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Literature Review

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Literature Review

Shape memory alloy-based smart RC bridges: overview of state-of-the-art

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Abstract. Shape Memory Alloys (SMAs) are unique materials with a paramount 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 along with sensing devices can be effectively used to construct smart Reinforced Concrete (RC) bridges that can detect and repair damage, and adapt to changes in the loading conditions. SMA can also be used to retrofit existing deficient bridges. This includes the use of external post-tensioning, dampers, isolators and/or restrainers. This paper critically examines the fundamental characteristics of SMA and available sensing devices emphasizing the factors that control their properties. Existing SMA models are discussed and the application of one of the models to analyze a bridge pier is presented. SMA applications in the construction of smart bridge structures are discussed. Future trends and methods to achieve smart bridges are also proposed.

Keywords: smart material; shape memory alloy; superelasticity; shape memory effect; fiber optic sensor; bridge.

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, there have been observed several incidents of collapse of bridges for instance the most recent highway bridge collapse in Laval, Quebec (CBC 2006). This clearly demonstrates that bridge structures require monitoring, evaluation and repair on a regular basis. This process 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 normal and severe loading conditions and thus requires minimum maintenance.

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This paper presents a review of the fundamental characteristic of SMA. It also offers a special focus on techniques for modelling SMA behaviour, a summary of the available SMA models in engineering software. A case study for using one of the models to analyze a bridge pier under base excitation is presented. Besides this, the paper provides a brief review of the basics of sensors having the potential to be used in RC bridges and a critical review of the state-of-art of possible applications of SMA in existing and new RC bridge structures. A concept for constructing smart RC bridge structures is discussed.

2. Shape memory alloys

Shape Memory Alloys are smart and 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 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, which is soft and ductile. When heated, its stiffness and strength increases with temperature and 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. Fig. 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 Fig. 1

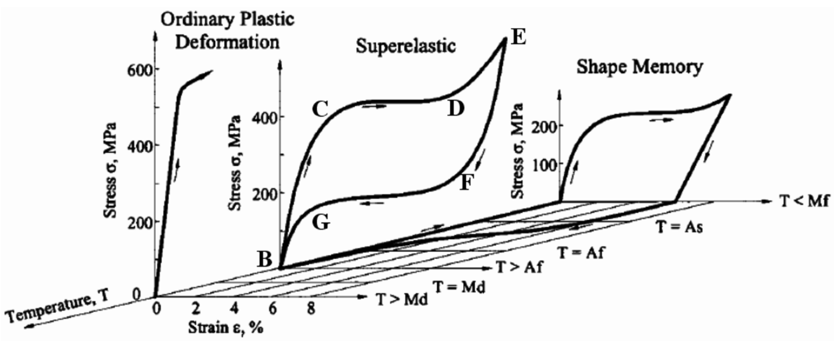

Fig. 1 3D stress-strain-temperature (σ-ε-T) diagram of SMA showing SME in martensite state, PE during austenite/martensite phase transformation and elastic-plastic behaviour of austenite at higher temperature (reprinted from DesRoches, *et al.* 2004 with permission)

(DesRoches, *et al.* 2004): (a) elastic response of austenite material at low strains (ε<1%) as denoted by BC; (b) stress-induced transformation from austenite to martensite with a long and constant stress plateau at intermediate strains (ε= 1-6%), indicated by CD; (c) elastic response in the stress-induced martensite state at large strain (ε> 8%) represented by DE; (d) elastic recovery of strain upon stress removal as shown by EF; (e) instinctive recovery of strain at an almost constant stress path because of the reverse transformation to austenite due to instability of martensite at $T > A_f$ as depicted by FG; and finally (f) elastic recovery in the austenite phase as indicated by GB. This exceptional property of SMA in 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 Fig. 1.

2.1. Modelling of SMAs

This section provides an outline on the modelling aspects of SMA, which is an integrated part of a comprehensive discussion of materials properties. It also provides some useful information for researchers and engineers on built-in SMA models in some FE packages where they can readily use such models to analyze structures incorporating superelastic SMA materials. SMA in the martensite phase under isothermal condition behaves like conventional metals up to a certain strain range, which can be modelled using such material models, whereas SMA's shape memory effect considers temperature induced transformation; its thermo-mechanical modelling is complex and beyond the scope of this paper. Since most civil engineering applications of SMA are related to the use of bars and wires, one-dimensional phenomenological models are often considered suitable. Several researchers have proposed uniaxial phenomenological models for SMA (Tanaka and Nagaki 1982, Liang and Rogers 1990, Brinson 1993, Auricchio and Lubliner 1997). The superelastic behaviour of SMA has been incorporated in a number of finite element packages e.g. ANSYS 10.0 (ANSYS Inc. 2005), ABAQUS 6.4 (Hibbitt, *et al.* 2003), and Seismostruct (SeismoStruct 2004) where the material models have been defined using the models of Auricchio, *et al.* (1997), Auricchio and Taylor (1996), and Auricchio and Sacco (1997), respectively. Fig. 2 shows the 1D-superelastic model used in ANSYS 10.0 (ANSYS Inc.

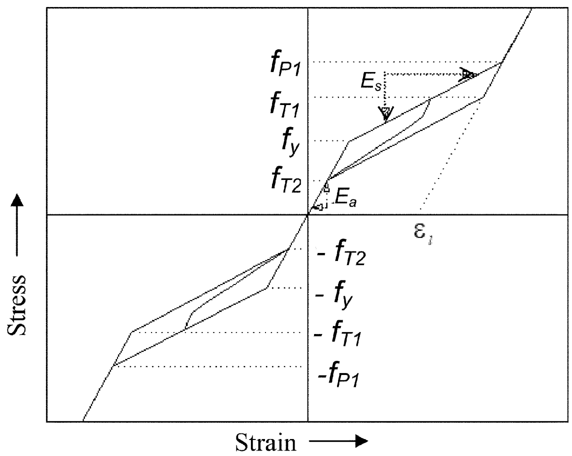

Fig. 2 1D-Superelastic model of SMA incorporated in FE Packages (reprinted from Auricchio, *et al.* 1997 with permission)

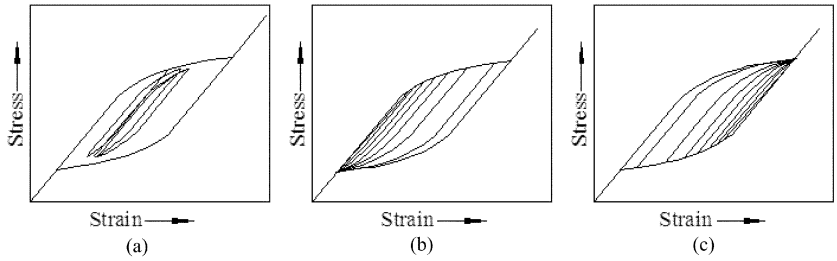

Fig. 3 1D-Superelastic model of SMA at constant temperature where the stress-strain curves are drawn after a complete transformation path followed by (a) PL and PU, (b) PL and CU, and (c) CL and PU (reprinted from Auricchio, *et al*. 1997 with permission)

