International Journal of Mathematical, Engineering and Management Sciences
Vol. 8, No. 3, 424-443, 2023
https://doi.org/10.33889/IJMEMS.2023.8.3.024

Design and Development of Shape Memory Alloy Actuator for Preventing and Protecting Electrical Wires

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(Received on August 10, 2022; Accepted on March 21, 2023)

Abstract
Fatigue failure of wires is a frequent issue that evolves over time as a result of utilizing the profile under variable stress and temperature. In this article, an innovative study makes it possible to propose a protective tool for metal profiles against fatigue using shape memory alloys (SMA). Smart actuators like SMA are able to push back sudden stresses above the elastic limit, therefore, are characterized by high resistance to fatigue and even against corrosion due to their strong thermomechanical coupling. Besides, the study provides the results necessary to add a layer based on the shape memory tube to protect the important connectors for industrial systems and automotive industries. The conductivity of electrical current in various electronic devices depends on the copper material, which is good at conducting electricity and heat but weak against mechanical forces and hence easily susceptible to fatigue. Thereby, the elastic regime of copper is different from that of SMA, and in order to adapt the properties of two materials, a mathematical study can describe the behaviour of two combined systems is important for the analysis of the cyclic effect and for adapting the proposed actuator in wiring technology. Therefore, the study shows the great potential of the proposed SMA tube with its superelastic behaviour to increase the predicted lifespan of metallic wires against corrosion and fatigue. The lifetime of the conduction system with the protective SMA is increased remarkably and can reach up to 10^5cycles under the action of the stress of an amplitude of 550 MPa, the finite element simulation shows that the system of SMA combined with a 4 mm wire undergoing significant stress up to 490 MPa that can reach a deformation of 7% and return to the initial state without residual deformation. The simulation's results look at the evolution of stress, strain, fatigue lifetimes, and anticipated damage, and they match the experimental results of SMA tube properties rather well. Consequently, the verification of the proposed model confirms the improvement in the lifespan of studied wires compared to wires without SMA encapsulation.

Keywords- Shape memory alloy, SMA, Cover protection, Electrical wires, Wire protection.

1. Introduction

Fatigue phenomena in an aggressive environment are the most common causes of structural and electrical power line cable failure (Xue et al., 2020). Wires are exposed to a combination of mechanical loads, vibration, and self-heating in service that creates cyclic stress and brings failure over time (Abavisani et al., 2021). Besides, the relative actions between wires, sides and plastic encapsulation produce fatigue and corrosion under stress, known as the fretting phenomena (Guan et al., 2022). The lifespan and operation reliability of the metallic wires are connected to the security of industrial systems, workers and productivity effectiveness. Because wire ropes have a finite lifespan, early replacement wastes resources, while late replacement increases the danger of damaging industrial systems during running. As a result, wire rope effectiveness and security is really a significant and beneficial study topic (Karna et al., 2021). In this way, cables and wires are essential parts for connecting the mechanisms of an electrical or mechanical system (Williams et al., 2010; Rizzello and Motzki, 2022). Nevertheless, these structures are constantly encountering various constraints, especially in mobile systems such as robotic machines (conveyor, manipulator robot arm, mechanical crane, etc.). The most field that utilizes different metallic wires is planes, cars, and locomotives which is any issue in the wire that can affect mobility and security (Lor et al., 2022). Hence, it is indispensable to protect these sensible organs against aggressive circumstances.

Wiring is increasingly being used in the car industry to help drivers or automate specific operations. Recently, much research has been conducted on material fatigue in order to increase the lifespan of wires. For instance, Laurino et al. (2014) investigated the fatigue effects on connecting wires in the automotive industry. As a result, it has been concluded that it is better to replace the copper used for wiring harnesses with aluminum alloys to beat fatigue and corrosion. Ross et al. (2020) developed a new strategy for preventing corrosion based on recently discovered mechanistic insights into corrosion prevention. It has been established that early testing runs can reduce the faults due to reliability requirements, which are necessary for self-driving vehicles and wearable electronics and microelectronics. Tobias (Werling et al., 2020) studied the electro-mechanical behaviour of automotive high-voltage busbars and the relationship between the critical load limits and failure behaviour in order to improve the voltage of battery systems. As a result, the operating conditions need to be improved in order to increase the estimation precision of precarious circumstances for optimizing high-voltage battery systems.

Besides, Hu et al. (2022) presented a numerical investigation of end-fixed wire bending fatigue failure characteristics. They come to the conclusion that the diameter contraction ratio increases as bending fatigue durations increase, but this growth slows down. Xue et al. (2020) investigates the behaviour of fretting phenomena as fatigue of high-strength metallic wire in service in order to establish a fatigue life prediction model taking into account the coupling effect between corrosion and fatigue. Wang et al. (2022) conducted fatigue experiments of a crack growth rate on high-strength steel wires under various stress ratios in order to build a numerical model. Experimental data and a statistical technique were used to determine the characterization parameters of fatigue crack development and critical fracture needed for numerical simulation. Hence, using encapsulation is indispensable for wiring, which uses tubing encapsulated cable and is suitable for facing the challenges of harsh environmental conditions associated with industrial systems. Jin et al. (2017) conducted an experimental study about tensile and uniaxial tension stress controlled fatigue on both the steel jacket and the copper conductor. The finding of the study shows that the system can be improved against fatigue by liberating the residual stress via heat treatment at high temperature.

Mittal et al. (2018) presented a deep analysis of multi-scale composites for protection and discussed the significant processing issues, and the multi-functionality of specifically developed multi-scale composites. The result demonstrates that the composite layer is capable of protecting the targeted system and can guarantee a reasonable degree of protection against important loads. Nevertheless, Ezrin and Lavigne, (2007) illustrates the various situations in which unexpected and unusual failures of polymeric materials can happen. As a result, polymeric materials cannot offer complete protection because damage might happen whenever they are in use under high fatigue cycle. Thus, it is important to choose the adequate material to improve the lifespan and the security of sensible important wires by protecting them from the exterior fretting phenomenon.

In this way, shape memory alloys (SMA) are multifunctional materials that have diverse features and can be a particular way against corrosion and fatigue as an exterior layer for protection. Actually, SMAs are commercially available in different forms: spring, tube, wire or ribbon. In this way, the selection of the particular shape of the SMA actuator for a specific task is based on the stress, the biasing force, the actuating/torque force and the operating frequency. As a result, the SMA geometry plays an important role in the actuation, so for an actuator to function properly, it is necessary to realize an important special to the selected geometry that is adequate to the active structure aimed at. Therefore, SMA encapsulated cable can be used as tubing to protect electrical and optical components from the pressure and corrosive effects of the harsh environment. In fact, shape memory alloys have the ability to find their earliest appearance after applied stress by heating under a specific temperature. Moreover, these materials have various thermo-mechanical features, which the most studied and researched are the pseudo-elasticity (PE) and the memory effect (ME) (Petrini and Bertini, 2020). At temperatures above final Austenite (Af), the alloy shows pseudo-elasticity, which can go back to its primary position after unloading. As well as the memory effect happens at temperatures under final Austenite after applying mechanical stress, then the alloy can return to its primary position after raising the temperature by heating (Wang et al., 2014).

In fact, all of the characteristics and qualities of the SMA that may be generated by heating or mechanical stress are because of martensitic transformation (Ko and Jeon, 2021). The latter is an outcome of the interaction between two phases a martensitic at a low temperature and austenite at a higher temperature (Li et al., 2020).

Martensitic transformation is a displacive phase change where atoms arrange with each other to generate a coordinated movement of atoms. Can be identified three transitions in the Ni-Ti by responding to the variation of the temperature and the variation of the stress.

At higher temperature (Af), the SMA is a full austenite phase as well as at a lower temperature (Mf), the SMA is fully martensitic. Actually, the Martensite can take two forms a self-accommodated (twinned martensite) form or an oriented Martensite (detwinned martensite) form (Chen and Wu, 2015). Thus, twinned martensite appears on decreasing temperature under Ms under unstressed conditions. In contrast, the variation of stress induced the material to alternate between austenite and oriented Martensite. Besides, the structure in detwinned martensite follows the stress direction while the temperature is under the martensite start (Figure 1).

