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SHAPE MEMORY ALLOYS FOR CIVIL ENGINEERING STRUCTURES – ON THE WAY FROM VISION TO REALITY

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Abstract

Shape memory alloys (SMA) have been known for many decades. They are mainly used in medicine, electronics, air, and space industry and in the consumer goods industry. Examples are medical implants and instruments, cell phone antennas, frames for glasses, pipe couplings etc. The most usual SMA material on the market is nickel–titanium (Ni–Ti). Until today, SMAs have found very limited applications in civil engineering probably due to their cost and to limited knowledge of the material in the civil engineering industry.

This paper presents existing applications, laboratory tests and new concepts of how to use shape memory alloys incorporated in energy dissipation devices, as well as for pre-stressing structures using SMA wires and for post stressing of existing structures using SMA tendons. Attempts to develop new generation of Iron based SMA for using in civil engineering structures will be presented as an alternative to existing high cost NiTi SMAs.

Streszczenie

Stopy z pamięcią kształtu znane są od wielu dziesięcioleci. Głównie są one wykorzystywane w medycynie, elektronice, przemyśle lotniczym i kosmicznym oraz w przemyśle towarów konsumpcyjnych. Przykładowo są to implanty i instrumenty medyczne, anteny telefonów komórkowych, oprawki okularów, złączki rurowe itp. Najbardziej typowym na rynku materiałem z pamięcią kształtu jest stop niklowo-tytanowy (Ni-Ti). Dotychczas stopy te miały bardzo ograniczone zastosowanie w budownictwie. Prawdopodobnie spowodowane to było kosztami i ograniczoną znajomością tego materiału w przemyśle budowlanym.

W artykule tym przedstawiono istniejące zastosowania, badania laboratoryjne i nowe pomysły na wykorzystanie stopów z pamięcią kształtu będących częścią urządzeń rozpraszających energię, jak również w celu sprężania konstrukcji wykorzystując druty z tych stopów oraz sprężanie istniejących konstrukcji przy użyciu kabli wykonanych z takich stopów. Próby rozwijania nowej generacji stopów z pamięcią kształtu na bazie żelaza do wykorzystania w konstrukcjach budowlanych zaprezentowano jako alternatywę dla istniejących, drogich materiałów niklowo-tytanowych.

Keywords: **Shape Memory Alloy; Energy Dissipation; Post tensioning; Iron based SMA.**

1. INTRODUCTION

Shape Memory Alloys (SMA, also known as memory metal) are materials capable of undergoing large recoverable strains of the 8% order while producing hysteresis. It is a metal that “remembers” its initial geometry during transformations. After a sample of SMA has been changed from its “original” conformation, it regains its original geometry during heating (one-way effect) or, at higher ambient temperatures, during unloading (pseudo-elasticity or super-elasticity). These extraordinary properties are due to the temperature and stress dependent phase transformation from a low-symmetry to a highly symmetric crystallographic structure. (Those crystal structures are known as martensite and austenite.)

The three main types of SMA are copper-zinc-aluminum, copper-aluminum-nickel and nickel-titanium (NiTi) alloys. NiTi alloys are generally more expensive and possess superior mechanical properties when compared to copper-based SMAs. Nickel-titanium alloys were first developed in 1962-1963 by the US Naval Ordnance Laboratory and commercialized under the trade name Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratories) [1]. Their properties were discovered by accident – anecdotally, samples of the alloy were being subjected to strength tests by being pounded with hammers to see how much force was required to deform them. After several dents were created, the researchers left the samples on a windowsill and went to lunch – upon their return, the researchers discovered that the dents had "repaired" themselves.

Following the first SMA development "shape memory euphoria" began. Many researchers have contributed to better understanding of this material, developing several constitutive models e.g. [2], [3]. Due to distinctive macroscopic behaviours, not present in most traditional materials, SMAs are the basis for innovative applications.

The first applications of SMAs were limited to medical purposes mostly made of NiTi because of the excellent biocompatibility and high corrosion resistance. Examples are arterial stents, coronary dilatators, etc [4].

A number of non-medical applications are listed in [3] and [5]. Examples are eyeglass frames, antennas for portable cellular telephones, adaptive aircraft wings, spring shaped actuators, pipe couplings (Fig. 1 and Fig. 2).

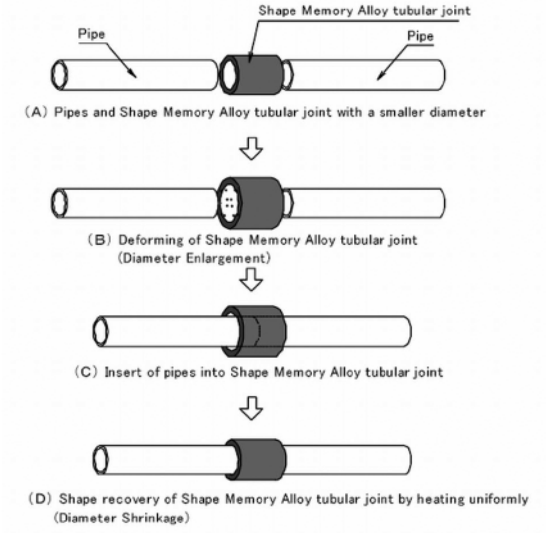


Figure 1.
Application for pipe joints [6]

Figure 2.
Curved steel pipe joints made of Iron based SMA for tunnel construction, pipe diameter 250 mm (Photo: Awaji Material)

Although SMAs have been known for decades, they have not been used much in the building industry until rather recently probably due to their cost, low elasticity modulus and to limited knowledge of the material in the civil engineering industry. For this reason particularly in large scale applications low cost SMAs are required. FeMnSi based alloys, which belong to the group of Iron based SMAs are an example of a potentially low cost SMAs. However, there is a need for certain improvements [7].

The current paper will first give a summary of the material characteristic. A couple of existing applications in civil engineering structures will be described. Results of a number of laboratory tests will then be presented to show the great potential of SMAs for civil engineering applications. Lastly, recent laboratory tests for developing a new generation of Iron based SMA, more suitable for civil engineering applications will be presented as an alternative to existing high cost NiTi SMAs.

