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INDUSTRIAL APPLICATIONS FOR SHAPE MEMORY ALLOYS

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ABSTRACT

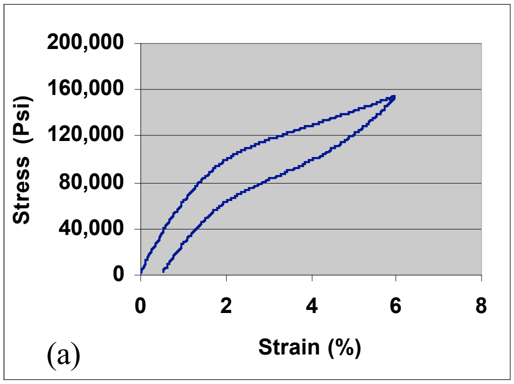
Although medical applications for shape memory alloys (SMA) now dominate in today's market, there are many applications in the industrial sector which have reached large volume production that far surpass the material usage in the medical fields. In the early growth of shape memory alloy technology the most important applications were for fasteners and couplings, mainly in the military sector. With the maturing of the technology, and the broader availability of alloys, industrial applications appear in a wide spectrum of commerce. Eyeglass frames were an early example of a new use of superelasticity which has grown to be a world wide product. Cellular phone antennas consume millions of feet of superelastic wire, and the development of underwire for women's brassieres, formerly limited to Asian market, is now expanding into a worldwide fashion. A new idea of using superelastic NiTi powder to enforce the resistance of SnPdAg solder against failure induced by thermal stress appears promising. In the automotive sector, European car manufacturers have long been using SMA actuators for transmission fluid control. Now, it is growing with the most recent success in using a NiTiNb plug for sealing high-pressure fuel passages in diesel engine injectors. SMA actuators continue to achieve steady growth in safety valves for both consumer and industrial applications. New actuator applications include a thermal interrupter for protecting lithium ion battery from uncontrollable thermal runaway. Research and development activities continue in vibration and damping principles. Employing either passive or active means are well proven but the commercialization has been slow to develop. Active tuning of resonance frequency and seismic vibration controls may find their niches in the near future. Micro-electromechanical (MEM) devices fabricated using thin film NiTi actuators will also be briefly discussed.

INTRODUCTION

In 1970, shortly before Christmas, the first successful demonstration of a shape memory alloy *Cryofit* tube coupling took place on a U.S. Navy F-14 fighter aircraft. This demonstration of the reliability of a shape memory device in a high pressure hydraulic system lead to the production of over a million couplings in the following years. Since that beginning there have been many thousands of patents issued for every conceivable application for shape memory alloys, yet, remarkably, the list of truly commercially successful devices is quite small. In this sense, by commercially successful we imply the production of a significant volume in at least many thousands per year. Indeed, as we know, the major applications for these alloys are in the field of medicine and orthodontics, with a few other areas of significance such as eyeglass frames, cellular phone antennas, women's brassiere underwires and automotive devices. While most attention has been focused on the medical devices due to the attractive value of the business, the consumption of shape memory alloy materials in the consumer and industrial sections however far exceeds the usage in the medical field, and the list of commercial applications is growing at a rapid pace. These newer markets as well as discussions on research and development will be inclusive in the subjects of this paper.

SUPERELASTIC APPLICATIONS

Among the various principles of SMA application, superelastic devices are the most significant in both material consumption and commercial value. Today, NiTi SMA has achieved a permanent place in high-end eyeglass frames. The use of superelastic SMA components for the nose piece (bridge) and ear pieces (temples) provide improved wearer comfort as well as great resistance to accidental damage. To achieve the highly kink-resistant superelasticity over a wide range of environmental temperatures, these components are usually highly cold-worked followed by a low temperature heat treatment to impart "work-hardened pseudoelasticity" [1,2]. "Work-hardened pseudoelasticity" illustrated by a stress-strain curve in Figure 1(a) differentiates itself from the conventional pseudoelasticity, Figure 1(b), by gentle sloped plateau with similar spring back characteristic. Because of the difficulty in welding NiTi to dissimilar materials, the ends of a NiTi bridge are mechanically crimped into a silver-nickel casing before being soldered onto the rims. NiTi frames are now manufactured world wide in the many designs with a wide variety in surface finish and coating dictated by fashion (Figure 2).



