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POTENTIAL APPLICATIONS OF SHAPE MEMORY ALLOYS IN SEISMIC RETROFITTING OF AN EXTERIOR REINFORCED CONCRETE BEAM-COLUMN JOINT

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Abstract

Shape memory alloys (SMAs) have the ability to undergo large deformations with minimum residual strain and also the extraordinary ability to undergo reversible hysteretic shape change known as the shape memory effect. The shape memory effect of these alloys can be utilised to develop a convenient way of actively confining concrete sections to improve their shear strength, flexural ductility and ultimate strain capacity. Most of the previous work on active confinement of concrete using SMA has been carried out on circular sections. In this study retrofitting strategies for active confinement of non-circular sections have been proposed. The proposed schemes presented in this paper are conceived with an aim to seismically retrofit a beam-column joint in non-seismically detailed reinforced concrete buildings.

The complex material behaviour of SMAs depends on number of parameters. Depending upon the alloying elements, SMAs exhibit different behaviour in different conditions and are highly sensitive to variation in temperature, phase in which it is used, loading pattern, strain rate and pre-strain conditions. Therefore, a detailed discussion on the behaviour of SMAs under different thermo-mechanical conditions is presented in this paper.

Introduction

Over the past few decades, intensive research efforts have been made to develop various seismic retrofitting techniques that aim to increase the seismic capacity of non-seismically detailed buildings. A large number of innovative techniques have been developed and different materials have been explored. A class of smart materials that has recently drawn attention in civil engineering is the super elastic shape memory alloy (SMA). SMAs belong to a group of smart materials which have the ability to undergo large deformations with minimum residual strain and also the ability to undergo reversible hysteretic shape change. They also have high strength, high energy absorption capacity, high damping, good fatigue resistance, good corrosion resistance and excellent recentering ability (Ozbulut et al., 2011). All these feature are highly desirable for civil engineering applications, especially seismic retrofitting.

SMAs offer a wide range of possible application in civil engineering. Due to their ability to undergo large deformations and reversible hysteretic shape change, SMAs make an excellent material for seismic retrofitting that can be used to increase the ductility and energy dissipation capacity of the structural systems. In general, SMAs can be employed to make use of only their *pseudoelastic* feature or in applications, such as active confinement and heat activated pre-stressing, that are principally dependent on its ability to undergo hysteretic shape change known as *shape memory effect*. However, the ability to exhibit these two contrasting features depends upon the working temperature and the phase in which the SMAs are used. It is therefore essential to have a thorough understanding of the behaviour

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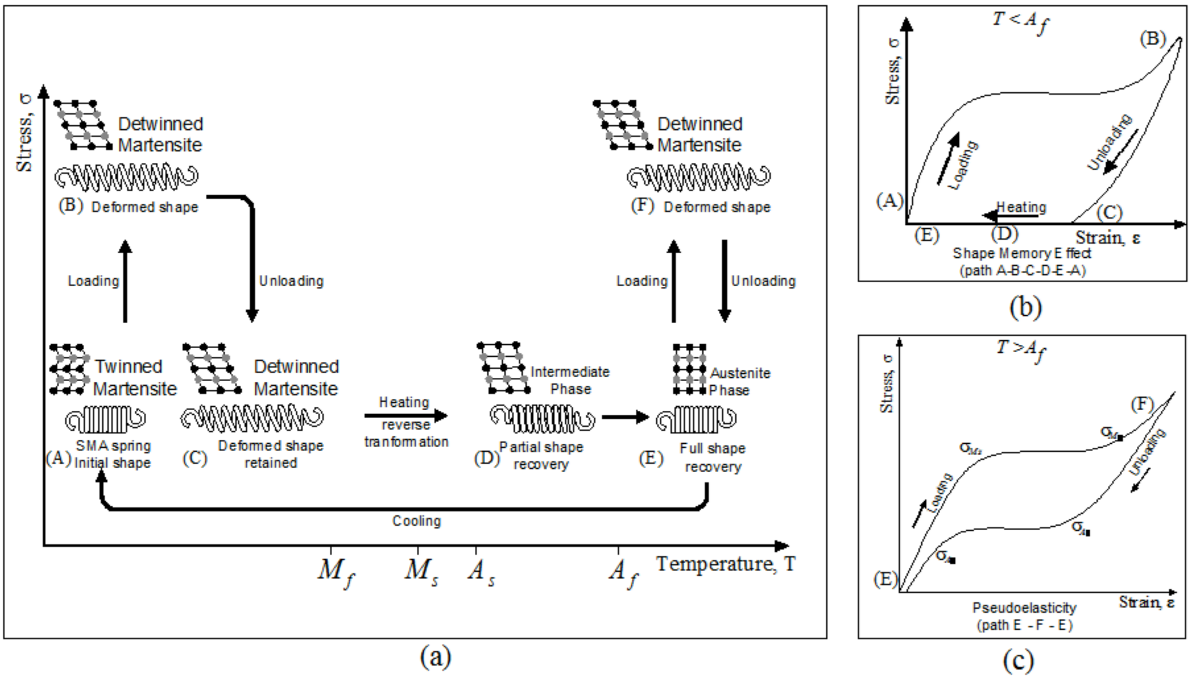
of SMAs in both phases under different working conditions. In view of this an overview of the pseudoelastic and shape memory effects of SMA is explained in the next section. A detailed discussion of the behaviour of SMAs under different thermo-mechanical conditions is presented after that. Finally, proposed retrofitting schemes of exterior reinforced concrete beam–column joints (BCJs) with non–circular section are presented.

