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# USE OF SHAPE MEMORY ALLOYS TO IMPROVE STRUCTURAL RESILIENCE FOR EXTREME LOADING CONDITIONS

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**Abstract**: *The present paper explores applications of Shape Memory Alloys (SMAs) in civil engineering structures to improve their resilience when subject to extreme events such as earthquakes and bomb blast. SMAs are able to undergo phase transformation resulting in the properties of superelasticity and Shape Memory Effect (SME). Superelasticity is the ability to recover large strains (4-8%), whereas SME refers to capability to attain a memorized shape. Nickel titanium alloys (NITI) are the most common SMA with excellent properties used in many diverse applications. However since they are expensive, low cost iron (FE) based SMAs are being explored as a viable alternative. The present paper illustrates through several examples the advantages of application of SMAs to civil structures. The application of SMAs in glazing systems subject to blast and reinforced concrete building subject to earthquake are discussed. Simulations are performed using finite element analysis to identify the potential performance benefits of including SMAs. In the façade analysis, significant reductions in cable stresses and reactions were observed when SMAs were included in the façade design. Suitable selection of SMA elements and fine tuning of their design is however necessary to maximise the benefit. The effectiveness of active confinement of the columns using SMA strips is shown by conducting a pushover analysis. It is concluded that SMAs show potential to improve the resilience and structural integrity of glazed facades subjected to blast and RC-buildings in earthquake zones.*

## Introduction

Structural resilience has become an important consideration in design of modern buildings and critical infrastructure not only in the UK, but worldwide. In order to make the buildings smart and robust, there is a drive to take advantage of innovative and advanced materials in construction. Shape memory alloys (SMA) have the unique property of being able to memorize a shape when heated above a transformation temperature, known as 'Shape Memory Effect (SME)'. If it is restrained from attaining its memorized shape, large recovery stress (or force) can be developed. SMAs also have the ability to undergo large recoverable strains of the order of 4-8%, known as super elasticity. They also have different Young's moduli in the martensitic and austenitic phases. Several applications of NITINOL i.e., the Nickel Titanium alloy and Iron based SMAs (Fe-SMAs) for civil structures are reported in literature (Janke et al. 2005). NITINOL has larger recoverable strain up to about 8%, whereas Fe-SMAs have only 3.5-4% strain. However NITINOL is prohibitively costly for civil structure applications, therefore Fe-SMAs are considered a promising alternative. Cladera et al. (2014) have presented an excellent review of literature on applications of Fe-SMAs for civil engineering structures.

Two applications of SMAs are explored in the present paper. First application is the intelligent use of NITINOL within the cable supported glass facades to enhance their blast resilience. Cable trusses utilise tension only members to support glazing systems. This is appealing from the point of view of SMA material as these perform best when loaded in tension and hence could benefit from its inclusion within design. Second application is the use of SMA in reinforced-concrete (RC) framed buildings to improve their earthquake resilience. The benefits of SMAs are investigated numerically in this paper.

The paper is structured in the following manner. Section 2 reviews the main properties of SMA and highlights the difference between Fe-SMA and NITINOL. Section 3 discusses the application of SMA in glass facades. Application of SMA in RC building and some preliminary

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pushover analysis of a building column are presented in Section 4. Advantages and limitations of the techniques adopted to improve structural resilience of facades and RC-framed buildings are discussed.

## Shape Memory Alloys

SMAs are a class of metal alloys that are able to recover relatively high strains (4-8%) when they are heated above a certain transformation temperature. SMAs have two stable phases – the high temperature austenitic phase and the low temperature martensitic phase. The martensitic phase can be in one of two forms: twinned and detwinned as shown in Figure 1.The property of SME is essentially due to reversible diffusionless transformation between two phases. Forward transformation from austenitic to martensitic phase occurs upon cooling the SMA from temperature $M_s$ to $M_f$ leading to 100% martensite. Reverse transformation occurs upon heating of martensitic form of SMA from temperature $A_s$ to fully austenitic phase at temperature $A_f$.

