Engineering Structures 173 (2018) 892–907

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Computationally effective and accurate simulation of cyclic behaviour of old reinforced concrete columns

Chang Seok Lee, Sang Whan Han*

*Department of Architectural Engineering, Hanyang University, Seoul 04763, Republic of Korea*

ARTICLE INFO

*Keywords:*
Shear critical
Pinching
Deterioration
Cyclic behaviour
Analytical model

ABSTRACT

To evaluate the seismic performance of existing old reinforced concrete (RC) buildings, it is important to use an accurate analytical model. Most columns in these buildings do not satisfy the reinforcement details specified by current seismic design provisions. Columns that possess insufficient reinforcement details can exhibit significant pinching and cyclic deterioration in their strength and stiffness. They can also experience flexure-shear and shear failure during large earthquakes. The objective of this study is to simulate the cyclic behaviour of old RC columns accurately and efficiently with the Pinching4 model considering pinching and cyclic deterioration. Modelling parameters are calibrated based on the test results of 40 collected flexure-shear and shear critical columns. Columns failed by other failure modes rather than shear and flexure-shear failure are not considered in this study. Forward stepwise regression analyses are conducted to determine statistically significant variables from 34 candidate predictor variables and to propose the empirical equations of the modelling parameters. It is shown that the Pinching4 model with the proposed empirical equations accurately simulates the cyclic behaviour of both flexure-shear and shear-critical columns including pinching and cyclic deterioration in strength and stiffness.

## 1. Introduction

Reinforced concrete (RC) buildings designed and built before modern seismic codes were adopted are susceptible to major damage or collapse during an earthquake. Among the components of existing old RC buildings constructed prior to the adoption of seismic design provisions (pre-1970s), columns are often the most critical component [1]. Old RC columns tend to have widely-spaced transverse reinforcements that do not use 135° seismic hooks and longitudinal reinforcements with short development length [2–6]. In particular, these columns are vulnerable to shear failure, which can lead to a rapid reduction in the lateral strength of structures and an acceleration of the side-sway instability of the entire structure [7,8].

To identify the damage potential in old RC columns and establish adequate retrofitting schemes, it is important to use an accurate analytical model of the RC columns. The model should properly account for in-cycle and cyclic deteriorations in strength and stiffness as well as pinching behaviour, which are typically observed in the cyclic behaviour of old RC columns during experiments.

Recently, nonlinear hysteretic models incorporating cyclic deterioration and pinching behaviour have been developed [8–10]. Ibarra et al. [10] implemented cyclic deterioration based on total accumulated energy-based damage index model (IMK model). Lowes and Altoontash [9] proposed a hysteretic model consisting of quad-linear backbone and energy- and displacement-based deteriorating rules for strength and stiffness. Lignos and Krawinkler [8] modified the IMK model by implementing asymmetric backbone and hysteretic rules.

For these analytical models, it is important to accurately estimate constituent parameters of backbone curve, cyclic deterioration and pinching [10]. Unless model parameters are accurately estimated, the actual cyclic behaviour of old RC columns cannot be reliably simulated using analytical models. Modelling parameters are strongly affected by geometric and material properties of the RC column. For ductile steel moment connections [8] and reinforced concrete components dominated mostly by flexure [11], empirical equations for estimating the parameters of cyclic deterioration and pinching were proposed with respect to the column geometry variables and material properties. Only a few studies have been conducted to develop empirical equations that relate the design parameters (geometric and material properties) and modelling parameters (backbone, cyclic deterioration, and pinching) for old RC columns dominated by shear and flexure-shear.

The purpose of this study is to simulate the cyclic behaviour of flexure-shear and shear-critical columns in old existing RC buildings including pinching and cyclic deteriorations in strength and stiffness.

* Corresponding author.
*E-mail address:* swhan82@gmail.com (S.W. Han).

https://doi.org/10.1016/j.engstruct.2018.07.020
Received 28 December 2017; Received in revised form 5 July 2018; Accepted 6 July 2018
0141-0296/ 

Engineering Structures 173 (2018) 892–907

An improved numerical model has been proposed to simulate the cyclic behaviour of old RC columns considering all the peculiar properties of old RC columns: pinching and cyclic deteriorations in strength and stiffness.

The paper is organized as follows. Section 2 summarizes the existing analytical models of RC columns, Section 3 introduces the proposed analytical model for RC columns and the RC column database used to propose the empirical equations of modelling parameters. Section 4 describes the modelling parameters of the Pinching4 model. In Section 5, empirical equations are proposed to calculate the modelling parameters. In Section 6, the accuracy of the proposed model is validated.

## 2. Summary of existing analytical models for simulating cyclic behaviour of old RC columns

To simulate the seismic behaviour of RC columns, various analytical models have been developed. Elwood [12] proposed a model that was capable of accurately predicting the shear failure of old RC columns, which was defined at a displacement when their shear strength decreased by 20%. In this model, flexure and shear responses are simulated by using fibre section elements and an elastic shear spring element, respectively (Table 1a). In this model, as the lateral drift of a column reaches a specified limiting value, the lateral strength of the elastic shear spring is enforced to decrease (in-cycle strength deterioration) to simulate the shear failure mechanism. However, pinching and cyclic deteriorations in the strength and stiffness were not considered.

