Soil Dynamics and Earthquake Engineering 115 (2018) 119–128

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Seismic behavior of steel eccentrically braced frames under soft-soil seismic sequences

Jorge Ruiz-García[a,*], Edén Bojorquez[b], Edgar Corona[b]

[a] Facultad de Ingeniería Civil, Universidad Michoacana de San Nicolás de Hidalgo, Edificio C, Planta Baja, Cd. Universitaria, 58040 Morelia, Mexico
[b] Facultad de Ingeniería Civil, Universidad Autónoma de Sinaloa, Calz. de las Américas y Boulevard Universitarios, Cd. Universitaria, 80040 Culiacán, Mexico

ARTICLE INFO

Keywords:
Eccentrically braced frame
Soft soils
Link rotation
Seismic sequences
Aftershocks

ABSTRACT

The goal of this paper is to examine the seismic response of eccentrically braced frames (EBFs) under artificial narrow-band mainshock-aftershock sequences by means of detailed analytical models representative of buildings designed under the Mexico City Code criteria. These analytical models take into account the nonlinear behavior of the links including a failure criterion. Relevant results for engineering practice showed that strong aftershocks could significantly increase interstory drift demands once the link fails, while surrounding members (adjacent beams, columns) behave nonlinearly, which is opposite to the design philosophy. In addition, it was noted the nonuniform distribution of hysteretic energy along-height of the links, which do not take fully advantage of the energy dissipating capacity of the shear links.

1. Introduction

Eccentrically Braced Frames (EBF) have become an attractive earthquake-resistant structural system in many countries worldwide since it provides high levels of both elastic stiffness (similar to concentrically braced frames) and ductility (similar to moment-resisting frames). In EBFs, the seismic energy induced to the building during earthquake loading is dissipated through the inelastic behavior of the links, while the remaining elements (beams, columns, and braces) are expected to behave elastically. Currently, the design procedure for EBF is prescribed in the 2016 AISC Seismic Provisions for Structural Steel Buildings [1], which specifies the link design, link rotation limits, and link overstrength factors, among other issues. Particularly, the link rotation is limited to 0.08 rad for links behaving in shear (i.e. for links with length equal or smaller than $1.6M_p/V_p$, where M_p and V_p are the plastic bending moment and the plastic shear strength of the link). A comprehensive review of relevant experimental and analytical research carried out on steel eccentrically braced frames is presented in Ref. [2].

The first reported worldwide failure in EBFs was observed in St. Asaph Street parking structure in the city of Christchurch as a consequence of the February 22, 2011 (M_w = 6.3) earthquake that struck the Canterbury region in New Zealand. A detailed forensic examination revealed that three main factors led to the unsatisfactory performance of this structure [3,4]: a) the intensity of the ground shaking (several times the intensity that was expected during a design-level event), b) the frame geometry, which severely amplified the imposed seismic demands, and c) observed fracture in the links from an erection (fit-up) error, since the link stiffener was not located (as specified) directly above the brace flange, producing a severe strain concentration. Although not examined in the aforementioned study, it should be noted that the February 22, 2011 seismic event was part of a sequence of strong earthquakes that hit the New Zealand's South Island that began with the September 3, 2010 (M_w = 7.0) Canterbury earthquake. Therefore, this lesson motivates examination of the behavior of EBFs in seismic regions under strong earthquakes (mainshock) and, in general, under seismic sequences.

It should be noted that it has been a growing interest in incorporating EBFs as a lateral-load resisting system for new buildings in Mexico City, as shown in Fig. 1. However, until recently, the Technical Requirements for Design of Steel Structures released in the 2017 Mexico City Construction Code [5] included design specifications for eccentric braced frames for the first time, which are entirely based on Ref. [1]. In addition, the 2017 Mexico City Construction Code prescribe a limiting maximum interstory drift of 0.02 to avoid collapse for the design of EBFs. However, there is a lack of information about the performance of EBFs built on very soft soil sites to judge at what levels of seismic intensity the EBFs can reach or exceed this limiting drift.

For the case of Mexico City, Mexican practicing engineers know that buildings, and other civil engineering structures, built on the former bed-lake of Mexico City are exposed to narrow-band earthquake ground

* Corresponding author.
E-mail address: jruizgar@stanfordalumni.org (J. Ruiz-García).

https://doi.org/10.1016/j.soildyn.2018.08.018
Received 5 April 2018; Received in revised form 2 August 2018; Accepted 13 August 2018
0267-7261/

Fig. 1. Examples of the use of eccentric braced frames in buildings: a) short link, b) long link.