Recently, much research has been conducted in order to integrate the shape memory alloy in different industrial and electrical devices due to their exceptional characteristics, which assure almost full protection against important stresses. Zhang et al. (2014) proposed a locking device that can look after the magnetic bearing reaction wheel from launch vibration damage. The finding shows that the shape memory alloy can protect the wheel and can withstand the thermal environment in the launch. Feng et al. (2021) experimentally investigated the electrical contact reliability of the SMA connector contacts against fretting, especially under fatigue and vibration conditions. The finding shows that the lower the frequency improved the pin wear that was opposed to contacting electrical efficacy. As a result, the use of shape memory alloys as a protection tool is very frequent in different fields such as actuators like spring, wire, cylinder and even tube forms. However, each actuator can be explained in a specific way, and it can be modeled for particular applications. Then the system can be validated the outcomes by following the steps and by starting the experimental process. Nevertheless, most of the time, a digital tool is indispensable in which that it can be utilized to obtain the required information in order to avoid wasting resources like time and money.

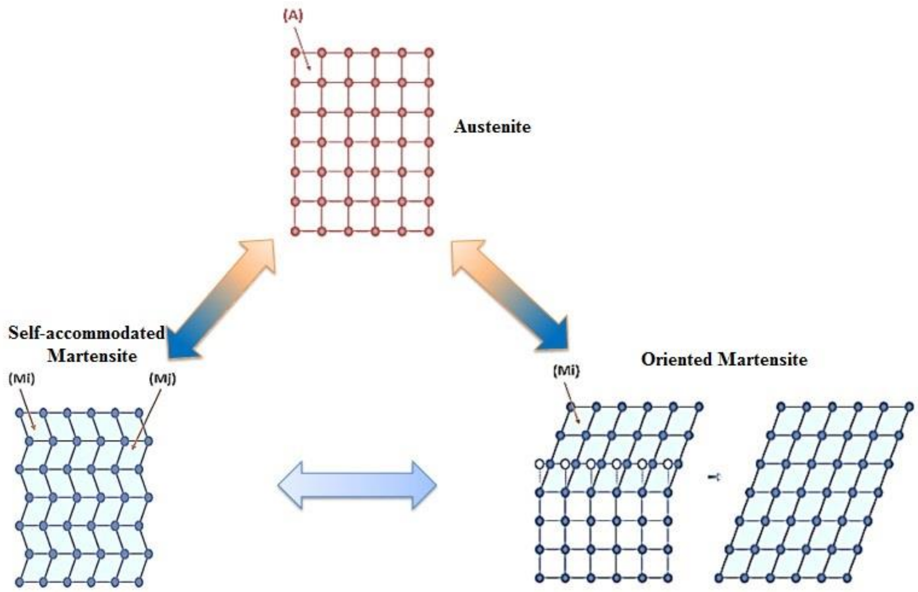

Figure 1. Description of types of fatigue in the shape memory alloy.

In order to ensure full protection of the electrical device against high and sudden stress, a thermomechanical actuator based on the shape memory alloy has been proposed. Then, thermo-mechanical modelling that can describe the SMA behaviour has been developed in order to adapt the proposed actuator to metallic wires under an adverse environment. Consequently, the novelty in this work is based on integrating a thermomechanical actuator tube based on the shape memory alloy with sensitive metallic wires as a layer of SMA actuator for preventing and protecting electrical wires against high and sudden stress, fatigue and even corrosion.

To summarize this introduction part, the main idea and purpose of the entire paper are laid out as follows: The Section 2 presents the procedure setup and research design. Section 3 deals with the modeling of the SMA material and suggested actuator. A comprehensive overview of the findings and discussion are discussed in Section 4. The research contribution was discussed in Section 5 just before conclusion and references.

2. Procedure Setup

In order to protect important wires in aggressive environment to avoid fatigue and fretting phenomena, an encapsulation of the shape memory alloy tube has been proposed. The proposed encapsulation is based on a shape memory alloy tube, as shown in (Figure 2).

For small stresses, shape memory alloys function in a super elastic way that enables them to absorb vibrations and dissipate them energetically either thermally or thermos mechanically. This prevents copper wire from wearing out over time, especially in vehicles that frequently endure mechanical fluctuations in the streets. For high stress amplitudes as mechanical shocks, the stress applied directly to the copper able to cut the electric current. Hence, experimentally, the addition of a plastic layer makes it possible to protect in a partial way the electric connection (Nasution et al., 2014; Khalid et al., 2020; Wan et al., 2022). Obviously, an inner part of SMA may absorb loads and vibrations, avoiding damage and fatigue (Tabrizikahou et al., 2022). Since the three layers work together to support each other, the SMA is able to keep the electrical wire linked and can avoid immediately detaching the electrical power.

The SMA tube is an effective technique for securing them from failure when fragile wires are subjected to varied stress and a harsh environment. The SMA encapsulation can help to delay failure following certain stressful events.

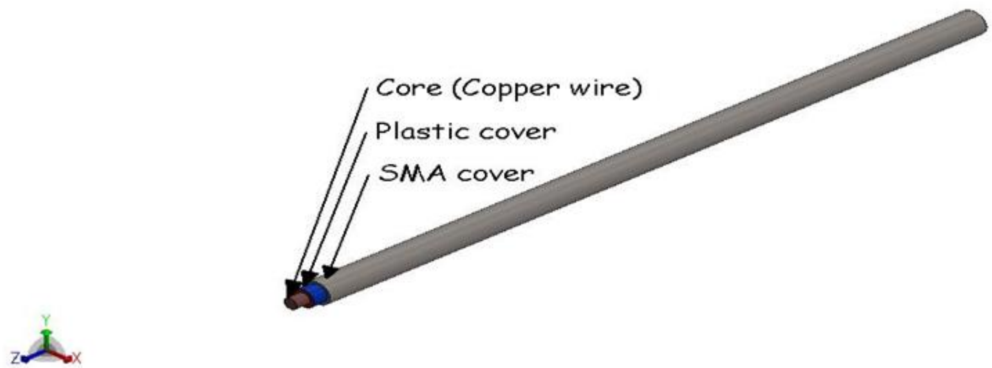

Figure 2. The proposed system of connector wire with SMA cover.

Actually, the wire can be subjected to different loading as tensile, compression or bending load. The bending stress induced by the deformation of a wire is in the cross-section of the wire (Figure 3). When the wire bends downward, there will be compression at the bottom and tension at the top. When the yarn bends upward, there will be compression at the top and tension at the bottom. For that reason, the study of tensile-compression loading is an implicit investigation of bending.

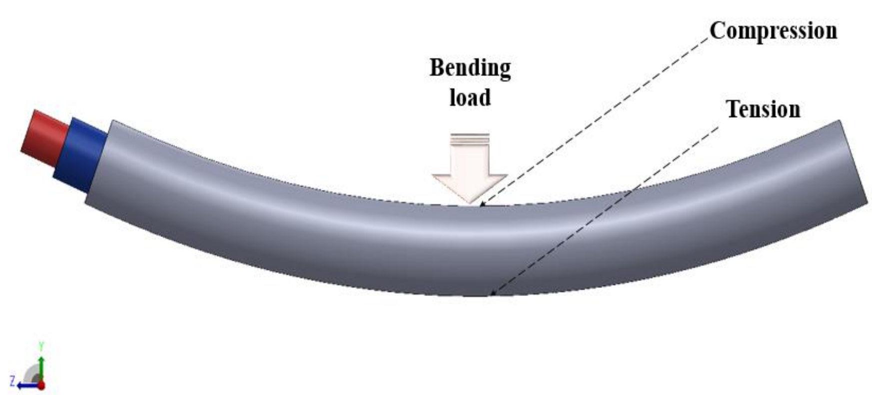

Figure 3. The proposed system under bending load.

3. Modelling

3.1 Modelling Coupled Thermo-Mechanical Governing Equations for SMAs

In this research, the developed model has been adjusted to describe the superelasticity and the memory effect in the SMA materials. The description of memory alloy behaviour can be carried out by the study of total deformation, which can be considered as the totality of partial deformations (Alhamany et al., 2004; Riad et al., 2017):

$$\xi_{tot} = \varepsilon^{e} + \varepsilon^{t} + \varepsilon^{Tr} \tag{1}$$

The elastic strain ε_e is:

$$\sigma = \mathrm{Y}.\,\varepsilon^{e} \tag{2}$$

where, σ is the mechanical stress, *Y* is the modulus of elasticity, the thermal strain ε^{t} is:

$$\varepsilon^{t} = \delta.(\mathrm{T} - \mathrm{T}_0) \tag{3}$$

As the volume of a constituent *V* it has been considered the f is the volume fraction. $\Delta T = (T\text{-}T_0)$ is the temperature variation and δ is the thermal expansion.

