Iron-based Shape Memory Alloy Strengthening of a 113-Years Steel Bridge

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Abstract

This paper presents an application of iron-based shape memory alloy (Fe-SMA) for the strengthening of metallic girder of a historical roadway bridge in Petrov nad Desnou, Czech Republic. This is, to the best of author´s knowledge, the first application of Fe-SMA for strengthening of bridge structure worldwide, as the previous applications were mainly on building structures. The shape memory effect (SME) of Fe-SMA was used for prestressing of the steel girder. The SME is material property of deformed Fe-SMA to return to its original shape upon heating and subsequent cooling. A mechanical anchorage system was developed to apply pre-strained Fe-SMA plates to the steel girders of the 113 years old bridge, which is daily subjected to passengers and heavy vehicles. The SME in the Fe-SMA was then activated by heating to approximately 260 °C using heating ceramic pads. The test results showed that achieved recovery stress of the Fe-SMA strips led to a maximum compressive stress of -33 MPa in the lower flange of the steel girder. This compressive stress could significantly increase the yield and fatigue strength of the strengthened girder. Before and after the strengthening, the bridge was loaded with a 45.34-ton crane. Prior to installation of the strengthening to the bridge a static test was performed in the laboratory to examine the efficiency of the proposed strengthening method.

Keywords: Shape memory alloy, shape memory effect, strengthening, historical steel bridge.

Introduction

Aging of historical steel bridges is worldwide problem. Majority of steel bridges in the Czech Republic are either at the end of their design life or have already overpassed 100 years of service. Existing state of steel bridges in the Czech Republic was described and evaluated with their damages and failures by Ryjacek et al.(2016). Similar situation across the whole world has been confirmed by Bien et al. (2007). Aging bridge structures and increase of the traffic volumes call for new versatile strengthening methods to help the sustainability of the current infrastructure.

Methods of strengthening metallic structures can be divided according to the desired effect which is to increase either ultimate or fatigue strength. Traditional strengthening comprises of bolting, riveting or welding of additional steel plates or now highly appraised FRP panels to the parent structure.

Thanks to the excellent material characteristics as high strength and durability, carbon fibre reinforced polymers (CFRP) were the main subject of research in strengthening for the last decades. Vůjtěch J. et al. (2017) studied the influence of CFRP reinforcements on fatigue life of deteriorated steel. To maximize the efficiency of used material, strengthening profiles of either steel or CFRP are prestressed. Furthermore, different types of prestressed unbonded retrofit (PUR) systems were developed for strengthening of steel girders (Hosseini et al., 2018, Kianmofrad et al., 2017, Ghafoori and Motavalli, 2015). The PUR systems were used for strengthening of old steel bridges in Switzerland (Ghafoori et al., 2015) and in Australia (Hosseini et al., 2019a, Ghafoori et al., 2018).

Unfortunately, prestressed members usually need big and complex anchorage systems to transfer the prestressing forces to the parent member. Placement of hydraulic actuators for prestressing is also complicated, due to lack of space near anchorage devices (Hosseini et al., 2019b). Material newly introduced to civil engineering, **Shape memory alloys (SMA)**, has great potential to resolve those

difficulties. A comparative study between Fe-SMA material and CFRP has been conduced in (Hosseini et al., 2019b).
This paper presents application of iron-based shape memory alloy (Fe-SMA) strengthening of historical steel bridge in Petrov nad Desnou, Czech Republic (Figure 1). It is, to the best of author's knowledge, the **first ever application of SMA strengthening on bridge structure in the world**. Petrov Bridge was built in 1906 and was in operation on one of the arterial roads of the Czech Republic for 113 years. Bridge was still in operation during and 2 months after the application of developed Fe-SMA strengthening. As an ideal representative of riveted I-beam, one of bridge cross girders was chosen for application of the strengthening. Fe-SMA was applied to work against the effects of traffic loadings.