2. MATERIAL BEHAVIOR

The temperatures at which the SMA changes its crystallographic structure are characteristic of the alloy and can be tuned by varying the elemental ratios. Ms denotes the temperature at which the structure starts to change from austenite to martensite upon cooling; Mf is the temperature at which the transition is finished. Accordingly, As and Af are the temperatures at which the reverse transformation from martensite to austenite start and finish, respectively (Figure 3). In Figure 4 most of the effects related to the SMAs is visualized by means of a stress-strain-temperature diagram. The metallurgical basis of any of these effects is the reversible phase transformation from the high temperature phase austenite into the low temperature phase martensite. The most important behaviour shown by SMAs can be summarized as follows:

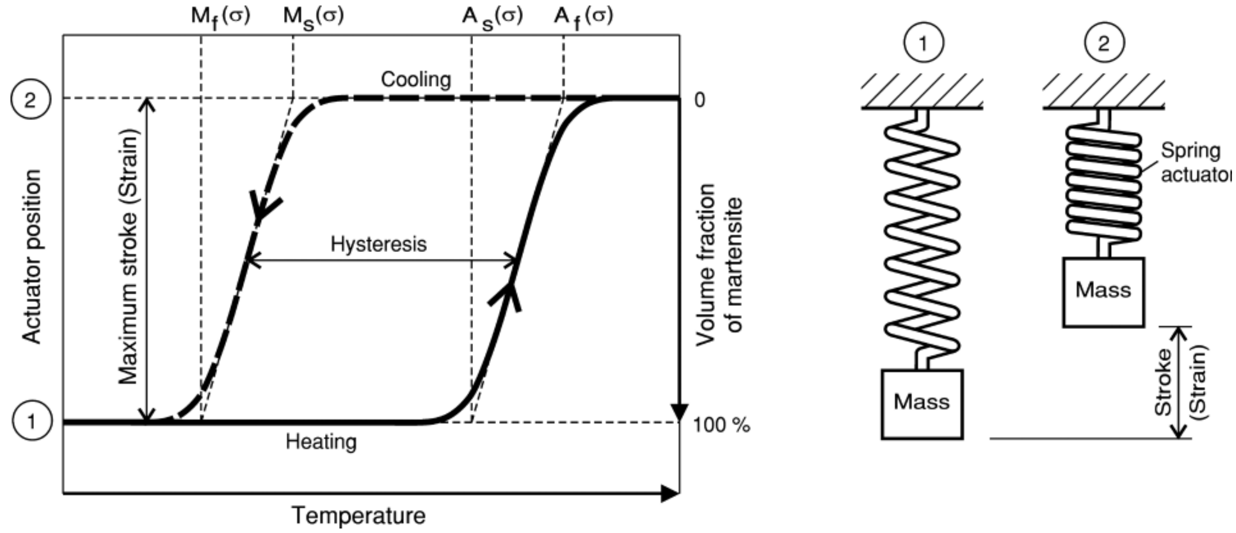


Figure 3.
Transformation temperatures in terms of the volume fraction of martensite and the actuator stroke and strain respectively. Spring actuators show the two way thermal shape memory effect schematically

In the absence of heating or cooling, the SMA is at ambient temperature. This temperature defines the phase state at which the alloy is stable without thermal actuation and at which phase changes can be expected under thermal actuation and mechanical loading. Below Mf the material is fully martensitic. The material is showing a pseudoplastic deformation behaviour and is able to undergo large pseudoplastic deformation of up to 8% (for example NiTi alloy). On heating, transformation starts at As and is completed at Af at which phase transformation from martensite to austenite is completed and the pseudoplastic deformation is almost fully recovered (see the spring actuator in Fig. 3). Note that all transformation temperatures are a function of the mechanical loading represented by the stress σ.

Between Af and Md the material is in the austenite phase. It is showing a pseudoelastic (super elastic) behaviour, where a stress induced martensite phase transformation occurs.

If the temperature is increased above a critical value called Md, the material loses its superelasticity again. The material is showing a deformation behaviour which is similar to the classical alloys such as steel.

The stiffness of the austenitic phase before yielding is usually higher than that of the martensitic phase before yielding. The yield stress of the austenitic state in SMAs is higher than that of the martensitic state, unless the thermal situation of the alloy permits the formation of stress induced martensite. The yield stress of the austenite in the latter case marks the beginning of the stress induced rearrangement of the crystal structure and is associated with low stiffness and large strains.

Mechanical properties of some selected SMAs are presented in Table 1.

As has been made clear, the material behaviour of SMAs is highly dependent on changes in (ambient) temperature. No attention was given so far to the role of time. This however, could be of great importance for dynamic engineering applications as both the number of cycles and the rate of loading affect the stress-strain behaviour. Although the martensitic

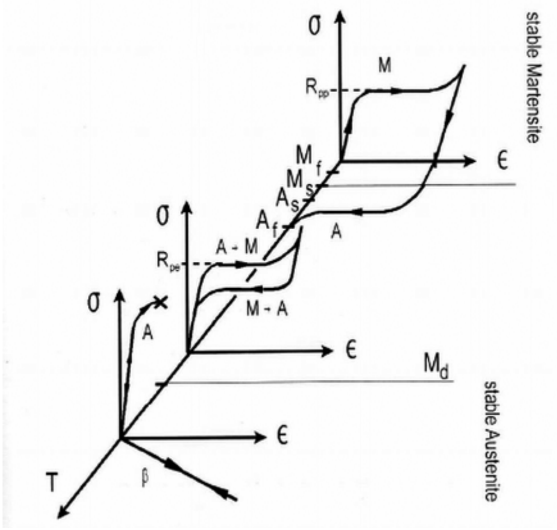


Figure 4.
Stress-strain-temperature diagram showing the effect of temperature change on the properties of NiTi [5]

Table 1.
Property values of selected shape memory alloys [7]

Property	Unit	Ni-Ti	Cu-Zn-Al	Cu-Al-Ni	Fe-Mn-Si-Cr
Young's modulus austenite martensite	GPa	70–98 27	70-100 70	80-100 80	(140)*
yield strength austenite martensite	MPa	100-800 50-300	150-350 80-300	150-300 150-300	(~200)*
ult. tensile strength austenite martensite	MPa	800-1500 700-2000	400-900 700-800	500-1200 1000-1200	650*
elongation at failure austenite martensite	%	15-20 20-60	10-15	8-10	29*
recovery strain	%	8	3.5	2	3.4**
max. recovery stress	MPa	600-900	400-700	300-600	400**

* measurements wit Fe-27%Mn-6Si-5Cr at 22°C; ** see [7]

transformation itself is rate independent the production of heat during transformation can lead to a self heating of the SMA part when subjected to high loading rates and therefore a significant change in stress-strain behaviour.

For a complete description of the material behaviour in micro and macro level, fatigue resistance, damping properties as well as constitutive modelling concepts can be refered to [2], [3] and [7].

3. APPLICATIONS AND NEW DEVELOPMENTS FOR CIVIL ENGINEERING STRUCTURES

3.1. Existing Field Applications

The number of field applications of SMAs in civil engineering is still limited. Therefore, the actually realized pilot projects, described in the following subchapter, are very important from the application point of view.

3.1.1. Retrofitting of the Basilica of San Francesco at Assisi, Italy

Earthquake induced vibrations may cause severe damage in particular to historical buildings, like the Basilica of San Francesco at Assisi. The Basilica was restored after being strongly damaged by an earthquake of 1997 [8]. E.g. the structural interaction of the basilica's transept south gable with the main structure needed to be modified. The retrofit measures aimed at limiting acceleration and forces transmitted from the roof of the main structure to the masonry gable with tympanum. Furthermore, energy dissipation capacity needed to be induced to the whole structure. The seismic upgrade was carried out under the framework of the ISTECH project (see section 3.2).

