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Experimental and numerical studies on hysteretic behavior of all-steel bamboo-shaped energy dissipaters

Chun-Lin Wang*, Ye Liu*, Li Zhou

Key Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education, Southeast University, Nanjing 210096, China

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ABSTRACT

Energy dissipaters constructed in precast structures play an important fuse-type role in concentrating damage and protecting the primary structure. The stable hysteretic behavior, easy fabrication and low cost are expected characteristics for high-performance energy dissipater. In this paper, an all-steel bamboo-shaped energy dissipater consisting of an inner bamboo-shaped core and an outer restraining tube was developed, which aimed at guaranteeing the performance of the energy dissipater under relatively high strain amplitude and avoiding the adverse effect of grouting and welding. Parametric studies on geometrical variables were performed to investigate the low-cycle fatigue behaviors and deformation patterns of the proposed bamboo-shaped dissipaters. Test results showed that all-steel bamboo-shaped dissipaters showed stable hysteretic curves and no local or overall buckling were observed. Failure modes of bamboo-shaped energy dissipater were affected by the lateral deformation resulted from bending, stress concentration around the fillet and the torsion in the segment. The torsion, contact conditions and the wavelength were discussed via finite element analyses and theoretical derivations.

1. Introduction

In China, the precast concrete structure, a substitute for the cast-in-place concrete structure, has been recently favored by the government's policies as well as by engineers and researchers, which is beneficial to protect environment and reduce labor cost in the construction. After the destructive 2008 WenChuan and 2010 YuShu earthquakes in China, how to efficiently apply precast structures in strong seismic regions through improving its seismic performance has been one of the major concerns. The metallic-yielding energy dissipation devices acting as ductile fuses are often employed in the precast prestressed concrete structures to increase the energy dissipation capacity [1]. In such structure, the precast concrete beams and columns are assembled together using prestressed tendons, and the prestressed tendons are designed to remain elastic during seismic loading to provide the structural self-centering capability.

As a popular type of steel energy-dissipating damper, the buckling-restrained brace (BRB), shows excellently stable hysteretic performance [2–4]. A typical BRB consists of a core member and an outer restraining member, where the former bears axial forces and the latter prevents the buckling of the core. To deepen the understanding of the working mechanism of BRBs in component level, a series work including the effect of weld of the rib [5], stopper [6], unbonding material [7] and local torsional buckling [8] on the low-cycle fatigue performance of BRBs was carefully investigated and analyzed. All achievements obtained in working mechanism of BRB are available in developing the new all-steel BRB.

However, the previously studied BRB had a bearing capacity more than 500 kN. When the high bearing capacity BRBs are applied in the precast prestressed concrete frame, a large amount of prestress will be necessary to re-center the structure to its original position [9]. Therefore, the development of relatively smaller energy dissipating bars is necessary. The smaller energy dissipating bars with lower bearing capacity have two advantages compared with conventional large BRBs: (1) Use a small amount of prestressed tendons while sustaining the self-centering property and (2) Spare enough space for architectural design.

As shown in Fig. 1(a), one type of energy dissipating bar with similar working mechanism of BRB has been recently developed [10], where the yielding segment was formed through weakening the cross section of the steel core. The epoxy or grout was filled into the gap between the yielding segment and the outer tube to constrain the lateral deformation of the steel core and prevent the buckling of the steel core. The application of this type of energy dissipating bars has been widely detailed and tested for different laminated veneer lumber (LVL) structural systems, such as LVL beam-column joints [11] and posttensioned timber walls [12]. Except for timber structure, energy dissipaters shown

* Corresponding authors at: School of Civil Engineering, Southeast University, Nanjing 210096, China.
E-mail addresses: chunlin@seu.edu.cn (C.-L. Wang), liuye_seu@qq.com (Y. Liu).

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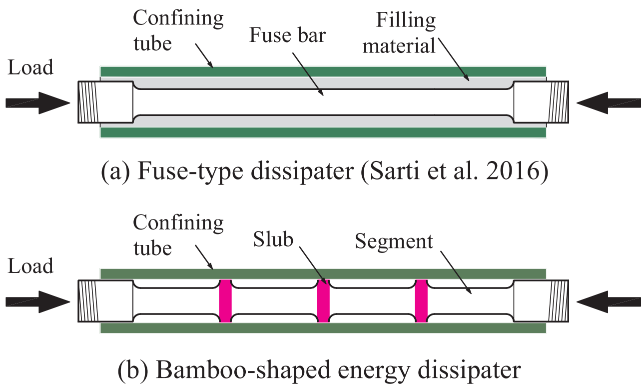

Fig. 1. Configuration of different dissipaters.

in Fig. 1(a) were also widely tested in concrete structural systems including rocking walls [13] and bridge piers [14].

However, only limited literature was referred to the behavior of energy dissipaters [10]. Problems of previously studied energy dissipaters cannot be neglected, which are addressed as difficult grouting, unsymmetric hysteretic performance and limited configurations in structures.