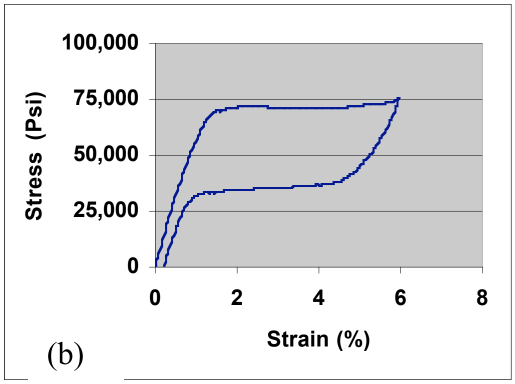


Figure 1. Illustrations of (a) work hardened pseudoelasticity and (b) conventional pseudoelasticity.

Figure 2. Photographs of NiTi eyeglass frames.

Figure 3. Photographs of cellular phone antenna.

The cellular phone is now ubiquitous being in view in almost every public arena. The cellular phone antenna, formerly of stainless steel, is now universally manufactured from superelastic NiTi alloy due to great resistance to permanent set on bending and accidental damage. Utilizing the same principle for manufacturing superelastic NiTi eyeglass frame, significant cold work is often used to enhance the low temperature superelasticity. Ni-rich chemistry or ternary addition is also used to achieve this desired property. A photograph of typical cellular phone antenna is shown in Figure 3.

Women's brassieres have both esthetic as well as structural requirements. The application of superelastic NiTi alloy to the wire re-enforcement, called the underwire, was first developed in Japan and is now a significant global market for SMA. NiTi underwires offer improved comfort due to the much lower elastic modulus than the conventional steel wires. An additional advantage is the fact that the superelastic NiTi wires are resistance to permanent deformation which can be the result of washing and drying cycles.

Various sizes and shapes are now available offering a wide range of stiffness and design options. Photographs of brassiere and NiTi underwires are shown in Figures 4(a) and 4(b), respectively.

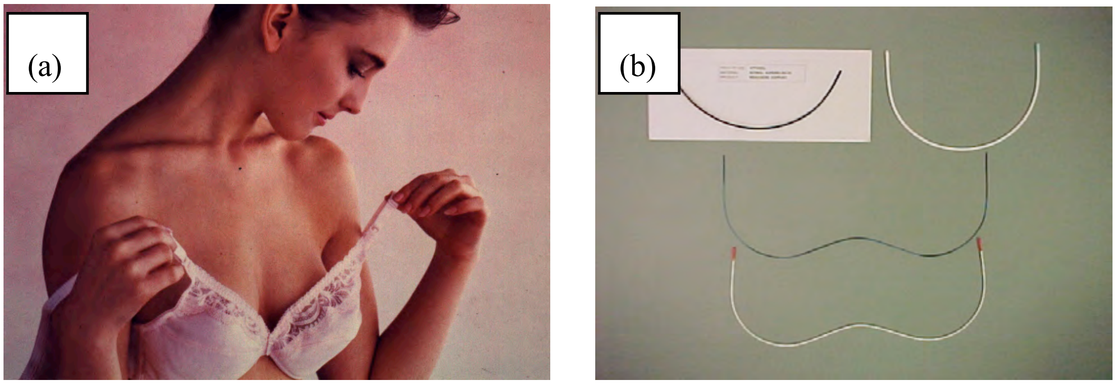


Figure 4: Photographs of (a) brassiere and (b) various designs of superelastic NiTi underwires.

A more recent development utilizes the superelastic properties of NiTi powder to enhance the resistance of SnPbAg solder to thermal fatigue [3]. As semiconductor circuits become smaller and more densely packed the need to control heat build up increases. Conventional solder for joining electronic devices onto printed circuit boards (PCB) often cracks and raptures when subjected to significant stress induced by the difference in thermal expansion coefficients between the component and the PCB. In order to obtain a useful dispersion of the small NiTi particles in the PbSnAg solder, the NiTi particles are coated with Cu by an electroless technique prior to being incorporated in the solder matrix. Cu-coated NiTi powder enforced SnPbAg solder shows improvements in both stiffness and ductility without significant changes in electrical conductivity as compared to the monolithic SnPbAg solder. Figure 5(a) shows a photograph of Cu-coated NiTi powder particle while the mechanical properties for SnPbAg solder paste with and without Cu-coated NiTi powder reinforcement are plotted in Figure 5(b).

