Iron based shape memory alloy strips, part 2: flexural strengthening of RC beams

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ABSTRACT: This paper presents the application of Fe-SMA strips as an external end-anchored and unbonded prestressing system for structural retrofitting. The strips are prestrained to 2%, removed from the tensile machine and subsequently anchored to the reinforced concrete beams with a commercially available direct fastening system. The activation of the strips is performed by resistive heating up to a target temperature. Strain gauges on the concrete surface and on the strips at midspan were used to assess the strain profile during and after the activation. Along with the measured uplift, the results clearly indicate that the Fe-SMA strips are prestressed and the structure is under compression stress over its height. Static loading tests demonstrate the increased cracking loads compared to the reference beam as well as to a beam with an unstressed CFRP strip. Furthermore, the overall structural behavior is very ductile due to the Fe-SMA excellent tensile behavior with large strains in tension and the robustness of the end-anchorage. Failure was eventually obtained due to concrete crushing without any anchorage failure at the strip ends.

1 INTRODUCTION

Strengthening of existing structures such as bridges and buildings has constantly gained in importance over the last decades. For more than 20 years, carbon fiber reinforced polymers (CFRP) were often used to enhance a structure's load carrying performance in bending or shear. This material was used either as an externally bonded reinforcement (EBR) in form of a strip or fabric, or as a near surface mounted (NSM) strip or bar fully embedded in a slot on the top surface (Bakis et al. (2002), Michels et al. (2013)). In both cases, epoxy resin is used to bond the composite reinforcement to the concrete substrate. More recent developments deal with shape memory alloys (SMA) in order to improve an existing construction's structural characteristics. These alloys have for instance the ability to (almost) regain their initial shape after having previously been permanently deformed at ambient temperature. This shape recovery is obtained when the material is heated up to a necessary phase transformation. Whereas initial compositions were on Nickel-Titanium based alloys, which due to their elevated production costs are unfortunately unsuitable for civil engineering purposes, a few iron-based alloys are nowadays also available. When the mentioned shape recovery is constraint, for instance due to an end-anchorage or a constant bond over the length to the surrounding material, the alloy develops a recovery stress instead. This stress recovery can be used as a prestress for existing constructions (Shahverdi et al, 2016a and 2016b).

This paper deals with an iron-based shape memory alloy (Fe-SMA) developed at Empa more than 10 years ago (among others Dong et al. (2009)), and currently commercialized by the company re-fer AG as strips or ribbed bars. In a companion paper (Shahverdi et al. (2017)), the principal material characteristics are presented. In the current investigation, externally applied and end-anchored Fe-SMA strips ('re-plates') with a cross-section of 100 mm x 1.5 mm are used to flexurally upgrade reinforced concrete beams. After the application, the strip is activated by resistive heating and finally the structural performance by means of a static loading tests is investigated.

2 BEAM GEOMETRY, TEST PROGRAM AND MATERIALS

2.1 Beam geometry and test program

The RC beams have total length *L* of 4.4 m, a width *b* of 0.5 m and a thickness *h* of 0.15 m. The upper and lower reinforcement ratio ρ was 0.32% (3 x ∅10mm). Additionally, ∅8mm stirrups were added on regular intervals (see Figure 1).

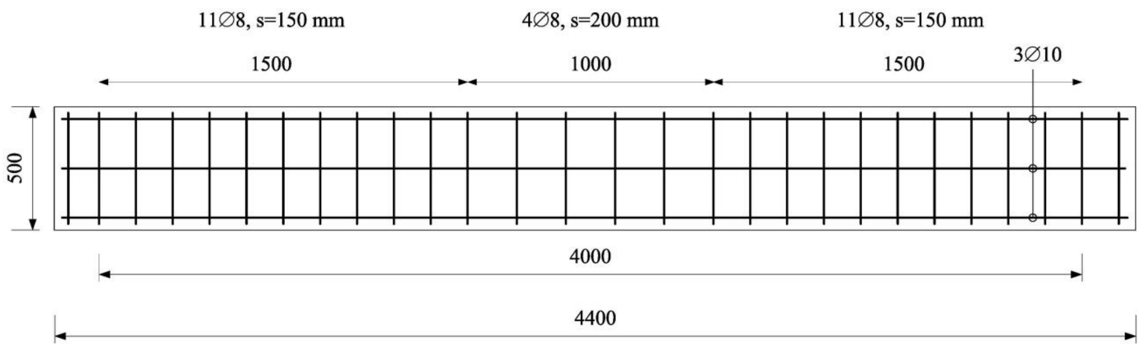

Figure 1. Internal steel reinforcement for all tested beams (top view).

