Engineering Structures 142 (2017) 110–127

Contents lists available at ScienceDirect

Engineering Structures

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

Rotational components of near-fault earthquakes effects on triple concave friction pendulum base-isolated asymmetric structures

H. Tajammolian, F. Khoshnoudian *, V. Loghman

Faculty of Civil Engineering, Amirkabir University of Technology (Tehran Polytechnic), Hafez St, Tehran, Iran

ARTICLE INFO

Article history:
Received 10 April 2015
Revised 13 March 2017
Accepted 20 March 2017

Keywords:
Rotational components
Mass eccentricity
TCFP isolators
Near-fault
Torsion

ABSTRACT

In this paper, attempts are made to demonstrate the effects of the rotational components of near-fault ground motions on asymmetric base-isolated structures. The effects of mass eccentricity in intensifying the impact of rotational components are investigated as well. A reasonable variety of superstructures with different aspect and slenderness ratios is considered. Three-dimensional models of superstructures with linear behavior mounted on nonlinear TCFP isolators with various effective periods and damping are studied elaborately. Base shear, isolator displacement, base torsional angle and roof acceleration are selected as prominent responses of base-isolated structures. Results demonstrate that rotational components play an essential role in raising the structural responses. Furthermore, the effects of mass eccentricity are notable. Structures with an aspect ratio in plan equal to 3, the roof acceleration can increase to 255% in the presence of rotational components and mass eccentricity simultaneously. In similar conditions, the base shear of a 9-story building enhances 135%. Generally, the torsional component of earthquake affects the isolator displacement, base torsional angle and roof acceleration, while the base shear is influenced by the rocking components. It is revealed that the effects of mass eccentricity on the isolator displacement could be ignored.

1. Introduction

Seismic isolation is one of the most effective tools used in recent years to reduce the structural damages caused by earthquakes. Seismic performance of base-isolated structures is improved as the base-isolation protects the structural and non-structural components against damages in strong ground motions. This technology can effectively provide safer buildings through an earthquake hence lowering their human and economic toll. Despite the many different types of seismic isolators used for isolation, bearings can be divided into two major categories: elastomeric and frictional ones. Single Friction Pendulum (SFP) and Double Concave Friction Pendulum (DCFP) are two different types of frictional isolators which are currently used in many buildings and bridges. The Triple Concave Friction Pendulum (TCFP) isolator is the latest generation of this type of isolator and the seismic behavior of it is being investigated by researchers.

The SFP isolator was suggested by Zayas et al. [1,2] and its application in different bridges was studied by Constantinou et al. [3]. Almazan et al. [4] investigated the performance of the isolated structures mounted on SFP bearings subjected to bi-directional as well as vertical components of ground motions. SFP's seismic behavior of multi-story structures subjected to both horizontal and vertical components of earthquake was also examined by Khousnoudian and Rabiei [5]. Kumar et al. [6] performed an investigation on the effects of sliding velocity, axial pressure and temperature caused by frictional heating on the friction coefficient of different types of concave friction bearings. Khoshnoudian and Haghdoost [7] have demonstrated that bi-directional interaction of frictional forces as well as vertical component of ground excitation can influence the responses of the sliding isolated structures. To improve the properties of the SFP isolator, the DCFP was invented by using two concave plates. The plates are located in the bottom and top of the isolator and separated by an articulated slider. The main advantage of the DCFP isolator, despite its smaller dimension, is to provide the same displacement capacity as the SFP. Hyakuda et al. [8] presented the force-displacement formulation of this kind of isolator. Fenz and Constantinou [9] investigated different regimes of isolator displacement as well. Kim and Yun [10] scrutinized the bi-linear and tri-linear behavior of DCFP isolators which are utilized in bridges. Their study denotes that using tri-linear seismic responses of these isolators will cause fewer amounts of base shear. Khoshnoudian and Hemmati [11] examined the tri-linear behavior of the DCFP too. The effect of vertical

---

* Corresponding author.
E-mail address: khoshnud@aut.ac.ir (F. Khoshnoudian).

http://dx.doi.org/10.1016/j.engstruct.2017.03.042

component of earthquake was considered in seismic responses of structures by Khoshnoudian and Rabiei [12]. Furthermore, the seismic responses of different structures mounted on DCFP bearings were presented by Rabiei, Khoshnohdian [13] and Bagheri, Khoshnuodian [14].

The TCFP isolator is the latest frictional-base isolator being considered in the literature. The isolator has two concave plates at the top and two plates in the bottom. An articulated slider is located in the middle of the isolator as indicated in Fig. 1a. The outer and inner bottom surfaces are called surfaces 1 and 2, while the top surfaces identifies as 3 and 4 in the same order. Each of the four concave sliding surfaces has an independent radii and friction coefficient. The radius of each plate and its friction coefficient can be selected in such a way that the isolator can exhibit a 5-regime backbone curve that is illustrated in Fig. 1b.

