Engineering Structures 146 (2017) 105–117

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic retrofit design method using friction damping systems for old low- and mid-rise regular reinforced concrete buildings

Ki Hoon Moon [a], Sang Whan Han [b,*], Chang Seok Lee [b]

[a] Disaster Prevention Research Team, Daewoo Institute of Construction Technology, Suwon, Kyungki-do 440-210, Republic of Korea
[b] Department of Architectural Engineering, Hanyang University, Seoul 133-791, Republic of Korea

ARTICLE INFO

Article history:
Received 18 January 2017
Revised 8 April 2017
Accepted 15 May 2017

Keywords:
Seismic retrofit
Friction damper
Braced frame
Damping system
Seismic performance
Reinforced concrete

ABSTRACT

In seismically active regions, many old low- to mid-rise reinforced concrete (RC) buildings are in use that have poor reinforcement details and suffer from material deterioration. Because these buildings are vulnerable to earthquakes, they represent a threat to human lives and economy. To impart such a building with satisfactory seismic performance, a friction damping system can be used, which consists of dampers and a braced frame. In this study, a method for the design of friction damping systems is proposed for the seismic retrofit of old low- to mid-rise regular reinforced concrete (RC) buildings. The proposed method is verified using a six-story RC building designed considering only gravity loads.

1. Introduction

Many old reinforced concrete (RC) buildings exist in densely populated areas. They usually have poor reinforcement details such as lap splices of column longitudinal bars located just above the floor level, widely spaced column transverse bars, short lap splice length, and insufficient development length of reinforcing bars. In addition, materials deteriorate with time. Such insufficient reinforcement details and deteriorated materials increase the vulnerability of old RC buildings to earthquakes. Most of these structures were designed considering only gravity loads, not seismic loads [1], and have columns weaker than adjacent framing elements that could cause inelastic displacement demands to concentrate on the columns during earthquakes [2]. During large earthquakes, many old RC buildings behaved poorly, suffering significant damage and collapse [3,4].

To improve the seismic performance of old building structures, various types of passive damping systems have been developed [5]. A damping system is defined as the collection of structural elements that includes all individual damping devices, all structural elements or bracing required to transfer forces from damping devices to the base of a structure [6]. Damping systems improve seismic performance and are also simple to install. Unlike conventional seismic retrofit procedures, those using dampers do not require significant demolition and replacement of existing elements; therefore occupancy and building operation are not significantly interrupted during the process of installing damping systems. Friction dampers are one type of displacement-dependent passive damping devices developed to efficiently dissipate the seismic input energy exerted on a structure. The response of a displacement-dependent damping device is primarily a function of the relative displacement between each end of the device, and is substantially independent of the relative velocity (Chapter 18 of ASCE 7–10 [7]). Because friction damping devices require lower cost and less maintenance effort compared to other damping devices, they have been widely used for the seismic retrofit of existing buildings [8,9].

Many friction damping systems have been developed [10–12]. In buildings with friction dampers, most seismic input energy is dissipated by the dampers during earthquakes, preventing significant damage in main structures [8,13]. Monir and Zeynali [14] reported that friction dampers reduced the lateral displacement and base shear force demands for multi-story building frames. The responses of torsionally irregular structures can also be reduced by using friction damping systems, resulting in improved seismic performance [15]. Seismic performance was evaluated using nonlinear response history analyses for structural systems with various types of friction and hysteretic dampers [16–18].

* Corresponding author.
E-mail address: swhan@hanyang.ac.kr (S.W. Han).

http://dx.doi.org/10.1016/j.engstruct.2017.05.031
0141-0296/

To guarantee that friction damping systems impart satisfactory seismic performance to existing buildings, a proper method should be developed for the design of damping systems [19,20]. In ASCE/SEI 7–10 [7], a design procedure is provided for new structures with damping systems, whereby seismic demands are estimated based on an equivalent linearization method using effective damping and secant stiffness [21,22]. However, the equivalent linearization procedures can lead to multiple results for individual ground motions [23], and produce maximum displacements much different than those obtained from nonlinear response history analyses (RHAs) [24,25]. Also, this procedure does not necessarily guarantee convergence in analyses.

