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New Smart Actuator Bases on Shape Memory Alloys for Avoiding Overheating and Preventing Fire in Electronic Devices

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Abstract: In the past few years, fire incidents in electronic systems have become frequent and caused many losses of life and property. Consequently, various studies have been conducted in order to establish effective ways to avoid fire caused by electrical devices. In light of the fact that electrical sensors frequently get damaged, it is crucial to develop a smart switch that can detect and control power outages during an unexpected heat increase or fire incident. Therefore, a new technique has been developed based on the shape memory alloys (SMA) that work as a smart actuator that can control the connection of electrical current by generating an important mechanical deformation under temperature variation. The proposed smart actuator can separate the two connectors of electrical current between an electrical power source and the device by generating significant deformation, which can stop the damage and overheating, thus avoiding any incident related to the temperature increase. Hence, a numerical study has been conducted that aims to integrate the SMA in electrical devices in order to protect them from fire accidents. Therefore, mathematical modelling have been conducted to adjust the smart actuator with any electrical device, with rules that will be developed to increase the actual detection rate. The simulation results of the proposed fire detection system have been compared with several current methods. The results show that the proposed engineering is very promising and can respond to a temperature change in 0.2 s and generate a total deformation of about 8%. The results show that the suggested method has a higher fire detection rate that can reach 90% for detection.

Keywords: Cast steel; hardness; composite; in situ; microstructure; reinforcement.

Nomenclature		**Greek letters**	
Y	Modulus of elasticity	ξ_{tot}	Total strain
T	Temperature	ξ^{e}	Elastic strain
V	Volume	ξ^{t}	Thermal strain
f	Volume fraction	ξ^{Tr}	Deformation of transformation
C_v	Thermal capacity	σ	Mechanical stress
E	Tensor of elasticity	δ	Thermal expansion

T0	The initial temperature	ε^{sat}	Saturation strain
I	Identity tensor	ψ	Total energy
S	Eshelby tensor	ψ^{e}	Mechanical energy
Abbreviations		ψ^{Tr}	Energy of thermal deformation
PID	Proportional-Integral-Derivative	ψ^{TF}	Energy of the transformation deformation
Ni-Ti	Nickel titanium	ξ_n	Local stain in the volume variant n

1. Introduction

Many companies, markets, and individuals have endured fire incidents caused by electrical devices such as chargers, computers, and cell phones due to overheating of the electrical circuit that caused the burning or exploding of one of their components [1]. Most of the time, the fire starts immediately away, the electrical alarms are destroyed since they are connected to the electrical system that has exploded, and it is usually too late to prevent the fire or even inform the people involved [2]. In fact, the overheating will have an effect for several minutes before the incident starts, which is, if the disconnection of electricity is done at the right time, it will avoid a fire cause. Likewise, the energy consumed by the charger is not used, and it heats the device, which eventually leads to a fire incidents. Therefore, there is an urgent need to develop effective methods for fire protection.

Over the past few decades, researchers have worked hard to develop effective methods for detecting and preventing fires caused by electronic gadgets [3]. In the beginning, fire detection methods were conventional and simple that the systems trigger an alarm or send messages to responders, but this system is characterized by delays and inefficiency [3]. Since these conventional detectors only activate after the fire has occurred, they cannot continually monitor the temperature changes of sensitive electronic devices in real time as the heat increases rapidly. In recent times, sensors of fire that incorporate into alarm systems are highly studied for immediately identifying an early fire, then saving enough time to evacuate and perform rescues. Recently, Sharma [4] proposed a new technique to detect fire that using the Internet of Things and image processing. They used wireless sensor technology and cloud computing to create the suggested fire detection system.

Several methods have been proposed that can detect overheating and control the passage of electric current before the fire starts, but they are still under development [5]. Lately, Yao Hong et al. [6] presented a new study on the effectiveness of a real-time PID (Proportional-Integral-Derivative) controller based on mechanical ventilation to prevent Smoke leakage from tunnel fires. The numerical results show a remarkable benefit with a better adaptation to the size of the anonymous fires. Indeed, the real problem is implementing intelligent systems and hardware sensors to prevent fires, which are part of the classic techniques of passive delay and active alarm systems. However, the heat can increase rapidly, which can cause a surprising explosion. In other manner, these fire alarm systems still need to be developed and improved to achieve the desired goals [3].