2005) where SMA has been subjected to multiple stress cycles at a constant temperature and undergoes stress induced austenite-martensite transformation. When Fig. 2 is compared with the middle curve in Fig. 1, the parameters used to define the material model are f_y (point C); f_{P1} (point E); f_{T1} (point F); f_{T2} (point G); superelastic plateau strain length or maximum residual strain, ε_l; modulus of elasticity, E_a; and the ratio of f_y under tension and compression, α. Fig. 3 shows stress-strain curves of the model (Auricchio, *et al.* 1997) with a complete transformation path followed by a) cycles with partial loading (PL) and partial unloading (PU), b) cycles with PL and complete unloading (CU), and c) cycles with complete loading (CL) and PU, respectively. Here, PL and PU refer to incomplete stress induced phase transformation, whereas CL and CU refer to complete stress-induced transformation in the loading unloading process.

2.2. Case study

This section presents a case study on the use of a superelastic SMA model to predict the behaviour of SMA RC bridge piers. This provides an example calculation for engineers and researchers. Two quarter-scale spiral RC columns representing RC bridge piers (Fig. 4a) were designed, constructed and tested using a shake table by Wang (2004). Figure 4b shows the reinforcement detailing of the bridge pier where SMA rebars are placed at the plastic hinge region and connected to the steel rebars with mechanical couplers. Fig. 5a shows the experimentally observed performance of the bridge pier with excellent recentering capability when subjected to earthquake loading. It was observed that SMA-RC

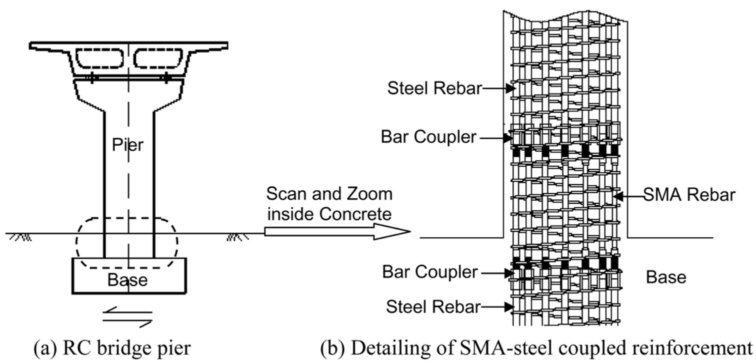

Fig. 4 RC bridge pier reinforced with coupled SMA-steel rebar

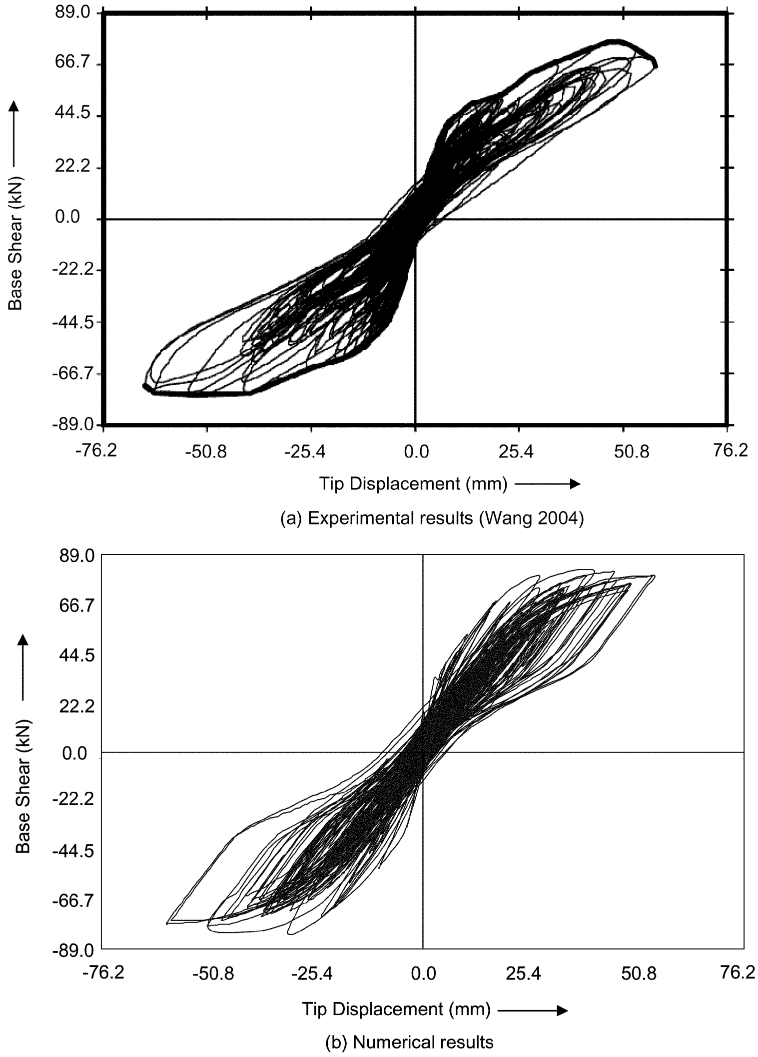

Fig. 5 Load versus tip-displacement for SMA-steel coupled reinforced concrete bridge pier under earthquake type loading

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).

In the present paper an inelastic dynamic analysis has been performed to predict the performance of the bridge pier tested by Wang (2004). SMA has been modelled according to Figs. 2 and 3. Fiber modelling approach has been employed to represent the distribution of material nonlinearity along the length and cross-sectional area of the member. 3D beam-column elements have been used for modelling the pier where the sectional stress-strain state of the elements is obtained through the integration of the nonlinear uniaxial stress-strain response of the individual fibers in which the section has been subdivided. Concrete and steel have been modelled using models of Martinez-Rueda and Elnashai (1997) and Monti and Nuti (1992), respectively. A finite element model for the bridge pier is shown in