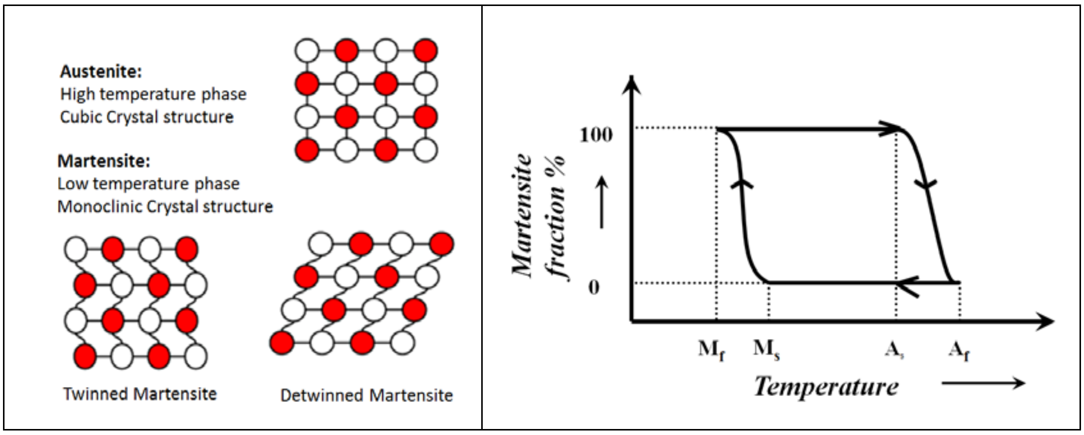


*Figure 1-Different phases of SMA*

Phase transformation in SMA can also be induced by application of pure mechanical loading. The two significant properties of SMAs associated with phase transformations are the shape memory effect (SME) and superelasticity.

*Shape memory effect (SME)*

In reference to Figure 2, the state of SMA at point (a), which is in austenitic phase at a temperature greater than $A_f$, is the memorized (parent) state. Upon cooling to temperature below $M_f$, it transforms to martensitic phase indicated by point (b). Process (b)→(c) represents loading of SMA in martensitic phase inducing strains of the order of 4-8% in NITINOL and 3.5-4% in Fe-SMA. The ability of martensitic phase to undergo large strains is primarily due to the phenomenon of twinning and de-twinning. This characteristic is also known as pseudo-elasticity. The process (c)→(d) represents unloading of martensite during which the elastic strain is recovered leaving a fairly large strain unrecovered. In state (d), when SMA is heated to temperature above $A_f$, it is transformed to austenitic phase and it attains its memorized (parent) state (a). The property of shape memory effect (SME) is characterized by process of shape recovery (d)→(a). The SME may be present as one way memory or as two way memory. In one way memory, the transformation occurs from (d) → (a) →(b). In two way memory SMA is conditioned to memorize two shapes one at lower temperature and the other at higher temperature. By heating/cooling of SMA, it can be taken from one memorized state to another.

*Super-elasticity*

The property of super-elasticity is present in NITINOL but is found to be absent in Fe-SMAs. When NITINOL in austenitic phase (at a temperature $\geq A_f$) is mechanically loaded, it undergoes a large strain of the order of 8-10%. In this process, it transforms from austenitic phase to martensitic phase, which is primarily stress induced i.e., not involving change of temperature (cooling). Upon unloading of SMA, entire strain is recovered and SMA transforms from martensitic to austenitic phase. In this process too there is no change of temperature (heating). As a result of loading and unloading process, a large hysteresis effect is observed as shown in

Figure 2. Hysteresis effect represents dissipation of energy in a cyclic process, and therefore can be used for vibration control.

