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Effects of semi-cyclic loading on the recovery stresses of iron-based shape-memory alloy bars

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Abstract

Shape-memory alloys (SMAs) have attracted considerable interest in structural engineering because of their ability to 'memorise' their original form when subjected to thermomechanical variations, a phenomenon termed the shape memory effect. By controlling the heating and cooling (activation) of SMAs under constrained deformation, recovery stresses can be generated, making SMAs suitable for use as prestressing reinforcement in concrete structures. However, recent studies suggest that the benefits of reinforcing with iron-based SMA (Fe-SMA) could be considerably reduced under semi-cyclic loading.
This paper focuses on analysing the behaviour of 16 mm diameter Fe-SMA reinforcing bars when subjected to consecutive activations and semi-cyclic tensile tests. Activations at different temperatures (160, 200 and 250ºC) were performed, followed by semi-cyclic load tests until high strain levels were carried out. The results show a correlation between the temperature reached during the activation and the recovery stress achieved. Furthermore, the data confirms that high strain levels induced by semi-cyclic loads can lead to a complete loss of the initially generated recovery stresses. However, by re-activating the Fe-SMA samples, it is possible to restore a similar level of the initial recovery stresses. Moreover, for practical structural engineering applications in RC beams, where strain increments might be modest, only partial stress losses would be produced. These partial losses could be treated, for designing, as a prestressing loss.

Keywords: Iron-based Shape Memory Alloys, Activation, Recovery stresses, Semi-cyclic loads

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1. Introduction

Shape memory alloys (SMAs) are smart materials with great potential to enhance civil engineering structures lifespan (Janke et al., 2005). In recent years, interest in the use of SMA as a reinforcing material has increased due to its unique ability to return to its original shape after being deformed, through an activation process involving heating and cooling back to ambient temperature. This property, known as the shape memory effect (SME), allows for the use of this material as prestressing reinforcement, as SMAs generate recovery stresses upon activation when the deformation is constrained. SME is the result of the reversible phase transformation between martensite and austenite that SMAs undergo in their lattice structure (Cladera, Weber, et al., 2014; Schranz, 2021). The lattice structure of the material initially undergoes a transformation from austenite to martensite (forward transformation) through mechanical deformation (prestraining). Subsequently, by heating the material to specific temperatures, martensite is converted back into austenite (reverse transformation). Through this process, the material attempts to recover its original shape. However, if the material's deformation is restrained during heating, recovery stresses are generated within it and can be used to apply prestress to civil structures (Lee et al., 2013; Mas et al., 2016).

Many practical applications of SMAs have been developed by Swiss Federal Laboratories for Materials Science and Technology (EMPA) in Central Europe (Schranz, 2021; Schranz, Czaderski, et al., 2019; Schranz et al., 2021). The development of iron-based Shape Memory Alloys (Fe-SMA), a less costly alternative to SMA, has extended the use of this technology, demonstrating exceptional potential for structural strengthening. This is further enhanced by the added benefit of its easy manufacturing process and installation (Cladera, Oller, et al., 2014; Izadi et al., 2018).

Despite these advantages, there are still unknowns regarding the capacity of SMAs to maintain recovery stress over time, particularly when the material is subjected to semi-cyclic loads. These loads, typical in the daily use of structures, are characterized for not producing tensile and compression inversion. Recent research has shown that under semi-cyclical loads the benefits of reinforcing with Fe-SMA are considerably reduced.(Schranz, Michels, et al., 2019).

This paper presents the results of an experimental campaign aimed at assessing and evaluating the losses in recovery stresses when subjecting the material to semi-cyclical loads. Different samples of a 16-mm Fe-SMA bar underwent to multiple activations (at 160ºC, 200ºC and 250ºC) and semi-cyclical load tests to assess the losses and to study the influence of the activation temperature on the generation and loss of recovery stresses. The tests conducted were part of a characterization campaign of the Fe-SMA bars, which were then used in a broader experimental campaign aimed at evaluating the effects of semi-cyclic loading on concrete beams elements strengthened with Fe-SMA bars.

2. Experimental campaign

2.1. Material

The 16-mm Fe-SMA bars were provided by the Swiss company *re-fer AG* (https://www.re-fer.eu/) with the composition of Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (mass%). The Fe-SMA bar was supplied in the martensitic phase with initial 4% prestraining, making the bar ready for activation to induce the reverse transformation and generate recovery stresses.

