USE OF SHAPE MEMORY ALLOY WIRES FOR THE CREATION OF PRESTRESS STATES IN CONCRETE BEAMS

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1. INTRODUCTION

Shape memory alloys (SMAs) are active materials that exhibit special properties such as pseudoelasticity and memory effect [1-2]. These properties are resulting from austenite vs. martensite reversible transformations governed by temperature and mechanical stress states. The austenite (parent phase) and the martensite (product phase) are present respectively at high and low temperature. A SMA has only one shape in an austenitic state, but it has the ability to retain the shape given to it in a martensitic state. A return to the original shape is obtained by returning the SMA to austenite by raising the temperature (memory effect). Because of their unique properties, SMAs have found applications in mechanical engineering, aerospace or for medical uses.

The use of SMAs in civil engineering is still very limited, partly because of their cost, but also because of a lack of knowledge of the mechanisms involved in their association with other materials such as concrete [3]. A few preliminary studies have provided insight into the benefits of exploiting the unique properties of these alloys by combining them with concrete in the form of internal or external reinforcements [4-6]. Other studies attempted to use the properties of these alloys, for example to create active structures able of adjusting their behaviour to the loading conditions [7]. Confinement effects were also obtained in concrete cylinders by means of SMA wires used as external reinforcements [8-9]. Also, damping effects related to the pseudoelasticity have been used to control dynamic effects [10-11] or for the seismic protection of bridges and historic buildings [12-15]. These studies have shown that the combination of concrete with SMA can provide significant gains in terms of strength and ductility or to delay cracking.

In the present study, nickel-titanium wires are used as external reinforcement to create prestress states in small-scale concrete beams. The aim of the study is to

investigate the relation between the mechanical properties of the SMA wires and the prestress states obtained. To this end, the austenite vs. martensite transformation temperatures were chosen so as to facilitate obtaining stresses at room temperature. At first, the wires were characterized in terms of their thermomechanical behaviour. In a second time, they were given a prestrain in a martensitic state before being firmly fixed on small scale concrete beams. The number of wires and the prestrain range were the parameters of the study. Thermal activation of the memory effect in the SMA wires caused their tensioning, which resulted in reaction in the creation of stresses in the tested beams. Progressive developments of the stresses in the concrete were assessed by measuring the strains induced in each tested beam.
From the experimental results, the influence of the magnitude of the initial stretching of the martensitic wires and the influence of the martensite vs. austenite transformation temperatures are finally discussed in view of the use of SMAs for the creation of prestress states in concrete components. In particular, it is shown that the magnitude of the prestressing force can be bounded in some cases by a production of martensite in the SMA wires upon return to ambient temperature.

2. CREATION OF FORCES USING SHAPE MEMORY ALLOY WIRES

2.1. Thermomechanical properties of SMAs

Depending on its temperature, a given SMA may exhibit very different mechanical properties. This section briefly reviews the physical phenomena involved in this study to create prestress effects in concrete components.
The macroscopic properties of SMAs originate from a phenomenon of solid-solid phase transformation governed by mechanical stress and temperature [1-2]. The parent phase is called austenite (marked *A* in the following). It has a body-centred-cubic crystal structure in all known SMAs. The product phase is called martensite (marked *M* in the following). Its crystal symmetry depends primarily on the composition of the alloy. Due to the loss of symmetry during the $A \rightarrow M$ transformation, martensite is in the form of several variants which correspond to the same crystal, but oriented differently in space relatively to the crystal of austenite. The displacement of atoms during the $A \rightarrow M$ transformation results in a transformation strain. When different variants exist in equal proportion, the macroscopic equivalent strain is almost zero. This is known as self-accommodating martensite [16].
Figure 1 presents the phase diagrams showing the status of the material as a function of stress and temperature. The material can be either purely austenitic (*A*), or purely martensitic (*M*) with different proportions of martensite variants, or a mixture of the two phases (*A+M*):

