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Seismic performance of controlled spine frames with energy-dissipating members

T. Takeuchi *, X. Chen *, R. Matsui *

Department of Architecture and Building Engineering, Tokyo Institute of Technology, Tokyo, Japan

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ABSTRACT

Recently, various controlled rocking systems have been proposed in seismic design to prevent damage concentration and to achieve self-centering against a wide range of input ground motion intensities. However, several obstacles must be overcome before these systems can be applied to actual buildings; for example, the requirement for large, self-centering post-tensioned strands and special treatment at uplift column bases must be addressed. This paper proposes a non-uplifting spine frame system with energy-dissipating members without post-tensioned strands, its self-centering function is achieved by envelope elastic-moment frames. The system is applied to an actual building constructed in Japan. Conventional shear damper and uplifting rocking systems with post-tensioned strands developed in prior studies are also applied to the same building structures, and the performances of the three systems, including damage distribution, energy dissipation, self-centering, robustness against severe earthquakes, and irregular stiffness, are compared and discussed through numerical simulations based on practical design criteria.

1. Introduction

Steel moment-resisting frames are susceptible to large lateral displacements during severe earthquake ground motions and require special attention to limit damage to nonstructural elements. In the last few decades, buckling-restrained braced frames (BRBFs) have become increasingly popular, particularly in Japan and the USA, because of their superior seismic performance in limiting damage, maintaining functionality, and facilitating repair. Well-balanced buckling-restrained braces (BRBs) are required for ensuring the high seismic performance of BRBFs. This means that the yielding forces of the BRBs in each story are proportional to the story stiffness thus the BRBs yield at the same time in a first-mode response pattern. However, after the yield of the main frame under large seismic intensity, the low post-yield tangent stiffness of the braces may concentrate damage and residual drift in limited levels, even though brace capacities are relatively well balanced over the height of the structure [1].

Self-centering seismic resilient structural systems possessing the ability to limit residual drifts to negligible magnitudes have also been proposed. There are roughly three types of self-centering systems: (1) moment-resisting frames with post-tensioned (PT) beam-to-column connections and flexible floor systems that allow gaps to open between the beam-to-column connections [2]; (2) braced frames with self-centering braces or buckling-restrained braces (BRBs) that can return after loading to their initial length because of super-elastic pretensioned elements [3,4]; and (3) rocking systems that can self-center, relying on the restoring force of gravity, and PT elements [5–8].

Rocking motions may reduce damage to structures during ground motions. This behavior was observed as early as 1963, by Housner [9]. Clough and Huckelbridge [10] conducted some of the earliest rocking frame tests and compared them with a conventional pin-base frame. They found that the member force of the rocking frame was lower than that of the conventional frame. Priestley et al. [11] developed a simple method to evaluate the rocking response of structures via the displacement response spectra using the equivalent damping of the rocking system.

In the last decade, the rocking system has been used frequently in both retrofitting and new building design. Wada et al. [12] employed a pivoting spine concept in the seismic retrofitting of a concrete building in Japan and Janhunen et al. [13] employed a similar spine concept in the seismic retrofitting of a steel building in the USA. A concrete wall acts as the core of the rocking to redistribute the lateral forces and displacements without adding significant strength. Günay et al. [14] investigated the seismic performance of a brittle reinforced concrete frame, which was retrofitted with rocking infill walls, and proved its efficacy in reducing soft-story failure risks.

Eatherton et al. [15–18] studied an uplifting rocking frame system with PT strands that provide self-centering resistance. Steel butterfly-shaped fuses and BRBs were employed as replaceable energy-dissipation members. Midorikawa et al. [5,19] conducted shaking-

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* Corresponding authors at: Tokyo Institute of Technology, M1-29, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan.

E-mail addresses: ttoru@arch.titech.ac.jp (T. Takeuchi), chen.x.ad@m.titech.ac.jp (X. Chen), matsui.r.aa@m.titech.ac.jp (R. Matsui).