The characterization campaign was conducted on a Instron universal tensile machine equipped with a 500 kN load cell (Figure 1). The Fe-SMA bar were cut into 3 samples, each 300 mm in length, and tested with a free length of 140 mm, with 80 mm placed inside each clamp to securely grip the bar and prevent sliding.

The mechanical properties of the 16-mm Fe-SMA bar are detailed in Table 1. These values were obtained from the analysis of a monotonic test up to failure for the as-provided (P) and activated (A) bars (to 250ºC). The 16-mm Fe-SMA bar had a cross-sectional area of 211 mm^2 and the ultimate stress (f_u) and strain (ε_u) of the as-provided bar were 786 MPa and 24.70%, respectively. The mean proof stress at 0.2% ($f_{0.2}$), determined through the offset method, was equal to 491 MPa. The modulus of elasticity (E_1) of the Fe-SMA bar, calculated between 150 and 250 MPa, were 118 GPa. For the activated 16-mm Fe-SMA bar, f_u and ε_u were equal to 782 MPa and 31.15%, respectively. The $f_{0.2}$ was 489 MPa, and E_1 was 50 GPa (computed between 350 MPa and 450 MPa). Figure 2 shows the stress-strain curve resulted from the monotonic test up to failure for the as provided and for the activated bar.

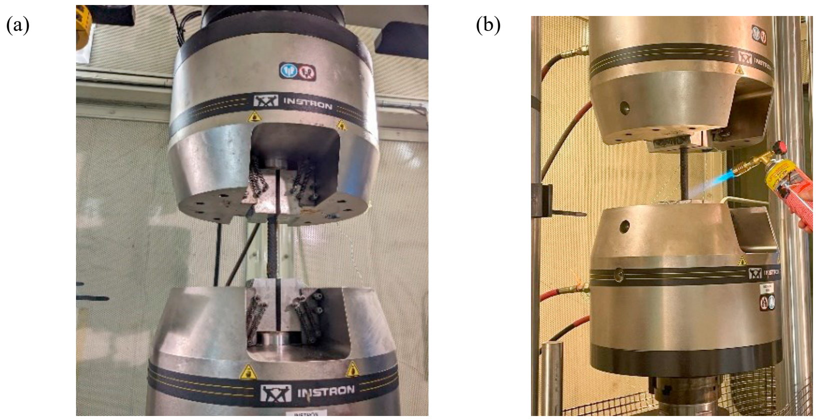


Figure 1. (a) Instron 500 kN universal tensile machine; (b) Heating of the Fe-SMA with a heat-gun

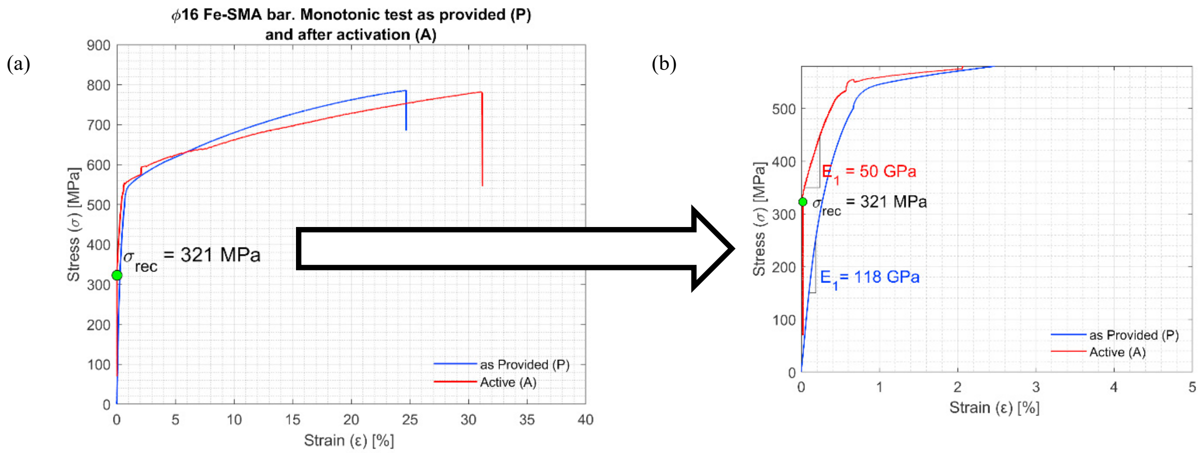


Figure 2. (a) Monotonic test up to failure for as provided bar (P) and activated bar (A); (b) Zoom of the low strain zone up to 5%.

