Engineering Structures 125 (2016) 266–279

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic response analysis of single-degree-of-freedom yielding structures with fluidic self-centering systems

Shoma Kitayama *, Michael C. Constantinou

Department of Civil, Structural and Environmental Engineering, 212 Ketter Hall, University at Buffalo, State University of New York, Buffalo, NY 14260, USA

ARTICLE INFO

Article history:
Received 13 October 2015
Revised 26 March 2016
Accepted 30 June 2016

Keywords:
Self-centering
Fluidic devices
Residual displacement
SDOF
Damping systems
Simplified analysis

ABSTRACT

Analyses of single-degree-of-freedom yielding structures with fluidic self-centering systems are performed for a wide range of parameters and the results are utilized to (a) illustrate the effect of the added fluidic self-centering devices on the behavior of the structural system, and (b) to arrive at conclusions on the appropriate strategy for selection of the structural system and self-centering system properties for design. The results suggest that the primary structural system could be designed for a base shear force not less than 75% of the minimum base shear force prescribed in ASCE 7-2010 for the building exclusive of the self-centering system, and that the drift criteria would be satisfied and the residual drift will be minimal when the fluidic self-centering system is designed for a preload equal to about (or more than) 20% of the story shear yield strength and a viscous damping ratio of at least 10% of critical under elastic frame conditions. Simplified methods of analysis are then presented and verified by comparison to nonlinear response history analysis results. The simplified methods of analysis are found to be reasonably accurate for most practical cases of structural system and self-centering system parameters except for cases of long period structures and when near-fault, pulse-like ground motions are considered.

1. Introduction

A number of studies investigated post-tensioned seismic-resistant self-centering systems (for example, [1–7]). Several analytical studies then followed which compared the behavior of structural systems having bilinear hysteretic and flag-shaped hysteretic behaviors by analyzing single-degree-of-freedom (hereafter, SDOF) representations [8–13]. The studies utilized generic representations of conventional structural systems and self-centering systems in which the conventional structural system behavior was modelled as bilinear hysteretic (perfect or deteriorating) and the self-centering system was modelled as bilinear elastic with added energy dissipation capability in hysteretic or viscous forms. Also, the studies utilized different ground motion suites, with some studies only considering far-field motions and others considering both far-field and near-fault motions. Invariably, these studies demonstrated that self-centering systems reduce or eliminate residual deformations [e.g., 8, 11 and 13]. Some studies also showed that the self-centering systems generate higher peak acceleration response (or peak shear force) than that of comparable elasto-plastic systems and that they result in residual deformations that are not sensitive to decreasing values of post-yielding stiffness [e.g., 8, 9 and 12].

The study reported in this paper follows the paradigm of these studies but concentrates on the behavior of inelastic structural systems with added fluidic self-centering devices [14–16]. These devices are double-acting fluidic springs with orifices similar to those of fluid viscous damping devices that are also pressurized and which are added to a structural system that by itself has resistance to lateral loads. These devices can readily deliver complex forms of damping behavior not previously contemplated as possible such as asymmetric force (e.g., more force on loading than on unloading) together with linear or nonlinear dependency on the velocity of motion. The dimensions and representative force-displacement loops of one such device are shown in Figs. 1 and 2 [16]. Loops under static and dynamic conditions are shown for two levels of initial fluid pressure in the tested device (29 and 116 MPa). The figures also include analytical results produced by a validated model of the fluidic self-centering devices [16]. This model is used in this paper for the description of the behavior of the fluidic self-centering system.

Moreover, this paper (a) considers seismic motions with far-field and near-fault characteristics, (b) distinguishes between motions with pulse-like and non-pulse-like characteristics based on contemporary classifications [17], (c) distinguishes between

* Corresponding author.
E-mail address: shomakit@buffalo.edu (S. Kitayama).

http://dx.doi.org/10.1016/j.engstruct.2016.06.057
0141-0296/

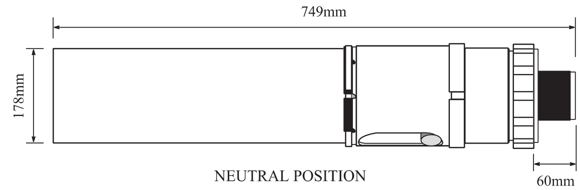

Fig. 1. Tested sample fluidic self-centering device [16].

design level and maximum earthquake level, and (d) selects and scales motions on the basis of the currently applicable ASCE 7-2010 standard [18].

Results are presented with the particular intention of (a) identifying values of preload as a fraction of the structural system's strength exclusive of the self-centering devices that result in acceptably small residual deformations, (b) observing the effect of the form of viscous damping (linear, nonlinear and asymmetric) on the response, and (c) comparing the ductility demand, peak displacement, residual displacement and peak acceleration of systems with and without fluidic self-centering devices. The results presented in this paper are representative of a much larger set of results that are available in a report [16].