To solve the above task, the gable was completely disconnected from the roof and was then linked to the roof again by means of Shape Memory Alloy Devices (SMAD's, Fig. 5 and Fig. 6) Each SMAD is designed to take both tension and compression forces, while consisting of SMA wires which are only subjected to tension. The wires are made of NiTi used in its superelastic condition. Consequently, the SMAD's work as isolators, however, the important box behavior of the building is still guaranteed. Principle load-displacement behavior of the SMAD's is illustrated in Fig. 7.

When subjected to normal horizontal loads, like wind and minor earthquakes, the SMAD's show almost linear elastic behavior and only small displacements occur (Fig. 7, load path I). However, in case of a major earthquake, the critical stress in the SMA is exceeded and the wires loose their stiffness (Fig. 7, load path II, superelastic plateau). The device allows for higher displacements and, as a result, permits to activate the damping of the connected masonry structure while acting as load limiter. Hysteresis is produced by unloading and cyclic loading. Finally, the SMAs increasing stiffness, when loaded above the superelastic plateau, prevents the gable from tearing of the main structure in case of an unexpected strong earthquake (Fig. 7, load path III). Note that the shown load-displacement behavior is a simplification. Details of the exact multi-plateau design of the SMAD's can be found in the literature [9] and [10].

This kind of application is a perfect example of how to use an expensive SMA material like NiTi with good economic sense in civil engineering. Use of the SMA within relatively small devices and selective application to the structure enabled an intelligent seismic upgrade of a large structure.

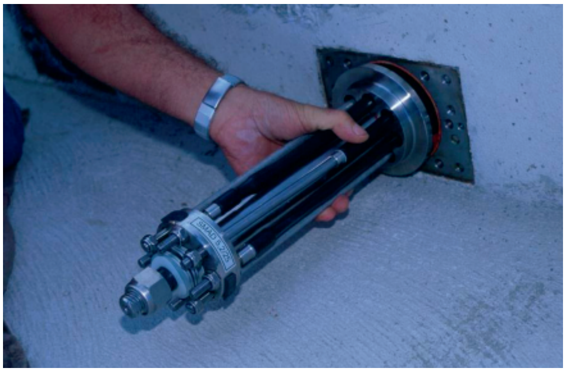


Figure 5.
Shape memory alloy device (Photo: FIP Industriale)

Figure 6.
Back view of the historic gable (Photo: FIP Industriale)

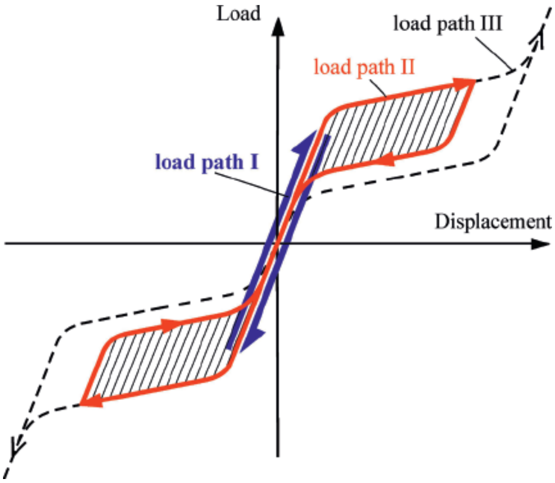


Figure 7.
Principal load displacement behavior of SMAD

3.1.2. Retrofitting of the bell tower of the Church of San Giorgio at Trignano, Italy

Seismic upgrade of the bell tower of the Church of San Giorgio at Trignano (Fig. 8) became necessary after being struck by a 4.8 Richter magnitude earthquake in 1996 [11] and represents one of the first known applications of SMAs to civil engineering. Retrofit design of the 17 meters tall masonry tower was carried out under the framework of the ISTECH project (see section 3.2).

As a result of analytical studies, increase of the tower walls' vertical tensile strength and stiffness by additional vertical reinforcement showed to be suitable for improving the overall integrity and bending resistance of the tower [12]. Furthermore, it was intended to improve shear strength of the masonry by vertical prestressing. However, reinforcement and prestress had to be considered with regard to the masonry's low compressive strength of only 1 MPa. Damage to the respective compression zone, caused by bending of the tower due to strong horizontal ground acceleration, would have been a problem otherwise.

Considering the aforementioned boundary conditions, the upgrade was carried out linking top and bottom of the tower by means of hybrid tendons [11]. In total four tendons are placed exposed in the corners of the tower. Tendons consist of conventional steel bars in series with one SMAD device each (Fig. 9). The SMAD is designed to take tension forces by means of 60 parallel superelastic NiTi wires of 1 mm diameter and 30 mm length. The tendon's prestressing was chosen to reach the superelastic plateau of the SMA. Consequently, the SMADs act as load limiters in case of an earthquake while providing moderate damping through hysteretic behavior. The tendon force is thus kept within a desired working range, even if large deformations occur (Fig. 9).

After a 4.5 Richter magnitude earthquake with the same epicenter in 2000, subsequent investigations of the retrofitted bell tower found no evidence of damage [13].

3.1.3. Repair of a cracked region of a highway bridge in Michigan, USA

The first field implementation using shape memory effect for posttensioning of a concrete structure was presented in [14]. The concerned bridge in Michigan on highway no. US-31 has suffered cracks due to insufficient shear resistance attributed to improper cutoff of longitudinal flexural reinforcement. The resulting shear cracks in the web of the reinforced concrete T-beam had an average width of 0.55 mm.

Figure 8.
St. Giorgio bell tower (taken from [10]

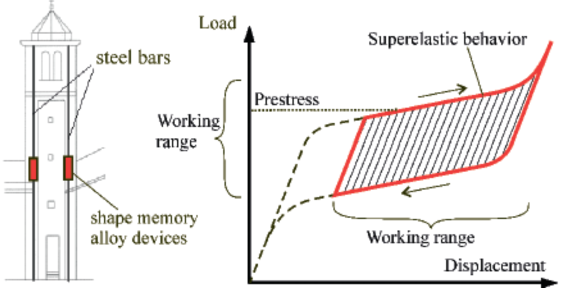


Figure 9.
Bell tower with tendons and principle load-displacement behavior of incorporated SMA devices (after [10])

For strengthening of the bridge girder, a harp-like assembly of shape memory alloy rods was mounted crossing the cracks at both faces of the web (Fig. 10). Iron-manganese-silicon-chromium (FeMnSiCr) SMA was used for the rods of diameter 10.4 mm. Each rod was heated by electrical power with 1000 Ampere current to achieve 300°C. Resulting recovery stress in the rods that remained after cooling down to ambient temperature was 120 MPa, while crack width was reduced by 40%.

This application is notable in particular as it uses an iron-based SMA. Despite the fairly low recovery stress achieved here as compared to commercial NiTi alloys, the FeMnSiCr SMA meets several important requirements for wider use of this technology in civil engineering: Low cost, high stiffness and high corrosion resistance. This gives motivation to intensive material development. Transformation temperatures of the alloy, recovery stress as well as strength of the austenite phase need to be improved. Recently, remarkable progress regarding this was made by researchers at Empa Switzerland (see section 3.4).

