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Performance-based seismic design of self-centering steel frames with SMA-based braces

Can-Xing Qiu [a,b], Songye Zhu [b,*]

[a] Department of Civil Engineering, Shandong University, Jinan, Shandong Province, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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ABSTRACT

This study proposes a performance-based seismic design (PBSD) method for steel braced frames with novel self-centering (SC) braces that utilize shape memory alloys (SMA) as a kernel component. Superelastic SMA cables can completely recover deformation upon unloading, dissipate energy without residual deformation, and provide SC capability to the frames. The presented PBSD method is essentially a modified version of the performance-based plastic design with extra consideration of some special features of SMA-based braced frames (SMABFs). Four six-story concentrically braced frames with SMA-based braces (SMABs) are designed as examples to illustrate the efficacy of the proposed design method. In particular, the variability in the hysteretic parameters of SMAs, such as the phase-transformation stiffness ratio and the energy dissipation factor, is considered in the PBSD method. Accordingly, four SMABFs are designed with different combinations of these hysteretic parameters. The seismic performance of the designed frames is examined at various seismic intensity levels. Results of nonlinear time-history analyses indicate that the four SMABFs can successfully achieve the prescribed performance objectives at three seismic hazard levels. The comparisons among the designed frames reveal that the SMABs with greater hysteretic parameters result in a more economical design in terms of the consumption of steel and SMA materials.

1. Introduction

Appropriately designed seismic-resisting structures are expected to respond satisfactorily to earthquakes without collapsing. However, they may still suffer from excessive permanent deformation, which may eventually lead to their demolition. For example, dozens of damaged reinforced concrete (RC) buildings were demolished because of large permanent inter-story drifts after the Michoacan earthquake in 1985 [1]. Recent investigations suggest that a residual inter-story drift ratio that exceeds 0.5% makes rebuilding a new structure more favorable than retrofitting or repairing a damaged structure [2]. Given that both the peak and residual deformation demands of structures are accentuated in modern earthquake engineering, various types of self-centering (SC) structural components and systems have been developed and studied in the past decades [3–13]. A popular means to implement SC structural systems is to combine a post-tensioned (PT) mechanism with energy dissipaters [3–12]. For example, Ricles et al. [4] proposed an innovative SC connection, in which PT strands ran through the frame width parallel with beams and were anchored at column flanges; bolted angles that connected beams and columns were used to dissipate energy. The test results showed that such SC connections demonstrated good energy dissipation capacity and experienced no residual deformation after a couple of inelastic cycles. Christopoulos et al. [7] developed an SC brace using PT aramid fibers, which underwent large axial deformation without structural damage and provided stable energy dissipation capacity.

Shape memory alloys (SMAs) comprise a class of metal alloys with appealing superelasticity and good energy dissipation [14–18]. After a number of preloading cycles (known as training treatment), SMAs can produces ideal flag-shape (FS) hysteresis without residual deformation [19]. Therefore, superelastic SMAs have gained increasing attention in the field of SC structural systems [20–37]. Dolce et al. [23] investigated the seismic performance of a scaled RC frame with SMA braces through shaking table tests, which showed that SMA braces greatly reduce the residual deformation of the RC frame. More studies can be found on SC steel frames with SMA-based braces (SMABs). For example, McCormick et al. [24] revealed the superiority of SMABs over conventional steel braces in limiting peak and residual inter-story drifts. Zhu

* Corresponding author.
E-mail address: ceszhu@polyu.edu.hk (S. Zhu).

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and Zhang [25] developed SMABs that were used in a multistory braced frame, which successfully diminished post-earthquake residual deformation. In particular, the hysteretic behavior of SMABs can be adjusted by tuning their friction level and wire inclination [26]. Compared with a buckling-restrained braced frame (BRBF), the proposed SC braced frames can achieve a similar peak deformation demand but a considerably smaller residual interstory drift.

In contrast to extensive investigations on SC building structures, the corresponding seismic design methods of such structures have been rarely studied [38–41]. Recently, Kim and Christopoulos [38] proposed and validated a design procedure for PT SC moment-resisting frames (MRFs), in which the prescribed performance targets were set similarly to those of welded steel MRFs. Eatherton et al. [41] developed a design method for an SC rocking frame by focusing on controlling several performance limit states; single and dual frames were designed using their method, but seismic performance was not examined.

However, a rational design methodology for steel braced frames with SC SMABs has never been reported in literature. To fill in this knowledge gap, the current study proposes an ad hoc performance-based seismic design (PBSD) method for SC steel braced frames with SMABs. The performance-based plastic design method [42], which was previously developed for traditional steel moment and braced frames, is extended to the design of emerging seismic-resisting SMA-based braced frames (SMABFs), in which SC braces employed SMA cables that possess stable and repeatable cyclic properties after proper preloading (or training) treatment. At a constant temperature, a multistory SC steel frame with novel SMABs is designed as an example in consideration of the prescribed seismic performance targets. Different SMA cables may exhibit various transformation stiffness ratio and energy dissipation capacities depending on material properties, and the effect of such variability on seismic response has been noted [27]. Therefore, a generalized FS hysteresis, in which the variability in these two factors is particularly considered, is adopted in the proposed PBSD method, which offers the necessary flexibility to apply the PBSD method to steel frames with different types of SMABs. Moreover, the effect of potential high modes in seismic response of SMABFs is also considered during the design process. A systematic numerical assessment validates that steel SMABFs designed via the proposed method can achieve the prescribed seismic performance satisfactorily. Although this study is intended for multistory frames with SMABs, the proposed design framework can be further extended to other SC structures with FS hysteresis.