Table 1. Mechanical properties of the Fe-SMA bars.

16-mm Fe-SMA bar	A_{SMA} (mm^2)	f_u (MPa)	ε_u (%)	$f_{0.2}$ (MPa)	E_{SMA} (GPa)*
As provided	211	786	24.70	491	118
Activated	211	782	31.15	489	50

* Measured between 150 and 250 MPa for the as provided ample and between 350 and 450 MPa for the activated sample.

2.2. Recovery-stress and semi-cyclical load tests

Three Fe-SMA samples were activated at three different temperatures (250°C, 200°C, and 160°C) to find a correlation between the activation temperature and the attainment of recovery stress, as well as to evaluate the material's capacity to generate consistent values of recovery stresses across multiple activations.

The recovery stress tests were conducted on a Instron universal tensile machine equipped with a 500 kN load cell, and the procedure consisted of two steps. First, an initial pre-load of 165 MPa was applied to prevent compression and buckling during heating, due to the thermal expansion effect. Second, the Fe-SMA bar was heated to 250°C, 200°C, and 160°C using a heat gun, as seen in Figure 1b. During the heating and cooling processes, bar deformation was prevented by maintaining a constant strain level, while the load cell measured the generated stresses to keep deformation impeded. Upon activation, as the sample wanted to shorten due to the reverse transformation, the tensile stress within the sample increased as the deformations were impeded, thereby generating recovery stresses. Heating and cooling temperatures were monitored using three thermocouples evenly distributed along the free length of the Fe-SMA bar. To ensure accurate temperature measurements, heating was conducted on the side opposite to where the thermocouples were positioned.

The recovery stress tests were followed by a semi-cyclical load test to assess the loss of recovery stress subjecting the material to these types of loads. This test consisted of five load and unload cycles (without sign inversion), with an increment in strain ($\Delta\varepsilon$) per cycle of 0.1%, reaching a total strain level of 0.5%.

These tests were consecutively repeated five times for each temperature. Consequently, each activation was followed by a semi-cyclical load test, and each semi-cyclical load test was followed by an activation. Note that, after the semi-cyclical load test, the preload of 165 MPa was applied each time.

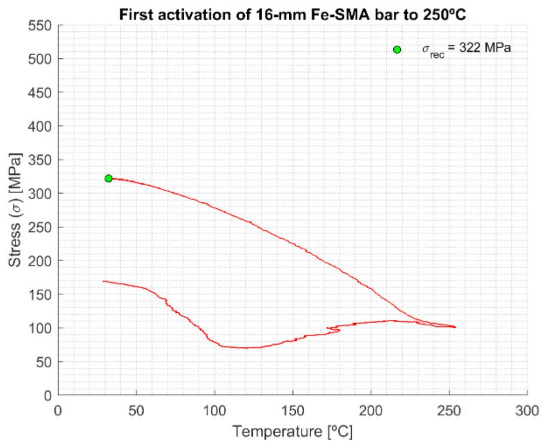
3. Results and discussions

3.1. Activation at 250ºC and semi-cyclical load tests

Figure 3a represents the stress-temperature curve during the 1st activation to 250°C. The thermal expansion of the bar led to a reduction in stress until 250°C was reached. When the bar was left to cool, the tensile stress increased due to the reverse martensitic transformation and the SME, generating a recovery stress of 322 MPa.

From that point, five semi-cyclical loads, each with an increment in strain of 0.1% per cycle, were applied. Figure 3b illustrates that the previously generated recovery stress is almost entirely lost upon the application of the semi-cyclical loads, as at the end of the test, the stress decreased from 322 MPa to 40 MPa.

(a)



(b)

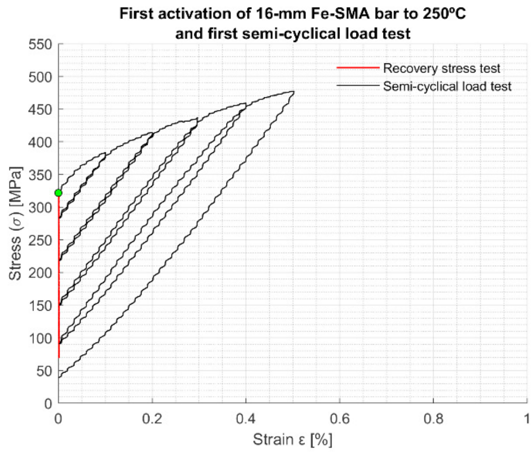


Figure 3. (a) Stress-strain temperature curve during the first activation to 250ºC; (b) Semi-cyclical load test after the first activation to 250ºC.