Shape Memory Alloys: Material Property Overview

SMA has two distinct phases, each with different crystal structure. One of these phases is stable at low temperatures and high stresses and is called *martensite* phase (M) and the other phase is stable at high temperature and low stresses and is called *austenite* phase (A). The associated transformation from one phase to another results from reversible shear lattice distortion (Kumar & Lagoudas, 2008). This reversible phase transformations from one phase to another and vice versa forms the basis of the unique behaviour of SMAs. Only a brief overview of this phenomenon is given here. A detailed description can be found elsewhere e.g. (Otsuka, 1999; D. Lagoudas, 2008; Ozbulut et al., 2011).

Phase transformation of SMA from *twinned martensite* to *austenite* phase is schematically explained using one way SMA spring shown in Figure 1. The transformation from one phase to another can be produced either by the changing the temperature of SMA or by the application of external mechanical load or both.



(a) (b) (c)

Figure 1. (a) Schematic of the one way shape memory effect (path A-B-C-D-E-A) showing phase transformation from *martensite* to *austenite* and back to *martensite* phase (loading, unloading and subsequent heating and cooling under no load conditions) and *pseudoelasticity* (path E-F-E) of an SMA spring; (b) representative stress-strain curve of SMA in *martensite* phase; and (c) representative stress-strain curve of SMA in *austenite* phase.

There are four characteristic temperatures associated with phase transformation. When the transformation from *austenite* to *martensite* phase takes place, it is called *forward transformation*. SMA in *austenite* phase, under zero load, begin to transform to *twinned martensite* phase at the *martensitic start temperature* (M_s) and a complete transformation to martensite phase is achieved at *martensitic finish temperature* (M_f) as shown in Figure 1(a).

Similarly, when the transformation from *martensite* to *austenite* phase takes place, it is called reverse transformation. The transformation begins at *austenitic start temperature* (A_s) and a complete phase transformation is achieved at *austenitic finish temperature* (A_f).

If a sufficient mechanical load is applied to SMA in the *twinned* state at temperatures lower than M_f, it is possible to *detwin* the *martensite* phase of SMA. An observable macroscopic shape change takes place. On removal of the external load, the deformed *detwinned* shape is retained as shown in Figure 1(a). A subsequent heating above A_s of the SMA spring results is reverse transformation from *detwinned martensite* to *austenite* phase and leads to shape recovery. Shape recovery is initiated at a temperature greater than A_s and a complete shape recovery is only achieved when the temperature is greater than A_f. On cooling from *austenite* phase, a forward transformation takes place to *twinned martensite* phase. In case of one way shape memory alloys no associated shape change is observed during this transformation. This process is described as one way shape memory effect and is schematically described in Figure 1(a) (path A-B-C-D-E-A). The associated stress-strain curve is shown schematically in Figure 1(b).

If however, the SMA is already in *austenite* phase i.e. if the temperature of the material is above A_f, the application of external force results in pseudoelastic deformation and upon removal of the forces (path E-F-E) of Figure 1(a), a complete shape recovery is observed unlike in *martensite* phase where a deformed state is retained. This phenomena is called *pseudoelasticity* or *pseudoelastic effect* or simply *super-elastic effect* (Kumar & Lagoudas, 2008). The associated stress-strain curve is shown schematically in Figure 1(c).