2. SMAB

Various configurations of SMABs have been developed, and they typically exhibit FS hysteretic behavior. Fig. 1(a) shows a representative configuration of the SMAB fabricated and tested by the authors at a room temperature in a laboratory. The brace is designed to be installed in a 1/4-scale two-story frame. The brace consists of two parts: (1) the core part, which is an SMA-based damper with an SC and energy-dissipation function, and (2) the extension parts, which are two steel tubes that extend the brace to a desired length. The mechanism of the SMA-based damper is shown in Fig. 1(b). This damper is composed of two steel blocks that slide against each other, two steel rods, and two bundles of Nitinol cables with the austenite finish temperature $A_f = -10\ ^\circ\mathrm{C}$. Axial displacement moves the steel rods in the slots of the steel blocks and stretches the SMA cables regardless of the damper being under tension or compression. Fig. 1(c) shows the cyclic testing result of the SMAB that has been properly trained before the formal test. The hysteretic behavior is associated with moderate energy dissipation and zero residual deformation upon unloading and can be idealized as a simple stabilized FS hysteresis, as shown in Fig. 1(c). Such FS idealization of the cyclic behavior of SMAs was commonly adopted in the previous studies [27–29]. A typical FS stress–strain relationship can be characterized by four parameters, namely, the initial modulus of elasticity E_{SMA}, "yield" stress σ_y, "post-yield" stiffness ratio α, and energy dissipation factor β. Notably, the Nitinol cables do not really yield in the cyclic test. In this case, "yield" refers to the yield-like stress plateau induced by the phase transformation of Nitinol. The parameters that correspond to Fig. 1(c) are $\alpha = 0.16$, $\beta = 0.5$, $\sigma_y = 465$ MPa, and $E_{SMA} = 46.5$ GPa, where σ_y and E_{SMA} are calculated based on the cross-sectional area and length of the Nitinol cables, respectively.

The Nitinol cables used in the tested brace may be replaced by a variety of other SMA cables with significantly different cyclic properties. The variability in FS hysteresis, particularly in two essential parameters (post-yield stiffness ratio α and energy dissipation factor β) should be considered in a design method if it is intended for different types of SMABs. Moreover, the deformation capacity of SMA cables also differs significantly. For example, the superelastic strain reaches up to 8% for Nitinol cables [14], 12% for Cu-Al-Mn SMA [20], 13.5% for FeNCATB SMA [43], and mono-crystalline Cu-Al-Be cables may exhibit superelastic strain of over 19% [18]. In addition, SMA-based damper is able to possess a very large superelastic capacity with a proper configuration [22]. Therefore, the proposed design in the current study assumes that SMAs' deformation does not exceed superelastic strain. Thus, the hardening behavior that may occur after the completion of superelastic phase transformation strain is not considered in this study. The adopted generalized FS hysteresis enables the extension of the proposed method to the design of other types of SC braced frames. It is noteworthy that the occurrence of hardening behavior and residual deformation at extremely large strain values may affect the seismic behavior of structures with SMA devices. Hardening behavior is generally beneficial to limiting structural displacement but tends to transfer a significant amount of force to adjacent structural members connected to braces. This phenomenon should be considered in design cases where SMA would likely deform under extremely large strain values. In addition, the FS hysteresis of SMAs is sensitive to ambient temperature, and the decreasing temperature that leads to a lower stress σ_y is often unfavorable in seismic response control. It should be noted that some types of SMAs are not suitable to low temperature applications [18]. Thus, SMABs are assumed to be applied in an indoor environment with stable room temperature and the effect of significant temperature variation is not considered in this study.

3. SC Single-Degree-of-Freedom (SDOF) system

The seismic behavior of structures is often dominated by structural fundamental modes. Nonlinear SDOF systems with FS hysteresis are systematically investigated under three suites of ground motions in this section.

3.1. Ground motions

Somerville et al. [44] developed three suites of ground motions that were generated for Los Angeles with exceedance probability of 50%, 10%, and 2% in 50 years. Each suite contains 20 records designated as LA01-LA20 (for design basis earthquakes, DBE), LA21-LA40 (for maximum considered earthquakes, MCE) and LA41-LA60 (for frequently occurred earthquakes, FOE). The 20 records were derived from ten historical records with frequency domain adjusted and amplitude scaled. The 20 earthquake records were modified from soil type S_B–S_C to soil type S_D. The 20 ground