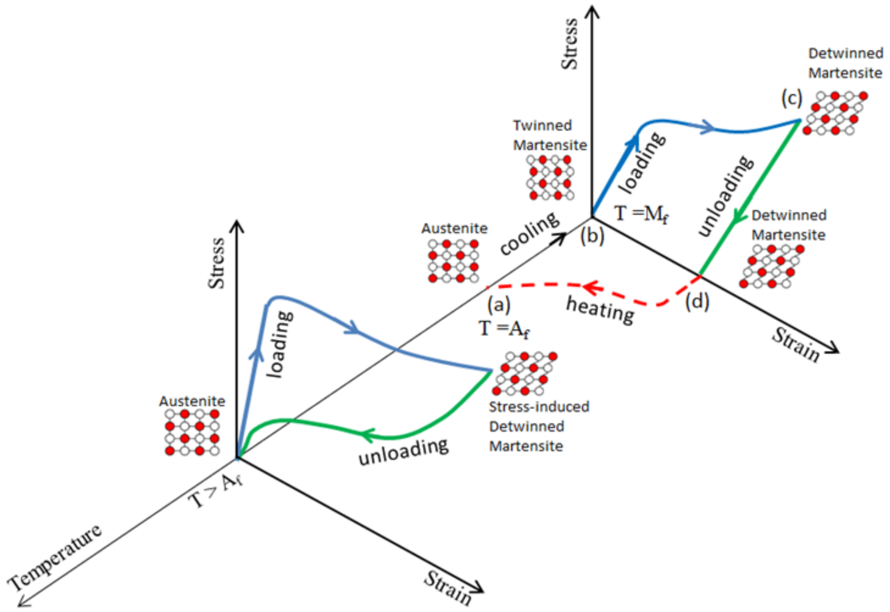


*Figure 2-Typical stress-strain response of super-elastic and shape memory effect SMAs*

*Recovery stresses*

During SME if SMA is restrained, the process (a) to (d) in Figure 2 will not be completed. While it will transform to austenitic phase, it will have a residual strain. Simultaneously it will develop stress corresponding to the residual strain as per the stress-strain characteristics in austenitic phase. This internal stress developed in SMA is known as 'recovery stress'. If SMA is restrained large recovery stresses of several hundred MPa can be generated in structural components, which can be used gainfully for design.

## Application of NITINOL in Cable Supported Glazing Facades

Cables or cable trusses utilise tension-only members to support glazing systems. This is appealing from the point of view of SMA materials as they typically perform best when loaded in tension and hence the glazing systems could benefit from their inclusion within their design.

*Figure 3–Example of bow truss tension cable glazing system*

The potential application would be to provide SMA wires at the interface with the main support structure. Special couplers could be used to connect SMA with steel as discussed by Billah and Alam (2012). The use of SMA would have the potential benefit of reducing the reactions and allowing some energy absorption before returning to the original position. In terms of blast loading, the presence of SMA could reduce the demand on the glazing resulting in less fragmentation and damage.

These aspects are investigated below by conducting preliminary FE analysis of a cable supported façade, Figure 3. The research paper by Amadio et al. (2012) was referenced to select a suitably designed cable-supported façade for the present study. Based on the description of the façade in the paper an FE model of the façade was developed and the benefits of SMA were explored by incorporating SMA at ends of the cable where it connects to the main structure.

### *Description and modelling of the facade*

The studied façade is 9m tall and consists of 1.55m wide and 3.0m high laminated glass sheets. The façade is assumed to be wide enough so that lateral restraints can be neglected and only one bay of 1.55m width can be considered for analysis. Since the panels considered are quite large, each panel was assumed to be supported on six point supports. A four-hole spider connector was used in the corner for connecting 4 adjacent panels to the cable, while a two-hole connector was introduced at the middle of the vertical edges for additional point supports. Following main components of the façade were included in the model:

- The laminated glass considered was 21.5mm thick comprising of two 10mm fully tempered glass sheets bonded by 1.52mm thick PVB interlayer. The glass was modelled using shell element of 21.5mm thickness and assigned elastic material properties of the glass; breakage of the glass was excluded from the comparative analyses.
- The cables were considered to be made of high strength steel having a diameter of 36mm. The cable was modelled using truss elements and assigned elastic behaviour of steel. The cables were pre-stressed with a load of 300kN.
- Spider brackets were also modelled using rigid elastic beam elements and constraints were applied between the bracket and the glass and the bracket and the cable.

