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Hybrid buckling-restrained braced frames

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ABSTRACT

Structural systems that are available in building codes are calibrated for good performance at severe performance objectives (like life safety) under high earthquake hazard levels. However, building performance under low earthquake hazards is uncertain. The optimum seismic structural performance depends directly on the ability of stable hysteretic energy dissipation of ductile systems. This paper introduces a new structural steel system called hybrid buckling-restrained braced frame (BRBF). The "hybrid" term for the BRBF system comes from the use of different steel materials, including carbon steel (A36), high-performance steel (HPS) and low yield point (LYP) steel in the core of the brace. Nonlinear static pushover and nonlinear incremental dynamic analyses were conducted on a variety of BRBF models to compare the seismic behavior of standard and hybrid BRBF systems. Hybrid BRBF systems are shown to have a significant improvement over standard BRBF systems in terms of various damage measures including a significant reduction in the problematic residual displacements of the standard BRBFs.

1. Introduction

Buckling-restrained braced frame (BRBF) is a special type of concentrically braced frame with a unique quality that the braces do not buckle in compression. Buckling-restrained braces (BRBs) yield in a ductile manner both in tension and compression and they exhibit a desirable energy dissipation behavior. The most important problem of the BRBFs is the possible large residual deformations occurring at high levels of seismic input because BRBFs do not have a recentering mechanism and have low post-yield stiffness. Sabelli et al. [1] conducted a numerical study and reported that the residual story drifts were about 40%–60% of the maximum drifts under design basis earthquake loads. Thus, although BRBFs exhibit excellent energy dissipating characteristics, having high residual drifts can increase the repair costs after a major seismic event. One of the solutions for the high permanent deformation problem of BRBFs is the use of a backup moment frame system in a dual frame to minimize the residual deformations. Previous studies show that residual drifts can be reduced by more than 50% when a dual system is used [2,3]. An alternative way of eliminating permanent deformation of BRBFs is to use self-centering energy dissipative braces where flag-shaped hysteretic responses with full recentering capability can be obtained using various methods such as the implementation of nickel–titanium shape memory alloy rods in the braces [4,5]. The drawback of self-centering braces is the increase in the cost of the systems. The second downside of yielding hysteretic energy dissipative systems like BRBFs is that they become active only after they sustain inelastic excursions. Thus, they are not effective in providing damping under low intensity vibrations.

The main objective of the hybrid BRBF study is to have a better and controlled sequence of plastification in the selected members of the structure. Fig. 1 illustrates the behavioral difference of a standard frame and the proposed hybrid frame on a pushover curve. As may be seen in Fig. 1, hybrid frames are expected to yield earlier than the regular frames and maintain positive global stiffness or delay negative post yield-slope at higher drift levels. Hybrid behavior can be achieved using various strategies including mixed materials and mixed systems. In a hybrid material strategy, the hybrid behavior shown in Fig. 1 can be achieved through the combination of LYP (low yield point) steel and HPS (high performance steel) in a multi-core BRB. In a mixed system strategy, different steel moment frames such as special (SMF), intermediate (IMF), and ordinary (OMF) with different detailing and ductility requirements can be combined in a single hybrid moment frame [6].

A hybrid material strategy is studied in this paper through the use of multi-material BRB cores. In hybrid BRBF, the LYP component of the BRB core yields earlier than the carbon steel and the energy dissipation due to early yielding helps the hybrid BRBF to minimize the response under low to mid-level earthquakes. The HPS provides the strength of the brace, and the high strain hardening of LYP steel counteracts the low post-yield stiffness of the standard BRBFs and reduces the likelihood of dynamic instability under high intensity ground motions. Note that dynamic instability, which can be defined as a precursor to collapse, and real collapse (structure falling down) are used interchangeably in the text.

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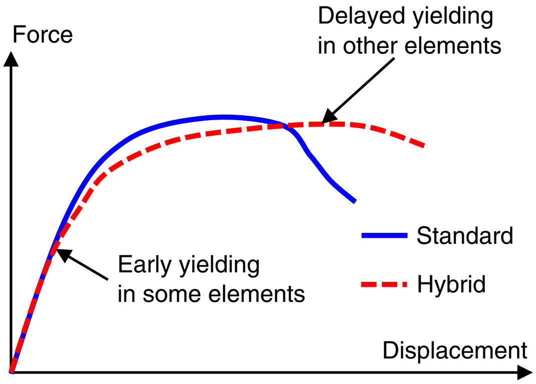

Fig. 1. Hybrid behavior on a pushover curve.

