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Equivalent damping ratio model of flexure-shear critical RC columns

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ABSTRACT

To describe the hysteretic behavior of flexure-shear critical reinforced concrete (RC) columns realistically, a hysteretic loop expression of flexure-shear critical RC columns under complete cyclic loading is proposed by investigating the characteristics of column specimens in PEER - Column Database. For the proposed expression, important characteristics of flexure-shear critical RC columns under cyclic loading, including pinching and stiffness degradation, are covered. And then, an equivalent damping ratio model suitable for flexure-shear critical RC columns is proposed by using the proposed hysteretic loop expression based on the Jacobsen's approach. The relationship between the equivalent damping ratio formula of two-column pier supported bridge and that of its columns is developed based on the energy dissipation capacity. A design example is provided to illustrate the application of the proposed model.

1. Introduction

Performance-based design concept has been well established to meet the objective of decreasing the damage losses due to earthquakes. Performance levels are generally described in terms of displacements, as previous seismic investigations have indicated that damage is more related to the relative displacement [1]. The most important parameter in displacement-based design is the inelastic displacement demand computed under a given seismic effect. Due to the fact that structures in seismic regions are designed to respond inelastically, and current seismic design practice is predominantly based on the use of elastic acceleration response spectrum, approaches for approximating the inelastic seismic demand by linearizing the nonlinear system from the elastic acceleration response spectrum gain primary importance [1–3]. Currently, two main approaches have been developed for this approximation: the R-factor approach [4–7] and the equivalent linear system (ELS) approach [3,8–10]. In the R-factor approach, the difference between inelastic and elastic responses is characterized by a single parameter R. In the ELS approach, the inelastic behavior is considered by two parameters: equivalent period T_{eff} and equivalent damping ratio ζ_{eff}.

Equivalent damping ratio was first proposed by Jacobsen in the equivalent linearization concept [11,12]. Thereafter, extensive research has been conducted to study this concept [13–23]. Until now, there have been multiple references reporting different equivalent damping ratio models [24–28]. Some are based on Jacobsen's approach [14,15], some on the substitute damping approach [16–18] and others on results of time history analyses.

Jacobsen approach, as the most commonly used procedure to estimate the equivalent viscous damping, estimates this factor based on the ratio between the elastic stored energy and the dissipated energy by a given hysteretic model [24]. In the general case, where different structural elements with different strengths and damping factors contribute to the seismic resistance of structures, the global damping of the whole structures can be estimated based on the energy dissipated by the different structural elements. In view of this, many available equivalent damping ratio models of RC members were proposed by researchers based on Jacobsen's approach in the previous studies. Obviously, in Jacobsen's approach, the equivalent damping ratio is mostly dependent on the hysteretic model, that is, the more realistic the hysteretic model adopted to describe the hysteretic behavior, the more reliable the obtained equivalent viscous damping model. Many hysteretic models (such as bilinear and Takeda) were used to develop equivalent damping ratio models, but most of these hysteretic models were originally developed based on experimental results of flexure critical RC members.

Observations of damage after earthquakes and experimental research have indicated that some columns may exhibit a rather complex failure mode: yielding in flexure then failing in shear due to the drop of shear capacity caused by shear-flexure interaction (referred to as flexure-shear critical columns) [29–38]. For flexure-shear critical RC columns, both flexure and shear mechanisms have different contributions to the response of columns.

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After flexural yielding, the action of shear force at plastic hinge region produces diagonal tension cracks to spread the zone of steel yielding further along the member. At the same time, shear forces induce an important deterioration of lateral stiffness and shear strength during crack closure and bond deteriorations, which consequently lead to a pinched load-deformation curve. Obviously, the equivalent damping ratio models developed based on the hysteretic model of flexure critical RC columns are not suitable for flexure-shear critical RC columns duo to the pinching behavior and poor energy dissipation. Therefore, it is necessary to develop an equivalent damping ratio model for flexure-shear critical RC columns.

To describe the hysteretic behavior of flexure-shear critical RC members, several smooth hysteretic models can be adopted [39–43]. Bouc-Wen hysteretic model [43], a differential model, has been one of the most widely accepted phenomenological models of hysteresis in mechanics. In this model, the restoring force and deformation were connected through a nonlinear differential equation containing many unspecified parameters. The generalized Bouc-Wen differential model, which can take account of strength degradation, stiffness degradation, and pinching characteristics of an inelastic structure, even contains 13 parameters. Although this hysteretic model can be used to describe the hysteresis curves with different characteristics by choosing the parameters suitably, it is very difficult to get an analytical solution of the nonlinear differential equation as required for the purpose of this paper.

In this study, an analytical expression of smooth hysteretic loop, which can predict the experimental results of flexure-shear critical columns well, and is convenient for the derivation of equivalent viscous damping, is proposed. Using the proposed hysteretic loop expression, an element-level equivalent damping ratio model is derived based on Jacobsen's concept. Then, a two-column pier supported RC bridge is taken as an example to show how the proposed element-level model is used in structural analysis.