SMA was introduced at ends of the cable in the form of a 36mm diameter bar to match the cable diameter. The material model for the super-elastic SMA that was implemented within ABAQUS is shown in Figure 4. Analyses were performed by including SMA at only one end of the cable and at both ends of the cable. The FE model of the façade developed is shown in Figure 5.

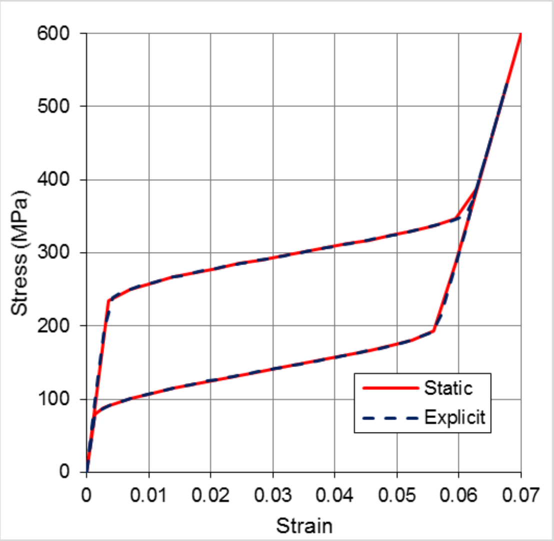


*Figure 4-Assumed stress-strain behaviour of NITINOL (based on Qidwai et al. 2000)*

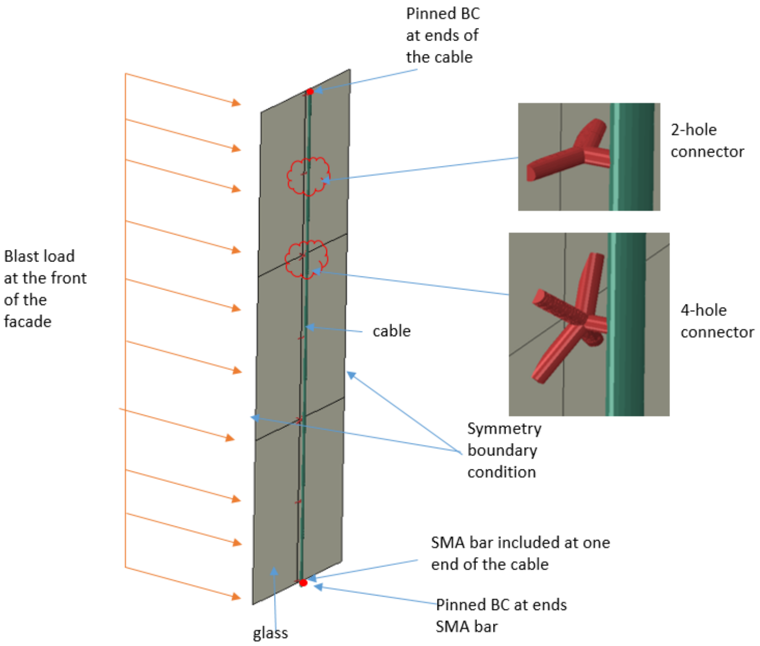


*Figure 5-FE-model of the cable supported façade with SMA bar at one end of the cable.*

*Blast load definition*

For initial investigation, peak pressure of 30kPa over a duration of 12ms was imposed on the front of the façade. Subsequently, higher blast load of 40kPa over a duration of 20ms was also considered.