Thermal incidents due to the increase in temperature result from the amount of energy used and transmitted between the different electrical systems, while industrial buildings are the most affected by this type of incident because it requires a large amount of electrical energy, then they can fall into the overheating then the declinations of fire or the explosion. Luo et al. [7] established a robust and fire-retardant wood-constructed triboelectric generator for autonomous self-powered building fire protection. The study increases the usage of autonomous devices for preventing building fires, which might considerably progress the construction of smart cities and structures. Jiang et al. [8] describe the use of numerical expertise for the smart control of construction fire safety systems in fire accidents. They develop research based on a simulation of a fire event and use it to test the viability of using digital twins and semantic web technology. Hsiao et al. [9] proposed a real-time fire safety system design for catastrophe protection, evacuation, and rescue operations in structures. As a result, cooperation between humans and machines will create a new standard for handling crisis situations.

The researchers are continuously investigating other ways to overcome obstacles to controlling overheating and preventing electrical fire in electrical devices by using autonomous actuators based on smart materials [10]. The viability of the suggested smart system idea examines how advanced smart composite materials can be implemented in commercial activities, with a focus on potential alarm applications. Loughlan et al. [11] conducted an experimental investigation to demonstrate, in a technically intelligent manner, the effectiveness of buckling control in structural composite parts using induced deformation actuation. The results show that the shape memory alloy (SMA) can sense and respond to temperature variations.

The smart actuator based on SMA can operate autonomously that can detect and control the passage of current in electrical devices, which is effective in responding to the variation of temperature and generates a mechanical actuation to prevent fire accidents [12]. In this way, the operating principle of this system is based primarily on the main properties of SMA that possess particular thermo-mechanical properties that can recover apparent permanent strains when heated above a definite temperature [13]. The exceptional SMA characteristics, such as one-way shape memory, two-way shape memory, and pseudo elasticity, make them suitable for actuators and sensors [14]. These materials can change their shape, stiffness, displacement, and natural frequency in response to stress or heating, which are useful in many fields, such as microsystems, robotics, and security [15]. SMA actuators have the advantage of simplicity and act simultaneously as sensors and actuators compared to other actuators [16]. This allows for great flexibility in design and application [17]. Thus, the use of the SMA actuator between the chargers and the electrical connectors avoids any incidents related to the rise in temperature, which can automatically prevent fires.

This paper aims to design an early fire detection system to eliminate fire events using smart actuators to detect and disconnect the electronic systems when there is an observable increase in temperature. The proposed actuator is based on the SMA; these materials have a robust thermo-mechanical coupling that reacts to temperature variation and generates a significant mechanical load. Therefore, a numerical study was conducted to adjust the proposed intelligent system for fire detection and prevention, and thermo-mechanical modelling was proposed to describe the behaviour of the SMA as an actuator and intelligent sensor for the fire prevention system. The results show that the proposed system is auspicious, and the simulation results of the proposed fire detection system are compared with several existing methods. It is found that the proposed method has a higher fire detection rate.

2. Modelling

2.1 The proposed system for preventing accidents in electronic devices

In this study, a new design has been developed in order to detect and control electrical devices that are sensitive to overheating. It's known that undetected problems cause the majority of electrical fires. Electrical systems can be avoid exploding or starting a fire if there is a preventive fault detection system that turns off the power before critical values are reached. Dedicated high-temperature identification and detection system is able to prevent fires and sudden accidents as it can cut off electric power and warn responsables as shown in Figure 1.

