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STRUCTURAL CONCRETE STRENGTHENING with Fe-SMA STRIPS: CASE STUDY with specific CONTROL AFTER ACTIVATION

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ABSTRACT: This paper presents the application of a novel prestressing technique by means of iron-based shape memory alloy (Fe-SMA) strips. This innovative material has the ability to regain its initial shape upon heating, after having initially been permanently prestrained at ambient temperature. Without any free movement caused by an end-anchorage, a prestress develops in the material. In our case, the alloy is in form of 1.5mm thick and 100mm wide plates, end-anchored with specific nails at each extremity.

An application of externally end-anchored and unbonded Fe-SMA strips was realized in a school building in France in 2017. The installation of three Fe-SMA strips was performed in order to obtain a crack closure in a reinforced concrete slabs. It was demonstrated the easy process of installation with no surface preparation, applying of anchorages and relative moderate power machines for activation of laminates. Measurements with 'Omega'-gauges over the crack demonstrated the efficiency of the prestressing.

A specific 'crossbow' technique was also developed to assess the prestressing force in the strip just after the operation and also 1 year later. The stress induced after the activation process was verified. It was also demonstrated the reduced relaxation after one year.

1 INTRODUCTION

Flexural strengthening of existing structures is often needed due to different causes. The strengthening technologies can be classified in two categories: passive strengthening and active strengthening methods. In the first ones FRP materials have been used for almost 25 years. They are used either as an externally bonded reinforcement in form of a strip or fabric, or as a near surface mounted (NSM) strip or bar fully embedded in a groove on the top surface (AFGC, (2007), Al-Mahmoud et al (2009)). However, in active strengthening methods, the structures are directly prestressed or actively confined when the strengthening material is placed.

An innovative active strengthening technology for concrete slab will be presented here using the shape memory effect of Shape Memory Alloys (SMA). This effect is the key property for the featured strengthening technology, and it refers to the phenomenon whereby SMAs are capable of returning to a predefined shape upon heating. If this recovery strain is constrained the SMA will generate recovery stresses when heated and cooled afterwards, prestressing the concrete element (Shahverdi et al (2016)).

Iron based SMA have already satisfactorily been used for the flexural strengthening of RC beams embedding them in a shotcrete layer (Shahverdi et al. 2016). It was also demonstrated by

static loading tests on concrete beams an increased cracking loads after reinforcement with SMA plates (Michels et al (2017)). In addition to the strain measurements, a simplified control of the prestressing force on the SMA strip based on the 'crossbow test' was also experimented with success (IFSTTAR (2015); Michels et al (2017)).
The objective was then to implement this technic on site and to propose an integrated solution with specific control of prestressing force at different times after activation.

2 INSTALLATION AND ACTIVATION

2.1 General presentation

This site application deals with the installation and activation of externally and end-anchored strips onto a slab of a school room. Three strips 5m long were proposed to reinforce a concrete slab against flexural solicitation and specified by a structural design. It was a complementary technic to CFRP reinforcement performed in other areas of the slab. A longitudinal crack 0.4 to 0.5mm wide was identified and susceptible to be closed after activation of the plates.

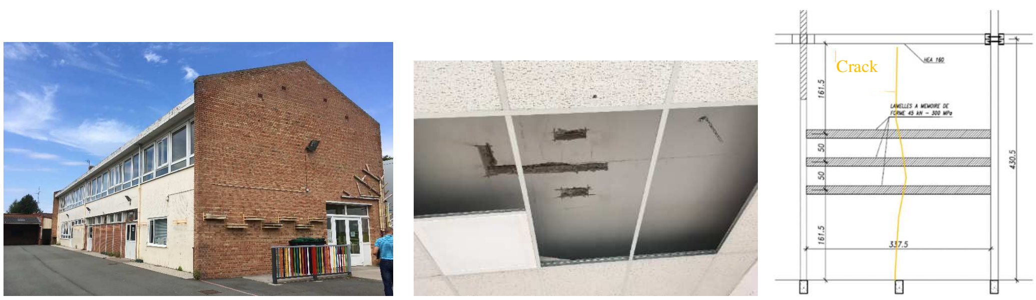

Figure 1. General view of jobsite, slab area with cracks and reinforcement disposition

The strips were mechanically fixed to the concrete substrate, using a direct-fastening system with nails. The activation of the shape-memory effect and hence initiation of the prestressing process was accomplished by resistive heating. The temperature of the strips was monitored with thermocouples in all cases.

