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# EMERGING HYSTERETIC-BASED SEISMIC SYSTEMS: CONVERGENCE OF IDEAS IN DUCTILE STEEL DESIGN

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## ABSTRACT

Hysteretic energy dissipation in conventional structural configurations can be undesirable if it is achieved by the damage of primary structural members. Ideally, this hysteretic energy dissipation should occur in structural elements that are "disposable" (i.e., structural fuses that can be replaced without disturbance to the main system, just like real fuses). Much work has been accomplished over the past decades to implement various strategies in that perspective. Yet, conventional structural configurations remain widespread. This paper reviews emerging hysteretic-based systems that are gaining in popularity and assess their effectiveness in the perspective of variant forms of the structural fuse concept as well as their competitive advantages over conventional structural configurations.

## INTRODUCTION

Earthquake-resistant design has long relied (implicitly at first, then explicitly) on the use of hysteretic energy dissipation to provide a life-safety level of protection to users of a particular infrastructure. For traditional structural systems, this ductile behavior has been achieved by the stable plastic deformation of structural members – effectively, damage to those members. In conventional structural configurations, other than for life-safety purposes, this behavior can be undesirable as it translate into property loss, and the need for substantial repairs, if it is achieved by the damage of primary structural members. In recent decades, many researchers have proposed that this hysteretic energy dissipation should instead occur in structural elements that are "disposable" (i.e., structural fuses that can be replaced without disturbance to the main system, just like real fuses). Much work has been accomplished over the past decades to implement various strategies in that perspective. Yet, conventional structural configurations remain widespread.

This paper reviews emerging hysteretic-based systems that are gaining in popularity and assess their effectiveness in the perspective of variant forms of the structural fuse concept as well as their competitive advantages over conventional structural configurations. This includes various innovative configurations of Steel Plate Shear Walls designed to rely on the development of diagonal tension yielding for seismic energy dissipation, Buckling Restrained Braced frames designed to meet Structural Fuse objectives; and; Rocking braced frames. These systems are "conventional" in spirit, in that they rely on structural steel, a material familiar to all structural engineers, and hysteretic energy dissipation. They are "special" in that they rely on capacity design principles. Some are the result of converging ideas in seismic design of ductile steel structures in that some engineers view them as conventional systems coupled with special structural elements only inserted for the purpose of providing hysteretic damping, while others see them as ductile systems designed as a unit to resist the entire applied forces using mostly conventional design procedures.

The convergence of ideas that has led to the development of these hysteretic energy dissipation system has been implicit, driven by a broad set of performance objectives to achieve overall seismic resilience. As a result, in some cases, the structural fuse concept is also becoming of interest in parallel to the greater awareness and recognition that extensive non-structural damage (in addition to structural damage) is undesirable and detrimental, as it can render buildings unusable for extended periods of time following earthquakes, and strategies are developed that couple non-structural damage control with the structural fuse concept.

## Structural Fuse Concept in Buckling-Restrained Braced Frames

The structural fuse concept has not been consistently defined in the past. In some cases, "fuses" have been defined as elements with well defined plastic yielding locations, but not truly replaceable as a fuse. In other cases, structural fuses were defined as elements with well defined plastic yielding locations and used more in the context of reducing (as opposed to eliminating) inelastic deformations of existing moment-resisting frames (also termed to be a "damage control" strategy) (Wada et al. 1992; Connor et al. 1997; Wada and Huang 1999; Wada et al. 2000; Huang et al. 2002). In applications consistent with the definition of interest here, fuses were used to achieve elastic response of frames that would otherwise develop limited inelastic deformations for high rise buildings having large structural periods (i.e., $T > 4$ s) (e.g., Shimizu et al. 1998; Wada and Huang 1995), or for systems with friction brace dampers intended to act as structural fuses (e.g., Filiatrault and Cherry 1989; Fu and Cherry 2000).