The test program is presented in the following Table 1. One beam serves as reference, one beam is strengthened with an unstressed externally applied and bonded (EBR) CFRP strip and two beams are retrofitted with activated Fe-SMA strips. The difference in cross section between CFRP strip and Fe-SMA strip is due to the different elastic modulus of both materials with growing
strain (Shahverdi et al. (2017)). The aim in this study was to compare two strengthening types with more or less identical axial stiffness *EA*.

Table 1. Geometry and strengthening beam characteristics.

Beam	b x h [mm²]	ρ [%]	Strengthening type	Prestressing
1	500 x 150	0.32	-	-
2	500 x 150	0.32	1 CFRP strip, 50 mm x 1.4 mm / bonded / (EA~11.6 x 10^6 N)	No
3	500 x 150	0.32	1 Fe-SMA strip, 100 mm x 1.5 mm / end-anchored and unbonded / (EA~12 x 10^6 N)	Yes
4	500 x 150	0.32	1 Fe-SMA strip / 100 mm x 1.5 mm / (EA~12 x 10^6 N)	Yes

2.2 Materials

A C25/30 concrete with a compressive strength on cube $f_{cm,cube}$ of 31.1 MPa at 28 days was used. The internal steel rebars exhibited a yield strength $R_{0.2}$ of 520 MPa and an ultimate strength R_m of 600 MPa with a corresponding average strain at failure $\varepsilon_{s,u}$ of about 5.2 %.

For Beam 2, a CFRP strip 1.4 mm x 50 mm distributed by S&P Clever Reinforcement with an elastic modulus E_f higher than 165 GPa was used. Epoxy resin of type S&P Resin 220 was applied as a bond agent. Data sheets can be found online on the cited company webpage.

The Fe-SMA strips with a cross section of 100 mm x 1.5 mm have an ultimate tensile strength $f_{SMA,u}$ of about 1'000 MPa with a corresponding strain at failure $\varepsilon_{SMA,u}$ of 40%. Please note that the material is extremely ductile compared to conventional reinforcements such as hot- or cold rolled steel bars, prestressing steel strands or CFRP strips. After activation, the elastic modulus of the Fe-SMA is about 80 GPa when the structure is loaded.

3 BEAM STRENGTHENING

3.1 CFRP strip application

The CFRP strip is applied according to the common rules for externally bonded reinforcements (EBR), i.e. concrete surface grinding and cleaning, strip cleaning, epoxy mixing, epoxy application on both concrete and CFRP strip surface, CFRP strip application, proper bonding by application of manual pressure with a roller.

3.2 Fe-SMA strip anchoring

The Fe-SMA strips are anchored at both ends by means of the Hilti direct fastening system X-NPH2. For this application, both the Fe-SMA strip and the concrete substrate have to be predrilled prior to the nail fastening. The nail, its application and the final anchorage are shown in Figure 2.

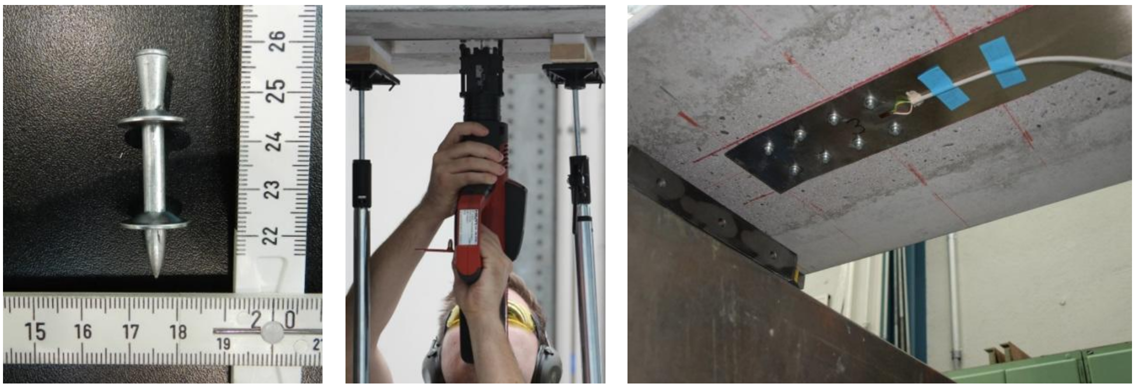

Figure 2. X-NPH2 nail (left), direct fastening (middle) and final anchorage (right).