2.2 Installation details

The laminates are delivered in rolls, stored in a dry atmosphere and at a temperature below 50°C, and cut on site to the required lengths.

Figure 2. Preparation of laminates and concrete surface

The preparation operations are the following:

- Cut to length of laminates and folding of the extremities
- Preparation of laminates and concrete surface
  - Check the flatness of the surface and detection of steel rebars (to avoid short circuit due to contact between nails and rebars during activation)
  - Mark position of laminates on the surface, drill of the anchoring holes onto the laminate
  - Concrete drilling, diam. 4.5mm and 25mm depth and nail installation with a Hilti powder gun

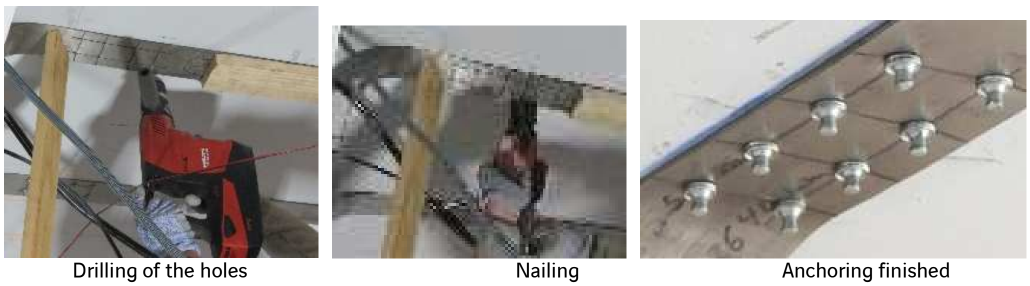

Figure 3. Anchoring steps

2.3 *Activation of the laminates and temperature controls*

The operation was performed and controlled by re-fer team. Three Thermocouples were installed at mid-span and each ¼ of each laminate and connected to acquisition system. Clamps are installed at each extremity. The generators are finally connected to power supplier.

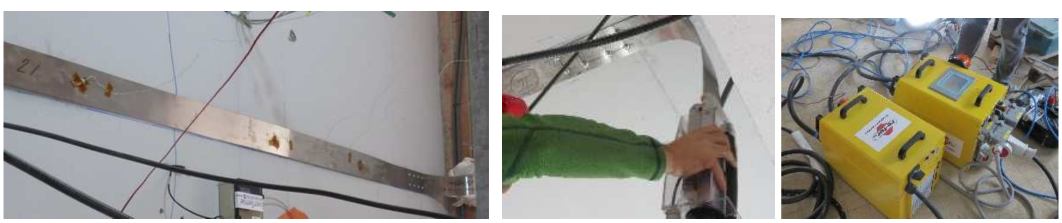

Figure 4. Thermocouples and clamps + generators installation

The activation consists in current circulation into the strip (400A, 36V). The strip if thus heated by joule effect until 160°C. The target temperature 160°C was reached after 30s for each laminate. Registered measurements are summarized in following graphs.

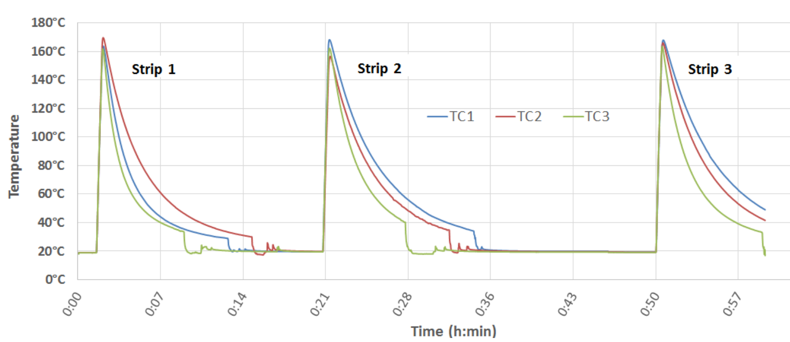

Figure 5. Temperature evolution during activation

2.4 *Monitoring of the crack*

Three Omega gauges (C1 to C3) were installed over the main longitudinal crack of the slab.