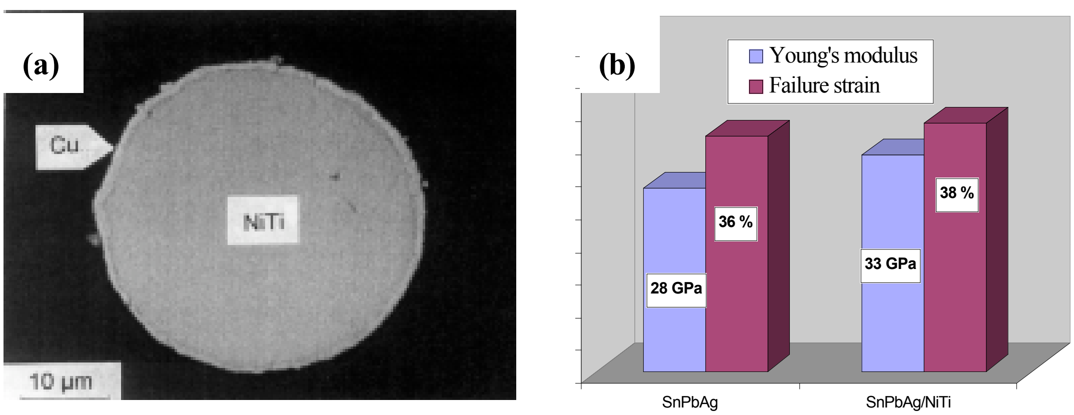


Figure 5: (a) Photograph of a Cu-coated NiTi powder particle, and (b) mechanical properties for monolithic SnPbAg and Cu-coated NiTi reinforced SnPbAg solder pastes.

CONSTRAINED RECOVERY APPLICATIONS

A classic example for the constrained recovery applications is Cryofit coupling [4]. As shown in Figure 6, the hollow cylinder of cryogenic NiTiFe alloy having an inside diameter smaller than the tubing diameter is first expanded and stored in the martensitic state until assembly. After installing the expanded coupling onto the tubing, the inner-diameter of the coupling recovers its original dimension and forms a strong joint with the tubing when the temperature warms to the environmental temperature. These couplings have been successfully used primarily for joining hydraulic systems in military aircrafts with a small volume utilized in petroleum, petrochemical and utility industries.

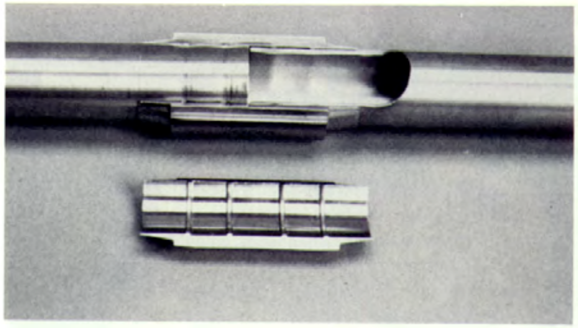


Figure 6. A photograph showing a cut-away section of Cryofit hydraulic fluid coupling.

Figure 7. Tinel Lock® rings for attaching shielding braid onto electrical connectors.

The advent of the wide hysteresis NiTiNb alloy has greatly enlarged the scope for coupling and fasteners enabling these devices to be further processed, stored, and transported in their deformed state at ambient temperatures. Devices of wide hysteresis NiTiNb alloy are heated to regain their original shapes. These ring devices now find use in a broad range of electronic and mechanical devices such as connectors, sealing devices and clamping components and provide reliable operation over a temperature range from –65°C to 300°C [5]. A photograph of Tinel Lock® rings for attaching shielding braid onto electrical connectors is shown in Figure 7.

The most recent success is the heat-to-recover NiTiNb plug for sealing high-pressure fuel passage in diesel fuel injectors [6]. A typical heavy-duty diesel fuel injector comprises of a solenoid control valve, a plunger cylinder and a fuel passage linking the first two elements, as illustrated in Figure 8. Through this passage a fuel communication is established where the fuel is delivered into the plunger cylinder via control valve. The plunger pressurizes the fuel in excess of 32,000 psi and the high-pressure fuel is injected through spray nozzle into engine combustion chamber. During manufacturing, this fuel passage is drilled from the outside of injector body, creating an open end that requires sealing at the end of the manufacturing process. Conventional sealing method utilizing a brazed steel plug often fails under prolonged exposure to extreme cyclical pressures. An alternate sealing method utilizing a heat-to-recover NiTiNb plug, a photograph of which is shown in Figure 9, offers a more reliable seal and can be installed at much lower temperatures than a brazed steel plug. These NiTiNb sealing plug are manufactured from rods that are longitudinally stretched to have a reduced diameter. The stretched rod is then cut and ground to a finished diameter of high precision. During installation, the plug is inserted into the open end of fuel passage and heat is applied to induce shape recovery of the NiTiNb plug. Stress generated from constrained recovery thus creates a tight seal around the cylindrical surface capable of withstanding extreme cyclical pressures.