The deformation of transformation (Riad et al., 2020), ε^{Tr}:

$$\varepsilon^{Tr} = \frac{1}{V}\int_V (\varepsilon^{Tr})\, dV = \frac{V_M}{V}\frac{1}{V_M}\int_V (\varepsilon^{Tr})\, dV = f\bar{\varepsilon}^{Tr} \tag{4}$$

As a result, the relation between the volume fraction *f* and strain transformation is:

$$\varepsilon^{Tr}(x,t) = f\,(t)\cdot \varepsilon^{sat} \tag{5}$$

Considering ε^{sat} the saturation strain is the accumulation of infinitesimal deformations:

$$f(x,t) = 1 \tag{6}$$

It has been considered that the model equation is derived from the total deformation that has been decomposed from the previous partial deformation. It also makes it possible to relate the variation of global deformation to changes in temperature and stress and to take into account the different aspects of interactions. Then, the total energy that describes the different energy interacts with the system (Riad et al., 2020) can be written:

$$\psi = \psi^{e} + \psi^{T} + \psi^{Tr} + \psi' \tag{7}$$

ψ^{e} is the mechanical energy stored in the system as elastic strain:

$$\psi^{e} = \frac{1}{2\rho}\,(\varepsilon^{e})\colon \mathrm{Y}\colon (\varepsilon^{e}) \tag{8}$$

W^{Tr} is the energy of thermal deformation:

$$\psi^{t} = C_v[\,(T - T_0) - T ln\frac{T}{T_0})\,] + \alpha(T - T_0)f \tag{9}$$

The amount of heat that supplied in the material can be described by C_v the thermal capacity.

W^{TF} : is the energy of the transformation deformation corresponding to the energy due to the incompatibilities of deformation between the austenite and the Martensite:

$$\psi^{TF} = \frac{1}{2}\psi\colon \sum_n \sum_k (\,(I - S^{K})\colon \left(\varepsilon_k^{Tr} - \varepsilon_n\right) f(x,t).\,\varepsilon_{sat} \tag{10}$$

Considering E is the tensor of elasticity, ε_n is the local stain in the volume variant n, $T0$ is the initial temperature, I is the identity tensor that transforms every tensor into itself and S is the Eshelby tensor that defines the variant geometry.

The free energy of Helmholtz writes:

$$\psi_{tot} = \frac{1}{2\rho}\,(\varepsilon^e):\mathrm{Y}:(\varepsilon^e) + C_v[\,(T - T_{moy}) - T ln\frac{T}{T_{moy}})\,] + \alpha(T - T_{moy}).f \; + \frac{1}{2}\psi:\sum_n \sum_k((I - S^K):\left(\varepsilon_k^{Tr} - \varepsilon_n\right)f\,.\varepsilon_{sat} + \psi' \quad (11)$$

The SMA represents simplicity and simultaneous actuation that can behave as a sensor or an actuator. As a result, the SMA can be thermally activated either by direct exposure to a temperature change in its immediate surroundings or can be mechanically activated by stress loading, which can provide a significant lot of design and application flexibility.

A harder material will endure plastic strain more efficiently as opposed to a less hard material which can be translated by the isotropic fourth-order tensor of elastic modulus Y_{ijkl} and its relationship with Poisson's ratio ϑ and Kronecker constant $\mathscr{k}$:

$$Y_{ijkl} = \frac{\vartheta Y}{(1+\vartheta)+(1-2\vartheta)}\mathscr{k}_{ij}\mathscr{k}_{kl} + \frac{Y}{2(1+\vartheta)}\left(\mathscr{k}_{ik}\mathscr{k}_{jl} + \mathscr{k}_{il}\mathscr{k}_{jk}\right) \quad (12)$$

We accept that dissipation energy can be described (Saleeb et al., 2015) by the below equation

$$\psi_{D,el} = \int \epsilon^2\,\frac{F^n}{\gamma}\,dF \quad (13)$$

On the other hand, the transformation function F can be denoted:

$$F = \frac{1}{\epsilon^2}\left[\frac{1}{2}\left(\sigma_{ij} - \alpha_{ij}\right) M_{ijkl}\,(\sigma_{kl} - \alpha_{kl})\right] \quad (14)$$

with

$$M_{ijkl} = \frac{1}{2}\left(\mathscr{k}_{ik}\mathscr{k}_{jl} + \mathscr{k}_{il}\mathscr{k}_{jk}\right) - \frac{1}{3}\mathscr{k}_{ij}\mathscr{k}_{kl} \quad (15)$$

Also, n and γ are rate-dependent parameters accounting for any observed variation in the material responses when loaded and unloaded mechanically at different rates.

The dissipation energy in the process of thermal cycling can be calculated from:

$$\psi_{D,el} = k\int(T - T_i)d\varepsilon^t \quad (16)$$

The global damages are considered as additive, one speaks of linear office plurality, and the rupture occurs when the parameter of damage reaches the unit value. With N and N_f are the current number of cycles and the final number of cycles when the fracture occurs respectively. When the damage variable D_{tot} = 1.0, the fracture of samples occurs (Zhao and Kang, 2022).

$$D_{tot} = \sum_{i=1}^{k} d_i = \sum_{i=1}^{k}\frac{n_i}{N_i} \quad (17)$$

In a multiaxial form, the damage variable D has always been identified as the ratio of the dissipation energy density collected before to the nth cycle to the total dissipation energy density collected up till the occurrence of fracture or:

$$D_{tot} = \frac{\sum_{i=1}^{N}(w_{M_i}+w_{th_i})}{\sum_{i=1}^{N_f}(w_{M_i}+w_{th_i})} \tag{18}$$

where, w_{M_i} and w_{th_i} are the mechanical energy and is the thermal energy of dissipation energy density for r (i_{th}) numbe cycle.

3.2 The Proposed SMA Tube Actuator

In order to exploit the proposed modelling in adaptive applications, a thermo-mechanical actuator has been suggested. The proposed actuator considers the different heat transfer ways, especially those that have external sources of heat transfer, for instance, forced convection and solar radiation. The latter is very useful for renewable energy and mechatronic applications.

Therefore, the stored heat in the SMA can be converted from thermal energy to mechanical work, as shown in (Figure 4).

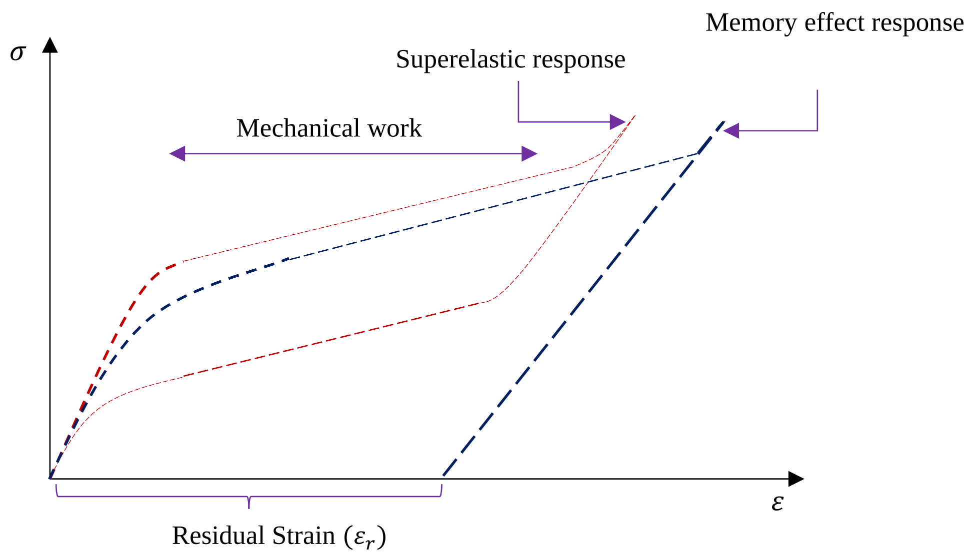

Figure 4. Mechanical work as a function of temperature variation.

The proposed system is an SMA tube that is designed to protect the metallic wire from the mechanical and thermal load to increase its life. The shape memory alloy tube returns to its original shape after stress that can remove the load thanks to its thermos-mechanical characteristics. On the other hand, the SMA tube can remember two forms (Figure 5) (Riad et al., 2017): an austenite phase (bent tube) and the second at martensitic phase (normal tube) (Zhu et al., 2016).

In fact, most wire failures are subjected to repeated bending stress that affects the cable. In this way, the studied SMA tube can remember two forms. The first shape is the normal form in ambient temperature without stress. The second shape is the bent form or in temperature under the martensitic point (Zareie et al., 2020).