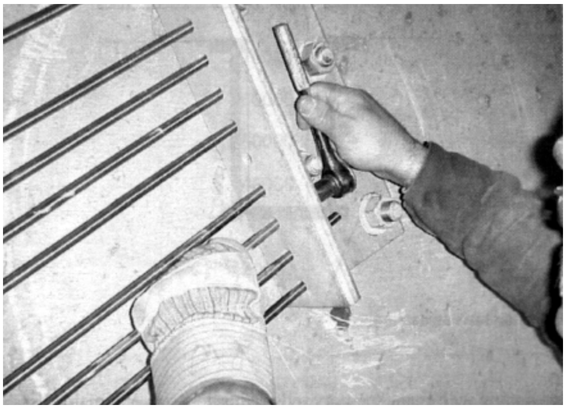


Figure 10.
Assembly of SMA rods for external strengthening of a bridge (taken from [14])

3.2. Worldwide Laboratory Projects

As early as at the beginning of the 1990's basic research in the field of damping civil structures with SMA dampers were published. In [15], NiTi was successfully used for the damping of seismic loads. Authors in [16] used copper (Cu) based SMA (CuZnAl) for torsion, bending and tension dampers incorporated in bracings.

Two past large international research programs on SMAs in relation to civil engineering are important to mention: Firstly, the "MANSIDE" project which ran from 1995 to 1999. "MANSIDE" stands for "Memory Alloys for New Seismic Isolation and Energy Dissipation Devices". Research on material behavior and modeling of SMAs was conducted. Seismic isolators and energy dissipating braces where developed, produced and lab tested. A comparison with other strategies for the attenuation of seismic vibrations was carried out. NiTi was found to be the most suitable material for the damping of seismic loads [17]. Furthermore, almost at the same time, between 1996 and 1999, the "ISTEC" project was carried out. The acronym stands for 'Development of Innovative Techniques for the Improvement of Stability of Cultural Heritage, in particular Seismic Protection'. This project focused on the development and exploration of SMA devices with superelastic behaviour with regard to the retrofitting of masonry structures [10]. Within this framework two examples of retrofitting historical structures were actually realized (see section 3.1).

The review in [7] gives detailed information on application concepts and testing up to 2005. Building up on [7], an overview of more recent laboratory projects concerning use of SMAs in civil engineering is given in the following. Fig. 11 illustrates research trends, as they are displayed by objectives and results of laboratory projects published. Different SMA features, superelasticity, martensite variant reorientation, shape memory effect, and dependence of electrical resistance on strain, lead to a number of potential applications.

The use of superelastic SMA reinforcement for deformation recovery of reinforced concrete (RC) beams was looked at in [18]. Simple beams were reinforced either with steel plus additional SMA tendons or with SMA tendons only. It is noteworthy that strands made up of 14 NiTi wires of diameter 0.75 mm were used as tendons. The SMA tendons were posttensioned before loading. Residual displacement of the beams, when being subjected to cyclic bending load beyond cracking, was looked at to compare the two reinforcement variants. It was concluded that the pure SMA reinforcement was able to recover large deformations after load removal. However, this was not the case for the combined reinforcement of steel and SMA, as plastic elongation of the steel almost fully hindered the recovery.

Based on a similar approach, [19] discusses the superelastic behavior of NiTi SMA when used as reinforcement in concrete beams. Small-scale concrete beams, with NiTi reinforcement were tested under half-cycle loads. The reinforcement ratio varied from 0.1 to about 0.9%. The experimental results showed that the average residual displacement in the NiTi reinforced beams was less than one-fifth of that of the steel reinforced test beams. The stiffness of NiTi reinforced test beams however was lower than those of the steel reinforced test beams. An analytical study of load-deflection relationship for a series of hybrid beams was undertaken. It was found that a hybrid system that incorporated NiTi combined with high strength steel or carbon fiber reinforced plastic bars was a better choice for design because of their relatively high stiffness.

Another example for passive damping by SMA technology is given in [20]. It is proposed to use superelastic SMA spring dampers for vibration mitigation of stay cables. The parameters in numerical and experimental investigations of a scaled down cable model were damper location and damper stiffness. The single damper consisted of three helical springs made of NiTi wire with 0.6 mm diameter. It was concluded that the spring damper slightly increases the modal frequencies and significantly enhances the damping capacity for the first few modes.

Several recent studies promote SMA based devices for use within bracings of steel frames or masonry walls to improve seismic resistance. Based on results of e. g. [16] also copper based SMAs come into question for passive damping. In consideration of the lower costs of copper based SMAs as compared to that of high performance NiTi alloys, this is of high interest for the building industry. E.g. in [21], superelastic copper-aluminum-beryllium (CuAlBe) wires of diameter 0.5 mm were used for damping devices, incorporated in bracings of a scale model of a three storey steel rigid frame structure. In comparison to the bare rigid structure, the peak acceleration and peak displacement of the SMA damped model reduced to near 60%.

A number of laboratory experiments were carried out with regard to prestressing of RC beams, e.g. [22], [23], [24] and [25]. All of them confirm the basic feasibility of prestressing concrete by SMA tendons.

Difficulties of achieving permanent prestressing are described in [22]. The often reported loss in tendon force upon cooling down to ambient temperature after thermal activation of shape memory effect is most likely caused by improper transformation temperatures of the SMA. Another potential reason is so called stress induced martensite formation of the SMA [7].

In [24] the behavior of concrete beams, actuated by embedded shape memory alloy wires, is investigated. NiTi SMA wires were used. Electrical power was used to heat the SMA wires. The experimental results indicate that a large recovery force in the concrete beam could be obtained when the SMA wires were heated and, accordingly, the SMA wires could be used as actuators to change the deflection of a concrete beam.

Besides most of the studies that use rather small specimen, SMA prestressed RC beams with almost 20 meter span were investigated in [25]. For the first time, full scale SMA strands were applied for experiments. The six NiTi SMA strands, each consisting of seven parallel wires of 5 mm diameter, were used without bond to concrete in series with conventional steel strands. The length of the SMA section was thus only 3.5 meter. Deflection of the beams and tendon forces could be controlled by electrical current. Despite the known limitations of thermal activation and deactivation rate for SMA rods, the aim of this work is to establish an adaptive prestressing concept for bridges. The prestressing is meant to be activated in case of high traffic loads like heavy trucks. The shortest activation time measured was about 5 minutes. Based on the test result and given equation in [7], activation time is always in the range of minutes for full scale dimensions of SMA rods. Deactivation time must be even longer, caused by inertia of heat transfer.

