25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

# COBEM2019-1857
# EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE BEHAVIOR OF NITI HELICAL MINI-SPRING UNDER LARGE STRAIN

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***Abstract.*** *This work has as its objective to simulate the behavior of a superelastic NiTi helical mini spring under large deformations (above 300%). Specifically, two types of loadings were used in these simulations, one simple ramp deformation and the other with an intermediate hysteric loop. These simulations were made by implementing two numerical models proposed by Auricchio based on the SMA properties, both models are within the ANSYS® software, which was used in the simulations. One model was based in the Superelasticity (SUPE) and the other based in the Shape Memory Effect (SME). The results were verified when directly compared to the mini spring experimental responses. In the simple loading case both models were able to reproduce the real phenomenon with enough precision. For the loading in loop, only in the SME model was it possible the representation the phenomenon. It was verified that the simulation using the SUPE model requires only 10% of the time for the simulation using the SME.*

***Keywords:*** *Superelastic mini spring, Shape Memory Effect, Superelasticity, Finite Element Method.*

## 1. INTRODUCTION

The term Shape Memory Alloy (SMA) is used to define alloys that have two peculiar properties: the Shape Memory Effect (SME) and the Superelasticity (or pseudoelasticity). The SME is due the capacity of initial shape recovery of the element after it is subjected to an adequate thermal field. The superelasticity allows the material to recover from large deformations. Both phenomena have their origin in the solid phase transformations that these alloys undergo when subjected to mechanical and thermal loads. These phenomena allow the usage of SMA as actuators and/or sensors, being part of the so-called smart materials (Lagoudas, 2008).

Due to these features, the SMA have been rather explored in the literature as an alternative to conventional actuators in various areas of engineering like aerospace, robotic, vibration control, among others. Analyses of the experimental thermomechanical behavior are usually done in works involving SMA elements. Furthermore, numerical simulations have increasingly been used to optimize devices projects, promoting good real phenomena representations. Among the various works in the literature we can mention the numeric analyses done in Aguiar et al (2009) e Da Silva (2014) using helical SMA springs.

Therefore, this work has as its objective to simulate the behavior of a superelastic NiTi helical mini spring under large deformations (above 300%). These simulations were made by implementing two numerical models of SMA within the ANSYS® software, one was based in the superelasticity (SUPE) and the other was based in the shape memory effect (SME). The simulations results were compared to the mini spring experimental responses.

## 2. MATERIALS AND METHODS

### 2.1 Helical Mini Spring

The actuator used in this work was a helical mini spring fabricated from a shape memory alloy superelastic wire of NiTi. The specific type of spring used in the analysis was M12, where "M" is the manufacturer designation and "12" is the number equivalent length between eyelets in millimeters, with useful length of 7.5 mm, totalizing 27 active turns (Emiliavaca, 2018). Both equivalent and useful lengths are showed in Fig. 1.

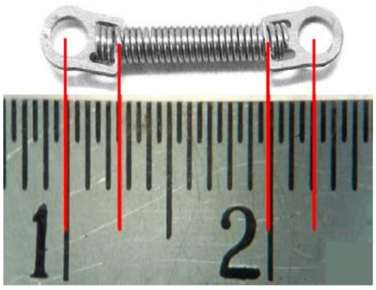



Figure 1. Mini helical SMA spring in scale.
Source: Emiliavaca (2016)

The spring is originally used for superelastic applications at room temperature given that its final austenitic temperature is around 17 °C. Under superelastic behavior, this element can recover a strain up to 500% without undergoing plastic strain. Under shape memory effect (SME) from the stress-induced martensite, it is necessary to identify the initial and final load conditions of each phase transformation (A→M e M→A).

### 2.2 Numeric Models

The commercial software Ansys Workbench® version 2015 was used for the numeric simulations using the superelastic (SUPE) and memory shape effect (SME) models proposed by Auricchio. The evaluation goal between these two models is related with the best representation of the hysteretic behavior of the mini helical spring, aiming for future simulations of some mechanisms.

The SUPE model, introduced in Auricchio (2001), consists of an efficient and robust algorithm used in computational tools using the finite element method for superelastic SMA. The necessary properties for this model are in Tab. 1.

