DEVELOPMENT OF SMA-BASED SMART RC BRIDGE FOR SEVERE LOADING CONDITIONS

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ABSTRACT - Shape Memory Alloys (SMAs) are unique materials with high potential for various applications in bridges. The novelty of this material lies in its ability to undergo large deformations, and return to its undeformed shape through stress removal (superelasticity) or heating (shape memory effect). In particular, Ni-Ti alloys have distinct thermomechanical properties including: superelasticity, shape memory effect, and hysteretic damping. SMA can be effectively used in developing a smart Reinforced Concrete (RC) bridge which will be able to sense and detect its own damage, repair its condition, and adapt to changes in loading conditions. Existing deficient bridges can also be retrofitted by external post-tensioning using SMA. In addition, seismic retrofitting can be effectively done using various SMA dampers, isolators and/or restrainers. This paper examines the fundamental characteristics of SMA emphasizing the factors controlling its properties. The paper also presents the concept of developing a smart RC bridge with SMA applications in the construction of bridge structures along with its future trends and applications.

RÉSUMÉ - Start here the abstract in French language, maximum 10 lines. For abstracts and text, use Times New Roman 13 pt, with single line spacing. The title and abstract will be translated by the scientific committee, if the authors do not to provide their own translation.

1. Introduction

The first reinforced concrete (RC) bridge in Canada, the Hurdman Bridge was constructed in Ottawa in 1906. Nowadays, the majority of small highway bridges worldwide are being built using RC. Such bridges constitute a large portion of the national wealth in many countries around the globe. Because of aging, environmental exposure, and increased traffic loads compared to original design levels, such structures require monitoring, evaluation and repair on a regular basis, which is costly and time-consuming. Conversely, if a bridge structure becomes adequately smart so that it can identify its damage, report its state and adapt to changes in the loading conditions then many problems associated with the inventory of bridges can be mitigated. This thinking has given rise to the invention of smart materials and structures, which are becoming increasingly popular in modern design. A smart bridge is a structure having the ability to adapt to the surrounding environment to appropriately monitor its condition and to adjust itself to ensure optimal and safe operation under expected and extreme loading conditions, minimum energy use, and low maintenance.

The first smart RC bridge in Canada was built in 1993 in Calgary, Alberta (Rizkalla and Tadros 1994). The bridge is equipped with a fiber optic sensor system. The sensors, connected through a network system to a computer, can measure the absolute state of strain at different locations at different stages of its construction and operation. The Taylor Bridge in Manitoba (Rizkalla et al. 1998), the Norwood Bridge in Winnipeg (Shehata and Rizkalla 1999), and the Confederation Bridge, the longest bridge over iced-water spanning 12.9 km from Prince Edward Island to New Brunswick (Mufti et al. 1997) are other smart bridges installed with fiber optic sensors along with conventional sensors. These bridges are smart in terms of self monitoring, but not in the sense of self take-caring and action taking.

This paper presents a critical review of the state-of-the-art of possible applications of a smart and novel material i.e. SMA in RC bridge structures for both new and existing ones. The paper briefly reviews the basics of SMA and also develops a concept for creating smart RC bridge structures, their functioning and performance under service and severe loading conditions.

2. Shape memory alloys

Shape Memory Alloys (SMAs) are novel materials that exhibit variable stiffness and strength associated with their different polycrystalline phases. The Shape Memory Effect (SME) and Pseudo-Elasticity (PE) are two distinct properties that make SMA a smart material. SME is the unique phenomenon by which an SMA can recover its predetermined shape by heating even after large deformations. A Superelastic SMA can restore its initial shape spontaneously even from its inelastic range upon unloading. Various compositions of SMAs such as Ni-Ti, Cu-Zn, Cu-Zn-Al, Cu-Al-Ni, Fe-Mn, Mn-Cu, Fe-Pd, and Ti-Ni-Cu have been developed and their properties have been investigated. Among these, Ni-Ti has been found to be the most appropriate SMA for structural applications because of its large recoverable strain, superelasticity and exceptionally good resistance to corrosion. In this paper, unless otherwise stated, SMAs are mainly referred to Ni-Ti SMA (commonly known as Nitinol).

