Engineering Structures 108 (2016) 113–133

Contents lists available at ScienceDirect

Engineering Structures

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

Inelastic displacement ratios of fully self-centering controlled rocking systems subjected to near-source pulse-like ground motions

Navid Rahgozar [a,*], Abdolreza S. Moghadam [b], Armin Aziminejad [a]

[a] Department of Structural Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

ARTICLE INFO

Article history:
Received 31 May 2015
Revised 4 November 2015
Accepted 9 November 2015
Available online 17 December 2015

Keywords:
Self-centering controlled rocking system
Inelastic displacement ratio
Near-field pulse-like ground motions
C_R spectra

ABSTRACT

Modern self-centering controlled rocking (SC-CR) systems are capable of reducing residual drift after severe earthquakes by swaying on their bases and concentrating damage in energy dissipation devices. The present research determines constant-strength (C_R) spectra for SC-CR systems subjected to far-field and near-field pulse-like (NF-pulse) ground motions. SC-CR systems are simulated as single degree of freedom models with a flag shape behavior. Nonlinear time-history analyses are conducted using 91 NF-pulse and 44 far-field records to derive the C_R spectra. Each point of C_R spectrum of a SC-CR system is the ratio of maximum inelastic to maximum elastic displacement. An extensive statistical study is carried out to examine the effects of ground motion and modeling parameters on the C_R spectra. It is found that the influences of pulse period, predominant period of ground motion, and modeling parameters on inelastic displacement ratios (C_R ratios) of SC-CR are significant, while other effects such as the source-to-site distance, earthquake magnitude, and site classes are not as much important. Finally, using two-stage regression analyses, formulas are developed for determining un-normalized (code-compliant) and normalized C_R spectra of SC-CR systems subjected to far-field and NF-pulse ground motions.

1. Introduction

Historical evidence from 1994 Northridge, California; 1995 Kobe, Japan and; 1999 Chi-Chi, Taiwan Earthquakes shows that near-fault ground motions cause severe damages to nearby structures. In near-field ground motions, when a fault ruptures toward the site at a velocity close to the shear wave velocity, there is a probability that considerable seismic energy can be released in a single large pulse of motion at the beginning of the velocity time history [1–3], which could lead to the imposition of higher seismic demands on structures compared with far-field ground motions and may cause intensive damages in conventional buildings, in which seismic energy dissipation mechanism occurs through the nonlinearity of primary elements.

This paper investigates the inelastic displacement responses of new self-centering controlled rocking (SC-CR) systems subjected to near-field ground motions in comparison with the far-field ones. SC-CR systems have an intrinsic ability to reduce seismic losses compared with the conventional systems by features such as rocking, self-centering, directing, and concentrating damage. The efficiency of rocking mechanism to reduce damage in pure rocking blocks was first studied by Housner [4] and has been recently confirmed for SC-CR systems. Controlled rocking concrete walls [5–12], self-centering concentrically steel braced frames [13–20], and self-centering timber systems [21,22] are samples of the SC-CR systems, which consist of pre-tensioned (PT) strands and energy-dissipating devices (ED).

Fig. 1 shows an example of steel SC-CR system and its behavior under only one cycle of loading. Fig. 1(a) demonstrates hysteretic curves of PT and ED elements. PT strands provide restoring forces and EDs concentrate damage through such devices as friction dampers [23,24], yielding fuses [25,26] or viscous dampers [27]. Fig. 1(b) shows a flag-shaped hysteretic curve as the key characteristic of SC-CR system, which is the combination of PT and ED behaviors. As shown, the hysteretic curve consists of three main branches: the first branch with an initial stiffness of K_{OA} is linear elastic that terminates at the SC-CR system to initiate an uplift (Point A; corresponding to uplift strength (V_{up}) and uplift drift (δ_{up}) values); then there is a hardening branch with the stiffness of K_{AB} to the system yielding point (Point B; corresponding to yield strength (V_y) and yield drift (δ_y) values). The yielding point is the beginning of post-yield hardening branch with the hardening ratio of α. At the unloading phase, the SC-CR system dissipates input seismic energy through flag-shaped hysteresis loop quantified as β that is an index

* Corresponding author.
E-mail address: n.rahgozar@srbiau.ac.ir (N. Rahgozar).
URL: http://srbiau.ac.ir (N. Rahgozar).

