Use of shape memory alloys for strengthening structures in fire

M. B. Wong*, H. Sadiq*, X.L. Zhao* and R. Al-Mahaidi**

**Department of Civil Engineering, Monash University, Melbourne, Australia 3800 (E-mail: bill.wong@monash.edu; Hussein.Sadiq@monash.edu; zhao.xiao.ling@monash.edu)*
***Faculty of Engineering & Industrial Sciences, Swinburne Univ. of Technology, Melbourne, Australia 3122 (E-mail: RALMAHAIDI@groupwise.swin.edu.au)*

ABSTRACT
The unique mechanical and thermal properties of shape memory alloys (SMA) enable widespread adaptation in industries including aerospace, medical and bridge construction. However, use of SMA in buildings is still uncommon and many applications in building structures are still at the experimental stage. Shape memory effect is the ability to undergo large deformations and subsequently to return to its original form upon heating above a specific temperature. Super-elasticity is the recovery of large strains during mechanical loading and unloading under isothermal conditions. At high temperatures, the stiffness of SMA may increase by 3-6 times and its strength by 3-5 times of that at room temperatures. This special feature of SMA has led to an innovative design concept through which SMA are used to strengthen structural elements in fire. In this paper, a description of testing a small scale steel beam strengthened with SMA wires is given. It will be shown that during the heating of the loaded beam, the force induced in the SMA wires reduces the bending effect of the beam, resulting in a dramatic decrease in beam deflection. The success in implementing this concept in structural fire engineering shows great opportunity for SMA to be used in this new area.

KEYWORDS
Fire; Shape memory alloys; Structural strengthening; Temperature.

INTRODUCTION

Shape memory alloys (SMA) have been used in many applications including aerospace, medical and bridge construction. The earliest reported use of the term ‘shape recovery’ was by Chang and Read (1951) while working with gold-cadmium alloys. The most common type of shape memory alloys were discovered by William Buehler and his co–workers in 1962 while working at the Naval Ordnance Laboratory. The commercial version of these alloys is made of nickel (Ni) and titanium (Ti) and is commonly known as Nitinol manufactured in the USA.

Shape memory alloys are special metals which exhibit unique mechanical and thermal properties such as shape memory effect and super-elasticity. Shape memory effect is the ability for the alloys to undergo large plastic deformations and subsequently to return to its original form upon heating above a specific phase transformation temperature. Super-elasticity is the recovery of large strains during mechanical loading and unloading under isothermal conditions. In addition, SMA are more resistant to corrosion than other common construction materials such as steel and concrete. These characteristics give great potentials for SMA applications in civil engineering. This paper gives a general description on the use of SMA and reports a pioneering project in which the unique characteristics of SMA are exploited. The concept makes use of the recovery stress generated in SMA during temperature rise, resulting in a prestressing effect which counteracts the bending actions imposed by the applied loading. Temperature rise in a structure can be arisen from different causes and this project looks at the scenario where the structural element is subjected to a temperature rise as a result of fire.

Characteristics of shape memory alloys

The shape memory effect of these alloys can be demonstrated by a thin wire made of NiTi shown in Figure 1. The wire shown in Figure 1(a) is initially straight but subsequently bent into an irregular shape as shown in Figure 1(b). The wire is then dropped into a beaker containing hot water at a temperature of above 60^{o}C and instantly regains its original shape as a straight wire shown in Figure 1(c).

(a) initial shape: straight wire (b) bent wire dropped in hot water (c) initial shape recovered

Figure 1. Shape memory effect of NiTi SMA.

The ability for SMA to exhibit the shape memory effect is mainly due to temperature rise through the phase transformation region in which the microstructure of the materials changes from its martensite phase at low temperatures to its austenite phase at high temperatures. The phase transformation temperatures depend on a number of factors and can be determined typically by Differential Scanning Calorimetry (DSC). A typical differential scanning calorimeter is shown in Figure 2.

Figure 2. Differential scanning calorimeter.

