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# Hourglass-shaped strip damper subjected to monotonic and cyclic loadings

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ABSTRACT

An hourglass-shaped strip damper (HSD) was proposed to improve on the conventional slit damper. The damper has non-uniform strips which have a smaller cross-sectional area close to the middle height. To find the structural capacities of HSD subjected to monotonic and cyclic loadings, experimental tests were carried out in this study. Test parameters were loading rate, material strength, and the number of damper plates. The results showed substantial load–resistance capacity under monotonic loadings, and excellent ductility and energy dissipation were exhibited under cyclic loadings, with even distribution of damage over the entire height of strips. Based on the test results, a simple hysteretic model using a combined isotropic–kinematic hardening rule was also proposed. The comparison demonstrated that it represents the tested cyclic load–displacement hysteresis well. It is expected that the proposed model can be successfully used to predict the behavior of HSD in real-world applications.

## 1. Introduction

Many older low- to mid-rise buildings were not properly designed for resisting seismic loads. Since these buildings have insufficient strength and stiffness, as well as non-ductile detailing, they are vulnerable to serious damage or collapse during a strong seismic event [1]. Therefore, in order to use them safely, seismic strengthening strategies should be employed in existing buildings which lack good seismic performance. Many types of passive control systems have been studied over the past 40 years, and these are very promising for seismic retrofitting. Such systems do not require an external energy supply, but rather are activated by the movement of the main structure [2]. Therefore, they continue to function even during a power outage.

A metallic damper is one type of passive damping device. It dissipates earthquake energy through the plastic deformation of metal. As a displacement-dependent damper, the metallic damper is less sensitive to changes in the external environment such as velocity, frequency, and temperature. Because it is fabricated and installed using conventional construction methods, a structure can be strengthened at a relatively low-cost. For seismic application of a metallic damper, the following characteristics are required according to the applied lateral loadings: (a) the damper should provide adequate stiffness to the structure under service loads, such as wind; (b) seismic energy dissipation by the damper, not by the main structural system, must be maximized by designing the damper to yield at a low load level.

By equipping a structure with metallic dampers, stiffness is usually added as well as increasing damping [3]. Added stiffness is affected by damping systems which incorporate damping devices and connection elements such as bracings and wall-type columns. However, in terms of the device's stiffness itself, metallic dampers which resist the applied load through in-plane behavior [4,5] are more efficient than those which resist load through out-of-plane bending [3,6,7]. Among dampers which display in-plane behavior, a shear panel damper made of low-yield-point steel has excellent elongation capacity and considerable strain hardening [5,8]. On the other hand, a slit damper uses a normal strength steel and has slits in a direction perpendicular to the horizontal load so that it can be activated at relatively low load level [4,9].

Due to the unvarying width and thickness of strips in conventional slit dampers, stress is concentrated at the ends when subjected to external loads. In order to improve ductility and fatigue

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performance, recent studies attempting to optimize strip shapes have been carried out. In the study by Ghabraie et al. [10], strips were optimized with diamond-shaped holes derived through the application of a bi-directional evolutionary structural optimization algorithm, and performance was evaluated experimentally. Several types of non-uniform strip shapes (a dumbbell-shaped strip, a tapered strip, and an hourglass-shaped strip) were proposed by Woo et al. [11] and Lee et al. [12,13] for the purpose of simplifying the design and improving performance. The proposed dampers were tested under monotonic and cyclic loadings. They showed superior ductility and energy dissipation capacity compared to a conventional slit damper.

This paper concentrates on a detailed investigation of the structural performance of an hourglass-shaped strip damper (HSD) proposed by the authors. With this purpose in mind, various conditions focusing on real-world applications of the damper were established as variables, specifically loading type, loading rate ($v$), material strength of the steel, and the number of damper plates used. In order to evaluate the effect of each variable, a total of eight full-scale specimens were tested. From the experimental results, the structural characteristics are compared and discussed in terms of failure mode, strength, stiffness, deformation and energy dissipation. In addition, a simple hysteretic model defined by the combined isotropic–kinematic hardening rule is also proposed for predicting the behavior of HSD. Finally, the validity of the proposed model is evaluated based on the test results.