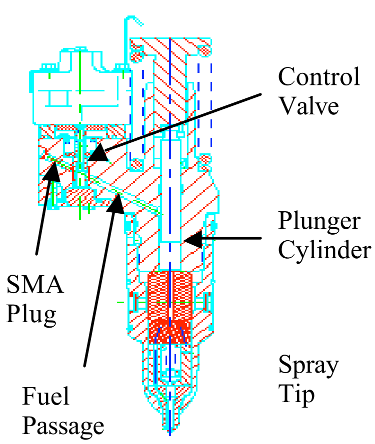


Figure 8. Typical construction of a diesel fuel injector

Figure 9. A photograph of NiTiNb plugs for sealing high- pressure fuel passage in diesel fuel injector.

ACTUATOR APPLICATIONS

Various SMA actuators such as wire, compression and tension springs and cantilever had been used in both electrical and thermal actuation systems. Utilizing direct I^2R heating of electrical current, one of the earliest volume application was for the remote opening and closing of louvers on automobile fog lights which provided protection against damage from road debris. Using indirect heating, an SMA device, the Frangibolt, is used for space deployment [7]. The bolt employs a pre-compressed cylinder which surrounds the bolt, and when heated, fractures the bolt at a machined notch. Deployment using Frangibolt avoids the use of explosive devices which are vulnerable to premature activation from electrical storms.

Thermal actuators of SMA are used as both sensors and actuators. An example now in production is a NiTiCu spring for controlling the opening of the door in a self-cleaning oven. For a period the Daimler Benz company used a similar spring to control the flow of transmission fluid in an automatic transmission during the period of initial warm up.

SMA thermal actuators are also used in domestic safety devices. One of the most frequent causes of injury in the household and in hospitality buildings such as hotels is excessively hot water in the sink, tub and shower. An antiscald valve is now being produced which employs a small cantilever NiTiCu element (Figure 10) which, when heated to 48°C, the temperature above which scalding will occur, closes the valve. The valve automatically reopens when the water temperature is safe [8]. A photograph of an antiscald shower valve is shown in Figure 11.

An industrial safety valve actuated by a NiTiCu spring is the Firecheck® valve shown in Fig. 12. Developed originally for the semiconductor industry, the valve when heated to a predetermined temperature, vents the air valve or manifold which controls the flow of processing gases used in the manufacture of semiconductors, closing the flow of gases which are either toxic or highly flammable. The advantage of this design is the ability to check the valve operation and then to reset it for use. In addition to the semiconductor industry, these valves are finding applications in petroleum and petrochemical plants where there is constant danger of fire.

Another recent SMA safety device is a thermally activated current interrupt mechanism for protecting high energy density batteries such as lithium ion cell from uncontrollable temperature increase due to overcharge or short circuit [9]. As shown in Figure 13, a bent NiTi disc actuator is placed in-between electrical contacts, which when exposed to over-temperatures regains its flat shape and breaks the electrical pathway. Although bimetallic actuators can also be used for this application, NiTi actuators offer the advantage for size miniaturization.

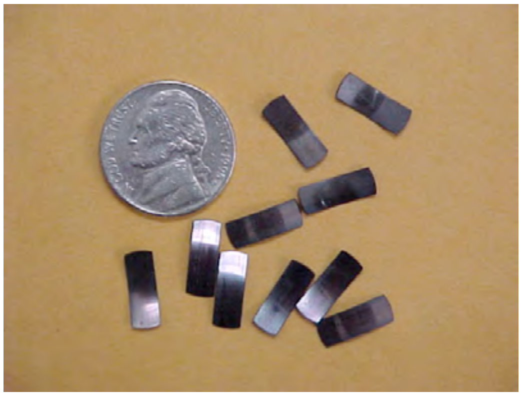


Figure 10. NiTiCu cantilever actuators used in antiscald safety valves.

Figure 11. Photograph of a Memrysafe® antiscald shower valve.

Figure 12. A photograph of Firechek® industrial safety valve.