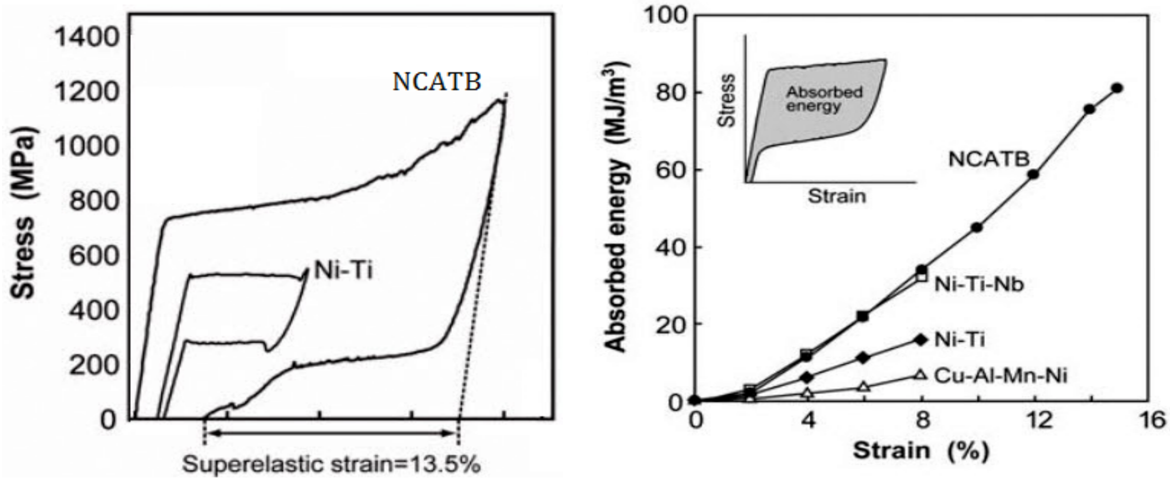
Thermo-mechanical properties of SMAs

The behaviour of SMAs in both *martensite* and *austenite* phases is complex and depends on a number of parameters. Depending upon the alloying elements, SMAs exhibit different behaviour in different conditions and are highly sensitive to variation in temperature, phase in which it is used, loading pattern, strain rate and pre-strain conditions. A brief overview on thermo-mechanical characteristics of the SMAs used in civil engineering is given below.

Effect of Alloying Elements on Transformation Temperatures and Strain Recovery

Since the discovery of Nitinol in 1963, many different composites exhibiting shape memory and super elastic effects have been synthesised. Not all SMAs are suitable for civil engineering applications. For brevity, only the relevant types of SMAs will be discussed in this paper. Depending upon the composition of alloying elements, SMAs can significantly differ in their transformation temperatures. For example, the transformation temperature of $Ni_{50}Ti_{50}$, is about M_f = 15 ^oC and Af = 89 ^oC (Funakubo, 1987). Since martensite finish temperature in this alloys is 15 degrees, this type of SMA will retain deformation at temperatures less than 15 ^oC and consequently makes it less useful in this state for civil engineering applications. The small increase in Ni content from 50% in equiatomic $Ni_{50}Ti_{50}$, to 51% in $Ni_{51}Ti_{49}$, the transformation temperatures reduce to $M_f = -153$ ^oC and $A_f = -40$ ^oC, respectively (Funakubo, 1987; Otsuka, 1999). With an *austenite* finish temperature less than room temperature in $Ni_{51}Ti_{49}$, these alloys will thus exhibit *pseudoelastic* effect at room temperature. With an addition of a tertiary element such as Niobium, for e.g. [$Ni_{47}Ti_{44}Nb_9$], the transformation temperature range of the SMA can be increased to 140 ^oC with $M_f = -175$ ^oC to $A_f = -35$ ^oC (Zhao et al., 1990). NiTiNb in this form can be used as *pseudoelastic* material at room temperature. An added advantage of this type of SMA is that by inducing a pre-strain in this composite, the transformation temperature range of NiTiNb can be further widened however, *austenite* start temperature may be shifted to a temperature greater than the room temperature (Takagi et al., 2006; Choi et al., 2013). The effect of pre-strain on transformation temperatures will be discussed in detail in the next section.