Factors affecting the phase transformation of SMA include the precise amount of chemical composition, the manufacturing history, the heat treatment temperatures and the stress level at which the materials are subjected to. Figure 3 shows results of the effect of heat treatment temperatures on the phase transformation temperatures of SMA samples made of NiTi (55wt%Ni, 45wt%Ti) using DSC tests carried out in the Department of Civil engineering at Monash University (Sadiq, et. al., 2010). In Figure 3, the top lines of the curves represent the heating of the samples from martensite to austenite while the bottom lines represent the cooling from austenite to martensite after subjecting the samples to different heat treatment temperatures. The spikes on the curves indicate transitions between phases. It can be seen that during the cooling process, an intermediate R-phase may also occur. As each phase transformation occurs over a range of temperatures, the phase transformation temperatures are usually described as A_s (austenite start) and

A_f (austenite finish) for a martensite to austenite phase transformation, and M_s (martensite start) and M_f (martensite finish) for an austenite to martensite phase transformation.

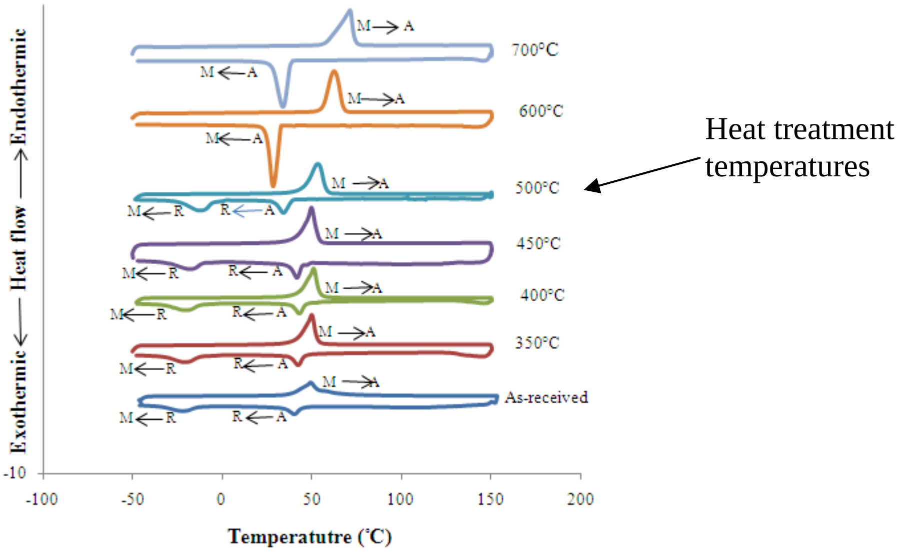


Figure 3. Effect of heat treatment temperatures on phase transformation of shape memory alloys (Sadiq, et. al., 2010).

Apart from the shape memory effect, SMA also possess super-elastic characteristics. The features of super-elasticity are schematically shown in a stress-strain diagram in Figure 4. At low temperatures below M_f when the sample is in its martensite phase, it behaves like typical ductile metals except that it can deform with very large strains at virtually constant stress. Upon unloading to zero stress, a residual strain exists. If the sample is then heated to a temperature above A_f without constraint, the stress path follows that of the thick dash line for the austenite phase in Figure 4 and reverts back to the origin of the stress-strain diagram. At this point, the sample regains its original shape.

If the sample with the residual strain is constrained when being heated to a temperature above A_f, a recovery stress will be induced as shown in Figure 4. This recovery stress pertains to a value on the stress path in the austenite phase where, under further loading, the ultimate stress at fracture could be more than 1000 MPa. It is this recovery stress which many industrial applications have been able to exploit. In most applications, temperature is raised to above A_f by supplying heat energy through electrical means.

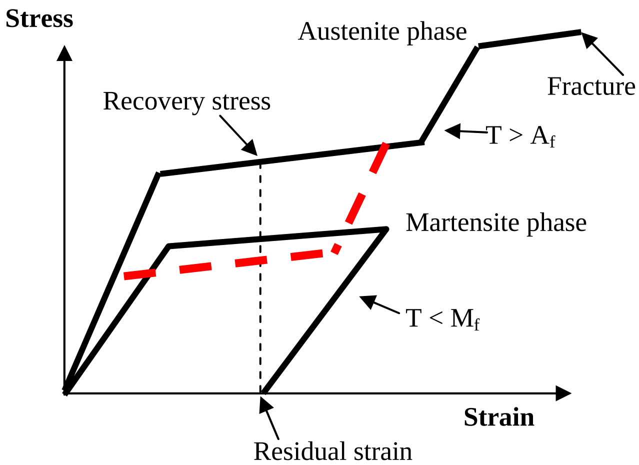


Figure 4. Super-elasticity and shape memory effect of SMA.