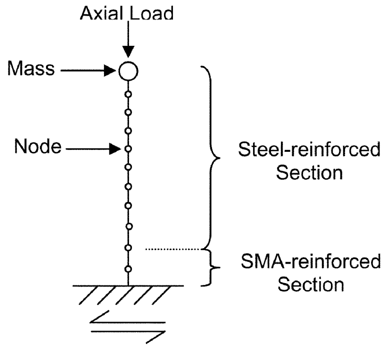

Fig. 6 Finite element model for SMA reinforced concrete column

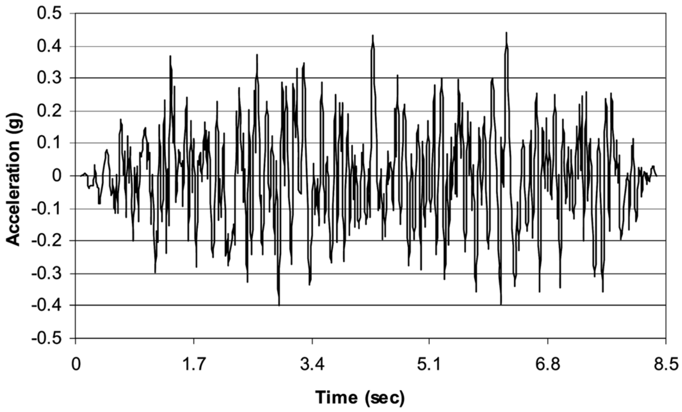

Fig. 7 Base acceleration time-history applied in SMA-reinforced concrete column (Wang 2004)

Fig. 6. The pier was divided longitudinally into 11 elements. Two of them represent the SMA reinforced part of the pier and the other nine represent the steel reinforced part. Each element was divided transversely into 200 by 200 fiber elements. No special modelling technique has been incorporated for bar couplers since the test results showed that they were able to transfer the force in the SMA to steel rebar and vice versa up to failure of the pier. The pier was subjected to a series of scaled motions ranging from 15% to 300% of the base acceleration time history shown in Fig. 7. Fig. 5b depicts the predicted base shear-tip displacement obtained using the numerical model. Comparing the predicted values to the experimental ones obtained by Wang (2004) shows that the model is fairly accurate in predicting the dynamic behaviour of SMA reinforced piers. The maximum base shear and the tip displacement were predicted as 81.5 kN and 62.0 mm compared to experimental values of 77.2 kN and 66.0 mm, respectively. The numerical results predicted by the model show good agreement with the experimental results which varies by only 5.6% for base shear and 6.1% for tip displacement. The accumulated energy dissipation was calculated as 48,160 kN.mm from the predicted load-displacement curve where as the amount of energy dissipation obtained from the experimental result was 44,010 kN.mm, which is only 9.4% lower than the calculated result. The experimental results show that the SMA-RC column failed at a displacement ductility of 5.9 by concrete crushing and yielding of SMA rebar., The numerical analysis predicted the same type of failure at a displacement ductility of 6.7.

3. Potential sensors

In support of an effective monitoring and maintenance program, comprehensive diagnostic information is required for the safe operation of bridges. This may involve mobilizing instruments such as electric resistance wire strain gauge, piezoceramic (Soh, *et al*. 2000), carbon fiber-reinforced concrete (Chen and Chung 1996), inclinometer (Hou, *et al*. 2005), vibrating wire strain gauge (Shehata and Rizkalla 1999), fiber optic sensors (Shehata and Rizkalla 1999), etc. for monitoring the bridge performance. Brief descriptions about these techniques are given below.

3.1. Electric resistance wire strain gauge (ERWSG)

Electric resistance wire strain gauges made of resistors are most widely used for strain measurements. Its principle is based on its resistance fluctuation with the variation of strain. It can measure strain up to a few thousand micro-strains (-2000 to + 2000) with an error of ±2 micro-strain (Cappa, *et al*. 2001). It is considered less costly and viable for short duration testing. It is sensitive to temperature variation and tends to change resistance with age (Omega 2006). Therefore, it is not suitable for continuous monitoring of of a bridge structure.

3.2. Piezoceramics (PZTs)

Piezoceramic patches or piezoelectric sensors (PZTs) have a unique property of producing electric charges when subjected to stress or strain, and vice versa. These PZTs can be calibrated in terms of electric voltages produced by specific stresses. PZTs can be embedded in concrete to detect possible internal cracks (Song, *et al*. 2006a) or bonded to a surface to measure strain of concrete and steel (Soh, *et al*. 2000, Bhalla and Soh 2004). These sensors can measure strain up to the order of 150 micro-strains (Sirohi and Chopra 2000). PZTs are low in cost and lightweight (Song, *et al*. 2006b) but they are sensitive to temperature fluctuations (Soh, *et al*. 2000).

3.3. Carbon fiber-reinforced concrete (CFRC)

Concrete containing short carbon fibers that conducts electricity has been found to be an inherently smart material. It has the potential to be used as a sensor for detecting damage during static or dynamic loading (Chen and Chung 1996, Bontea, *et al*. 2000), monitoring of traffic, estimating the weight of moving vehicles (Shi and Chung 1999), and measuring variation of temperatures within concrete elements (Sun, *et al*. 1999). High expenses might be the reason why CFRC, although having good potential, has not got its practical application as sensors in RC bridges.

3.4. Inclinometer

Inclinometer can be used for measuring static and dynamic deflections of bridge spans under load (Hou, *et al*. 2005). It measures deflection using an angle-measuring sensor, which consists of a capacitance transducer and a passive servo system. There is an inertial pendulum inside the inclinometer, which rotates with the pendulum rotation under loading. The pendulum inclination can be sensed by the capacitor, which generates a voltage output by an elaborately designed circuit proportional to the corresponding angular change of the bridge section. From the voltage output, the angular change of the bridge section can be calculated. The deflection profile of bridge span at a particular time can be evaluated with a number of inclinometers placed at some selected position on the bridge span. Its sensitivity is about 100 mV per minute of angle. The measuring range of the inclinometer is 10 minutes of angle. The inclinometers are low cost, and as they are installed directly on the bridge, they are suited for measuring deflection for bridges over rivers, sea, highways, railways, and also with high clearances and other obstructions underneath.

3.5. Vibrating wire strain gauge (VWSG)

Vibrating wire strain gauges operate on the principle that a tensioned wire, when plucked vibrates at a frequency proportional to the strain of the wire (DGSI 2006). These gauges comprise of two end blocks with a tensioned steel wire between them. The vibrating wire is placed in a case to vibrate freely. Its two end blocks are embedded in concrete or attached to a steel section. Under loading, the end blocks move relative to each other causing a change in the wire tension and thus, altering its resonant frequency. An electromagnet is used to pluck the wire and measure the vibrating frequency. Finally, the strain is calculated by applying calibration coefficients to the measured frequency with an accuracy of 0.5 micro-strain (Neild, *et al*. 2005). The strain gauges provide strong signal and can transmit reliably over a long distance with properly shielded cable.