Fenz and Constantinou [15–18] have derived the force-displacement relations of the TCFP isolators in different regimes. They also performed several experimental tests to verify the equations of motions for this isolator. Additionally, a series model for idealizing the behavior of the TCFP isolator in SAP2000 software was introduced by Fenz and Constantionu [16]. In another distinct investigation, Becker and Mahin [19,20] suggested a model for predicting the seismic responses of the TCFP isolated structures subjected to bi-directional earthquake excitations. Morgan and Mahin [21,22] applied a set of numerical analysis and experimental tests on different TCFP isolators as a database in order to study the damage states in various hazard levels of earthquakes. Loghman et al. [23] have revealed the significance of utilizing the vertical component of ground motion in anticipating the seismic responses of superstructures mounted on TCFP isolators. They have denoted that ignoring the vertical component of earthquakes may lead to notable errors in calculating the base shear of low-rise superstructures. Dao et al. [24] performed the experimental tests and they suggested a new model for three-dimensional analysis of a TCFP isolator in OpenSees software. Becker and Mahin [25] have studied the effects of isolator supports on the seismic behavior of the TCFP isolators. Their results suggest that flexible supports have negligible effects on the global performance of the superstructure subjected to different ground motions. Sarlis and Constantionu [26] have developed the formulations of force-displacement equations in a way that can predict the real behavior of TCFP isolators in uplift conditions.

Analysis of structures is usually done by applying two or three translational components of earthquakes. Although the contribution of three rotational (two rocking and one rotation) components of a ground motion may significantly affect the responses of structures, their impact on the results of structural responses are unknown because these components cannot be recorded by accelerographs in the free field [27].

Many researchers have attempted to derive rotational components by using various mathematical equations and the properties of surface and body waves as well as geological parameters of soil. Penzin and Watable [28] expressed that the most of the earthquake energy travels from the epicenter to the structure through the principal plane which is defined as the vertical plane that encompasses the ground motion epicenter and the recording station. They also revealed that translational components of an earthquake along and normal to this principal plane are uncorrelated. The Fourier amplification spectra of rotational components of an earthquake were derived by Trifunac [29]. In this investigation, the surface waves of an earthquake were ignored and only the effect of body waves (P, SH or SV) was considered. Castellani and Boffi [30,31] carried out the first investigation on the contribution of both surface and body waves. They decomposed the contributions from the body and surface waves using a procedure introduced by Sugito et al. [32]. Then, the contribution of body waves was decomposed into P and S waves by the means of a theory developed by Haskell [33]. Finally, rotational components were derived from P and S waves using some mathematical relationships. Gomberg and Bodin [34] utilized some data from the Little Skull Mountain (LSM) and Landers earthquakes to estimate rotational components in a recording station. The station was located a distance of 26 and 280 km from the epicenter of LSM and Landers ground motions, respectively. In most of these studies, the rotational components are calculated based on the data from a single recording station. Therefore, this method is identified as a Single Station Procedure (SSP) [27].

The geodetic method which was introduced by Spudich et al. [35] utilized the data from different recording stations in a three-dimensional space to calculate the rotational components of an earthquake. This method is based on the relative displacements between each station recording pairs. In another study, Laouami and Labbe [36] computed the torsional component of an earthquake using data recorded at different stations. These stations were located in Lotung (Taiwan). The data were recorded in 15 surface stations through the Large Scale Seismic Test (LSST) from 1985 to 1991. During this period, signals from 30 ground motions were recorded.

Effects of rotational components of an earthquake on different structures have been studied by a number of investigators. Newmark [37], Hart et al. [38], Bycraft [39], Wolf et al. [40] and Politopoulos [41] are some of these researchers. Basu et al. [27] reviewed most of these investigations. They have compared the results of different methods of calculating the rotational compo-

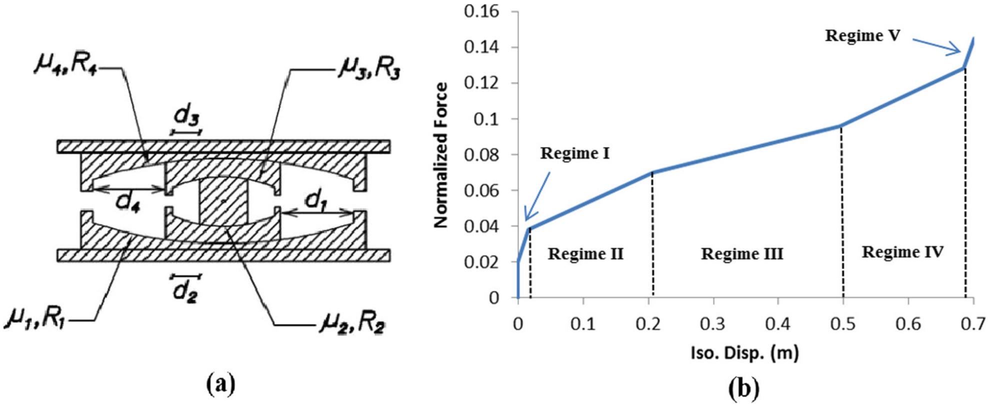

Fig. 1. (a) TCFP isolator, (b) backbone curve of a TCFP.