Most of the Nickel based SMAs have a similar range of pseudoelastic strain recovery, about 6−8% (Kumar & Lagoudas, 2008). Several other composites such as Iron based SMAs have a pseudoelastic strain recovery ranging between 2.5−4.5% (Otsuka, 1999). Recently, Tanaka et al. (2010), reported 13% pseudoelastic strain recovery in Iron based *NCATB* (Fe-28Ni-17Co-11.5Al-2.5Ta-0.05B)(Atomic %age). *NCATB* is not yet available commercially therefore NiTi and NiTiNb are the popular choices in civil engineering at the moment and subsequently the focus of this paper. A comparison of strain recovery and energy dissipation capacity of these alloys is shown in Figure 2 (a) and (b), respectively.



(a) (b)

Figure 2. (a) Graph of stress vs strain curve for Ni-Ti and NiTiNb (excerpt form (Tanaka et al., 2010); and (b) graph of absorbed energy vs strain for different shape memory alloys (Tanaka et al., 2010)

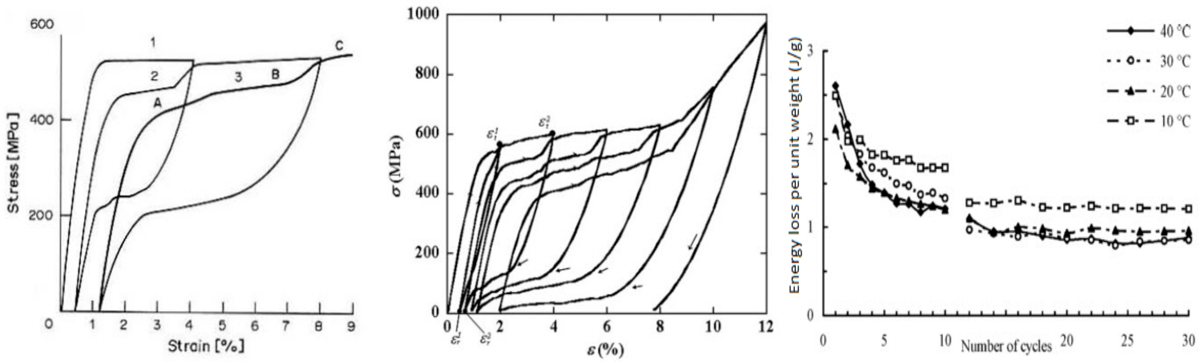
Effect of Pre-Strain on the Transformation Temperatures

As discussed in the previous section, the transformation temperature of the *austenite* and *martensite* phases of SMAs is highly dependent on the alloying elements, and is the most important parameter that determines the suitability of SMA for civil engineering applications. Not all SMAs have transformation temperatures suitable for active confinement of concrete. In order to achieve active confinement of reinforced concrete through heat activated pre-stressing of SMA a suitable transformation temperature is required to ensure pre-deformation of the SMA is retained at room temperature. In some SMAs, for example NiTiNb, pre-setting a given amount of pre-strain can significantly widen the transformation temperature hysteresis to a range that enables utilisation of shape memory effect for active confinement. Choi et al. (2013) reported a shift in transformation temperatures from $M_f = -65.9$ °C and $A_f = 22.0$ °C to $M_f = -74.3$ °C and $A_f = 139.2$ °C by introducing a pre-strain of 4.7%.

A detailed investigation on the influence of transformation temperatures due to pre-strain was carried out by Takagi et al. (2006). Takagi et al. (2006) used 30% cold drawn 1mm diameter $Ni_{47.6}Ti_{46.4}Nb_{6.0}$ wire *austenite* at room temperature. The wire was deformed to strain values ranging from 0% to 18%. As expected little difference in transformation temperature was observed up to 8% strain, which is the *pseudoelastic* strain recovery range of $Ni_{47.6}Ti_{46.4}Nb_{6.0}$. A strain value over 8% lead to the stress induced martensite (SIM) transformation (forward transformation) and a drastic change in the transformation temperatures from $A_s = -29.2$ °C to $A_s = 37.1$ °C was reported. This increase in transformation temperature results from relaxation in the internal strained energy stored due to pre-strain (Piao et al., 1999). Approximately 8% strain was retained at room temperature due to increment in reverse transformation temperature. Increases in pre-strain over 15% may result in plastic strain not only in β-Nb particles but also in the Ni-Ti matrix (Takagi et al., 2006).