Figure 1. Historical steel road bridge in Petrov nad Desnou

Iron-based shape memory alloys (Fe-SMA)

Name of the material itself suggests its special characteristics as shape memory effect (SME) and super-elasticity. Sato et al. (1982) published study about first iron based SMA's which were developed in the 1980s in Japan. Sato et al. (1984) pointed out overall much lower production cost of Fe-SMA over the Nickel-Titanium SMA. Fe-SMA developed in Swiss Federal Laboratories for Materials Science and Technology (Empa) by Dong et al. (2009) were used for the Petrov bridge strengthening. The Empa's Fe-SMA has been developed in the last few years and shown great potential for efficient use in civil engineering. The mechanical properties and the production procedure of the latest alloy composition (which has been used in this study) can be found in (Ghafoori et al., 2017). Empa's Fe-SMA are currently manufactured in shape of bars for use in reinforced concrete and plates of 120 x 1.5 mm. Until now their use was focused mainly on application and reinforcement of concrete "building structures" as presented by Ghafoori et al. (2019).
Fe-SMA is heated to certain activation temperature and subsequently cooled down to ambient temperature. During the activation procedure (heating and subsequent cooling) Fe-SMA develops prestressing force acting to return the material to its original shape. Izadi et al. (2018b) measured the resulting stress in Fe-SMA of 406 MPa upon activation to 260°C (Figure 2). Fe-SMA strips has been so far developed and used for fatigue strengthening of steel plates (Izadi et al., 2018b, Izadi et al., 2018a), girders (Izadi et al., 2019a, Fritsch et al., 2019) and bridge connections (Izadi et al., 2019b).

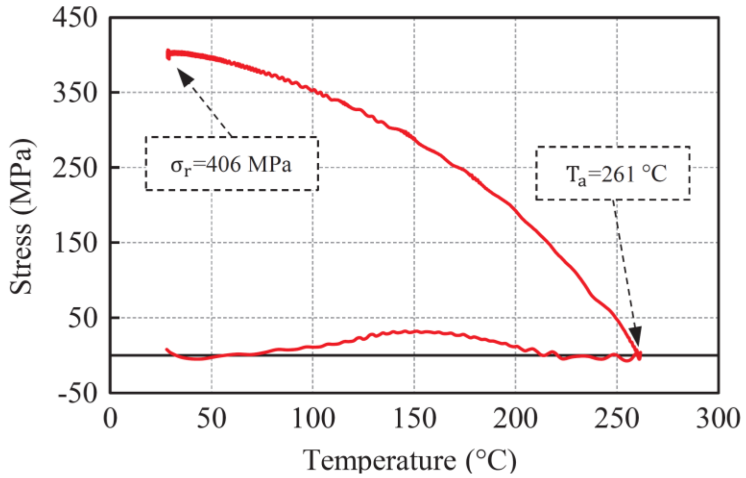


Figure 2. Stress-Temperature of Empa's Fe-SMA, Izadi et al. (2018b)

Design of the retrofit system

Use of several unbonded Fe-SMA plates for the strengthening was considered, due to limited range of plates on the market. The cross beam was selected as a strengthened member of the historical roadway steel bridge. Connection of the strengthening into the historical structure is always difficult detail. In the ideal case, connection should be completely reversible and should not cause any permanent intervention into the parent historical structure (Ghafoori, 2015).
In this case, Fe-SMA was installed at the bottom flange of the cross beam (Figure 3). Fe-SMA plates were placed between two steel angles and bolted with HSFG bolts of HRC system. Instead of drilling of new holes into the cross beam, holes from several old rivets were used for the new bolts.