Haselton et al. [11] proposed a model based on an elastic element with lumped plastic hinges (Table 1b). A nonlinear zero-length rotation spring element [10] was used for the lumped plastic hinges. The rotational spring was controlled by a trilinear backbone curve and accounted for the cyclic strength deterioration. However, the cyclic stiffness deterioration and pinching were not considered in the model because this model was developed for flexure-critical columns.

LeBorgne and Ghannoum [13] proposed a rotation-based shear spring element as shown in Table 1c. It was observed from shaking table tests that shear failure occurred in old RC columns when the maximum inelastic rotation reached a critical value [14,15], indicating that shear failure can be more accurately represented by using rotational-based shear spring element than using lateral drift-based shear spring element. The model in Table 1c was also capable of incorporating pinching and cyclic strength deterioration. Additional fibre-section elements were added in the model to prevent strain localization, and one fibre-section-based zero-length element was also included to simulate bond-slip response.

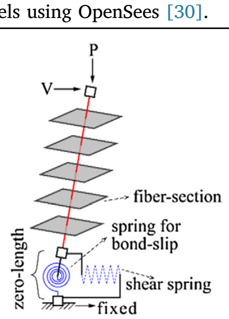
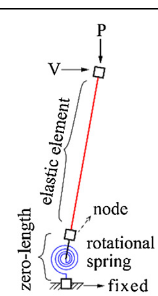
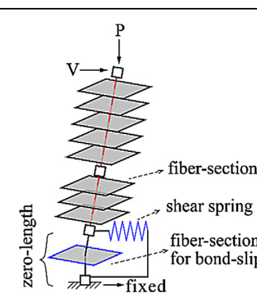
Several studies [16–19] predicted the force-deformation response of RC elements using the Bouc-Wen model. However, a major shortcoming of the Bouc-Wen model is that there are many modelling parameters to be identified. The parameter identification of Bouc-Wen hysteretic systems is a challenging task due to its highly nonlinear nature [20]. Optimization schemes are often adopted to identify the modelling parameters than may produce non-unique solutions.

Many rational models exist [12,21–28] that can separately predict the contributions of flexure, bond slip and shear responses and simulate cyclic strength deterioration due to these contributions. As shown in Table 1a and c, the effect of bond slip due to strain penetration was incorporated into the model either by implementing additional zero-length rotation spring [12] or by additional zero-length fibre-section [13]. However, it is difficult to determine the property of these spring elements because it is a difficult task to extract the bond slip response from column tests [29]. To avoid such difficulties, a single lumped rotational spring element [11] can be used without installing independent spring elements representing the individual components of column responses. Sezen and Chowdhury [29] also pointed out that none of separate spring models were verified for their accuracy by using separated response components extracted from column tests.

The coefficient of determination ($R^2$) of existing empirical equations predicting modelling parameters for old RC columns is generally low, which ranges from 0.4 to 0.7 due to the variability in cyclic behaviour of old RC columns. In the case of models using fibre-section element [12,13], analytical results can be affected by the number of fibre sections, and stress-strain rules used for reinforcement and concrete. Strain localization is also a problem for fibre-section model when a material model incorporating strain softening is used. To resolve strain localization problem, concrete was modelled to hold its strength after attaining its peak strength [12], which may not be a realistic assumption. As shown in Table 1c, LeBorgne and Ghannoum [13] placed an additional fibre element in the plastic hinge region to solve strain localization problem. However, an addition of fibre elements can increase computation significantly and cause numerical convergence problem. Analytical model proposed by Haselton et al. [11] is simple and requires the least computation among the models in Table 1. Numerical convergence problem in softening branch is rare when using this model, compared to other models in Table 1. However, Haselton et al. [11] developed empirical equations for model parameters for RC columns mainly controlled by flexure.

In the present study, the cyclic responses are simulated for old RC columns governed mainly by shear and flexure-shear. For this purpose, an elastic element with lumped plastic hinges (zero-length nonlinear rotation spring elements) are used as a basis model, as shown in Table 1b. Since this model has a simple arrangement with a spring element and an elastic element, the cyclic responses of the columns can be simulated efficiently via computation without losing convergence. In addition, the rotation spring element used in the present study can

**Table 1**
Summary of existing RC column models using OpenSees [30].

| Models | <br>(a) Model EL | <br>(b) Model HT, PR | <br>(c) Model L-G |
|---|---|---|---|
| Considered failure types | Flexure-shear | Flexure, flexure-shear | Shear, flexure-shear |
| Considered deteriorations | In-cycle strength deterioration | Strength deterioration | Strength deterioration, pinching |
| Reference | Elwood [12] | Haselton et al. [11] and the present study | LeBorgne and Ghannoum [13] |