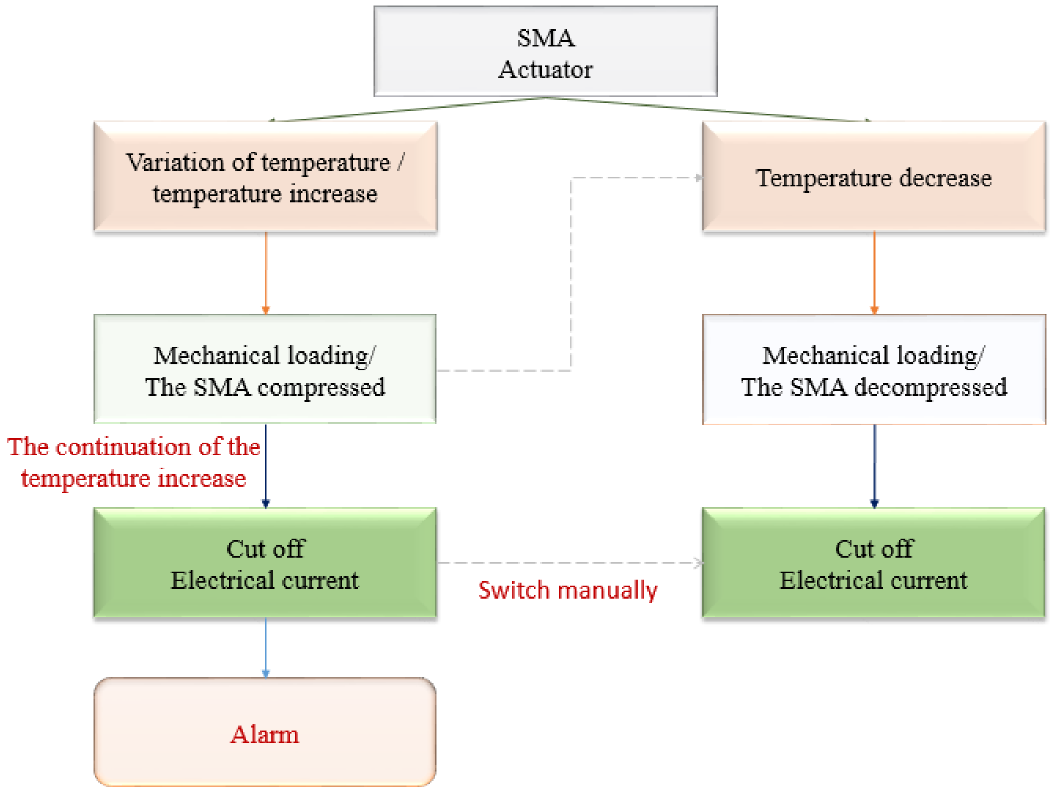

Figure. 1: *Flow chart to explain the process of the work.*

The SMA actuator can be integrated directly into the electrical circuit, or we can be integrated the smart actuator with an adapter that can be adjusted to any electrical device, as shown in Figure 2:

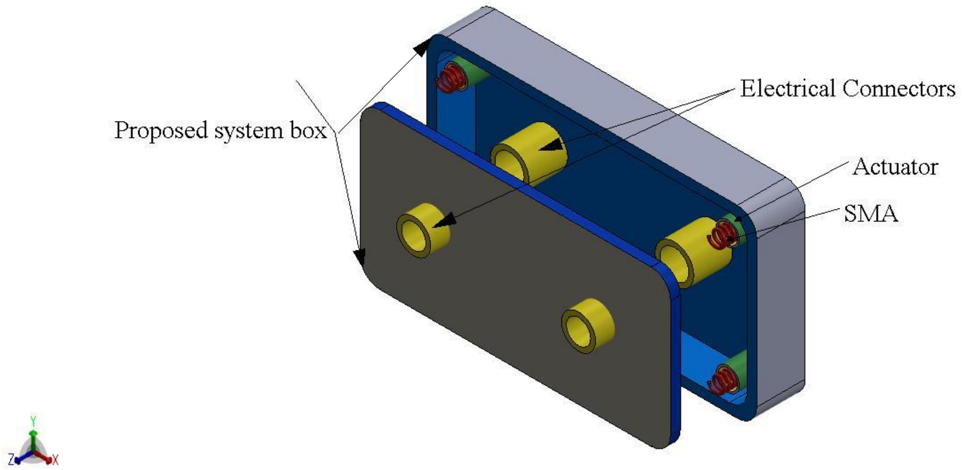

Figure. 2: *The proposed smart system for SMA smart switch*

A conductive connector and a SMA actuator constitute the fire protection system. The system can exist in two states: the first, in which the electrical conductor connectors operate normally at ambient temperature, and the second, in which they disconnect as the temperature rises.