3.6. Fiber optic sensors (FOS)

Fiber optic sensors have been widely used in measuring strains, temperature and stresses in RC structures, providing means for early warning of initiation of cracks/damage and risk of failure. They offer numerous advantages over conventional sensing devices in terms of stability, immunity to electromagnetic, light weight, small size, low transmission loss, and high resistance to corrosion (Shehata and Rizkalla 1999). There are a number of fiber optic sensors available such as the Fiber Bragg Grating (FBG) sensor, Fabry-Perot (FP) sensor, Brillouin Fiber Optic sensor (BFO) etc.

In case of FBG sensors, light is sent through fiber to the sensors; this light interacts with the grating and is reflected by the sensors in a very narrow band centered about the Bragg wavelength. The fiber refractive index and the grating pitch vary with changes in strain or temperature such that the Bragg wavelength shifts in a wavelength spectrum (Shehata and Rizkalla 1999). Besides single FBG sensor, there are multi-FBG sensors having multi grating on a single strand capable of monitoring distributed strain over a certain length. These sensors are capable of predicting strain even less than 1 micro-strain (Mueller, *et al*. 2006). An FP sensor is contained in a glass capillary consisting of two fibers facing each other with cavity length between them. At the tip of each fiber, semi-reflecting coatings are deposited as mirror reflectors. A white light is directed toward the FP sensor. The light signal is reflected back down the fiber into a read-out unit as the wavelength is modulated by the sensor. The strain is then derived from the change in cavity length, which is the space between two reflective surfaces. BFO sensors work on the principle of Brillouin effect, which is a scattering process arising from the interaction between optical (photons) and acoustic waves (photons) propagating in the same physical medium (Bastianini, *et al*. 2005a). When the medium is illuminated with a monochromatic light source, there will be a partial energy transfer between the colliding photons and photons that produce scattered photons characterized by a certain frequency shift with respect to the incident photons (Brillouin 1922). The recently developed self-heterodyne technique has made it possible to scan the spectrum Brillouin scattered light with high resolution that allows assessing an empirical correlation between strain level and Brillouin frequency shift (Horiguchi, *et al*. 1989), which proves to be suitable for strain sensing. Detailed descriptions of the properties and functions of FBG, FP and BFO can be found in Shehata and Rizkalla (1999) and Bastianini, *et al*. (2005a and b), respectively.

4. New bridges

The Beddington Trail Highway Bridge involved the use of sensors and new reinforcing materials and was built in 1993 in Calgary, Alberta (Rizkalla and Tadros 1994). It is a two span continuous skew highway bridge consisting of T-section precast concrete girders pretensioned by carbon fiber-reinforced polymer (CFRP) tendons along with steel strands. FBG sensors were connected through a network to a computer to measure and report strains at different locations at different stages of construction and operation. After six years of construction, the bridge was tested under dynamic and static loading to assess the durability of FOSs. The results proved the functionality and long-term reliability of FOSs (Mufti 2002).

The Taylor Bridge in Manitoba, constructed in 1997, is one of the world's largest highway bridge reinforced with FRP and being monitored using FOSs (Tennyson, *et al*. 2004). It utilized FBG technology coupled with conventional strain gauges and thermocouples embedded in bridge girders, deck slab and barrier wall (Rizkalla, *et al*. 1998). The 165.1 m long bridge consists of 40 girders of which four are prestressed with CFRP tendons. The performance of the bridge is continuously monitored under traffic loads and extreme environmental exposures. A camera has also been used to monitor the traffic condition, where the video information is synchronized with the sensor data. Strain data for concrete helps in determining crack width and stress data in prestressing tendon helps in observing the safe stress limit since CFRP tendon is elastic but brittle material. Thus, the stress-strain data monitored during the bridge operation can be used for making important decisions regarding the safe operation, maintenance, and repairing of the bridge. The measured strains from the most heavily loaded girders have been analyzed and it was found that the values of dynamic load allowances is reduced by about 24% while doubling the weight of the vehicle, which indicates the reliability of the dynamic load factors (Bakht, *et al*. 2003).

The Norwood Bridge in Winnipeg consists of 85 precast slender RC girders with complex shapes and was required to be monitored during transportation, erection, construction, and service (Shehata and Rizkalla 1999). FOSs and VWSGs were used for monitoring the bridge. The measured tensile strain data demonstrated the safety of the girders against cracking during transportation and erection.

The Confederation Bridge, the longest bridge over iced-water spanning 12.9 km from Prince Edward Island to New Brunswick, Canada is a multi-span precast RC box girder structure installed with FBG sensors along with conventional ERWSG sensors, thermocouple arrays, closed circuit cameras, and a weather monitoring station to observe the long-term effects of wind, ice, temperature and traffic loads on the bridge (Mufti, *et al*. 1997). Due to severe environmental exposure, the fiber optic sensors, bonded to rebar have been used to continuously monitor strains in concrete, while thermocouples measure the temperature gradient through the web from its inside to the outside. These data were used for the verification of existing analytical models to predict thermal curvatures and stresses for deeper sections of a bridge. It was found that the existing analytical models could not estimate thermal curvature and stresses satisfactorily and hence, a new model needs to be developed for better estimation (Li, *et al*. 2004).

5. Proposed SMA-based smart bridge

A new generation bridge needs to be smart, which will not only be able to monitor itself, but also take necessary actions if required. The design, construction and performance of the different components of a proposed SMA-based smart RC bridge are described below.

5.1. 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 that will perform elastically. In conventional seismic design, steel is expected to yield in order to dissipate energy while undergoing permanent deformation. The unique ability of superelastic SMAs to undergo large deformations and return to their undeformed shape by removal of applied stresses allows them to be used as reinforcing bars that yield when subjected to high seismic loads but do not retain significant permanent deformations (Wang 2004). It is proposed that superelastic SMA longitudinal reinforcements be used in the plastic hinge area of the Smart RC Bridge. This will allow the pier to regain its original position even after inelastic deformations have occurred thus keeping the structure serviceable and reducing retrofitting costs.

5.2. Bridge girder and deck

Prestressed bridge girders can be either pretensioned or post-tensioned. Both types of prestressing can be done 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 any 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. This strain energy can be used to generate significant prestressing forces 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. For instance, Maji and Negret (1998) used Ni-Ti strands for prestressing concrete via the shape memory effect of SMAs. Pre-stretched SMA strands/tendons in the martensite phase are passed through post-tensioning ducts after placement of concrete, and then post-tensioning is induced by heating. 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. For instance, El-Tawil and Ortega-Rosales (2004) used SMA tendons to permanently prestress concrete. Other advantages of using martensite SMA bars/tendons are their ability to damp vibrations and to provide high fatigue resistance for sections subjected to a low or high number of flexural load cycles (Dolce and Cardone 2005).

