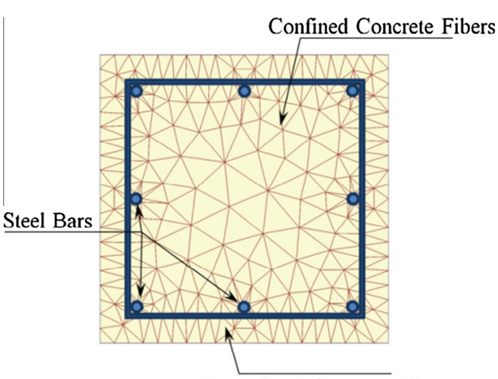

Fig. 1. Fiber representation of a square cross section.

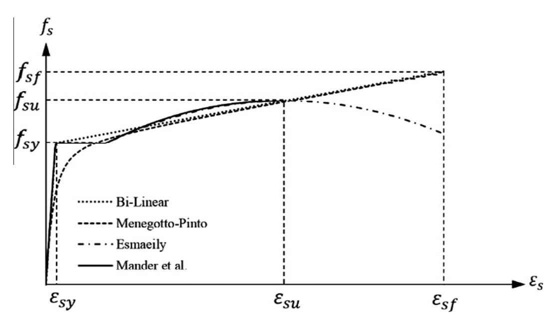

Fig. 3. Uniaxial monotonic stress–strain models for longitudinal steel.

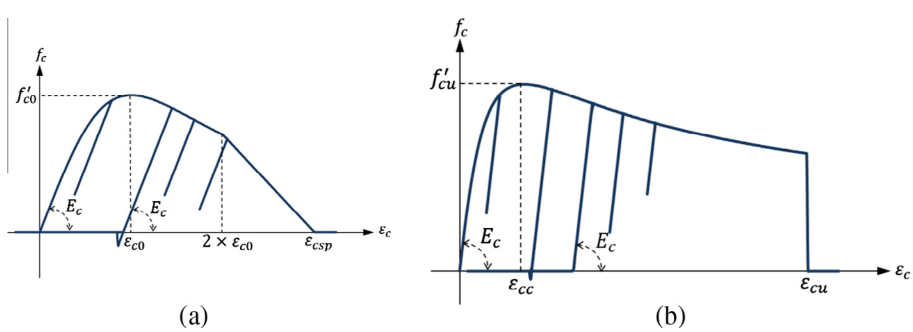

Fig. 2. Monotonic and hysteretic stress–strain relation of (a) plain, and (b) confined concrete fibers.