In the present study, a simple and accurate method is proposed for the design of friction damping systems consisting of braced frames and friction dampers for the seismic retrofit of existing old low- to mid-rise RC buildings whose seismic responses are usually dominated by the fundamental mode. Using the proposed design method, friction damping systems are designed for a structure to reduce its maximum inelastic displacement to ensure that it remains within a limiting displacement during a design-level earthquake. The limiting displacement considered herein is the lateral displacement in excess of which the structure experience a drop in lateral strength. The maximum inelastic displacement demands for original and retrofitted structures are estimated herein using the elastic displacement of an equivalent single-degree-of-freedom (SDF) system and an inelastic displacement ratio, rather than using the equivalent linearization procedure with secant stiffness and equivalent damping. As a model structure, we study a six-story RC building that was designed considering only gravity loads. To verify the proposed design method, we compare the seismic performance of the original and retrofitted model structures based on the results obtained from nonlinear RHA.

2. Structures retrofitted using damping systems with braces and friction dampers

Structures can be retrofitted using friction damping systems to improve their seismic performance during earthquakes. A friction damper activates and dissipates energy when the friction force exerted on the dry surface of the friction damper reaches its maximum friction force (slip force); however, before its activation, the friction damper acts as a rigid element, which normally increases the lateral stiffness of the structure.

A damping device is often installed with a braced frame (Fig. 1). Recently, toggle braces with dampers (Fig. 1d) have been developed for improving the efficiency of dampers [26].

Fig. 2 illustrates original old structure, damping system (braced frame with dampers), and retrofitted structure (original structure retrofitted with the damping system) and their respective pushover curves. The ordinate and abscissa in the pushover curves are the base shear force (V) and the roof displacement (u_r), respectively. In Fig. 2, the subscripts O, D, and R respectively refer to the original structure, the damping system and the retrofitted structure.

Old RC structures constructed designed without consideration of seismic loads are vulnerable to earthquakes. Since these structures are not sufficiently ductile, their strength may drop abruptly after reaching their maximum lateral strength (Fig. 2a).

In contrast, damping systems with braced frames and friction dampers (Fig. 2b) behave in a ductile manner similar to that of elastoplastic systems. In Fig. 2b, the elastic stiffness of the damping system (K_D) is the same as that of a braced frame because a damper placed in the brace acts as a rigid element before it starts to slip. If V in the damping system reaches the slip force (V_{d-D}), the dampers start to slip and dissipate energy due to friction. Once the dampers

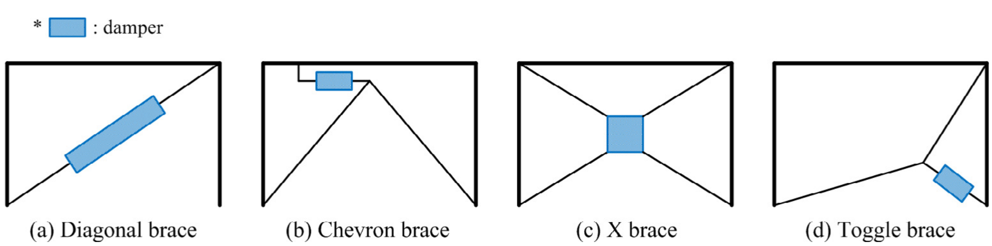

Fig. 1. Damping systems with braces and dampers.

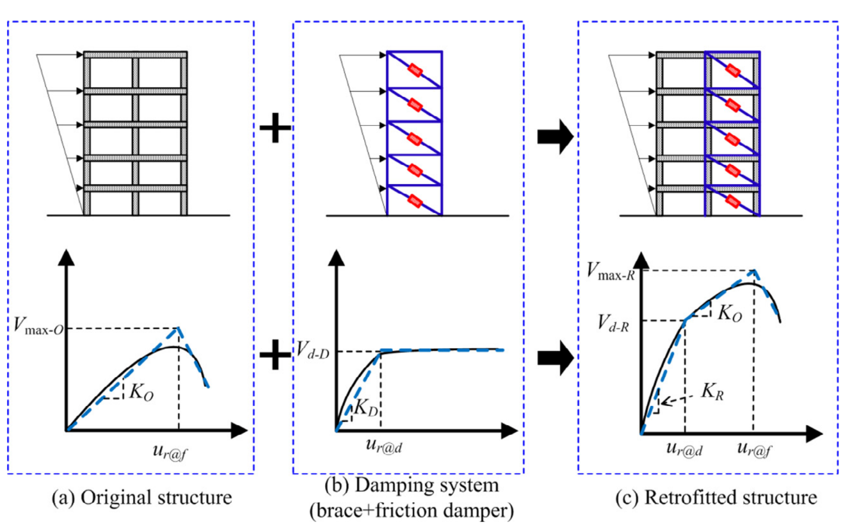

Fig. 2. Existing, damping and retrofitted structures and their pushover curves.