A systematic and simplified design procedure to achieve and implement a structural fuse concept that would limit damage to disposable structural elements for any general structure, without the need for complex analyses, can be helpful. One such procedure is presented on the NEHRP Recommended Provisions (FEMA 450) in the perspective of dampers. Another procedure proposed by Vargas and Bruneau (2006a; 2006b) focused solely on hysteretic energy dissipation fuses for designing purposes, in which all damage is concentrated on passive energy dissipation (PED) devices, (a.k.a. metallic dampers). The PED selected for this purpose were Buckling-restrained braces (BRB). BRB have received much attention in recent years in the U.S., and other authors have extensively covered the latest research and knowledge on this topic (Sabelli et al. 2003, Uang and Nakashima 2003). Design requirements for BRB frames are easily accessible (AISC 2005), even though at this time, most BRB systems are proprietary (as a result, testing of components and representative sub-assemblies are typically required). Many uniaxial tests of diverse types of BRBs have been conducted to date, consistently exhibiting stable hysteresis behavior (with full hysteresis loops) and excellent low-cycle fatigue life.

Vargas and Bruneau (2006a; 2006b) investigated the use of BRB frames as part of a structural fuse concept that would limit damage to disposable structural elements for any general structure, without the need for complex analyses. A systematic and simplified design procedure to achieve and implement such a concept was proposed for multi-degree-of-freedom (MDOF) structures, relying on results of a parametric study, considering the behavior of nonlinear single degree of freedom (SDOF) systems subjected to synthetic ground motions. Examples of frames designed following this procedure are presented in Vargas and Bruneau (2006a).

As a proof of concept to the developed design procedure, a three-story frame was designed and subjected to shake-table testing (Fig. 1a) (Vargas and Bruneau 2006b). One of the main purposes of the structural fuse concept being to concentrate seismically induced damage on disposable elements, this experimental project assessed the replaceability of BRB designed as sacrificeable and easy-to-repair members. BRB replaceability was examined in a test-assessment-replacement-test sequence. BRB were also connected to the frame using removable and eccentric gusset plates (Fig. 1b), especially designed to prevent performance problems observed in previous experimental research (Tsai et al. 2004, Mahin et al. 2004, and Uriz 2005). Design and behavior of this type of connection was also investigated in this experimental project. Another objective of this test was to examine the use of seismic isolation devices to protect nonstructural components from severe floor vibrations. For demonstration purpose, the seismic isolation device selected consisted of a bearing with a spherical ball rolling in conical steel plates, a.k.a. Ball-in-Cone (BNC) system. This type of seismic isolator was installed on the top floor of the frame model, and its response in terms of acceleration and displacement was investigated.

In all tests, seismically induced yielding was successfully concentrated in the BRB, as intended. Replaceability of the BRB was also accomplished successfully 3 times, using four different sets of braces connected to the frame. The removable eccentric gusset-plate also exhibited good performance, and did not experience local or out-of-plane buckling. Similarly, the BNC isolators were observed to be effective to control the acceleration transmitted to nonstructural components in structural fuse systems. Furthermore, good agreement was generally observed between experimental results and seismic response predicted through analytical models. Further information and other examples of application can be found in Vargas and Bruneau (2006a; 2006b).

(a) (b)

**Figure 1** (a) Three-story Shake-Table Test Specimen; (b) Removable and Eccentric Gusset Plates (Vargas and Bruneau 2006b)

## ROCKING TRUSS PIERS

Steel truss bridges are found in nearly every region of the U.S. Many existing steel truss bridges consist of riveted construction with built-up, lattice type members supporting a slab-on-girder bridge deck. These built-up lattice type members and their connections can be the weak link in the seismic load path, with limited or no ductility (Lee and Bruneau 2004; Ritchie et al. 1999). While strengthening these existing vulnerable elements to resist seismic demands elastically is an option, this method can be expensive and also gives no assurance of performance beyond the elastic limit. Therefore it is desirable to have structures able to deform inelastically, limiting damage to easily replaceable ductile structural “fuses” able to produce stable hysteretic behavior while protecting existing non-ductile elements and preventing residual deformations using a capacity-based design procedure.

Failure of, or releasing of, the anchorage connection allows a steel truss pier to rock on its foundation, partially isolating the pier. Addition of passive energy dissipation devices (such as BRB) at the uplifting location can control the rocking response while providing energy dissipation (Pollino and Bruneau 2004; 2007). This system can also be designed to provide an inherent restoring force capability that allows for automatic re-centering of the tower, leaving the bridge with no residual displacements after an earthquake. Also, this strategy limits the retrofit effort by working at a fairly accessible location.

