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ORIGINAL ARTICLE

A new beam-column model for seismic analysis of RC frames – Part I: Model derivation

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Abstract In this study, a reliable and computationally efficient beam-column model is proposed for seismic analysis of Reinforced Concrete (RC) frames. The model is a simplified version of the Flexibility-Based Fiber Models (FBFMs), which rely on dividing the element length into small segments and dividing the cross section of each segment into concrete and steel fibers. In the proposed model, only the two end sections are subdivided into fibers and uniaxial material models that consider the various behavioral characteristics of steel and concrete under cyclic loading conditions are assigned for the cross section fibers.

The proposed model is simpler than the FBFMs as it does not require monitoring the responses of many segments along the element length, which results in a significant reduction in computations. The inelastic lengths at the ends of the proposed model are divided into two inelastic zones; cracking and yielding. The inelastic lengths vary according to the loading history and are calculated in every load increment. The overall response of the RC member is estimated using preset flexibility distribution functions along the element length. A flexibility factor η is utilized to facilitate selecting the proper flexibility distribution shape. The proposed model is implemented into the computer program DRAIN-2DX.

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1. Introduction

Intense research has been dedicated in the last few decades to the development of beam-column models to predict the inelastic seismic response of RC frame structures with a reasonable balance between accuracy and efficiency. Improving the accuracy of beam-column models often increases their computational demands and may reduce their efficiency. Seismic evaluation of frame structures often requires repeated solutions of the response of multi-degrees of freedom systems. The computations involved in such evaluation can become excessive and simplicity of the modeling approach may be an important issue to accomplish the analysis in a reasonable time.

Beam-column models can be represented using two main modeling approaches in accordance with the increasing level of complexity. The first is global modeling, where each RC member is modeled as one element and the second is microscopic modeling, where the members are divided into a large number of finite elements.

Microscopic modeling is suitable only for studying critical regions, since it is computationally expensive for the seismic analysis of multi-story frames. Global modeling, on the other hand, represents the best compromise between simplicity and accuracy as it provides a considerable information on the seismic inelastic response of frame structures in a reasonable time.

Global beam-column models, which are the focus of this study, can be divided into two types: (a) Lumped Plasticity Models (LPMs), and (b) Distributed Plasticity Models (DPMs). LPMs rely on the fact that the inelasticity of the RC frames under seismic excitation often concentrates at the member ends. Thus, an early approach to model this behavior was by means of zero length plastic hinges in the form of non-linear springs located at the member ends. The hysteretic force–deformation relations of these end springs are usually based on phenomenological rules. Examples of the LPMs include the two-component model of Clough et al. [1] and the one-component model of Giberson [2].

The two-component model consists of two components acting in parallel. The first component is linear elastic to represent strain-hardening, while the second component is elastic perfectly plastic to represent the plastic deformations concentrated in plastic hinges at the element ends. The one-component model, on the other hand, consists of two non-linear rotational springs attached in series at the ends of an elastic element. This model is more popular than the two-component model because of its simplicity as well as its ability of describing more complex hysteretic behavior by the selection of proper moment–rotation relations for the end springs.

Several hysteretic rules with empirical control parameters are proposed to describe the moment–rotation relationships of the non-linear springs. Examples of these rules include Takeda et al. [3], Park et al. [4] and Otani [5]. Typically, these hysteretic rules are based on experimental data obtained by testing of RC sub-assemblages.

A third type of LPMs is the fiber hinge model [6,7], which relies on using inelastic zero-length hinge element at each end of the RC member. The hinge element consists of a number of axial springs that represent the force–displacement relations of the reinforcing steel and the concrete. This approach is capable of simulating the axial–flexural interaction in RC members in a more rational way than the one- and the two component models.

The basic advantage of the LPMs is their simplicity that reduces computations and storage requirements along with improving the numerical stability. However, most LPMs oversimplify certain important aspects of the cyclic behavior of RC members such as the post-yield response and the axial–flexural interaction which could produce inaccurate results. Moreover, the use empirical control parameters in the LPMs limits their generality as the values of these parameters are usually selected by trail and error to produce model response that fit with experimental results of a limited number of RC components.

In the DPMs, material non-linearity can take place at any section along the length of the RC member and the element behavior is derived by integrating the section responses. This results in a more accurate description of the inelastic behavior of RC members. DPMs can be classified into two types, namely, curvature spring models and fiber models.

Curvature spring models include the model proposed by Meyer et al. [8] and later modified by Roufaiel and Meyer [9]. In this model, two springs are considered at the member ends to represent the moment–curvature relations of the end sections. The monotonic moment–curvature relation is derived with ignoring the concrete tensile strength. The hysteretic response is based on phenomenological rules that account for the behavioral characteristics of RC members under cyclic loading. The inelastic lengths at member ends are calculated in every load increment based on the assumption of linear distribution of bending moments along the element length. The element response is determined by assuming a uniform distribution of flexibility along the lengths of the plastic zones.

Another example of the curvature spring models is the model proposed by Park et al. [10]. In this model, the monotonic moment–curvature relationship is derived with considering the concrete tensile strength, while the element response is determined by assuming a linear distribution of flexibility along the lengths of the inelastic zones. The main limitations of the curvature spring models are in oversimplifying the axial–flexural interaction and the flexibility distribution along the plastic hinge regions.

Fig. 1 shows a member idealization in the fiber models, where the element is subdivided into segments distributed along the member length, and the cross section of each segment is subdivided into steel and concrete fibers. The section response is determined by integrating the uniaxial stress–strain relations of the fibers. In practice, only the behavior of a limited number of segments at each end of the member is monitored. Two types formulations are used in the fiber models, the first is displacement-based (stiffness-based) and requires a predefined displacement shape-function to interpolate the displacements along the element length with respect to the nodal displacements and the second is force-based (flexibility-based) and requires using interpolation functions to estimate the forces along the element length with respect to the nodal forces.

Taucer et al. [11] stated that the most promising models for non-linear analysis of RC members are the flexibility based fiber models. Several Flexibility-Based Fiber Models are proposed for seismic analysis of RC members. Examples of theses models include, Kaba and Mahin [12] and Taucer et al. [11]. The only limitation associated with the fiber approach when used for modeling of RC frame members is the substantial amount of computations required for monitoring the responses of several cross sections along the element length and the responses of several fibers over each cross section. On

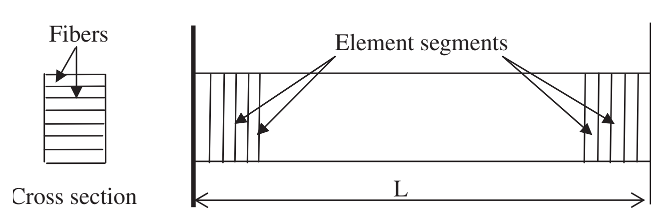

Figure 1 The fiber beam-column model.