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Numerical and experimental analysis of combined behavior of shear-type friction damper and non-uniform strip damper for multi-level seismic protection

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ABSTRACT

A new hybrid damper which combines a friction damper and steel strip damper is proposed for improving the seismic performance of structures at multiple levels of ground motion. In order to investigate the combined behavior of the proposed damper, quasi-static cyclic tests were carried out on ten specimens. Experimental results demonstrated that hysteretic response was stable, and multi-phased behavior (i.e., activation of two different kinds of dampers) functioned as intended. However, depending on the type of strip damper applied, the behavior and failure modes showed distinct differences due to rotational motion induced during combined behavior; deformation and energy dissipation capacities were enhanced when a strip damper with adequate out-of-plane stiffness was applied. Furthermore, numerical analysis based on both material strength and expected strength well represented behavioral characteristics of the damper, and dissipated energy was reliably predicted. It is expected that the proposed analytical model can be practically applied to predict the performance of structures strengthened by the hybrid damper.

1. Introduction

Over the past few decades, a considerable amount of research has been conducted concerning structural vibration control in order to safely protect buildings from earthquake hazards. These innovative systems can be categorized into seismic isolation systems and supplemental damping systems. Seismic isolation systems limit the input energy transmitted to the structure through an elongation of the fundamental period of a building, and isolators are generally installed between supports of the superstructure and the foundation [1]. On the other hand, supplemental damping systems aim to minimize damage to main structural components by absorbing seismic energy with mechanical dampers, which can also partially reduce the energy dissipation demand on the structure. Among these systems, those with passive devices are advantageous in practical implementations because of their low cost and maintenance requirements.

Passive damping devices can be classified into motion-dependent dampers (MDD), displacement-dependent dampers (DDD), and velocity-dependent dampers (VDD) based on the factors which govern their behavior. MDD are mainly used to improve human comfort for wind-induced vibration and are normally installed on the top of a building. Tuned mass dampers (TMD) or tuned liquid dampers (TLD) are included in this category. DDD and VDD are applied to absorb vibration energy caused by wind or earthquakes, and they are commonly placed between floors. Friction dampers (FD), metallic dampers (MD), and buckling-restrained braces (BRB) are examples of DDD, and viscous fluid dampers (VD) and viscoelastic solid dampers (VED) are types of VDD [2]. Various types of passive dampers have been implemented in buildings [3,4]. However, those are primarily aimed at controlling the structural response against a single source of vibration.

In order to achieve greater cost-efficiency and optimize implementation, further studies have been carried out recently on hybrid dampers which use a single device to control different levels of external vibration. To control motion from both wind and seismic loads, Smith et al. devised a damped outrigger system using VD and implemented it in a building in the Philippines [5],

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and Kim et al. proposed the H-BRB system which combines VD and BRB [6]. To control dynamic vibrations of tall coupled shear wall buildings, the concept of the viscoelastic coupling dampers was introduced by Christopoulos et al. [7], and its performance was subsequently verified experimentally [8]. For the purpose of controlling multiple levels of earthquake-induced vibrations, Ibrahim et al. combined VED and MD [9], and Marshall and Charney developed a hybrid damper comprised of VED and BRB [10]. Also, Karavasilis et al. performed characterization tests on compressed elastomer dampers which displayed viscous-like damping performance under small deformations and friction-like damping performance under large deformations [11]. In their study, the applicability to seismic design of steel moment frames was evaluated through nonlinear time history analyses, and it further validated using real-time hybrid simulations [12]. Finally, a type of self-centering system was also presented which combined a self-centering device and VED [13]. As shown above, most of the previously proposed hybrid dampers used viscous or viscoelastic materials as part of the system. This partially helps to prevent excessive forces from occurring in structural members because the response of the damper is out of phase with structural forces to some degree. On the other hand, the behavior of those materials, in general, does show dependency on frequency, strain, and temperature [14,15].

Many buildings currently in use are low-to-mid-rise buildings. Generally, they are sufficiently stiff so that wind-induced dynamic response is negligible [16], and their lateral load-resisting systems are usually chosen based on earthquake loads. Nevertheless, even when passive dampers are applied for seismic vibration control in a rehabilitation (or new construction), to satisfy the drift criteria for wind-induced forces, the lateral stiffness of the implemented system should not be lower than that of the original system. Furthermore, since the concept of performance-based seismic design is being introduced into building codes in many countries, it is necessary to ensure seismic performance for different levels of ground motion.