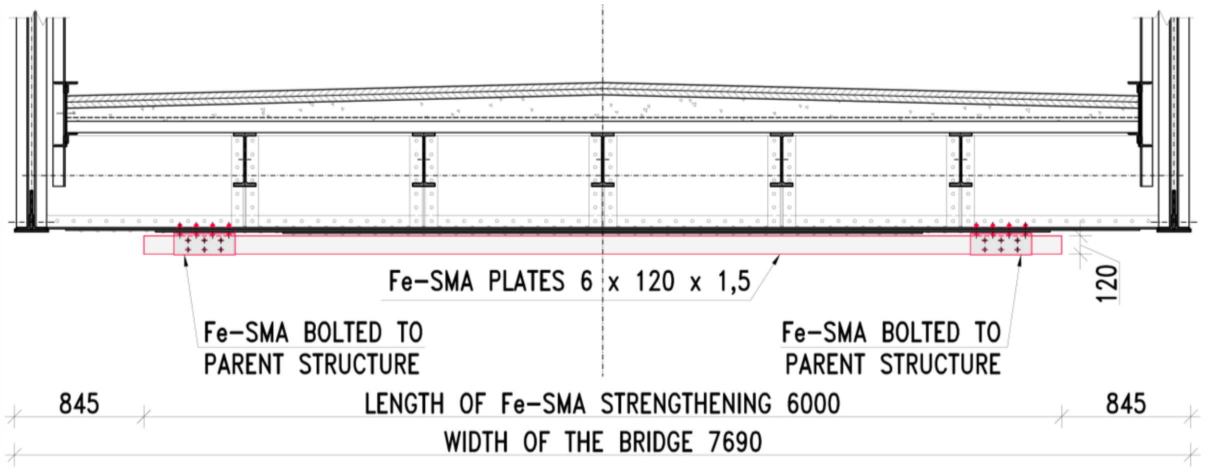
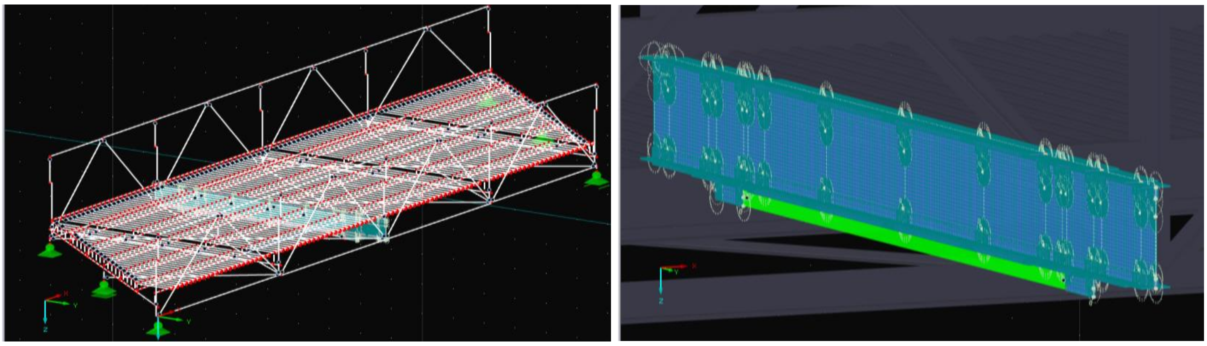


Figure 3. Cross-section of Petrov bridge deck with Fe-SMA strengthening

Targeted strengthening effect of this experimental application was to achieve permanent pressure in the bottom flange of the cross beam to increase the fatigue resistance. According to this criterium, totally six Fe-SMA plates were used. The quantity of plates needed was established with preliminary calculation and verified using the numerical model of the whole bridge.

Numerical model

Numerical model (Figure 4) of Petrov bridge was used to determine the effects of the strengthening on the structure. It was created in Dlubal RFEM software version 5.20. Model of the bridge consists of beam and shell members. For more precise results, shell members were used to model the strengthened cross beam. Shell members consist of elements S4 of max. finite element length 25 mm. Strengthening was modelled with one beam member with assigned dimensions and variable width, depending on the number of used Fe-SMA plates. Prestressing was simulated with uniform temperature load on the Fe-SMA. Dead load comprising the own weight of the structure and upper estimate of weight of the deck and railing results in +32 MPa of tensile stress in the bottom flange in the mid-span of the cross girder.



a) b)

Figure 4. Numerical model: a) whole Petrov bridge b) Strengthened cross girder using shell elements.

Results showed that the designed Fe-SMA strengthening with use of six plates of 120 x 1.5 mm each is sufficient to overcome the effects of dead load. The activation of Fe-SMA plates to the temperature of 260°C will ensure permanent pressure in bottom flange of the cross girder.

Fe-SMA strengthening of Petrov Bridge

Application of Fe-SMA on real structure of Petrov bridge took place in June 2019 right after the laboratory experiment. Application was conducted without any intervention into the traffic on the bridge. Fe-SMA plates were installed from a temporary scaffolding under the bridge, built for this application. Rivets in the location of anchors were removed and replaced with HRC bolts bolting the Fe-SMA plates to the bottom flange of cross girder.

Monitoring

Heating of Fe-SMA was monitored with use of ten thermocouples during each activation step. Thermocouples were placed along the plates to reassure the uniformity of the heating. The effect of SMA strengthening on cross girder was measured with the use of strain gauges placed in the thirds and in the middle of the cross girder. For each measured cross section there were two strain gauges at each side of the bottom flange and one on the web.