Following the proposal in [7], authors in [26] report from their experimental results, where concrete cylinders were confined using martensite shape memory alloy wires. Shape memory effect was activated by a heating jacket. The resulting confining pressure caused an increase in strength and ductility of the cylinder under axial compressive load. From the published abstract, it was not clear, if the increase in ductility is relative to the unconfined cylinders or relative to the unstressed confined samples. In this study, SMA wire of 1mm diameter was used for confinement. The cylinders had the length of 300 mm and the diameter of 150 mm. After being compressive loaded, the cylinder was bulged and the SMA wire was strained. At this state, the wrapped cylinder was heated by the heating jacket. Then, a portion of the

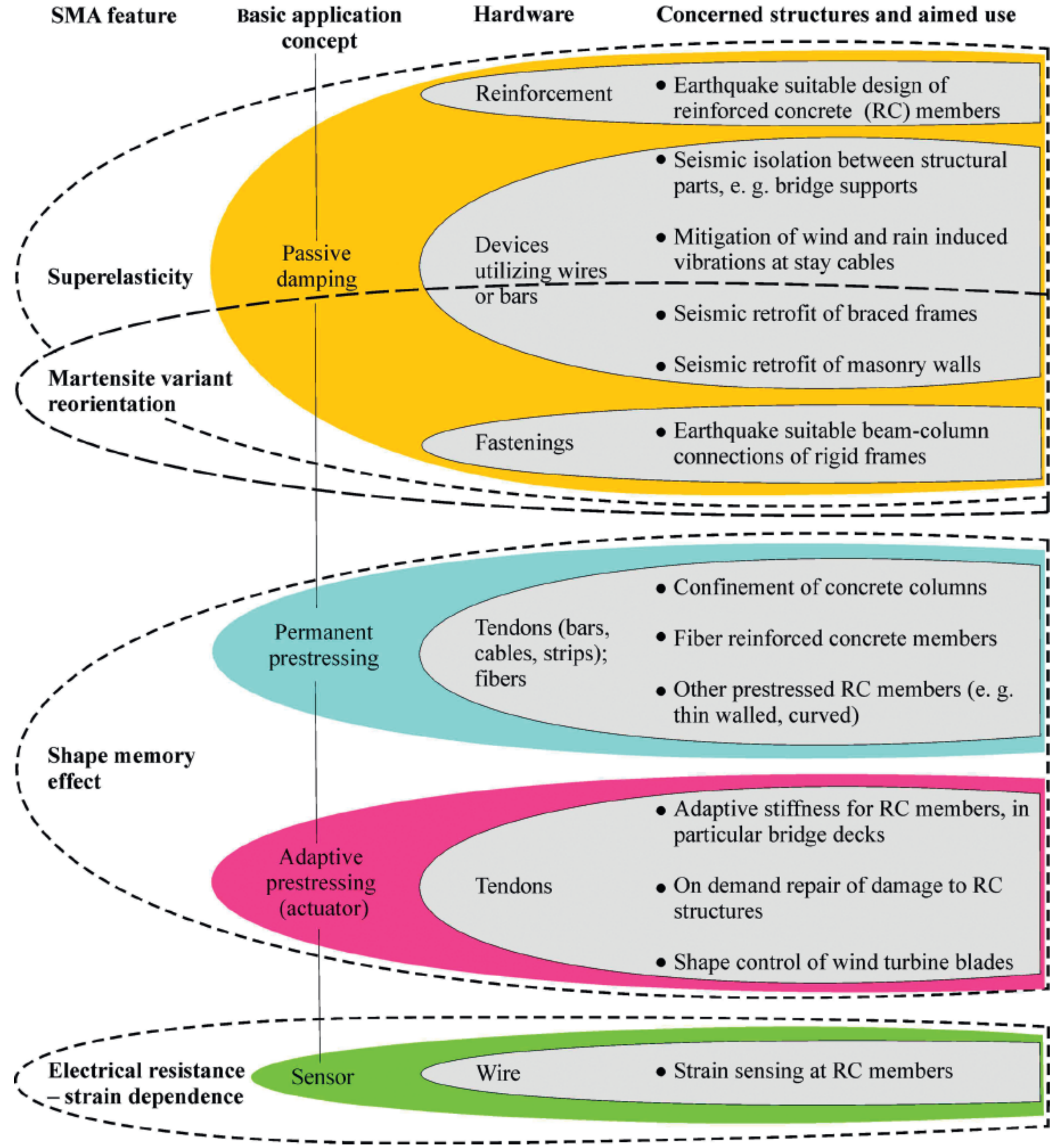


Figure 11.
Overview of potential SMA applications in civil engineering structures, as displayed in recent research

bulge of the cylinder was recovered and the cylinder showed good strength and ductility in the second compressive test.

The utilisation of the electrical resistance – strain dependence of e.g. NiTi SMA for estimation of crack width was recently experimentally treated in [27].

3.3. Laboratory Projects at Empa

3.3.1. RC Beams reinforced with SMA rebars

A concrete beam reinforced with shape memory alloys (SMA) wires was tested and compared with a conventionally reinforced concrete (RC) beam, see [28] and [29]. It was possible to vary pre-stress, stiffness and strength of the SMA beam.

A purpose of the study was to determine whether it is possible to combine SMA wires with concrete in order to achieve an adaptive structure that has the potential to react to a changing environment. The further aim was to obtain valuable experience regarding the behavior and practical application of SMAs. For the tests, NiTi (Nickel/Titanium) wires approximately 4.3mm in diameter were used to reinforce the underside of a concrete beam with a span of 1.14m (Fig. 13). To improve the bond behavior, the surfaces of the SMA wires were sand-blasted and coated with quartz sand using an epoxy adhesive. The temperature in the NiTi wires was increased by electrical resistance heating.

The green line in Fig. 12 shows the load-deflection behavior of the conventionally reinforced reference beam. Several deformation cycles were performed on the test beam reinforced with SMA wires (beam SMA) to investigate the variable load-deflection behavior (Fig. 12). The first deformation cycle (blue curve), with heated SMA wires, produced a distributed crack pattern. Deformation cycles no. 2 to 4 (red curves) were carried out to demonstrate the memory effect. That is, after deforming the beam at room temperature, the wires were heated beyond their phase transformation temperature to bring the beam back to the approximate level of deformation at the start of the cycle. During cycles no. 5 to 7 (pink curves) the SMA wires were heated, thereby illustrating the change in beam behavior due to higher SMA wire stiffness and strength. Cycles no. 8 and 9 (turquoise curves) were performed to determine how much load can be mobilized using the shape memory effect of the SMAs. Once the beam had been subjected to large deformations in the cold state, the SMA wires were heated and the deformation of the beam was held approximately constant, consequently causing the load increase.