Behaviour of SMAs under Cyclic Loading

Due to the cyclic nature of the seismic loading it is important to understand the cyclic behaviour of SMAs prior to implementation in a practical retrofitting strategy. Several researchers have previously investigated the cyclic behaviour of SMAs. Eucken et al. (1989) investigated the cyclic behaviour of NiTi wires loaded gradually up to a strain of 8%. Eucken et al. (1989) observed a continuous decrease in the forward transformation stress (see Figure 3(a)). A remarkable feature of NiTi wires observed from the stress–strain curves is that during reloading, the reduction in forward transformation stress and the plateau stress is exhibited only up to the strain level experienced by the wire in the past cycle. Once the strain exceeds maximum strain in the loading history, the forward transformation stress increases and reaches the initial plateau level. This implies, "*the material "knows" how far, and how many times, it has been prestrained*" (Eucken et al., 1989). Cyclic behaviour of NiTiNb (*austenite* at room temperature) was investigated by Takagi et al (2006). The same phenomenon was observed in NiTiNb also. From the stress–strain curve in Figure 3(b), it can be observed that not all *pseudoelastic* strain is recovered during unloading instead some residual strain is retained in each cycle. However, the residual strain is minimal within the *pseudoelastic* range and is stabilised after a given number of cycles.



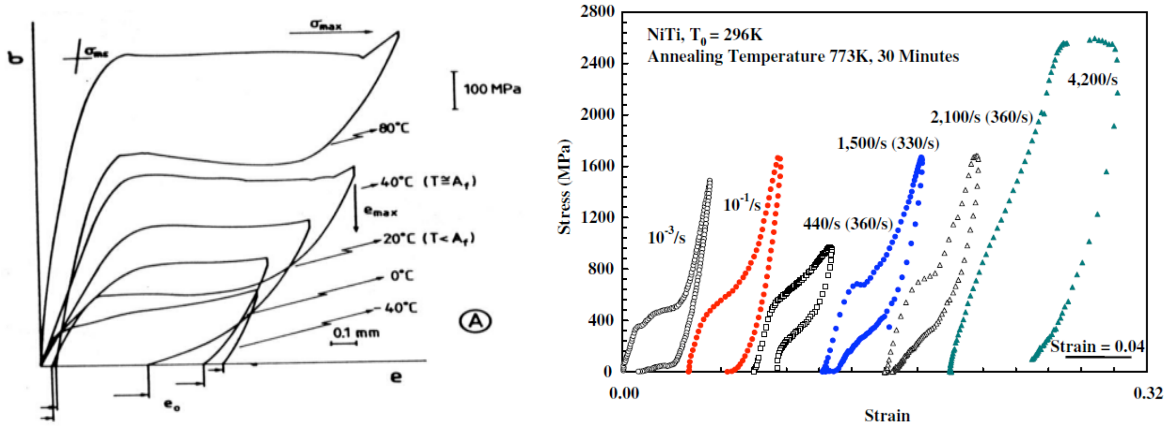
(a) (b) (c)

Figure 3. (a) Stress–strain curves of *underaged* Ti-50.85 at % Ni wire specimen (Eucken et al., 1989); (b) stress–strain curves of $Ni_{47.6}$ $Ti_{46.4}Nb_{6.0}$ wire specimen tested at 20 °C (Takagi et al., 2006); and (c) effect of repeated cyclic deformation on energy loss (Dolce & Cardone, 2001).

From Figure 3(a) and (b) it is can be seen that the stress hysteresis is NiTiNb (Figure 3(b)) is considerably larger that the stress hysteresis observed in NiTi (Figure 3(a)). Consequently, the energy dissipation capacity of NiTiNb is greater than NiTi, however in both cases this is reduced with the increase in number of cycles. The influence of repeated cycles on energy dissipation capacity is shown in Figure 3(c).

Effect of Temperature on Stress–Strain Response of SMAs

The influence of temperature on the stress–strain response of SMAs is the single most important factor governing the behaviour of SMAs. SMAs are highly sensitive to variation in temperature. Material stress and temperature are inversely-related, meaning that a decrease in temperature is equivalent to increase in stress level at which the SMA will be stable. In other words, the *martensite* proportion in SMA is increased. Similarly, if the temperature is increased, higher stress values are required to induce the transformation. The effect of temperature on stress–strain response of NiTi is shown in Figure 4(a). As shown in Figure 4(a), if the temperature of SMA is decreased to a level where the phase of the SMA is changed from *austenite* to *martensite*, instead of recovering the *pseudoelastic strain,* it will be retained. This can pose a significant design issue if the operating temperatures are not within the range that the SMA is designed to be operational.



