Engineering Structures 75 (2014) 590–603

Contents lists available at ScienceDirect

Engineering Structures

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

Fuzzy-logic based inelastic displacement ratios of degrading RC structures

Selma Ozkul [a], Ashraf Ayoub [b,*], Abdusselam Altunkaynak [c]

[a] Iv-AGA Texas, LLC, Houston, TX 77042, USA
[b] Dept. of Civil Eng, City University London, London, UK
[c] Dept. of Civil & Env. Eng, Istanbul Technical University, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 8 November 2012
Revised 9 May 2014
Accepted 19 June 2014
Available online 11 July 2014

Keywords:
Fuzzy logic
Expert systems
Inelastic displacement ratios
Displacement estimates
Degradation

ABSTRACT

The existing classical methods for estimating the inelastic displacement ratios of reinforced concrete (RC) structures subjected to seismic excitation are built upon several assumptions that ignore the effect of uncertainties on the concerning phenomenon. Uncertainty techniques are more appropriate to modeling such phenomenon that inherits impreciseness. This research presents a new method predicting the inelastic displacement ratio of moderately degrading RC structures subjected to earthquake loading using expert systems such as fuzzy logic approach.

A well-defined degrading model was used to conduct the dynamic analyses. A total of 300 earthquake motions recorded on firm sites, including recent ones from Japan and New Zealand, with magnitudes greater than 5 and peak ground acceleration (PGA) values greater than 0.08 g, were selected. These earthquake records were applied on five RC columns that were chosen among 255 tested columns based on their beam–column element parameters reported by the Pacific Earthquake Engineering Research Center (2003) [1]. A total of 96,000 dynamic analyses were conducted. The results from these analyses were used to develop the fuzzy inelastic displacement ratio model inheriting uncertainties in terms of strength reduction factor (R) and period of vibration (T). The performance evaluation of the new fuzzy logic model and four classical methods were investigated using different independent data sets. As a result, more accurate results were predicted using the new fuzzy logic model.

1. Introduction

Lately, the performance based design concept has been more and more integrated into seismic design provisions throughout the world. As the life expectancy of structures in seismic areas increases, predicting the seismic behavior of systems at different hazard levels becomes more important. Hence, it is essential to predict the seismic demands as accurately as possible.

The existing classical methods predicting the inelastic displacement ratio of SDOF structures are based on several assumptions. The uncertainties that RC columns inherit by nature are simulated using several assumptions which may filter down the effect of vital uncertainties and, therefore, result in estimating the inelastic displacement ratio of SDOF structures less accurately.

In this research, a new method was developed for predicting the inelastic displacement ratio of seismically excited and moderately degrading SDOF RC structures using a Fuzzy Logic approach. A well-defined energy-based degrading model that takes softening of columns into account was used in the analytical studies. The studies were performed on five tested RC columns with similar beam–column element parameters that were proposed in PEER Report 2007/03 [2]. A large earthquake record database consisting of 300 earthquake records measured on firm sites was used in the analyses to increase the statistical significance of the results. Each record was selected to have magnitude greater than 5 and PGA value greater than 0.08 g.

Procedures for estimating maximum inelastic displacements of SDOF systems have been developed during the past 50 years. The first research work was conducted by Veletsos and Newmark [3] who investigated the relationship between the maximum inelastic displacements and elastic displacements of SDOF systems. The hysteretic behavior of SDOF systems was assumed to be elasto-plastic and three earthquake records were used. The results of this study have led to the very well-known "equal displacement rule". Using the equal displacement rule in low frequency regions was also recommended in other studies [4,5].

* Corresponding author. Tel.: +44 20 70408912.
E-mail address: Ashraf.Ayoub.1@city.ac.uk (A. Ayoub).

http://dx.doi.org/10.1016/j.engstruct.2014.06.030
0141-0296/

Analyses of non-degrading SDOF structures using five different hysteretic models was conducted in [6]. Either bilinear or Clough model [4] were used in their numerical studies and the analyses were performed only using one earthquake record. They concluded that the equal displacement rule applies for periods higher than the characteristic period, which is defined as the period between the constant acceleration and constant velocity regions of the response spectra, regardless of which hysteretic model is used.

In the beginning of 1990s, Krawinkler and his co-workers [7,8] investigated SDOF columns using bilinear, Clough or pinching models. They considered either strength degradation or stiffness degradation in their modeling process. Moreover, they derived an equation to estimate the inelastic displacement ratio of SDOF systems [9]. Miranda [10,11] analyzed the ratio of maximum inelastic displacement to maximum elastic displacement of elasto-plastic SDOF models subjected to 124 earthquake records. He studied the inelastic displacement ratios on three different soil types in short period regions and investigated the limiting period where the equal displacement rule starts to apply. He furthered his study on constant ductility inelastic displacement ratios using 264 earthquake records and developed ratio versus period plots based on different earthquake magnitude, distance to the source, and local soil types [12]. He concluded that neither the earthquake magnitude nor the epicenter distance affects the inelastic displacement ratio under the same constant ductility ratio. He also found that different site conditions do not have a significant effect on the constant inelastic displacement ratio when the average shear wave velocity of the upper 30 m (100 ft) of the sites is higher than 180 m/s (600 ft/s). In addition to his findings, he developed an equation that estimates the inelastic displacement ratio of elasto-plastic SDOF structures. In a later study, he pointed out that maximum inelastic displacements could be related to maximum elastic displacements either through inelastic displacement ratios or strength reduction factors, which are known as direct and indirect methods respectively [13]. He showed that the indirect method underestimates the maximum inelastic displacements compared to the results obtained from the direct method.