At a relatively low temperature SMA exists in the martensite phase. When heated, it experiences a transformation to the austenite phase (crystalline change). In the stress (σ) free state, SMA is characterized by four distinct transformation temperatures: martensite start (M_s), martensite finish (M_f), austenite start (A_s), and austenite finish (A_f). SMA exists in a fully martensite state when $T<M_f$ and in a fully austenite state when $T>A_f$. During the phase change from martensite to austenite and vice versa, both martensite and austenite phases coexist with temperatures between A_s and A_f, and M_s and M_f, respectively. In the martensite state when $T<A_s$, some residual strain will remain upon unloading as shown in the rightmost curve of Fig. 1. Upon heating, the material regains its original shape, known as SME.

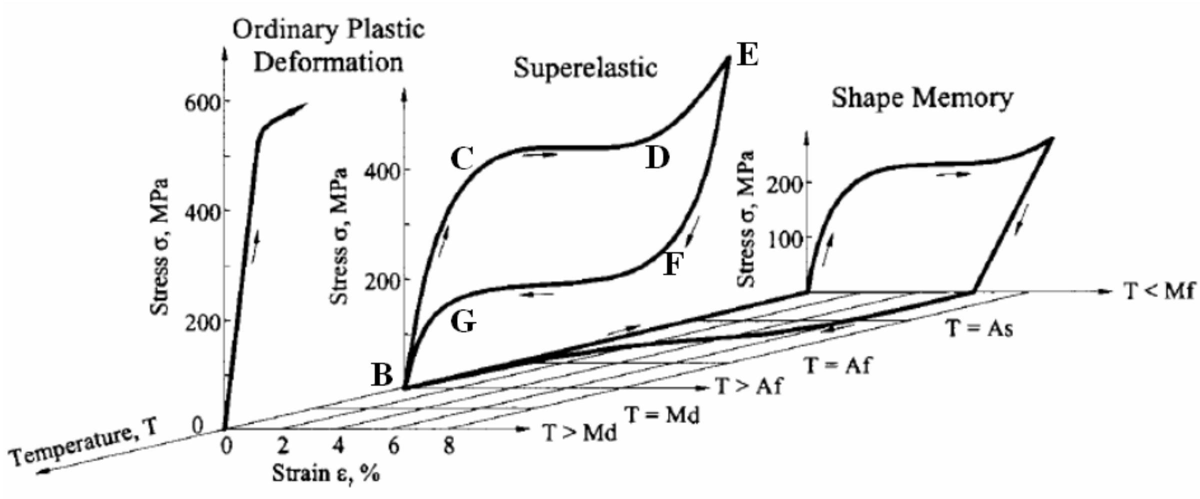


Figure 1. 3D stress-strain-temperature (σ-ε-T) diagram of SMA showing SME in martensite state, PE during austenite/martensite phase transformation and elastic-plastic behaviour of austenite at higher temperature (DesRoches et al. 2004).

Figure 1 (the curve on the T-ε plane) shows the temperature effect on residual strain. In the austenite state (T slightly higher than A_f), six distinctive features can be recognized in the middle stress-strain curve of Figure 1 (DesRoches et al. 2004): (a) BC – elastic response of austenite material at low strains (ε <1%) ; (b) CD – stress-induced transformation from austenite to martensite with a long and constant stress plateau at intermediate strains (ε = 1-6%); (c) DE – elastic response in the stress-induced martensite state at large strain (ε >8%); (d) EF – elastic recovery of strain upon stress removal; (e) FG – instinctive recovery of strain at an almost constant stress path because of the reverse transformation to austenite due to instability of martensite at $T > A_f$; and finally (f) GB – elastic recovery in the austenite phase. This exceptional property of SMA with the ability of recovering substantial inelastic deformation upon unloading yields a characteristic hysteresis loop, which is known as superelasticity (PE). If the temperature in the austenite phase exceeds the maximum temperature at which martensite occurs (M_d), then PE of SMA is completely lost and it behaves like an elastic-plastic material as shown in the leftmost curve of Figure 1.

