Pushing the Envelope in Structural Concrete Design: Applications of Superelastic Shape Memory Alloys

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Shape memory alloys (SMAs) are smart materials with the capability to return to their original shape after experiencing large strains. The medical, aerospace, automotive, and robotic industries have incorporated SMAs in various devices. More recently, SMAs have attracted the interest of the structural engineering research community. This interest has emerged primarily due to the capability of the alloy to restore to its original shape after sustaining large deformations, levels which would cause permanent deformations in conventional reinforcing and structural steels. Potential applications of SMAs include: reinforcing in concrete structures, connections in structural steel assemblies, bracing members in structures, and prestressing rods in concrete elements (Alam et al. 2007). SMAs can also be used to mitigate unseating of bridges, and to provide damping to and isolation strategies for civil structures. The focus of this article is to summarize state-of-the-art research being conducted in Canada on the use of superelastic SMAs in concrete structures.

Material behaviour

The commonly recommended form of SMAs for civil structures is nickel-titanium (NiTi), which consists of approximately 56% nickel and 44% titanium. Other forms of the alloy are also available, including iron- and copper-based SMAs. In general, SMAs exhibit two distinct crystalline phases: martensite and austenite. SMAs exist in the fully austenite phase when their temperature is above the austenite finish temperature. This phase is characterized by superelastic behaviour; the SMA returns to its original shape by simply removing the external load.

Figure 1 illustrates a typical cyclic response of an NiTi superelastic solid bar with a diameter of 12.5 mm and the behaviour of a 10M deformed reinforcing steel bar routinely used in reinforced concrete (RC) design. It is evident that the SMA bar has the capability to recover imposed strains up to 6%. Thereafter, residual strains begin to accumulate, albeit insignificant relative to the permanent straining experienced by the steel bar. The behaviour of the SMA is characterized by an initial linear elastic response in the austenite phase. This is followed by a near constant stress plateau, equivalent to yielding in steel reinforcement. This plateau is the result of stress-induced forward transformation from the austenite phase to the martensite phase in the SMA bar.

At the maximum superelastic strain where the material has fully transformed to martensite, a second linear elastic response is experienced. This initiates after 6% straining for the SMA in Figure 1. The unloading response is initially linear, followed by a lower,

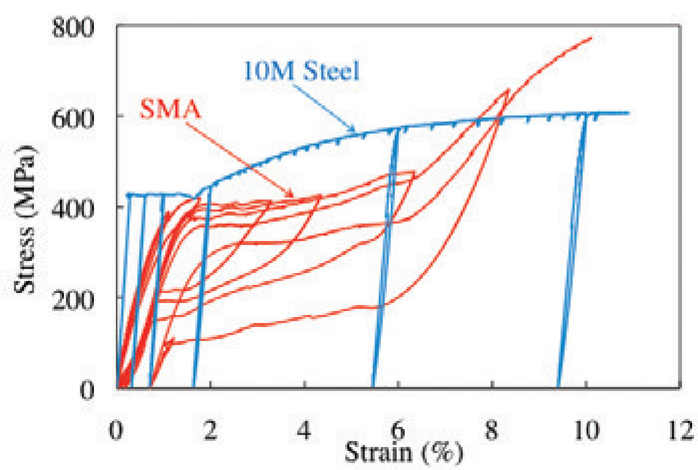

Figure 1: Cyclic stress-strain response of SMA rod and 10M deformed steel reinforcement (Abdulridha 2013).

near constant stress plateau. This phenomenon arises due to the reverse transformation from martensite back to austenite leading to recovery of the imposed strains. When the material returns to the fully austenite phase, a final linear unloading behaviour to zero stress occurs. A constitutive model applicable for modeling superelastic SMA bars was developed by Abdulridha et al. (2013). It is notable that the forward transformation stress of the SMA bar and the yield strength of steel bar are similar. An SMA reinforced member would be designed to response within the forward transformation range. Elbahy et al. (2010) proposed stress block parameters suitable for designing SMA reinforced sections.

Applications

To optimize the SMA given its higher cost relative to steel reinforcement, these materials are typically placed in the plastic hinge region and coupled to steel reinforcement outside this zone. Threaded mechanical and screw lock couplers have been used to facilitate the coupling. The latter is more practical and eliminates the need to thread the SMAs, which is a challenging task requiring carbon bits. However, slip between the SMA and screw lock coupler can arise (Alam et al. 2010).