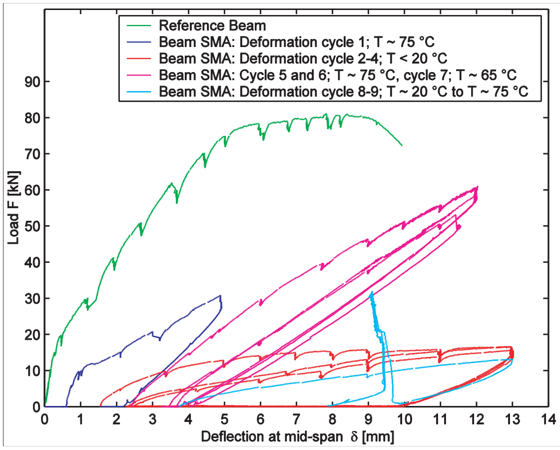


Figure 12.
Test cycles on the test beams (taken from [28])

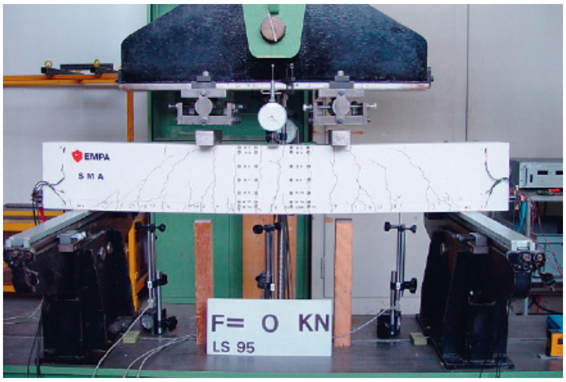


Figure 13.
Beam reinforced with SMA wires in the test set-up (taken from [28])

The test results proved that by using coated SMA wires it is possible to produce a RC beam with variable stiffness and strength. The tests also showed that a pre-stress in the SMA wires could be achieved by using the shape memory effect.

3.3.2. SMA Short Fibre Reinforced Cement Based Material

The addition of steel fibers to building materials is common practice where increased fracture energy is needed. So far, the introduction of meso-scale pre-stress in a fiber reinforced building material, FRC (an evolution similar to the step from RC to pre-stressed RC, as schematically shown in Fig. 14) could not be realized, missing a technical solution for pre-stressing short fibers embedded in a material.

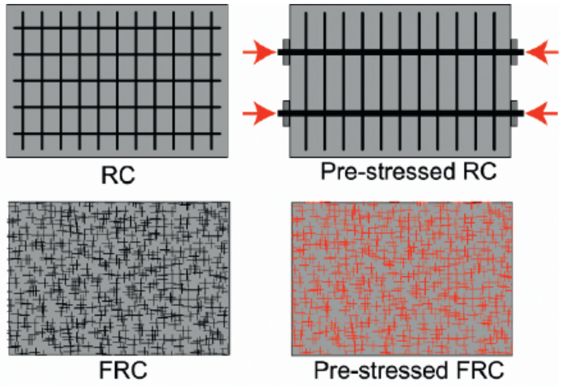


Figure 14.
Pre-stressed FRC

In the study ([30] and [31]) shape memory alloy (SMA) wires were embedded in mortar. The wires had been shaped by inelastic elongation into loop- and star-shaped fibers, as shown in Fig. 15 and 16, in order to demonstrate the feasibility of pre-stressed fiber reinforced concrete. The shape of the fibers was chosen so as to minimize loss in pre-stressing due to the fiber anchorage length and to optimize the small scale production process.

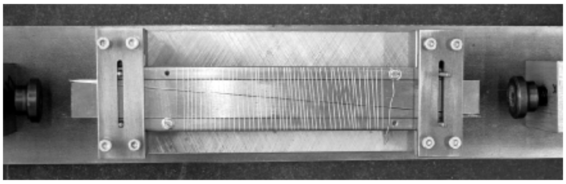
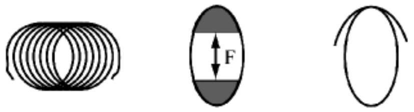
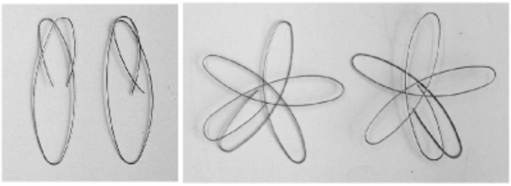


Figure 15.
Device used for pre-deformation of small batches of fibers (taken from [31])



a) schematic procedure



b) loop-fibers c) star-fibers

Figure 16.
Production of loop- and star-fibers from annealed wire coils (taken from [31])

After hardening of the mortar, the specimens were heated up in order to activate the tensile stress in the fibers, thereby causing a pre-stress of the surrounding mortar. The effect was monitored by length measurements both on specimens with and without fibers, as shown in Fig. 17.

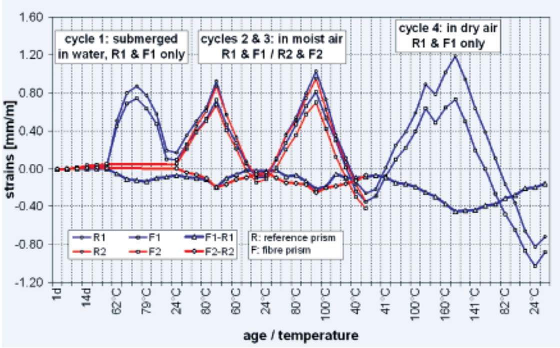


Figure 17.
Strains of mortar prisms during temperature cycles (taken from [31])

Compression stresses in the cement mortar were estimated by multiplying the difference in strain between fiber-reinforced and reference prisms by the Young's modulus of the matrix. Thus, compression of some 6 MPa was reached in the experiments. It was concluded that for practical applications, alloys with suitable temperature domains of austenitic and martensitic transformation, most likely Fe-based, and efficient methods for the production of such fiber mortars are to be developed. A practical application of such internally pre-stressed cement based materials is envisioned in repair mortars, in which the differences in hygro-thermal histories of the freshly applied mortar layer and the pre-existing substrate can lead to the formation of shrinking induced cracks [32]. The application of compressive stresses to the matrix may help overcome this problem. This approach will help meet the need for crack free rebar cover for the rehabilitation of reinforced concrete structures.

3.3.3. Prestressed column wrapping

Confinement can be used for post-strengthening of reinforced concrete columns. This is of particular interest for earthquake regions. However, the conventional unstressed wrapping of columns, by fiber reinforced polymers or steel belts, suffers the following shortcomings: activation of confinement action for post-strengthening purposes depends on additional loads over and above the column's already existing load level. This is a problem for highly uti-