## 2. Hourglass-shaped strip damper

The typical configuration and geometry of an hourglass-shaped strip damper (HSD) is shown in Fig. 1. The strips each have identical dimensions. After removing unnecessary volume to optimize the shape, the strips have an hourglass shape in which the cross-section decreases from the ends to the middle. The shape was designed so that the plastic bending moment ($M_p$) can be reached at all cross sections simultaneously, and the area of the central part of the strip was decided in order to safely resist shear force [12] (detailed dimensions are given in Section 3.2). The damper material is KS SS400 steel which has a relatively low nominal yield stress ($F_{yn} = 235$ MPa) and is widely used in Korea.

The equations for the characteristics of non-uniform strip dampers are presented in Eqs. (1)–(3), which were derived from pure flexural behavior [12]. Plastic strength ($P_p$) denotes the horizontal force when the entire cross sections of the strip reach $M_p$, and Eq. (1) was formulated based on the cross section of the ends.

$$P_p = 2F_y t_1 b_1^2/4h \tag{1}$$

$$K_e = c\frac{E}{24\int_0^{h/2}(x^2/b_x^3 t_x)dx} \tag{2}$$

$$\delta_y = \frac{1}{c}\frac{2F_y t_1 b_1^2}{6h}\frac{24\int_0^{h/2}(x^2/b_x^3 t_x)dx}{E} \tag{3}$$

where $F_y$ is the yield stress, $t_1$ and $b_1$ are the thickness and width of the strip at the ends, $t_x$ and $b_x$ are the thickness and width at location $x$, $h$ is the height of the strip, $c$ is the stiffness coefficient, and $E$ is Young's modulus.

To calculate elastic stiffness ($K_e$) and yield displacement ($\delta_y$) of the strip in Eqs. (2) and (3), semi-fixed end conditions were assumed and $c$ was incorporated. The stiffness coefficient ($c$) is expressed as a ratio compared to the stiffness for fixed–fixed ends. The theoretical process for deriving these equations was explained by Lee et al. [12]. From the prior study, it was verified experimentally that the structural characteristics of the damper are predicted well by the equations.

## 3. Test program

### 3.1. General

A series of experimental tests for HSD were performed previously, the results of which are discussed in Refs. [11,12], including the fundamental behavior under monotonic and cyclic loadings. The previous research showed that the shape of HSD was well designed to improve ductility and fatigue performance. Valuable insight was gained from these efforts, but a limited number of conditions was covered by those tests. Forcing velocity and the tensile property of the damper plate may vary in real-life situations, so the impact of these variables should be evaluated. Additionally, behavioral characteristics need to be investigated with the number of damper plates as a variable in order to extensively design and

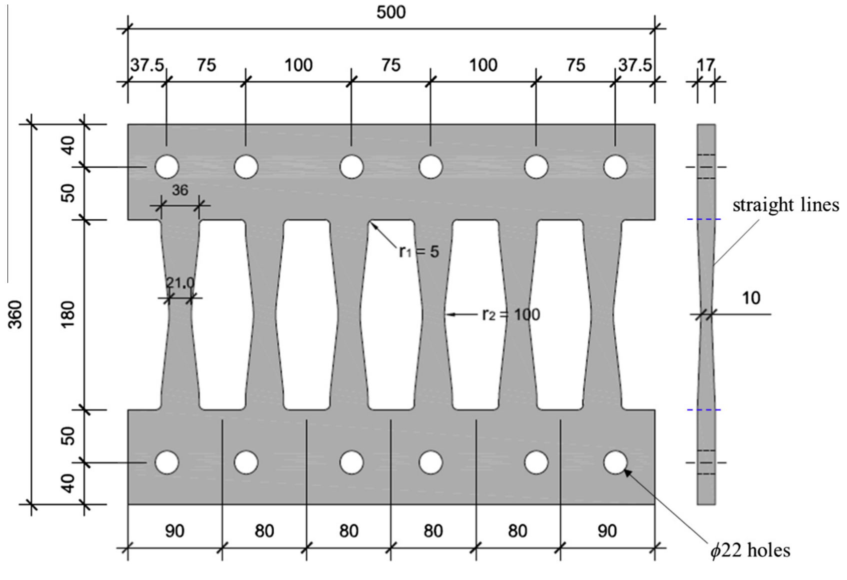

**Fig. 1.** Configuration and geometry of HSD.