

# Recent Advancements in Development and Application of an Iron-based Shape Memory Alloy at Empa

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**Abstract:** The Fe-SMA developed at the Swiss Federal Laboratories for Materials Science and Technology (Empa) has an alloy composition of Fe–17Mn–5Si–10Cr–4Ni–1(V,C) and exhibits an excellent shape memory effect on heating at 160 °C or above. The shape memory effect feature equips Fe-SMA with a unique self-prestressing ability that can be exploited for many civil engineering applications. In addition to the self-prestressing ability, Fe-SMA has a high elastic modulus (165 GPa), low cost, and high machinability compared to the nickel and copper-based SMAs, which makes it more suitable for structural applications. The current work provides an overview of the recent advancements in the research and development of Fe-SMA at Empa. To this end, the advancements related to the material development, applications of Fe-SMAs in prestressing reinforced concrete (RC) and metallic structures, and the introduction of Fe-SMA reinforcements to the market along with some recent field applications are presented. The paper concludes with an overview of the opportunities and challenges associated with using Fe-SMA reinforcements in civil infrastructure.

**Keywords:** Concrete structures · Recovery stress · Shape memory alloys (Fe-SMAs) · Steel structures · Structural strengthening



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**Dr. Elyas Ghafoori** and his team are working on engineering solutions and the basic knowledge that can be utilized to increase the sustainability index of steel structures. The research topics are mainly related to applications of FRP composites, shape memory alloys, structural adhesives, and metal additive manufacturing techniques.



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## 1. Introduction

Shape memory alloys (SMAs) belong to the family of smart materials that can respond to any changes in their condition by external stimuli (*i.e.* stress, temperature). These characteristics enable SMAs to exhibit unique properties, including superelasticity and shape memory effect, due to which they can recover inelastic deformations upon unloading (superelasticity) and heating (shape memory effect).<sup>[1,2]</sup> Among the available SMAs, nickel- and copper-based SMAs generally show excellent superelasticity, whereas iron-based SMAs (Fe-SMAs) exhibit a stable shape memory effect.

The Fe-SMA developed at the Swiss Federal Laboratories for Materials Science and Technology (Empa) has an alloy composition of Fe–17Mn–5Si–10Cr–4Ni–1(V,C), and exhibits an excellent shape memory effect on heating at 160 °C or above. This shape memory effect equips Fe-SMA with a unique self-prestressing ability that can be exploited for many civil engineering applications. The stress-strain behavior of Fe-SMA in comparison with different strengthening materials such as the structural steel (*e.g.* S355 and S275) and normal modulus CFRP composites is shown in Fig. 1. A detailed comparison between the fatigue behavior, creep and relaxation, corrosion resistance, thermal compatibility and fire behavior of these materials can be found in ref. [3].

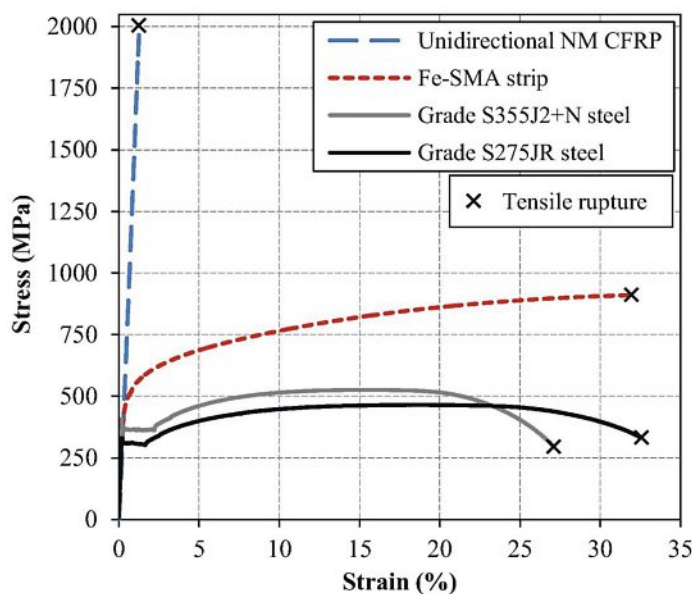


Fig. 1. Stress–strain behavior of various strengthening materials in comparison with structural steel. Reprinted from *Construction and Building Materials* 2019, 226, 976 Copyright (2019), with permission from Elsevier.