(a) (b)

Figure 4. (a) Effect of temperature on the behaviour of Ni-Ti (Strnadel et al., 1995); and (b) effect of strain rate on the stress-strain curves of NiTi at initial temperature of 296K (each curve starts at zero strain) (Nemat-Nasser et al., 2006).

Effect of Strain Rate

The *pseudoelastic* behaviour of SMAs is not an isothermal process. The amount of heat absorbed or released by SMA during loading and unloading results in a change of its internal temperature. As the strain rate increases, the change in internal temperature becomes predominant and may cause a rise of few degrees of temperature (Dolce & Cardone, 2001). Considering SMA is highly sensitive to variation in temperature and the expected non-uniform nature of strain rate in seismic loading, it is essential to investigate the behaviour of SMAs under different strain rates. Nemat-Nasser et al. (2006) investigated NiTi under a wide range of strain rates, ranging from 0.01/s to 4,200/s. An increase in transformation stresses at higher strain rates (>2100/s) was reported by them. At strain rates greater than 4200/s, the plateau range i.e. the transformation region between *austenite* and *martensite* phase also vanishes. However, for smaller ranges of strain-rates (between 0.1 to 2100/s), the behaviour of the NiTi SMA does not appear to alter significantly other than the observations that the forward transformation stress increases with an increase in strain rate. Dolce & Cardone (2001) investigated the effect of strain rate in NiTiNb wires that were *pseudoelastic* at room temperature. They also reported a stable behaviour of the NiTiNb wires subjected to strain rates ranging between 0.0008−0.32/s. However the dissipation of energy at higher strain rates is reduced and a considerable loss in equivalent damping takes place.

Application of SMAs in Seismic Retrofitting

Several researchers, (Ocel et al., 2004; Saiidi & Wang, 2006; Youssef et al., 2008; and DesRoches et al., 2010), investigated the application of SMAs in seismic retrofitting and reported a significant enhancement in ductility, energy dissipation and the overall seismic performance of structural components retrofitted with SMAs. Ocel et al. (2004) experimentally evaluated two steel beam-column connections partially restrained by four SMA tendons. A significant increase in ductility and energy dissipation was reported. A recovery of about 76% of the residual tip displacement upon heating was achieved. Andrawes et al. (2010) compared SMA with carbon fiber reinforced polymer (CFRP) and found an increase of 38% in the strength of column confined with SMA wire jacket with respect to the column retrofitted with CFRP. Park et al. (2011) compared the cyclic behavior of columns confined with SMA and steel jacket, column retrofitted with SMA showed more circumferential strain recovery than steel jackets alone. A more detailed review of the application of SMAs in structural engineering can be found elsewhere (Menna et al., 2014).

SMAs as a Material for Active Confinement

The shape memory effect can be utilised to develop a convenient way of tensioning SMA wires to act as wrapping in retrofitting strategies for reinforced concrete structures. Confining concrete with prestressed wrapping is termed as 'active confinement' and is found to be much more effective than 'passive confinement' which becomes effective only when the concrete starts to dilate. The concept of active confinement using other materials such as steel and FRP has been studied in the past by many researchers. Yamakawa et al., (2005) investigated active confinement of concrete using prestressed aramid fiber belts and reported that active confinement of concrete contribute significantly to increasing the shear strength, axial load carrying capacity and restraint to circumferential strain of concrete. Moghaddam et al. (2010) used prestressed metal strips to actively confine concrete prismatic and cylindrical specimens. Their experimental work demonstrated a significant increase in strength and ductility of actively confined concrete. However, in spite of encouraging results from these works, practical implementation of active confinement of reinforced concrete using conventional mechanical pre-stressing techniques faces many obstacles due to many practical limitations. Since active confinement using SMAs does not require any mechanical prestressing, its practical implementation tends to be easy and therefore widens the domain of active confinement of reinforced concrete to even awkward locations e.g. beam-column joints (BCJ).