Activation

Use of electrical resistive heating (ERH) or infrared heating (IR) technique as proposed by Izadi et al. (2018), Ghafoori et al. (2019), respectively, was not considered. Activation was done with heating ceramic pads and insulation coating. In comparison with ERH and IR the advantage of this method is lower need of power supply. Electrical insulation of the parent structure is also not required opposed to use of ERH. For those reasons the heating with ceramic pads was chosen as most suitable technique for activation of Fe-SMA in field conditions. Activation process was managed in two steps. One half of Fe-SMA was activated in each step (Figure 5). This was the case solely because of number of the heating ceramic pads used for activation.

Figure 5. Heating of the second half of the Fe-SMA plates.

Installation of heating ceramic pads with insulation coating was followed with heating of Fe-SMA plates to the maximum activation temperature of 260°C (Figure 6). This temperature was determined in the preliminary numerical model. Temperature of Fe-SMA and strain values on the cross girder were monitored during both steps of the activation.

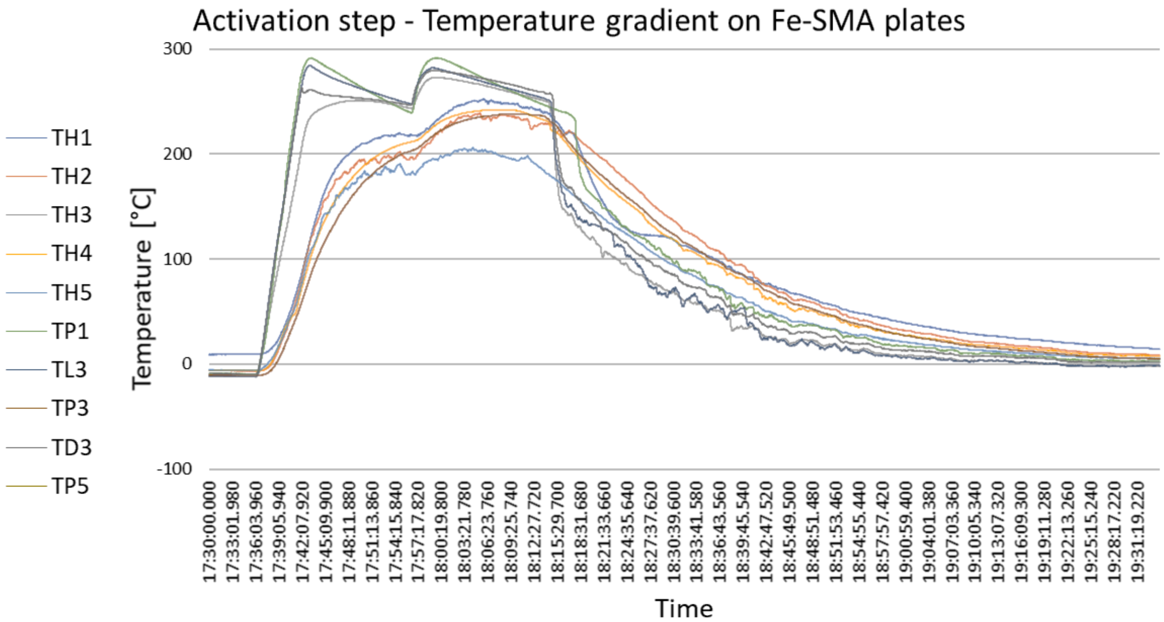


Figure 6. Typical temperature-history on the Fe-SMA plates during activation process.

Strengthening effect

In terms of the strengthening effect, the most important values were the ones obtained from the strain gauges in the mid span of the cross girder. Strain gauges C222 and C223 were located on the bottom flange of the cross girder. Strain gauge C221 was measuring the strain state on the web of cross girder in the mid-span. This section summarizes the achieved strengthening effect and compares the measured results with the ones obtained from the numerical model of Petrov bridge. Next figure (Figure 7) shows the stress state in the mid-span during first and second step of the activation. Note that the stress values were reset to zero. Sudden jumps occurring on the curves represent heavy trucks passing the bridge.