http://dx.doi.org/10.1016/j.engstruct.2015.11.030
0141-0296/

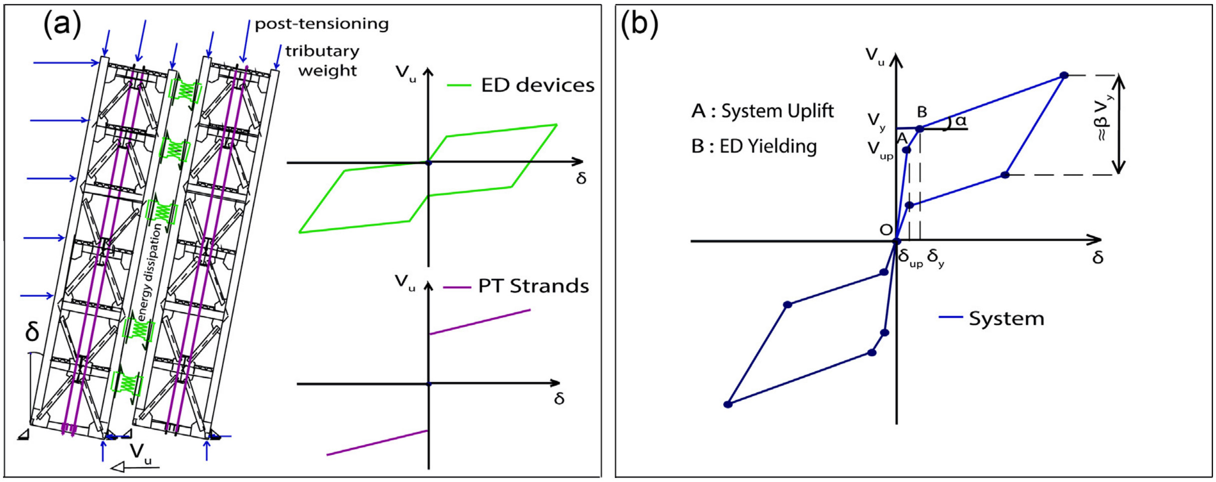

Fig. 1. (a) Example of steel SC-CR system and hysteretic curves of ED and PT elements; (b) Ideal flag-shape behavior of a SC-CR system.

to compare the energy dissipating ability of different self-centering systems. The energy-dissipating ratios equaling 0% and 100% are lower and upper bounds of energy dissipation capacity of SC-CR systems, respectively. Unbound PT precast concrete wall and steel self-centering frame with yielding fuses are examples of SC-CR systems without ($\beta = 0$) and with ($\beta > 0$) hysteretic energy dissipation capacity, respectively. It is worth noting that the initial stiffness (K_{OA}) and post-yielding stiffness (K_{AB}) of the SC-CR system are typically close to each other [28].

This paper introduces new formulas for determining constant-strength inelastic displacement spectra of SC-CR systems. Although several analytical studies have been focused on evaluating the inelastic displacement demands of SC-CR systems, they are only limited to constant-ductility of rocking systems subjected to far-field earthquake ground motions. However, to examine the displacement demands of the SC-CR systems subjected to near-field ground motions, there is a need to determine the C_R spectra of the SC-CR systems under near-field records. For this purpose, the main objective of this paper is to obtain C_R equations for the SDOF SC-CR systems subjected to near-field pulse-like (NF-pulse) compared with far-field records. In the following parts of this paper, first the literature on inelastic displacement ratio is reviewed. Then the considered SC-CR systems are introduced and nonlinear time history analyses (NTHA) are conducted using NF-pulse and far-field record sets. Finally, based on results of statistical studies, the new formulas are derived to estimate the mean inelastic displacements for SC-CR systems.

2. Inelastic displacement ratio

Within the framework of performance-based earthquake engineering (PBEE) both simplified and complex methods [29,30] are employed for estimating lateral deformation capacity and the displacement demand of a structure under a given ground motion. As an example, coefficient method is employed in the nonlinear static methods (pushover) of modern guidelines such as FEMA-273/274 [31], FEMA 356 [32], and FEMA 440 [33] for determining target displacement (Δ_{target}) demand in a specific hazard level. A key parameter in Δ_{target} formulation is the inelastic displacement ratio (C_1), which is the maximum inelastic displacement (Δ_i) of a nonlinear SDOF system to the maximum linear displacement (S_d) of an elastic SDOF system. The coefficient of C_1 is an approximation of exact constant-R (C_R) inelastic displacement ratios (C_R ratios) of bilinear SDOF systems [34]. C_R is the inelastic displacement ratio of a SDOF system with different periods at constant strength R subjected to a ground motion set. Ruiz-Garcia and Miranda [35,36] introduced the following equation for defining C_R ratio [37]:

$$C_R = \frac{\Delta_i}{S_d} \tag{1}$$

where Δ_i denotes the maximum inelastic displacement and S_d is the elastic spectral displacement of a SDOF system. Parameter R, lateral strength coefficient, is the ratio of the required strength ($m{\cdot}S_a$) to the yield strength (F_y):

$$R = \frac{m \cdot S_a}{F_y} \tag{2}$$

Miranda [38,39] examined the effects of soil type, earthquake magnitude, and source-to-site distance on C_R ratios of bilinear SDOF systems. Ruiz-Garcia and Miranda [40,41] proposed C_R formulas for bilinear SDOF systems subjected to the records taken from soft soil site and Ruiz-Garcia and Gonzalez [34] used these formulas for the seismic assessment of steel structures. The effects of near-fault and repeated earthquakes on C_R ratios have been studied by other researchers such as Baez and Miranda [42], Zhai et al. [43], Iervolino et al. [44], Chopra and Chintanapakdee [45], Amadio et al. [46], and Hatzigeorgiou [47]. Ruiz-Garcia [48] statistically investigated the effect of normalizing the C_R spectra to pulse period (T_p) and predominant period of velocity spectrum (T_g) for stiffness and strength-degrading systems subjected to NF-pulse records. Pincheira et al. [49,50] and Ozkul et al. [51] have examined effects of uncertainty in stiffness and strength deterioration on the inelastic displacement ratios of degrading systems using statistical and fuzzy logic-based methods, respectively.

Recently, limited studies have been reported on the inelastic displacement responses of SDOF self-centering systems. Christopoulos et al. [52,53] studied the effects of hysteretic shape and residual displacement on the constant-ductility ratios of flag-shape system. Seo and Sause [54] evaluated the effects of strength modification, post-yielding, and hysteretic energy dissipation on the constant-ductility spectra of the system. The effects of energy dissipation index and strength modification factor on partially self-centering systems were also examined by Eatherton and Hajjar [55]. However, these studies have been only focused on examining the effects of some parameters on constant-ductility spectra of limited flag-shape models under far-field ground motions and have not derived their mathematical equations. Therefore, in the present paper, C_R spectra of various SC-CR systems subjected to both far-field and NF-pulse records are determined for different modeling and ground motions parameters; furthermore, their formulas are derived based on statistical studies.