*Analysis result*

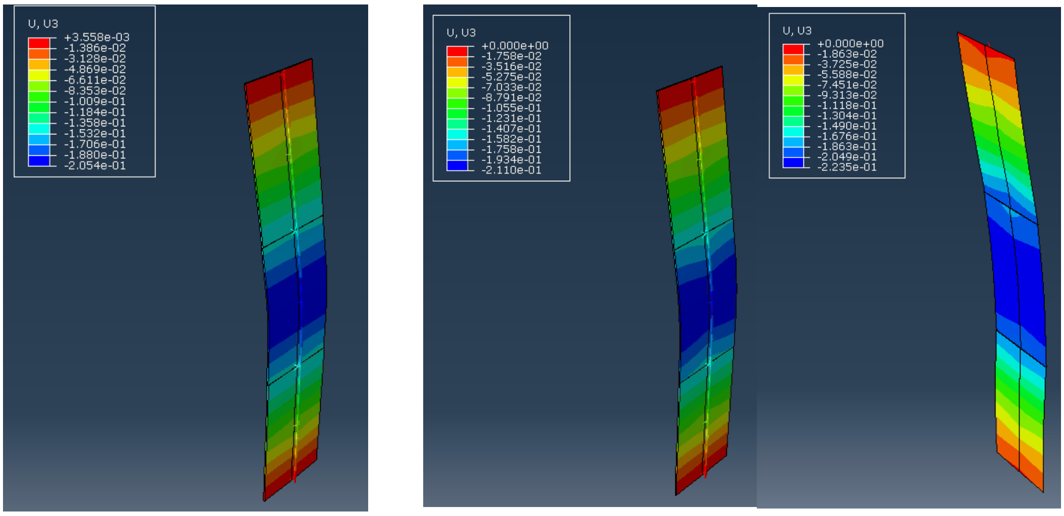
The results presented below are for the case of lower blast load of 30kPa peak pressure and 12ms duration.

The displaced shape of the façade when subject to the blast load is shown in Figure 6. The mid-span displacement of the cable is shown in Figure 7. It is observed that the displacement of the façade increased slightly due to inclusion of SMA. The maximum displacement of the façade without SMA was observed to be 205mm, while with SMA included at one and both ends the maximum displacement increased to 211mm and 223mm, respectively.

The resultant of the reaction forces at the end of the cable and the axial stress experienced by the cable are shown in Figure 8. It can be observed that with inclusion of SMA, the reaction forces and stress in the cable reduce at the expense of a small increase in the overall displacement of the façade. For the case of SMA included only at one end of the cable, the benefit observed is limited as reduction in stresses and reactions is only marginal. For this case, it was also observed that the stresses and reactions did not change appreciably at the other end where SMA was not included. Hence, to maximise the benefit in terms of limiting the transfer of reactions to the main structure at both ends and reducing stresses in the cable, it is advisable to include SMA at both ends of the cable. This is evident from the results obtained in this study where significant reductions in cable stresses and reactions are observed for the case of SMA at both ends of the cable.

Reduction in the reaction forces and cable stresses with inclusion of SMA indicate benefits for the cable and the supporting structure. No significant improvement was noted in the response of laminated glass panes.

The behaviour of the SMA is shown in Figure 9, where it can be seen that the maximum strain in the SMA for the case of lower blast load is less than 6% indicating that it remains within the austenitic phase. The blast analysis was repeated for a higher load (40kPa peak pressure with 20ms duration) for which it was observed that the SMA strain exceeds 6% and goes into martensitic phase. In this case, the overall benefits of using SMA were considerably less as no reduction in the reactions or the cable stresses were noted with inclusion of SMA. This indicates that to maximise the potential benefits of using SMA in cable supported facades, the design should be finely tuned so that behaviour of SMA's can be limited to austenitic phase.



Deformed shape of cable supported façade with pinned BC at cable ends.