APPLICATIONS OF SHAPE MEMORY ALLOYS

The special characteristics of SMA enable the materials to find the way in many industrial applications. Due to the complexity of the thermo-physical properties of SMA and their sensitivity to chemical composition, the design of any application of SMA requires a thorough understanding of its physical and thermal behaviour.

The aerospace industry is a major user of SMA such as couplings for tubing connections where the phase transformation occurs only at very low temperatures. To release the grip of the coupling, extremely low temperature must be applied to enable phase transformation to occur. The new Boeing 787 Dreamliner uses SMA for shape control for the rear part of the engine to reduce engine noise.

The medical industry uses SMA for various purposes such as the manufacture of artificial body parts, stents for blocked blood vessels, guide wires for medical procedures and super-elastic orthodontic devices.

Structural engineering applications

In recent years, there have been various developments of SMA for structural engineering applications. Using SMA actuators as dampers for vibration control of bridges becomes increasingly popular (Graesser & Cozzarelli, 1991). In such applications, a pre-strained SMA rod is attached to the structural component of the bridge. When excessive vibration of the bridge is detected, an electric current is passed through the rod so that temperature of the rod changes and a pulling force is generated to achieve the damping effect. The actuation requires careful control of the relation between the input voltage and the generated force. Large amount of research has been carried out on SMA actuators. Typical examples are Wilde, et. al. (2000) for use of SMA on bridges and Dolce, et. al. (2000) on buildings. An overview of the use of SMA's damping capability for structures is presented by Humbeeck (2003).

Experimental evidence showed that SMA wires can be used in 'smart bridges' (Maji & Negret, 1998; Li, Li & Zhang, 2007) where exceptionally heavy loading is detected and the beams in the bridge are temporarily strengthened. The strengthening is achieved by installing SMA in the concrete beams as part of the reinforcements. Through electrical heating of the wires, a tensile force is generated to counteract the bending induced by the loading and the beam is strengthened for the duration of the heating.

At high temperatures, the stiffness of SMA may increase by 3-6 times and its strength by 3-5 times of that at low temperatures. The 'shape memory' capability also enables the SMA materials to be used as a rehabilitation tool when the structural system is accidentally overloaded beyond its serviceable limit. Li, Liu & Ou (2006) demonstrated that SMA wires embedded in a concrete beam could be used to close the concrete cracks temporarily in the beam which was subsequently strengthened by carbon fibre reinforced polymer plates. In this investigation, the wires were heated by electric current for closing the cracks.

Due to the unique characteristics of SMA, it is possible that the alloys can be used to enhance safety of structures during extreme conditions such as fire. For the alloys to undergo such high temperatures, the heat transfer process is important in monitoring the stress-strain variation over a wide temperature range. Therefore, an understanding of the thermal characteristics of SMA at high temperatures is important. Unfortunately, test results for the thermo-mechanical properties of SMA at such high temperatures are virtually non-existent. An exploratory project for strength enhancement of steel beams in fire is being undertaken in the Department of Civil Engineering at Monash University. The concept is illustrated in Figure 5 in which the beam subjected to a load is strengthened by a pre-strained SMA wire underneath. When the temperature of the wire rises due to the fire, a force due to the recovery stress is generated, subsequently reducing the bending effect imposed by the load. Initial tests, as described in the next section, showed that this concept was feasible and the deflection of the beam was reduced dramatically during rising temperature.

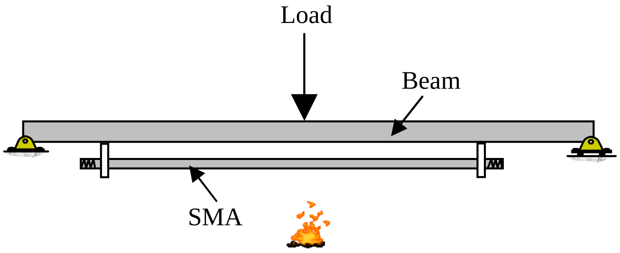


Figure 5. Steel beam strengthened by SMA wire in fire.