The SME model, presented in Auricchio (2002), was based on the 3D thermodynamic model for solid phase transformations induced by strain. Within the classical structure of thermodynamics, the model can reproduce all the main functions of the SMA in a 3D strain state. To implement such a model the properties present in Tab.2 are necessary.

Table 1. Input data used in the SUPE model.

| Parameter | Description | Value |
|---|---|---|
| E | Austenite Young's Modulus (MPa) | 75000 |
| $\upsilon$ | Poisson's ratio | 0,3 |
| $\sigma_s^{AS}$ | Starting stress for the forward phase transformation (MPa) | 560 |
| $\sigma_f^{AS}$ | Final stress for the forward phase transformation (MPa) | 1050 |
| $\sigma_s^{SA}$ | Starting stress for the reverse phase transformation (MPa) | 430 |
| $\sigma_f^{SA}$ | Final stress for the reverse phase transformation (MPa) | 320 |
| $e_L$ | Maximum residual strain (mm/mm) | 0,07 |
| $\alpha$ | Parameter measuring the difference between material responses in tension and compression | 0 |

Table 2. Input data used in the SME model.

| Parameter | Description | Value |
|---|---|---|
| E | Austenite Young's Modulus (MPa) | 75000 |
| $\upsilon$ | Poisson's ratio | 0,3 |
| h | Hardening parameter (MPa) | 560 |
| $T_o$ | Reference temperature (K) | 250 |
| R | Elastic limit (MPa) | 100 |
| $\beta$ | Temperature scaling parameter (MPa/K) | 6,8 |
| $E_m$ | Martensite Young's Modulus (MPa) | 75000 |

| | | |
|---|---|---|
| $e_L$ | Maximum transformation strain (mm/mm) | 0,07 |
| m | Lode dependency parameter | 0 |

All values in Tab. 1 and 2 were obtained through experiments using the mini helical spring in the laboratory.

### 2.3 Parameters used in the Ansys Numeric Simulation

To analyze the spring using FEM, it was used the element SOLID136 and mesh with 14003 nodes, enough for the result convergence. The environment temperature used in the simulations as well as in the experimental evaluation was 27 °C. One of the ends of the spring was fixed, while in the other was applied a load. In Fig. 2 is presented the spring with its respective mesh, designed in the Ansys Workbench®.

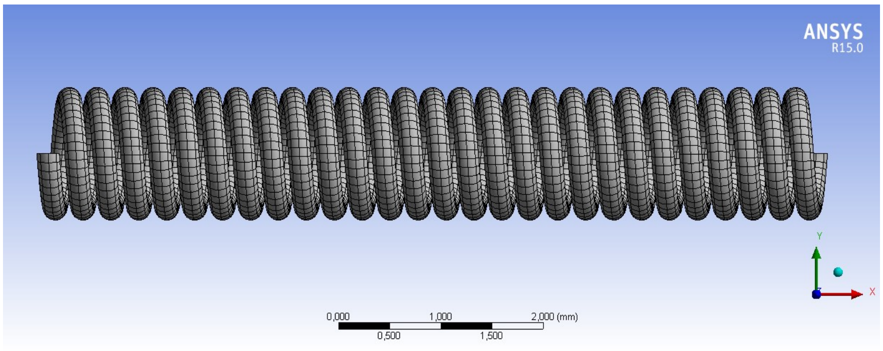



Figure 2. Spring with mesh designed in the Ansys Workbench®.

It was applied two types of mechanical loading about the mini spring in both evaluated models: SUPE and SME. The first type of loading was simply a ramp strain to the spring followed by the return to its original length, needing only two steps, each divided into 350 substeps for phenomenon representation, as presented in Fig. 3. These analyses were perfomed under strain of 300, 350 and 400% of the initial useful length of the spring. In the second type of loading, to represent a hysteretic loop, the spring was initially deformed until 30 mm (400%) in the end of the 1st step, in the 2nd step it was reduced to 22,5 mm (300%), again in the end of the 3rd step the spring reaches the displacement of 30 mm, and at the end of the 4th step occurs the unloading of the spring to its original length. The four steps are presented in Fig. 4. It was necessary to use 550 substeps in each step for correct representation of the real phenomenon.