Deformed shape of cable supported façade with inclusion of SMA at one end and both ends

*Figure 6-Deformation of the façade for 30kPa-12ms blast load*

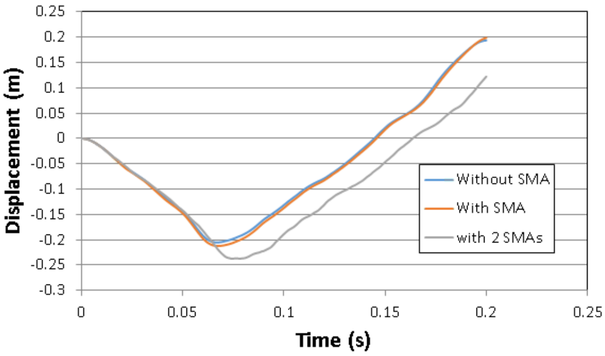


*Figure 7- Mid-span displacement of the cable for 30kPa-12ms blast load*

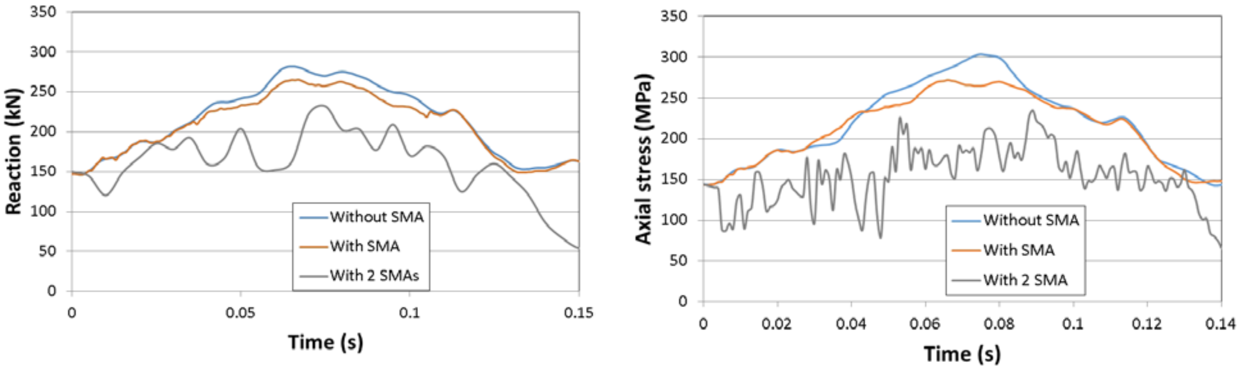


*Figure 8- Reaction force at the cable end and axial stress in the cable for 30kPa-12ms blast load*

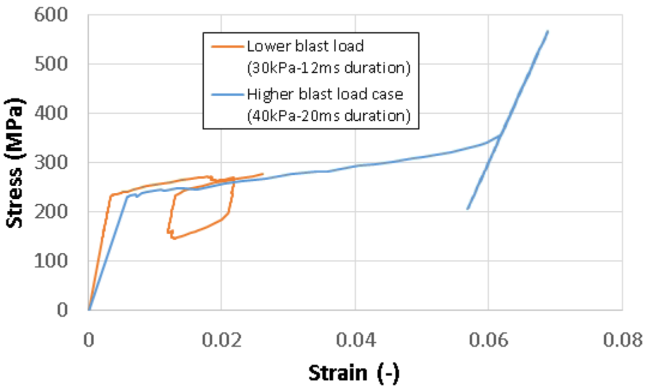


*Figure 9-Behaviour of SMA at lower and higher blast loading*

## Application of SMA in RC buildings

Researchers have been exploring various applications of SMA in concrete structures for the purpose of rehabilitation of damaged structures, retrofitting as well as new designs. SMAs are now available in different forms such as wires, strips, rods, beams and plates. Judicious use of SMA elements in concrete structures utilizing the properties of SME, recovery stresses and super-elasticity (in NITINOL) can make structures more resilient to extreme loads such as earthquake and blast.

To improve the performance of the concrete structures an active or a passive structure control can be adopted. Passive structure control takes advantage of high damping property of SMA to reduce the response and control plastic deformation. Tamai and Kitagawa (2002) and Cardone et al. (2004) have explored the use of SMA within the bracing of multi-storey RC frames. DesRoches and Delemont (2002) have studied the use of SMA in seismic retrofitting of bridges.

