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A hybrid passive control device for steel structures, II: Physical testing

Justin D. Marshall [a,*], Finley A. Charney [b,1]

[a] Civil Engineering Department, Auburn University, Auburn, AL, USA

[b] Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

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ABSTRACT

A hybrid passive control device (HPCD) consisting of a high-damping rubber (HDR) damper in series with a buckling-restrained brace (BRB) provides an innovative two-phase system for improving structural response to earthquakes. The initial phase provides damping for all magnitudes of vibration through an HDR damper. The second phase is initiated by a locking mechanism in the damper. Once engaged, the mechanism transfers sufficient force to yield the BRB. Component testing of an HPCD prototype was used to demonstrate performance and validate device design. The experimental results reported in this paper show the expected phased behavior and energy dissipation. The physical testing provides a proof-of-concept for the HPCD and supplies the motivation for further development.

1. Introduction

A structural engineer is tasked with designing structures to be safe, economical and resilient. Depending upon the locality, natural hazards including hurricanes, tornadoes, tsunamis, or earthquakes must be considered in the design. An effective design which results in a structure surviving a significant hazard has far-reaching effects. First and foremost is life-safety. A second issue is how quickly after the event a structure can be safely utilized for the designed purpose. The aim of this paper is to present experimental component test results for a prototype Hybrid Passive Control Device (HPCD). This innovative device has the potential to provide improved structural response for a broad range of earthquake magnitudes as well as for significant wind events. A companion paper [1] describes the analytical development of the HPCD including response of a multi-story prototype structure with a simplified HPCD model.

Developing effective seismic protective systems for structures requires striking a balance between stiffness, strength and energy dissipation. It is not economically feasible to design a structure to remain elastic even during a moderate seismic event. The primary options to effectively design a structure for seismic events are to allow the structure to dissipate energy through inelastic deformation of structural members, to seismically isolate a structure, or to provide a structural control device or a system to dissipate energy and reduce deformations.

A conventional lateral force resisting system results in a life-safety design that experiences significant structural and non-structural damage. This fact was highlighted by the 1994 Northridge, California and 1995 Kobe, Japan earthquakes. Both events were less severe than the design ground motion but caused excessive damage, even to engineered structures. The resulting damage initiated a re-examination of connection details for steel moment frames and a transition to Performance-Based Seismic Design (PBSD) [2,3]. The key to improved structural performance and more predictable levels of damage is to provide a seismic protective system such as base isolation or structural control within the framework of performance-based design.

Structural control systems use specially designed elements to control structural response. The four classes of structural control are active, semi-active, hybrid and passive. Active control systems are the most complex. They require an external power source for the controller, the structural monitoring system and an element to induce motion or force. They are most commonly used in aerospace applications [4,5]. Semi-active control devices are more common in civil applications. A semi-active device has been described as a controllable passive device. The mechanical properties of the device can be modified by the controller based on structural response. Examples include magnetorheological fluid, electrorheological fluid and variable-orifice fluid dampers [5,6]. Power requirements for semi-active devices can be met by a battery. A hybrid control system, not to be confused with a hybrid passive control device, is a system with control elements from two other classes. An example would be the hybrid actuator–damper–brace system consisting of a control system with a hydraulic actuator and a passive viscoelastic damper [7]. Active, semi-active and hybrid control devices can be effective at

* Corresponding address: Civil Engineering Department, 238 Harbert Engineering Center, Auburn University, Auburn, AL 36849, USA. Tel.: +1 334 844 7145; fax: +1 334 844 6290.

E-mail address: jdmarshall@auburn.edu (J.D. Marshall).

1 Department of Civil and Environmental Engineering, Virginia Tech, 200 Patton Hall (0105), Blacksburg, VA 24061, USA.

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improving structural response to earthquakes. The difficulty is in the additional cost and complexity associated with the structural monitoring and control systems.

Passive control devices, the most common in civil applications, require no external power or structural monitoring system. Control forces or energy dissipation is provided by deformation across the device. Examples of displacement-dependent passive devices include metallic yielding and friction devices. The amount of energy dissipation is based on the device displacement and the properties such as yield or slip force. Displacement-dependent devices only provide stiffness until the device yields or slips at which time they have significant energy dissipation capacity and reduced stiffness. The magnitude of energy dissipation for velocity-dependent devices is based primarily on the velocity across the device as well as the size and viscous properties of the damping device. Examples of these are viscoelastic solid dampers (VED) and viscous fluid dampers (VFD). VFDs dissipate energy by deforming a viscous fluid in a sealed cylinder. Viscous dampers possess very little static stiffness. VEDs dissipate energy through deformation of a viscoelastic solid, typically in shear. One type of viscoelastic material is high-damping rubber (HDR). HDR has been used extensively in bearings for seismic isolation [8,9] and has also been investigated for applications as a dissipative brace [10–12].