EXPERIMENTAL PROCEDURE

Preparation of specimens

Mild steel plates with dimensions of 700×50×5 in mm were selected to act as a simply supported beam under bending due to a point load acting at mid-span. The span L between the two supports was 500 mm. Four holes of 8 mm were made at a distance L/4 away from each support to provide a proper stainless steel joints designed to attach the NiTi wires to the plate beams. Figure 6 depicts the assembly of the NiTi wires of 1 mm in diamater and the stainless steel joints with the mild steel beam. In this case the distance between the two joints was 250 mm so that the negative bending moment exerted from the force induced by the recovery stress in the heated NiTi wires will act on the middle half of the steel beam only.

The stainless steel joints were machined from Sandvik 253 MA raw material. The joints were designed to hold ten wires of NiTi in one horizontal plane which is eccentric from the steel beam surface by 30 mm as shown in Figure 6. The joints were connected to the steel beam using Grade 8.8 M8 bolts and nuts. The wires were slightly pre-tensioned by suspended weights to avoid slacks in the system.

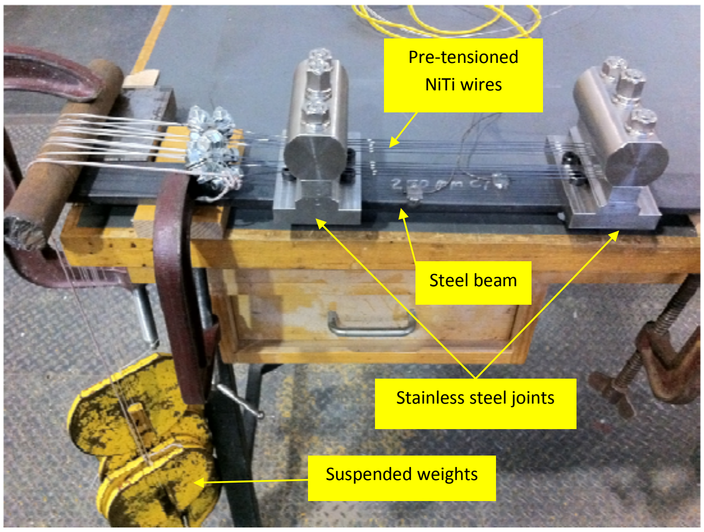


Figure 6. Specimen assembly for the high temperature test.

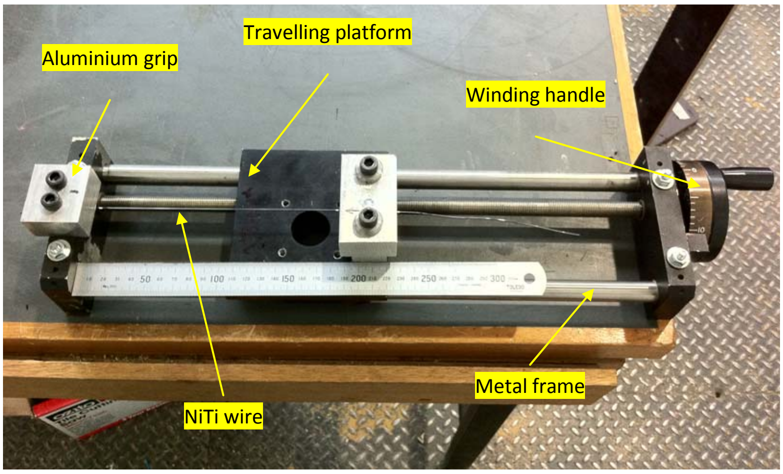


Figure 7. Pre-straining equipment for NiTi wires.

Prior to attaching the NiTi wires to the steel beam at the stainless steel joints, the wires were loaded and unloaded to provide about 5% residual strain. This strain can be fully recovered when the wire is heated above the austenite finish temperature, A_f. By preventing the strain from recovering when rigidly fixing the wires to the joints, a tensile force is generated in the wires. The minimum threshold value for pre-straining the wires is 2.41% in order to attain the maximum recovery stress when the wires are heated above A_f. (Sadiq et al., 2010).

Figure 7 shows the pre-straining equipment that is used to pre-strain the NiTi wires. The wires were constrained at the ends using aluminum gripping blocks allowing for 180 mm wire gauge length between the grips. One of the grips is fixed on the metal frame of the equipment and the other is fixed on a metal platform that travels between the ends of the metal frame as shown in Figure 7. The movement of the travelling plate is precisely controlled by a winding handle that rotates a threaded shaft confined inside the metal frame.

