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Self-centering eccentrically braced frames using shape memory alloy bolts and post-tensioned tendons

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ABSTRACT

Conventional eccentrically braced frames dissipate seismic energy through plastic deformation of link beams. However, large residual deformation after strong earthquakes often makes the damaged structure necessary for costly repair. This paper proposes a self-centering eccentrically braced frame system which incorporates shape memory alloy bolts and post-tensioned high strength steel tendons to provide a self-centering response behavior with moderate energy dissipation. An analytical model which has taken into account the super-elastic constitutive of shape memory alloys and the changing contact condition at the link-beam interface is formulated to predict the cyclic load behavior of the system. The feasibility of the proposed concept is demonstrated by cyclic load analysis of a prototype self-centering eccentrically braced frame. Finite element simulations are carried out to verify the analytical model and to further investigate the effects of the configuration details of the link-to-beam connection to the cyclic performance of the self-centering EBF system.

1. Introduction

Eccentrically braced frames (EBFs) were proposed as seismic force resisting structural systems to meet modern seismic design objective at a moderate expense [1]. The key components of the EBF system include columns, collector beams, braces and active links (Fig. 1). The active links are designed to provide ductility and energy dissipation through yielding under design basis earthquakes, while all other structural members are designed to be stronger than the links and stay in elastic range. As a result, a properly designed EBF structure has large elastic stiffness and exhibit significant ductile deformation during strong seismic events [1–6]. In the view of structural control, the active link which dissipates seismic energy through plastic deformation is act as a passive energy dissipative sacrificial device. Similar concept has been used in ADAS device, yielding shear panel device, steel slit damper and so on [7–9].

When extreme loads are involved, conventional earthquake design strategy has focused primarily on prevention of collapse to ensure life-safety, and some structural damage is unavoidable. For EBFs, seismic energy is dissipated through the plastic deformation of links during a major earthquake. However, the plastic deformation of links can result in a permanently deformed frame that is difficult to repair after the earthquake.

There are two alternative strategies to address this problem. One is to use replaceable link beams while the other is to keep the entire structural system damage free. The concept of replaceable links which use bolted endplate connections instead of welded connections and can be removed after occurrence of plastic deformation belongs to the first strategy. The feasibility of using replaceable links in EBFs was demonstrated by Dubina et al. [10] and its performance was also studied experimentally by Mansour et al. [11]. Practical applications of EBFs with replaceable links in several rebuild projects have been reported in New Zealand [12]. An example of the second strategy is the self-centering steel structural system which has been attracting considerable attention. Ricles et al. reported the first study of post-tensioned beam-to-column connection for steel moment-resisting frames (MRFs) [13, 14]. High strength steel strands were used to post-tension beams to columns in order to enable the connection self-centering behavior. Top and seat angles were added to provide energy dissipation and redundancy under seismic loading. Self-centering MRF connection was experimentally studied by Christopoulos et al. [15]. In their tests, steel bars that are able to yield in axial tension and compression were used as energy dissipation elements. Moreover, friction devices were also used to dissipate seismic energy in post-tensioned beam-to-column moment connections [16–18]. Roke extended the concept of self-centering by post-tensioning the whole structural system of multi-story braced frames [19]. Recently, Cheng et al. investigated the feasibility of applying the self-centering idea to the link-beam connections of EBFs [20]. They showed that by post-tensioning links to collector beams the whole EBF can be kept in damage free at designed drift. A flag-shaped hysteresis loop is typical of such self-centering systems, which is able to reduce (or even eliminate) residual structural deformation while dissipating a moderate amount of seismic energy.

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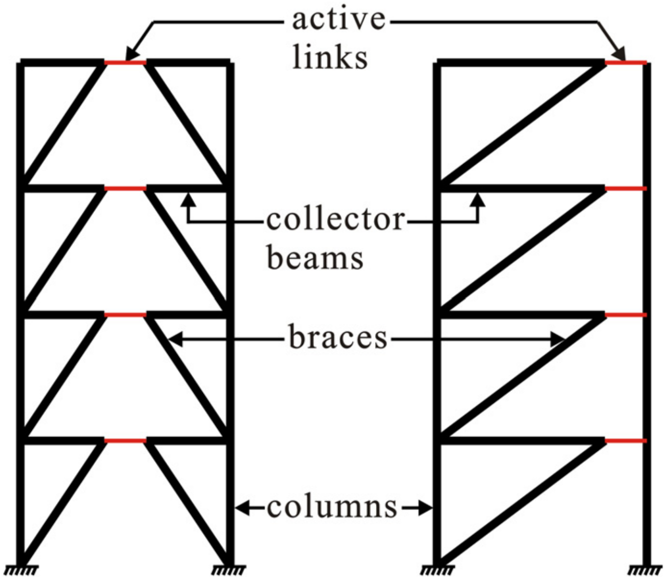

Fig. 1. Typical configurations for EBFs.

Metal alloys such as shape memory alloys (SMAs) also exhibit flag-shaped stress-strain curve. Due to its unique energy dissipation behavior and high fatigue life, SMA has been studied for use as damping device in seismic resistant structures [21–24]. In particularly, SMAs based connections have emerged recently as an encouraging solution to self-centering seismic resistant structures. Abolmaali et al. investigated the feasibility of using SMA bolts in *T*-stub connections [25]. It was found that energy dissipation of the T-stubs with SMA bolts was higher than those with steel bolts. Speicher et al. carried out an experimental investigation of a beam-to-column connection reinforced with SMA tendons [26]. The results demonstrated that the proposed SMA-based connection had excellent ductility, energy dissipation, and re-centering properties. Ma et al. proposed a proof-of-concept self-centering SMA bolted beam-to-column connection with an extended end-plate [27, 28]. Further to Ma's work, Fang et al. [29] and Yam et al. [30] experimentally validated the concept and proposed an improved hybrid connection after a finite element (FE) simulation based parametric study.