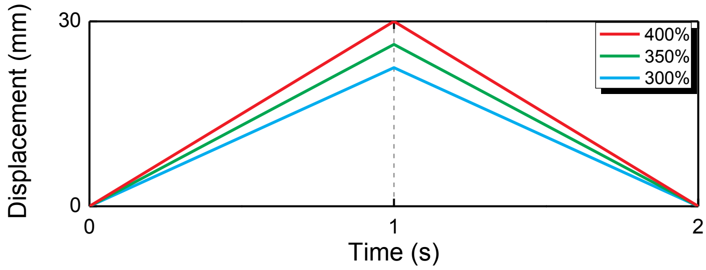



Figure 3. Simple mechanical loading cycle using strain 300, 350 and 400% of the springs initial length.

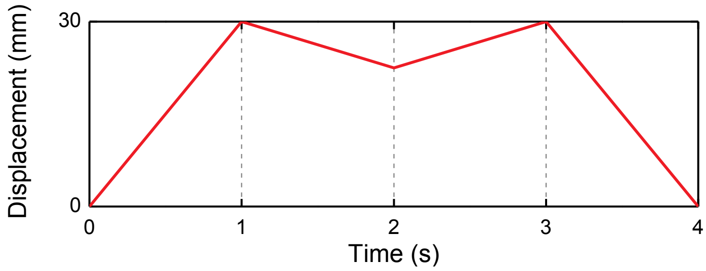



Figure 4. Mechanical loading used for hysteretic response evaluation. itial length.

## 3. RESULTS

The experimental and simulation results for the SUPE and SME models related to the 300, 350 and 400% strain for the simple ramp loading of Fig. 3 are presented in Fig. 5, 6 and 7. Through these pictures, it is observed the great similarity between the SUPE and SME models. There is a small difference between the simulations when compared to the experimental curve for the 400% strain. This case is common in the representation of SMA strain, due that the models are not able to predict a second linearity after plateau. As already described, both models can be used to represent the hysteretic behavior of the spring, but it is worth to point out that the simulation time for the SUPE model was only around 10% of the simulation time of the SME model.

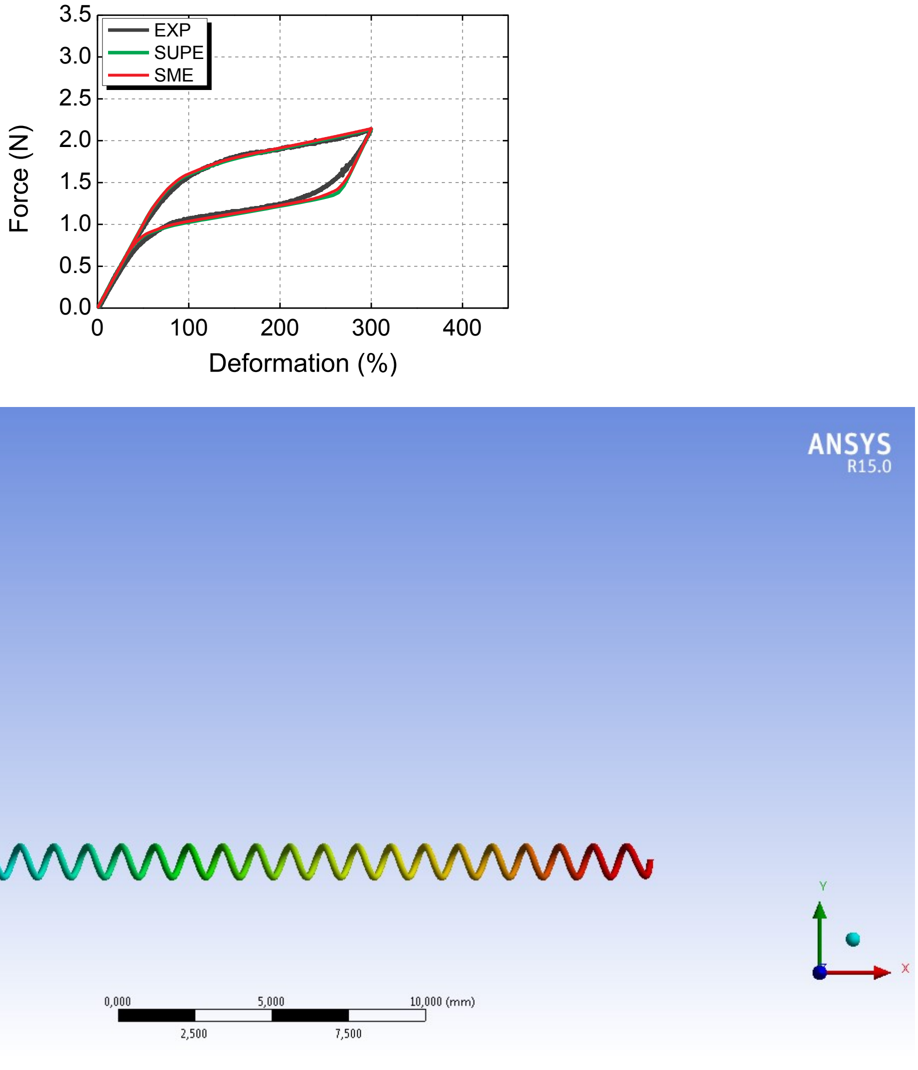
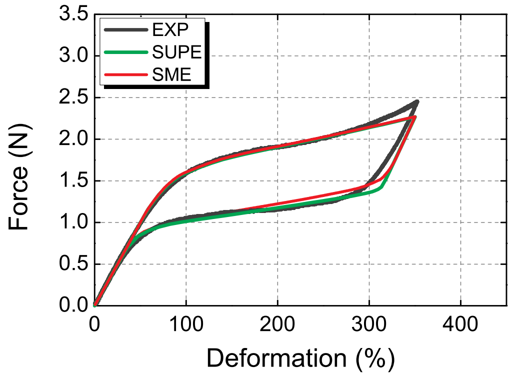