3.3 Fe-SMA strip activation (prestressing)

The Fe-SMA strips are activated by resistive heating. A custom-designed power supply station is connected to the strip at both ends by means of two pincers as presented in Figure 3. The electrical intensity (in the range of 5 A/mm^{2}c) can be defined in order to reach the requested heating temperature. Various automatic switching-off criteria for safety purpose, such as the total energy (kWs) or total heating duration can be defined.

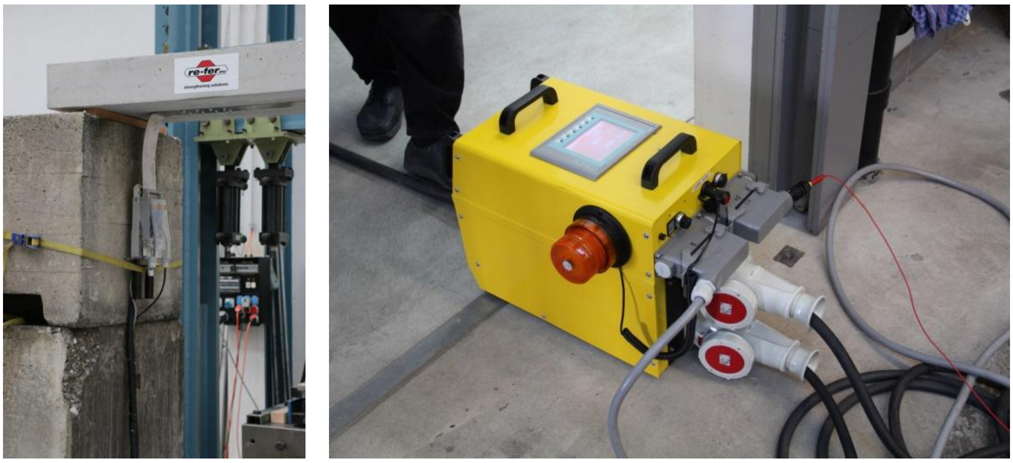

Figure 3. Pincer for resistive heating of the Fe-SMA strip (left) and power supply control station (right).

For Beam 3, the ultimate heating temperature was about 280°C, whereas the one for Beam 4 was approximately 220°C. For Beam 4, strain gauges were installed at midspan on the upper and lower concrete surface. Furthermore, an LVDT was installed on top of the concrete surface. Both the strain $\varepsilon_{c,b}$ and $\varepsilon_{c,t}$ evolutions as well as the midspan uplift v_p during the Fe-SMA heating and cooling process are shown in Figure 4. Both strain values are initially in the range of -100 and +100 µm/m due to the dead load, as the measurements were started the moment when the beam was installed on the supports with a 4 m span. The prestressing effect is evident as the concrete beam moves upwards due to the ongoing stress development until ambient temperature is again reached in the Fe-SMA strip. The strain measurements reveal an upper strain of about -45 µm/m and an upper strain of about -15 µm/m, indicating that eventually the full cross-section is under compression. By establishing a back calculation of the prestressing force necessary to generate such a strain profile, a prestressing force $F_{p,SMA}$ of 61 kN is obtained.

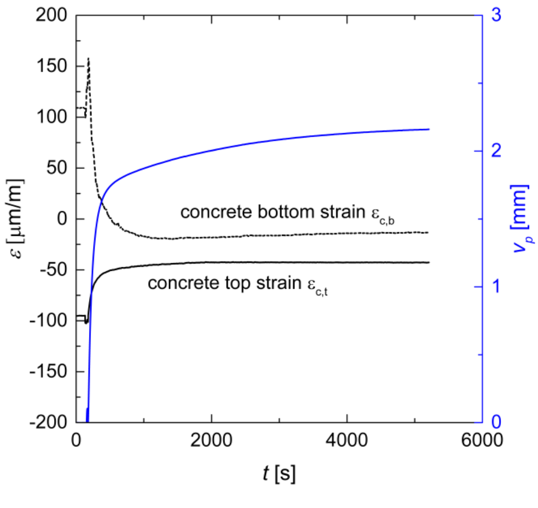

Figure 4. Evolution of concrete top and botton strains at midspan as well as midspan uplift during the heating and cooling of the Fe-SMA strip for Beam 4.