2.2 The SMA Actuator

The proposed system is based on the SMA actuator, a smart system capable of reacting to a change in temperature and creating mechanical load. The electrical circuits generate important thermal energy in the environmental area. Moreover, the Joule effect offers a substantial amount of thermal energy that can be transferred to the smart actuator by radiation, convection and conduction. The variation of temperature in the smart system can induce the martensite transformation that can provide an important mechanical energy, forcing the smart switch to disconnect the electrical current. The heating-cooling cycle can be repeated as depicted in Figure 3 [18]:

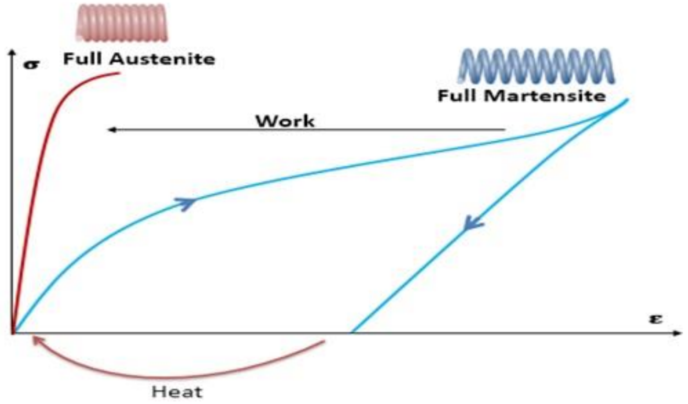

Figure. 3: *Work extraction from SMA.*

The SMA connects two conductors and allows electric current to pass easily when the temperature is average (room temperature), indicating that the material was already in the Martensite phase and is therefore expanded. However, as the temperature rises due to a fire, the material's temperature rises, transforming into the austenite phase, which causes the actuator to expand. This extension eliminates both conductors, preventing electric current from passing through the charges. The device is then deactivated automatically. The intelligent switch is comprised of an SMA actuator that functions normally at average temperatures; it links the two electrical conductors, one from the electrical connector and the other from the charger, allowing electrical current to pass through the devices. However, when an increase in temperature is detected, the SMA actuator responds progressively: the spring decompresses, and thermal energy is converted into mechanical energy, resulting in the separation of the two conductors. As a result, the switches are turned off, eliminating any potential fire source. After the temperature has returned to normal, the appliances can resume regular operation.

The actuator provided for fire protection has numerous advantages, including ease of movement, reduced power consumption, high-stress workout, operating as a natural mechanism system, and long fatigue life (10,000) [19]. This work validates the purpose of numerically developing a new generation of SMA actuators for safety-related electronic systems.

2.3 Thermomechanical modelling of the smart SMA actuator

A new actuator design made of SMA has been created to produce a system capable of detecting and preventing fires. For integrating the actuator into the proposed system, it is necessary to develop numerical models that accurately represent their complex behaviour. Therefore, the proposed model has been adapted to account for the superelasticity and memory effect in SMA materials. The behaviour of SMAs can be understood by analyzing the total strain, which is the sum of the partial deformations [18; 20]:

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

The elastic strain ε_{e} is:

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

where, σ is the mechanical stress, Y is the modulus of elasticity.

The thermal strain ξ^{t} is:

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

As the volume of a constituent V has been considered, the f is the volume fraction. ΔT = (T-T0) is the temperature variation and δ is the thermal expansion.

The deformation of transformation [21], ξ^{Tr}:

$$\xi^{\mathrm{Tr}} = \frac{1}{\mathrm{V}}\int_{\mathrm{V}}(\xi^{\mathrm{Tr}})\,\mathrm{dV} = \frac{\mathrm{V_M}}{\mathrm{V}}\frac{1}{\mathrm{V_M}}\int_{\mathrm{V}}(\xi^{\mathrm{Tr}})\,\mathrm{dV} = \mathrm{f}\,\bar{\xi}^{\mathrm{Tr}} \tag{4}$$

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

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

Considering εsat the saturation strain is the accumulation of infinitesimal deformations:

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

It was conceived that the model equation would be derived from the total deformation, which was decomposed from the previous partial deformation. This also allows the variation in total strain to be related to temperature and stress variations and to consider the different aspects of the interactions. The total energy describing the different energies interacting with the system can then be written [16]:

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

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

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

ψ^{T} is the energy of thermal deformation:

$$\psi^{\mathrm{t}} = \mathrm{C_v}[\,(\mathrm{T} - \mathrm{T}_0) - \mathrm{T}\ln\frac{\mathrm{T}}{\mathrm{T}_0})\,] + \alpha(\mathrm{T} - \mathrm{T}_0)\mathrm{f} \tag{9}$$

The amount of heat that supplied in the material can be described by $\mathrm{C_v}$ the thermal capacity.