These tests were performed consecutively five times. Figure 4a illustrates the five activations at 250°C, along with their corresponding recovery stress values, and Figure 4b shows the five semi-cyclical load tests performed after each activation. The results indicate that the recovery stresses generated by activating the Fe-SMA bars are lost when the bars are subjected to semi-cyclical loads. By applying five semi-cyclical loads with 0.1% strain increments per cycle and reaching a final strain level of 0.5%, the bars lose the previously generated recovery stress. However, this stress can be fully recovered if the bars are reactivated, as the values of recovery stresses obtained after each activation were all between 308 MPa and 322 MPa. The differences in these values may be explained by the difficulty in heating the bar homogeneously with the heat gun.

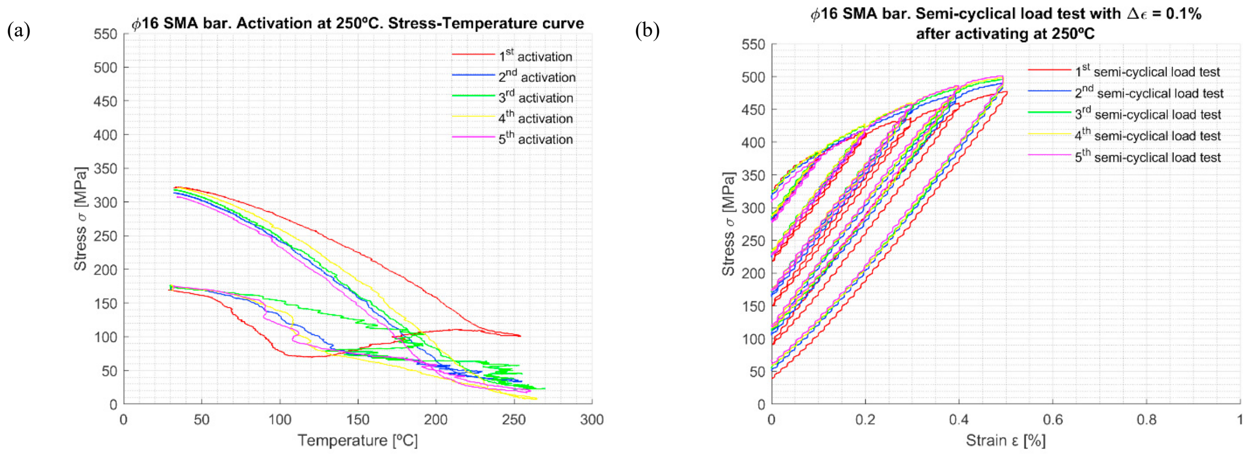


Figure 4. (a) Five activations at 250ºC; (b) Five semi-cyclical load test performed after each activation at 250ºC.

3.2. Activation at 200ºC and semi-cyclical load test

The same procedure was followed to heat the bar to 200°C. The results indicated that recovery stresses were totally lost when the Fe-SMA bar was subjected to semi-cyclical loads (Figure 5b). After each activation, the recovery stress values ranged between 237 MPa and 248 MPa, showing full recovery after the application of the semi-cyclical load test (Figure 5a).