In addition to the strain measurements, a simplified control of the prestressing force based on the 'crossbow test' (IIFSTAR, 2015) was performed on the Fe-SMA strip. With this technique, a defined mass is applied to the Fe-SMA strip and its corresponding deflection downwards is measured. This is repeated a few times in order to have mass-displacement relation. With simple geometric calculations, the prestressing force in the Fe-SMA strip can be deducted. In the present case, a prestressing force $F_{p,SMA}$ of 59 kN was determined. This value is in very good agreement with the concrete strain measurements presented earlier. Therefore, the prestress was about 400MPa.

4 STATIC LOADING TESTS

4.1 Test setup

The test setup is shown in Figure 5. The beam is simply supported with a span of 4 m. Two hydraulic jacks at a distance of 1.7 m from the side support apply loads under displacement control of about 2 mm/min. Midspan deflection and forces were recorded by means of an LDVT and a load cell, respectively. On both, the CFRP strips and the Fe-SMA strips, strain gauges were installed to record the tensile behavior of the additional outer strip reinforcement.

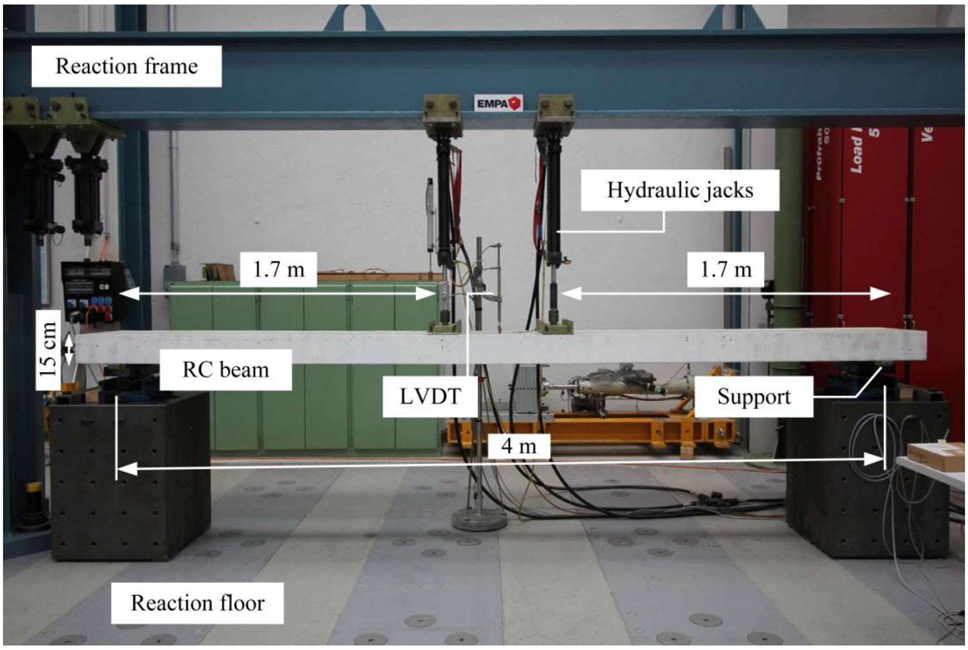

Figure 5. Test setup for the static loading tests.

