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Seismic performance of Concentrically Braced Frames with non-buckling braces: A comparative study

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ABSTRACT

Bucking-restrained braces (BRBs) can help limit the maximum transient inter-story drifts of Concentrically Braced Frames (CBFs) under earthquake loading, but they are not effective in mitigating the post-earthquake residual inter-story drifts in the CBFs. Shape Memory Alloys (SMAs) can exhibit flag-shape hysteretic loops with zero or negligible residual deformations under cyclic loading, suggesting their excellent superelasticity and energy dissipation capacity. With the limitation of the conventional BRBs and the favorable feature of the SMAs, it has been questioned that if the SMA braces (SMABs) can be used as alternatives to the conventional BRBs to further reduce the residual inter-story drifts while limiting the maximum transient inter-story drifts in CBFs. Focusing on a six-story demonstration CBF which has representative geometries, the SMABs were designed to enable the demonstration CBF to achieve similar maximum transient inter-story drift responses to the same CBF consisting of the BRBs under the design-level earthquake excitations. Seismic performances of the two designs (with the SMABs and the BRBs, respectively) were investigated through nonlinear static analyses and nonlinear response history analyses based on three suites of ground motion records representing different seismic hazard levels. Analysis results show that the SMABs are as effective as the BRBs in limiting the maximum transient inter-story drifts in the considered CBF but are more effective in reducing the residual inter-story drifts of the CBF. Moreover, it is found that the CBF with the SMABs can achieve a more uniform transient inter-story drift distribution in the system compared with the system consisting of the conventional BRBs. Finally, the advantage of the SMABs over the conventional BRBs is demonstrated through probabilistic analyses and interpretations of the results from the nonlinear response history analyses.

1. Introduction

A conventional steel brace, when subjected to cyclic axial loading, often exhibits limited ductility and unsatisfactory hysteretic energy dissipation capacity due to its buckling failure under compression [1–4]. Recent research has revealed that the Concentrically Braced Frames (CBFs) consisting of the conventional steel braces (even the code-compliant ones) may develop excessive inter-story drifts or have damages concentrating at some stories [1–4]. As a favorable non-buckling alternative to the conventional steel braces, Buckling-Restrained Braces (BRBs) have been developed and proved to have high initial stiffness, excellent ductility and stable hysteretic energy absorption capacity. Past research has shown that seismic performance of a CBF consisting of BRBs can be superior to that of the same system consisting of the conventional steel braces [5]. While the research outcomes to date help promote the use of BRBs in CBFs, it is reported that the post-earthquake residual deformations appear inevitable in the CBFs consisting of BRBs (even after the earthquakes with the intensities lower than the design level) [5,6], impeding the widespread acceptance of BRBs in CBF designs.

According to a recent investigation [7], a residual inter-story drift higher than 0.5% makes demolishing the damaged structure and building a new one more favorable than repairing the damaged structure. Although not yet prudently stipulated in the current seismic design provisions [8], the significance of post-earthquake residual deformations has been gradually recognized in the past decades with the increasing emphasis on earthquake resilience that requires fast recovery to minimize the social and economic impact of earthquake hazards [9,10]. As such, research efforts have been made to develop high-performance self-centering non-buckling braces to mitigate the residual inter-story drifts in CBFs [11–13].

Among the various types of self-centering non-buckling braces, those based on Shape Memory Alloys (SMAs) have recently aroused increased research interests and progressively gained popularity in the

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field. SMAs can recover their deformed shapes upon heating (known as the *shape memory effect*) or unloading (known as the *superelastic effect*) [14]. The properly trained superelastic SMAs can exhibit the classic Flag-Shape (FS) hysteretic curves under cyclic loading and remain elastic while absorbing hysteretic energy. A variety of SMA-based devices and structural members have been developed [15–21]. Song et al. [22] and Ozbulut et al. [23] provide comprehensive reviews of the applications of these devices in civil structures. Although past investigations have led to an improved understanding of the fundamental behavior of the SMA Braces (SMABs) [24–28], further investigations are still needed to expand the use of the SMABs in CBFs.

With the recent research progresses, many practitioners have posed the following question: how a typical CBF would benefit from the use of the SMABs compared with the conventional BRBs. The main objective of this paper is to quantitatively address this issue. The authors took a six-story CBF building as a demonstration structure. Note that other researchers have designed the BRBs for the CBF according to the recent seismic design provisions [29]. The authors designed the SMABs for the demonstration structure. To achieve a fair and direct comparison between the CBF consisting of the BRBs (which was designed by others) and the one consisting of the SMABs, the SMABs were designed to enable the CBF to exhibit the transient inter-story drift responses under the design-level seismic forces similar to that of the CBF consisting of the conventional BRBs. Seismic performances of the two systems were subsequently evaluated through nonlinear static analyses and nonlinear response history analyses using three suites of ground motions associated with different earthquake hazard levels. Based on the analysis results, this study compared the seismic performances of the two CBF systems. The following first briefly describes the SMA and the SMAB considered in this research. Then, basic information of the demonstration building is presented together with design of the SMABs for the demonstration building. Next, the paper reports development of the computer models and selection of the ground motions followed by description of the analyses performed and discussion of the analysis results. At the end, this paper summarizes the concluding remarks.