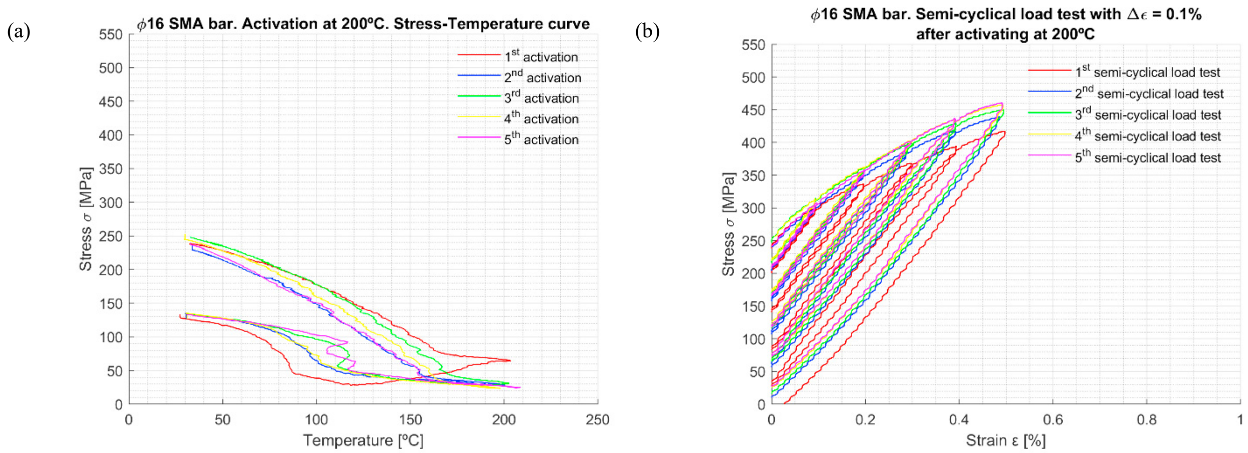
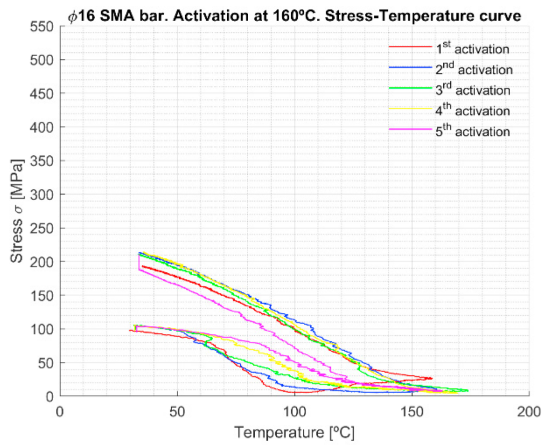


Figure 5. (a) Five activations at 200ºC; (b) Five semi-cyclical load test performed after each activation at 200ºC.

3.3. Activation at 160ºC and semi-cyclical load test.

The results of activating at 160°C followed the same trend as with activations at 200°C and 250°C, as seen in Figure 6. Recovery stresses were lost when semi-cyclical loads were applied to the Fe-SMA bar. Nonetheless, these losses were counteracted by activating the bar again and obtaining recovery stress values between 194 MPa and 214 MPa.

(a)


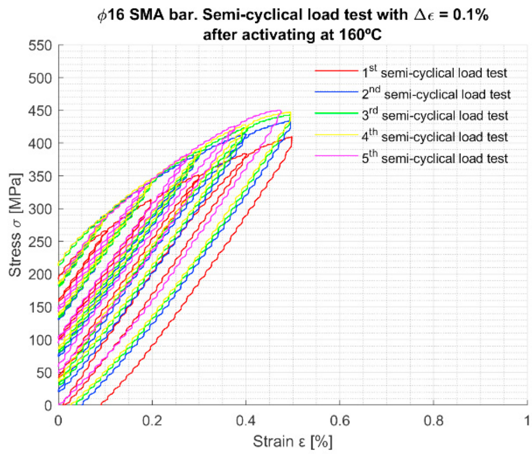
(b)


Figure 6. (a) Five activations at 160ºC; (b) Five semi-cyclical load test performed after each activation at 160ºC.

3.4. Comparison of results

Table 2 and Figure 7 present the recovery stresses obtained after activating the 16-mm Fe-SMA bar at three different temperatures. These results indicate a linear correlation between the activation temperature and the attainment of recovery stresses, exhibiting a 30% increase in stress for 50°C increment and approximately 20% for 40ºC increment. Figure 7 shows the linear increase in recovery stresses with the activation temperature.

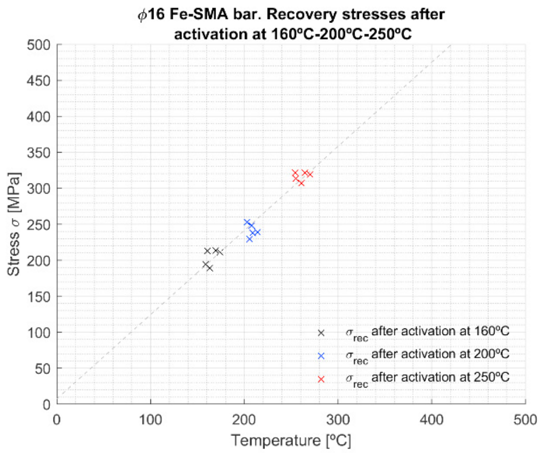


Figure 7. Recovery stresses after activations at 160-200-250ºC.