2. Proposed devices

2.1. Concept of a new energy dissipater

These problems addressed above are urged to be solved for expanding the application of energy dissipaters in precast structures. As demonstrated in Fig. 1(b), a new fuse-type energy dissipating bar was proposed recently. The working mechanism of the proposed energy dissipater can be idealized as a laterally restrained bar loaded under compression, where lateral supports externalized as slubs. The components between slubs, called segments, can be ideally viewed as short bar, which is favorable to prevent buckling of the segment by adjusting the length of the segment. The application of the new fuse-type energy dissipater can be extended to both compression and tension range, due to the prevention of the buckling. The shape of the core of the energy dissipater is similar to the bamboo, so the new energy dissipating bar is named as bamboo-shaped energy dissipater (BED) hereinafter.

Considering the advantages such as low density, high strength-to-weight ratio, excellent formability and recyclability of aluminum alloy, the aluminum alloy BED was previously studied [15]. The experimental results showed that the unsatisfactory hysteretic behavior of the aluminum alloy BED was obtained under relatively large axial deformation, while the similar results were proved in other literature [16]. To develop BED specimens with better hysteretic behavior under relatively large strain amplitude, the all-steel BED specimens were investigated. A series of tests including 12 all-steel BED (SBED) specimens was performed to compare the key design parameters and address the low-cycle fatigue performance and deformation patterns under relatively large nominal axial deformation. The details of specimens, the test set-up and the test results are summarized as follows.

2.2. Configuration and dimensions

Referring to Fig. 2, a typical SBED specimen consists of an inner bamboo-shaped core and an outer restraining tube. The core is composed of a succession of slubs, segments and transition zones depicted in Fig. 2(b). The transition zone is set between the segment and the fixed end to spare enough space for the actuator moving back and forth without touching the tube. In the middle slub, an opening with a radius of 1.5 mm is prepared for the stopper which is made of a nail with a radius of 1.4 mm and length of 40 mm. The stopper is added to control the relative movement between the core and the tube along the longitudinal direction. The red paint is sprayed on the surface of segments. If any possible contact occurs between segments and the tube, the contact conditions can be apparently shown by the scratches of the red paint. From the cross-section details of the SBED specimen shown in Fig. 2(d), it is demonstrated that the core is surrounded by the tube, and small gaps, d_1 and d_2, are respectively provided between the slub and the tube and between the segment and the tube. The Q235b steel bars were adopted in the fabrication of the bamboo-shaped cores via computer numerical control lathe processing. The average material property obtained from coupon tests listed in Table 1. Measured geometric dimensions of SBED specimens are given in Table 2.

2.3. Preliminary design

An appropriately designed SBED specimen is expected to have such characteristic: failure concentrated in segments and no damage observed in slubs and transitional zones, which means the slubs and transitional zones are 'overstrength' compared with segments. By adjusting ratio of the sectional area of slubs A_{sl} to the sectional area of segments A_{se}, the slubs can be designed elastic and the segments are able to enter plasticity. The fulfillment of Eq. (1) ensures an appropriately designed SBED specimen.

$$A_{sl}/A_{se} = (d_{sl}/d_{se})^2 \geqslant \sigma_u/\sigma_y \quad (1)$$

where σ_u/σ_y is computed as 1.46 from Table 1, and values of $(d_{sl}/d_{se})^2$ for all SBED specimens given in Table 2 satisfies Eq. (1).

To avoid the squeeze between the slubs and the inner surface of the tube, the incremental diameter of the slub after loaded, Δ_d, should be limited less than the gap provided between slubs and the tube, d_1. Taking Poisson's ratio, υ, into consideration, Eq. (2) as follows should be satisfied:

$$\Delta_d = 0.5 d_{sl}\varepsilon_1 = 0.5 d_{sl}(-\upsilon\varepsilon_2) < d_1 \quad (2)$$

where ε_1 and ε_2 are strains in the radial and longitudinal directions of slubs, respectively. In the experimental protocol, the design of slubs satisfied the requirement of Eq. (2). Besides, two 50-mm fixed ends in each SBED specimen are prepared for actuators to achieve enough holding force. All tubes made of Q235b steel have 20.0-mm inner diameter (d_{in}) and 30.0-mm external diameter (d_{ex}). The design of tubes satisfied the requirement of the overall buckling proposed by Usami et al. [17].

2.4. Nomenclature

The first part of the label represents geometric dimensions of the SBED specimen. L refers to the length of the segment and S means the length of the slub. The second part shows the adopted testing protocol. C1, C2, C3 and C4 respectively refer to a 1%, 2%, 3% and 4% constant strain amplitude loading, while V1 and V2 indicate two different variable strain amplitude loading methods (detailed in Section 3). All SBED specimens have four segment and three slubs. For instance, L40S20-C1 means that the SBED specimen has four 40-mm segments, three 20-mm slubs and is tested under 1% constant strain amplitude. However, L40S5-V1 indicates that the SBED specimen has four 40-mm segments, two 5-mm side slubs, one 10-mm middle slub and is tested under variable strain amplitude VSA1. The middle slub in specimen L40S5-V1 expanded to 10 mm is designed to prevent damage caused by the stress concentration around the opening from happening before the failure of the segments.

3. Test setup and loading patterns

The test setup is shown in Fig. 3 and a SBED specimen was installed in the hydraulic servo universal testing machine MTS 810, which is capable of producing up to 250 kN loading and maximum displacement