Controlled heating of SMA bars allows 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 up to a certain limit or remedy prestress losses over time. This active control will require precise monitoring of the performance of the bridge girders. This can be done using FOSs to continuously monitor the strain of the SMA strands.

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 residual deformations.

5.3. Smart isolators

Dampers are passive protection devices that are effective in dissipating seismic energy for new and retrofitted structures. Even though various types of dampers have been developed utilizing various technologies, they have numerous limitations related to ageing and durability (e.g. rubber-based dampers), maintenance (e.g. viscous fluid dampers), reliability in the long run (e.g. friction dampers), temperature dependent mechanical performance (e.g. rubber-based dampers, viscoelastic dampers), and geometry restoration after a strong earthquake (most dampers) (Dolce, *et al*. 2000). SMA materials have the potential to overcome many of these limitations when applied in such devices.

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.

Adachi and Unjoh (1999) proposed an energy dissipation device made of SMA plate, designed to absorb seismic energy and reduce the seismic force through its pseudo yield effect. Their study mainly focused on the increase in the damping effect of the device fitted to bridge structures. A series of shake table tests were performed to verify the effectiveness of such devices under earthquake excitations. It was found that SMA plate damping devices significantly reduced the seismic response of the bridge structure.

Bondonet and Filiatrault (1996) conducted an analytical study using a two-degree-of-freedom lumped mass model of a bridge pier/superstructure system with a single SMA device installed between the pier and the superstructure. They found that ground accelerations could be reduced by up to 90% by the SMA device and that the self-centering characteristics of the superelastic device resulted in negligible residual displacements.

Wilde, *et al*. (2000) proposed an isolation system for an elevated highway bridge, which consisted of a simple SMA bar combined with a laminated rubber bearing. Two isolation systems: a) proposed smart isolator (SMA), and b) conventional laminated rubber bearing with lead core and displacement restrainer (NZ) were considered and analyzed for a sinusoidal excitation and the North-South ground motion components of the 1995 Kobe earthquake. For the smallest excitation (0.2 g), a stiff connection was obtained between the pier and the deck. For a medium excitation (0.4 g), an increase in the damping capacity was observed due to stress-induced martensite transformation of the alloy. For the strongest excitation (0.6 g), the SMA bars provided hysteretic damping and acted as a displacement control device due to hardening of the alloy after complete phase transformation. It was found that in each excitation the maximum relative displacement between the pier and superstructure was lower for the SMA system compared to that of the NZ system. Also, the maximum damage energy of the bridge with the SMA system was 14% smaller than that with the NZ system. Since the isolation device is composed of SMA bar working in tension-compression, this may be subjected to buckling.

Prestrained SMA wires wrapped in the longitudinal direction of a conventional elastomeric bearing can be used as an isolator in the smart RC bridge (Choi, *et al*. 2005). An analytical study was conducted by Choi, *et al*. (2005) to determine the effectiveness of SMA-rubber bearing (SRB) compared to that of conventional lead-rubber bearing (LRB). A three span continuous bridge fitted with SRB and LRB were subjected to scaled ground motions (PGA of 0.2 g, 0.4 g, 0.6 g, 0.8 g and 1.0 g) of El Centro and Loma Prieta earthquakes. The results showed that the LRBs retain residual deformation even with the weakest ground motion whereas the SRBs recover all the deformation even after the strongest motion. The size of SMA wires needs to be optimized such that SRBs have high-energy dissipation capacity compared to LRBs. The installation of the proposed SRB is also easy and will not require any additional work since the SMA wires are unified into the elastomeric bearing (Choi, *et al*. 2005).

5.4. Sensors for smart bridge

Multi-FBG sensors are proposed to be installed in the smart bridge where the sensors will be bonded to reinforcements of the bridge deck, girder and piers to measure strains in rebars and its surrounding concrete. The FOSs will be aligned with the axis of the rebar and bonded to its surface. FOSs will also be installed at the bottom face of the bridge girder along its length to directly monitor the crack growth in concrete. Some conventional VWSGs will be installed in close proximity to the FBGs to facilitate comparison between the two results. A thermocouple array will be installed through the depth of the girders for measuring the temperature gradient. This can be used to compensate the thermal strain from the FBG strain data. A number of inclinometers will be installed in the bridge span to measure the deflection profile at a given time.

6. Smart monitoring, decision making and automated response

Important bridges that have been developed for the last ten years are capable of monitoring their present condition in terms of cracks or other forms of damage, and thus can help in decision making, e.g. need for retrofitting, closing the bridge, etc. There has been so far no such smart bridge, which can make its own decisions and take the required actions. Incorporating SMA in RC bridges along with sensing devices, cameras, and weighing machines interacting through computers can develop such a smart bridge which will not only monitor its structural health but can also take decisions and actions when necessary. A detailed description of the different components of the proposed bridge and its performance has already been discussed in previous sections. This section confers to the whole operation scenarios of the smart bridge and the interaction between its various components.

6.1. Current system

In Canada, important bridges are typically instrumented with sensing devices to monitor its condition. A truck that is heavier than the standard truck seeks permission from the Ministry of Transportation (MT) to cross bridges. In many cases, the axle is increased so that the load is distributed along the length of the bridge (Metz 1979). If this is not possible, then a decision will be made by a Bridge Engineer. The bridge must be analyzed to confirm safety and a decision is made whether to allow the truck to cross or not. The truck has to be monitored by a global position system (GPS), and the data generated by the sensors during crossing are instantly analyzed by the engineer to generate a structural health report and maintenance suggestions, if necessary. The FBG sensors used in bridges are also capable of detecting damage, locating its position. If the sensors are connected to a local computer, it can process data and send online warnings to monitoring stations.

6.2. Proposed system

Although current structural health monitoring systems have been found effective and useful for the safe operation of bridges, their major drawback is their lack of self-control, i.e. the inability of decision-making and action taking. Such a control can be achieved by introducing SMA materials in bridges along with sensing devices. An SMA-based smart simply supported bridge system is illustrated in Fig. 8 where the bridge deck, girders and piers are reinforced with SMA rebars, and fiber optic sensors are installed along the length of each bridge component members. SMA-based isolators are placed in between girders and bridge piers. The smart bridge monitoring, decision making and action taking is presented by a flow diagram in Fig. 9. The bridge is instrumented with cameras at various locations starting from the approach road to measure vehicle speed, locate vehicle position, and identify particular vehicles. On the approach slabs of the bridge, there are measuring scales to weigh moving vehicles. The data acquisition system collects real-time data from sensors, cameras and measuring scales, which are processed into a computer that analyzes data. The processed data is then used for decision-making and action generation. The raw data, pre-processed data and processed data are transferred online to bridge engineers and saved into a database in the bridge monitoring station.