The self-prestressing of Fe-SMA can be achieved by preventing the recovery of inelastic strains during the heating stage by using clamps and/or end anchorages.<sup>[4,5]</sup> As a result, recovery stress of up to 300–400 MPa can be generated upon heating Fe-SMA in the temperature range of 160 °C–300 °C.<sup>[6]</sup> In addition to the self-prestressing ability, Fe-SMA has a high elastic modulus (165 GPa), low cost, and high machinability compared to the nickel- and copper-based SMAs, which makes it more suitable for civil engineering applications.

The prestressing of civil structures using Fe-SMA requires two actions: pre-straining and activation, as shown in Fig. 2 (left panel). At first, the Fe-SMA reinforcement is generally pre-strained to 2–4% and then unloaded. This is followed by the activation stage, which involves heating to the target temperature and

then cooling back down to ambient temperature while the reinforcement is clamped/fixed/anchored to the structure. This generates recovery stress in the Fe-SMA reinforcement (refer to the right panel in Fig. 2), which subsequently prestresses the parent substrate. After that, the material exhibits the stress-strain behavior on service loading as shown in the left panel in Fig. 2. It is worth noting that prestressing of the civil structures can be accomplished more conveniently using Fe-SMA reinforcement than the conventional prestressing methods, which require the use of heavy mechanical equipment and, therefore, are cumbersome and inefficient.

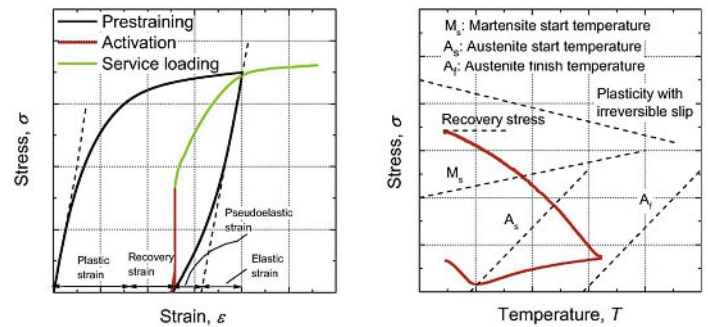


Fig. 2. Left: Schematic illustration of application of Fe-SMA for prestressing; Right: Schematics of activation and recovery stress development. Reprinted from *Construction and Building Materials* 2018, 173, 586. Copyright (2018), with permission from Elsevier.

With this background about the unique properties of Fe-SMA, this paper aims to provide an overview of the recent advancements in the research and development of an Fe-SMA at Empa. The advancements related to the material development are presented in the next section, followed by a brief description of the applications of Fe-SMAs in prestressing reinforced concrete (RC) and metallic structures. Introduction to the market with field applications of Fe-SMA are then presented towards the end. Finally, the paper concludes with an overview of the opportunities and challenges associated with using Fe-SMA reinforcements in civil infrastructure.

## 2. Advances in Material Development

Fe-SMA rebars and strips have been characterized extensively.<sup>[6–12]</sup> More recent efforts are focused on characterizing the behavior of Fe-SMA wires, which can be produced from the rebars. These wires can be utilized to manufacture prestressed fiber-reinforced concrete and active confinement purposes. Apart from wire manufacturing and investigation, the Fe-SMA's material development-related research work at Empa has three main thrusts. These include a) the development of an ultra-high Fe-SMA with superior mechanical properties, b) the development of a pseudo-elastic Fe-SMA with higher recoverable strains, and c) additive manufacturing of Fe-SMA. The following subsections will present a brief overview of the ongoing research on these topics.

### 2.1 Ultra-high Fe-SMA

The yield strength and recovery stress of conventional Fe-SMA when heated are less than 350 MPa. It is, therefore, essential to increase the Fe-SMA's yield strength and recovery stress to make it more competitive with traditional prestressing materials (*i.e.* steel strands, tendons, *etc.*). For this purpose, the current research efforts at Empa are focused on the development of an ultra-high Fe-SMA that has superior properties to conventional Fe-SMA. Currently, investigations are underway to study the effect of various types of heat treatments, with different aging temperatures and durations, on the recovery stress behavior of

Fe-SMA. In addition, modifications in the alloy composition are also being considered to improve the recovery stress behavior. Preliminary investigations<sup>[13]</sup> have revealed that aging at 600 °C for 144 hours can generate recovery stress of up to 500 MPa at the activation temperature of 160 °C, which essentially is 70% higher than the recovery stress of the as-received material.