Figure 5. Experimental and simulation responses for loading up to 300% deformation.



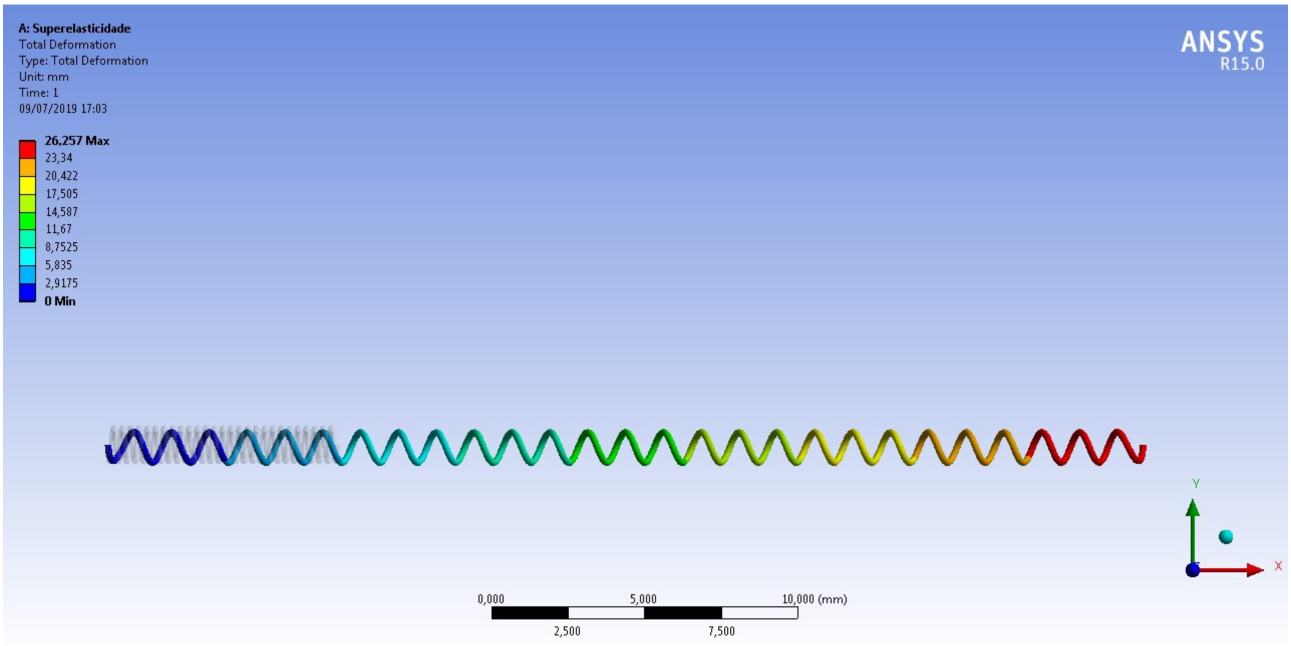
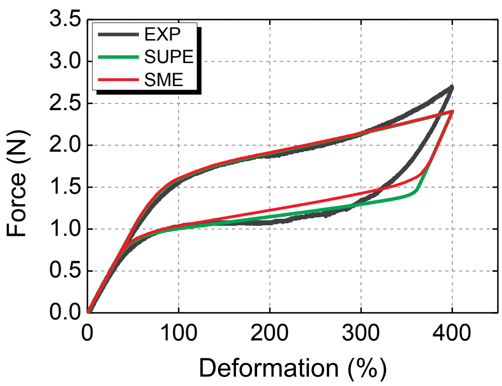