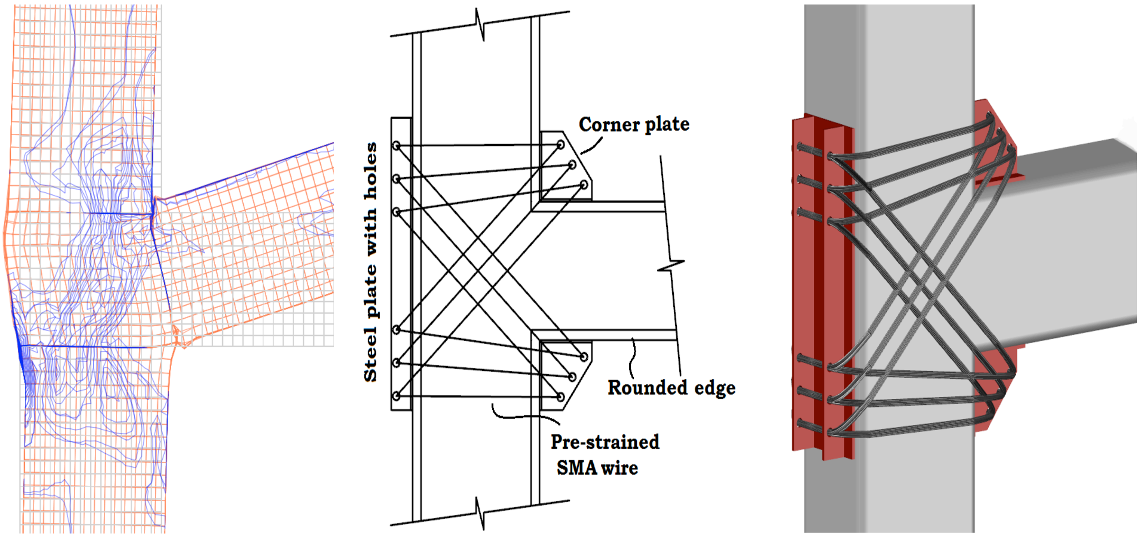
Many researchers (Andrawes et al., 2010; Park et al., 2011; Choi et al., 2011; Chen & Andrawes, 2014) have studied active confinement of concrete using SMAs and reported a significant enhancement in the strength and ductility of retrofitted sections. However, in almost all of these studies, investigations were carried out on circular sections in which uniform application of hoops stresses due to active confinement can be easily achieved using SMA spirals. The application of active confinement to non-circular section using simply SMA spirals will not be as effective as in circular sections due to non-uniform distribution of the confining stresses therefore, different techniques to confine non-circular sections needs to be developed. In an attempt to explore a method to provide active confinement to non-circular sections using SMAs, Chen et al., (2014) proposed a technique using hallow steel tubes and SMA wires. The arrangement of the tubes and SMA wires was designed in such a way that when the SMA wires were heated, bearing pressure on the two opposite faces of the concrete section were generated resulting in unidirectional confinement. The same arrangement was provided on the other two faces of the section and therefore bi-directional confinement of section was designed. In continuation to the development of active confinement of non-uniform circular sections, techniques combining perforated steel plates/sections with pre-strained SMA wires, essentially utilising shape memory effect of SMAs to develop active confinement of non-circular section, are proposed in the following section. In this research, a series of cyclic experiments will take place to validate proposed new SMA retrofitting strategies.

Proposed Retrofitting Strategies

The proposed retrofitting schemes have been conceived with an aim to retrofit BCJ of non-seismically detailed (NSD) reinforced concrete buildings. The BCJ of NSD reinforced concrete buildings can undergo different failure modes, for example shear failure of BCJ core (see Figure 5), shear failure of columns, bond failure of reinforcement, etc. Based on the active confinement strategy discussed in the previous section, retrofitting schemes are devised for BCJs with an aim to improve their shear strength, flexural ductility and bond strength of the reinforcement. The underlying principle in the proposed retrofitting schemes is to modify the rectangular shape of the as-built section to an elliptical shape for effective confinement of the section and to reduce the joint distortion using loops of SMA wires in diagonal direction around the joint core region. The effectiveness of this scheme depend on the tension in the SMA wires, thus SMA wires are intended to be used in a pre-strained condition so that heat activated pre-stress can be conveniently developed in the wires.

The first scheme (S-1) focuses only on the shear failure of the BCJ core and therefore only the joint core is retrofitted by means of diagonal and horizontal pre-strained SMA (hereafter referred to as SMA only unless the differentiation between undeformed and pre-strained SMA is necessary) loops as shown in Figure 5(b) and (c). The diagonal SMA loops are anchored using anchor plates provided with perforations. The end plate and the perforations in the endplates are located in such a way that SMA wires results in the effective transference of the confining stresses to the concrete section. Anchoring SMA wires by passing through the perforations also allows SMA wires wound in diagonal and horizontal direction to be effectively held in position. The size of the perforations is chosen such that multiple loops are accommodated through single holes and thus reducing the number of holes required. Sharp edges are chamfered to distribute confining stresses and also to reduce the radii of the SMA loops.