Miranda and Ruiz-Garcia [14] evaluated six approximate methods, four of them based on equivalent linearization and two based on multiplying the maximum elastic displacement with a factor, that estimates the maximum inelastic displacement of SDOF systems. They also studied the effects of period of vibration, lateral yielding strength level, site conditions with shear wave velocity higher than 180 m/s (600 ft/s), earthquake magnitude, epicenter distance and strain hardening ratio on inelastic displacement ratio [15]. They derived an equation to predict the inelastic displacement ratios of existing structures on firm sites restricted to elasto-plastic systems. They also worked on the inelastic displacement ratio of SDOF systems on soft soils [16,17].

In the late 1990s and early 2000s, several other studies were also conducted. SDOF systems subjected to 15 earthquake records were investigated in [18]. Degradation effect was incorporated in the system using a three-parameter model. Numerical studies on non-degrading Bouc-Wen model [19] subjected to 20 earthquake records were conducted in [20]. Inelastic displacement ratio of structures subjected to 12 ground motions considering strength and stiffness degradation effect only were performed in [21]. In another study, Chopra and Chintanapakdee [22] investigated the inelastic displacement ratio of new and existing structures which were modeled as non-degrading elasto-plastic and bilinear systems subjected to 214 earthquake records. Chenouda and Ayoub [23,24] and Ayoub and Chenouda [25] developed a new energy-based model, which takes several degradation effects into account, to perform dynamic analysis and predict collapse of structures subjected to seismic excitation. Bilinear and modified Clough models [4] were used in this study. They proposed a new equation, originally based on a study by Krawinkler and Nassar [9], to estimate the maximum inelastic displacement of degrading systems. In addition, they compared their inelastic displacement ratio curves with several other proposed equations.

Hatzigeorgiou and Beskos [26] investigated the effect of repeated or multiple earthquakes on inelastic displacement ratio of elasto-plastic SDOF systems. They used 112 earthquake records recorded at sites with USGS soil types A, B, C and D in their study. After numerical studies, they proposed an equation not only to estimate the inelastic displacement ratio of SDOF systems subjected to single earthquakes but also subjected to multiple earthquakes. Zhang et al. [27] developed inelastic displacement ratios accounting for shear–flexure interaction behavior of concrete structures. Lately, Erberik et al. [28] used an energy approach to develop degrading models for reinforced concrete columns, and used them to derive new inelastic displacement ratios.

The main purpose of this study is to develop a fuzzy logic model for predicting the inelastic displacement ratio of moderately degrading SDOF RC structures subjected to earthquake loading. The analytical model used takes degradation into consideration. A qualitative and quantitative comparison with the results of existing classical methods is then performed. A brief description of the earthquake records used and the analytical model adopted is presented first.

2. Earthquake records

A large database of earthquake records was used in this research in order to increase the statistical significance. The database set used in this research consists of 300 earthquake records with PGA values varying between 0.08 g and 2.73 g. Each record corresponds either to NEHRP soil type C or D (stiff soil or soft rock) based on their shear wave velocities (180–760 m/s). Magnitudes in the records were greater than 5 and the distances to the source were greater than 5 km. Most of the earthquake records were selected from the PEER Ground Motion Database [29]. Significant earthquake records that occurred recently were also collected from the Kyosin Network (K-Net) [30] and GeoNet – Strong Motion Data [31]. The horizontal components with max PGA values of selected earthquake records were used in the analytical modeling. A total of 266 earthquake records with PGA values greater than 0.08 g were selected from the PEER Ground Motion Database. A total of 18 earthquake records of Honshu–Japan earthquake (3/11/2011) with PGA value varying between 0.768 g and 2.731 g were selected from Kyosin Network. The shear wave velocities (V_s) of the records were given rather than their soil types. Therefore, the corresponding NEHRP soil types were based on the NEHRP Site Classification (FEMA 450 [32]). A total of 16 earthquake records from the Christchurch-New Zealand earthquake (2/21/2011) with PGA values varying between 0.082 g and 0.881 g were selected from the GeoNet database. The records correspond to NZS 1170.5:2004 soil types B, C and D [33] which are equivalent to NEHRP soil types C and D.

Scaling of earthquake records for any seismic performance evaluation purpose has been one of the important issues in engineering applications. Huang et al. [34] investigated the nonlinear response histories of SDOF systems using four scaling methods and presented their advantages and disadvantages. The first method was the Geometric-Mean scaling method used by Somerville and his co-workers [35] which is based on amplitude scaling of a pair of ground motion. According to Huang et al.'s findings, it is difficult to select ground motions for this method with median spectrums that closely match the target spectrum of a wide range of periods. The second method was the spectrum-matching method which is often used for computing the seismic demands in structural framing systems. This particular method was found to underestimate