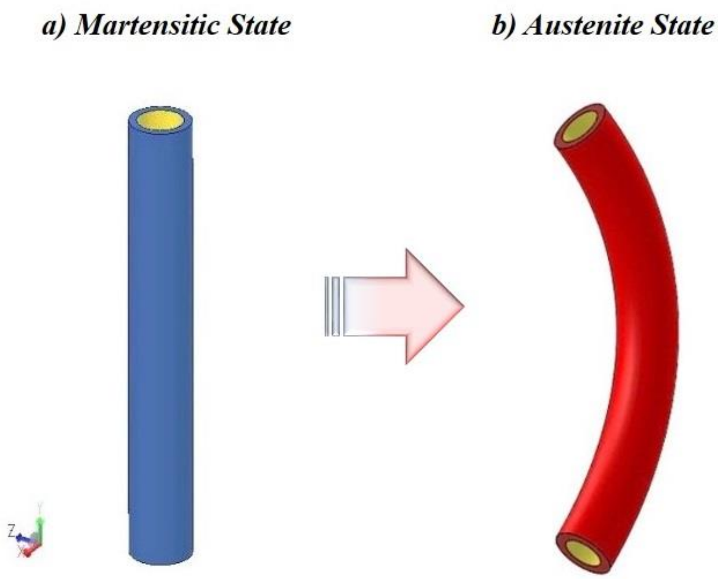

Figure 5. Ni-Ti tube reply to a thermal radiation.

4. Results and Discussion

The SMA is used as a cover to protect the core of the wire by using the super elasticity and shape memory effect for the dissipation of mechanical energy. The superplastic effect appears during the application of significant stress while the temperature is higher than the final Austenite. Therefore, the cable or wire returns to the original at equilibrium.

The current model represents the fundamental characteristics of the designated behaviour, and the required SMA characteristics were taken from the literature Biffi et al. (2022) and Zhao et al. (2022) as shown in the Table 1.

The experimental process considers an SMA tube with an outer diameter D = 4 mm, an inner diameter d = 3.8 mm and a length of test section l = 2, 5 mm; the phase change temperature from austenite to martensite was measured by a DSC test (Trommnau et al., 2019; Matos et al., 2022).

The data was considered because of its proximity to the proposed study, which takes into account the SMA Ni-Ti tube, which has many properties. The input data of the simulation can be demonstrated the transition point, the phase change between austenite and martensite and the material characteristics of Ni-Ti. The entries of these data in the mathematical model make it possible to provide numerical results, which make it possible to verify and validate them with the experimental results; Consequently, it is possible to add modifications and improve the experimental procedure before the manufacturing process.

The study describes a thermo-mechanical system that exploits the thermomechanical behaviour of SMA to control the mechanical displacement of the SMA tube. In this way, the numerical study is going to verify the proposed modelling to describe the real behaviour of the proposed SMA system.

Table 1. Characteristics of the Ni-Ti SMA used for damping activities.

SMA actuator specifications		
Composition of SMA		
Melting point	°C	1250
Fusion heat	J/cm3	2322
Density	g/cm3	6.45
Thermal conductivity	W/m K	10-18
Thermal diffusivity	cm2/s	0.125
Specific heat J/kg K		490
Young's modulus a -Austenite -Martensite	GP	 70 30-35
Yield stress	MPa	100-800
Reversible deformation -one-way memory effect -two-way memory effect	 % %	 8 3.2
Tensile strength	MPa	2000
Final critical stress σ_s^{cr}	MPa	**0**
Final critical stress σ_f^{cr}	MPa	**800**
C_A Transformation Constants	°C	**10**
C_M Transformation Constants	°C	**5**
Maximum residual strain	%	**7**
The required tube actuator		
tube diameter	mm	10
The maximum strain ε	%	8
Austenite temperature		> 20
Maximum stress	MPa	≤1000
Martensite temperature	°C	< 5

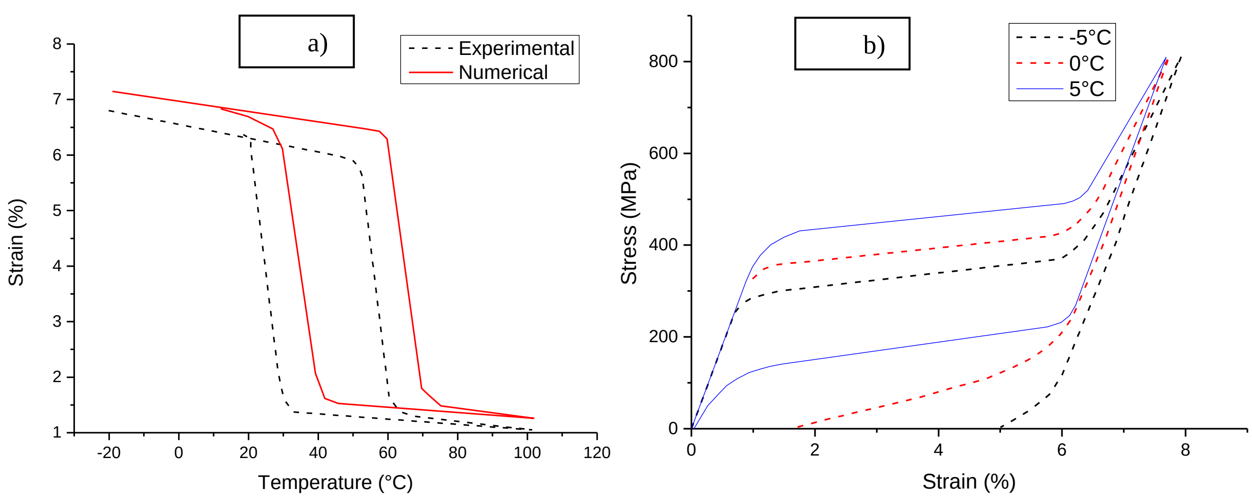

Figure 6. a) The evolution of temperature as a function of strain; b) the relationship between the superelasticity and shape memory effect as a temperature.

First of all, the stress provides important deformation in SMA material that transforms the material from austenite phase to the oriented martensitic phase then the SMA recuperates the first position.

Figure 6 shows the variation of deformation against variation of temperature and stress for both experimental and simulation results. The experimental results are taken from the work of Qian et al. (2013), who investigated a Ni-T-based refocusing shape memory alloy damper used for seismic applications. In some sense, we want to study the effect of energy dissipation and the damping of cyclic stress over time, which corresponds with the objectives of this study. In this way, the investigation displays that the numerical simulation is in good agreement with experimental results (Auricchio et al., 2007; Qian et al., 2013; Kazinakis et al., 2022). Consequently, the system {SMA+wire} acts such as superplastic manner that repulses the stress and returns to the original shape. It is known that fatigue occurs in the material even if the applied stress is under the elastic resistance of the wire over time. For that reason, the ability of the SMA is acted as a perfect damper of stress that dissipates mechanical energy through the hysteresis cycle, which reduces the applied load on the whole system. In fact, the temperature variation strongly influences the SMA actuator that shows various behaviours such as the material's superelasticity and shape memory effect. If the applied stress is very important above the elastic resistance and under the austenite temperature, a residual deformation occurs in the material. Hence, the increase in temperature provides an internal load due to the transformation martensitic and the material return to the original shape, which protects the wire from deformation and from creep for a long time (Figure 6(a)). Actually, the wire can be exposed to diverse loading-unloading forces (Mehrabi et al., 2015), and the study of tensile-compression loading is an implicit analysis of the bending load (Figure 6(b)).

As a result, the tension-compression loading analysis implies an evaluation of the many ways the position should respond to a temperature change (Figure 7).

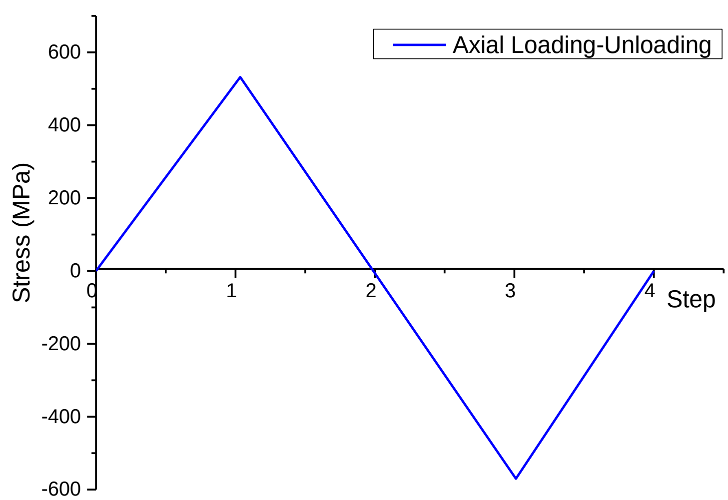

Figure 7. Proportional loading path.