The achievement of consistent recovery stress values during multiple activations enables the counteraction of recovery stress loss induced by the semi-cyclical load tests. Hence, these results demonstrate that the efficacy of the martensitic transformation was not affected during either the multiple activations or the semi-cyclical load tests.

Table 2. Recovery stresses at different temperatures (250ºC, 200ºC and 160ºC) of 16-mm Fe-SMA bar.

	Activation temperature		
Recovery stresses	250ºC	200ºC	160ºC
1st σ_{rec} (MPa)	322	238	194
2nd σ_{rec} (MPa)	314	237	213
3rd σ_{rec} (MPa)	319	248	211
4th σ_{rec} (MPa)	321	253	214
5th σ_{rec} (MPa)	307	239	212
Mean (MPa)	317	243	209
Standard deviation (MPa)	6.2	7.1	8.3

Figure 8a represents the evolution and losses of the recovery stresses during the semi-cyclical loads applied after the activations at three different temperatures. By activating at 160ºC and 200ºC, the Fe-SMA bar exhibits higher stress losses for each increment of strain, achieving a loss of 100% after reaching a strain level of 0.5% for 160ºC and 200ºC (Figure 8b). At 250°C, there was a mean stress loss of 89.44%, indicating that at a strain level of 0.5%, stress losses do not depend on temperature; however, whether the loss is total or partial depends on it.

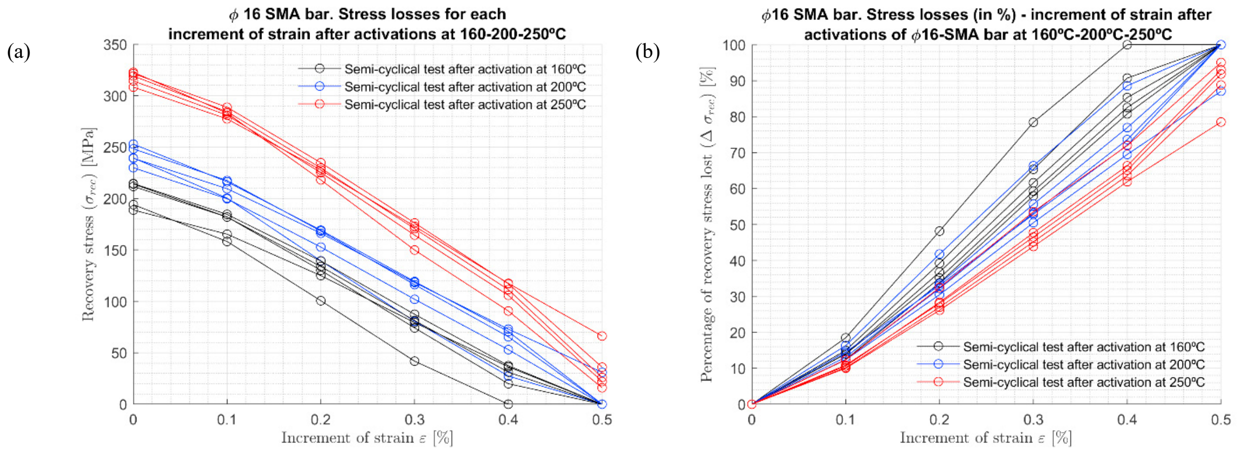


Figure 8. (a) Recovery stresses after activations at 160-200-250ºC; (b) Stress losses (%) for each increment of strain during semi-cyclic load test.

4. Conclusions

The results of the 16-mm Fe-SMA characterization campaign confirmed that there is a loss of recovery stresses at the material level when semi-cyclical loads are applied to Fe-SMA bars. For the samples activated to 160°C and 200°C, a 100% loss was observed for strain increases equal to 0.5%, while bars activated to 250°C experienced an average stress loss of 70.22% for the same strain increase. However, by reactivating the Fe-SMA bars, these losses were counteracted, as consistent values of recovery stresses were obtained in the multiple activations performed after the semi-cyclical load tests.

The results also indicate a linear correlation between the activation temperature and the attainment of recovery stresses, exhibiting a 20-30% increase in stress for every 40-50°C increment.

Future work will encompass investigating the behaviour of Fe-SMA under semi-cyclical loads after exposure to a high-temperature treatment. This research aims to further understand the material's response to different activation temperatures, potentially enhancing the design and application of Fe-SMA in structural engineering.

These tests were part of a characterization campaign for a broader experimental campaign that consists of manufacturing eight beams strengthened with Fe-SMA bars, which were subjected to semi-cyclical loads and various activation procedures.

5. Acknowledgements

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