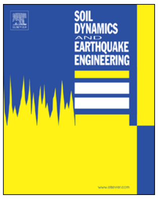
Soil Dynamics and Earthquake Engineering 84 (2016) 190–203

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



Efficiency of low-rise steel rocking frames founded on conventional and rocking foundations

A. Riahi Nouri [a,*], I. Anastasopoulos [b,1], M.G. Vetr [a], A. Kalantari [a]

[a] *International Institute of Earthquake Engineering and Seismology, Iran*
[b] *University of Dundee, UK*

ARTICLE INFO

Article history:
Received 20 November 2015
Received in revised form
30 January 2016
Accepted 1 February 2016

Keywords:
Base plate rocking
Foundation rocking
Low-rise
Uplift
Steel frame
Soil–foundation–structure interaction

ABSTRACT

Steel rocking frames have been proposed as an alternative to steel-braced frames, aiming to reduce seismic damage. Energy dissipation members, such as yielding base plates and “butterfly” fuses are introduced, while the restoring forces are provided by self-weight and post-tensioned cables. Rocking is constrained within the superstructure, with uplifting taking place at the base-plate level. An alternative is to allow rocking at the foundation level, simply by under-sizing the foundation. This paper explores the efficiency of such design alternatives, using a 3-storey building as an example. Three alternatives are compared, using a steel-braced frame as reference. The performance of a *Base Plate Rocking Structure* is compared to that of a *Foundation Rocking Structure*, along with a hybrid solution combining both mechanisms. The study is performed employing the finite element method, accounting for geometric and material nonlinearities. The models are validated against published experimental results, thus offering credible insights.

1. Introduction

Conventional Steel Braced Frames (SBFs) are widely used as earthquake-resisting units for steel structures, as they are simple and rather economical to construct, and can be easily integrated in the structural system. Despite their good and well-documented seismic performance, the absorption of seismic energy is in the form of brace buckling. In such systems, the seismic damage is distributed throughout the main structural members, and the post-earthquake residual drifts may be concentrated in a single story (typically the ground floor), rendering their post-earthquake repair costly and time-consuming, if not impossible. Aiming to improve the seismic performance and facilitate post-seismic repairs, earthquake-resisting units equipped with specially-designed fuse elements have been proposed [1–5]. Such systems have a clear advantage, as the damage is concentrated in easily replaceable fuse elements, thus offering superior performance and reduced repair cost.

Among such modern seismic design concepts, rocking systems are considered to offer a valid alternative in terms of control and reduction of the seismic damage in buildings after major seismic events [6,7]. Several experimental and numerical studies have been performed to investigate the seismic performance of steel rocking frames [8–14]. In such Steel Rocking Structures (SRS), various energy-dissipating members such as yielding base plates [14] and butterfly steel shear fuses [13] are introduced. The restoring forces are provided by the structure’s self-weight and Post-tensioned (PT) cables. According to the previously mentioned studies, such rocking systems offer significant reduction in terms of base shear demand and Flexural Story Drift (FSD).

In the research conducted so far, rocking is constrained within the superstructure, with uplifting taking place above the foundation. These systems are termed Base Plate Rocking Structures (BPRS), as special “uplift-free” base connections are employed to allow uplifting at the base plate level. An alternative is to allow rocking at the foundation level, simply by under-sizing the foundation to promote full mobilization of its bearing capacity [15]. To date, several studies have highlighted the advantages of allowing such strongly nonlinear foundation response (e.g. [16–26]). In such a case, termed hereafter Foundation Rocking Structure (FRS), conventional fully-fixed base plates can be used to connect superstructure elements to the foundation. As discussed [15], the foundations are intentionally under-dimensioned so as to uplift and mobilize the strength of the supporting soil, acting as a *rocking–isolation* mechanism.

Despite the extensive research on the development of such innovative structural systems, their application in engineering practice is still limited. In many cases, the analyzed or tested systems are not accurate representations of real structures, and

---

* Corresponding author.
E-mail addresses: a.riyahi@iiees.ac.ir, Abolfazlriahinouri@gmail.com (A. Riahi Nouri).

[1] Past address: National Technical University of Athens, Greece.

http://dx.doi.org/10.1016/j.soildyn.2016.02.002
0267-7261/

therefore the derived results are not necessarily relevant for their design [14]. One such practical aspect, which is typically ignored by considering simplified assumptions for base conditions, is the presence of soil underneath the foundation and the associated soil–structure interaction [27]. The latter may alter the response of the rocking system, and its effect should be explored. Moreover, in order to promote their application in practice, it is necessary to comparatively assess their performance to that of conventional systems.

This paper explores the seismic performance of such rocking systems, using a typical low-rise 3-storey building as an illustrative example. The selected structure is among the ones used by the SAC Joint Venture Project [28], and has been adopted by [13] for the detailed study of their proposed Base Plate Rocking Structure (BPRS). Three different rocking design alternatives are comparatively assessed, using a (fourth) conventional Steel Braced Frame (SBF) as a reference. The efficiency of a BPRS system is compared to a FRS, along with a hybrid solution which combines both rocking mechanisms (structural or within the foundation soil).

2. Problem definition

As schematically illustrated in Fig. 1, the present study investigates the seismic response of a typical low-rise Steel Rocking Structure (SRS), aiming to derive insights on the key factors affecting its performance. Among the buildings of the SAC Joint Venture Project [28], a 3-storey structure is selected for the conducted analyses, being considered representative of typical low-rise structures. As illustrated in Fig. 2, the studied structure is a typical 4×6 bay residential 3-storey building, with typical floor and roof framing, designed under the assumption that it is located near Los Angeles, CA. In each direction, two lateral earthquake-resisting units are installed along the exterior axes, with the remaining structural members designed purely against gravity-loading, assuming that the seismic loads are solely undertaken by the earthquake-resisting units.