3. Proposed SMA-Based Smart Bridge

The design, construction and performance of the different components of the proposed SMA-based smart bridge are described below. This bridge is not only capable of monitoring itself, but can also take necessary actions if required.

3.1 Bridge pier

Bridges in seismic regions are susceptible to severe damage due to excessive lateral displacements. Earthquake resistant bridge structures should be designed to behave elastically under moderate earthquakes. Under strong ground motions, it is not economically feasible to build bridges which will perform elastically. In conventional seismic design, steel is expected to yield in order to dissipate energy while undergoing permanent deformation. SMAs are unique alloys that have the ability to undergo large deformations, but can return to their undeformed shape by heating or through removal of stress. Therefore, if SMA is used as reinforcement, it would yield when subjected to high seismic loads, but will not retain significant permanent deformations (Wang 2004). Two quarter-scale spiral RC columns with SMA longitudinal reinforcement in the plastic hinge area were designed, constructed and tested using a shake table (Wang 2004). It was observed that SMA-RC columns were superior to conventional steel-RC columns in limiting relative column top displacement and residual displacements; they withstood larger earthquake amplitudes compared to that for conventional columns (Wang 2004). Therefore, it is proposed that SMA longitudinal reinforcements will be used in the plastic hinge area of the Smart RC Bridge, which will be able to regain its original position even after inelastic deformation under a strong ground motion and keep the structure serviceable, thereby reducing rehabilitation and other associated costs. Figure 2b shows the reinforcement detailing of the bridge pier (Figure 2a) where the SMA rebars are placed at the plastic hinge region and connected to steel rebars with couplers. Figure 3 shows the expected performance of the bridge pier with excellent recentering capability when subjected to earthquake loading.

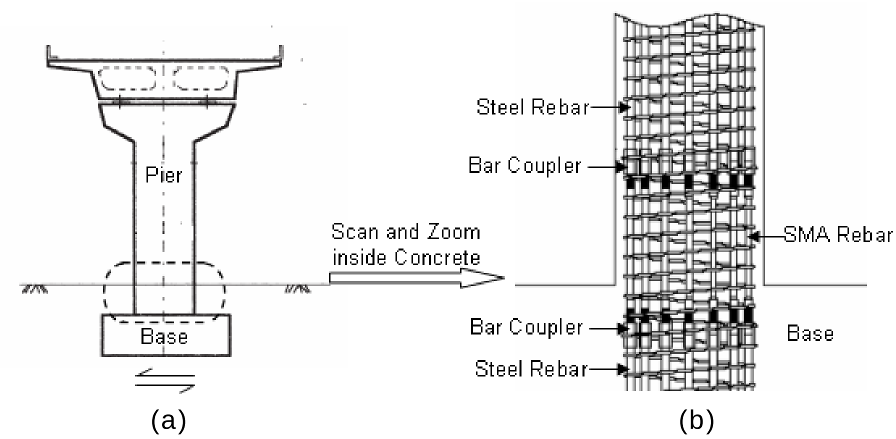


Figure 2. a) RC bridge pier and b) SMA-steel coupled reinforcement detailing of the bridge pier.

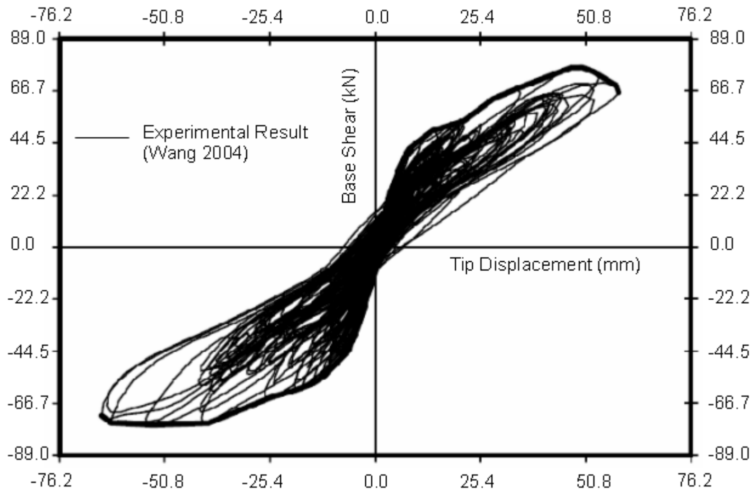


Figure 3. Experimental results of SMA-steel coupled reinforced concrete bridge pier under earthquake type loading (Wang 2004).