2. Selection and scaling of earthquake ground motions

Analysis of generic single-degree-of-freedom systems with fluidic self-centering devices was conducted with seismic motions selected from historic events and scaled to represent in an average sense particular response spectra at the design and the maximum earthquake levels. A Risk-Targeted Maximum Considered (MCE_R) response spectrum was constructed per ASCE 7 (2010) [18] for a location in California (latitude 37.8814°N, longitude 122.08°W) with characteristic values of S_{MS} = 1.875 g and S_{M1} = 0.9 g. The Design level response spectrum (DE) has characteristic values equal to 2/3 of those of the MCE_R, so S_{DS} = 1.25 g and S_{D1} = 0.6 g. The spectra of the two levels of earthquake are shown in Fig. 3.

Sets of motions representative of the MCE_R spectrum and with near-fault pulse-like, near-fault non-pulse-like or far-field ground motion characteristics were used in the study. The distinction between pulse-like and non-pulse-like motions was necessitated by the recognition that substantially larger displacement demands occur in the case of pulse-like motions than in the case of non-pulse-like motions when systems with large effective period are considered [19]. The selection of the near-fault ground motions was based on the procedure described in [19], which was based on the classification of Baker [17]. The selection of far-field ground motions was based on FEMA [20]. The ground motions selected and some of their characteristics are presented in Tables 1–3 for the near-fault pulse-like motions, the near-fault non-pulse-like motions and the far-field motions, respectively. Note that each selected ground motion was rotated along the fault-normal and fault-parallel directions and that only the fault normal components were used in the analysis (the fault-parallel components are typically less intense and were disregarded in this study). Each of the three ensembles of motions consisted of seven components. The selected ground motions were spectrally matched to the MCE_R response spectrum using procedures described in [21]. Each of the scaled motions was lengthened with 15 s of zeroes to allow for the calculation of the free vibration response and any residual deformation.

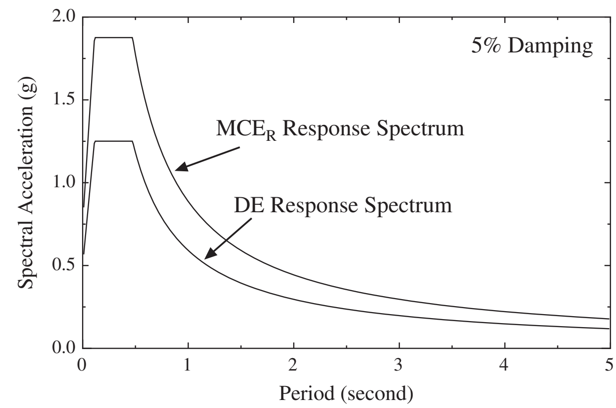

Fig. 3. MCE_R and DE response spectra (5% damped) considered in study.

3. Analyzed single-degree-of-freedom systems

The analyzed SDOF system exhibited bilinear hysteretic behavior representing the primary structural system and with added fluidic self-centering devices. The selection of parameters of the primary structural system followed the paradigm of Ramirez et al. [22,23] in the study of damping systems. Fig. 4 (left) shows the lateral force-displacement relation of the primary system. The primary system is represented as a SDOF system with mass m, elastic stiffness K_e, base shear (yield) strength F_y, yield displacement D_y, and inherent damping ratio β_i. The post-elastic stiffness is expressed as a fraction of the elastic stiffness and given by αK_e. Its

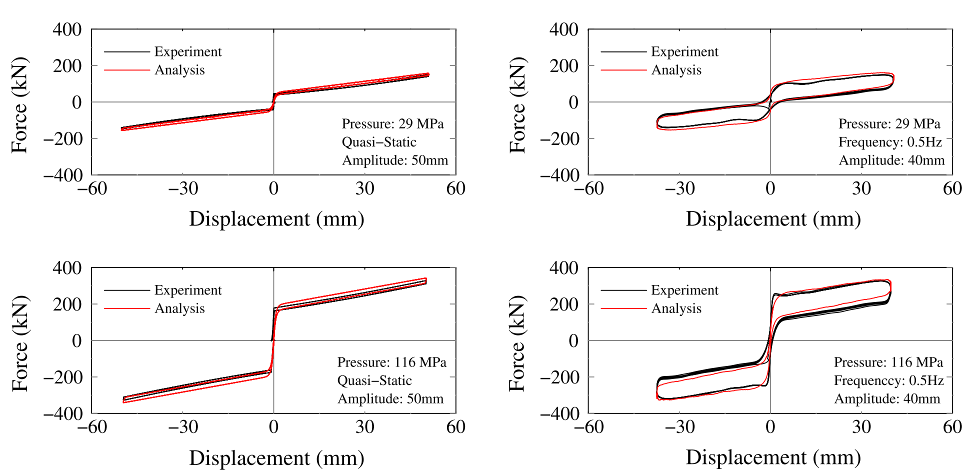

Fig. 2. Force-displacement loops of tested fluidic self-centering device [16].