Engineering Structures 140 (2017) 177–188

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

SMA tension brace for retrofitting concrete shear walls

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ARTICLE INFO

Article history:
Received 2 February 2017
Revised 14 February 2017
Accepted 16 February 2017

Keywords:
Shape Memory Alloy
Tension-only braces
Seismic retrofitting
Reinforced concrete
Shear walls
Testing
Numerical analysis

ABSTRACT

A Shape Memory Alloy (SMA) tension brace was developed as a retrofit device to improve the seismic response of deficient reinforced concrete squat shear walls. Three, tension-only SMA braces and two, companion tension-only steel braces were built and subjected to cyclic loading. The braces consisted of SMA and reinforcing steel links, respectively, placed at the centre of the bracing system and connected to rigid hollow structural steel members. A total of four links were utilized for testing: two SMA links and two reinforcing steel links. A superelastic, nickel-titanium rod, capable of recovering large nonlinear strains was used for one SMA link; while a nickel-titanium, shape-memory rod lacking the capacity to recover strains after the removal of load was used in the other SMA link. Deformed reinforcing steel bars that experience significant residual strains during the inelastic range of loading were incorporated into the steel links. Testing illustrated that the pseudo-yield and ultimate strengths, and energy dissipation capacity of the SMA braces were comparable to the steel braces. Furthermore, the SMA braces experienced superior elongation recovery. Testing and retesting of the SMA braces illustrated their potential to act as resettable braces. Complementary nonlinear finite element analyses were conducted to assess the application of the braces to enhance the seismic response of reinforced concrete shear walls. The analyses demonstrated that the SMA braces can improve the lateral strength capacity, energy dissipation, and re-centering of reinforced concrete shear walls, while reducing strength and stiffness degradation associated with shear-related damage.

1. Introduction

A large stock of existing buildings designed and constructed prior to the enactment of seismic provisions that appeared in building codes during the 1970 s and 80 s lack sufficient reinforcement detailing. As a result, these buildings are vulnerable to current design-level earthquakes. Pre-1970 s shear walls, therefore, may require retrofitting to improve the response to current seismic demands and to mitigate the potential damage. An emerging retrofit strategy, as suggested herein, incorporates Shape Memory Alloys (SMAs). SMAs are smart materials that recover their original shape (negligible residual deformations) with the application of heat or the removal of stress due to two-way, forward-reverse, transformation of the internal crystalline structure [1]. Transformation due to heat is known as the shape memory effect, and transformation due to stress is known as the superelasticity effect. Both shape memory and superelastic SMAs have been investigated for civil engineering applications [2–4]. Superelastic SMAs are appealing as reinforcement and passive control due to the loading-unloading nature of earthquakes that benefits re-centering. In comparison to black carbon steel, superelastic SMAs recover substantially larger deformations, while sustaining similar stress levels. Superelastic SMAs, specifically nickel-titanium SMAs (Fig. 1), typically recover up to 6% deformation, while carbon steels recover only approximately 0.2%. The potential benefits of retrofitting concrete walls with superelastic SMAs include: increases in lateral strength, drift, and energy dissipation capacities; improvement in re-centering (reduction of permanent deformation); reduction of shear stresses; and mitigation of damage.

Applications of superelastic SMAs in reinforced concrete structures have focused on implementing the alloy as internal reinforcement for new structures, while limited research has been documented on external applications for seismic retrofitting of existing concrete structures. Testing of concrete structural elements reinforced with superelastic SMAs has demonstrated the re-centering capacity of SMAs. Nickel-Titanium SMA rods have been experimentally studied as alternative reinforcement for concrete beams [5,6], concrete columns [7,8], concrete beam-column joints [9,10], concrete frames [11], and concrete shear walls [12]. In each of these studies, the SMA rods contributed to reductions of permanent deformations and damage of the concrete relative

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http://dx.doi.org/10.1016/j.engstruct.2017.02.045
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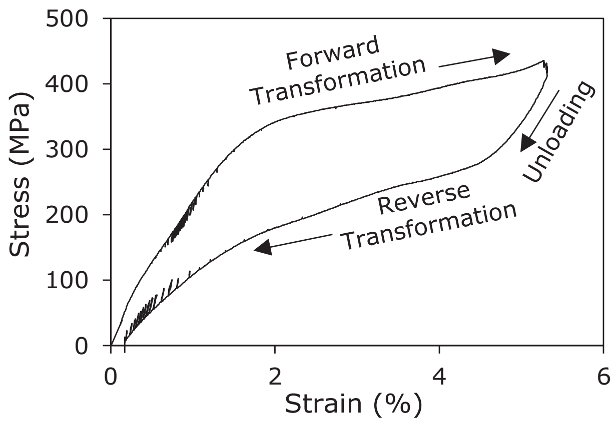

Fig. 1. Typical stress-strain response of superelastic nickel-titanium SMA.

to companion elements reinforced with black carbon reinforcing steel. Furthermore, testing has demonstrated that the flag-shaped stress-strain response with low modulus of elasticity, typical of nickel-titanium SMAs, results in concrete elements with reduced initial stiffness and energy dissipation capacity. However, the reduced energy dissipation does not necessarily imply a deficiency in the SMA material. Christopoulos et al. [13] demonstrated that flag-shaped hysteretic behaviours can match or improve the seismic response in comparison to elasto-plastic hysteretic behaviours. Further applications of SMAs have been studied numerically, including concrete columns [14,15], concrete beam-column joints [16], and concrete frames [17–19]. The analyses have highlighted that SMA rods and SMA-based composite materials possess the capability to increase strength and drift, while reducing damage and permanent deformations.

