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Probabilistic seismic performance evaluation of steel moment frame using high-strength and high-ductility steel

Kuo-Wei Liao [a,*], Yu-I Wang [b], Cheng-Cheng Chen [c]

[a] Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei 106, Taiwan
[b] CTCI Corporation, Taipei, Taiwan
[c] Department of Civil & Construction Engineering, National Taiwan University of Science & Technology, Taiwan

HIGHLIGHTS

- Using ductile and high-strength steels, a damaged-controlled frame is designed.
- Kinematic hardening and two surface theories are coded as an ABAQUS UMAT for BRB.
- A design recommendation is provided for engineers based on the optimal structure.
- The economic feasibility of using high-strength steel in a frame is revealed.

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ABSTRACT

To shorten a steel building recovery time after an earthquake, a dual and damaged-controlled system is proposed, in which the seismic energy is absorbed by a highly ductile buckling restrained brace (BRB) and the gravity load is resisted by high-strength column. Because the seismic energy is mainly dissipated by the BRB, to accurately simulate the BRB hysteretic behavior is essential. Thus, kinematic hardening and two surface theories are adopted and coded as an ABAQUS user-defined material (UMAT). Particle swarm optimization (PSO) is used to find the optimal design equivalent to a corresponding traditional structure. The performance of the optimal frame is verified by nonlinear time history and fragility analysis. Based on the found optimum, a practical design guideline is recommended. The performance of high-strength steel and a high-ductility structural system such as the inter-story drift, maximum roof acceleration, property of BRB hysteresis, strength ratio between the main frame and BRB and cumulative fatigue damage are investigated. In addition, the economic feasibility of using high-strength steel in the structural system is compared to that using traditional steel materials.

1. Introduction

A dual system is often employed indesigning a building to reduce the seismic damage potential. The dual system consists of two major components: non-dissipative and dissipative members. Based on this concept, many different designs have been developed. For example, Zhang and Zirakian [1] employed low yield point (LYP) steel plate shear walls (SPSWs) as the primary dissipative members in moment resisting frames resulting in a better seismic performance. Tenchini et al. [2] proposed using high-strength steel (HSS) in non-dissipative members and mild carbon steel (MCS) in dissipative zones. Perri et al. [3] investigated the cost and low-cycle fatigue characteristics of Y-shaped steel bracing that is often adopted for retrofitting buildings in medium-to-low seismic intensity area. Marshall and Charney [4] studied the seismic response of steel frame structures using a hybrid passive control system. Experimental and numerical studies of buckling restrained braces (BRB) have revealed that BRB, all-steel or concrete filled, is an effective dissipative structural member [5,6]. The performance of high- and low-strength steel in a moment frame has drawn much attention and is the focus of the current study. To be specific, this study addresses HT690, SN490 and A36 for use in building construction and includes a probabilistic seismic assessment. The performance of the aforementioned hybrid structure under seismic excitations is investigated and compared to that of a building constructed from traditional steel having normal yield strength. The motivation of using such a hybrid structure is that yield occurs only in the dissipative components, and through the quick-recovery characteristic of the dissipating

* Corresponding author.
E-mail address: kliao@ntu.edu.tw (K.-W. Liao).

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system, structures are restored to their original function in the shortest time possible.

Because the majority of seismic energy is absorbed by the BRB, accuracy in modeling the hysteretic behavior of BRB is essential. Budaházy and Dunai [5] emphasized that the behavior of the BRB is complex. Instead of being numerically simulated, it is often studied by experimental tests. For example, Chen et al. [7] conducted cyclic loading tests with low yield steel (LYS 100) as the main load-bearing element of the BRB and combined the BRB with ductile concentrically braced frames (DCBF) for a reduced-size structure shaking table test. This combination aims to achieve a lower strength ratio in the main frame system and a higher strength ratio in the braces to ensure that plastic deformation occurs on the BRB. The strength ratio is the quotient of the strength demand (e.g., flexural and shear) from external force to the strength capacity provided by the considered structural member. The results indicate that compared to traditional braces, the BRB provides relatively good strength capacity, ductility and energy dissipation behavior, the DCBF exhibits good seismic behavior and the BRB reduces structure acceleration response and provides effective control in terms of the inter-story drift after yielding. The inter-story drift is a ratio of the relative translational displacement between two consecutive stories to height of that floor. Although much BRB research has been conducted through experiments, some numerical models have been proposed. For example, OpenSees provides a material called Steel BRB that can be used to investigate the hysteretic properties of BRB core material [8]. Cofie and Krawinkler [9] used a bounding surface model based on monotonic and cyclic stress-strain curves to simulate the nonlinear behavior of structural steel. In their model, the upper and lower stress bounds are controlled by hardening, softening, and mean stress relaxation, the strain amplitude of the last excursion and the previous stress-strain history. Wang [10] adopted the bounding surface model developed by Cofie and Krawinkler [9] to establish an all-steel BRB hysteretic model under a DRAIN-2D environment, in which three different steel materials, LYS, A572Gr.50 and TMCP, were used as the main load-bearing elements of BRB. The bounding surface model was also adopted by Ling et al. [11] to simulate the mechanical behavior of geosynthetic reinforcements that often exhibit large plastic strains, highly nonlinear and hysteretic behaviors under cyclic loading.