Displacement-dependent devices add significant stiffness which reduces displacements. The drawback is increased base shear and acceleration with no energy dissipation until the device yields or slips. The benefit is the large capacity to dissipate energy. Unlike displacement-dependent devices, velocity-dependent devices dissipate energy for all magnitudes of dynamic deformation. HDR dampers provide some additional stiffness due to the material storage stiffness. The added stiffness from HDR dampers is significantly smaller than for displacement-dependent devices and comes with the benefit of supplemental damping. The innovative idea behind the hybrid passive control concept is the combination of two different devices in a configuration that exploits individual strengths and offsets weaknesses.

Simple combination of passive control elements does provide some benefits. An analytical study which added viscous dampers to a system with metallic yielding devices found that the VFDs were effective but reduced the effectiveness of the hysteretic devices [13]. Because the VFDs were placed in an already stiff lateral system, they were not able to function as effectively as a dual system with the metallic device. Another combination included the use of partially restrained (PR) moment connections coupled with viscoelastic dampers [14]. The response of the structure improved markedly. The most effective configuration only provided 10% critical damping. The key to the system effectiveness was that the PR moment-frame was flexible enough to allow deformation in the dampers. Yielding of the PR connections supplemented the energy dissipation of the rubber dampers without significant damage to the frame.

Work on hybrid passive devices includes the Visco-Plastic Device (VPD) and the Visco-Hyperelastic Device [15,16]. The VPD consists of two curved plates or channel sections sandwiching a block of high-damping rubber material. For small displacements, the unique geometry amplifies the axial deformations of the rubber resulting in increased damping. For large displacements, the stiffness of the device increases due to the geometry and the nonlinear stress–strain behavior of the rubber. Supplemental energy dissipation capacity is provided through yielding of the steel elements. The VPD was analytically studied in a 9-story steel moment resisting frame and found to improve structural response to seismic events.

The VHD consists of concentric steel rings sandwiching a viscoelastic material. This device would be connected in the center of a structural bay. The ring of viscoelastic material is deformed and dissipates energy under small displacements. The steel rings provide supplemental energy dissipation upon yielding. The geometry of the VHD creates an increasing stiffness with increased displacement prior to yielding. Increasing stiffness with displacement defines a hyperelastic device which has been shown to be beneficial for reducing the impact of p-delta effects [17]. Based on the research completed to date, the concept of hybrid passive control has demonstrated potential for seismic protective systems.

The purpose of this research is to further develop and then experimentally test a prototype hybrid passive device. The VPD was selected initially as having the most promise for continued development due to the amplified strains across the damping element. Upon further investigation, manufacturing of a rubber block of the size envisioned in the original work was not practical. It was decided to pursue a simpler option. The end result of this development is the hybrid passive control device. The work presented in this article is the testing of the prototype. The goal is to experimentally demonstrate the concept of hybrid passive control which will supplement the analytical validation presented in the companion paper [1].

2. HPCD prototype

2.1. Prototype description

The HPCD is a simple configuration of a hybrid passive device. A schematic of the device is shown in Fig. 1. It consists of a high-damping rubber damper in series with an all-steel buckling-restrained brace element. The damper is configured with a lockout mechanism as the stiffness of the rubber material is not sufficient to yield the BRB element at the desired displacement. Slotted holes in the outer plates allow the damper to deform a specified amount until the bolts engage. Once locked, enough force can be transferred across the damper to yield the BRB.

The HPCD test specimen is a 1/2-scale version of a device designed for the bottom story of a 9-story steel frame structure designed for the seismic hazard of Los Angeles, CA. The device was sized to provide approximately 10% total damping in the first mode of vibration. The BRB element of the device is designed to yield at the equivalent lateral force loads specified in ASCE 7-05 Minimum Design Loads for Buildings and Other Structures [18]. Another primary design variable is the gap prior to the lockout of the damper. A gap of 25 mm (1 in.) was selected for the full size prototype device. For a typical story height, the maximum story displacement is 75 mm (3 in.), corresponding to a 2% drift and a story height of 3.8 m (12.5 ft). This leaves a total of 50 mm (2 in.) of drift that must be accounted for by inelastic deformation in the BRB element. Assuming a steel yield of 248 MPa (36 ksi) and a length of 2.4 m (8 ft), the yield deformation is 3.0 mm (0.12 in.). If the design displacement of the BRB element is divided by the yield displacement, the result is a ductility demand at the design displacement of 16.8. This value is higher than typical BRBs because of the reduced length of the core. The reduction in the core length is due to the need to provide space for the rubber damper element.

The rubber slabs in the full size damper are 19 mm (0.75 in.) thick by 1.2 m (48 in.) long by 0.4 m (15 in.) wide. The rubber used for the device is a highly damped butyl rubber compound developed and supplied by Corry Rubber Corporation of Erie, Pennsylvania. The properties developed during the mechanical testing and used for device design and structural analysis are a shear storage modulus (G') of 0.60 MPa (87 psi) and a shear loss modulus of 0.21 MPa (31 psi) (G''). These values correspond with a loss factor of 0.36 [19]. The tests showed that the properties vary with frequency, displacement and strain rate. The listed values correspond to the first mode of the 9-story structure at the specified maximum displacement. The resulting stiffness