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Cyclic behavior of connections equipped with NiTi shape memory alloy and steel tendons between H-shaped beam to CHS column

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ABSTRACT

Shape memory alloys (SMAs) are a class of smart materials which are able to undergo large deformations while reverting back to their original undeformed shape upon heating or by relieving the stress that causes the deformation. When they are equipped in connections within a structural steel frame, this unique property could enhance the recentering capability of the structure after severe event. In this paper, a novel connection – integrating superelastic SMA tendons with steel tendons, is proposed between a H-shaped beam to a CHS column. Six full-scale prototype specimens with different combination of SMA and steel tendons were tested to evaluate the recentering capability and the energy dissipative performance. The novel connection consists of SMA tendons with original diameter of 12 mm, steel tendons with original diameter of 12 mm, extended end-plate, external diaphragm and beam flange ribs. Test results showed that connections equipped with SMA tendons exhibit moderate energy dissipation, double-flag-shaped hysteresis loops and excellent recentering capability after being subjected to cyclic loads up to 6% interstory drift angle.

1. Introduction

Traditional steel moment-resisting frames, incorporating welded beam–column connections, are susceptible to brittle fracture and commonly show large residual deformation after earthquakes. Therefore, a novel steel structural system which has the capability of recentering and dissipating energy is needed to address such problems. Recently the application of shape memory alloys (SMAs), particularly with NiTi, has attracted considerable attention in the community of civil engineering researchers. SMAs are a class of alloys which display a unique ability to undergo large deformation and return to their original undeformed shape upon heating (known as the shape memory effect – SME), or by relieving the stress that causes the deformation (known as the superelastic effect – SE) [1]. Owing to these two extraordinary properties, SMAs have already been successfully applied in civil engineering projects [18].

Gardone et al. [2] conducted an experimental investigation to compare superelastic SMA-based bracings with conventional steel bracings. Results demonstrated that the SMA-based bracing system was able to recenter the reinforced-concrete frame with negligible residual displacement. Janke et al. [3] discussed a successful engineering application of a SMA-based device to retrofit the bell tower of the Church of San Giorgio in Italy. The superelastic SMA-based devices were used to protect the masonry building from failure. DesRoches et al. [4] conducted a nonlinear analysis to compare SMA-based restrainer bars with conventional steel cable restrainers in a typical multi-span and simply-supported bridge. Results indicated that the SMA-based restrainers were more effective in reducing the relative hinge displacements at the abutment. Successful application of SMA-based dampers has also been discussed in Sharabash and Andrawes [19], Torra et al. [20] and Dieng et al. [21]. Experimental results from Miller et al. [22] demonstrated that SMA-based self-centering buckling restrained braces could provide stable hysteretic response.

Recent research focuses on applying large-scale SMA bars in beam–column connections for recentering purpose. Ocel et al. [5] first applied SMA NiTi bars with a diameter of 35 mm in a conventional H-shaped beam to H-shaped column connection. By heating the SMA bars above the transformation temperature, results showed repeatable and stable hysteretic behavior. Penar [6] applied superelastic NiTi tendons in a partially restrained steel beam–column connection. The tendons with an original diameter of 0.75 in. (~19.05 mm) were machined into a dog-bone shape with a reduced diameter of 0.5 in. (~12.7 mm). Results showed

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better recentering performance than connections with A36 steel tendons. Speicher et al. [7] investigated the performance of superelastic NiTi tendons in a half-scale interior beam–column connection. The tendons were machined from a 19.1 mm diameter bar to a 12.7 mm diameter reduced section. Comparing to other connections which incorporated steel and martensitic NiTi tendons, results showed significant recentering performance with negligible residual deformation under cyclic loads up to 5% interstory drift angle. Fang et al. [8] investigated eight extended end-plate connections which included seven connections with SMA bolts and one conventional connection with high strength bolts. The SMA connection specimens showed excellent recentering performance and moderate energy dissipation, while the conventional connection with high strength bolts showed good energy dissipation but with considerable residual deformation.

However, limited research has been conducted on applying SMA tendons to H-shaped beam to CHS column connection to date. This paper thus investigates the seismic performance of an exterior H-shaped beam to CHS column connection with the use of long NiTi tendons. This novel connection consists of SMA tendons with original diameter of 12 mm, steel tendons with original diameter of 12 mm, extended end-plate, external diaphragm (commonly adopted in beam to CHS column connection [9–11]), and beam flange ribs. By exploiting the SMA's superelasticity, the connection is expected to withstand large deformations and revert back to its undeformed shape automatically upon unloading. To enhance the energy dissipation, steel tendons were also applied. In addition, the tendon configuration and tendon length were also examined. Overall, six connections were designed and tested to validate the performance of such novel connections.