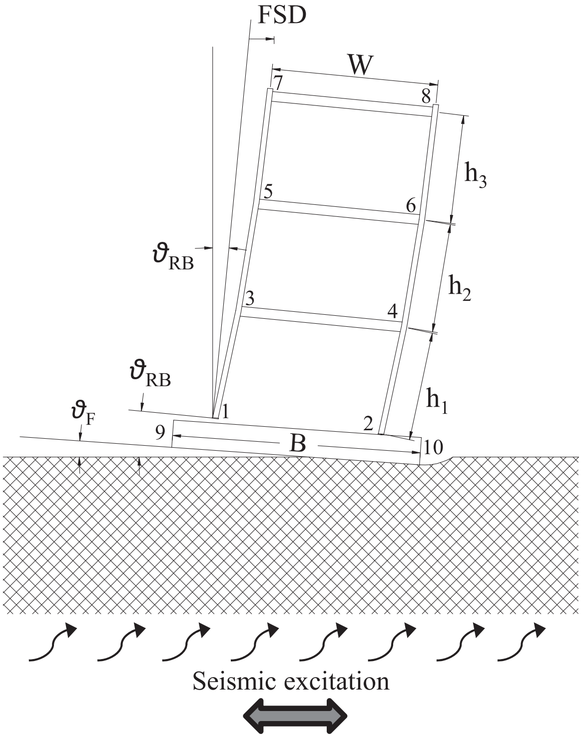


Fig. 1. Typical low-rise Steel Rocking Structure (SRS) subjected to seismic loading: problem definition and key parameters.

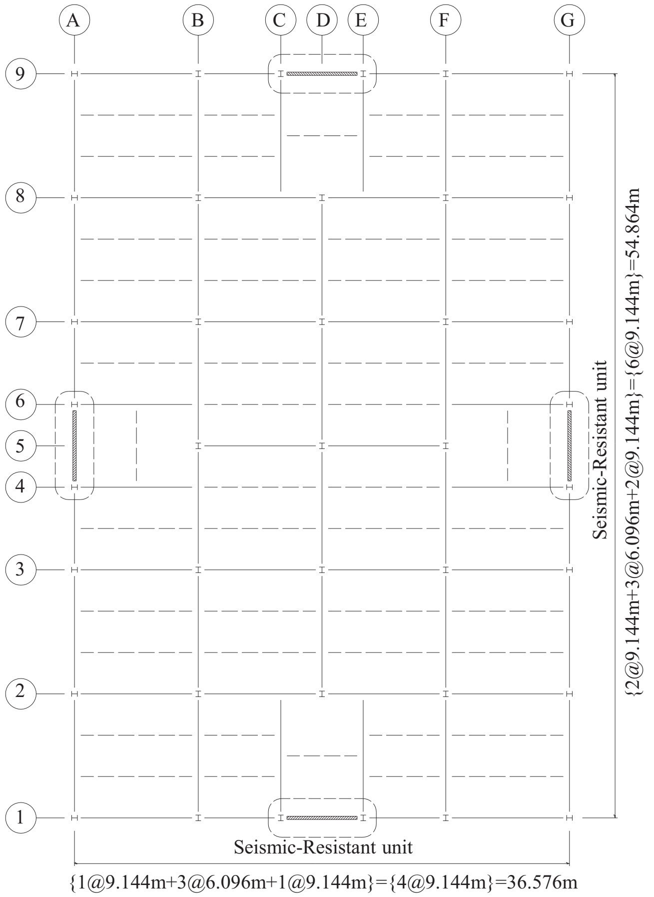


Fig. 2. Plan view of the structure showing the locations of the seismic-resistant units.

Fig. 3 summarizes the key dimensions and the specifications of the earthquake-resisting units, for both the rocking and the conventionally-designed structures. The study adopts the design proposed for a Base Plate Rocking Structure (BPRS) in the literature [13], utilizing butterfly shear fuses and PT-cables, as illustrated in Fig. 3a. A conventional Inverted Chevron-Braced Frame (IVBF) is also designed for the same prototype building, to be used for comparative assessment purposes (Fig. 3b). The dimensions of key structural components for the conventional and the rocking structures are summarized in Table 1.

As summarized in Table 2, four design alternatives are comparatively assessed: (a) a conventional IVBF on a conventional (code-designed) foundation (CF), denoted as IVBF-CF; (b) a BPRS structure on a conventional foundation (CF), denoted as BPRS-CF; (c) a BPRS structure, but using an intentionally under-designed rocking foundation (RF), denoted as BPRS-RF; and (d) a Foundation Rocking Structure (FRS), also using a rocking foundation (RF), and denoted as FRS-RF. The rocking foundation is intentionally under-designed to promote uplifting and full mobilization of bearing capacity, as proposed by [29] and further explored by [15]. In this particular case (FRS), since the uplifting takes place at the foundation level, the butterfly fuse and the PT-cables are not required. The associated cost reduction is considered as a comparative advantage of the FRS design alternative, provided of course that the performance is not adversely affected.

While the first two design alternatives (IVBF-CF and PBRS-CF) can be analyzed assuming simplified base conditions, for the two SRS systems with under-designed rocking foundations (BPRS-RF