## 2.2 Pseudoelastic Fe-SMA

The current composition of Fe-SMA exhibits little pseudoelasticity. For instance, the pseudoelastic strain of the ribbed Fe-SMA rebar is about 0.1% at a 4% prestrain level. This makes the current composition of Fe-SMA unsuitable for applications that require superelastic behavior. To address this issue, recent research efforts at Empa aim to improve the pseudoelasticity of the Fe-SMA by using different alloy treatments, including heat treatment and aging. The results of the preliminary investigations conducted in this regard are promising and show a fourfold increase in the pseudoelastic strains when Fe-SMA rebar is aged at 750 °C for 6 hours.

## 2.3 Additively Manufactured Fe-SMA

Additive manufacturing of Fe-SMA is another promising area where research is being carried out at Empa. The Laser Powder Bed Fusion technology<sup>[14]</sup> has been employed in a recent study to produce additively manufactured Fe-SMA. The results of the preliminary investigation are promising and show that the additively manufactured Fe-SMA exhibits superior pseudoelasticity and shape memory effect compared to Fe-SMA manufactured using conventional methods. Further to this, such proof-of-concept study demonstrates that Laser Power Bed Fusion technology can be used to fabricate Fe-SMA's in complex geometries with good dimensional accuracy. This development can potentially open up new promising avenues for the application of Fe-SMA.

## 3. Recent Developments in Prestressing Civil Structures with Fe-SMA

Fe-SMA rebars and strips have been used extensively for prestressing concrete and metallic structures. This section summarizes the recent developments in the application of Fe-SMA reinforcements for civil structures.

### 3.1 Concrete Structures

In the recent past, the effectiveness of Fe-SMA reinforcement in prestressing concrete structures has been evaluated for applications involving the flexural and shear strengthening of beams and slabs. Nowadays, the effectiveness of prestressed Fe-SMA reinforcement is being explored for other innovative applications such as self-centering of concrete columns and prestressing of 3D printed concrete. A brief overview of the investigations carried out at Empa to explore the various applications of Fe-SMA for concrete structures is provided below.

#### 3.1.1 Flexural Strengthening of Beams and Slabs

In past studies, Fe-SMA has been used in the form of near-surface mounted (NSM) strips<sup>[15]</sup> and embedded rebars (ribbed) in a shotcrete layer<sup>[16]</sup> for the flexural strengthening of RC beams, as shown in Fig. 3. In these studies, the thermal activation of Fe-SMA (at 160 °C) was accomplished using electric resistive heating. The experimental results showed a significant increase in the cracking strength and a notable reduction in the mid-span deflection of the strengthened beams.

More recently, ribbed Fe-SMA rebars were installed as NSM reinforcement for the flexural strengthening of RC bridge decks,<sup>[17]</sup> as shown in Fig. 4. It was observed that the strengthened slabs exhibited a significant improvement in load capacity and ductility compared to the reference slabs.



Fig. 3. Flexural strengthening of RC beams using Fe-SMA: (a) near-surface mounted strips; (b) Fe-SMA rebars, which will be embedded in mortar. Reprinted (Fig. 3a) from *Construction and Building Materials* **2016**, 112, 28. Copyright (2016), with permission from Elsevier, and (Fig. 3b) from *Engineering Structures* **2016**, 117, 263. Copyright (2016), with permission from Elsevier.

In addition, experimental investigations have been carried out to study the bond characteristics of NSM Fe-SMA rebars with concrete to determine an adequate anchorage as well as prestress transfer length for these rebars in the aforementioned prestressing applications.<sup>[18–21]</sup>

Besides cementitiously anchored bars, strengthening RC structures in bending can be performed through unbonded external strips. Anchoring is performed at the strip ends by means of direct mechanical fasteners, as shown in Fig. 5. Activated, hence prestressed, Fe-SMA strips induced a higher cracking load compared to slag applied CFRP strips as well as more ductile structural behavior with eventually crushing of the upper concrete zone in compression.