The controlled rocking bridge pier system considered can be shown to develop a flag-shaped hysteresis similar to the self-centering systems described above (Fig. 2). This is due to the combination of pure rocking response from the restoring moment provided by the bridge deck weight and energy dissipation provided by yielding of the BRB.

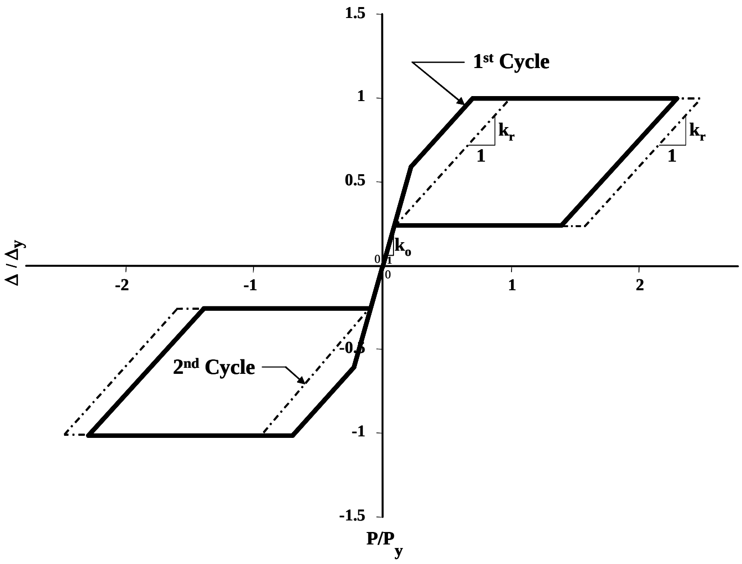



**Figure 2** Hysteretic Behavior of Rocking Truss Pier (Pollino and Bruneau 2004)

A parametric study was undertaken in order to provide a preliminary understanding of system behavior. Results obtained were then used to assist in formulating a design procedure that can reliably predict the system's ultimate seismic response. A capacity based design procedure was also proposed to protect non-ductile elements while limiting energy dissipation to the specially detailed steel yielding devices. A recently completed shake table testing program verified and validated the proposed design procedure. Due to the small scale of specimen in those tests, Triangular Address Damping and Stiffness (TADAS) were used as energy dissipating devices. Results confirmed the adequacy of the proposed design procedure. The tower re-centered (as expected) in all cases, and could be subjected to repeated earthquake excitations. The TADAS devices were replaced 3 times, without problems. One of the test cases used viscous dampers instead of hysteretic dampers, and one considered free (unrestrained) rocking. All specimens performed satisfactorily (Fig. 3).

(a) (b)