– Figure 1-a: starting from austenite, martensite can be obtained either by decreasing the temperature or by applying a mechanical stress. The two tilted lines correspond to the beginning and the end of the $A \rightarrow M$ transformation. Upon cooling down at zero stress, the transformation begins at temperature M_s (martensite start) and it ends at temperature M_f (martensite finish). Note that the martensite obtained is entirely self-accommodating, so there is no macroscopic strain. Martensite can also be obtained by mechanical loading at a given temperature. In this case, it is not self-accommodating: the orientation of the martensite variants caused by the mechanical stress results in a significant transformation strain (stretching of the martensite).
– Figure 1-b shows the phase diagram when one starts from the martensitic state. Stretching of the martensite at constant temperature results in a change in the proportions of martensite variants, while keeping the total percentage to 100%. The martensite is said to “orient” and the resulting deformation is preserved upon unloading. One can thus obtain different macroscopic forms after unloading. A return to the austenitic state is obtained by a temperature rise. At zero stress, the $M \rightarrow A$ transformation starts at temperatures A_s (austenite start) and ends at temperature A_f (austenite finish). The transition to the austenitic state is accompanied by a return of the material to its original shape. This unique property, called “memory effect” is thus obtained by simple thermal activation.

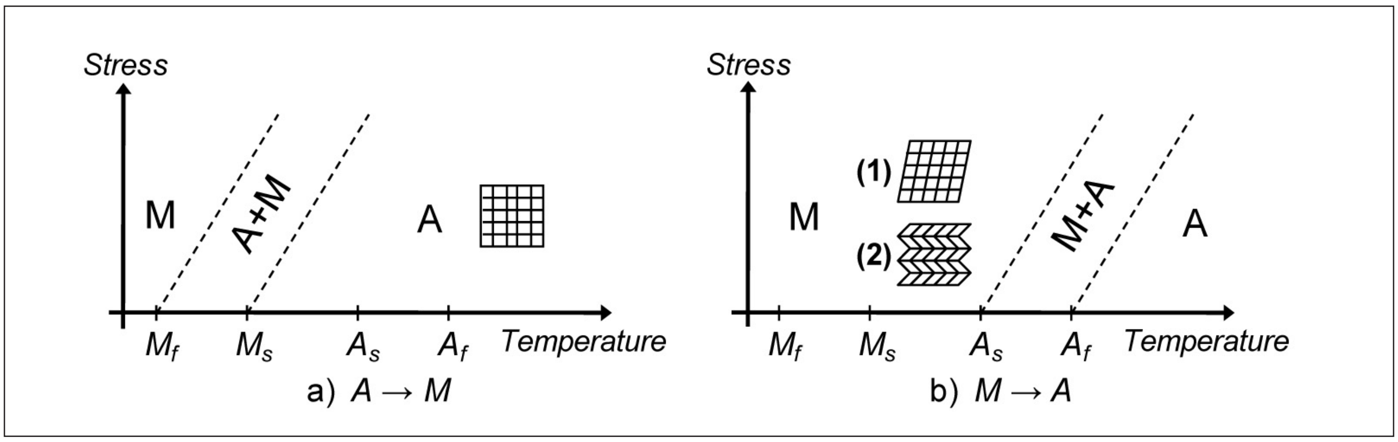

Figure 1. Phase diagrams between austenite (A) and martensite (M): (1) oriented martensite, (2) self-accommodating martensite.

2.2. Creation of forces by memory effect

In the present study, the creation of permanent forces at room temperature ($T_A \approx 20°C$) was made possible by choosing a nickel-titanium SMA wire for which $M_s < T_A < A_s$. A key issue concerned the thermomechanical loading to apply in order to create a force in a SMA wire. Figure 2 describes the seven steps procedure defined to this purpose [17]:

– Steps (1) to (3): heating (T > A_f) to put the wire in an austenite state, then cooling down (T < M_f) to put the wire in a self-accommodating martensite state, finally returning to room temperature T_A.
– Steps (4) and (5): stretching of the wire aiming at causing a deformation by orientation of the martensite. The residual strain after unloading is denoted ε_{mart} (prestrain).
– Step (6): heating of the wire (T > A_f) while keeping its length constant. Since the wire cannot recover its initial length, the memory effect induced by the return to the austenitic state causes the creation of a tensile force in the wire. The magnitude of the obtained force depends on the amplitude of the prestrain ε_{mart}.
– Step (7): return to room temperature T_A while keeping the wire length constant. Figure 2-b shows that two cases can possibly occur. In case 1, the stress reached after heating is preserved upon cooling down. In case 2, a partial production of martensite at the end of the cooling period causes a drop in the stress in the wire. Therefore, the final level of the force strongly depends on the test conditions.

NB: Steps (1) to (5) correspond to the preparation of the wires before setting up on the beams; Steps (6) and (7) simulate the response of the wires connected to the beams during activation of the memory effect.

3. THERMOMECHANICAL CHARACTERIZATION OF THE SMA WIRES USED

Nickel-titanium wires were used in the present study, with the following features: diameter 1 mm, composition $Ni_{50.8}$-$Ti_{49.2}$ (% at.), transformation temperatures A_s = 23°C, A_f = 28°C, M_s = -10°C, M_f = -25°C. Characterization tests were performed on 150 mm long wire coupons by means of a MTS testing machine ±15kN. The ambient temperature T_A was 19°C ± 1.5°C. The objective was to determine the relationship between the prestrain ε_{mart} at the end of step 5 and the force obtained in the wire during the thermal cycle. More precisely, two particular values were derived from the experimental measurements:

– the maximum value of the force obtained upon heating of the wire after return to the austenitic state (end of step 6). This value is denoted F_{aust} in the following.
– the ultimate value of the force obtained upon cooling down after return to room temperature (end of step 7). This value is denoted F_{res} in the following.

Figure 3 shows the values obtained for F_{aust} and F_{res} in terms of ε_{mart}. It is observed that F_{aust} increases with ε_{mart}. This force is preserved upon cooling down ($F_{res} = F_{aust}$) for low ε_{mart} *values*. A loss is observed ($F_{res} < F_{aust}$) after cooling down (end of step 7) when ε_{mart} exceeds a given value. This effect was expected in view of Figure 2-b (case 2), but the fact that F_{res} is constant whatever ε_{mart} over the limit

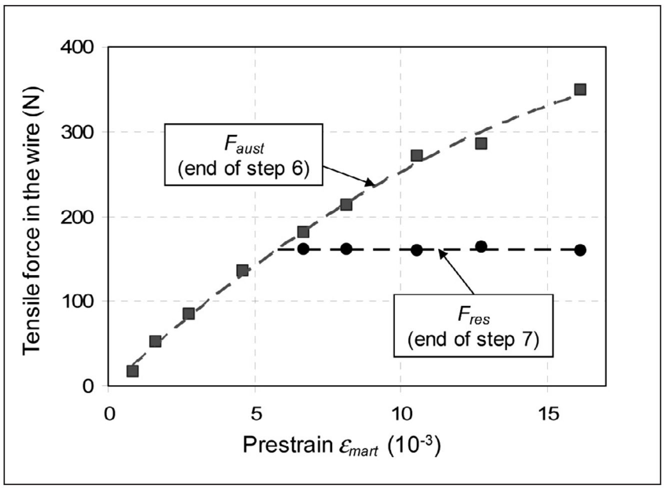

Figure 3. Maximum value F_{aust} and final value F_{res} of the tensile force obtained after thermal activation of the memory effect, in terms of the prestrain ε_{mart} given to the wire in the martensitic state.