In order to tie the ends of SMA wires with continuing loops, gritted crimp sleeves/ U-clips are used. Once SMA wires are anchored in the arrangement specified, active confinement of the joint core can be conveniently developed by heating the SMA wires.

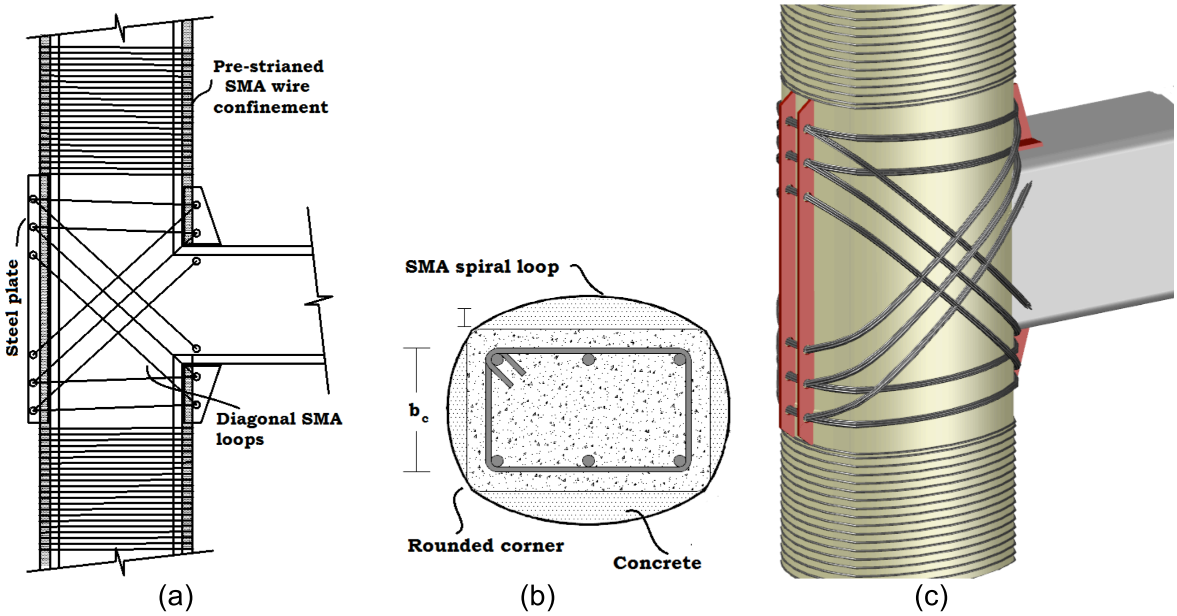


(a) (b) (c)

Figure 5. (a) Deformed joint core (scaled) and the associated von-Mises stress contour in a typical non-seismically detailed beam-column joint (FEM); (b) schematic of the proposed retrofitting strategy (S-1); and (c) 3D enlarged view of the S-1 showing diagonal SMA loops and its anchorage arrangement.

The first scheme (S-1) is extended to provide active confinement in the plastic hinge zone of the column section in scheme (S-2) as shown in Figure 6. Since looping the SMA wire simply around the rectangular section will not be as effective as desired, modifying the rectangular section to elliptical shape is necessitated. Shape modification can be achieved in a number of ways such as using precast concrete bolsters to obtain circular or elliptical shape (Priestly and Seible, 1995), or using prefabricated FRP shell with concrete infill (Teng and Lam, 2001). In the proposed scheme (S-2), shape modification is achieved using concrete cast in elliptical shape as show in Figure 6(b). Steel plates as used in the S-1 are embedded in the newly cast concrete to anchor the diagonal SMA loops.

The effectiveness of the confining strategies described above will be compared and in the future computational models will be developed to further understand the seismic behaviour of the experimentally investigated strategies.



(a) (b) (c)

Figure 6 (a) Schematic of the prosed Scheme-2; (b) cross-section of the retrofitted column section; and (c) 3D enlarged view of the Scheme-2 showing modified cross-section, SMA winding and anchorage arrangement of SMA loops.

Conclusion

Past research on active confinement of concrete and reinforced concrete using SMA was critically reviewed in this paper. An underlying theory for development of active confinement is disused in detail and an overview of the thermo-mechanical characterisation of SMAs is presented with a focus on seismic application. Finally, this paper presents retrofitting strategies of reinforced concrete beam–column joints using SMA. The strategies will be experimentally investigated through cyclic testing.

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