Cyclic loading produces variable, repeated, alternating or fluctuating stresses. Fatigue damage is the progressive degradation of structures subjected to cyclic stresses over time, which results in the appearance and evolution of cracks that lead the material to ruin. Hence, the amplitude may be in either tension or compression and may fluctuate over time, but the opposite stress cycle should be adequate to initiate a fatigue crack.

Therefore, the model can capture the thermomechanical behaviour of the SMA actuator, as can be shown in (Figure 8) below:

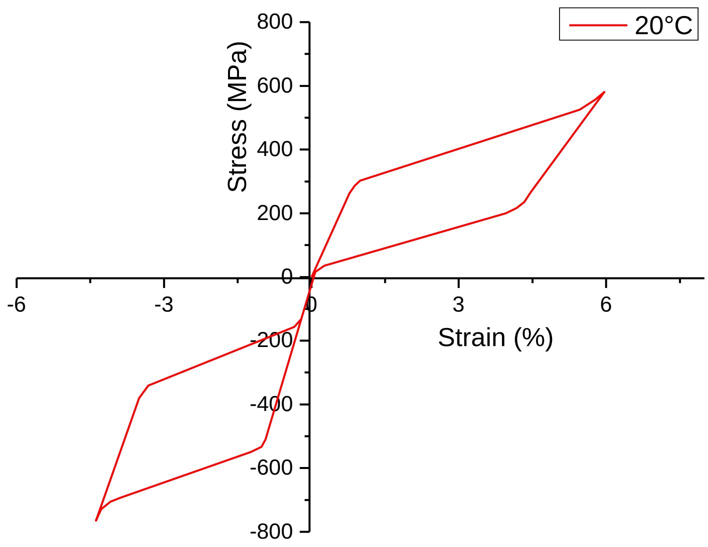

Figure 8. The evolution of strain as a function of stress for tensile and compression load.

Figure 8 describes the material's behaviour during the tensile-compression tests that show an asymmetrical stress-strain curve. The tension testing is compared with the compression, that showing a higher transformation start for compressed stress and lower transformation strain is in the order of 3% to 4%, unlike the tensile tests, which achieved a strain in the order of 6%. Indeed, these changes are due to one cycle after another; the solicitation generates defects (dislocations, twins...) which causes internal stresses. These additional stress fields influence the behaviour around the defects, which makes the inverse transformation not complete, and the residual Martensite accumulates during cycles.

4.1 Cyclic Study for SMA Actuator

In reality, mobile systems have a great possibility of encountering variable stresses (static or dynamic) over time. For this reason, the wires with SMA reduce the mechanical energy, which is an effective solution for automotive applications, industrial materials that undergo vibrations and even for buildings in areas of seismic activity. In this investigation, the load applied is based on loading protocol in order to take into account diverse loading conditions (Filiatrault et al., 2018). The variation of the strain over time generates a cyclic loading that can affect the material behaviour. Therefore, the SMA actuators have strong resistance against fatigue, and the cyclic load does not affect the material behaviour very much. The numerical results show the stress-strain curve that describes the evolution of strain under cyclic stress and shows the SMA behaviour under the loading protocols.

According to (Figure 9), there was no obvious contradiction in the forward and reverse transformation stresses when compared to the hysteretic loops with the static load illustrated in Figure 9. Besides, the SMA material keeps the superelastic behaviour and shows significant resistance to fatigue under stress over time. As a matter of fact, other potential causes of deformation, such as softening due to a rearrangement of dislocations and the irreversible cyclical, slip are all factors that influence hysteretic curves (Dornelas et al., 2020; Varughese and El-Hacha, 2020; Ju et al., 2022).

Indeed, the cyclic applied stress has an impact on the SMA actuator, which memorizes a microscopic residual deformation over time which is reduces the material's lifespan. The type of stress applied to the SMA material can affect the structure, and the response can be changed as a function of the direction of the loading. Therefore, a numerical study investigates the loading protocol for tensile loading, as shown in (Figure 10):

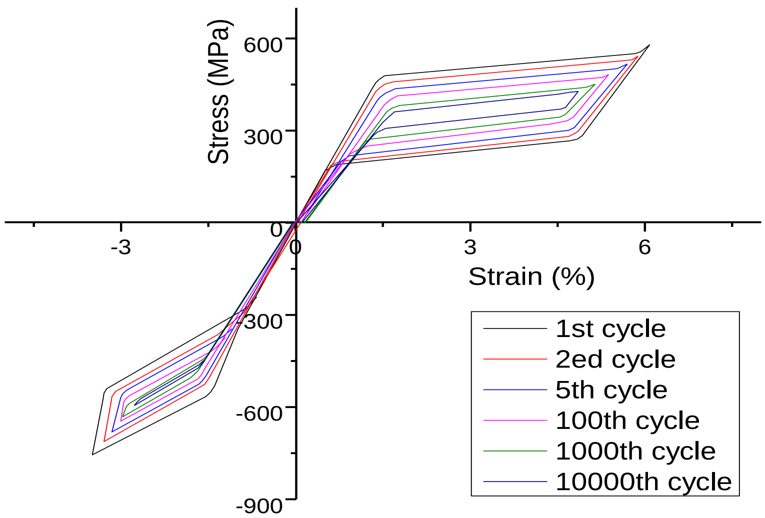

Figure 9. The strain evolution under cyclic loadings for shape memory alloy.

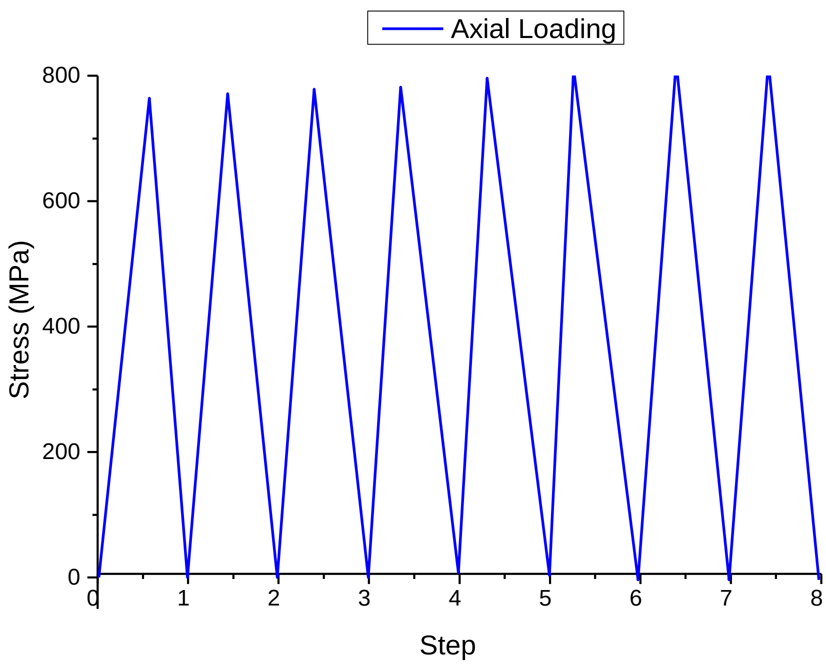

Figure 10. The loading protocol for tensile loading.

The results show the cyclic stress as a function of deformation, taking into account literature results as shown in (Figure 10) It can be concluded from the simulation that in each cycle, the residual deformation increase compared with the recoverable strain that decreases in response to the applied stress.