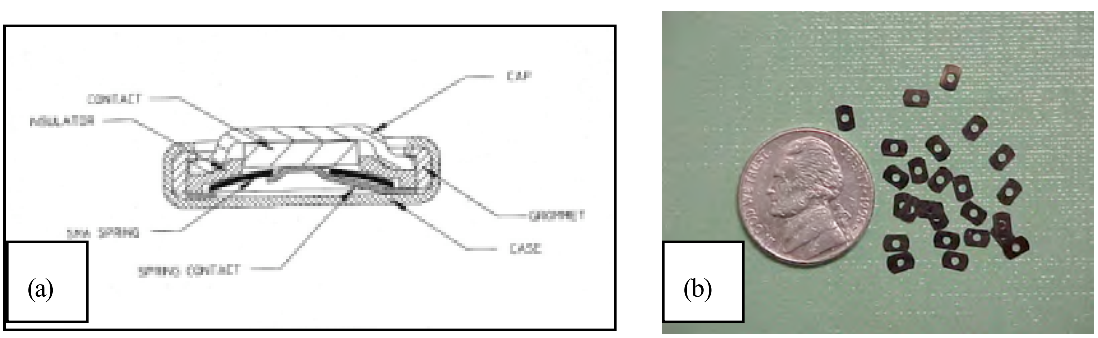


Figure 13. (a) A sketch illustrating the construction of current interrupter, and (b) NiTi actuators used in current interrupter.

No discussion of SMA actuator applications would be complete without mention of micro-electromechanical devices, MEMS. These devices have grown from laboratory fabrications to large scale manufacturing, principally as a result of the introduction of semiconductor etching technique which make possible MEM units with micron size dimensions. Mini-valves, one of the more important MEM device geometry's have been developed with performance and pressure capabilities matching electrically actuated valves orders of magnitude greater in size and weight. NiTi films are sputter-deposited on silicon substrates and then etched to form the actuator element. The film is then back etched to separate it from the silicon substrate. Mini-valves are then assembled with an “O” ring and a biasing element and two etched silicon top and bottom plates to create the completed valve with typical dimensions of 15mmx9mmx7.5mm. A pneumatic mini-valve with enclosure is shown in Figure 14. These MEM devices are used for the control of liquid and gas flow in manufacturing processes, as pneumatic controls in instruments, and, potentially, for medical delivery systems. Other MEM devices are being developed for various optical and electro optical systems [10].

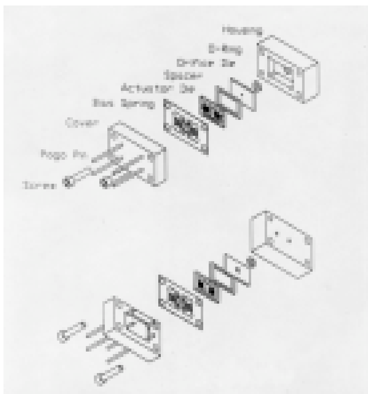


Figure 14. Construction of a thin-film SMA actuated pneumatic mini-valve.

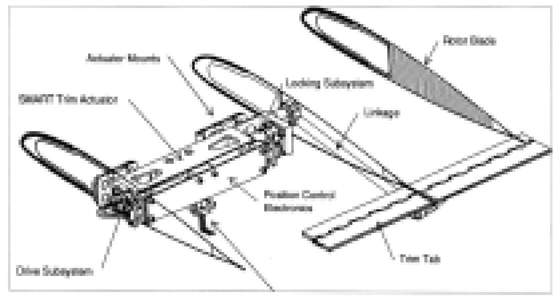


Figure 15. SMA actuator system for helicopter blade tab control.

RESEARCH AND DEVELOPMENTS

Smart materials and adaptive structures are now common terms and large government supported programs are underway to develop and utilize them in aeronautical and space structures. A number of international meetings on smart materials take place every year under the aegis of SPIE and ASME. One major effort has been to develop smart rotors for helicopters to minimize the problems of noise and vibration. Helicopters have never reached their full commercial potential because of environmental noise problems, the high maintenance resulting from their vibration, and passenger comfort. The principal source of noise and vibrations blade vortex interaction which is the result of the blade impacting the vortex thrown off by the blade in front. A second source of vibration is due to small differences in blade geometry resulting from the manufacturing process. This requires each blade be adjusted so that it tracks in the same plane as the other blades which when properly carried-out minimizes vibration. To date this tracking adjustment has required the manual bending of small tabs in the trailing edge of the helicopter blade which causes the blade to fly higher or lower. A SMA tracking control which makes it possible for the pilot to adjust trailing edge tabs from the cockpit has been developed utilizing twin tubular NiTi torsion actuators [11]. When heated the tubes twist to move the tab through a linkage with a motion of $\pm 7.5^{o}$ with an accuracy of $\pm 0.25^{o}$. Critical in the design of this actuator for a smart helicopter was weight and volume which recommended the use of SMA because of the high force and strain output. The actuator system shown in Figure 15 weighs only 440 gm and is 2.5cmx2.5cmx16.5cm, including all electronic controls.