When vehicles heavier than standard trucks are permitted by MT, they are monitored along its way by GPS. The information about their weight, distribution of the wheel loads and GPS data are fed into the analyzer. The analyzer predicts the arrival time from the GPS data. As the vehicle reaches closer to the bridge, considering the vehicle arrival time and actuation time to heat SMA tendons, the power switch gets automatically on, and this is being regulated by the temperature-capacity curve provided by the designer to heat SMA tendons to a pre-specified temperature. Alternatively, vehicles heavier than standard trucks may use a special transponder from MT, which can be detected by the cameras at the approach road. As soon as the vehicle approaches, this triggers the switch of heating SMA rebars. With the increase in temperature, the stiffness and strength of SMA will increase, which in turn will increase

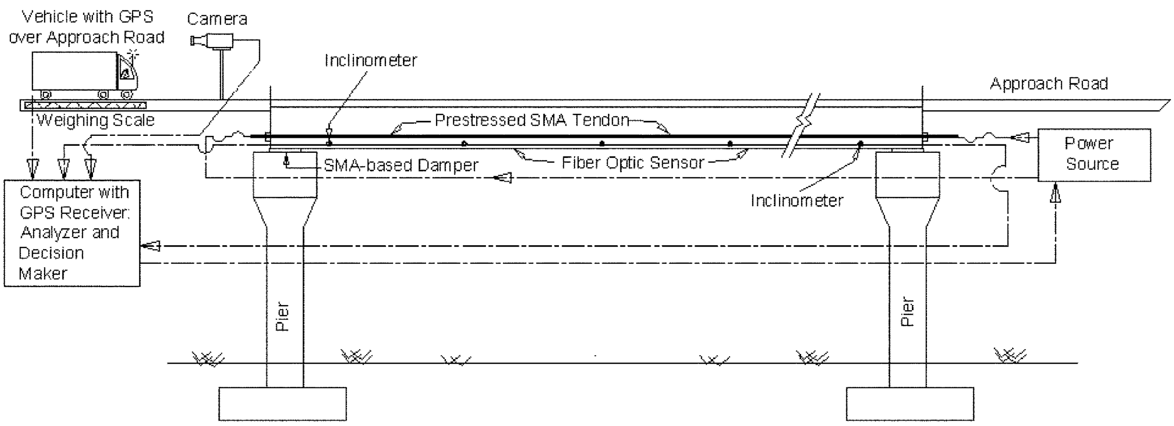

Fig. 8 Highly instrumented SMA-based smart RC bridge

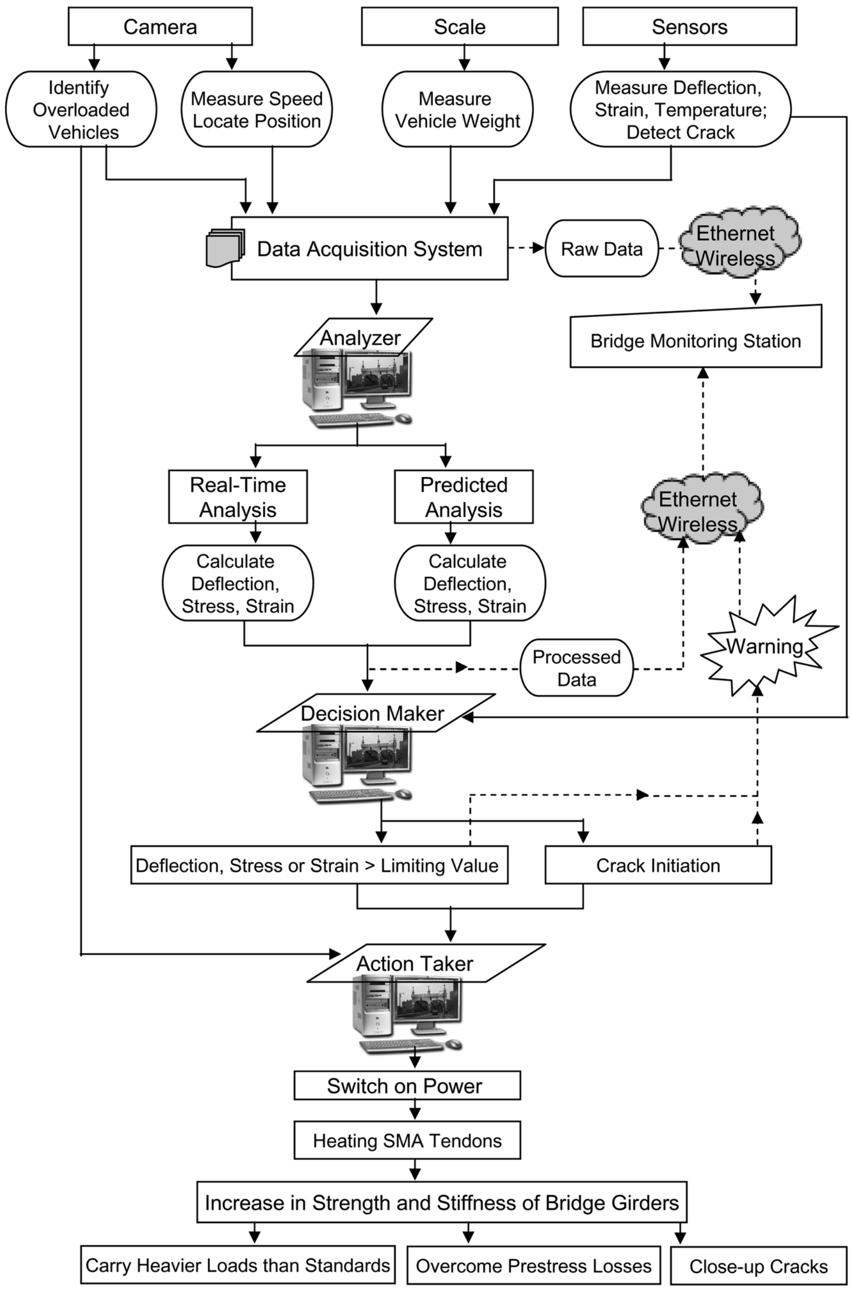

Fig. 9 Maintenance and operational flow diagram of proposed SMA-based smart RC bridge

the stiffness and strength of the bridge. This will ultimately help in maintaining a crack free concrete. With time as the temperature falls down, the strength and stiffness of SMA as well as the bridge capacity goes down. It is to be noted that heating or actuation of SMA rebars is a fast process when compared to its cooling/de-actuation process (Janke, *et al*. 2005). Thus, the smart bridge will be able to handle heavier vehicles whenever required without being cracked or damaged.

