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Non-linear damping of FRP-confined damaged reinforced concrete columns

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ABSTRACT

Despite the dynamic property of FRP-confined damaged RC (FRP-C DRC) columns are gaining attention, no non-linear material damping of FRP-C DRC has hitherto been evaluated. In this paper, the hysteretic behavior of two tested FRP-C DRC circular columns was first simulated by the confinement model of FRP-C DRC. Through analyzing the energy dissipation of the FRP-C DRC circular columns under cyclic loading with the validated model, a six parameter stress-dependent damping model for FRP-C DRC circular columns was proposed. Based on the proposed damping model, the non-linear material damping and dynamic response of the FRP-C DRC circular columns were evaluated by an iterative numerical method. The calculated results show that when the columns vibrate at resonance, the loss factor of the FRP-C DRC circular columns increases with an increase of the columns' initial damage, and the increase of their non-linear damping effectively reduces the dynamic response of the FRP-C DRC circular columns.

1. Introduction

In recent years, Fiber Reinforced Polymers (FRP) as repairing materials has obtained a great application in civil engineering. With the development of the studies on the static behavior of FRP-confined damaged reinforced concrete (FRP-C DRC) structures, a number of researchers explored the dynamic behavior of FRP-C DRC members. Nevertheless, these dynamic analysis mainly focused on the issues of earthquake-resistant capacity [1,2] and the modal parameter estimation (see the modal testing in [3,4]) of FRP-C DRC members. In addition, these previous dynamic behavior analysis were conducted with constant damping ratio of concrete material. However, as an empirical fact, the damping indicates non-linear behavior, simply adopting the constant damping ratio will get smaller analytical results and make FRP-C DRC structure seismic design unreliable.

Damping is often utilized to suppress the vibration amplitude using various energy dissipation mechanisms, is an important factor in the solution of complex vibration problems. Despite the significance of damping, evaluation of damping is still quite primitive [5]. At present, since viscous and hysteretic damping models are well understood and most widely accepted in the description of dynamic behavior of reinforced concrete (RC) structures, and for simplicity in engineering calculation and analysis, both the viscous and hysteretic damping coefficients are generally defined as constant [6]. But by the evaluation of internal material damping experimentally, the damping depends upon many factors causing the non-linear property, such as displacement ductility, stress, and temperature. Lu et al. [7] observed that effective damping is influenced by the displacement ductility of RC frames, and deduced an effective damping ratio relationship based on their dynamic tests. Lazan's study on the damping of materials [8] shown that the damping is affected not only by the material quality but also the stress distribution, he established the relation between the damping and the bending stress of metal material. Following this idea, Newmark and Hall [9] focused their research on determining the damping, and found that the damping varies greatly with the difference of the working stress. Kume et al. [10] also proposed a similar method and presented a damping-stress diagram for a cantilever beam, assuming that the stress amplitude developed in the beam is applied to evaluate the loss factor for every natural frequency. About damping versus temperature, Audenino et al. [11] presented the theoretical relation between temperature increment and internal damping in metals through thermographic analysis and specific damping measurement.

For the material damping in civil engineering, existing dynamic analysis based on non-linear damping mainly focused on the metal material and reinforced concrete. Gounaris and Anifantis [12] proposed an auto-determination method for calculating the loss factor of a cantilever steel beam based on successive iterations. Liu et al. [6] obtained the non-linear relation of dissipation factor versus

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strain amplitude of high-damping alloy by experiment and applied it to the dynamics of elastic linkage mechanism. To study the dynamic behavior of RC structure with non-linear damping, Elmenshawi and Brown [13] and Vintzileou et al. [14] applied cyclic loadings at the top or at the midspan of RC specimens, and quantified the hysteretic damping of the specimens through studying hysteretic energy dissipation of each cycle. Crambuer et al. [15] considered damping in nonlinear time history analysis by identifying a local constitutive model in reverse three-point bending tests on RC beams, and numerical free vibration tests were conducted using the defined damping matrix. Wang and Li [16] applied stress-related damping model and viscous damping model to a RC frame structure respectively, and compared the dynamic response of two damping models.

At present, no non-linear damping models of FRP-C DRC material have hitherto been available, and very little is known about the application of non-linear damping to the dynamics of FRP-C DRC columns. Since there are still no clear agreements on evaluation and application of the non-linear damping of FRP-C DRC material, and the application of FRP-C DRC material has become more widespread in practical engineering, the studies on the damping properties and dynamic response of FRP-C DRC members with non-linear damping are required.