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

$$\psi^{\mathrm{Tr}} = \frac{1}{2}\psi\colon \textstyle\sum_{\mathrm{n}}\sum_{\mathrm{k}}(\,(\mathrm{I} - \mathrm{S}^{\mathrm{K}})\colon \left(\xi_{\mathrm{k}}^{\mathrm{Tr}} - \xi_{\mathrm{n}}\right)\mathrm{f}(\mathrm{x}, \mathrm{t}).\,\xi_{\mathrm{sat}} \tag{10}$$

Considering E is the tensor of elasticity, ξ_{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:

$$\psi_{\mathrm{tot}} = \frac{1}{2\rho}\,(\xi^{\mathrm{e}})\colon \mathrm{Y}\colon (\xi^{\mathrm{e}}) + \mathrm{C_v}[\,(\mathrm{T} - \mathrm{T_{moy}}) - \mathrm{T}\ln\frac{\mathrm{T}}{\mathrm{T_{moy}}}\,] + \alpha(\mathrm{T} - \mathrm{T_{moy}}).\,\mathrm{f} + \frac{1}{2}\psi\colon \textstyle\sum_{\mathrm{n}}\sum_{\mathrm{k}}(\,(\mathrm{I} - \mathrm{S}^{\mathrm{K}})\colon \left(\xi_{\mathrm{k}}^{\mathrm{Tr}} - \xi_{\mathrm{n}}\right)\mathrm{f}\,.\,\xi_{\mathrm{sat}} + \psi' \tag{11}$$

The SMA is characterized by its ease of use and simultaneous actuation, allowing it to function as a sensor or an actuator.

Therefore, the SMA can be thermally activated by direct exposure to a temperature change in its immediate environment or mechanically activated by a stress load, providing great design and application flexibility.

3. Results and discussion

3.1 Validation of the SMA modelling

In this study, a numerical analysis that compares numerical findings with experimental data published in the literature has been conducted in order to validate the proposed model, which adjusts SMA behavior to the fire alarm system. The same thermophysical parameters and operating conditions of the electrical alarm system and SMA material utilized in the references are regenerated similarly in the validation investigation.

Bhatt et al. [22] experimentally investigated the variation of temperature as a function of time in the SMA actuator spring. As shown in Figure 4, the present model indicates good agreement with the numerical results of the reference.