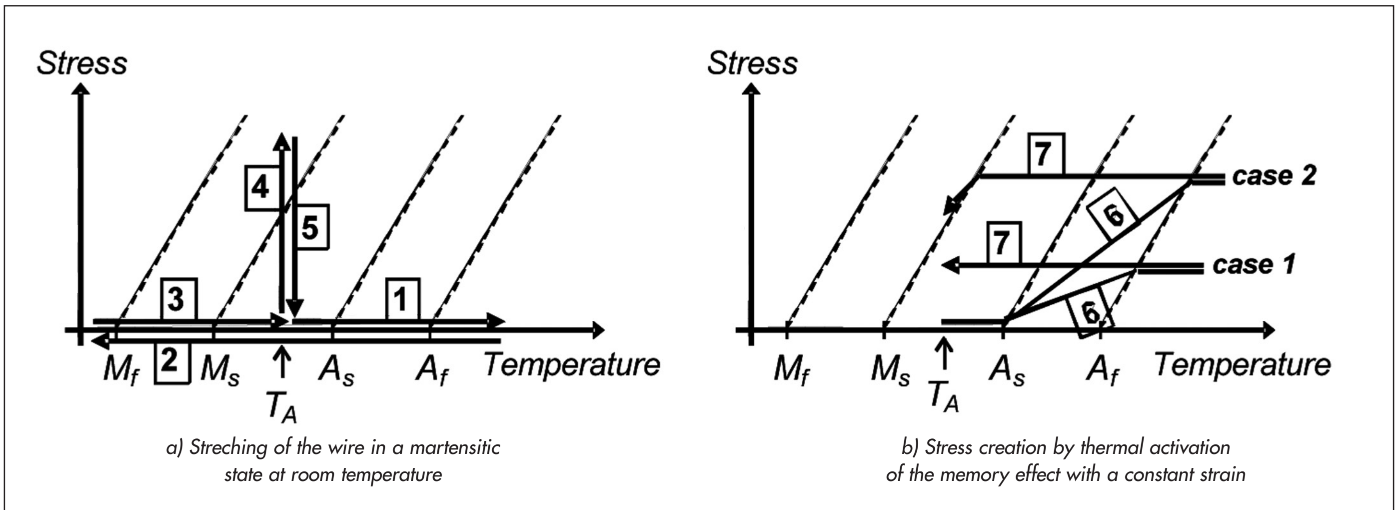

Figure 2: Seven steps procedure for the creation of a tensile force in a SMA wire by thermal activation of the memory effect.

value was not obvious a priori. An additional tensile test provided the Young's modulus of the wire in the austenitic state (62.9 GPa).

4. CREATION OF PRESTRESS STATES IN THE CONCRETE BEAMS

4.1. Preparation of the beams

Three plain concrete beams 48x60x520 mm in size were prepared for the tests. Given the size of the beams, the aggregate maximum size was limited to 8 mm. The beams were stored in plastic foils to prevent moisture loss during 28 days. Then they were kept in the ambient atmosphere of the laboratory until the tests performed between 6 and 10 weeks after casting day. Each beam was equipped with two strain gauges 30 mm in length bonded at mid-span on its upper and lower faces along the longitudinal axis. The modulus of elasticity of concrete was determined at the time of testing from strain measurements on the beams tested in three points bending (19.9 ± 1.7 GPa).

Anchor devices consisting of screws and steel plates were glued to the concrete at both ends of each beam (Figure 4). They were designed to securely attach the AMF wires onto the beam during the tests. Each anchor device was designed to accommodate 4, 8 or 12 wires. The wires were prepared according to the following procedure before being attached to the beams:

– Let the wires in a self-accommodating martensitic state – in this aim, the wires were heated to a temperature of +50°C (above A_f) and then cooled down to a temperature of -30°C (below M_f): see Figure 2-a, steps 1-3.
– Stretch the wires at room temperature (below A_s) to obtain a residual prestrain ε_{mart} in a oriented martensitic state after unloading: see Figure 2-a, steps 4-5.

