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Development of a new partially restrained energy dissipater: Experimental and numerical analyses

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ABSTRACT

Energy dissipaters constructed in structures play an important fuse-type role in concentrating damage and protecting the primary structure. A stable hysteretic behavior, easy fabrication and a low cost are expected characteristics of high-performance energy dissipaters. Previously studied energy dissipaters have disadvantages such as difficult grouting, insufficiently hysteretic capacity and low material utilization. In this paper, a new partially restrained energy dissipater consisting of an inner core bar and an outer partially restraining tube was developed. The inner core bar is milled along the longitudinal direction of the core bar, avoiding the adverse effects of grouting and welding and improving the utilization of the material. Parametric studies on geometrical variables were performed to investigate the low-cycle fatigue behaviors and deformation patterns of the proposed partially restrained energy dissipaters. Test results showed that the partially restrained energy dissipaters demonstrated stable hysteretic performance, and no local or overall buckling was observed. Design guidelines concerning the prevention of torsion buckling, control of section expansion and avoidance of local failure of the transitional segment were developed. The buckling responses, contact conditions and plastic deformations were analyzed via validated numerical models.

1. Introduction

Methods of protecting main structures from damage during strong earthquakes have been proposed since the 2008 *Mw* 7.9 WenChuan (China) earthquake [1] and the 2010 *Mw* 7.1 YuShu (China) earthquake [2]. One feasible solution to this problem is the application of various energy-dissipating dampers, which act as 'structural fuses', in structural systems [3,4]. Among the applied energy-dissipating dampers, the conventional metallic energy-dissipating damper, called a buckling-restrained brace (BRB), shows stable hysteretic behavior under cyclic loading and has been extensively investigated. Detailed research studies on welded ribs [5], stoppers [6], unbonding material [7] and local torsional buckling [8] were conducted to deepen the understanding of the working and failure mechanism of the BRB and to improve its operational reliability. Different restraining systems for BRBs were also developed and enriched, such as the partially restrained BRB by Wang et al. [9] and triple-truss-confined BRB by Guo et al. [10].

All these BRBs investigated previously were characterized as large scale and as having a high bearing capacity. When BRBs with high bearing strength are incorporated into a structural wall with rocking capacity, a large amount of prestress can be required to achieve the structural rocking capacity [11]. The existence of the high prestress results in difficulties in restoring main structures and repairing energy-dissipating dampers. In addition, large-scale BRBs installed in structures often occupy much space, which presents challenges to architectural design. The described conditions limit the application of metallic energy-dissipating dampers in structural systems, so the development of relatively small energy dissipaters is thus required, which aims at achieving the following aspects: (1) extend the field of application of metallic energy-dissipating dampers in structural systems and (2) maintain sufficient space and provide more possibilities for architectural design.

Some significant research studies on energy dissipaters have already been conducted. As shown in Fig. 1(a), a fuse-type energy dissipater was proposed by Sarti et al. [12]. The fuse-type energy dissipater was made from a milled-down mild steel bar and grouting. Structural tests were conducted to verify the applicability and seismic performance of the relatively small energy dissipater [13,14]. According to existing research results, with a sufficient number of energy dissipaters and an appropriate configuration, this kind of energy dissipater, small scale and with a low bearing capacity, shows good seismic behavior and is in accordance with the structural requirements proposed to contend with significant seismic action. Furthermore, the potential of a small-scale energy dissipater in the structural seismic field has been proven via its application in

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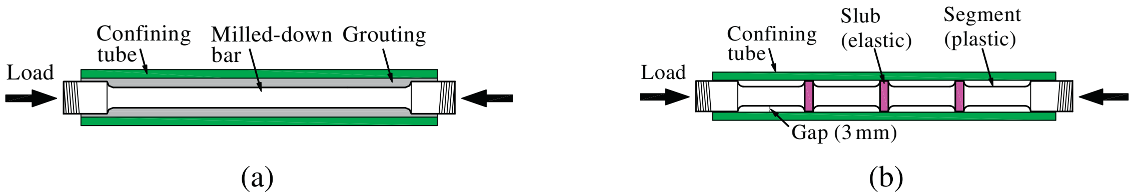

Fig. 1. Evolution of energy dissipaters: (a) fuse-type energy dissipater (Sarti et al. 2016 [12]) and (b) bamboo-shaped energy dissipater (Wang et al. 2017 [17]).

several buildings, including the Learning and Research Building at Victoria University in Wellington [15] and Trimble Navigation Offices in Christchurch, New Zealand [16]. However, the problems of the previously studied fuse-type energy dissipaters [12] cannot be neglected. These issues are identified as difficult grouting, insufficient compression performance and limited configurations [17].