3.2. Bridge girder and deck

Smart bridge girders can be prestressed by either pretensioning or post-tensioning using SMA since bridge girders prestressed with SMA cables/wires have the ability of producing variable stiffness and strength after construction simply by heating without need for mechanical effort (Czaderski et al. 2006). The benefits of employing SMAs in prestressing include a) active control of the amount of prestressing with increased additional load carrying capacity, b) no involvement of jacking or strand cutting, and c) no elastic shortening, friction and anchorage losses over time.

Pretensioned SMA strands/wires in the martensite state are embedded in concrete, then electrically heated to transform from the martensite-to-austenite phase, thus undergoing large shrinkage strains and generating a significant prestressing force in concrete. The application of conventional prestressing by pretensioning wires requires jacking devices, but if SMA is used for prestressing it requires no jacking or strand cutting (Maji and Negret 1998). For permanent prestressing, A_f should be above the ambient temperature to prevent accidental activation of SMA during construction. Also, the M_s should be below the lowest operating temperature for the prestressing to be active during operation (El-Tawil and Ortega-Rosales 2004). Controlled heating of SMA bars will allow controlling the strength and stiffness of the girder, thus the amount of prestressing can be increased or decreased as required. Such structures could for instance actively accommodate additional loading or remedy prestress losses over time. This active control will require precise monitoring of the performance of the bridge girders. To serve this purpose, fiber optic sensors can be bonded to the prestressed SMA cables/wires to observe its effective prestressing stress, sensors will also be bonded to the bottom of the girders for measuring concrete strain.

Superelastic SMA wires/rebars can also be effectively employed in bridge decks for its self-restoration capacity. Bridge decks reinforced with superelastic SMA wires will be able to regain its original position even after being deflected in the inelastic range (Sakai et al. 2003) since SMA reinforcements in the martensite phase have the ability to recover from residual deformations induced by earthquakes, simply by heating.

3.3. Smart isolators

Isolation devices are a special kind of dampers that introduce discontinuity between a superstructure and its substructure allowing relative horizontal displacements. They act as a filter through which the seismic energy transferred from the substructure to the superstructure is greatly reduced. The main aspect of an effective isolator is to have a large energy dissipation capacity. Considering their full recentering and good energy dissipation capacity, SMAs are very promising for use in such vibration isolation devices (Bondonet and Filiatrault 1996, Wilde et al. 2000).

4. Retrofitting existing bridges with SMA

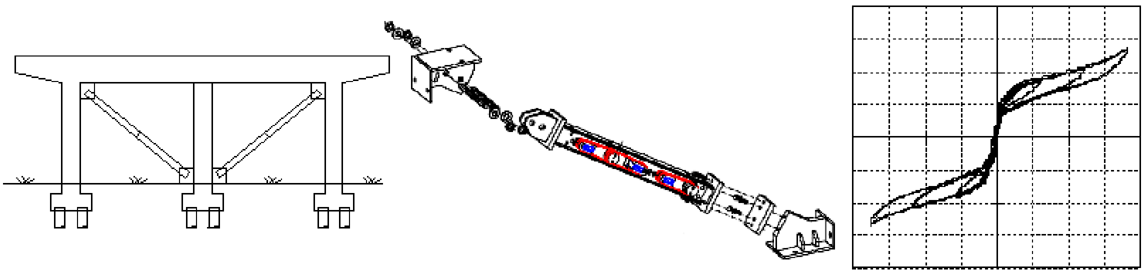
A bridge structure or one of its components can become deficient to withstand the applied loads and risk of failure due to various reasons for instance inadequate design, faulty construction, impact and dynamic loading, time-dependent etc. In such cases SMA has the potential to be used as an excellent retrofitting material.