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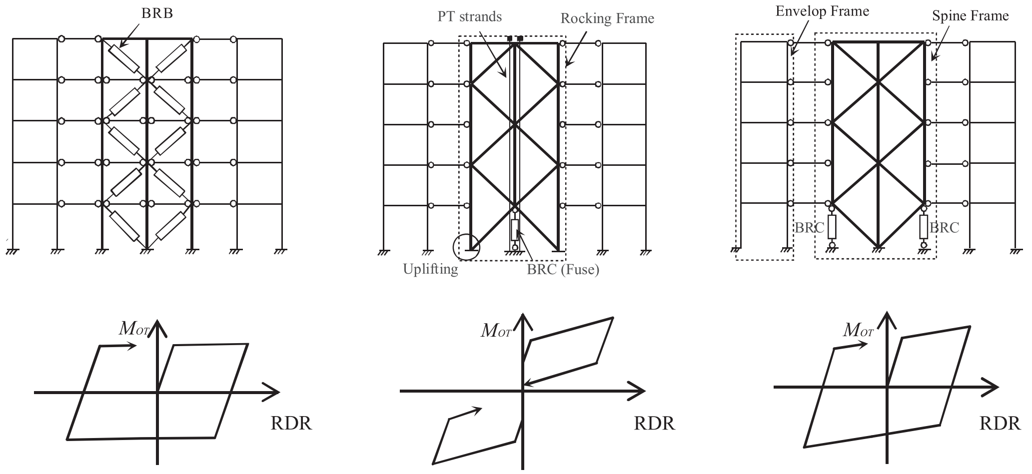

(a) Shear Damper (SD) system (b) Uplift (LU) system (c) Non-uplift (NL) system

Fig. 1. Concept of element configuration and hysteretic curves of the three structural systems.

table tests of a half-scale three-story rocking frame after installing yielding plates at the bases of columns to dissipate energy. Wada et al. [7] used a similar concept at the connections of columns in the middle story of a slender, tall frame. Tremblay et al. [8] proposed a braced steel frame with viscous dampers vertically equipped between the column bases and the foundations.

Ikenaga et al. [20] developed a column base consisting of PT bars and steel plate dampers. Takamatsu et al. [21] proposed a column base with anchor bolts that dissipate energy by elongation. Takeuchi and Suzuki [22] used buckling-restrained columns (BRCs) at the bases of truss frames to concentrate major damage into the BRCs and prevent collapses caused by the buckling of members in the main structure.

As mentioned above, effective and economical structural systems eliminating damage concentration and residual drift after large earthquakes are needed and have been frequently investigated; however, applications to actual buildings are not yet popular. This is mainly because several obstacles must be overcome, such as the need for large, self-centering PT strands and special treatment at uplift column bases. To eliminate these difficulties, in this paper, we investigate a non-uplifting spine frame system without PT strands whose self-centering function is achieved by envelope elastic-moment frames. The proposed system was tested by applying it to an actual building structure under construction, and its performance is compared with a conventional BRBF and controlled rocking frame with PT strands.

2. Design and modeling of structural systems

2.1. Concepts of non-uplifting spine frame systems

Fig. 1 shows the three structural systems examined in this paper and the relationship between the overturning moment (M_{OT}) and roof drift ratio (RDR) of the proposed system compared with the two existing systems. A conventional frame with shear dampers as BRBs (hereafter referred to as the SD system; Fig. 1(a)) generally shows excellent performance as long as the main structure is well balanced in terms of stiffness and remains elastic. However, for unbalanced and elasto-plastic ranges of the main frames, damage concentration at weak stories and residual deformations are expected after an earthquake. To decrease such risks, a controlled uplifting rocking frame system (hereafter referred to as the LU system; Fig. 1(b)) was proposed [24], in which a rocking spine frame was introduced to distribute damage uniformly throughout the stories and PT strands were introduced to achieve self-centering functions. However, the prestressed forces required for PT strands are higher than the expected residual forces of energy-dissipation fuses (BRCs), which often reach to several thousand kN in actual projects, and the details of uplifting systems tend to be complicated. To overcome these problems, a non-uplifting spine frame system

Fig. 2. Materials Research Center for Element Strategy (MCES), Tokyo Tech.

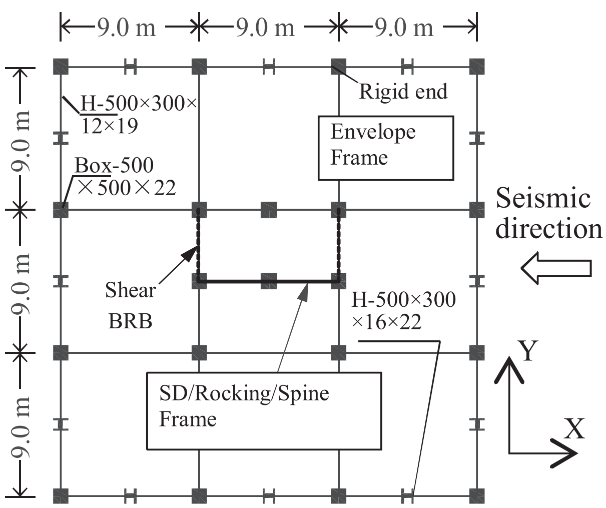

Fig. 3. Plan of the building.