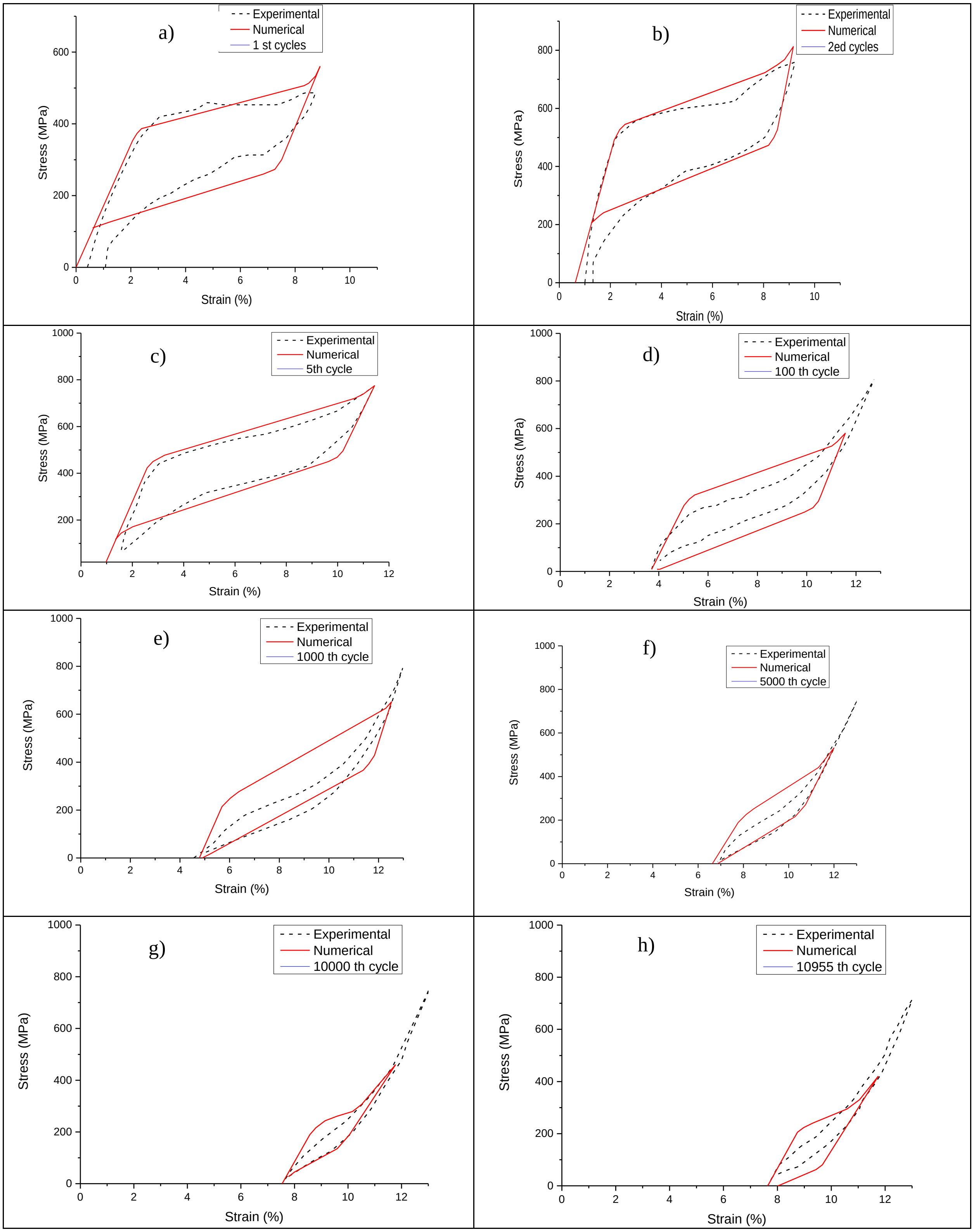

Figure 11. Comparison between numerical and experimental results.

Figure 11 displays the deformation evolution as a function of stress for SMA material that captures precisely the superelastic behaviour or numerical results and experiments. Besides, the SMA material captures the fatigue phenomena under cyclic stress over time, which shows the increase of residual strain as a function of time. Moreover, under cyclic tensile loading, the most noticeable distinction in (Figure 13) was the considerable drop in forward transformation stress with increasing strain amplitudes. The creation of persistent slip, which facilitated the stress-induced change to Martensite, was credited with this impact. The significant rise in cumulative residual deformation under cyclic tensile stress in the tension–compression loading test was another difference. The mechanical (Superelastic) responses are still not entirely stabilized even after 100 cycles, but the temperature variations are already substantially stabilized after just 50 training cycles.

The degradation of the fatigue performance can even occur under very low-stress amplitudes in the very high cycle regime, as shown for high-purity HPT copper and Ni-Ti tube.

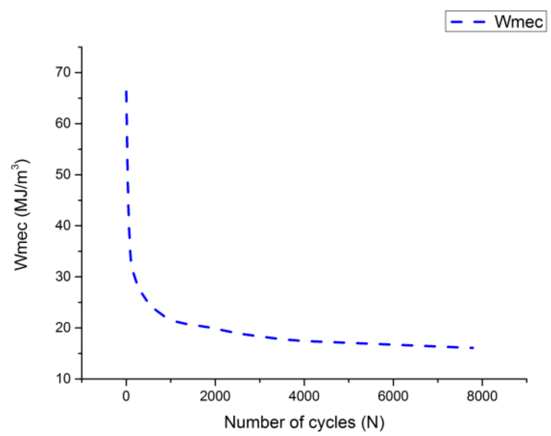

Figure 12. Comparison between numerical and experimental results.

Figure 12 illustrates the outcomes of the fatigue analysis that were achieved through studies with various loading pathways and loading levels. From Figure 12, it is explained that the fatigue growth with the diminution of stress levels if the loading paths are the same. However, if the stress levels are the same, the fatigue achieved in the investigations with the uniaxial path are the highest. As a result, the fatigue results predict the number of cycles as a function of the mechanical energy dissipated, which shows that the established equations for the prediction of fatigue life based on damage are in agreement with literature results described in the work of Zhao et al. (2022) that conducted an experimental study on fatigue damage and life estimation of Ni-Ti SMA.

4.2 The Simulation

The numerical study makes it possible to analyze the evolution of the deformation as a function of the applied stress. The investigation is carried out with the COMSOL software, which has a library for diverse material as shape memory alloys. The governing equations for describing SMA material are resolved via Souza-**Auricchio** mathematical **modelsn** that have been a very powerful tool for this study. The material parameters given in Tables 1 for the NiTi matrix. The mesh of the proposed actuator can be considered automatically in the software, as shown in (Figure 13) Thus, the precision can be increased by raising the number of elements, which can achieve about 13210 elements in this study. Depending on the regularity of the geometry, the study is based on a free quadratic triangular mesh with an element size between 20 nm and 50 nm.

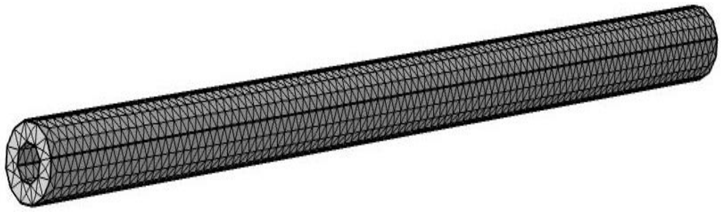

Figure 13. Mesh results for an SMA tube in this study.