4.2 Results and discussion

Force deflection behavior of the four beams are presented in Figure 6, key results are summarized in Table 2. Firstly, it can be noticed that the cracking load is enhanced when an activated Fe-SMA strip was used. This is a direct consequence of the Fe-SMA prestressing effect on the concrete beam. A back-calculation with the observed cracking loads confirms the previously stated prestressing loads of around 60 kN of prestress force for Beam 4. For Beam 3, a prestress force of around 70 kN can be derived. This value leads to a prestress of about 450 MPa, which is in line with the observed prestress-temperature relation as presented in (Shahverdi et al, (2017)). Such a prestress force is Related to this observation is the fact that for low force levels in the serviceability area, the corresponding deflections are much smaller than for the reference beam or the one with an unstressed CFRP strip. Beam 2 finally reaches its ultimate load carrying capacity shortly before the CFRP strip debonds (Figure 7 (left)) at a tensile strain of about 6’900 µm/m (0.69%) on the CFRP strip. Beams 3 and 4 on the other hand exhibit a much more ductile behavior with larger deflections at failure, which is eventually reached by concrete crushing at 2’500 and 2’400 µm/m (0.25% and 0.24%), respectively (Figure 7 (right)). These values for the crushing strain in case of an unbonded tendon are in agreement with the literature (Brühwiler and Menn (2003)). No anchorage failure was observed for the Fe-SMA strengthening system.

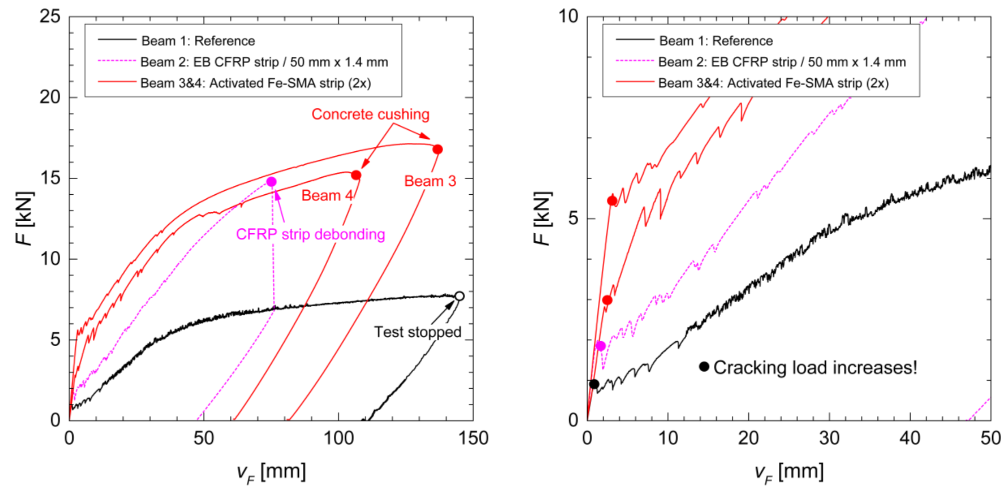

Figure 6. Force-deflection curves up to failure (left) and zoom to the initial loading stages (right).

Table 2. Key results for all beam tests ($F_{p,0}$=prestressing force, F_{cr}=cracking load, F_u=ultimate load, δ_u=deflection at ultimate load, $\varepsilon_{c,u}$=concrete compressive strain at ultimate load, ε_f=CFRP and ε_{SMA}= Fe-SMA strip strain at ultimate load, *=test stopped, **=expected failure mode).

Beam	1	2	3	4
$F_{p,0}$ [kN]	-	-	~60	~70
F_{cr} [kN]	1	2	5.6	3.5
F_u [kN]	7.9	14.9	17.1	15.4
δ_u [mm]	145	75	105	135
$\varepsilon_{c,u}$ [%]	0.2*	0.1	0.25	0.24
ε_f, ε_{SMA} [%]	-	0.69	0.62	0.45
Failude mode	concrete crushing**	strip debonding	concrete crushing	concrete crushing

Crack pattern after test end is shown in Figure 8. As expected, cracks extend to a larger span for the reference beam and the one with an initially unstressed CFRP strip. On the contrary, prestressing with an unbonded external tendon reduces the area over which the flexural cracks develop. Crack spacing does not seem not significantly differ between the four tested beams.