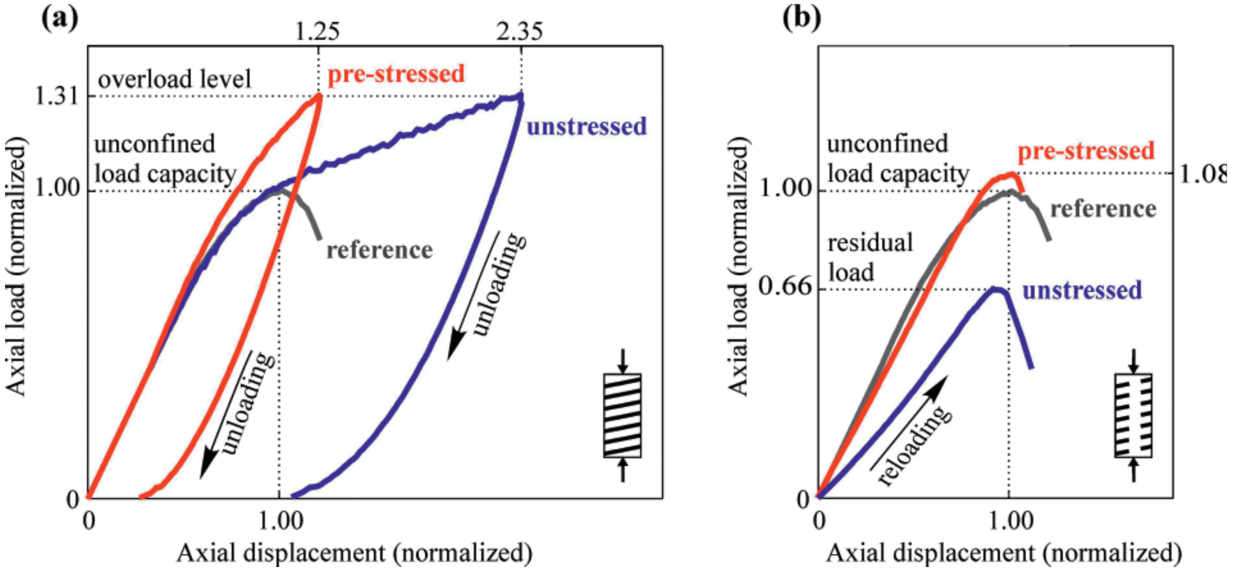


Figure 18.
Typical load-deformation behavior of concrete cylinders strengthened by prestressed vs. unstressed confinement: (a) when being subjected to overload in confined state and (b) for unconfined reloading after preceding overload in confined state

lized columns. Furthermore, it was shown that concrete residual load capacity is reduced significantly for unstressed confined concrete columns after they have been subjected to overload (Fig. 18). However, residual load capacity is important as it is understood to be the load which can be absorbed in case of ineffective or damaged confinement by a column previously subjected to high loading in a confined state.

Developing the proposal in [7], prestressed confinement is investigated as a method to overcome these shortcomings. Recent experiments, conducted at the Structural Engineering Research Laboratory of Empa, Switzerland, confirmed a significant increase in concrete residual load capacity, caused by confinement prestressing [33]. Fig. 18 shows typical load-deformation behavior measured at 600 mm high concrete cylinders with 150 mm diameter. Unstressed and prestressed cases were compared.

These results give reason to further development of low cost SMAs, as SMA technology is a highly potential pre-stressing method for continuous wrappings.

3.4. Development of a New Generation of Iron Based SMAs at Empa Switzerland

The proof of concept projects presented in sections 3.3.1 and 3.3.2 was carried out using NiTi Shape Memory Alloys. These alloys are generally used in applications with a relatively high value density (expressed in €/cm^3 or USD/cm^3), such as biomedical, automotive, aero-space or the special civil engineering applications in which very small amounts of alloy are needed. High volume applications, such as the ones described in sections 3.3.1 and 3.3.3 can only be successful for practical purposes, if the price of the alloy is of the order of the price of steel (i.e. 1-2 USD/kg). So far, given the cost of the raw materials (Nickel and Titanium) and the additional production costs, Nickel-Titanium based alloys do not seem to be very promising candidates. Additionally, standard NiTi alloys available off-the-shelf do not present phase transformation temperatures that match perfectly the requirements set by the applications. Further optimisation would be needed, in order to obtain alloys with suitable properties. On the other hand, Iron based SMA (FeSMA) are more likely to be available at prices that are compatible with market expectations, but so far the phase transformation temperatures Af and As were in the region of 250°C and above. Such temperatures are not compatible with applications including cement based matrices.

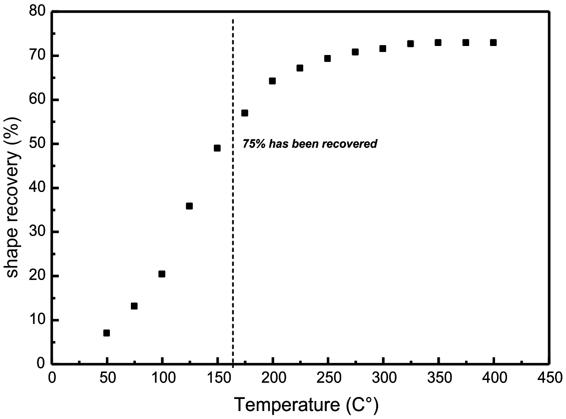


Figure 19.
Degree of shape recovery for one of the investigated Iron based shape memory alloys at Empa Switzerland

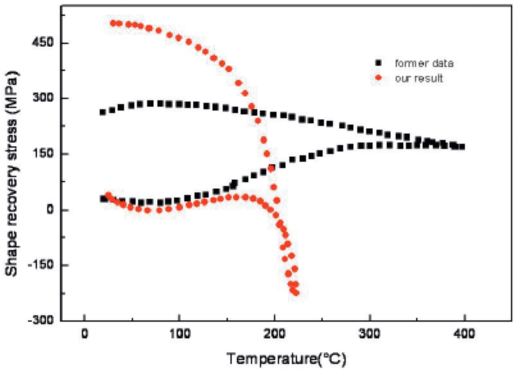


Figure 20.
The stress vs. temperature diagram for a newly developed and an existing FeSMA shows the generation of higher stresses at lower temperatures

The FeSMA development project at Empa Switzerland yielded a new alloy with lower transformation temperatures that are expected to be compatible with the cement based matrix. Higher shape recovery stresses than in previously developed FeSMA were also observed [34].

4. CONCLUSIONS

Although SMAs have been known for decades, they have not been used much in the building industry until rather recently probably due to their cost, low elasticity modulus and to limited knowledge of the material in the civil engineering industry.

In this paper several field applications of SMA materials were presented such as retrofitting of San Francesco at Assisi and Church of San Giorgio in Trignano, Italy, where the superelastic behaviour and damping effects of SMA were used. A cracked highway bridge girder was repaired by SMA rods using the recovery stress of the SMA rods. Furthermore, a number of laboratory projects was presented that illustrate the potential of this material in the field of civil engineering. A concrete beam reinforced with SMA wires was tested and compared with a conventionally reinforced concrete beam. It was possible to vary pre-stress, stiffness and strength of the SMA beam. Also in the field of pre-stressed confinement of concrete columns, as well as pre-stressed short fiber reinforced concrete, SMAs have shown a great potential.

Particularly in large scale applications low cost SMAs is required. Iron based alloys are an example of potential low cost SMAs. The FeSMA development project at Empa Switzerland yielded a new alloy with lower transformation temperatures that are expected to be compatible with the cement based matrix. Higher shape recovery stresses than in previously developed FeSMA were also observed. The project is ongoing and further material optimizations are planed.

