Engineering Structures 147 (2017) 77–89

Contents lists available at ScienceDirect

Engineering Structures

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

Behaviour and modelling of hybrid SMA-steel reinforced concrete slender shear wall

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ARTICLE INFO

Article history:
Received 9 June 2016
Revised 15 December 2016
Accepted 9 April 2017

Keywords:
Superelastic SMA
Reinforced concrete shear walls
Strain recovery
Energy dissipation
Hysteretic response
Constitutive modelling
Finite element analysis

ABSTRACT

Superelastic Shape Memory Alloys (SMAs) possess unique mechanical characteristics that make them appealing as alternative reinforcement for seismic applications; specifically, the capacity to recover large strains upon unloading, levels that would result in permanent deformations in steel reinforcement. An experimental study was conducted to assess the performance of a ductile, hybrid SMA-deformed steel reinforced concrete shear wall. A companion wall with deformed steel reinforcement only was also investigated. The walls were subjected to reverse cyclic displacements to failure. The results of the experimental program demonstrate that the hybrid SMA wall was significantly more effective at restoring resulting in marginal residual displacements after being subjected to drifts exceeding 4%. The hybrid SMA wall experienced similar lateral strength and displacement capacities to the steel reinforced wall. The hybrid SMA wall provided substantial, albeit less, energy dissipation and lower stiffness at yielding; the influence of these performance parameters on seismic behaviour is noted in the paper. A hysteretic constitutive model based on a trilinear envelope response, and linear unloading and reloading rules provided satisfactory simulations of behaviour of the SMA wall. Discrepancies in response are attributed to bond modelling of the smooth SMA bars. Furthermore, finite element analysis is also used to illustrate the effect of axial load on the re-centering capacity of the shear walls.

1. Introduction

In high seismic regions, reinforced concrete structures that are classified as normal importance, are designed to sustain severe damage and permanent deformations during design-level earthquakes, while preventing collapse and safeguarding against loss of life. This is generally achieved by assigning plastic hinges at pre-defined locations in a structure. The plastic hinges are designed to be controlled by flexural yielding, while preventing non-ductile modes of failure. Although the main performance objective may be achieved, the damage and permanent deformations could prevent a structure from being serviceable after a seismic event and, in addition, prohibit post-earthquake repairs. Due to these shortcomings, Shape Memory Alloys (SMAs) have attracted interest from researchers due, in most part, to their capability to recover displacements upon removal of stress (superelastic SMA) or with the application of heat (shape memory effect). In addition, SMAs can dissipate energy through hysteretic damping and provide strength and displacement capacities comparable to conventional deformed reinforcement. SMAs are also gaining popularity due to their high fatigue and corrosion resistances. SMAs have a number of structural applications [1–3], ranging from reinforcement in new construction or as a retrofitting material for existing structural elements, to serving as strands for prestressing and post-tensioning. In addition, other uses include SMA-based devices for passive, semi-active or active control of structures.

Shortcomings of SMAs include the higher cost relative to traditional steel reinforcement; this leads to optimization of the material. Furthermore, the superelastic properties of SMAs are dependant on the operating temperature; the smooth bar surface results in a reduction in bond to the surrounding concrete leading to fewer, but larger cracks; and the lower elastic modulus (approximately 60 GPa) relative to steel reinforcement (200 GPa) results in larger displacements under service loads.

A number of studies have focused on material characterization and on the mechanical properties of superelastic SMA bars and wires to evaluate their applicability for structural applications [4–6]. DesRoches et al. [7] highlighted that SMA in wire form experiences higher strength and damping properties compared to SMA bars; however, the form of the SMA does not influence the re-centering capacity. McCormick et al. [8] investigated the behaviour

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http://dx.doi.org/10.1016/j.engstruct.2017.04.058
0141-0296/

Notation

A_s	area of flexural reinforcement	l	length of displacement cable transducer
A_g	gross cross sectional area of concrete section	Δ_y	yield displacement
E_i	initial stiffness of reinforcement	δ	change in length of displacement cable transducer
E_s	modulus of elasticity of reinforcement	ε_m	current maximum strain of reinforcement
E_{sh}	strain hardening stiffness of reinforcement	ε_p	plastic offset strain of reinforcement
P	axial load	ε_{r1}	first unloading strain
d	original length of displacement cable transducer	ε_{r2}	second unloading strain
f'_c	concrete cylinder compressive strength	ε_{sh}	the strain at the onset of strain hardening
f_{unl}	unloading plateau stress of reinforcement	ε_u	ultimate strain of reinforcement
f_y	yield stress of reinforcement	ε_y	yield strain of reinforcement
h	height of displacement cable transducer	γ_{avg}	average shear strain

of large diameter superelastic SMA bars and concluded that decreasing the bar size results in an increase in re-centering capacity and equivalent viscous damping. Other studies [9–13] have concentrated on the cyclic response of SMA wires and large diameter bars with respect to strain amplitude, loading frequency, number of cycles, and ambient temperature.