Damage propagation in RC structures is a slow process. In case there is a little flexural crack in the structure or the deflection exceeds the limiting range, the smart bridge using its real time analyzer will be able to overcome the damage by heating the SMA tendons of the girders and deck and thereby increasing the stiffness and strength of the bridge within a few minutes (Janke, *et al*. 2005). Also in case of emergency, if the bridge sensors are not functional, the smart bridge system will also be able to do real-time analysis depending on the real-time position, speed and weight of vehicles. Analyzing such data, the system can also be able to detect cracks and take actions e.g., heating will cause large shrinkage strains in the pretensioned martensite SMA strands/wires, which will allow closing cracks in the girder. The same procedure can be applied to overcome prestress losses by SMA tendons.

The sensors can also continuously monitor the bridge condition under thermal effects, wind gust and earthquake loading. Under earthquake loading the bridge will be able to take care of itself because of the high recentering capability of the bridge piers as discussed earlier. In case of strong wind events and earthquakes, the SMA-based dampers will also be able to absorb a significant amount of energy and reduce the force transferred to the superstructure.

7. 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 load etc. In such cases SMA has the potential to be used as an excellent retrofitting material.

7.1. 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 (ability to bring the member back to its original position even after inelastic deformation). These limitations can be overcome by introducing SMA restrainers. For instance, DesRoches and Delemont (2002) evaluated the efficiency of SMA restrainer bars through an analytical study of a multi-span simply supported bridge subjected to a set of ground motion records. The performance of SMA restrainers were compared with that of conventional steel restrainers. The results demonstrated that SMA restrainers are capable of reducing relative hinge displacements much more effectively than conventional restrainers due to its high recentering capability. Moreover, Andrawes and DesRoches (2005) conducted nonlinear time history analyses on a typical RC box girder bridge to assess the performance of superelastic restrainers and conventional steel cable restrainers. High damping and elastic strains of superelastic elements significantly reduced relative hinge displacement compared to that of steel restrainers. Therefore, application of SMA restrainers in existing simply supported bridges is an effective way of preventing unseating under lateral loading.

7.2. SMA bracings

Deficient bridges supported by column frames that are vulnerable against lateral loading can be effectively retrofitted with SMA bracings (Fig. 10a). Bracings have been found to be very effective in

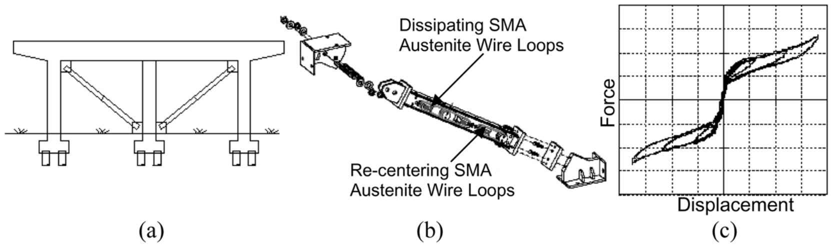

Fig. 10 (a) Retrofitting of highway RC bridges with SMA-based supplemental re-centering bracing, (b) arrangement of the SMA wires inside the device and (c) typical cyclic force-displacement behaviour (reprinted from Cardone *et al*. 2004 with permission)

retrofitting frames. Dolce, *et al*. (2004) retrofitted an RC frame structure where the retrofit design was based on the use of special braces (Fig. 10b) with recentering characteristics determined by the superelastic properties of SMA austenitic Ni-Ti wires used as main components of each brace. The expected typical force-displacement relationship is shown in Fig. 10c. The test results demonstrated that the passive protection system based on the use of SMA wires provided the tested RC frame structure with a strong recentering capability, increased safety at the Ultimate Limit State, and enhanced displacement control at the Damage Limit State. SMA-based bracings in frame structures 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).

7.3. Post-tensioned SMA rods

Post-tensioned SMA bars can be used for the rehabilitation of bridge girders deficient in shear. 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%.

8. Issues to be addressed to have a smart RC bridge

The concept of the smart RC bridge is based on its unique ability to actively control the stiffness and strength of the structure by using the actuation mechanism of SMAs. The smart bridge also utilizes the superelasticity of SMA in piers and restrainers to exhibit its recentering capability.

Although there have been various successful applications of SMA actuation in a number of fields, almost all of them require smaller actuation forces than those experienced in civil engineering applications. The SMAs' actuation mechanism has been incorporated in civil structures but mostly at a smaller scale and only for laboratory testing. Recently a few field applications of SMA actuation have been successfully conducted (Soroushian, *et al*. 2001). They utilized 24 martensitic SMA rods of 10.4 mm diameter for repairing a deficient RC bridge girder against shear. The SMA rods were anchored on to the girder with the help of an anchorage system composed of two angles firmly attached to the girder with high strength rods. The SMA rods were actuated with electrical resistance heating with 1000 A current to achieve 300 ºC temperature, which produced a post-tensioning force of 352 kN and increased the nominal shear strength of the beam by more than 35%. A large-scale test on SMA actuation has been performed by Ocel, *et al*. (2004). They tested two full-scale partially restrained steel beam-column connections (S1 and S2) using SMA in martensite phase. The connections consisted of four large diameter SMA bars connecting the beam flange to the column flange serving as the primary moment transfer mechanism. After the initial testing series of drift cycles, the tendons were heated to recover the residual beam tip displacements. Propane torches were used to heat the tendons of specimen S1. After 8 minutes it could recover a displacement of 18 mm, which corresponded to 76% recovery of residual tip displacement. In case of S2, the tendons were heated while the connection was under load. Propane and oxy-acetylene torches were used in several steps, which could recover 54% recovery after 54 minutes. After initiating the shape memory effect within the tendons, the connections were retested, displaying repeatable and stable hysteretic behaviour.

The superelasticity of SMA has been effectively implemented in various civil engineering projects, for instance in Indirli, *et al*. 2001, Dolce, *et al*. 2004. Trignano S. Giorgio Church built in 1302 in Italy was seriously damaged by a 4.8 Richter magnitude earthquake on October 15, 1996. The masonry column supported bell tower within the church was critically damaged and needed to be retrofitted. In order to increase the flexural resistance of the tower, four vertical prestressing steel tie bars anchored at the roof and foundation were inserted in the internal corners of the structure. Four post-tensioned SMA devices were put in series in each tie bar, with the aim of maintaining the maximum force applied by each SMA device to the masonry always compressive and below 20 kN since numerical analysis indicated that a compression of 20 kN for each tie bar was found sufficient to reduce tensile loads in the masonry below the design failure limit. Each SMA device included sixty superelastic SMA wires of 1 mm diameter and 300 mm length. The performance of the innovative rehabilitation scheme was positively verified after the tower was shaken by another 4.5 Richter magnitude earthquake. No forms of distress or damage were noticed after the shock. Dolce, *et al*. (2004) conducted a test on an existing 2-storey RC structure designed according to 1970's standards aiming at assessing the cyclic behaviour of the retrofitted structure. The retrofit design was based on the use of special braces with recentering characteristics determined by the superelastic properties of SMA austenitic NiTi wires used as main components of each brace. The results demonstrate that the passive protection system based on the use of SMA wires provided the tested RC structure with a strong recentering capability, increased safety at the Ultimate Limit State, and enhanced displacement control at the Damage Limit State.