#### 3.1.2 Shear Strengthening of Beams

In a recent study, U-shaped Fe-SMA stirrups embedded in a mortar layer were used to strengthen large-scale shear-deficient bridge girders,<sup>[22]</sup> as shown in Fig. 6. The results showed a significant enhancement in the shear capacity of the beams due to the active confinement provided by the Fe-SMA stirrups. Furthermore, fewer cracks and smaller beam deflection were observed. It was also noticed that the stresses in the internal steel stirrups reduced significantly due to the inclusion of activated Fe-SMA stirrups.

#### 3.1.3 Self-centering of Columns

Self-centering is the ability of a structural element to regain its original undeformed configuration after extreme loading events

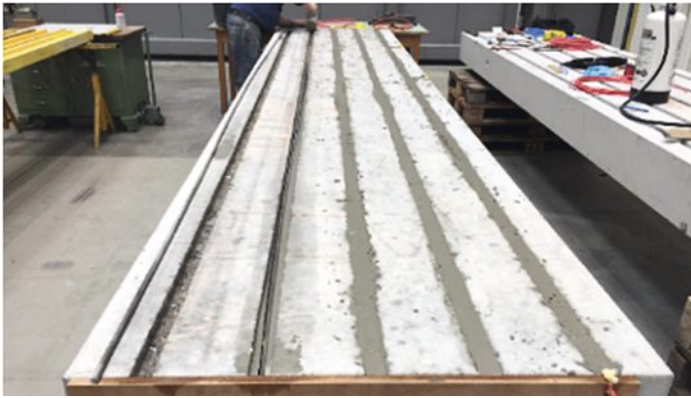


Fig. 4. Flexural strengthening of RC slabs using near-surface mounted Fe-SMA rebars. Reprinted from *Engineering Structures* 2021, 241, 112467. Copyright (2021), with permission from Elsevier.



Fig. 5. Flexural strengthening of RC slabs using externally unbonded Fe-SMA strips. Reprinted from *Structural Concrete* 2018, 19, 876. Copyright (2018), with permission from John Wiley and Sons.

(e.g. earthquakes). Currently, the feasibility of using prestressed Fe-SMA rebars to incorporate a self-centering behavior into existing RC bridge columns is under investigation at Empa. The proposed retrofitting method involves four steps: i) removal of the concrete cover, ii) installation and anchorage of Fe-SMA rebars into the top and bottom foundation, iii) activation, iv) embedment of Fe-SMA rebars in an additional shotcrete layer. It is expected that during an extreme loading event, the prestress of the Fe-SMA rebars will provide a restoring force to the column to return to its original position. This development is promising because currently, it is not possible to prestress existing bridge columns with traditional prestressing methods, owing to the involvement of heavy mechanical equipment (hydraulic jacks, end anchorages, etc.).

Other ongoing research efforts include the development of ultra-high-performance concrete prestressed with Fe-SMA fibers and a feasibility study on the integration of Fe-SMA reinforcement with 3D printed concrete. In addition, the bond behavior of Fe-SMA rebar with 3D printed concrete is also under investigation.



Fig. 6. Shear strengthening of RC beams using Fe-SMA: (a) u-shaped stirrups; (b) embedment in a mortar layer. Reprinted from *Construction and Building Materials* 2021, 274, 121793. Copyright (2021), with permission from Elsevier.

### 3.2 Metallic Structures

The application of Fe-SMA in metallic structures has mainly been in the area of fatigue and flexural strengthening. For instance, in a recently proposed fatigue strengthening solution, Fe-SMA strips were bonded to the cracked steel plates using adhesives, as shown in Fig. 7. A series of lap-shear tests of SMA-to-steel adhesively bonded joints were conducted using different structural adhesives.<sup>[23]</sup> The proof-of-concept study demonstrated a superior ability of prestressed Fe-SMA strips in retarding fatigue crack growth compared to CFRP strips.<sup>[24]</sup>

In another study,<sup>[25]</sup> mechanically end-anchored prestressed Fe-SMA strips were used for retrofitting double angle connections in a steel bridge, as shown in Fig. 8. The results showed a significant reduction in the bending stress at the connection owing to the prestress of Fe-SMA. A comparative study on the cost and performance of different Fe-SMA systems was conducted in ref. [3]. Based on this study, although the initial material cost of Fe-SMA is greater than that of CFRP composites, both systems (prestressed SMA and CFRP) would end up to almost the same cost. The reason is that prestressing CFRP needs a delicate anchorage system (because it is a brittle composite) while Fe-SMA requires only a simple anchorage system (because it is an isotropic ductile material with good weldability).<sup>[3]</sup>

