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Improving seismic performance of non-ductile reinforced concrete frames through the combined behavior of friction and metallic dampers

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ABSTRACT

This paper describes a seismic strengthening technique using a wall-type damping system (DS), targeted at moment-resisting frame buildings. The DS under consideration is a hybrid damper which works through the combined and multi-phase action of a friction damper (FD) and a metallic damper (MD). To assess the seismic effectiveness of the proposed system, full-scale cyclic tests were conducted on a bare reinforced concrete (RC) frame with non-ductile detailing and four damper-strengthened frames. The RC frame showed highly pinched behavior, whereas the hysteresis curves of strengthened frames were more stable due to the activation of FD and/or MD, forming a larger loop area. The deformation capacities of the RC frame and strengthened frames were not significantly different, but the maximum strength, stiffness, and energy dissipation capacities were significantly improved in the strengthened frames. The calculated strength and stiffness equations accurately represented the actual behavior of the RC frame. Conversely, the stiffness values of the DS were considerably lower than predicted by theoretical equations as a result of the softening of anchorage fixity according to the connection details.

1. Introduction

Many older buildings are still in use which were designed only for gravity loads, without consideration of lateral forces. The majority of these are low-rise reinforced concrete (RC) frame buildings, and the effect of wind load is not significant enough to compromise their safety. However, the seismic capacity of such buildings is likely to be lower than the demand level required by current code standards. In particular, since they generally possess non-ductile structural details, serious damage can be caused by earthquake ground motions [1,2]. To enhance the seismic performance of existing low-rise buildings, strengthening techniques such as the addition of concrete infill walls [1,3] and steel bracings [4,5] have traditionally been employed. These strategies can greatly increase the lateral stiffness of buildings, and therefore story drift can be reduced.

New retrofit approaches have also been applied to existing RC buildings. These can reduce structural damage to existing frame members by concentrating seismic energy dissipation on reusable or replaceable damping devices [2,6–9]. More recently, studies have been carried out on multi-phase devices with combined behavior. Ibrahim et al. proposed a visco-plastic damper which combines a displacement-dependent device and velocity-dependent device [10]. Marshall et al. devised a hybrid passive control device comprised of a high-damping rubber damper and a buckling-restrained brace [11], and its performance was validated experimentally [12]. Karavasilis et al. verified the seismic performance of steel moment frames equipped with compressed elastomer dampers [13], and they also proposed self-centering viscoelastic damping devices [14]. In addition, a viscoelastic coupling damper was developed for tall buildings [15], and research was conducted to characterize the configurations of multi-phase systems using single-degree-of-freedom models [16].

Through an extensive review of experimental and numerical cases for a total of 165 buildings presented in previous research papers, Lee [17] confirmed that story drifts and base shear forces could be greatly reduced through the application of a supplemental damping system (DS). However, that study reported that incorporating dampers into a structure using bracing elements could cause large response acceleration and thereby increase potential economic losses associated with nonstructural damage. Consequently, a wall-type DS has been recommended as a feasible solution for existing moment frame buildings.

Based on this, a new type of hybrid DS called a SAFE Damper, which enables multi-level seismic protection and a moderate level of stiffness

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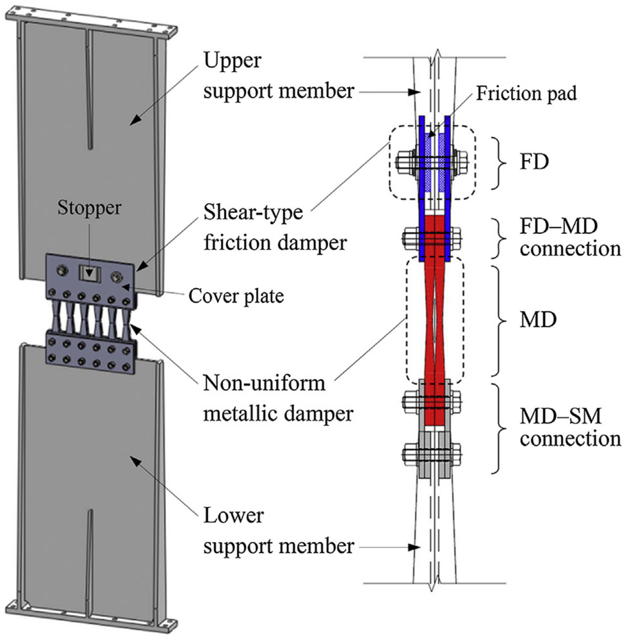

Fig. 1. Conceptual configuration of the hybrid damping system (SAFE Damper).