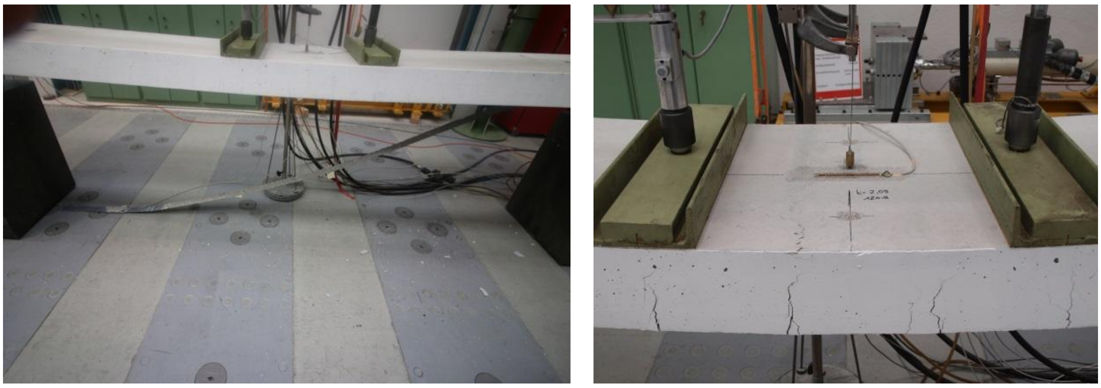

Figure 7. CFRP strip debonding for Beam 2 (left) and concrete crushing for Beams 3 & 4 (right).

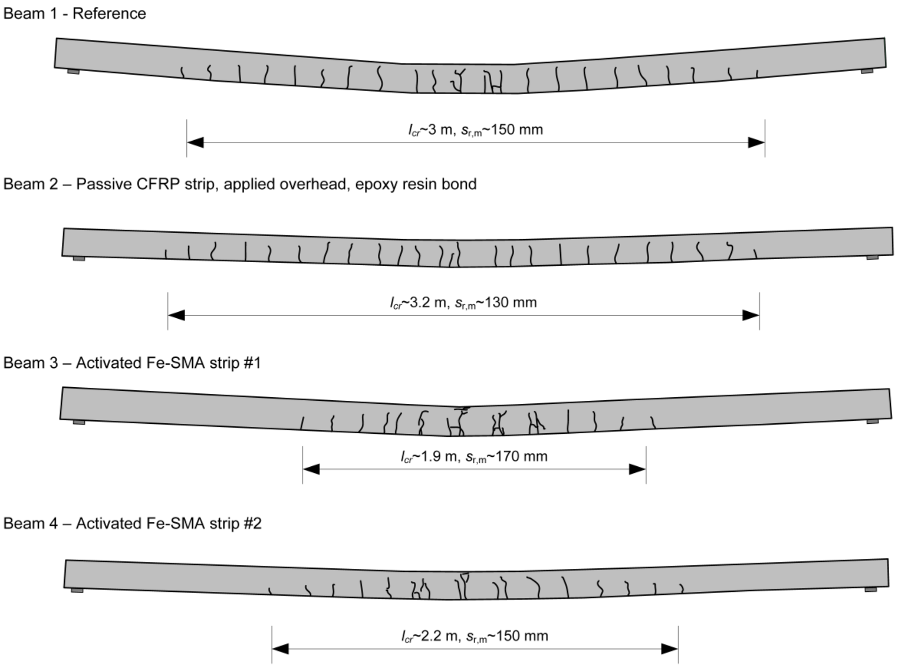

Figure 8. Final crack pattern after test end.

5 CONCLUSIONS

The following conclusions can be retained from the presented investigations:

- The Fe-SMA strips from the company re-fer AG worked well as an externally applied prestressing element.
- The application process of the end-anchored Fe-SMA strip is very simple and fast. Compared to for instance prestressed CFRP strips requiring heavy anchorages, the direct fastening method allows for a simple installation process. The activation by resistive heating is also very short.
- The presented strain and uplift measurements as well as the modified cross-bow test demonstrated the present prestressing in the structure.
- The overall structural behavior is very ductile. The Fe-SMA material itself has a failure strain much larger than any other currently used material in civil engineering. A failure in tension on the Fe-SMA strip can be excluded, as internal steel reinforcement and concrete would fail earlier in tension or compression, respectively. Additional investigations not presented here, showed that the anchorage resistance of the direct fastening solution is high enough to exclude such a failure mode, too. No strip debonding as for CFRP strips was noticed.
- The Fe-SMA strips are applied as an external prestressed tendon. Thus, no epoxy resin is necessary, which is beneficial regarding the exposure to elevated temperatures or even fire.
- Further experimental investigations will focus on stress corrosion, relaxation, creep, and fatigue of this type of reinforcing system.
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