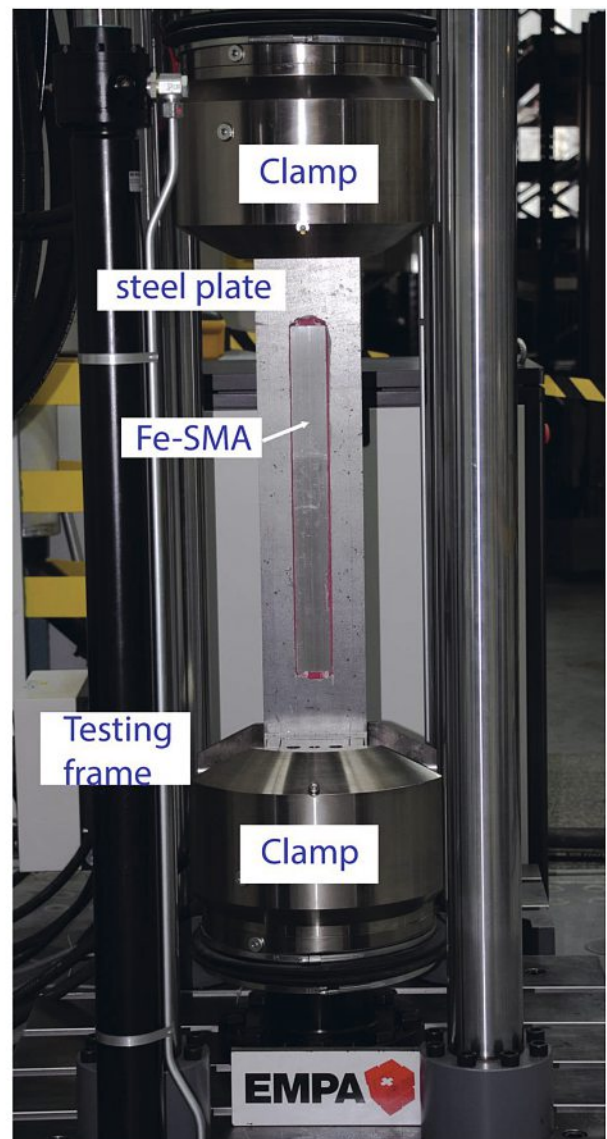


Fig. 7. Adhesively bonded Fe-SMA strips to steel plate. Reprinted from *International Journal of Fatigue* 2021, 148, 106237. Copyright (2021), with permission from Elsevier.

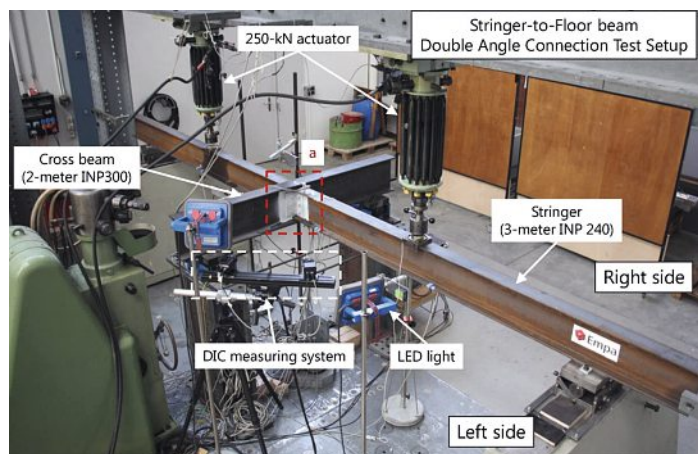


Fig. 8. Mechanically end-anchored Fe-SMA strips for retrofitting double angle connection. Reprinted from *Engineering Structures* 2021, 245, 112827. Copyright (2021), with permission from Elsevier.