Although there are several examples of successful implementation of SMA in engineering projects, still there are several constraints that need to be addressed and dealt with to make the smart bridge an effective one. A summary of these constraints is given in the following sections.

8.1. Cost and economy

Although there is a substantial potential for utilizing SMA in bridges, the cost of this material is a primary restraining factor to the full-scale implementation of SMA in bridge construction. The forces acting on bridges are typically very large requiring substantial amount of materials, which is another hurdle for the use of still costly SMA. However, there has been a significant reduction in prices of Ni-Ti over the last ten years, from more than 1000 USD to below 150 USD per kg at present. The price is still considerably higher than that of other construction materials, and thus the development of low-cost SMAs is essential for initiating large-scale applications. Janke, *et al*. (2005) presented Fe-Mn-Si-X alloys as a potentially low-cost SMA. A low-cost SMA (Fe-Mn-Si-Cr) has been successfully implemented in bridge rehabilitation by Soroushian, *et al*. (2001). The feasibility of using SMA materials and devices in full-scale construction projects has been studied by Bruno and Valente (2002). They considered various costs in their study including direct (structural, non-structural) and indirect (injuries and life losses) in the construction phase and also when induced by earthquakes. The cost of SMA-based dampers, isolation devices or bracings turned out to be of the same order as that of conventional steel devices. SMA devices have been found much preferable in the sense that they do not require maintenance and replacement. The efficiency of these devices is unique in both reducing economic losses and minimizing human risk associated with natural disasters. The smart bridge will also require sophisticated and relatively costly instrumentation and higher labour charges during construction and equipment installation.

8.2. SMA actuation: method, time and energy

SMA actuation is its temperature induced phase change from martensite to austenite, which can be accomplished by heating. Actuation method, energy required and time are three important factors for proper functioning of a smart bridge. Although there are several ways for heating SMA e.g. using propane torch, oxy-acetylene torch, electrical resistance, the torches are usually time consuming and not feasible for smart bridges whereas electric resistance heating converts nearly 100% of the energy in the electricity to heat (NREL 1997). Besides this, heat losses to the environment will be minimum since the SMA strands are located inside a duct filled with grout, which has low heat transfer capacity. Electric heating is also the quickest way of heating a metallic object (Janke, *et al*. 2005). Therefore, electrical resistance heating is recommended to be used for actuating SMA.

The actuation time is the period of time required to transform SMA from one phase to the other. The amount of energy required for SMA actuation can be found from its geometric and electrical properties. The required parameters for determining the required actuation time and amount of energy for an SMA strand are its length (L), cross-sectional area (A), mass (m), resistivity (ρ), specific heat capacity (C), supplied current (I), and required change in temperature for phase transformation (ΔT). The amount of energy (E_1) and activation time (t) can be found using the following equations.

Resistance of SMA strand, $R = \frac{L\rho}{A}$ (1)

Total power flowing through SMA, $P = I^2 R$ (2)

Energy demand for heating SMA above transformation temperature, $E_1 = C.m.\ \Delta T$ (3)

Estimated actuation time, $t = \frac{E_1}{P}$ (4)

As an example, a 16 mm diameter 50 m long nitinol strand with resistivity of $1.25\times10^{-6}\ \Omega m$, specific heat capacity of 500 *Joule/kg.K,* austenite finish temperature of 35 °C and having an ambient temperature of -25 °C, requires 2.3 Mega Joule energy with a 300A current supply to change its temperature by

70 °C and transform from martensite to austenite phase. The required actuation time is 82 sec. If 1000A current can be supplied, the activation time will be reduced to 7 sec. In this calculation, heat transfer to the environment and energy demand for phase transformation have been neglected. This will increase the activation time.

8.3. Other factors

If SMA is used in its martensitic form, M_s should be set such that it is always greater than the maximum ambient temperature to which it will be exposed. In that case if the minimum and maximum temperature range varies over a wider range, then more energy will be required to transform SMA from martensite to austenite during the coldest period. For instance, if the lowest temperature during winter is -15 °C and the highest temperature is 35 °C, then SMA should have M_s greater than 35 °C if it is to be used in the martensite phase. When SMA is used as a superelastic material, A_f needs to be always less than the minimum ambient temperature to which it is exposed.

Furthermore, designing civil engineering structures requires proper knowledge of the mechanical properties of the material to be used. SMAs have good potentials to be used as prestressing strands since they can overcome most of the short-term and long-term prestress losses significantly except for stress relaxation. Recently few researches have been performed on stress relaxation of superelastic SMA, which shows 15% to 30% stress drop from its f_y (Pieczyska, *et al*. 2006, Matsui, *et al*. 2004). Most of the investigations were done on small diameter superelastic wires at a constant strain rate. Still researches need to be performed on the stress relaxation of large diameter martensite or austenite SMA strands with its short and long term effects. Fatigue resistance in bending under large deformation cycles is another aspect, which needs to be considered during the design of prestressing systems with martensite SMA strands. Also, the mechanical properties of SMAs largely depend on the heat-treatment temperature, where a slight variation can cause significant changes in properties. To implement a wider use of SMAs in the bridge industry, manufacturers need to produce SMAs in large scale with proper control of its properties and transformation temperatures.

9. 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, decision making and action taking system. The 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.

It has been evident that many bridges are carrying greater average loads than predicted during their design periods (Wang, *et al*. 2005) and do occasionally fail (DeWolf, *et al*. 1989). An SMA-based smart bridge fitted with a computer analyzer, GPS, sensors, cameras and scales can be a future solution with ability to track vehicles heavier than standard loads, increase its strength and stiffness upon the arrival of vehicles to avoid damage. 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 can 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. Bridges built with carbon fiber-reinforced concrete along with SMA have a greater potential for the development of a new generation of smart RC bridges. A major limiting factor for the wider use of SMA in bridge construction is its high cost. If price can be lowered, SMA's capability to allow the development of smart bridges with active control of strength and stiffness and ability of self-healing and self-repairing can open the door for exciting opportunities, making it the construction material of the future.

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