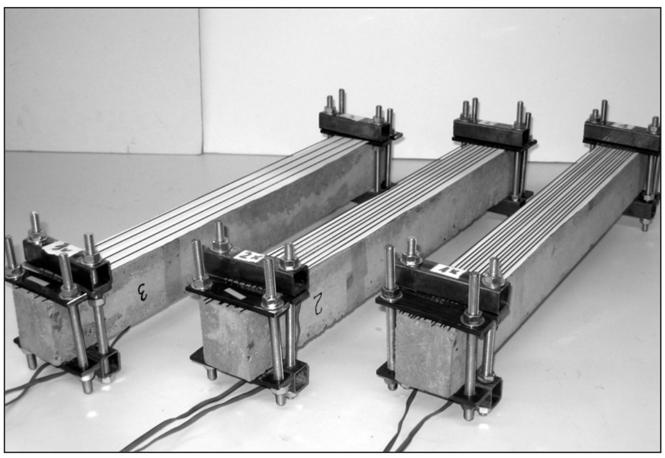

Figure 4: View of the three concrete beams equipped with AMF wires.

Six series of tests, each comprising three beams were conducted (Figure 4). Each series corresponds to a fixed value of the prestrain ε_{mart} in the oriented martensitic state. The selected values are given in Table 1 for each of the six series.

series:	1	2	3	4	5	6
$\varepsilon_{mart}(10^{-3})$:	1.6	2.6	4.0	6.0	8.2	10.2

Table 1: Prestrain of the AMF wires in an oriented martensitic state for the six test series.

4.2. Realisation of the tests

Each test series began with the preparation of the AMF wires according to the procedure explained above. Then, the wires in the prestrain martensitic state were attached to each of the three beams (4, 8 or 12 wires). The beams were placed in a controlled thermal chamber. The temperature was raised to 60°C at a rate of 1.6°C / min., then cooled down to room temperature at a rate of 0.8°C / min. The temperature rise beyond A_f caused the wires to return to an austenitic state. Since the wires were not free to recover their original length, the $M \rightarrow A$ transformation yielded the emergence of a tensile force in the wires which acted as a prestressing force and caused the deformation of the beam.

The strains measured during the tests are presented in Figure 5 for the three beams of Series 4 (ε_{mart} = 6.0 10^{-3}). For each beam, the solid line represents the longitudinal strain measured at mid-span on the side equipped with the AMF wires, while the dotted line represents the strain on the opposite side. Starting from a zero initial deformation, one observes that the strains increase in absolute value from about 27°C and then stabilize beyond 58°C. These strains result from the progressive tensioning of the wires due to the thermal activation of the memory effect (gradual return from an oriented martensitic state to an austenitic state). The slope observed upon cooling down results from the thermal contraction of the wires in the austenitic state.

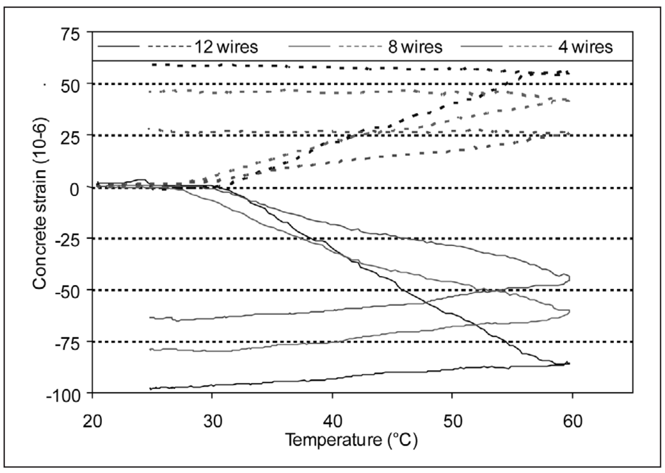

Figure 5. Measured strains vs. temperature for the three beams of series 4.