Active structural control using SMA is achieved by activating the SMA at the time of installation. It utilises the property of SME for generation of recovery stresses. Hong et al. (2018) have experimentally investigated the use of Fe-SMA in strengthening of RC structures. Shahverdi et al. (2018) have discussed the material behaviour and characterisation of Fe-SMA strips for strengthening of RC members. They have shown the effectiveness in using Fe-SMA strips as external end-fixed reinforcement for strengthening of RC structures. Michels et al. (2018) have discussed mechanical performance of Fe-SMA ribbed bars for concrete pre-stressing. Fe-SMA strips and bars are being produced at industrial level for civil engineering applications.

Another method of improving the structural resilience is by confining the concrete column with SMA strips or wires. The concept of wrapping is well-established and has been a common method of strengthening reinforced concrete columns. Generally FRP sheets or steel jacketing is used to confine the concrete. For the active confinement, the FRP or jackets are pre-stressed in a traditional manner by mechanical or hydraulic means. The active confinement using SMA is rather straightforward as they can be activated easily by heating. Fastest method to heat is applying an electric current. This technique could also be of use when SMAs are not fully exposed and embedded within the concrete.

SMA materials are best utilized in civil structures such as buildings or bridges by placing them at the plastic hinge location. For buildings or bridge piers when they are excited by earthquake, plastic hinge is usually formed at beam-column connections as well as at the base of the column. This approach of strengthening columns by Fe-SMA wrapping at the base is investigated below.

### *Active confinement of RC columns with Fe-SMA wrapping*

A typical column of an RC building shown in Figure 10 was considered. The strength of the column with and without SMA was evaluated numerically by undertaking a lateral pushover analysis. The column considered was of concrete class C25/30 and had dimensions of 400mm x 400mm. It was reinforced with 4 H20 and 4 H16 longitudinal bars and 10mm links spaced at 200mm centres. The effective length of the column was 3m. The column was modelled in ABAQUS, where concrete was modelled using 8-node solid elements, while reinforcing bars, links and SMA strips were represented using beam elements. For the reinforcing bars, an elastoplastic material model was used where yield strength of 500MPa was assumed. The concrete plasticity damage model was used to define the behaviour of concrete. Fe-SMA strips were modelled based on the stress strain curve provided in paper by Shahverdi et al. (2018).

The SMA strips considered were 1.5mm thick and 10mm wide and wrapped around the concrete as shown in Figure 10. The enhancement of the column by external Fe-SMA strips was considered over a length of 600mm, which was in excess of the plastic hinge zone. Based on tests performed by Shahverdi et al. (2018), it was noted that when restrained Fe-SMA strip with a pre-strain of 4% was heated to 160°C, a recovery stress of about 325MPa was generated. This was used to calculate the confining pressure on the concrete column due to wrapping and the compressive stress strain curve of the confined concrete based on Mander et al. (1988). About 30% increase in the compressive strength was estimated due to active confinement.

For the concrete column with SMA, the properties of the concrete confined by SMA were enhanced as described above. For the concrete column without SMA, properties of the concrete were based on confinement due to links, although this was found to be much less in comparison to the active confinement with SMA.

Concrete column was assumed to be fixed at the base and subject to a gradually increasing lateral load. A nominal axial load of 400kN was also considered on the column. The load-deflection curve obtained from the pushover analysis is shown in Figure 11. The results indicate that SMA wrapping increases the pushover strength of the column by about 20%. The area under the curve signifies the energy absorbed in the deformation of the column. With SMA, the RC column demonstrates higher ductility and higher energy dissipation, which suggests that it should perform better in an event of extreme loads such as earthquake and blast. It should also be noted that the shear capacity of the wrapped column is significantly higher, although since the shear failure is not triggered in the pushover analysis, the enhancement in the shear strength is not reflected in the load-deflection curve.