Two examples of the successful implementation of SMAs are provided in Figures 2 and 3, showing a slender concrete shear wall and a concrete beam-column joint, respectively. In both cases, longitudinal SMA bars were placed in the critical (plastic hinge) region, at the base of the wall and at the end of the beam adjacent to the joint. The longitudinal reinforcement in the plastic hinge region in the beam-column joint consisted entirely of SMAs, while the critical section of the shear wall was reinforced with a combination of SMAs and steel reinforcement. The longitudinal SMAs were confined to the end boundary regions of the wall, while longitudinal steel reinforcement was placed in the web section. Thus, the shear wall represented a hybrid SMA-steel reinforced member. In both structural components, regular deformed steel was used for shear reinforcement, and for the anti-buckling reinforcement in the boundary elements of the shear wall.

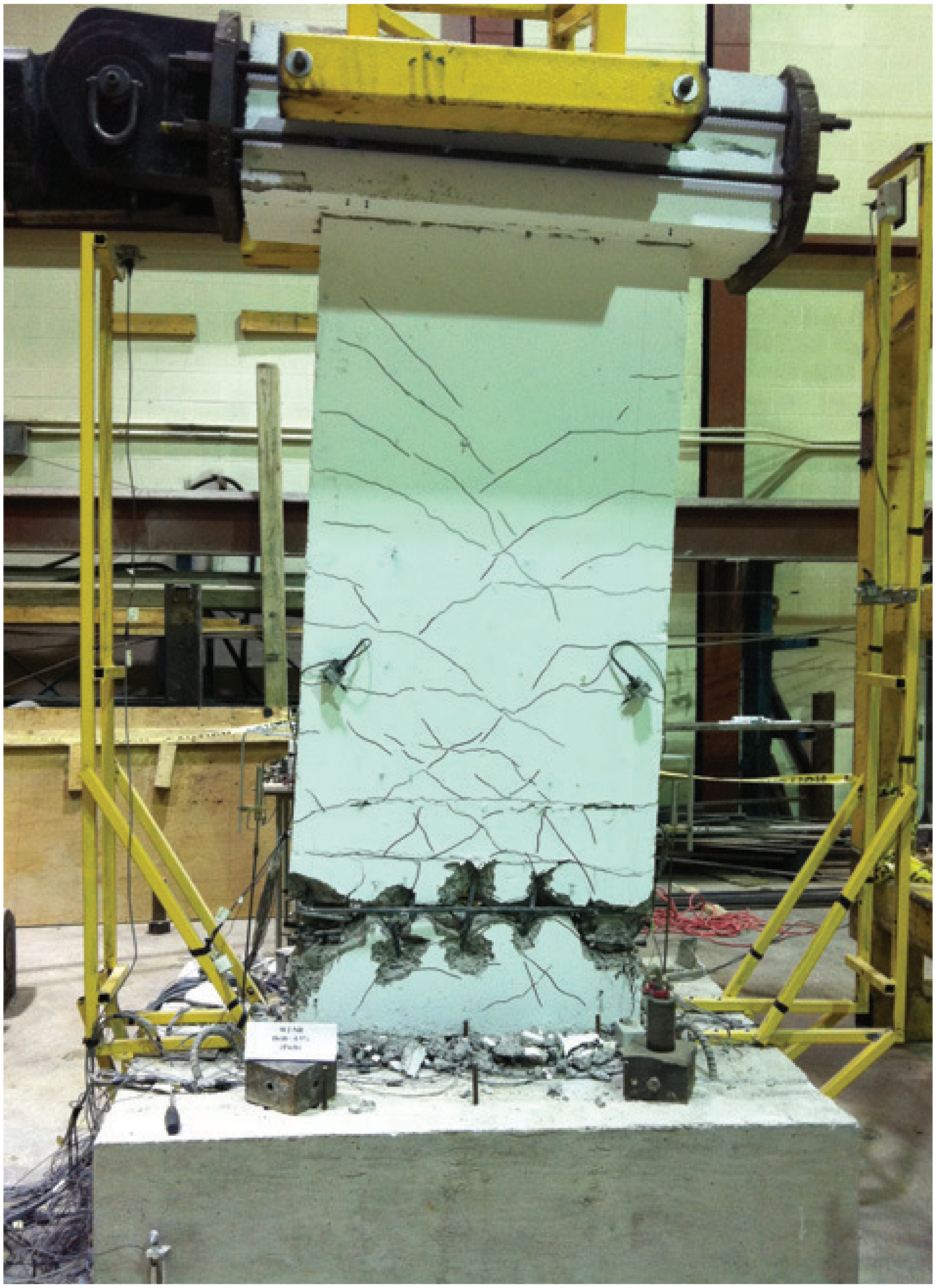

Figure 2(a): SMA shear wall (Abdulridha and Palermo 2013).