Figure 6. Experimental and simulation responses for loading up to 350% deformation.



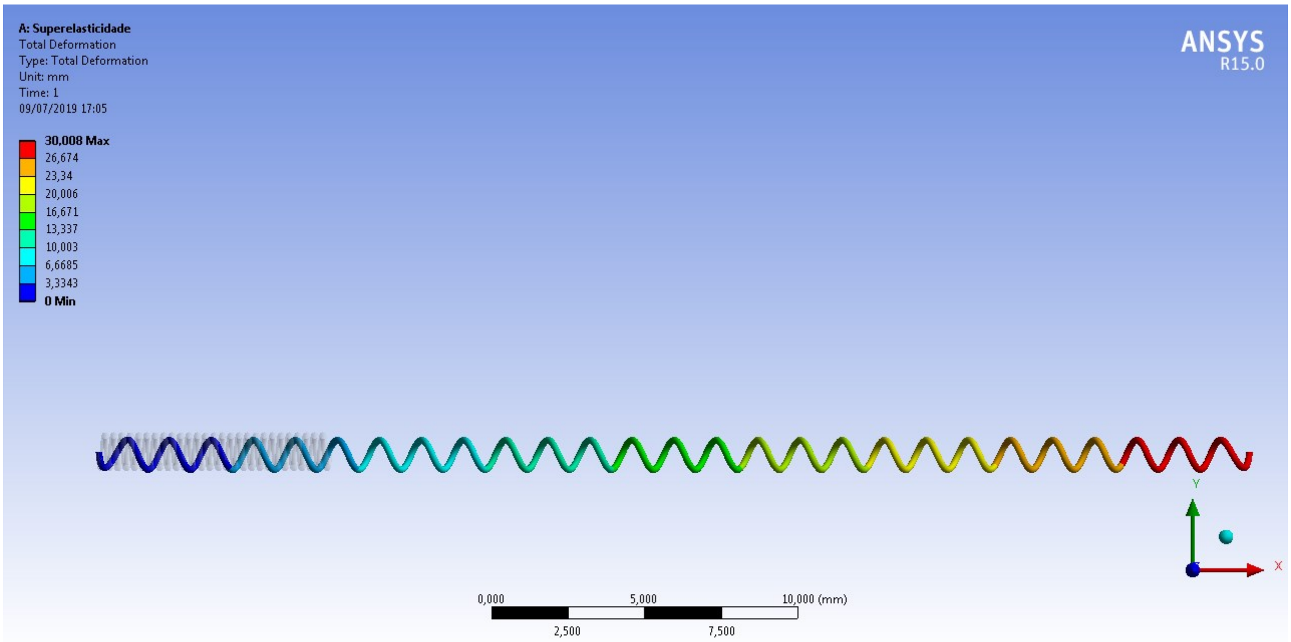




Figure 7. Experimental and simulation responses for loading up to 400% deformation.

In Fig. 8 are presented the results experimental (EXP) and of simulations SUPE and SME for the mechanical loading of Fig. 4. In all curves, a hysteretic loop is observed in the region of 300 to 400%, but in the SUPE model the reaction force of the spring after the first unloading is inferior to the reaction force using the SME model. In this case, the simulation using SUPE model does not represent well the hysteretic intermediate behavior as well as the SME.