4.1 SMA restrainers

One of the major problems of bridges during earthquakes is their unseating due to excessive relative hinge opening and displacement (Schiff 1998). Limitations of existing unseating prevention devices include small elastic strain range, limited ductility, and no recentering capability. These limitations can be overcome by introducing SMA restrainers. For instance, DesRoches and Delemont (2002) evaluated the efficacy of SMA restrainer bars through an analytical study of a multi-span simply supported bridge subjected to a set of ground motion records. The results demonstrated that SMA restrainers are capable of reducing relative hinge displacements much more effectively than conventional steel restrainers.

4.2 SMA bracings

Bridges supported by column frames can be effectively retrofitted with SMA bracings. Bracings have been found to be very effective in retrofitting frames under lateral loads. Experimental results confirmed that using SMA-based bracings in frame structures (Fig. 4) have a great potential and practical feasibility owing to greater initial stiffness and lower weight, and more importantly a recentering capability, compared to steel braces (Cardone et al. 2004).



(a) (b) (c)

Figure 4. a) Retrofitting of highway RC bridges with SMA-based supplemental re-centering bracing, b) arrangement of the SMA wires inside the device and c) typical cyclic force-displacement behavior (Cardone et al. 2004).

4.3 Post-tensioned SMA rods

Post-tensioned SMA bars can be used for the rehabilitation of deficient bridge girders. The SMA bars are pre-elongated in the martensitic phase and anchored to the deficient structural element. Upon electrical resistance heating and transforming to austenite, the constraint shape recovery causes transfer of corrective forces to the structure. The approach has been verified by Soroushian et al. (2001) by testing a RC beam that was deficient in shear. After loading, beam shear cracks occurred. The RC beam was subsequently repaired through post-tensioning with SMA rods and tested to failure. The results show that the initial ductility and load carrying capacity of the rehabilitated beam were almost fully regained. The practical demonstration of this repairing approach was applied in a bridge in Michigan, which lacked in shear strength and suffered cracks in T-beams extending into the deck. The repair process involved local post-tensioning of the cracked region with SMA rods and successfully reduced the average crack width by about 40%.

6. Conclusions and recommendations

SMAs' unique properties make it an ideal contender to be used for kernel components in the development of a smart RC bridge. This paper proposes the development and function of a SMA-based RC bridge with smart structural health monitoring, and action taking system. This paper also presents the distinctive properties and several applications of shape memory alloys in the proposed smart structure. A number of experimental and analytical studies on the applications of SMA and its devices (dampers and base isolators) in RC structures proved them to be effective in improving the response of bridges to earthquake loading. In particular, the recentering capability of SMA can be very efficient in reducing the cost of repairing and retrofitting bridges even after severe earthquakes. SMA has been proposed to be used as reinforcement at critical regions of the smart RC bridge piers along with conventional steel, where the SMA is expected to yield under strains caused by seismic loads but potentially recover deformations at the end of the earthquake event.

A prospective use of SMA is in prestressing, which can help a bridge to actively accommodate additional loading or remedy prestress losses over time simply by heating SMA above its transformation temperature. Post-tensioning with SMA wires and tendons also proves to be a better option over conventional steel tendons in retrofitting works. Smart bridges fitted with fiber optic sensing devices and SMA materials will be able to sense external stimuli, via internal sensing and/or actuation and then respond with active control to those stimuli in real or near real time. Such a smart bridge will respond and adapt to changes in condition or environment by integrating the functions of sense, logic, action and control usually in a repetitive manner (Hardwicke, 2003).

Applications of SMA in bridges are numerous, while new ideas of using it with other smart materials and in new applications are still emerging. Extensive research work still needs to be done. A major limiting factor for the wider use of SMA in the bridge construction is its high cost. If price can be lowered, its capability to allow the development of smart bridges with active control of strength and stiffness and ability of self-healing and self-repairing open the door for exciting opportunities, making SMA the smart construction material of the future.

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