Figure 2(a) illustrates the level of damage sustained by the hybrid SMA-steel reinforced concrete shear wall, while Figure 2(b) provides the lateral load-displacement response. Figures 3(a) and (b) illustrate the condition of the SMA reinforced beam-column joint and the corresponding beam tip load-storey drift behaviour, respectively. The responses of the SMA shear wall and beam-column joint demonstrated superior recovery capacity relative to companion steel reinforced specimens. In addition, the SMA members sustained similar lateral load and lateral displacement capacities to their companion specimens. The photos illustrate that failure of the SMA reinforced components was concentrated along a major crack, which is attributed to the smooth surface of the SMA bars. This tends to promote rocking-type behaviour along the dominant crack. Both structural components demonstrated stable hysteretic response with significant energy dissipation, although less than the companion steel reinforced members. The other notable difference between the SMA and steel reinforced members is the initial stiffness; the SMA members are less stiff owing to the reduced elastic modulus of the material.

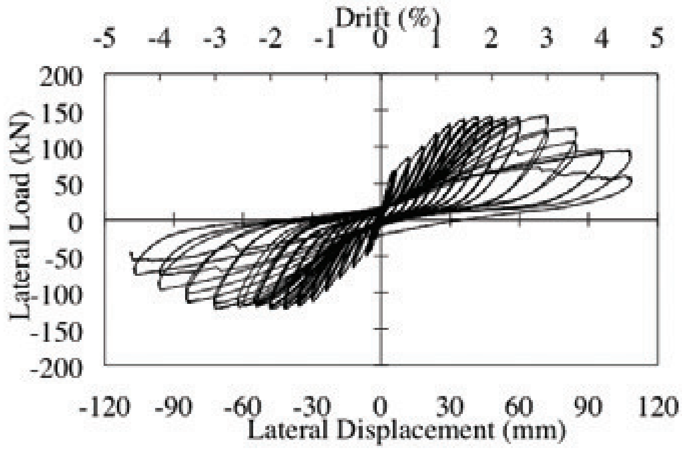

Figure 2(b): Response of SMA shear wall (Abdulridha and Palermo 2013).

Analytical models that simulate the behaviour of SMA reinforced members were developed by Alam et al. (2008), Billah and Alam (2012), and Abdulridha et al. (2013). A study by Youssef and Elfeki (2012) on full-scale frames reinforced with SMAs demonstrated that improved seismic performance is possible when using SMA bars in the beams of critical floor levels. Alam et al. (2012) demonstrated that overstrength in SMA RC frames is similar to that of steel RC frames; however, SMA RC frames possess less ductility due to its reduced stiffness.

Summary

Shape memory alloys offer the unique characteristic of recovery of high deformations after removal of load (superelasticity). This salient feature provides new opportunities for concrete structural design. The superelastic phenomenon is an attractive attribute for seismic performance, permitting the development of self-centering structural components. Large-scale experimental research has successfully demonstrated this potential in structural concrete. Analytical models that can predict the performance of SMA reinforced concrete elements have also been developed. Research of RC frame structures has also highlighted the advantages of using SMA bars in beams located on critical floor levels.

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Figure 3(a): SMA beam-column joint (Youssef et al. 2008).

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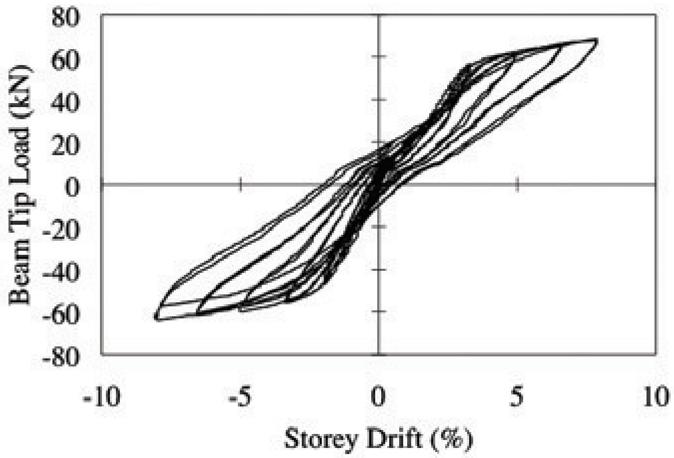

Figure 3(b): Response of SMA beam-column joint (Youssef et al. 2008).

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