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Cyclic loading testing of repaired SMA and steel reinforced concrete shear walls

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ABSTRACT

This paper presents the results of reverse cyclic load testing of a repaired slender concrete shear wall reinforced internally with superelastic Shape Memory Alloys (SMAs) in the boundary zones within the plastic hinge region. In addition, a companion-repaired wall reinforced with deformed mild steel was also tested. Provided herein is an assessment of the performance of the repaired walls against the same set of walls previously tested in their original condition. The repair strategy included removing heavily damaged concrete within the plastic hinge region, replacing ruptured and buckled reinforcing steel, and shortening of the SMA bars in the boundary zones. High-strength, self-consolidating concrete replaced the removed concrete. The concrete above the plastic hinge region remained intact given the negligible damage (hairline cracking) of the original walls in this zone. The test results demonstrated that SMA-reinforced concrete structural components are self-centering, permitting repair of damaged areas. Furthermore, the SMA bars were re-usable for the repair application due to their capacity to reset to their original state within the range of inelastic strains of up to 6%. The repaired walls were capable of restoring the yield and ultimate lateral load capacities, but sustained lower drift capacities. The repaired SMA wall was capable of recovering the imposed lateral drifts up to 2%, after which residual displacements accumulated due to rupturing of the SMA bars in the boundary zone. The repaired walls dissipated up to 7.8% more energy than their original walls for a significant portion of the loading range. The length of the SMA bars and the presence of starter bars in the original walls were influencing factors in the location of failure of the SMA- and steel-reinforced walls.

1. Introduction

Although reinforced concrete shear walls have demonstrated satisfactory performance during past earthquakes [1,2], recent earthquakes in Chile in 2010 [3–5] and New Zealand in 2011 [5,6] have highlighted deficiencies that have resulted in severe damage and collapse of mid- to high-rise buildings. In a number of buildings, flexural and shear-related damage in the shear walls was responsible for large permanent displacements that resulted in buildings that were not economical to repair. This brings to light the limited post-earthquake functionality of traditionally reinforced concrete structures. To address this, the design of structures should incorporate sustainable and resilient systems that, in addition to providing proper seismic detailing to prevent brittle failure and loss of stability, encompass a self-centering mechanism capable of resisting the seismic forces and have the capacity to recover the majority of the inelastic deformations. Such systems can potentially reduce post-earthquake repair costs. The importance of self-centering systems has previously been recognized by others [7,8].

The advancement of smart materials, such as Shape Memory Alloys (SMAs), for civil infrastructure is providing new opportunities to develop novel self-centering structures. Research related to self-centering structural systems based on SMAs has intensified over the last decade in response to the need to develop cost-effective resilient structures that can reduce damage experienced during large seismic events. The most appealing mechanical characteristic of SMAs is the recovery of strains by the application of heat (Shape Memory effect) or by the unloading of stress (Superelastic effect). Shape-memory SMAs can be utilized to provide active confinement [9–12] and post-tensioning [13–17] in concrete structures. Superelastic SMAs have been successfully used as internal reinforcement for new concrete construction [18–27]. More recently, superelastic SMAs have been implemented in external bracing systems to retrofit seismically deficient concrete structures [28,29]. Structural concrete components internally reinforced with superelastic SMAs have repeatedly demonstrated the capacity of the SMA to

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promote a self-centering phenomenon. This response has furthered been honed with the development of damage-free concrete components [25,26], where a combination of superelastic SMA longitudinal reinforcement and Engineered Cementitious Concrete (ECC) are used in plastic hinge regions.

The capacity of superelastic SMA reinforced concrete components to restore and minimize permanent deformations [19] allows the repairing option to be viable; whereas this is not necessary the outcome for traditional deformed steel-reinforced concrete components that experience large residual displacements. In addition, the large recovery strain limit (6%) of superelastic SMAs enables the material to be reused in a repair and/or retrofit strategy [28,29]. Previous research has demonstrated that although the upper plateau stress decreases with the number of cyclic repetitions (up to approximately 40%), the hysteretic characteristics of large SMA bars is maintained for up to 20 cycles to the same strain [30]. Other repair methods have successfully recovered the strength and stiffness of slender reinforced concrete shear walls by replacing damaged concrete [31–34], replacing damaged reinforcing steel (yielded, buckled, or ruptured) [31,34], or attaching external steel plates [35] or fibre reinforced polymers (FRP) [36]. The majority of these repair techniques, however, do not address re-centering. Only one technique, structural weakening [37], is known by the authors to focus on re-centering. This technique, however, has been applied only to retrofitting of existing walls.

2. Research significance

The objective of this paper is to investigate the capacity of recycled superelastic SMA bars to provide restoring capacity to a repaired, SMA-reinforced concrete shear wall subjected to reverse cyclic lateral loading and to illustrate the applicability of repairing SMA-reinforced components. The SMA bars serve as the principal longitudinal reinforcement in the boundary zones within the plastic hinge region, while the web region is reinforced with deformed mild steel in the longitudinal direction. To the best of the authors' knowledge, this is the first study to test a repaired heavily damaged SMA-reinforced shear wall.