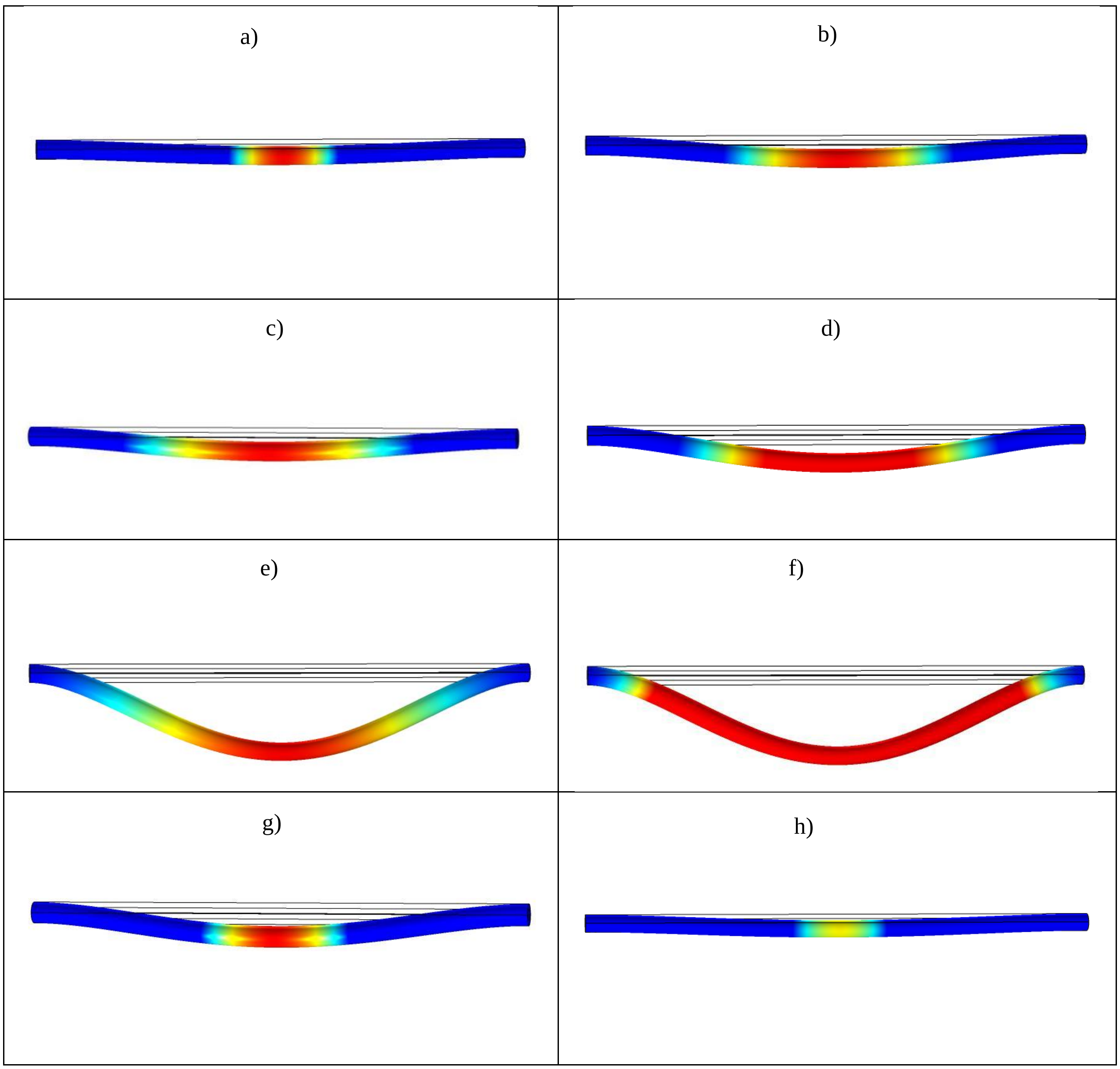

Figure 14. The hat transfers in the SMAA during phase transformation.

It is assumed that the system is subject to different constraints, but the most influential constraint is the bending from the above constraint; on the hand, the sides are subjected to a rigid constraint.

The SMA is characterized by a strong thermomechanical coupling the martensitic transformation changes the stress into heat dissipating in the forms hysteresis via the thermomechanical damper, as shown in (Figure 14).

According to (Figure 14), the study is to correctly simulate the thermo-mechanical behaviour of shape memory alloys. It can be observed that the SMA actuator performs in a superelastic way where it pushes back the applied constraint and returns to its initial state after the stress removal (Figure 13h). Besides, the simulation can anticipate that the middle is the part most expected to encounter fatigue after a number of cycles over time.

Finally, it is necessary to take into account the other surroundings and the other phenomena that come into consideration in real circumstances, such as corrosion, the multi-axial loads, the boundary conditions.

5. Conclusion

In this study, a new SMA actuator for protecting important electrical wires, especially for locomotives and mechatronic systems, has been established in order to increase the lifetime and protect the system from sudden stresses and fatigue. The study makes it possible to add an SMA tube as an encapsulation around wires to be protected in order to reduce the interaction between the inner wire and the applied stress. This functionality is acquired from the shape memory alloy, which mainly characterizes by several characteristics due to the strong thermo-mechanical coupling. The investigation shows the great potential of the proposed SMA tube, with its superelastic behaviour, to increase the predicted lifecycle of metallic wires against sudden stresses and fatigue. The proposed model has described the superelasticity and the memory effect precisely. Therefore, the system is subjected to a stress lower than the austenite temperature, and it will return to its initial shape after the increase in temperature at ambient. If the temperature is already in the ambient temperature, the SMA behaves elastic, and the cable returns to its initial shape after the deformation. The lifetime of the conduction system with the protective SMA is increased remarkably and can reach up to 10^5 cycles under the action of the stress of an amplitude of 550 MPa. The latter can, in normal conditions, ruin conventional materials that will experience an electrical wire break. The finite element simulation shows that the system of SMA combined with a 2.5mm copper wire with the SMA cover that can reach 4mm undergoing significant stress up to 490 MPa that can reach a deformation of 7% and return to the initial state without residual deformation. The verification of the proposed model shows improvement in the lifespan of considered wires compared to wires without SMA encapsulation. The current study presents an electrical wire blanket created from SMA material that shows good agreement with previous publication results of SMA tube, as well as the results show that SMA materials are promising thermomechanical actuators for protection electrical wires.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

Acknowledgement

This article has not received any additional funding or grant from any outside source. The authors would like to express their gratitude to the editors in chief and reviewers for their thorough review of the article.

References

Abavisani, I., Rezaifar, O., & Kheyroddin, A. (2021). Multifunctional properties of shape memory materials in civil engineering applications: A state-of-the-art review. *Journal of Building Engineering*, *44*, 102657. https://doi.org/10.1016/j.jobe.2021.102657.

Alhamany, A., Bensalah, M.O., & Fehri, O.F. (2004). Couplage dans les AMF. *Comptes Rendus - Mecanique*, *332*(11), 941-947. https://doi.org/10.1016/j.crme.2004.06.006.

Auricchio, F., Reali, A., & Stefanelli, U. (2007). A phenomenological 3D model describing stress-induced solid phase transformations with permanent inelasticity. In Miara, B., Stavroulakis, G., & Valente, V. (eds) *Topics on Mathematics for Smart Systems* (pp. 1-14). https://doi.org/10.1142/9789812706874_0001.

Biffi, C.A., Fiocchi, J., & Tuissi, A. (2022). Relevant aspects of laser cutting of NiTi shape memory alloys. *Journal of Materials Research and Technology*, *19*, 472-506. https://doi.org/10.1016/j.jmrt.2022.03.146.

Chen, C., & Wu, S. (2015). Observations of self-accommodated R-phase morphologies in a Ti50.3Ni48.2Fe1.5 SMA. *Materials Characterization*, *107*, 202-210. https://doi.org/10.1016/j.matchar.2015.07.021.

Dornelas, V.M., Oliveira, S.A., & Savi, M.A. (2020). A macroscopic description of shape memory alloy functional fatigue. *International Journal of Mechanical Sciences*, *170*, 105345. https://doi.org/10.1016/j.ijmecsci.2019.105345.

Ezrin, M., & Lavigne, G. (2007). Unexpected and unusual failures of polymeric materials. *Engineering Failure Analysis*, *14*(6), 1153-1165. https://doi.org/10.1016/j.engfailanal.2006.11.048.

Feng, C., Lin, X., Hu, J., Shen, B., Hu, Z., & Zhu, F. (2021). Study on the influence of fretting wear on electrical performance of SMA connector. *Microelectronics Reliability*, *118*, 114047. https://doi.org/10.1016/j.microrel.2021.114047.

Filiatrault, A., Perrone, D., Brunesi, E., Beiter, C., & Piccinin, R. (2018). Effect of cyclic loading protocols on the experimental seismic performance evaluation of suspended piping restraint installations. *International Journal of Pressure Vessels and Piping*, *166*, 61-71. https://doi.org/10.1016/j.ijpvp.2018.08.004.

Guan, J.H., Pei, Y.C., Zhang, H., & Wu, J.T. (2022). An investigation on the driving characteristics continuous measurement of reverse deformation SMA springs. *Meccanica*, *57*(2), 297-311. https://doi.org/10.1007/s11012-021-01421-4.

Hu, Z., Wang, E., & Jia, F. (2022). Study on bending fatigue failure behaviors of end-fixed wire ropes. *Engineering Failure Analysis*, *135*, 106172. https://doi.org/10.1016/j.engfailanal.2022.106172.

Jin, H., Vostner, A., Wu, Y., Macioce, D., Sgobba, S., Huang, C., Rodriguez, C.R., Pison, P.F., Langeslag, S.A.E., Santillana, I.A., Long, F., Yu, M., & Tao, B. (2017). Fatigue performance evaluation for ITER IVC conductor component materials. *Vacuum*, *145*, 86-94. https://doi.org/10.1016/j.vacuum.2017.08.023.

Ju, X., Moumni, Z., Zhang, Y., Zhang, F., Zhu, J., Chen, Z., & Zhang, W. (2022). A multi-physics, multi-scale and finite strain crystal plasticity-based model for pseudoelastic NiTi shape memory alloy. *International Journal of Plasticity*, *148*, 103146. https://doi.org/10.1016/j.ijplas.2021.103146.

Karna, P., Prabu, S.S.M., Karthikeyan, S.C., Mithun, R., Jayachandran, S., Resnina, N., Belyaev, S., & Palani, I.A. (2021). Investigations on laser actuation and life cycle characteristics of NiTi shape memory alloy bimorph for non-contact functional applications. *Sensors and Actuators, A: Physical*, *321*, 112411. https://doi.org/10.1016/j.sna.2020.112411.

Kazinakis, K., Kyriakides, S., & Landis, C.M. (2022). Effect of tension/compression asymmetry and anisotropy on the response of pseudoelastic NiTi tubes under equibiaxial stress. *Extreme Mechanics Letters*, *53*, 101689. https://doi.org/10.1016/j.eml.2022.101689.