To accurately describe the nonlinear behavior of BRB subjected to seismic excitations, this study develops a uniaxial equivalent constitutive model that incorporates strain softening and hardening. The hysteretic model is constructed based on experimental results of monotonic and cyclic stress-strain curves and implemented in ABAQUS through its user subroutine interface - user-defined material (UMAT). After calibration, the established UMAT is applied to BRB members of steel moment frames for nonlinear time history analysis.

The structural members of the hybrid frame are minimized using particle swarm optimization (PSO) with performance constraints to ensure it is equivalent to that of the dual moment frame using normal strength steel. A probabilistic seismic performance evaluation and a fragility analysis are conducted for the optimal frame, and the performance measurements of interest in this study are the inter-story drift, maximum roof acceleration, BRB hysteretic behavior, strength ratio between main frame and BRB and cumulative fatigue damage. In addition to the structural performance, the economic feasibility of using high-strength steel in the structural system is also compared to that of using traditional steel materials. Based on these research results, this study provides a design guideline that includes the strength ratio values for column, beam and brace to leverage the results of the adopted optimization process and streamline the design process. Because the non-linear behavior of the structure system mainly occurs in the BRB members, the common beam element with potential plastic hinges at two ends is adopted to simulate the main structure frame system. The details of this study are provided below.

2. BRB tests and test results

The Structural Engineering Laboratory, Department of Civil and Construction Engineering, National Taiwan University of Science and Technology successively completed over 40 large-size all-steel BRB load-bearing tests [7]. The main load-bearing elements of the test specimens ranged from 10 to 20 mm in thickness and approximately 2800 mm in length and are tested through displacement-controlled cyclic loading. The main load-bearing elements are fabricated from LYP, A36, A572 Gr. 50 and SM570 steel. The details of a tested BRB and test arrangement of the BRB specimens are shown in Fig. 1. The loading cycle is divided into two groups (LV and LC). The LV loading group used a gradual increment of displacement amplitude as shown in Fig. 2, and its results can provide the necessary statistics for establishing the hysteretic model. The LC series specimens, in contrast, used a fixed displacement amplitude to provide the parameters needed to

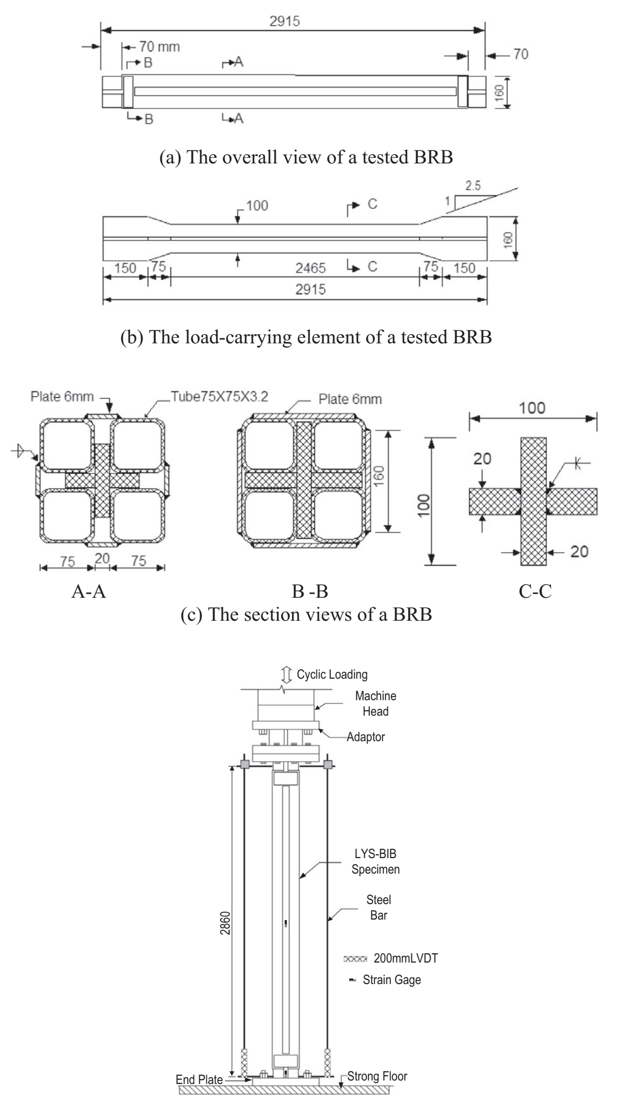

Fig. 1. (a) The overall view of a BRB (b) The load-carrying element of a BRB (c) The section views of a BRB (d) Experiment setup for BRB specimen.