4.3. Interpretation of the test results

Basing on the classic equations of the beam theory, it is easy to deduce the evolution of the tensile force in the SMA wires from the strains measured during the tests. As an example, the values vs. time are plotted in Figure 6 for the three beams of series 4. Each of the curves presented can be analyzed in three phases. The initial phase where the force remains equal to zero corresponds to the time required to reach the temperature corresponding to the beginning of the austenite to martensite transformation. The rising phase that follows it (up to 1800 s.) corresponds to the thermal activation of the memory effect. During this phase, the gradual return to the austenitic state is accompanied by a cancellation of the prestrain given to the SMA wires in the oriented martensitic state. Since this transformation occurs in blocked strain condition, it induces a gradual development of a tensile force in the wires. The third phase (beyond 1800 s) corresponds to the cooling phase of the wires in an austenitic state. The slightly ascending plateau observed during this phase is due to the gain of additional force resulting from the thermal contraction of the austenitic wires during this cooling phase. The final value of the force is the total prestressing force exerted on each beam by the AMF wires after return to room temperature in the austenitic state.

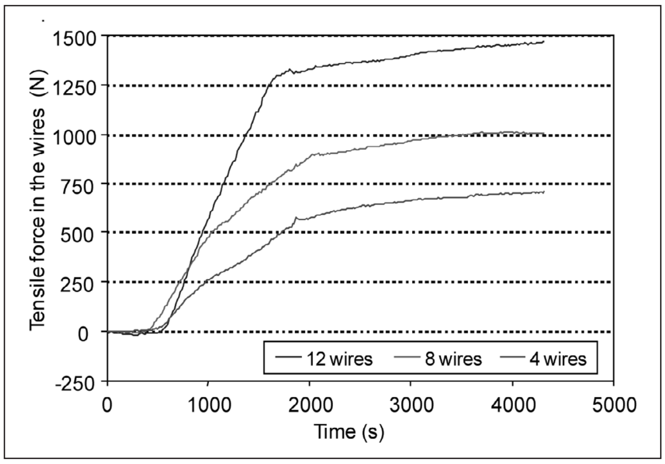

Figure 6. Evolution of the total tensile force in the wires for the three beams of series 4.

Figure 7 compares the evolutions of the tensile forces for the six beams equipped with 12 wires (series 1-6). It is observed that for the beams of series 1-4, which correspond to values of the prestrain ε_{mart} between 1.6 10^{-3} and 6.0 10^{-3}, the ultimate tensile force increases with the value of the prestrain ε_{mart} given to the wires in the martensitic state. For beams of series 5 and 6, corresponding to prestrains ε_{mart} equal to 8.2 10^{-3} and 10.2 10^{-3}, the tensile forces decrease during the cooling phases to a final value of approximately 1400 N close to that achieved for the series 4 beam. This result can be compared with the relationship shown in Figure 3 for the SMA wire behaviour. One observes in this figure that beyond a prestrain equal to about 6.0 10^{-3}, the F_{aust} force induced in the wire by thermal activation of the memory effect decreases to reach the value F_{res} after return to room temperature. As shown for case 2 in Figure 2-b, this phenomenon results from a stress induced production of martensite when the $A \rightarrow M$ threshold is reached upon cooling down. Since the $A \rightarrow M$ transformation temperature increases with the stress in the SMA, this phenomenon occurs only when the force in the wire exceeds its limit value at room temperature.

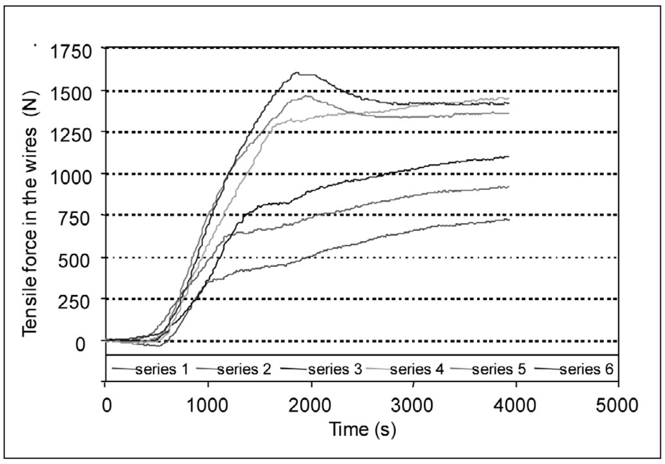

Figure 7: Evolution of the total tensile force for the 12 wires beams.