High temperature test setup

Both the steel beams with and without SMA wires were tested at the Civil Engineering Laboratory, Monash University. The test setup of the specimens at high temperatures is shown in Figure 8. The setup consists of electrical furnace, temperature controller, loading system and data acquisition. The temperature controller adjusts the temperature environment inside the electrical furnace by following a predefined heating curve. The heating curve was designed in a manner to enable gradual change in beam deflection.

A constant load was used in each of the tests. The load was rested on steel loading platform connected to a cylindrical shaft which was attached to the mid-span of the beam inside the electrical furnace. A supporting frame was installed to support the load as well as to allow only the vertical movement of the load without tilting or rotation. The beam deflection was monitored using string-pot installed between the loading platform and the supporting frame. The tested specimens are supported by a rigid square hollow steel beam running through the bottom of the electrical furnace.

RESULTS AND DISCUSSIONS

The tests were conducted at high temperature. The measured mid-span deflections and the temperature-time profile of the beams are shown in Figure 9. The dashed line represents the results of the steel beam which contrasts those of the steel-NiTi composite beam represented by the solid line. Initially, the two beams were subjected to a constant load at 32% of their respective section capacities. The load was maintained while the beams were exposed to increasing temperature. From Figure 9, the steel beam shows a steady increase in mid-span deflection as both the stiffness and strength of the beam deteriorate at high temperatures. The deflection continues to increase as the temperature is increasing until a runway deflection occurs at temperatures around 600°C at which the beam can no longer sustain the load. At this point, the beam is considered to have failed.

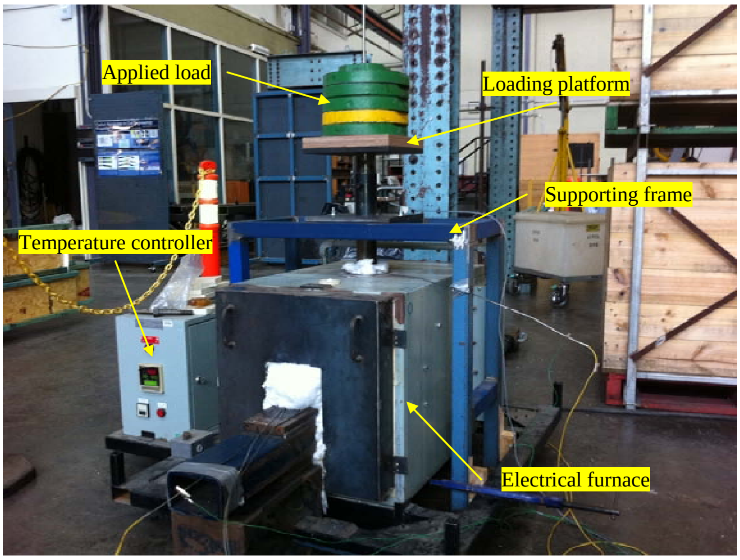
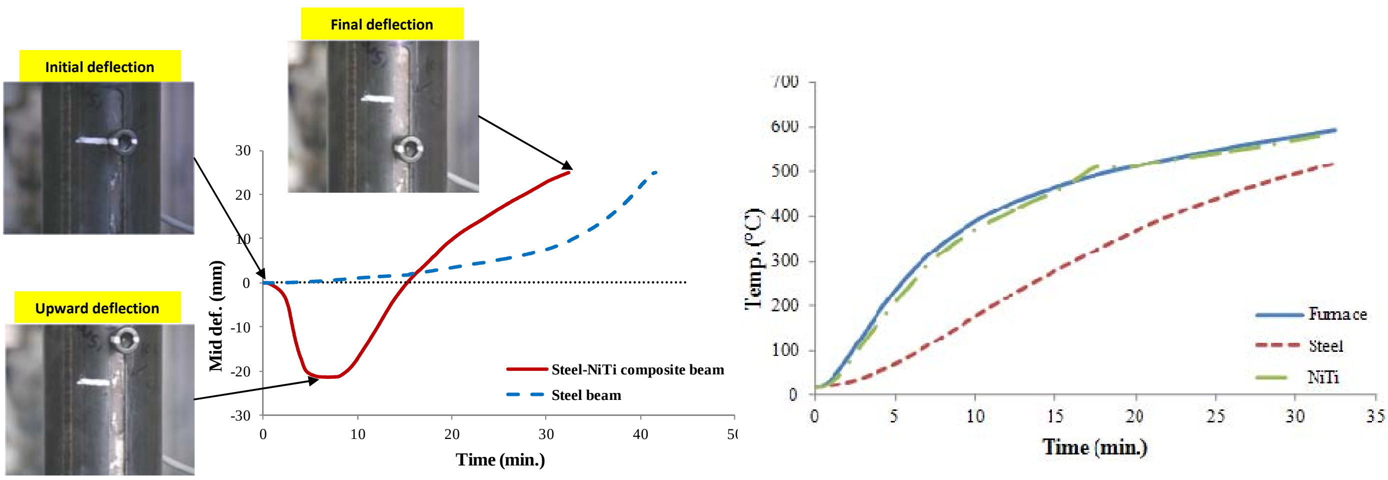