With this background in mind, a new type of hybrid damper which improves the stiffness of a building under wind loads and is activated in phases according to the level of seismic demand is proposed in this study. In order to achieve high energy dissipation efficiency and stable behavior with less impact from external factors such as frequency and displacement, the proposed damper combines two different kinds of hysteretic devices (i.e., FD and MD). Additionally, because the dampers are fabricated using common steel construction methods and component materials are easily available, they have a lower initial cost. However, the behavior of FD may be influenced by various conditions, such as surface finish, sliding velocity, normal force, contact pressure, wear, and temperature [17]. To obtain reliable performance and a high friction coefficient, Hwang et al. [18] and Lee [19] proposed a shear-type friction system which had new low-steel composite friction pads and milled-steel surface, adapted from automotive braking technology. In their experimental studies, the system provided high friction performance compared to existing FD. Also, its behavior was not significantly affected by loading amplitude, frequency, velocity, and ambient temperature, even under hundreds of repetitive cycles. For the above stated reasons, the hybrid damper (Fig. 1) is comprised of a shear-type FD [18] and a non-uniform MD [20] which were developed in advance. In this system, seismic energy is dissipated by FD which can form stable and uniform hysteresis under a number of repetitive motions in low-to-moderate demand level. During a strong earthquake, MD continuously dissipates energy through inelastic deformation after the operation of FD. By limiting the operating range of different kinds of dampers according to the seismic demand, repair and replacement costs can be minimized, which will ultimately save life cycle costs.

This paper investigates the multi-phase performance of the proposed hybrid damper. The full makeup of the damper and concept of multi-phased behavior are described first. For experimental verification, a total of 10 specimens were tested cyclically. The global hysteretic responses among specimens are compared from the results, and the distinctive behavioral characteristics and failure modes are analyzed and discussed. Then frictional behavior, strain behavior, hysteretic behavior of strip dampers, and energy dissipation capacity are evaluated sequentially. A discussion is also included of the analytical process by which the multi-phased behavior is predicted, and a comparison of the analysis and test results follows.

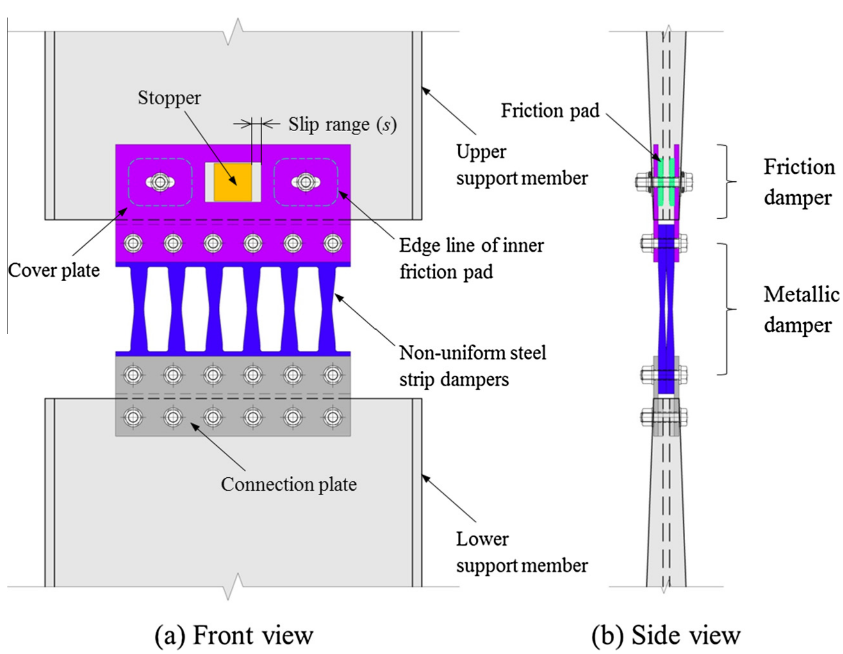

Fig. 1. Conceptual configuration of the hybrid damper.