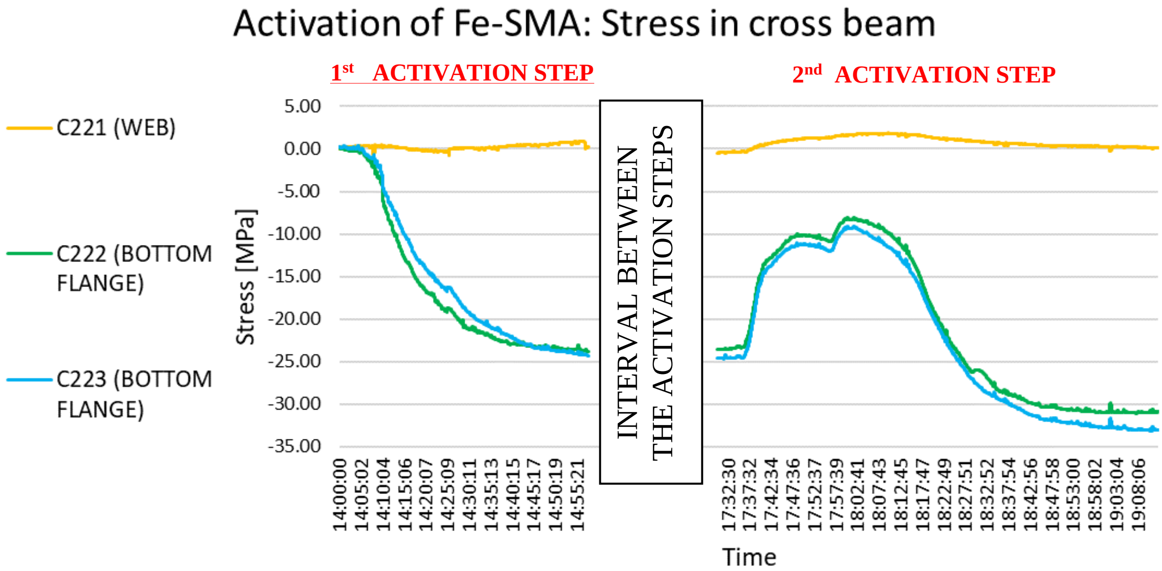


Figure. 7 Stress state of the mid-span section of strengthened cross girder during both activation steps.

Strengthening effect on the cross girder from both steps of the activation as well as the overall effect is shown in the following table (Table 1). Table also compares the overall strengthening effect with the results from the numerical model of Petrov bridge.

Table. 1 Strengthening effects on cross girder of Petrov bridge: Experimental / Numerical

MEASURED STRENGTHENING EFFECT AND VALUES FROM NUMERICAL MODEL							
Cross girder		*Strain gauge*	*Strengthening effect*			*Numerical model*	*Units*
Section	*Part*		*1.activation*	*2.activation*	*Total*		
Mid-span	*Web*	*C221*	*0.21*	*1.05*	*1.26*	*0.71*	*[MPa]*
	Bottom flange	*C222*	*-24.78*	*-7.77*	*-32.55*	*-35.273*	*[MPa]*
		C223	*-25.20*	*-8.62*	*-33.82*	*-35.273*	*[MPa]*

What should be pointed out is that the strengthening effect of the first activation of SME is significantly higher than the second one. Strengthening effect of the second activation is approximately third size of the first one.
Results from the numerical model showed as accurate in comparison with the real stress values measured on the strengthened structure. State of permanent compression in bottom flange of the strengthened cross girder has been achieved. Activated Fe-SMA strengthening (Figure 8) was monitored until the end of July 2019, when the old Petrov bridge was demolished. Monitoring proved no sign of relaxation of the Fe-SMA's SME.

Figure 8. Final configuration of the SMA-strengthened girder of Petrov Bridge.

Conclusion and remarks

A new type of strengthening with prestressing of iron-based shape memory alloys was successfully installed on historical steel road bridge. Application verified functionality of this method for strengthening of the bridge steel structures.
A new way of activation using heating ceramic pads was developed and successfully used for activation of strengthening on real bridge structure. Prestressing with heating ceramic pads showed as reliable technique for activation of SMA. Its lower need of power supply proved it to be the most suitable technique for field applications.
With the Fe-SMA strengthening application, permanent compression in bottom flange of the crossbeam has been achieved. The fatigue resistance of the cross beam has been increased.
Values obtained from numerical model of strengthening corresponded well with the measured stress values and showed minimal difference. Correspondence of the experimental and numerical values confirmed adequacy of technique used for modelling of SMA's SME.

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