Limited experimental studies have focused on incorporating superelastic SMAs as reinforcement in concrete structural members. Deng et al. [14] investigated the capacity of embedded SMA wires to recover and reduce permanent deformations of concrete beams. Saiidi and Wang [15] studied the contribution of SMAs to reduce residual displacements in concrete columns reinforced with SMA bars in the plastic hinge area. The authors also evaluated the seismic performance and damage of an SMA reinforced column repaired using engineered cementitious composites. In another study [16], the seismic behaviour of columns reinforced with SMA bars and engineered cementitious concrete was investigated in an attempt to reduce permanent displacements and damage in columns subjected to strong earthquakes. Youssef et al. [17] investigated the seismic behaviour of a beam-column joint reinforced with superelastic SMAs in the plastic hinge region. Abdulridha et al. [18] investigated the response of large-scale concrete beams reinforced with SMAs in the critical region under monotonic, cyclic and reverse cyclic loadings. Each of the above experimental studies has demonstrated the effectiveness of SMAs to restore a structural member to its original position. Other experimental studies have included the combination of SMAs with fiber-reinforced polymers [19,20]. SMAs used as external reinforcement has also been investigated. A study by Ayoub et al. [21] investigated the behaviour of small-scale beams reinforced with externally anchored, superelastic SMA bars as the principal longitudinal reinforcement. The work of Effendy et al. [22] focused on external SMA diagonal bracing for squat concrete shear walls.

While advancements have been made in the application of SMAs in structural members, there is a lack of knowledge on the behaviour of SMA reinforced shear walls, yet shear wall-type elements are routinely incorporated in the lateral force resisting systems of structures.

2. Research significance

This paper investigates the performance of a concrete shear wall reinforced with superelastic SMAs in the plastic hinge area. SMAs are used only as the principal longitudinal reinforcement in the boundary zones, while the longitudinal reinforcement in the web region consists of deformed steel reinforcement, thus leading to a hybrid SMA-steel member. To the author's best knowledge, this is the first study to use SMAs as internal reinforcement in slender shear walls and to use a hybrid of SMA and steel along the critical section.

In addition, this experimental study is used to provide a benchmark to develop modelling procedures and to corroborate a hysteretic constitutive model for superelastic SMAs based on linear unloading and reloading rules that explicitly considers accumulation of permanent straining and decaying of the unloading plateau stress.

3. Experimental program

Two ductile shear walls were tested under reverse cyclic lateral loading. The walls were named W1-SR and W2-NR, where S and N distinguish between the steel reinforced and the hybrid NiTi SMA-steel reinforced walls, respectively. The NiTi SMA had a chemical composition of approximately 56% Nickel (Ni) and 44% Titanium (Ti) by weight. Details of the concrete and reinforcement are provided in Table 1. The shear walls had a rectangular cross section: 150 mm in thickness and 1000 mm in length. The height of the walls was 2200 mm resulting in an aspect ratio of 2.2, which was selected to promote ductile flexural response. The walls were designed according to the seismic detailing provisions for ductile walls prescribed by the Canadian Standards Association Standard A23.3-04 Design of Concrete Structures [23]. While no explicit provisions exist for SMA reinforced members, the design of the SMA wall followed that of the steel reinforced wall.

The walls were reinforced with two layers of orthogonal steel reinforcement in the web. The vertical reinforcement consisted of three pairs of 10 M (100 mm^2 and 11.3 mm diameter) deformed bars spaced uniformly at 150 mm, whereas the horizontal reinforcement consisted of fifteen pairs of 10 M bars spaced uniformly at 150 mm. As a result, each shear wall had the same web vertical and horizontal reinforcement ratio of 0.88%. The only difference between W1-SR and W2-NR was the longitudinal reinforcement used in the plastic hinge region within the end boundary zones. For W1-SR, four-10 M deformed steel bars were used; while for W2-NR, the deformed longitudinal bars were replaced with 12.7 mm-diameter superelastic SMA bars. The choice of SMA bar size was based on two factors: (1) readily available bar size; and (2) an equivalent A_sf_y to the deformed reinforcement used in the boundary zone of the steel reinforced wall. Mechanical couplers were used in W2-NR to connect the SMA bars with 15 M deformed steel bars (16 mm diameter and 200 mm^2 area) extending above the plastic hinge region. The larger bar area above the plastic hinge was intended to prevent yielding of reinforcement outside this region. The total length of the SMA bars was 1200 mm. The length from the top of the foundation into the wall was 950 mm including the 150 mm length that extended into the couplers, while the remaining 250 mm extended into the foundation. The length of