2. Equivalent damping ratio concepts

The damping that occurs when earthquake ground motion drives the structure into inelastic range can be viewed as a combination of viscous damping and hysteretic damping [44], that is

$$\zeta_{\mathrm{eff}} = \zeta_{\mathrm{c}} + \zeta_{\mathrm{hys}} \tag{1}$$

where ζ_{eff} is the total equivalent damping; ζ_{hys} is the equivalent viscous damping; and ζ_{c} is the elastic viscous damping inherent in the structure. The characterization of elastic viscous damping ζ_{c} has been investigated by Priestley and Grant [45]. Analyses in Ref. [45] indicate that although it has been more common in the past to use a 5% initial elastic damping, tangent-stiffness proportional viscous damping is a more realistic assumption for inelastic systems, and the necessary correction factor is significant if the elastic viscous damping coefficient is assumed to be constant in equivalent linearization of structural response. Considering that a 5% elastic damping has been adopted in many current codes, such as ATC 40, and the aim of this study is mainly to investigate the hysteretic damping ζ_{hys}, a value of 5% elastic viscous damping is used in calculation.

Jacobsen's approach assumes complete loops of hysteretic models under sinusoidal excitation (Fig. 1a). According to this concept, ζ_{hys} is determined by equating the hysteretic energy of the inelastic system to the damping energy of the equivalent linear system for one load-displacement cycle (Fig. 1). So, ζ_{hys} is calculated as

$$\zeta_{\mathrm{hys}} = \frac{1}{4\pi}\frac{E_{\mathrm{diss}}}{E_{\mathrm{sto}}} = \frac{1}{4\pi}\frac{E_{\mathrm{hys}}}{E_{\mathrm{ela}}} = \frac{1}{2\pi} \times \frac{S_{(B'AB+BEB')}}{S_{(OAF+OEG)}} \tag{2}$$

where E_{diss} and E_{sto} are the dissipated and stored energy in the system; E_{ela} is the elastic deformation energy of the system, calculated as the sum of triangle areas, $\Delta_{(OAF)}$ and $\Delta_{(OEG)}$ (as shown in Fig. 1c and d); and E_{hys} is the hysteretic energy dissipated in one cycle of the inelastic system (i.e., the area $S_{(B'AB+BEB')}$ enclosed by the hysteretic loop shown in Fig. 1c and d).

Based on Jacobsen's concept, several equivalent damping ratio models, such as Rosenblueth and Herrera's model [14] as well as Kowalsky's model [15], were developed by using the assumed symmetric polygonal hysteretic loops. In Ref. [42], an equivalent damping ratio model for flexure critical RC columns in column pier supported bridges was developed using the fitted smooth hysteretic loop (Fig. 1c), which was established based on the flexure critical columns in PEER - Column Database:

$$\zeta_{\mathrm{eff}} = \zeta_{\mathrm{c}} + \zeta_{\mathrm{hys}} = \zeta_{\mathrm{c}} + \frac{1}{\pi}\left[\frac{2\mu}{\gamma} - \left(\frac{\mu^2}{\gamma^2} - 1\right)\ln\left(\frac{\mu+\gamma}{\mu-\gamma}\right)\right] \tag{3}$$

where μ is the displacement ductility level, calculated as the ratio of the maximum displacement in hysteretic loops, Δ_1, to the yield displacement of specimens Δ_{y}; and $\gamma = 0.765(\mu - 1)^{1.074}$.

Different from flexure critical columns, flexure-shear critical columns are characterized by significant pinching and poor energy dissipation, as shown in Fig. 1d. The development of hysteretic loop expression and the derivation of equivalent damping ratio model for flexure-shear critical columns are presented in the following section.

3. Equivalent damping ratio model of flexure-shear critical columns

3.1. Development of hysteretic loop expressions

Typical hysteretic loop of columns failing in flexure-shear mode is shown in Fig. 1d or Fig. 2a. Hysteretic behavior of columns is affected by material properties, longitudinal steel ratio, transverse steel ratio, transverse hoop spacing/diameter, axial load ratio, shear stress in the column, and so on. In this study, the hysteretic loop is normalized with the yielding force and displacement on the primary curve, in order to eliminate or mitigate the effects of these factors. The normalized hysteretic loop is shown in Fig. 2b, where y-axis represents the ratio of lateral force P to yield force P_{y}, and x-axis represents the ratio of lateral displacement Δ to yield displacement Δ_{y}. P_{y} and Δ_{y} are determined based on the equal energy approach [46].

The longitudinal reinforcements in the two loading directions of RC columns are often designed to be identical, so the hysteretic loop is assumed to be symmetrical with respect to the origin point under symmetric reverse cyclic loading. To facilitate the development of hysteretic loop expression, semi-hysteretic loop, curve *ABCDE* in Fig 2b, is investigated. Points *A*, *B*, *C*, *D*, and *E* are five key points defined in the investigated semi-hysteretic loop curve (Fig. 2). Points A (x_1, y_1) and E $(-x_1, -y_1)$ are points with maximum absolute displacements in the positive and negative directions of hysteretic loop, and are also two symmetric points in the envelope curve of hysteretic curve about the origin of the coordinate system. Points B $(x_2, 0)$ and C $(0, -y_3)$ are the intersections of semi-hysteretic loop with x-axis and y-axis, respectively. Point D $(-x_2, -y_2)$ is the point in the semi-hysteretic loop with the same horizontal distance to y-axis with point B $(x_2, 0)$. Points B' $(-x_2, 0)$, C' $(0, y_3)$ and D' (x_2, y_2) are three symmetrical points with points *B*, *C*, and *D* about the origin of coordinate system for the other semi-hysteretic loop, respectively, as shown in Fig. 2b.

To get hysteretic loop expressions with similar forms, curve *ABCDE* is derived into three partially overlapped segments, *ABC*, *BCD* and *CDE*, which all pass through three key points in hysteretic