The purpose of this paper is to obtain the non-linear damping model of FRP-C DRC material and apply it to the dynamic analysis of FRP-C DRC columns. The damage simulation method will be presented first for one tested RC specimen to quantitatively predict initial damage levels of RC columns. Subsequently, the cyclic test data of two FRP-C DRC circular columns were numerically reproduced by the confinement model of FRP-C DRC and hysteretic module in the finite element procedure. Using the validated model, the calculations of the energy dissipation of FRP-C DRC circular columns are then carried out, and the non-linear damping formula of FRP-C DRC material is proposed by equaling the hysteretic damping coefficient and the loss factor of the material. Finally, based on the proposed damping equation, a numerically iterative scheme is developed for the computation of the non-linear damping and the dynamic response of FRP-C DRC circular columns.

2. Damage assessment of RC columns

This section presents a non-linear finite element method (FEM) and predicted initial damage indices for the hysteretic behavior simulation of FRP-C DRC columns, these will be required for the unit energy dissipation computation in Section 3.

2.1. Damage simulation in OpenSees

To study the effect of different initial damage on the damping of FRP-C DRC member, it is necessary to simulate the damage process mathematically to accurately predict the initial state of the damaged column before it is repaired with FRP. In this paper, the damage indicator D in terms of concrete compressive strain from reference [17] was selected to quantify the damage of RC members, which can be denoted as:

$$\begin{cases} D = 0 & 0 \leqslant \varepsilon \leqslant \varepsilon_{\mathrm{f}} \\ D = \frac{\varepsilon - \varepsilon_{\mathrm{f}}}{\varepsilon_{\mathrm{u}} - \varepsilon_{\mathrm{f}}} \frac{\varepsilon_{\mathrm{u}}}{\varepsilon} & \varepsilon_{\mathrm{f}} \leqslant \varepsilon \leqslant \varepsilon_{\mathrm{u}} \end{cases} \tag{1}$$

where ε is the concrete compressive strain, ε_{f} is the concrete compressive peak strain, and ε_{u} is the concrete compressive ultimate strain.

In this study, the above damage model was introduced into Open System for Earthquake Engineering Simulation (OpenSees), at every converged step, the element response was fed into the damage model, and the damage index at the element level was calculated directly from the strain at a Gauss integral calculus point. The recorded damage indices of overall elements were used for updating the constitutive parameters of the concrete by the elastic modulus reduction,

$$E_i^{\mathrm{d}} = (1 - D_i)E_i \quad i = 1 \sim n \tag{2}$$

where D_i is the damage index of the ith element, E_i and E_i^{d} are the elastic modulus of the ith undamaged concrete element and the effective elastic modulus of the ith damaged concrete element respectively.

To validate the accuracy of the above numerical method, one tested RC column subjected to monotonic loading conducted by Zhong [18] was taken as a calibration example. Dimensional and material details of the column can be found in Table 1. The RC specimen was modeled using the non-linear beam-column element of OpenSees and divided into 8 elements of equal length. Three integral points were set for every element, and the cross-section of the beam-column element consisted of core concrete, cover concrete and steel reinforcement. The constitutive model of Kent-Park [19] modified by Scott et al. [20] was selected as the backbone curve for the concrete material, and a constraint index K was introduced to improve the concrete strength and ductility of the core concrete. The steel bar was modeled by the non-linear model of Giuffre–Menegotto–Pinto [21], and with the value of 0.01 to account for the isotropic strain hardening. The experimental result was reproduced numerically by the above OpenSees non-linear FEA procedure, as shown in Fig. 1(a). One can see that the numerical result is in good agreement with the test result.

2.2. Predicted initial damage index

The unconfined column of Tao and Yu [22] explained in details in Section 3 is used here for the evaluation of the initial damage index. The circular column was subject to the lateral increasing loads until a 2% drift ratio occurred. Assuming that the damage recorded in the middle integral point section of every element was a uniform distribution within the entire unit. The damage progression of three elements near the column base throughout the load history (D_1, D_2, D_3) was calculated by the above validated OpenSees damage simulation program, as shown in Fig. 1(b). Three damage indices of the circular column base 0.18, 0.28, 0.38 corresponding to the drift ratios 0.25%, 0.29% and 0.37%, respectively, were

Table 1
Properties of column specimen of reference [18].

Source	Specimen	Axial load (kN)	b (mm)	h (mm)	L[a] (mm)	Longitudinal reinforcement	Stirrups	f'_{c0} (MPa)	f_y[b] (MPa)	f_{yh}[c] (MPa)	f_t[d] (MPa)	f_{th}[e] (MPa)
Zhong [18]	No. 3	180	200	200	1100	4Φ12	6@100	42.5	400	325	612	480

[a] L is the overall height of the columns.
[b] f_y is the longitudinal reinforcement yield strength.
[c] f_{yh} is the yield strength of stirrups.
[d] f_t is the longitudinal reinforcement tensile strength.
[e] f_{th} is the tensile strength of stirrups.