REFERENCES

[1] *Buehler W.J., Wang F.E.*; A Summary of Recent Research on the Nitinol Alloys and Their Potential Application in Ocean Engineering. Journal of Ocean Engineering, 1967. 1; p.105-120

[2] *Helm D.*; Formgedächtnislegierungen: Experimentelle Untersuchung, phänomenologische Modellierung und Numerische Simulation der thermomechanischen Materialeigenschaften, PhD Thesis in German, in Institut für Mechanik., Universität Gesamthochschule Kassel, Kassel, 2001

[3] *Fugazza D.*; Shape Memory Alloy Devices in Earthquake Engineering: Mechanical Properties, Constitutive Modelling and Numerical Simulations, Msc Thesis. Universita Degli Studi Di Pavia, Rose School, European School of Advanced Studies in Reduction of Seismic Risk, Pavia, 2003

[4] *Fischer H., Welle B.V.A.*; Applications of Shape Memory Alloys in Medical Instruments. Minimally Invasive Therapy & Allied Technologies. 13(4), 2004; p.248-253

[5] *Mertmann M.*; Non-Medical Applications of NITI-NOL. Minimally Invasive Therapy & Allied Technologies. 13(4), 2004; p.254-260

[6] *Kubo H., Maruyama T.* ; Densizairyo, 2002(4); p.56

[7] *Janke L., Czaderski C., Motavalli M., Ruth J.*; Applications of Shape Memory Alloys in Civil Engineering Structures – Overview, Limits and New Ideas. Materials and Structures. 38(5), 2005; p.578-592

[8] *Castellano M.G.*; Innovative Technologies for Earthquake Protection of Architectural Heritage. in International ICOMOS Congress, Bethlehem, Palestine, 2000

[9] *Castellano M.G.*; Development and Experimental Characterization of Shape Memory Alloy Devices. in Final Workshop of ISTECH Project. Ispra, Italy, 2000

[10] European-Commission-JRC. Shape Memory Alloy Devices for Seismic Protection of Cultural Heritage Structures. in Final Workshop of ISTECH Project. 2000. Ispra, Italy

[11] *Indirli M.*; The Demo-Intervention of the ISTECH Project: The Bell-Tower of S. Giorgio in Trignano (Italy). in Final Workshop of ISTECH Project. Ispra, Italy, 2000

[12] *Azevedo J., Sincraian G.*; Numerical Models of Masonry Structures with and without SMADs – Using the Discrete Element Method. in Final Workshop of ISTECH Project. Ispra, Italy, 2000

[13] *DesRoches R., Smith B.*; Shape Memory Alloys in Seimsic Resistant Design and Retrofit: A Critical Review of their Potential and Limitations. Journal of Earthquake Engineering. 7(3), 2003; p.1-15

[14] *Soroushian P., Ostowari K., Nossoni A., Chowdhury H.*; Repair and Strengthening of Concrete Structures through Application of Corrective Posttensioning Forces with Shape Memory Alloys. Transportation Research Record, 2001(1770); p.20-26

[15] *Graesser E.J., Cozzarelli F.A.*; Shape Memory Alloys as new Materials for Seismic Isolation. Journal of Engineering Mechanics ASCE, 117(11), 1991; p.2590-2608

[16] *Wittig P.R., Cozzarelli F.A.*; Shape Memory Structural Dampers: Material Properties, Design and Seismic Testing. in Technical Report NCEER-92-0013 (State University of New York at Buffalo), 1992

[17] Brite-Euram-Manside-Project, Memory Alloys for New Seismic Isolation and Energy Dissipation Devices - Final Project Workshop. 1999, Rome, Italy

[18] *Li H.-N., Cui D., Song G., Mo Y.L.*; Experimental Investigation on Self-Rehabilitation of Intelligent Concrete Beams Reinforced with Superelastic Shape Memory Alloys. in Earth and Space 2006 – Proceedings of the 10th Biennial International Conference on Engineering, Construction, and Operations in Challenging Environments. Houston, 2006

[19] *Saiidi M.S., Sadrossadat-Zadeh M., AyoubC., Itani A.*; Pilot Study of Behavior of Concrete Beams Reinforced with Shape Memory Alloys. Journal of Materials in Civil Engineering, June 2007. 19(6); p.454-461

[20] *Liu M., Li H., Song G., Ou J.*; Investigation of Vibration Mitigation of Stay Cables Incorporated with Superelastic Shape Memory Alloy Dampers. Smart Materials and Structures, 16(6), 2007; p.2202-2213

[21] *Cerda M., Boroschek R., Farias G., Moroni O., Sarrazin M.*; Shaking Table Test of a Reduced-Scale Structure with Copper-Based Energy Dissipation Devices. in 8th U.S. National Conference on Earthquake Engineering. San Francisco, California, 2006

[22] *El-Tawil S., Ortega-Rosales J.*; Prestressing Concrete Using Shape Memory Alloy Tendons. ACI Structural Journal. 101(6), 2004; p.846-851

[23] *Li H., Liu Z.-Q., Ou J.*; Behavior of a Simple Concrete Beam Driven by Shape Memory Alloy Wires. Smart Materials and Structures. 15, 2006; p.1039-1046

[24] *Denga Z., Lib Q., Suna H.*; Behavior of concrete beam with embedded shape memory alloy wires. Engineering Structures, October 2006. 28(12); p.1691-1697

[25] *Li L., Li Q., Zhang F.*; Behavior of Smart Concrete Beams with Embedded Shape Memory Alloy Bundles. Journal of Intelligent Material Systems and Structures,. 18(10), 2006; p.1003-1014

[26] *Choi E., Baik-Soon C., Young-Soo C., Tae-Hiun N.*; Confining Concrete Cylinders using Martensite Shape Memory Alloy wires. in E-MRS Fall Meeting 2007, Symposium E. September 17-21, 2007. Warsaw University of Technology, Poland

[27] *Song G., Mo Y.L., Otero K., Gu H.*; Health Monitoring and Rehabilitation of a Concrete Structure using Intelligent Materials. Smart Materials and Structures. 15, 2006; p.309-314

[28] *Czaderski C., Hahnebach B., Motavalli M.*; RC beam with variable stiffness and strength. Journal of Construction and Building Materials. 20(9), 2006; p.824-833

[29] *Hahnebach B*.; Formgedächtnislegierungen für adaptive Tragwerke, Master Thesis in German, in Fakultät Bauingenieurwesen. Bauhaus-Universität Weimar and Empa Switzerland: Weimar, Germany and Dübendorf, Switzerland; 2003

[30] *Bergamini A., Moser K., Christen R.,Czaderski C*.; Innerlich vorgespannter zementgebundener Baustoff und Verfahren zu seiner Herstellung, Patent Number 01935/04, in Empa Switzerland, S. Patentanmeldung, Editor, Switzerland, 2004

[31] *Moser K., Bergamini A., Christen R.,Czaderski C*.; Feasibility of Concrete Prestressed by Shape Memory Alloy Short Fibers. Materials and Structures,. 38(5), 2005; p.593-600

[32] *Martinola G*.; Rissbildung und Ablösung zementgebundener Beschichtungen auf Beton, in Institute for building materials. ETH: Zurich, 2000; p.497

[33] *Janke L., Czaderski C., Ruth J., Motavalli M*.; Experiments on the residual load-bearing capacity of prestressed confined concrete columns. Engineering Structures. 31(10), 2009; p.2247-2256

[34] *Dong Z., Klotz U., Leinenbach C., Bergamini A., Czaderski C., Motavalli M*.; A Novel Fe-Mn-Si Shape Memory Alloy With Improved Shape Recovery Properties by VC Precipitation. Advanced Engineering Materials. 11(1-2), 2009; p.40-44