The control of blade vortex interaction is more complicated requiring that the blade tips move at the rotational speed of the blades, approximately 600 rpm, or 10Hz, far to rapid for SMAs. The newly discovered magnetically activated shape memory effect in Ni_2MnGa alloys may potentially lead to the effective use of SMAs at higher frequency; experiments have shown that shape change frequencies as high as 400 Hz have been observed.

For the control of aerodynamic performance in different regions of the flight envelope, particularly for planes capable of supersonic speeds, a number of studies [12,13] are evaluating methods for embedding or attaching to an aircraft wing structure SMA wires and tendons which can change the wing contour in flight. A barrier to this goal is the fact that two very opposite requirements are involved, the wing must be stiff to provide flight control and yet must be flexible in order to change contour. A variety of flexible ribs and spars have been studied to solve this dilemma. Another technique which has been tested for flight control is to provide wing twist using a large torsion tube actuator. The required angle of twist to alter the flight characteristics is quite small and quarter scale wings with SMA actuation have been successfully tested. Programs in adaptive structures have also been carried out to control the performance of hydrofoils such as the control surfaces on submarines.

Vibration in bridges can lead to dangerous stresses. The wind-induced vibration of the suspension cables in suspension bridges is an example. It has been shown that vibration can effectively be suppressed by shape memory energy absorbers [14,15]. The European Union sponsored a recently completed study of earthquake damage and how structures can be modified to sustain high levels of seismic vibration. Using shape memory tendons, a four-story building model was constructed with the tendons strategically placed to minimize structural damage during an earthquake. Placed on the world's largest shake table in Greece, the model was subjected to vibrations scaled to the model size representing the vibration profile of a recent quake. A building model which was not modified with SMA devices was destroyed, while one so equipped survived with little damage. As a result of these experiments the basilica on the shrine at Assisi, Italy, which had been almost destroyed by a recent earthquake, is being rebuilt with SMA tendons to limit future earthquake damage. Using the superelastic effect, the tendons can absorb energy and at the same time provide a righting moment after the shock wave has passed. Other SMA devices have been proposed for the repair of structures damage in the California North Slope earthquake of several years ago. The repair of failed welded beam to column joints using a shape memory couple offers considerable savings over the alternative of re-welding the joint. Concrete columns which support overhead roadway have also been the subject of an SMA repair technique. Cable of SMA would be pre-stretched and then wrapped around the column and secured; upon heating by the passage of electric current, the cable would contract and impose a large compressive force on the column, restoring it to its original integrity [16].

Similar to earthquake damage amelioration is the application of shape memory tendons to pre-stressing or post-stressing concrete structures [17]. The usual technique involves stretch high strength steel tendons on either end of a beam of concrete, maintaining the tension with large abutments. After the cement has been cast and set, the tension on the steel tendons is release, putting the concrete in compression and thus greatly increasing its load carrying ability. This requires large jacks and heavy steel abutments to carry out, particularly difficult on the job site. An alternative method now being evaluated involves pre-straining shape memory alloy tendons in a shop and transporting them to the site, just as would conventional re-enforcing rod be transported. At the site, the rods would be laid in the concrete forms in the desired array and the concrete poured. Once cured, the tendon ends could be heated using a welding generator for I^2R heating, causing the tendons to shrink to their designed strain recovery and imparting the desired pre-stress.

Several years ago the Electric Power Research Institute convened a conference on the potential application for SMA devices in the electric power industry [18]. The Russians in particular have advanced the use of SMAs for the control of various functions in nuclear power plants. Other proposed devices include remote temperature sensing, transmission line sag control, ice removal from overhead transmission lines and for circuit breakers. The recent devastating ice storm in the North East has intensified the search for a method of ice removal; that particular storm brought down over 350 miles of transmission towers and high-tension lines. A model SMA actuator has been demonstrated which produces a mechanical shock wave in the ice covered power line, causing the ice to fracture and fall off. Programs are now being considered in the U.S., Canada and Japan for the extension of this technique to full scale. Line-sag, which occurs as the result of line overload combined with high ambient temperatures, can be compensated by SMA devices, and this application is under active development in Canada.

ACKNOWLEDGMENTS

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