Recently, a bamboo-shaped energy dissipater (BED) without grouting, depicted in Fig. 1(b), was proposed and tested by Wang et al. [17]. At the expense of material utilization, these BEDs addressed problems of the fuse-type energy dissipater, which were solved through uniformly distributed elastic slubs, and symmetric and stable compression and tension behaviors were finally achieved in BEDs. The elastic slubs controlled the lateral deformation along the BED's core but lost the energy dissipation capacity. One major concern for the BED was to improve the material utilization because a large ratio of elastic parts without energy dissipation capacity to plastic parts existed in the BED. An upgraded energy dissipater with stable, symmetric behavior and high material utilization should be further developed.

2. Conceptual proposal

For the recently developed energy dissipaters without grouting and welding, such as the bamboo-shaped energy dissipater, the ratio of the elastic portion without energy dissipation capacity to the plastic portion was relatively high, which reduced the utilization of the material. To quantitatively evaluate the material utilization in the energy dissipater, a factor called the material utilization factor, U_m, is introduced, as defined in Eq. (1).

$$U_m = V_p/(V_p + V_e) \tag{1}$$

where V_p is the volume of the plastic portion and V_e is the volume of the elastic portion. The material utilization factor was approximately 0.42 for a BED with four 40-mm segments and three 20-mm slubs. For details of the BED's geometrical dimensions, refer to the cited paper [17]. Less than half of the material was utilized in a typical BED in terms of the material utilization factor, which is uneconomical.

An upgraded conceptual proposal, shown in Fig. 2, was thus introduced herein to solve the disadvantage observed for the BED. Compared with the typical bamboo-shaped energy dissipater depicted in Fig. 1(b), the yielding segments in Fig. 2(b) were designed without slubs in the new proposal. By discarding the elastic slubs, the material utilization factor, U_m, can be largely increased. However, a problem with the deformation control occurred due to the absence of slubs, which were employed to control the lateral deformation of the bamboo-shaped core in BEDs. Inspired by the new restraining system (see Fig. 2(a)) discussed by Wang et al. [9], a similar mechanism was employed to provide effective restraining of yielding segments in the new proposal. The edges of the yielding segments were partially restrained by the partially restraining tube, so the possible lateral deformations of the yielding segments can be limited within the air gap (see Fig. 2(b)) between the corner of the yielding segment and the inner surface of the partially restraining tube. The yielding segments are designed to dissipate energy by entering the plastic regime while the other parts remain in the elastic regime during loading. To achieve this, the ratio of the cross-sectional area of the yielding segment, A_y, to the cross-sectional area of the other part, A_e, should be less than the ratio of σ_y to σ_u, as expressed in Eq. (2):

$$A_y/A_e \le \sigma_y/\sigma_u \tag{2}$$

where σ_y and σ_u are the measured yield stress and the ultimate tensile stress of the adopted material, respectively. The requirement proposed by Eq. (2) means that the stress in other parts remains less than σ_y, even if the stress in the yielding segments reaches σ_u.

This proposed type of energy dissipater is named the partially restrained energy dissipater (PED). Compared with the previously studied fuse-type [12] and bamboo-shaped [17] energy dissipaters, some advantages of the PED are summarized as follows:

(1) High material utilization. The removal of some elastic parts, such as slubs, increases the material utilization factor U_m. Most of the material is employed to dissipate the energy via plastic deformation.
(2) Effective restraining mechanism. In BEDs, the gap between the plastic segment and the confining tube is relatively large, up to 3 mm, as shown in Fig. 1(b). However, the gap between the corner of the yielding segment and the inner surface of the partially restraining tube is significantly reduced to approximately 1 mm

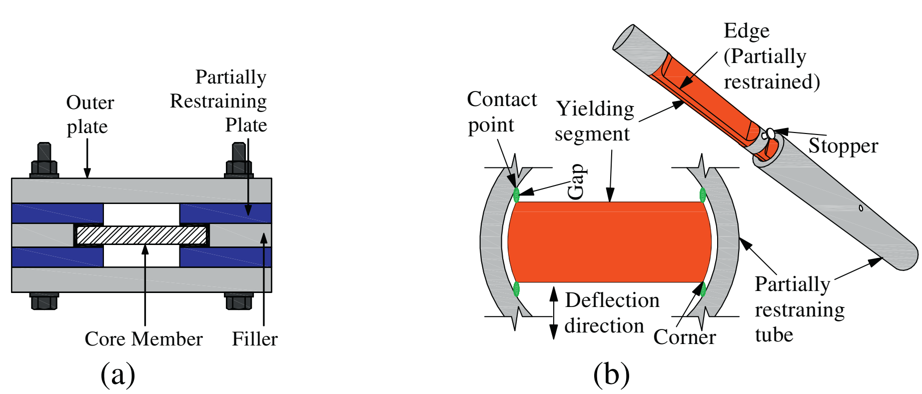

Fig. 2. Sketches for (a) a partially buckling-restrained brace (Wang et al. 2017 [9]) and (b) the PED.