In this paper, a new concept of self-centering EBFs is proposed. SMA bolts are employed into the link-beam connection of EBFs for energy dissipation and re-centering. Post-tensioned tendons are also used to further tune the cyclic performance of the system. An analytical model which has taken into account the super-elastic constitutive relationship of SMAs and the changing contact condition at the link-beam interface is formulated to predict the cyclic load behavior of the self-centering EBF. A prototype self-centering EBF is developed to demonstrate the proposed concept. A multi-scale FE model is established for numerical investigation of the prototype system. A general agreement between the analytical result and the numerical result of the cyclic response of the prototype system is observed. The general effects of PT tendons and SMA bolts on the cyclic performance of the self-centering EBF are revealed. Further numerical simulations are carried out to investigate the effects of the configuration details of the link-to-beam connection to the cyclic performance of the self-centering EBF.

2. SMA material model

SMAs exhibit two distinct crystal structures, martensite and austenite. Typically martensite exists at low temperatures while austenite exists at high temperatures. For SMAs in austenite, martensite is induced when they are loaded to a critical stress level, resulting in a stress plateau in stress–strain curves, as shown in Fig. 2. The martensite becomes unstable upon unloading, and it transforms back to austenite with restoring the initial undeformed shape (Fig. 2). The reversible strain of SMAs can be up to 8% and a moderate amount of energy can be dissipated through the flag-shaped stress-strain response [31]. This unique characteristic of SMAs is called super-elasticity or pseudoelasticity. In this paper, the isothermal material model proposed by Auricchio et al. [32] is employed to simulate the super-elastic response of the SMA bolts used in the proposed self-centering EBFs. Auricchio's model considers the Drucker-Prager type loading function, which is a robust solution applicable to general Finite Element packages such as ANSYS [27, 28] and ABAQUS [30]. The stress-strain response of the adopted model is defined by six constants which include critical stress at the start of martensite σ_{Ms}, critical stress at the finish of martensite σ_{Mf}, critical stress at the start of austenite σ_{As}, critical stress at the finish of austenite σ_{Af}, Young's modulus E_Y, and maximum transformation strain ε_L, as shown in Fig. 2.

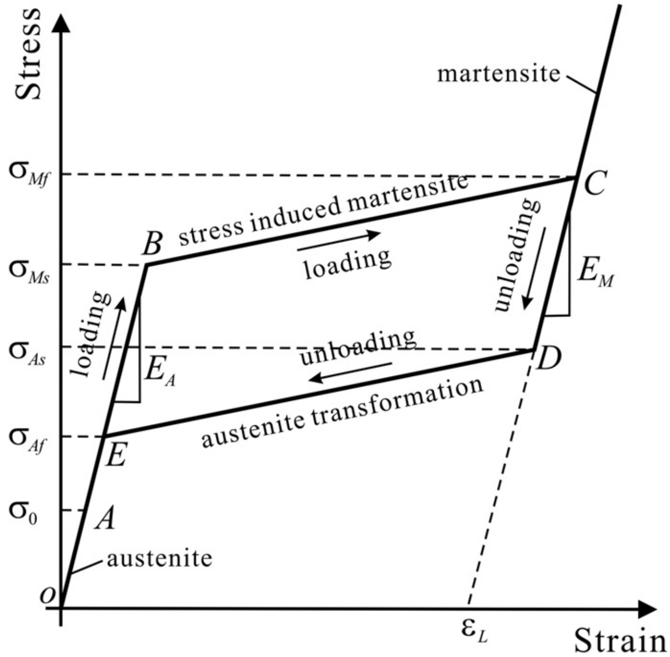

Fig. 2. Constitutive model for SMAs.

3. Concept of self-centering EBFs

Typical configurations of the proposed self-centering EBFs are shown in Fig. 3. The detail of the link end connection with a gap opening is given in Fig. 4. Note that the adjacent components in Fig. 4 could be a collector beam or a column, depending on the EBF configuration. On each side of the link beam web, a high strength steel post-tensioned (PT) tendon is located at the middle depth of the beam. They are post-tensioned to provide a pre-compression force P_{t0} in the beam. A number of SMA bolts are symmetrically placed in the link-to-beam connection. The SMA bolts are fixed on anchor plates whose distance to the interface is determined by the bolt length. A certain pretension p_{b0} is applied to the bolts to increase the pre-compression between the link and the adjacent component. Shear keys are used to prevent vertical slip between the link and the adjacent component if the friction on the interface is deemed insufficient to resist the shear force in the link.

The proposed EBF relies on the pretensioning of PT tendons and SMA bolts to maintain contact between the link and the adjacent components. Nonlinear elastic behavior is activated by a gap opening at the link-to-beam interface, as shown in Fig. 4. Under the target design drift of the EBF, the SMA bolts intend to be in the recoverable strain range, and all the other components of the system are designed to be in their elastic range. As a result, the deformation of the system is totally