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Online test of building frame with slit-wall dampers capable of condition assessment

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ABSTRACT

This paper presents the development of a passive damper device, consisting of a steel plate shear wall with vertical slits. The segments between the slits behave as a series of flexural links providing a ductile response without the need of out-of-plane stiffening. By altering the slit's configuration, condition assessment capabilities can be achieved. The feasibility of the modified slit configuration is demonstrated by finite element analyses. A three-storey building is studied, where steel plate shear walls with modified slit configurations are implemented as shear-resisting elements. The structure was tested using an online hybrid testing technique. The experiments indicate that the shear walls exhibited stable hysteresis, providing excellent energy dissipation and ductility. The condition assessment capabilities of the proposed device were demonstrated by recording the spreading of strain through the steel plates.

1. Introduction

In seismic design of steel structures, passive dampers have gained popularity as a response to the shortcomings of conventional structural designs [1,2]. The purpose of passive dampers is to concentrate hysteretic behavior in specially designed zones that initiates for interstorey drift levels smaller than those of other structural elements, thus delaying inelastic behavior in the gravity load-resisting elements of the structure.

Thin steel-plate shear walls may serve as passive dampers in both new construction and seismic upgrade of existing structures. However, unless heavily stiffened, the response of thin steel-plate shear walls is commonly accompanied by significant pinching in their hysteretic response, although the strength deterioration is compensated for by the development of a tension field [3]. The research on thin steel-plate shear walls was extended by experiments to investigate the behavior and failure mode of steel plate walls with different slenderness ratios [4], and the reduction of the earthquake-induced forces in beam-to-column connections when steel plate shear walls are used [5]. Summaries of research on modeling and design provisions on steel plate shear walls are documented in, for example, [6,7].

A passive damping device that consists of a steel plate shear wall with vertical slits (SW hereafter) has been previously devised [8] (Fig. 1). In this system, the steel plate segments between the slits behave as a series of flexural links, which undergo large flexural deformations relative to their shear deformation, providing a ductile response without significant out-of-plane stiffening of the wall. The stiffness and strength of the SWs can be controlled fairly independently of one another by changing the slit design (i.e., slit length, number of slit tiers, and distance between slits) [8,9]. The SWs are bolted to the surrounding frame, through connection plates welded to the flanges of the beams as seen in Fig. 1(b). The SW installation is carried out after the concrete floor slabs are placed in order to minimize the effects of gravity.

This study tries to extend the unique capacity of SWs so that they can also serve as a tool for structural condition assessment. Structural condition assessment [10] focuses on techniques for evaluating the integrity of a structure after an earthquake event to ascertain the danger that it represents for re-occupation of the building. Since its introduction, this evaluation has been performed through health-monitoring (for example [11,12]), or through performance-evaluation analyses that rely on detailed computer models of the structure. Unfortunately, the required technologies remain untested against actual large earthquakes, and the cost of implementing this technique restricts its use to important structures, such as large spatial structures, bridges, dams, and high-rise buildings. The small number of sensors used in these structures is only sufficient to identify the existence of damage by observing global changes in the vibration modes and frequencies. These restrictions encourage the development of a simpler method of estimating the damage sustained by a structure.

To comply to the serious need, this study proposes an alternative slit design in which condition assessment capabilities are added to SWs, whilst retaining their original function as damper devices. Unlike the conventional SWs in which the distance between slits is constant, the proposed SW features slitting with

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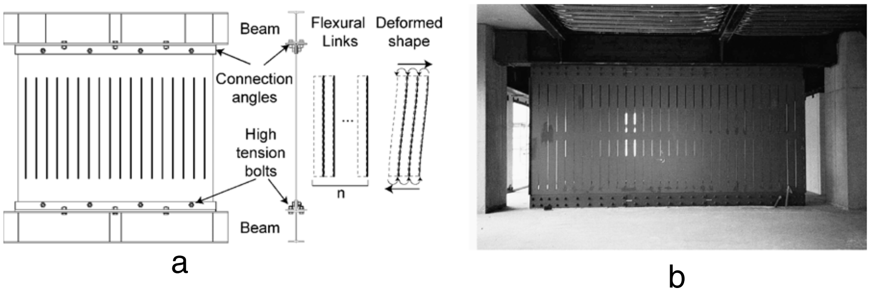

Fig. 1. Steel shear walls with slits: (a) Slit wall configuration; (b) Slit wall application.

unequal distances. This enables strain patterns that vary significantly over the plate and an eventual gradual spread of yielding with the increase of interstorey drift. This gradual spread is the key for the condition assessment, in which the experienced maximum interstorey drift is correlated with the yield region. For the identification of the yield region, brittle paint is considered in this study, since the flaking of brittle paint provides a permanent recording of the maximum strains experienced within the SW [13].