#### 4. Finite Element Modelling of Fe-SMA Strengthened Structures

Few recent studies have employed finite element models to assess the potential of prestressed Fe-SMA in improving the structural behavior. The first numerical study to investigate the behavior of Fe-SMA strengthened structures was conducted by Abouali *et al.*<sup>[28]</sup> The cited study simulated the behavior of RC beams retrofitted with prestressed Fe-SMA strips, which were installed as NSM reinforcement. The concrete damaged plasticity and isotropic hardening models were used for defining the plastic behavior of concrete and Fe-SMA, respectively. The load-deflection behavior of the numerical model showed a good agreement with the previous experimental results. The results of the numerical simulation indicate that strengthening with Fe-SMA strips can lead to enhanced ductility and energy dissipation compared to strengthening with CFRP strips.

Dolatabadi *et al.*<sup>[29]</sup> developed finite element models of RC beams strengthened with prestressed Fe-SMA rebars embedded in a shotcrete layer. The models were validated with the experimental results of RC beams strengthened using this technique at Empa. The results of the parametric study revealed that prestressing with Fe-SMA can enhance the cracking and yielding load significantly. In contrast, the increase in the ultimate load capacity is only negligible. More recently, Rezapour *et al.*<sup>[30]</sup> used finite element simulations to study the seismic behavior of masonry walls strengthened with prestressed Fe-SMA strips. The results showed a 100% increase in stiffness compared to the reference wall. In addition, a significant increase in the strength and energy dissipation capacity was also observed.

#### 5. Field Applications

The first on-site applications of Fe-SMA took place in May 2017 in a carpentry storage in Switzerland by re-fer AG and contractor Stahlton. A strengthening was necessary due to the reconversion of the space (removal of a load carrying concrete wall) below a 24 cm thick reinforced concrete slab. Fe-SMA plates were applied in combination with CFRP strips, a steel beam and a steel column.<sup>[26]</sup> Since then, a large number of projects have followed in Switzerland and abroad.

In the field of re-plate, *i.e.* the mechanically end-anchored strips used for concrete strengthening, notable projects are an industrial building in Freienbach, a bridge in Mörschwil, a parking lot in Nussbaumen, or a hospital in Thun (photos can be found in Fig. 9). It is important to stress the easier fire protection for

re-plate compared to composite materials: investigations at Empa on the material behavior at elevated temperature have revealed a critical temperature of roughly 300 °C for Fe-SMA, hence clearly above glass transition temperature of commercially available epoxy resins. This implies that the fire protection can be performed with less invasive procedures, such as with a sprayed fire protection mortar. The efficiency of such a system has been recently tested with a large-scale setup at the MFPA Leipzig (Germany).



Fig. 9. Pilot application with re-plate in 2017 (left) and strengthening in a parking garage in Nussbaumen in 2020 (right)

Important milestones for applications with re-bar in combination with cementitious mortars were a shear strengthening in Baden, a flexural upgrading of concrete bridges near Basel and in Courrendlin as well as punching strengthening in a family house in Dättwil (photos can be found in Fig. 10). While most applications up to date were focused on the Swiss market, activities abroad with focus on the DACH region as well as the Benelux countries and France have started since late 2020.

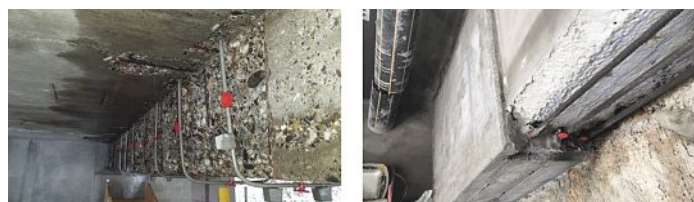


Fig. 10. Shear strengthening in a theatre building in Baden (photo shows the re-bar stirrups prior to sprayed mortar embedment, left), and bridge strengthening in Courrendlin (photo shows the anchoring of the bars at the end prior to activation and sprayed mortar application, right)

In the area of metallic structures, a pilot demonstration with Fe-SMA strips has been realized in the strengthening of a historic steel bridge in the Czech Republic.<sup>[26]</sup> In this project, multiple Fe-SMA strips were mechanically anchored to the steel girders (Fig. 11). The strips were later activated using ceramic heating pads. The strengthening solution was first evaluated at the laboratory scale before onsite application. The experimental test results showed the effectiveness of the strengthening system in enhancing the yield and reducing the deformations of the girders. The onsite monitoring of the bridge showed that most of the prestress loss of Fe-SMA occurs in the first 30 days after installation. More recently, a large-scale application of mechanically fastened smooth re-bar with a diameter 18 mm was conducted in Czech Republic (see Fig. 10, right panel).