The only experimental study, known by the authors, on the external application of superelastic SMA rods to reinforce concrete structures was conducted by Effendy et al. [20]. SMA rods were externally connected to barbell-shaped squat shear walls in a bi-diagonal pattern as replacement of internal reinforcement. In comparison to a companion reinforced wall, the SMA retrofitted walls were stronger, less ductile, and exhibited narrower hysteretic response with less energy dissipation. The long SMA rods, in addition to the relatively small lateral deformation of the walls, limited the straining experienced by the SMA and, therefore, reduced the re-centering effect. Furthermore, the long SMA rods buckled during testing. SMA bracing concepts have also been considered in other studies. Auricchio et al. [21] numerically modelled steel frames braced with reduced-length superelastic SMA elements, while Dolce et al. [11] tested reinforced concrete frames with SMA bracing devices. The braces studied by Auricchio et al. consisted of SMA elements assumed to resist compressive forces without buckling. These braces, however, may not achieve the full-recovery strain of the SMA before buckling given the probable high compressive stresses at large lateral displacements of the frames. The braces tested by Dolce et al. incorporated a device with SMA wires (some of them pre-strained), capable of sustaining tensile and compressive stresses. Although effective for improving the response of structures, the braces require specialized fabrication that may not be feasible for field applications.

2. Research significance

To address challenges with the application of long SMA rods as external reinforcement for concrete shear walls, an optimized external, SMA tension-only bracing system is proposed, where the length of SMA rods is sized to fully utilize the range of deformation recovery. In addition, buckling is eliminated in the brace through a mechanism that releases compressive stresses. The proposed tension-only SMA brace is a simple, easy to construct, retrofitting element capable of improving the seismic response of structures subjected to large displacements. The brace system is scalable and can be utilized for retrofitting a wide range of structures, including reinforced concrete or steel frames, and reinforced concrete shear walls. Furthermore, the braces are designed such that the SMA rods can be removed and replaced, while the bracing system remains in place.

3. Conceptual design of SMA retrofitting system

The proposed tension-only SMA bracing system consists of nickel-titanium SMA links, coupled with rigid hollow structural steel elements that are connected with anchor plates to the base and top of a shear wall (Fig. 2(a)). The SMA braces act as flag-shaped energy dissipaters that, in addition to increasing lateral strength, can potentially improve drift, energy dissipation, and re-centering (Fig. 2(b)). In comparison to a similar steel retrofitting system, the SMA bracing is expected to reduce damage, improve closing of cracks during load reversals, reduce permanent deformations, and promote more stable hysteretic cycles with reduced strength and stiffness degradation.

4. Design of full-scale SMA retrofitting system

The proposed SMA braces were first conceived at full-scale as a retrofitting system to improve the seismic response of a 6000 mm-long × 6000 mm-high × 300 mm-thick shear wall of a two-storey prototype building subjected to the demands corresponding to the high seismic region of Western Canada (Fig. 3). The shear walls were designed following the 1965 edition of the National Building Code of Canada, NBCC-1965 [22], assuming material properties that were representative of construction practices of the 1960s: cylinder compression strength of concrete and yield stress of reinforcing steel equal to 21 MPa and 280 MPa, respectively. The design of the prototype wall resulted in minimum reinforcement in the longitudinal (0.18%) and transverse (0.21%) directions. Seismic detailing such as confinement and anti-buckling reinforcement was not prescribed in the NBCC-1965.

The capacity spectrum method of ATC-40 [23] and FEMA 440 [24] was used to assess the performance of the retrofitted wall (Fig. 4). The capacity curves of the original and retrofitted walls were established from the envelope of the lateral load-displacement hysteretic responses predicted with program VecTor2 [25]. The capacity curves were converted to spectral coordi-

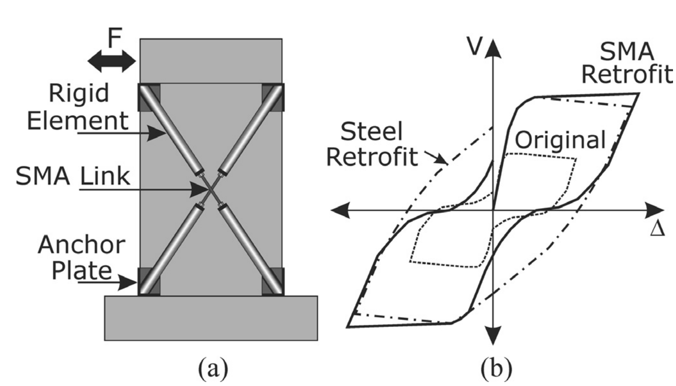

Fig. 2. Retrofit with SMA: (a) retrofit scheme with SMA braces; and (b) expected response of SMA-retrofitted wall compared to original (non-retrofitted) and steel-retrofitted walls.