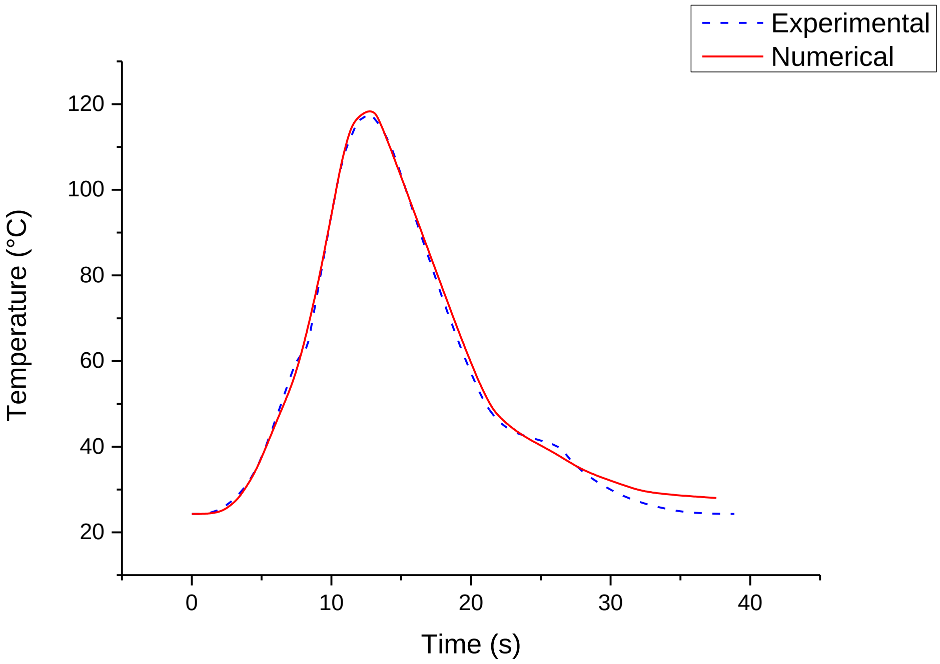

Figure. 4: *The proposed smart system for detection system response*

Further validation has been performed by exactly comparing the SMA Actuator system of the present modelling with the numerical results [22]. As seen in Figure 4, the SMA actuator's temperature rises progressively over time until it reaches the switch's critical temperature. In this instance, the actuator regulates the temperature by cutting the electrical current. Eventually, the actuator needs a manual check to start the flow of electrical currents again. It is obvious that the actuator operates at peak efficiency at extremely high temperatures when the deviation is almost negligible. Accordingly, the numerical model matches the experimental results. So far, there are a few minor variances when the temperature is low, but they don't impact the system's effectiveness because it is fire safe.

Figure 5 shows how the simulation method could analyze melting precisely and show a convincing agreement between numerical findings and the experimental data where the total martensite fraction starts from ‘1’for both springs and reaches ‘0’during complete martensite to austenite transformation. Another important variable in SMA transformations is stress-induced martensite fraction.

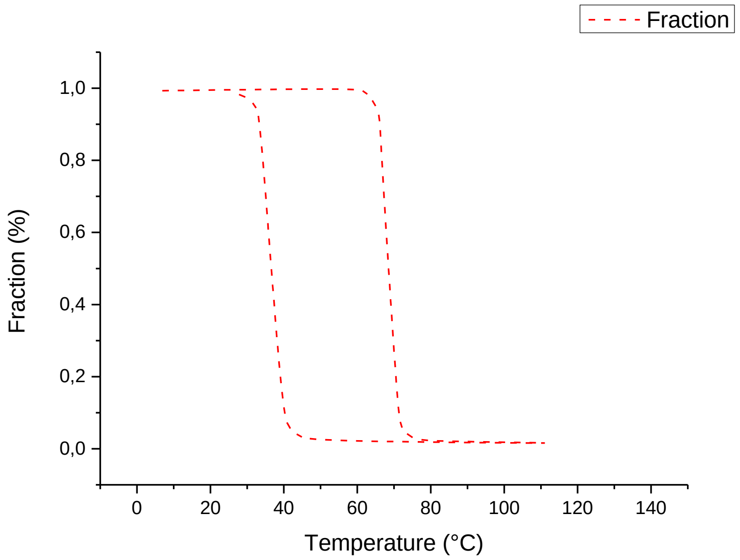

Figure. 5: *The proposed smart system for fire detection*

3.2 The Thermo-mechanical behaviour of the SMA

The proposed system is a fire accident detection and prevention system, is based on a SMA actuator. The actuator can alternate between two positions using the shape memory effect. Then, when the system operates under normal conditions, it connects two electrical connectors. However, if an anomaly occurs, the two connectors move apart, disconnecting the electricity. The numerical study will validate the effectiveness of temperature variation detection and mechanical effect generation and the system's adaptability to capture the shape memory effect. The proposed model allows the behaviour of the SMA to be explored in an articulated manner, which allows appropriate results to be obtained. The results are compared with the experimental measurements, as shown in the Figures below.

The current model represents the essential properties of the specified behaviour, and the SMA characteristics required for numerical simulation have been established from the literature.

The behaviour of the SMA reacts to the variation in thermal induction as a function of strain and temperature. Regardless of the heat source (solar radiation, joule effect, hot air, or hot water...), the heat effect can activate the martensitic transformation under the same circumstances of thermal energy and material properties. In contrast, the absence of thermal energy deactivates the transformation, as shown in Figure 6 below:

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

SMA actuator specifications	
composition of SMA	
Final critical stress σ_s^{cr}	**0**
Final critical stress σ_f^{cr}	**800**
C_A Transformation Constants	**10**
C_M Transformation Constants	**5**
Maximum residual strain (%)	**$\varepsilon_L \approx 7$**
The required spring actuator	
spring diameter (mm)	10
The maximum strain ε (%)	8
Austenite temperature	> 20
Maximum stress (MPa)	≤1000
Martensite temperature	< 5