#### 6. Opportunities and Challenges

The application and development of novel materials such as Fe-SMA bring opportunities and challenges. A few of the challenges and future research opportunities in prestressing civil structures with Fe-SMA are outlined below.



Fig. 11. Installation of Fe-SMA on a steel bridge as prestressing members. Reprinted from *Engineering Structures* 2021, 248, 113231. Copyright (2021), with permission from Elsevier.

## 6.1 Challenges

### 6.1.1 Recovery Stress Relaxation and Creep

The short and long-term prestress loss of Fe-SMA owing to the phenomenon of stress relaxation and creep must be fully understood for their implementation in the strengthening and design of civil structures. As noted earlier, the existing research shows that most of the prestress loss occurs in a short period after installing the Fe-SMA reinforcement. To address this issue, research efforts are underway to improve the stress relaxation and creep behavior of Fe-SMA.

### 6.1.2 Behavior on Loading after Activation

It has been reported that the elastic modulus of Fe-SMA reduces from 165 GPa to 75 GPa on loading after activation.<sup>[5]</sup> This reduction is significant and has mainly been attributed to the greater austenite to martensite transformation during the activation process.<sup>[27]</sup> However, despite this reduction, the elastic modulus of prestressed Fe-SMA is higher than the other available SMAs.

Another critical issue that requires attention is the loss of prestressing of Fe-SMA on cyclic loading after activation. Recent ongoing studies have shown that the complete loss in prestress of the as-received Fe-SMA occurs when the cyclic strain amplitude is about 0.4–0.5%. This implies that Fe-SMA should be used as unbonded or partially bonded reinforcement for applications involving large tension-compression reversals (e.g. earthquake actions) to delay the straining and associated loss in the prestress. Alternatively, different types of alloy treatments can be applied to increase the cyclic strain amplitude limit for retaining the prestress.

### 6.1.3 Corrosion Resistance

It is generally expected that the composition of Fe-SMA developed at Empa can exhibit a satisfactory corrosion performance due to 10% chromium. This, however, needs to be experimentally assessed, particularly for applications of Fe-SMA reinforcement in corrosion-prone environments.

## 6.2 Future Research Opportunities

Most of the existing applications of Fe-SMA have focused on the strengthening and design of beams and slabs only. Furthermore, the existing studies have evaluated the performance of the strengthened structures under monotonic loading scenarios in most cases. On the other hand, most structures are expected to experience cyclic loading reversals resulting from earthquake actions at some point during their service life. Therefore, Fe-SMA seems to have a promising potential for such strengthening and design applications. For instance, Fe-SMA can be used for prestressing reinforced concrete beam-column joints, which are considered to be the weakest link under earthquake actions. Other promising future applications of Fe-SMA include the devel-

opment of innovative low damage structural systems, including post-tensioned precast concrete walls for high-rise buildings and prestressed segmental concrete columns for accelerated bridge construction. The prestress of Fe-SMA can incorporate a rocking behavior in these systems, thereby enabling them to incur low damage in extreme loading events. The main advantage offered by Fe-SMA in developing these structural systems is the ease with which Fe-SMA rebars can be installed, anchored, and prestressed onsite as compared to the conventional prestressing tendons, strands, etc.

## 7. Concluding Remarks

Fe-SMA rebars and strips have been used extensively for prestressing concrete and metallic structures. The Fe-SMA material in terms of ecological impact and circular economy is unique. Upon deconstruction, the material can be fully recycled and re-introduced into the stainless steel production (already done now by re-fer with small remaining SMA material and test samples).

The effectiveness of Fe-SMA reinforcement in prestressing concrete structures has been evaluated for applications involving the flexural and shear strengthening of beams and slabs. In addition, the efficacy of prestressed Fe-SMA reinforcement is being explored for other innovative applications such as self-centering of concrete columns and prestressing of 3D printed concrete. Although the first on-site applications of Fe-SMA took place in May 2017 in carpentry storage in Switzerland by re-fer AG and contractor Stahlton, many new applications have happened since then. re-fer AG has already realized more than 200 real applications.

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