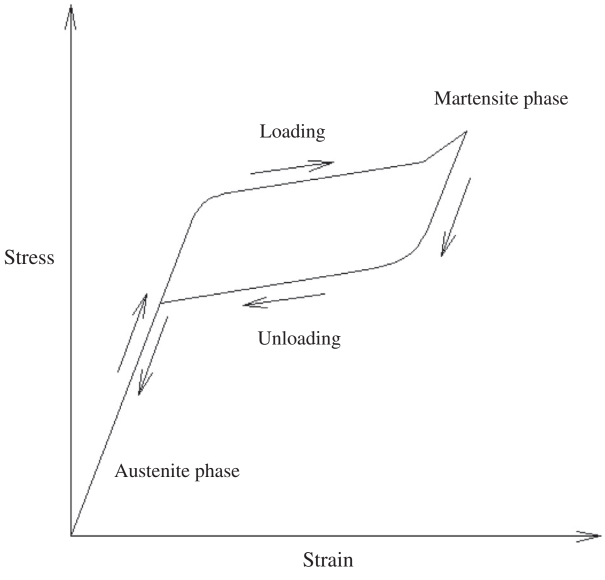

Fig. 1. SMA's superelasticity.

2. Shape memory alloy

2.1. Superelasticity

When temperature is higher than the austenite finishing temperature A_f, the SMA material exhibits superelasticity [1]. As shown in Fig. 1, when the SMA is loaded to a certain stress level, the austenite phase will start to transform into the martensite phase. This creates a loading plateau. While unloading the SMA after phase transformation, the stress will decrease and the SMA material will revert back to the previous shape. When the stress hits zero, there will be almost no residual strain left. The hysteretic loop developed is the main source of energy dissipation for the SMA material.

2.2. Material tests

To investigate the material property of the SMAs, bar coupons (Fig. 2) manufactured by the Xi'an Saite Metal Materials Development CO., Ltd. were tested. The weight percentage of titanium in this alloy is 55.82%. Original bar coupons were heated to 400 °C for 30 minutes and the austenite finishing temperature is around −10 °C to ensure superelasticity under room temperature. Fig. 3 shows the coupon testing setup and the cyclic tension tests were carried out under the loading protocol as shown in Fig. 4. The testing procedures followed that from Chen et al. [12,23]. Fig. 5 shows a typical stress–strain relationship for the SMA coupon. After being loaded to 7% strain, the coupon displayed good superelasticity, with a residual strain of 0.5%. Three coupons were tested and the average initial elastic modulus and the transformation or “yield” stress during the initial cycles were approximately 33 GPa and 360 MPa respectively.

3. Experimental program

3.1. Connection details

For conventional extended endplate connection, energy is dissipated through yielding of the steel components. However, for recentering connection, this yield mechanism is not favorable as it will result in unrecoverable residual deformation. The anticipated mechanism for recentering connection is that all of the inelastic deformation should be concentrated on the replaceable tendons, while the remaining components of the connection should remain elastic. In this paper, the SMA tendons are the only component that experience large deformation and end up with no residual strain due to its superelasticity.

To achieve the targeted mechanism, the connections were designed accordingly and the details are shown in Fig. 6. The H-shaped beam and CHS column is connected by the extended end-plate with eight long SMA tendons (in their austenitic phases) or steel tendons. As indicated in Section 1-1 of Fig. 6(a), for each beam flange, there are two rows of tendons with one row above the flange and another one below. The beam flanges are strengthened by the stiffeners (14 mm in thickness) centered over the beam web. These flanges help transfer the shear force from the applied

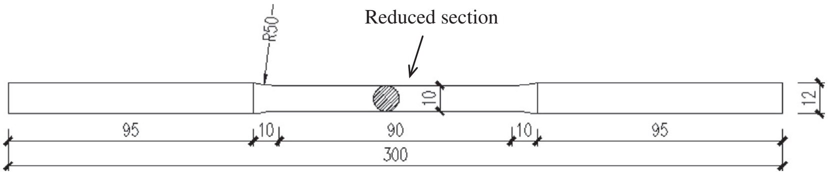

Fig. 2. SMA coupon dimensions (units: mm).