Figure 8. High temperature test setup.

In contrast, the steel-NiTi composite beam shows a reduction in deflection as the temperature rises. This is shown physically by an upward movement of the beam until a maximum is reached at a temperature of about 8 minutes (350°C). The upward movement is resulted from the recovery stress produced by the heated NiTi wires attached to the steel beam. By increasing the temperature, the constrained NiTi wires produce a tensile force which counteracts the bending action imposed by the constant load. In this manner the stiffness and the strength of the steel-NiTi composite beam as a whole are increased with the increasing temperature. When the NiTi wire temperature exceeds 350°C, the maximum recovery stress of the wire starts to decrease with minimal value left at about 550°C. This process is accompanied by an increase in mid-span deflection. Corresponding markers indicating the rise and fall of beam movements at different stages during the test are also shown in Figure 9(a).



(a) Time-deflection profile (b)Time-temperature profile

Figure 9. Mid-span deflections and temperatures of steel and steel-NiTi composite beams.

To sustain the recovery stress thus reducing the bending actions on the beam during fire, the heating rate of the NiTi wires must be kept low for as long as desirable in fire engineering design. This can be done by applying an insulation material around the NiTi wires. This part of the project is still ongoing.

CONCLUSIONS

Use of shape memory alloys has become increasingly popular in various fields of applications. Their use in structural engineering has a great potential due to a number of advantages over other metals including the shape memory effects, super-elasticity and corrosion resistance. The fact that these alloys are relatively unknown in the Australian civil engineering fraternity and can only be procured from overseas is a hindrance to its further development in Australia. This situation may change very quickly as more countries have started manufacturing these alloys and taking advantages of their superior properties.

The concept of strengthening steel structures during a fire incident using shape memory alloys, NiTi, is feasible as demonstrated in this study. The fire resistance level of a structural steel member can be improved by taking advantage of the shape memory effect and the recovery stress of those shape memory alloys.

REFERENCES

Chang, L. C. and Read, T. A. (1951) *Trans. AIME*, 189, 47.

Dolce M., Cardone D., Marnetto R. (2000). Implementation and testing of passive control devices based on shape memory alloys. *Earthquake Engineering and Structural Dynamics*, 29, 945-968.

Graesser, E. J. and Cozzarelli, F.A. (1991). Shape-memory alloys as new materials for aseismic isolation. *J. Eng. Mech., ASCE*, 117(11), 2590-2608.

Humbeeck J.V. (2003). Damping capacity of thermoelastic martensite in shape memory alloys. *J. of Alloys & Compounds*, 355, 58-64.

Maji, A.K. and Negret, I. (1998). Smart prestressing with shape-memory alloys. *J. Eng. Mech., ASCE*, 124(10), 1121-1128.

Li, L., Li, Q. and Zhang, F. (2007). Behavior of smart concrete beams with embedded shape memory alloy bundles. *J. Intelligent Mat. Syst. Struct.*, 18, 1003-1014.

Li H., Liu Z.Q., Ou J.P. (2006). Experimental study of a simple reinforced concrete beam temporarily strengthened by SMA wires followed by permanent strengthening with CFRP plates. *Eng. St.*, 30, 716-723.

Sadiq, H., Wong, M.B., Al-Mahaidi, R. & Zhao, X.L. (2010). The effects of heat treatment on the recovery stresses of shape memory alloys. *Smart Materials and Structures*, 19(3), 035021.

Wilde K., Gardoni P., Fujino Y. (2000). Base isolation system with shape memory alloy device for elevated highway bridges. *Eng. St*, 22, 222-229.