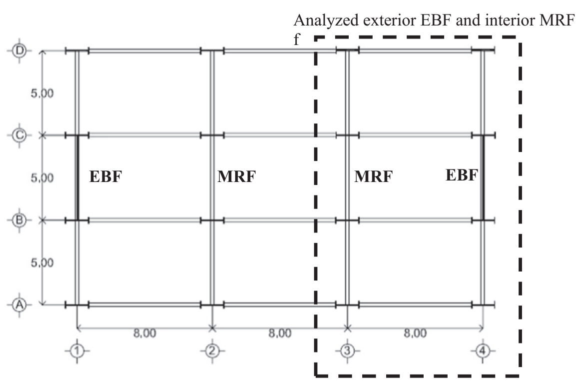

Fig. 2. Plan view of case-study steel buildings [units in meters].

motions characterized by relatively long predominant periods and low-frequency content, along with large energy demands e.g., [6–8]. In addition of this fact, buildings might also be subjected to strong aftershocks that may compromise their structural safety. For instance, a clear example of the effect of strong aftershocks was observed after the September 19, 1985 Michoacan earthquake (Mw = 8.0) and the following aftershock on September 20 (Mw = 7.6) that struck Mexico City [9]. After these events, it is well documented that medium-rise buildings located in the old bed-lake zone of Mexico City suffered moderate-to-severe structural damage as a consequence of the mainshock and many buildings increased their post-mainshock state of damage, or suffered excessive permanent displacements as a result of the strong aftershock that shook the city the following day [9]. In spite of the 1985 experience, very limited research has been conducted to investigate the effect of aftershocks in the response of buildings located in soft soil sites, in such a manner as to caution practicing engineers about the importance of considering full seismic sequences during earthquake-resistant design, and the few studies focused on building moment-resisting frames [10,11] and buckling-restrained braced frames [12] as structural system for buildings. Therefore, evaluating the seismic behavior of buildings incorporating EBFs under a strong mainshock and aftershock ground motions is pertinent and relevant for the Mexican structural engineering community.

The primary objective of the research reported in this paper was to investigate the seismic behavior of eccentrically braced frames (EBFs) subjected to both mainshock earthquake ground motions and mainshock-aftershock earthquake ground motions sequences representative of those recorded in the soft-soil sites of Mexico City. For this purpose, two typical steel office buildings having 4- and 8-story incorporating EBFs were designed as part of this investigation. The case-study buildings were modeled and analyzed with the computational platform *OpenSees* [13]. Particular emphasis was placed in the nonlinear modeling of the links, which includes a failure criterion. It should be mentioned that the particular influence of the soil-structure interaction in the seismic response of the case-study building models was outside of the scope of the paper.

2. Case-study EBF buildings

2.1. Description and design of EBFs

Two steel buildings having 4 and 8 stories were considered as part of this investigation. The buildings were assumed to be designed for office occupancy and located in the lake-bed zone of Mexico City. They were designed by an experienced structural engineering office to satisfy the 2004 Edition of the Technical Requirements for Seismic Design included in the Mexico City Building Construction Code [14]. Fig. 2 shows the typical plan view of the steel buildings. Moment-resisting frames (MRF) were provided in the longitudinal direction, while exterior EBFs and interior MRF acting as a dual system were incorporated in the transverse direction. Design of interior frames as MRFs is a common assumption in Mexican structural engineering practice. The EBFs were incorporated for drift control since the weak-axis of the columns is oriented in this direction as shown in Fig. 2. Therefore, the lateral stiffness is similar in both directions to avoid torsional effects during the seismic response. Fig. 3 displays the distribution along height of the frames including position of eccentric braces. A typical story height of 3.5 m was assumed for both buildings. Design dead load of 680 kgf/cm^2 (66.69 MPa) were assumed for all stories, while design live load of 70 kgf/cm^2 (6.86 MPa) and 180 kgf/cm^2 (17.65 MPa) for the roof and typical story, respectively, were considered according to the Mexico City Building Construction Code. An equivalent static linear analysis, which is commonly used in the Mexican design practice, assuming a triangle inverted distribution of code-specified base shear was employed for sizing the frame members. For this purpose, elastic acceleration design spectrum ordinates were reduced by a response modification factor equal to 3 and 4 in the longitudinal and transverse direction, respectively, which takes into account the ability of the structure to undergo inelastic deformations, without consideration of structural overstrength. Particularly, links in the EBFs were set as 1.0 m long to design short links expected to fail in shear. It was also assumed a plastic rotation capacity of 0.06 rad and an overstrength factor equal to 1.5 to compute the shear web capacity in the links. Square HSS steel sections were employed as diagonal braces assuming a nominal yield strength of 3515 kgf/cm^2 (344.7 MPa). Tables 1, 2 reports the final sections of the links and braces for the 4- and 8-story frames,