2. Descriptions of the SMA and the SMAB

Numerous types of SMABs have been proposed [15,24–28]. These SMABs differ from resistance and working stroke. This research emphasizes on a new type of SMAB recently developed for civil structures [30,31]. This section first introduces the SMA used in the SMAB and then describes the SMAB.

The considered SMAB is based on the Nitinol SMA wire which has a recoverable strain limit between 6 and 8%. Fig. 1 shows test result of a typical Nitinol SMA wire under cyclic tension at the rate of 1.0 Hz [32].

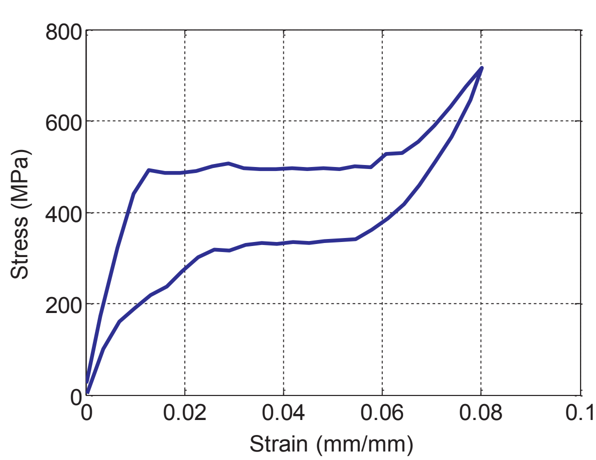

Fig. 1. Stress-strain relationship of the Nitinol SMA wire (test data from Qu and Zhu 2014 [32]).

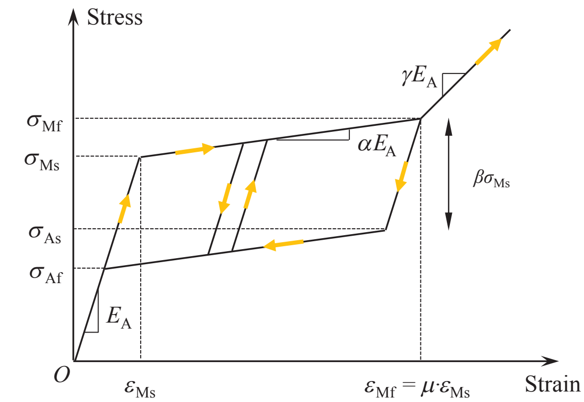

Fig. 2. Simplified hysteretic behavior of the SMA.

As shown, the Nitinol wire exhibits two plateaus along loading and unloading paths, respectively. When the Nitinol wire is loaded beyond a critical stress (about 500 MPa as shown in Fig. 1), austenite to martensite phase transformation is activated, resulting in the stress plateau. Beyond the strain of about 6%, the Nitinol wire begins to exhibit strain hardening. The maximum superelastic strain of the wire is around 8%. Notably, different from the yielding behavior of mild steel, the "yield" point for Nitinol refers to the onset of the yield-like stress plateau induced by the phase transformation. With removal of the axial loading, the martensite becomes unstable, transforming back to austenite along a lower stress plateau. As shown in Fig. 2, the loading and unloading stress-strain curve is usually simplified as a FS hysteresis [25,30,31], which can be characterized by the following parameters: the initial modulus of elasticity E_A, the "yield" stress σ_{Ms}, the "post-yield" stiffness ratio α, and the energy dissipation factor β, and the martensite stiffness ratio, γ. Table 1 summarizes the mechanical properties of the idealized FS hysteretic model for the Nitinol wire based on the test result shown in Fig. 1.

Fig. 3(a) shows the prototype SMAB considered in this research (which is based on the Nitinol wire). Note that behavior of the prototype SMAB has been experimentally verified. More detailed information about the SMAB and the test results are presented elsewhere [30,31]. This section only briefly introduces the SMAB. Fig. 3(b) schematically shows the SMAB components. As shown, the SMAB consists of three segments: the interior segment which consists of the SMA wires to achieve the self-centering hysteretic behavior and the energy absorption capacity; and the two exterior segments, which are two steel tubes (i.e., Parts A and B) connecting the interior SMA segment to the surrounding frame. Parts A and B slide towards or away from each other along the slots under the axial compression or tension, respectively. It is recognized that the axial loads (either tensile or compressive) always stretch the SMA wires with the design shown in Fig. 3(b). Note that diameter of the SMA wires should be properly selected so that they can be conveniently bundled. Moreover, SMA bars may be used as alternatives to the SMA wires in the SMAB.

3. Demonstration building

A six-story building consisting of chevron CBFs as the seismic force resisting systems was selected as the demonstration building in this research. Note that the building actually has been studied in a number of past investigations [2–5,25,28,30]. The demonstration building locates in downtown, Los Angeles. Fig. 4(a) presents floor plan of the demonstration building. As shown, six bays are braced along each direction to resist the horizontal seismic forces. The bay width is 9.14 m. The story height is 5.49 m for the first story and 3.96 m for the other stories. Further design information about the demonstration building can be found elsewhere [5].

Sabelli et al. designed BRBs for the demonstration building based on