Khalid, H.U., Ismail, M.C., & Nosbi, N. (2020). Permeation damage of polymer liner in oil and gas pipelines: A review. *Polymers*, *12*(10), 2307. https://doi.org/10.3390/polym12102307.

Ko, W.S., & Jeon, J.B. (2021). Atomistic simulations on orientation dependent martensitic transformation during nanoindentation of NiTi shape-memory alloys. *Computational Materials Science*, *187*, 110127. https://doi.org/10.1016/j.commatsci.2020.110127.

Laurino, A., Andrieu, E., Harouard, J.P., Odemer, G., Salabura, J.C., & Blanc, C. (2014). Effect of corrosion on the fatigue life and fracture mechanisms of 6101 aluminum alloy wires for car manufacturing applications. *Materials and Design*, *53*, 236-249. https://doi.org/10.1016/j.matdes.2013.06.079.

Li, B., Shen, Y., & An, Q. (2020). Structural origin of reversible martensitic transformation and reversible twinning in NiTi SMA. *Acta Materialia*, *199*, 240-252. https://doi.org/10.1016/j.actamat.2020.08.039.

Lor, C., Phon, R., Lee, M., & Lim, S. (2022). Multi-functional thermal-mechanical anisotropic metasurface with shape memory alloy actuators. *Materials and Design*, *216*, 110569. https://doi.org/10.1016/j.matdes.2022.110569.

Matos, I.M., Araújo, J.A., & Castro, F.C. (2022). Fretting fatigue performance and life prediction of 1120 aluminum alloy wires of overhead conductors. *Theoretical and Applied Fracture Mechanics*, *121*, 103521. https://doi.org/10.1016/j.tafmec.2022.103521.

Mehrabi, R., Andani, M.T., Kadkhodaei, M., & Elahinia, M. (2015). Experimental study of NiTi thin-walled tubes under uniaxial tension, torsion, proportional and non-proportional loadings. *Experimental Mechanics*, *55*, 1151-1164. https://doi.org/10.1007/s11340-015-0016-2.

Mittal, G., Rhee, K.Y., Mišković-Stanković, V., & Hui, D. (2018). Reinforcements in multi-scale polymer composites: Processing, properties, and applications. *Composites Part B: Engineering*, *138*, 122-139. https://doi.org/10.1016/j.compositesb.2017.11.028.

Nasution, F.P., Saevik, S., & Gjøsteen, J.K.O. (2014). Finite element analysis of the fatigue strength of copper power conductors exposed to tension and bending loads. *International Journal of Fatigue*, *59*, 114-128. https://doi.org/10.1016/j.ijfatigue.2013.09.009.

Petrini, L., & Bertini, A. (2020). A three-dimensional phenomenological model describing cyclic behavior of SMA. *International Journal of Plasticity*, *125*, 348-373. https://doi.org/10.1016/j.ijplas.2019.10.008.

Qian, H., Li, H., Song, G., & Guo, W. (2013). Recentering shape memory alloy passive damper for structural vibration control. *Mathematical Problems in Engineering*, *2013*, 1-13. https://doi.org/10.1155/2013/963530.

Riad, A., Ben, M., Alhamany, A., & Mansouri, M. (2020). Bio-sun tracker engineering self-driven by thermo-mechanical actuator for photovoltaic solar systems. *Case Studies in Thermal Engineering*, *21*, 100709. https://doi.org/10.1016/j.csite.2020.100709.

Riad, A., Zohra, M.B., & Alhamany, A. (2017). The SMA actuator controlled by the Sun's radiation. *Materials Research Express*, *4*(7), 075701. https://doi.org/10.1088/2053-1591/aa75bb.

Rizzello, G., & Motzki, P. (2022). Smart materials for mini-actuators. In Manfredi, L. (ed) *Endorobotics Design, R and D and Future Trends* (pp. 117-163). Academic Press. https://doi.org/10.1016/B978-0-12-821750-4.00006-2.

Ross, N., Asokan, M., Issac, G., Kumar, A., Caperton, J., Alptekin, J., Salunke, A.S., & Chyan, O.M. (2020). Microelectronics reliability mechanistic study of copper wire-bonding failures on packaging devices in acidic chloride environments. *Microelectronics Reliability*, *113*, 113917. https://doi.org/10.1016/j.microrel.2020.113917.

Wang, S.L., Qin, Y.A.N.G., Li, X.L., Peng, H.B., & Wen, Y.H. (2014). Influence of recovery heating rate on shape memory effect in up-quenched Cu–Al–Mn alloy. *Transactions of Nonferrous Metals Society of China*, *24*(10), 3196-3200. https://doi.org/10.1016/S1003-6326(14)63460-9.

Saleeb, A.F., Dhakal, B., Dilibal, S., Owusu-Danquah, J.S., & Padula, S.A. (2015). On the modeling of the thermo-mechanical responses of four different classes of NiTi-based shape memory materials using a general multi-mechanism framework. *Mechanics of Materials*, *80*, 67-86. https://doi.org/10.1016/j.mechmat.2014.09.001.

Tabrizikahou, A., Kuczma, M., Łasecka-Plura, M., Farsangi, E.N., Noori, M., Gardoni, P., & Li, S. (2022). Application and modelling of shape-memory alloys for structural vibration control: state-of-the-art review. *Construction and Building Materials*, *342*, 127975. https://doi.org/10.1016/j.conbuildmat.2022.127975.

Trommnau, J., Kühnle, J., Siegert, J., Inderka, R., & Bauernhansl, T. (2019). Overview of the state of the art in the production process of automotive wire harnesses, current research and future trends. *Procedia CIRP*, *81*, 387-392. https://doi.org/10.1016/j.procir.2019.03.067.

Varughese, K., & El-Hacha, R. (2020). Design and behaviour of steel braced frame reinforced with NiTi SMA wires. *Engineering Structures*, *212*, 110502. https://doi.org/10.1016/j.engstruct.2020.110502.

Wan, D., Hagen, A.B., Viespoli, L.M., Johanson, A., Berto, F., & Alvaro, A. (2022). In-situ tensile and fatigue behavior of electrical grade Cu alloy for subsea cables. *Materials Science and Engineering A*, *835*, 142654. https://doi.org/10.1016/j.msea.2022.142654.

Wang, G., Ma, Y., Guo, Z., Bian, H., Wang, L., & Zhang, J. (2022). Fatigue life assessment of high-strength steel wires: Beach marks test and numerical investigation. *Construction and Building Materials*, *323*, 126534. https://doi.org/10.1016/j.conbuildmat.2022.126534.

Werling, T., Geuting, P., Höschele, P., Ellersdorfer, C., & Sinz, W. (2020). Investigation of the electro-mechanical behavior of automotive high voltage busbars under combined electrical load with varying indenter geometry and environmental conditions. *Journal of Energy Storage*, *32*, 101861. https://doi.org/10.1016/j.est.2020.101861.

Williams, E.A., Shaw, G., & Elahinia, M. (2010). Control of an automotive shape memory alloy mirror actuator. *Mechatronics*, *20*(5), 527-534. https://doi.org/10.1016/j.mechatronics.2010.04.002.

Xue, S., Shen, R., Chen, W., & Miao, R. (2020). Corrosion fatigue failure analysis and service life prediction of high strength steel wire. *Engineering Failure Analysis*, *110*, 104440. https://doi.org/10.1016/j.engfailanal.2020.104440.

Zareie, S., Seethaler, R.J., Issa, A.S., & Zabihollah, A. (2020). Recent advances in the applications of SMA in civil infrastructures: A review. *Structures*, *27*, 1535-1550. https://doi.org/10.1016/j.istruc.2020.05.058.

Zhang, X., Yan, X., Zhang, S., & Nie, J. (2014). Development of a novel shape memory alloy-actuated resettable locking device for magnetic bearing reaction wheel. *Review of Scientific Instruments*, *85*(1), 015006. https://doi.org/10.1063/1.4863340.

Zhao, T., & Kang, G. (2022). Experimental study and life prediction on fatigue failure of NiTi shape memory alloy under multi-axial one-way shape memory cyclic loadings. *International Journal of Fatigue*, *155*, 106609. https://doi.org/10.1016/j.ijfatigue.2021.106609.

Zhu, P., Feng, P., Sun, Q.P., Wang, J., & Dai, H.H. (2016). Determining the up-down-up response through tension tests of a pre-twisted shape memory alloy tube. *International Journal of Plasticity*, *85*, 52-76. https://doi.org/10.1016/j.ijplas.2016.07.002.