**Figure 3** Rocking Tower (a) Specimen; (b) Energy Dissipating System (Pollino and Bruneau 2007)

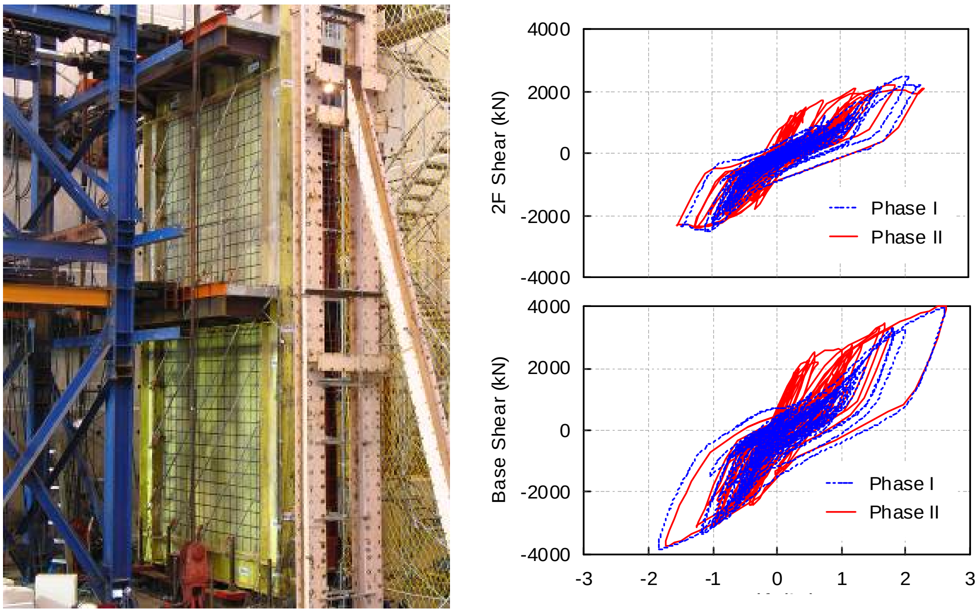
## STEEL PLATE SHEAR WALLS

The selection of steel plate shear walls (SPSW) as the primary lateral force resisting system in buildings has increased in recent years as design engineers discover the benefits of this option, particularly for SPSW designed to rely on post-buckling strength (Thorburn et al. 1983, Lubell et al 2000, Driver et al. 1997, Caccese et al 1993, Berman and Bruneau 2003b, 2004 among many). Recent work has also focused on the use of light-gauge cold-rolled and low yield strength (LYS) steel for the infill panel (Berman and Bruneau 2003b, Vian and Bruneau 2004), and on the placement of a pattern of perforations to decrease the strength and stiffness of the panel by a desired amount (Vian and Bruneau 2004). In addition, the use of reduced beam sections at the ends of the horizontal boundary members has been investigated as a means of reducing the overall system demand on the vertical boundary members (Vian and Bruneau 2004). Recent work (Berman and Bruneau 2003a) has also illustrated how plastic design can be used to assess the ultimate capacity of SPSW and prevent undesirable local story-failure modes.

To resolve uncertainties regarding the seismic behavior and design of intermediate beams in SPSW (intermediate beams are those to which are welded steel plates above and below, by opposition to top and bottom beams that have steel plates on only below or above respectively), and expand on a limited investigation of this problem by Lopez-Garcia and Bruneau (2006) using simple models, an experimental program was developed to test a two-story SPSW having intermediate composite beams with RBS connections. The testing program also investigated how to replace a steel panel after a severe earthquake and how the repaired SPSW would behave in a second earthquake.

In Phase II of this MCEER/NCREE cooperative project (Lin et al. 2007, Qu et al. 2007), a full scale two-story steel plate shear wall was obtained by replacing the buckled panels by new panels prior to submitting the specimen to further testing. To experimentally address the behavior of the repaired specimen in a new earthquake and the seismic performance of the intermediate beam in the first stage of Phase II, the specimen was tested under pseudo-dynamic loads equivalent to the first earthquake record considered in the Phase I tests. The specimen was subjected to cyclic testing to failure in the next stage of the Phase II tests to investigate the ultimate behavior of the intermediate beam and the cyclic behavior as well as the ultimate capacity of the specimen. It was shown that the repaired specimen could survive and dissipate significant amounts of hysteretic energy in a new earthquake without severe damages to the boundary frame or overall strength degradation. It is also found that the specimen had exceptional redundancy and exhibited stable force-displacement behavior up to the drifts of 5.2 % and 5.0 % at the first and second story respectively.

Comparing the hysteretic curves from the Phase I and Phase II tests shown together in Fig. 4, the two specimens are found to behave similarly under the same strong ground motion except that the initial stiffness of the repaired specimen is higher than that of the original one. This is because the intermediate concrete slab suffered premature cracks and two anchor bolts fractured at the south column base at the time step of 9.5 sec and 24 sec of the first earthquake record in the Phase I tests respectively, as mentioned in (Lin et al. 2007). The Phase I tests resumed after the specimen load transfer mechanisms were strengthened at those locations. The results shown in Fig. 4 for the specimen in Phase I are those obtained after the specimen was repaired due to the aforementioned failures. Therefore, the infill panels had already experienced some inelastic deformation before these unexpected failures occurred.




(a) Specimen prior to Phase II tests (b) Hystereses of Phase I and Phase II

**Figure 4** Buckled panels in Phase II pseudo-dynamic test

## CONCLUSIONS

The above overview of some recently developed options for the seismic design and retrofit of steel building and bridges illustrates instances for which replacement of sacrificial structural members (considered to be structural fuses dissipating hysteric energy) was accomplished, in some cases repeatedly. These innovations were accomplished for systems designed without considering the fuses as dampers, but rather as structural elements resisting a specified share of the lateral load. In a sense, these dampers are treated as conventional structural elements.

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