The prestressing effect created during the activation of the memory effect in the AMF wires can be estimated from the curvature of the beams derived from the longitudinal strains measured on the upper and lower faces of each tested beam. The final values obtained for the curvature after return to room temperature are shown in Figure 8 for the eighteen tested beams. One observes that the effect of prestressing increases quasi-linearly with the prestrain ε_{mart} as far as it does not exceed 6.0 10^{-3}. Beyond this value, increasing the prestrain has no more influence on the final curvature, which is limited for each of the beams due to the limitation of the prestressing force due to a production of martensite in the wires upon cooling down.

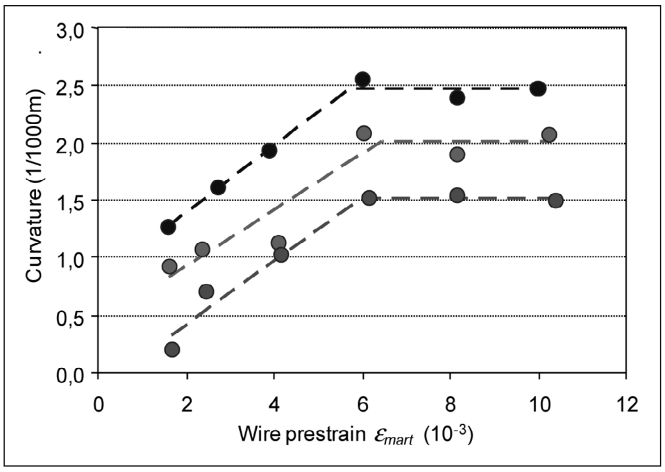

Figure 8: Final curvature induced in the beams by the prestressing effect.

This result emphasizes the influence of the transformation temperatures on the final effective prestressing force. An inappropriate choice can lead to an instant loss by partial production of martensite upon cooling down. Long term losses of a similar nature can also occur if the component is exposed to an excessive fall in temperature during its existence (outdoor works especially). Thus, one sees that the choice of the transformation temperatures is critical to minimize the losses and ensure the permanence of the prestress states created in concrete components by memory effect.

5. CONCLUSION

The present study demonstrates the possibility to induce prestress states in concrete beams using nickel-titanium SMA wires. The procedure is to stretch the wires in a martensitic state before securely fasten them on the concrete beams. The memory effect is activated by raising the temperature above the transformation temperature A_f in order to cause the return of the wires to an austenitic state. This transformation causes the emergence of a tensile force in the wires which acts as a prestressing force towards the concrete component. This force has been estimated from the deformations measured in every tested beam. The tests enable to describe the process of developing the prestressing force during the thermal activation of the memory effect. The intensity of the force obtained depends on the number of wires and the prestrain given to the wires in the martensitic state. In the present case, it is highlighted that the final value of the prestressing force after return to room temperature is bounded by the value obtained for a prestrain equal to 6 10^{-3}. This effect results from a partial production of martensite which limits the prestressing force in the wires upon cooling down. An inspection of the relationship obtained between the prestrain and the curvature induced after return to room temperature shows that this effect results from the thermomechanical properties of the alloy constituting the wires, but it is not affected by the number of wires fixed to the beams. These results show that the choice of the transformation temperatures is a key point to ensure the permanence of the prestressing and to prevent losses in case of temperature fall.

Although the cost of nickel-titanium alloys can be an obstacle to their use for the creation of prestress states in concrete components, activation of the memory effect by simply raising the temperature is a significant advantage over other conventional methods of prestressing. There exists also iron-based SMA with lower performances than nickel-titanium SMA, but with lower costs more suited to industrial applications. A possible field of application could be the use of SMA as an alternative method for behaviour improvement or strengthening of existing structures.

6. REFERENCES

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