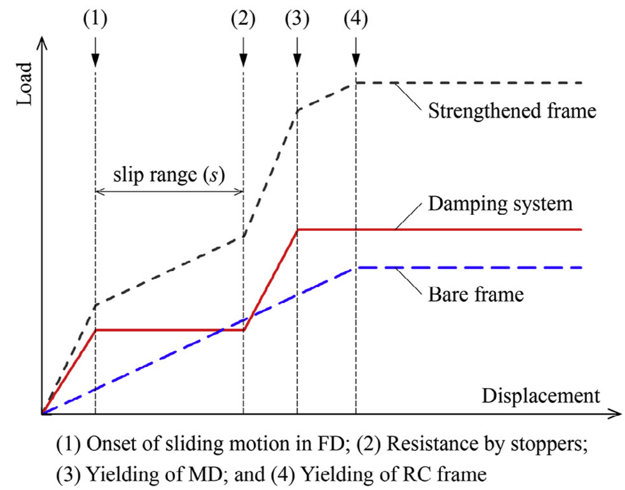

Fig. 2. Behavioral concept of a SAFE Damper-strengthened frame.

enhancement, has recently been proposed for strengthening existing frame-type buildings [17]. In this system, a hybrid damper (HD), comprised of a friction damper (FD) and a metallic damper (MD), is connected to floor beams through wall-type upper and lower support members (SM) (Fig. 1). In component tests performed previously, the individual structural performances of FD [18,19] and MD [20–23] were investigated in detail. It has also been confirmed through subassembly tests on HD [24] that combined multi-phase behavior between FD and MD functioned as intended. The actual behavior may differ from the idealized condition when the DS is installed in a building frame, but this has not yet been explored. This lack of empirical evidence regarding the actual behavior of damper-strengthened frames and uncertainty due to the use of scaled-down specimens raised the need for experimental validation on full-scale specimens [24].

Accordingly, this paper investigates the seismic improvement of non-seismically designed RC frames through the application of the hybrid SAFE Damper, thereby assessing the effectiveness of the proposed DS. The concept of the system is introduced first. Next, details of quasi-static cyclic tests are described which were carried out on five full-scale frame specimens (a bare RC frame and four damper-strengthened frames) for experimental verification. Based on load–displacement relationships and observed failure modes, the overall strengthening effect of the application of DS is evaluated. The results, such as deformation capacity, strength and stiffness characteristics, and energy dissipation are compared among specimens and explored in more detail. Additionally, by comparing theoretically predicted characteristics with experimental values, discussion and recommendations on factors that affect the actual behavior of DS are presented.

2. Description of the system

SAFE Dampers dissipate seismic input energy through the combined behavior of two different types of dampers. This system combines FD and MD so that a stable and predictable response can be obtained with less dependence on environmental conditions. As shown in Fig. 1, the DS consists of hysteretic components (FD and MD), FD–MD and MD–SM connection parts (CP), and upper and lower SMs, which can be easily installed using conventional steel construction methods.

Fig. 2 displays the behavioral concept of a frame strengthened with the SAFE Damper. The initial lateral stiffness of a frame is increased due to the addition of DS. When shear force transferred to DS reaches a predetermined slip load, a sliding motion of FD begins (Phase 1). The slip range (s) can be controlled by changing the dimensions of stoppers welded to the upper SM and the inner holes on cover plates. When the relative displacement (δ) of FD reaches s, the sliding friction motion ends. At this point, the stiffness of DS increases again, through the bearing resistance of the stoppers. Additional energy is dissipated through inelastic deformation after MD yields (Phase 2), followed by the yielding of frame members. In this way, the behavior is controlled in multiple phases according to the seismic demand level, which can reduce damage on component devices and thereby lower repair costs following an earthquake.

To determine the optimal configuration of DS, a series of experimental evaluations were designed as shown in Fig. 3. The present study focuses on full-scale frames, and the configuration and detailed dimensions of hysteretic component devices have been derived from prior studies on shear-type FD [19,24] and non-uniform metallic dampers (i.e., hourglass-shaped strip dampers) [21–24]. HD is connected vertically to existing frames through wall-type SMs with I-shaped cross-sections. SMs are designed to have tapered flanges so that double curvature bending moments can be efficiently resisted while maintaining adequate out-of-plane stiffness. By properly designing the flexural rigidity of SMs, a large portion of shear force, which may have been resisted by existing frames when subjected to lateral loading, can be transferred to DS. Simultaneously, excessive forces are prevented from being delivered to existing columns (which have limited cross-sectional strength and non-ductile detailing), and the need for seismic retrofit of foundations can also potentially be reduced. Notwithstanding, bending moments which may occur in existing beams due to the application of DS should be carefully considered and their effects taken into account when making a strengthening scheme with the given DS.

DS slightly increase the lateral stiffness of buildings since the bays are not fully braced. For this reason, seismic force reduction can be expected due to increased damping without great concern for an increase in acceleration response. SMs up to 800 mm wide are considered in this study, and thus only a small space is taken up by the DS. This feature minimizes damage to existing nonstructural functions and interference with necessities such as lighting and external appearance. All components are prefabricated at the factory, and only anchoring and fastening work is required on site. In addition, because only partial removal of existing partition walls (if they exist) is required before installation, the retrofit construction is expected to be relatively quick, easy, and inexpensive to implement.