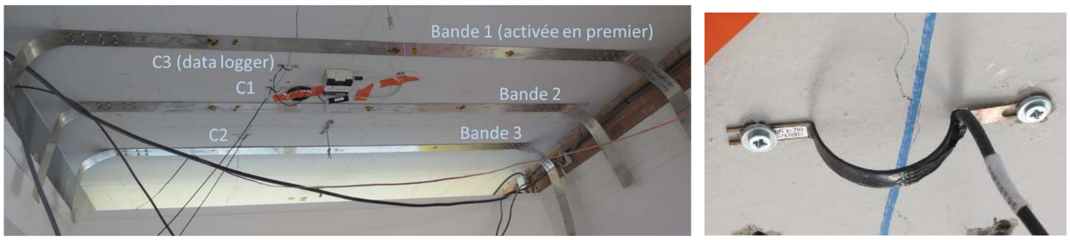

Figure 6. Monitoring of the crack with Omega-sensors

Deformation of each sensor is registered all along activation process. It clearly appears that the three sensors measured the closure of the crack (0.4 to 0.5mm wide before reinforcement), relatively quickly after activation and then delayed in the following hours (creep of the slab). C1 and C3 were close to the plate and gave closing less important than C2.

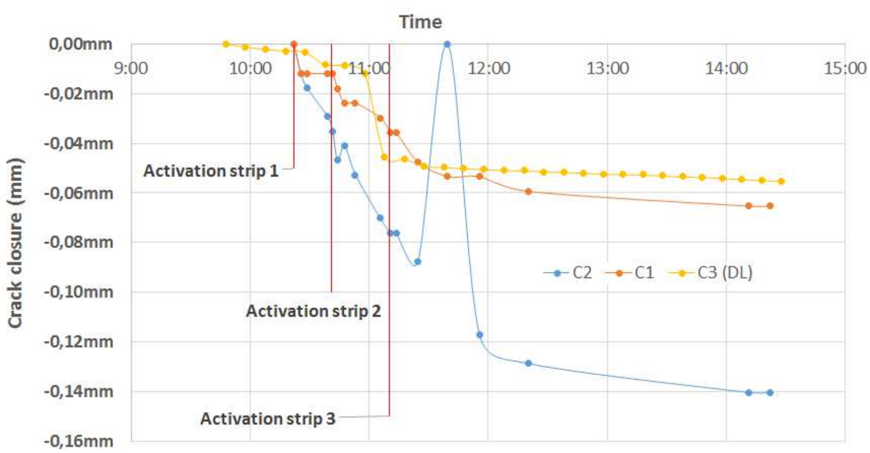

Figure 7. Crack progressive closure all along activation process

A monitoring of the crack was then performed for 15 days with C3 gauge. We can observe the activation at initial stage and a relative creep during the following days. Successful reduction of existing crack width was thus demonstrated.

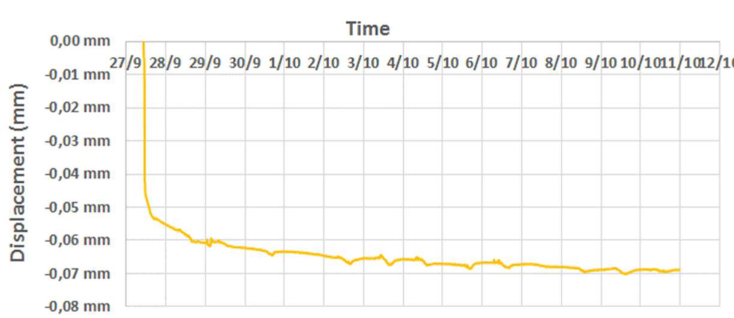

Figure 8. Crack monitoring 15 days after activation

3 CONTROL & TENSION MEASUREMENT

As presented previously, there is no visible effect of tension into the strip after activation. The temperature and its target value is the only parameter measured and controlled on the strip. This is judged insufficient because other phenomena could potentially lead to lose of efficiency and not being measurable. A demonstration of the tensile effort into the strip is necessary as a control of conformity.
This is the reason why Freyssinet Technical Department designed and developed a specific equipment (crossbow) in order to verify the correct tension into them after activation.

3.1 Equipment and principle of measurement

The elements are presented in the following picture. The main one is a sensor measuring the effort when applying a flexural deformation to the plate.
The experiment was performed on one of the three plates, the other ones not being accessible after school re-opening.