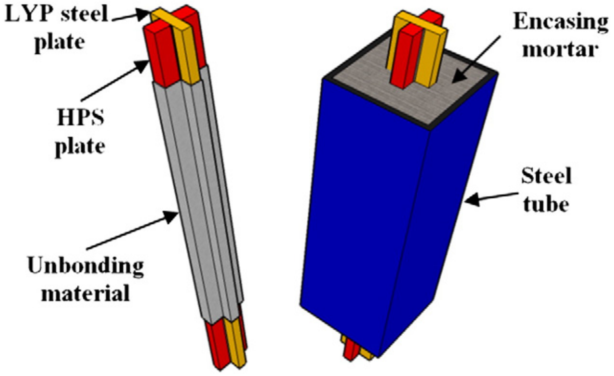

Fig. 2. Hybrid BRB with multi-material yield core.

1.1. Motivation

The motivation of this research is to modify the design and detailing rules to make the traditional BRBF systems perform better at multi-level hazards. The primary objectives are to obtain better performance at low-level ground motions, to minimize the residual displacements at design basis and maximum considered earthquake (DBE/MCE) levels, to increase the reliability of the current systems, and to reduce the likelihood of dynamic instability. While enhancing the performance, it is also essential to keep the economic impact at a minimum.

1.2. Relevant prior research

The possibility of a new type of buckling-restrained brace (BRB) with a core made from a combination of high strength steel (WT780) and low strength steel (LYP100) was mentioned in a report by Sugisawa et al. [7]. The multi-core BRB specimens were tested on a 1000 t structure testing machine and the specimens provided stable hysteresis characteristics and uniform strain distribution when subjected to gradually increasing loading to achieve an axial strain of 1%. When the multi-core BRB was used, the increase in the energy dissipation capacity due to low yield point steel was manifested and this confirmed the feasibility of a new type of BRB featuring both earthquake resistance and vibration control [7].

2. Hybrid brace materials and implementation in practice

2.1. Low strength steel

Early yielding in members can be achieved by using materials having low yield point (LYP) compared to the standard structural steel grades of A36 or A572. These materials with low yield strain will induce inelastic behavior and will start to dissipate energy under small drifts. It is necessary to have better ductility from these materials for seismic applications. This can be explained with the buckling-restrained brace frame (BRBF) design requirements. The cyclic test provisions [8] require every BRBF design to have the capacity to undergo a certain number of cyclic loads corresponding to the design story drift. If the material has low yield strain, by the end of loading cycles, the cumulative inelastic deformation will be much greater than the cumulative inelastic deformation observed for standard structural steel grades. Thus, raising the energy dissipating capability should be accomplished without allowing fatigue failure due to repeated cycles of tension and compression.

Two low carbon steel alloys (carbon content: 0.01%–0.1% or lower) have been identified that possess lower yield strength and higher ductility compared to the structural steel grade. The materials are called LYP and are available in two grades, LYP100 and LYP235, having 100 MPa and 235 MPa average yield stress respectively. When LYP100 is compared to mild carbon steels equivalent to ASTM A36, its modulus of elasticity is similar, the stress at initial yield is approximately one-third as high, no distinct plastic yield plateau appears, strain hardening is relatively larger, and the rupture strain is about 1.5–2 times larger [9]. The overall fatigue life is similar for the plate steels with different yield strengths [10–12]. The energy dissipation capacity of low yield steels is not superior to that of mild steels when total strain amplitude is more than 0.8%, but it is extremely good when total strain amplitude is less than 0.7%. Especially between 0.1% and 0.3% strain amplitude, where mild steels are elastic and have no energy absorption capacity, low yield point steels have an excellent energy dissipation capacity [10].

LYP grades are used in seismic control devices in Japan, primarily in BRBs and steel plate shear walls. A study conducted by Chen et al. [13] on a simple three story frame with BRB specimens including LYP100 steel as load carrying elements has been reported to have shown excellent performance by assigning higher strength ratio (required strength divided by provided strength) to braces and a lower strength ratio to the beams and columns. This approach ensures that yielding occurs in brace members keeping the other members elastic during major earthquakes. Shear yield type devices with LYP steel have also been studied before. In one of these studies by Nakashima et al. [9], LYP100 type steel was used as shear panels. The tested shear panels yielded at a shear force that is approximately one-third of the yield shear force of equivalent shear panels made of common mild steel. Shear panels exhibited stable hysteresis ensuring large energy dissipation capacity. Sufficient strain hardening was observed in the shear panels tested and energy dissipation capacity of about 1.5 times larger than that of an equivalent linear elastic-perfectly plastic system was obtained [9].

2.2. Hybrid BRB material combinations

Hybrid BRBs were developed by combining various steel materials with different yield strengths in a single hybrid brace. It was assumed that different steel cores are connected in parallel, thus, in the numerical model, two or three brace elements were assigned on top of each other. Fig. 2 shows the multi-material core BRB used in the models. Note that the multi-material BRB lab test specimen explained in Section 1.2 also had a similar configuration as shown in Fig. 2.

When a multi-material BRB was modeled, the total brace stiffness and strength were kept the same as the standard BRB. The stiffness

Table 1
Material properties.

	A36	LYP-100	HPS-70W	HPS-100W
F_y (Mpa)	290	107	503	745
E (Gpa)	200	186	200	200