3. Experimental program

Abdulridha and Palermo [19] previously tested the slender SMA-reinforced and the steel-reinforced concrete shear walls repaired in this study. The original walls were named W1-SR and W2-NR, while the repaired walls of this study were renamed RW1-SR and RW2-NR. Fig. 1 provides details of W2-NR. W1 and W2 correspond to walls 1 and 2, and the leading R is used to indicate repaired. The SR and NR refer to the steel and Nickel-Titanium (NiTi) SMA bars, respectively, that were used as the longitudinal reinforcement in the boundary zones within the plastic hinge.

3.1. Original walls

3.1.1. Design details

The original walls were 2200 mm in height, 1000 mm in length, and 150 mm in thickness, resulting in an aspect ratio of 2.2. This aspect ratio was selected to promote a ductile flexural response. The walls were constructed on 1700 mm-long, 500 mm-high, and 1400 mm-wide foundation blocks that were clamped to the laboratory floor during testing. In addition, the walls had 1500 mm-long, 400 mm-high, and 400 mm-wide top loading beams that distributed the applied lateral loading.

Walls W1-SR and W2-NR were reinforced with two layers of vertical and horizontal steel in the web. The vertical web reinforcement consisted of three pairs of 10 M (11.3 mm diameter) deformed bars and the horizontal web reinforcement consisted of fifteen pairs of 10 M bars. The bars were spaced at 150 mm in each direction. In the boundary zones, Wall W1-SR contained four continuous 10 M bars, whereas W2-NR included four, 1200 mm-long, 12.7 mm-diameter superelastic SMA bars, which were mechanically connected above the plastic hinge to four-15 M (16 mm diameter) deformed steel bars with single-barrel screw lock couplers. The SMA bars extended 950 mm above the foundation level into the wall, including 150 mm length that extended into the couplers, whereas the remaining 250 mm length penetrated into the foundation. The 800 mm-effective SMA length was approximately equal to the estimated plastic hinge height of 760 mm. The longitudinal reinforcement in the boundary zones were confined with 10 M closed ties spaced at 75 mm and 150 mm within and above, respectively, the plastic hinge region. In addition, the web section of the original walls contained four pairs of 10 M starter bars that extended 300 mm into the wall. The sole purpose of these bars was to increase the resistance to shear sliding at the interface between the wall and the foundation. The Canadian Standard for Design of Concrete Structures CSA-A23.3–14 [38] recognizes the contribution of added vertical bars to the sliding resistance.

3.1.2. Damage characteristics

The condition of W1-SR and W2-NR at the end of testing, after being subjected to drifts of approximately 4% and 4.5%, respectively, is illustrated in Fig. 2. Both walls experienced widespread damage, with more cracking surfacing in W1-SR. The reduced cracking in W2-NR was attributed to the smooth surface of the SMA bars, which reduced bonding to the surrounding concrete, resulting in fewer but wider cracks. Heavier damage was concentrated above the base of the wall at a height of approximately 380 mm and 350 mm for W1-SR and W2-NR, respectively. This was slightly above the location of the termination of the stater bars. In both walls, failure initiated along this damage plane. In W1-SR, the longitudinal reinforcement in one of the boundary zones experienced significant buckling, while the two exterior longitudinal reinforcing bars in the opposite boundary zone ruptured. The vertical reinforcement in the web experienced moderate buckling. Fig. 3 illustrates the state of the reinforcement in W1-SR after the concrete was removed. In W2-NR, the horizontal crack above the starter bars controlled the response of the wall. Additional cracking in W2-NR was minor and played a negligible role in the overall response. Upon removal of the concrete within the plastic hinge region, it became evident that three vertical deformed steel bars had ruptured along the damage plane in the web, while the other vertical bars experienced buckling. The SMA bars in the boundary zones experienced moderate local buckling, while no slip was evident at the location of the couplers. One SMA bar, however, had ruptured adjacent to the mechanical coupler at approximately 800 mm from the base of the wall. This was the result of concentrated damaged introduced in the SMA by the sharp-end screws of the mechanical coupler. Fig. 4 illustrates the damage sustained by the reinforcement in W2-NR.

3.2. Repaired walls

Prior to repairing the walls, external lateral load was required to recover the permanent lateral displacements and to re-align W1-SR. Conversely, W2-NR had experienced self-centering due to the presence of the SMA bars. This demonstrates that SMA-reinforced concrete structures can be repaired more readily than traditional reinforced components.

The repair of W1-SR and W2-NR included complete removal of heavily damaged concrete in the plastic hinge region as illustrated in Fig. 5. The height of the concrete removed in the boundary zones corresponded to the location of the mechanical couplers used to connect the SMA to the deformed steel bars. The extent of the concrete removed in W1-SR was similar to allow for a consistent comparison of the test results of the repaired walls. In both walls, the exposed transverse reinforcement in the web and boundary zones was removed to allow replacement of damaged (ruptured and/or buckled) longitudinal