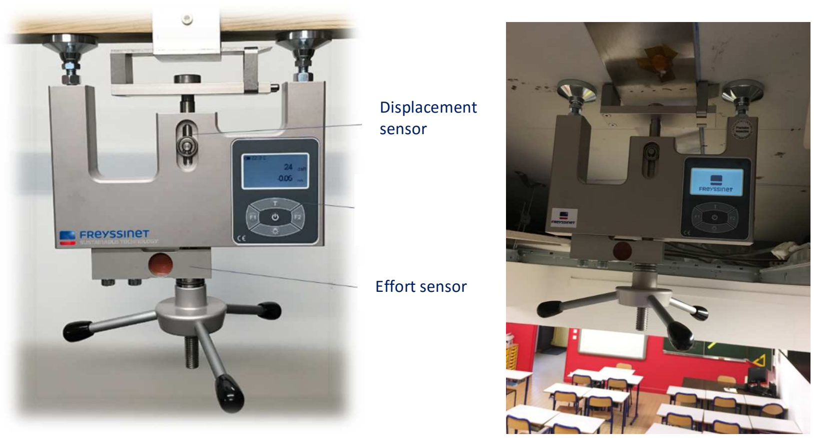

Figure 9. General view of the equipment installed on a plate

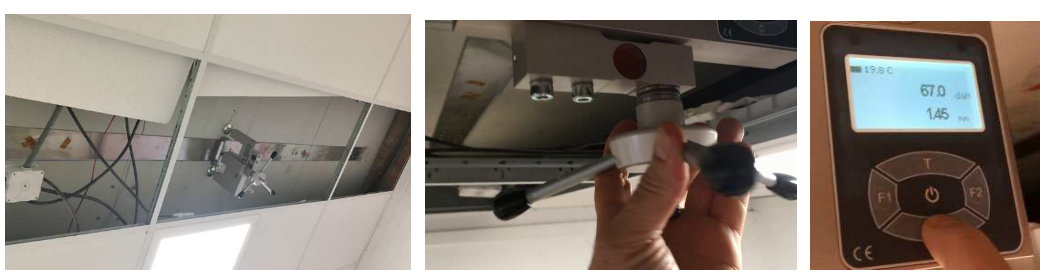

Figure 10. Measurement on plate n°1

The principle of measurement is the following:

- Clamp is applied under the strip in its mi-span and the footpad are adjusted to fix the equipment
- The effort (P) is then applied thanks to the wheel
- Tensile strength (T) and displacement (d) are recorded

Measurements are analyzed as follow. The method is similar to the tensile measurement on cable with a crossbow. A weigh P is applied in the mid-span of the plate and the deflection is measured. The deviation being negligible compared to the length L (T=constant) leads to an approximation less than 0.7%.

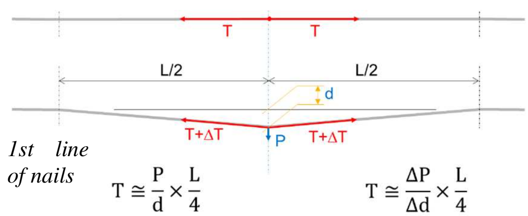

Figure 11. Determination of tension by weighing operation

The calculation is then performed from the slope of the curve load/deflection.
It is important to notice that the loading evolution leads directly to articulation into the 1st anchoring line. This moment is visible on the curves.

3.2 *Results and analysis*

The materiel was not available at the period of activation. Measurements were performed after two different periods: 15 days and 13 months after activation.
On the following figure, three different weighing tests performed on strip n°1 13months after activation are detailed.

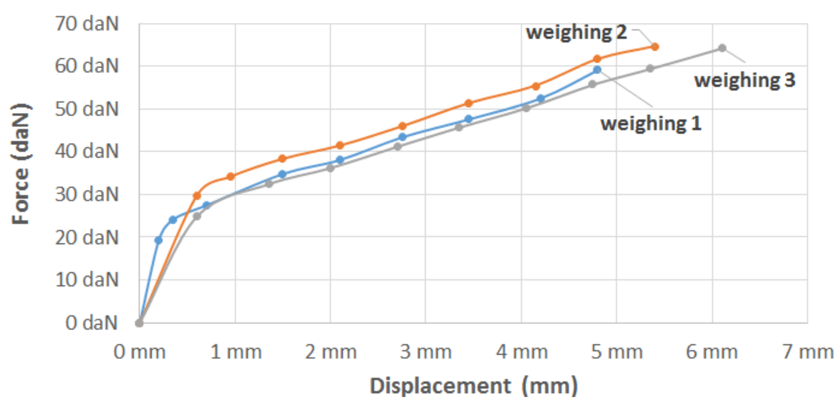

Figure 12. Three different weighing results on strip n°1

The slope in linear section of the curve and the length value lead to the tensile force in the strip.