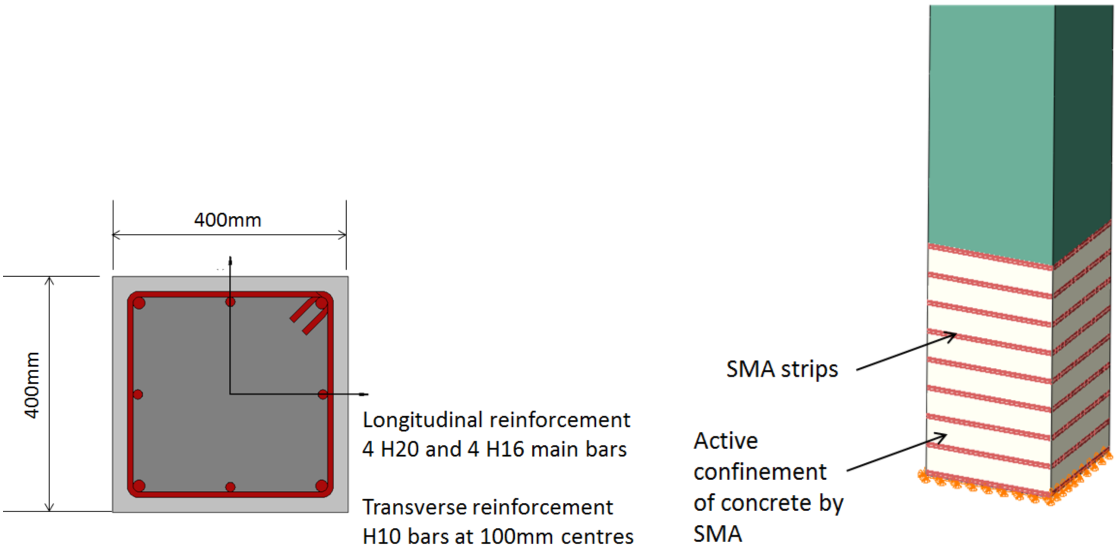


*Figure 10- Details of RC column and SMA wrapping*

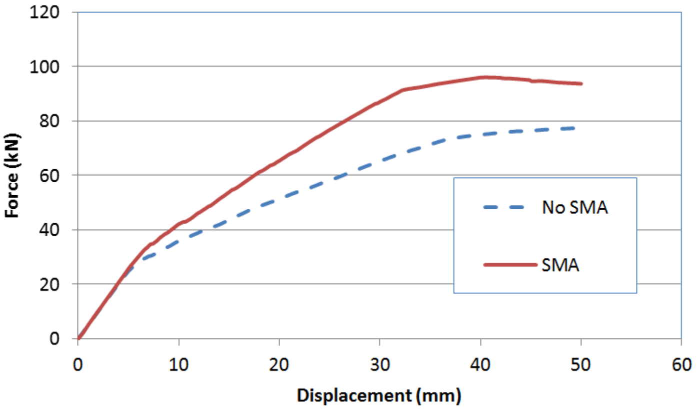


*Figure 11- Load deflection curve of RC column with and without Fe-SMA wrapping.*

## Conclusions

In this paper a brief review of SMA material properties have been presented and two applications in Civil Engineering have been discussed.

Application of NITINOL in cable supported façade systems to improve the blast resilience is studied. The results obtained for the cable supported façade system are encouraging and demonstrate that the blast performance of cable supported facades can be improved through the provision of SMA end supports. In order to maximise the benefits, SMA should be included at both ends of the cable. Significant improvement in terms of limiting the reactions transferred to the main structure and stresses in the cable are noted for this arrangement. It is however realised that suitable selection of SMA elements and fine tuning of their design is necessary to limit its behaviour to austenitic phase to maximise the benefit.

Further, it is shown how Fe-SMA can be used in improving the seismic resilience of RC columns. The results show that active confinement of the columns with SMA can increase the strength and ductility of the columns by increasing the confinement. Activation of Fe-SMAs by heating is considered to be advantageous compared to traditional methods of pre-stressing by mechanical/hydraulic means. It is noted that in addition to increasing the shear strength of the column, wrapping confines the concrete and prevents the catastrophic failure of the concrete column.

It is concluded that SMAs show a great potential in increasing resilience of structures when subjected to extreme loads, however, they have to be used judiciously to ensure that the cost of the project does not increase significantly.

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