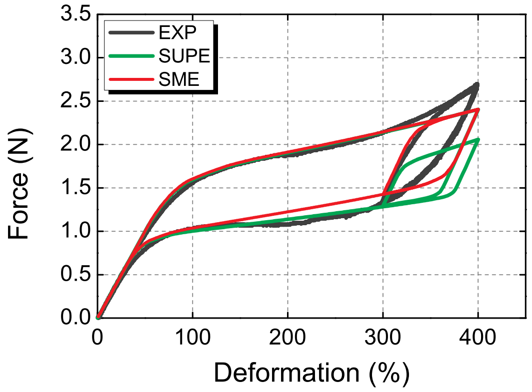



Figure 8. Experimental and Simulation responses to the hysteretic loading of Fig. 4

## 4. CONCLUSIONS

The presented results demonstrated the proximity between the studied models and the experimental data. As expected, the largest variations of 22.69% and 13.85% for the SUPE and SME models, respectively, were obtained for the 400% strain test. With respect to simulation time, the SME model requires approximately 10 times time longer than the SUPE model.

The aim of this paper was to verify the best representation of the phenomenon with the shortest processing time during simulations. This fact occurred for the SUPE model.

Thus, this spring, as well as the SUPE model, will soon be employed to perform numerical simulations on an SMA springs-driven rotary motor as outlined in Fig 9.

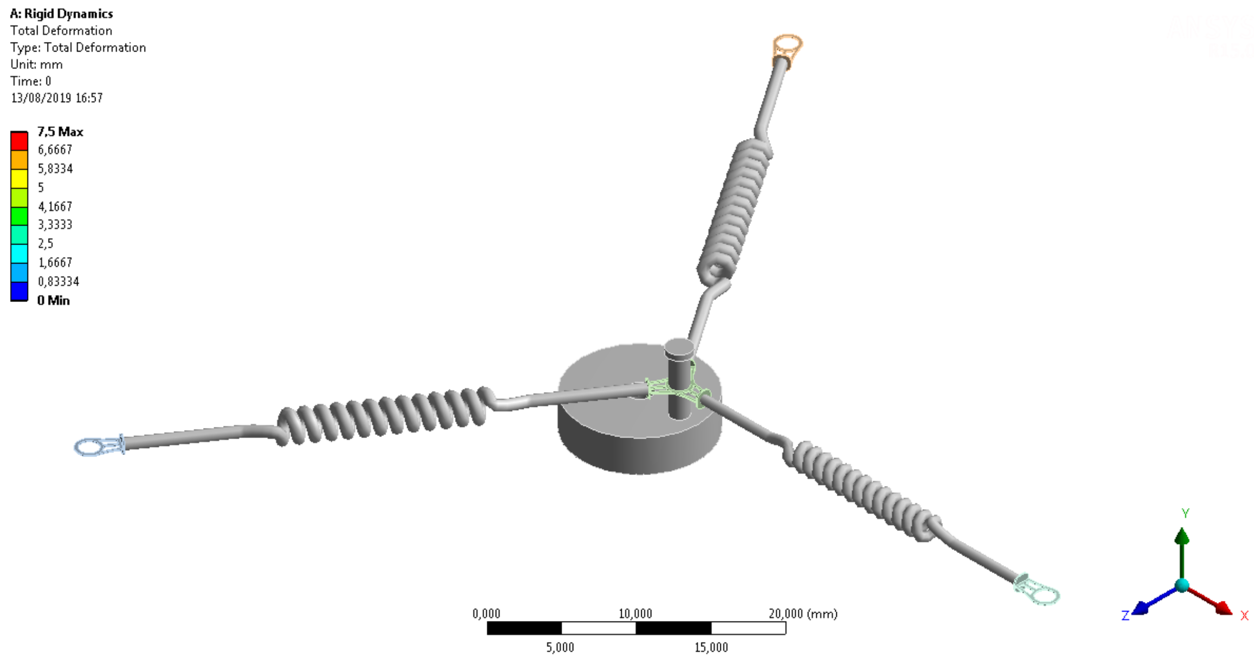



Figure 8. Modelo trifásico de um motor rotativo acionado por molas de SMA.

## 5. ACKNOWLEDGEMENTS

The authors thank to the Active Structures and Systems Laboratory (LaSEA) and the Coordination for the Improvement of Higher Level Education Personnel (Capes) by the research financing.

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## 7. RESPONSIBILITY NOTICE

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