This paper first demonstrates an application of unequally slitted SWs as an alternative to conventional SWs with comparable energy dissipation capacity and the advantage of added condition assessment capabilities. To examine the capacity as hysteretic dampers of the unequally slitted SWs, an online hybrid test is conducted for a three-storey building installed with unequally slitted SWs. The structure is divided into two substructures; i.e., the shear-resisting span featuring the SWs that is tested physically and the backup frame that is treated numerically. Third, the performance of SWs for condition assessment is evaluated through the study of paint flaking and plastic strain distribution.

2. Steel shear walls and condition assessment

Procedures to estimate the elastic stiffness and ultimate strength of conventional SWs have been reported in [8] as well as recommendations on the width-to-height and width-to-plate thickness ratios of the flexural links that ensure the formation of plastic hinges at their ends. The slit designs used in this study follow these recommendations. Each flexural link can be examined independently from one another, and its behavior can be approximated to that of a double curvature column in the sense that each flexural link develops plastic hinges at the ends (See an inset in Fig. 1(a)). Therefore, the aggregated behavior of the flexural links can be approximated to a series of columns connected in parallel.

2.1. Unequal slitting to provide gradual yielding

This study is based on the assumption that it is possible to estimate the experienced maximum interstorey drift from the yield regions identified in the SWs. Several issues have to be considered when selecting a slit design for condition assessment purposes. First is the necessity of preserving the hysteretic (damping) characteristics of the slit wall by reducing unduly large strain concentrations at a portion of the plate. The second condition, directly related to the condition assessment capability, is to provide the maximum differentiation possible among the yield regions defined by different interstorey drifts. This can be achieved by spreading the higher strains generated at the end of slits over a larger area of the steel plate instead of concentrating larger strains in a small area. The spreading of the strains at the end of the slits prevents fractures that would otherwise occur when the SW is subject to large interstorey drift demands. Furthermore, a larger strain area increases the area where brittle coating flakes, which facilitates the identification of the interstorey drifts by the flake patterns.

The target slit design is to display strain patterns that gradually change or grow as the drift angle increases. Fig. 2(a) (top) shows an example of a conventional SW with dimensions that are plausible for a real application (3900 mm in width, 3000 mm in height and a plate thickness of 18 mm). This conventional SW was selected as a starting point for the search for a suitable modified slit design. The design consists of two unslitted sections at the top and bottom of the steel plate and a central section with slits of a uniform distance of 200 mm and a height of 2000 mm. A finite element model was constructed in ABAQUS [14] to estimate the hysteretic characteristics of the SWs. The model was constructed using thick shell elements of quadrilateral and triangular geometries. The model was fixed at the bottom boundary; the rotation at the top was restrained but not the vertical displacement. Out-of-plane deformations were restrained only at the top and bottom boundaries, and an initial imperfection equivalent to 1/100 of a half-sinusoidal wave was used to induce buckling. The model indicates that the uniform slit design defines a SW with an initial stiffness and maximum strength of 48 kN/mm and 576 kN, respectively. Fig. 2(b) (top) shows in different shades of gray the spread of the yield strain on the SW for interstorey drifts of 0.5%, 0.75%, 1.0% and 2.0%. Higher strain concentrations are observed at the ends of the slits, associated with the discontinuity in the strain field produced by the slits. It is apparent that there is scant differentiation among the yield strain regions for each drift angle; this discourages the possibility of associating the yield strain regions with drift angles.

Modified slit designs are proposed and analyzed in this paper to achieve a higher differentiation of the strain pattern for different drift levels. In the studied designs, the width and height of the flexural links were altered along the length of the wall. By carefully adjusting the geometry of each flexural link, the properties of the SW can be fine-tuned to attain a performance that is similar to conventional SWs while providing more freedom to the slit design.

To illustrate this concept, two examples of variable slit designs are shown in Fig. 2(a), and their respective yield patterns are shown in Fig. 2(b). The slitting used for “Type A” design (Fig. 2(a) (center)) presents a uniform width of the flexural links (180 mm) and slits whose length diminishes from 1800 mm at the edge of the plate to 600 mm at the center of the plate. It is apparent from comparing the yield region of this SW and the conventional slit design in Fig. 2(b) that larger yield regions can be achieved by this design. The slitting used in “Type B” design (Fig. 2(a) (bottom)) presents slits of a uniform length of 1800 mm, but the width of the flexural links varies from 125 mm at the edge of the plate to 375 mm at the center of the plate. In this case the wider flexural link generates higher stresses at the ends of the slits and therefore larger yield regions than the conventional design. Fig. 2(c) shows a comparison in the hysteretic response between the conventional and the modified slit walls obtained from finite element analyses,