Table 1. Results and determination of effort

		Weighing 1	Weighing 2	Weighing 3	
Slope	daN/mm	7.29	6.93	6.80	
Length	mm	2415	2415	2415	**Average**
Effort	**kN**	**44.0**	**41.8**	**41.1**	**42.3**

These values are then compared to the previous measurements performed 15 days after activation. The values obtained at the two different periods are reported on a logarithm scale graph. The extrapolation until the origin leads to a force equal to 46.5kN, in accordance with the usual values previously obtained on the plates.
The slope of the curves gives a coefficient of 2.5% per decade, also in accordance with previous relaxation lab tests. Future tests and applications on site could help to confirm these measurements at short time and also higher time.

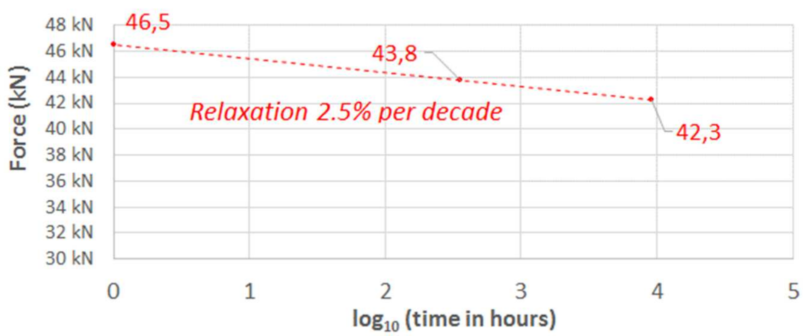

Figure 13. Force evolution as a function of time after activation and relaxation evaluation

3.3 Equipment improvement

During the operation, a few jamming/unjamming were noticed and could be due to friction.
For future operations, an adaptation with crowned articulation between the pin and the caliper will be proposed, in order to reduce the potential transversal effort on the flexible strip.

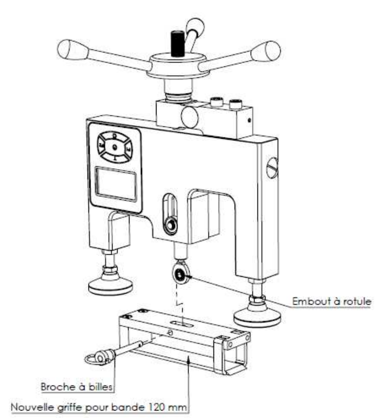

Figure 14. Modification of the equipment

4 DURABILITY

As presented previously, there is no visible effect of tension into the strip after activation. It was noticed that strips and anchorage had no sign of degradation nor corrosion after 1 year. It was also verified that the crack had stayed stable and didn't enlarge or developed after 1 year.

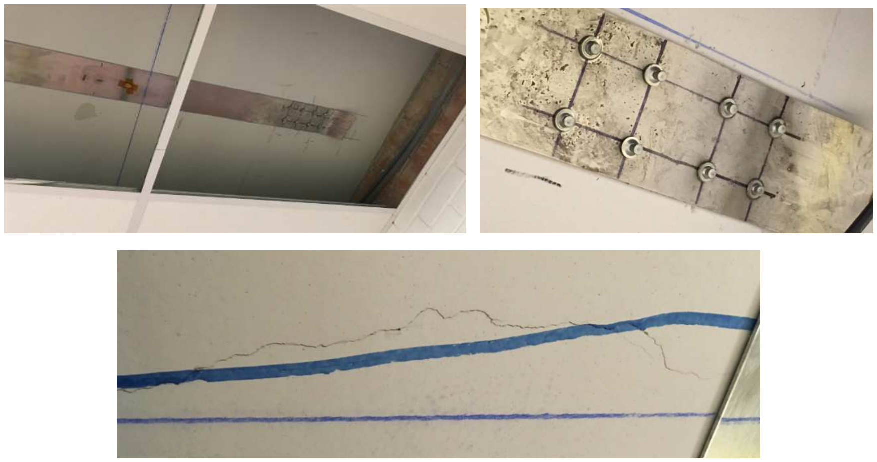

Figure 15. strip, anchorages and view of the crack after 1 year

5 CONCLUSIONS

The presented example demonstrated the easy and successful application of new effective strengthening method for reinforcement of existing concrete structures using Fe-SMA plates. Successful reduction of existing crack width thanks to deformation monitoring demonstrated the efficiency of the prestressing.

The Fe-SMA laminates make it possible to strengthen concrete slabs and beams submitted to flexural and shear forces. A specific equipment was developed to measure and confirm the exact tensile force in the laminate by crossbow weighing.

ACKNOWLEDGEMENTS

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