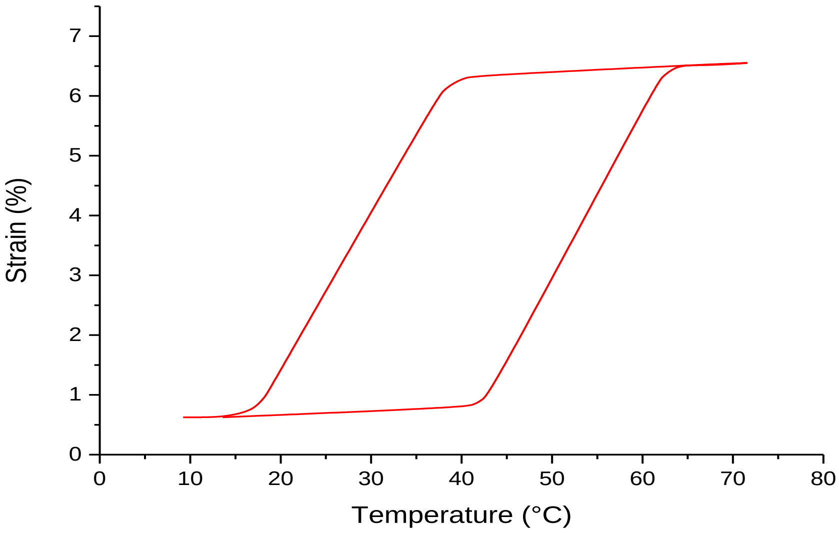

Figure. 6: *The Strain-Temperature curve of the SMA; the model response for a thermal cycle as a function of strain under constant stress*

Figure 6 show a thermal loading cycle of cooling followed by heating while maintaining a constant stress level. The curve shows a significant variation in the transformation strain as a function of temperature. The level of macroscopic deformation obtained increases with the level of stress imposed. This deformation depends directly on the orientation of the martensite variants, which in turn depends on the value reached by the norm of the average transformation deformation. As the stress increases, this norm increases until it reaches its saturation value.

This work describes a thermo-mechanical system that controls mechanical displacement by using the thermo-mechanical behaviour of the SMA. The numerical analysis can validate the proposed modelling to represent the actual behaviour of the proposed SMA system.

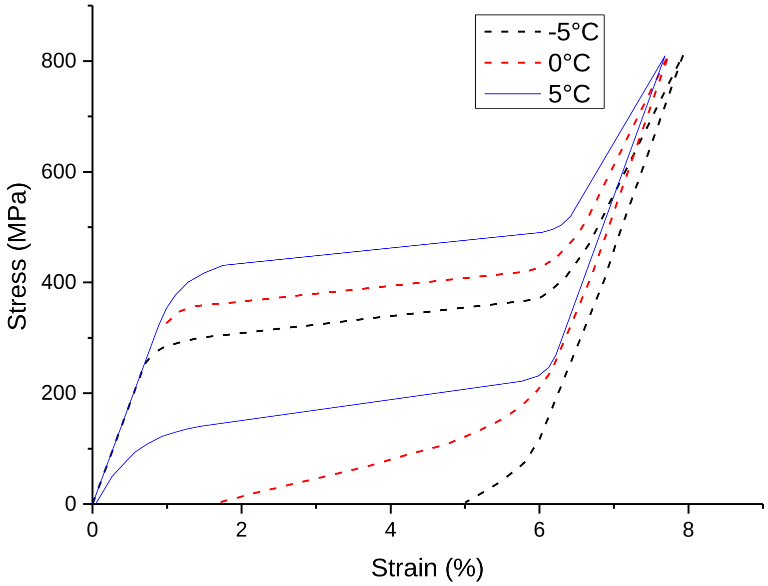

Figure. 7: *The evolution of temperature as a function of strain; b) the relationship between superelasticity and shape memory effect as a function of temperature.*

Initially, the stress causes a large deformation in the SMA material, transforming the material from the austenitic to the oriented martensitic phase, and then the SMA recovers the first position. As a result, the system acts as a superplastic way to repel the stress and return to its original shape. Temperature change substantially influences the SMA actuator, which shows diverse behaviours, such as superelasticity and shape memory effect. The material will undergo residual deformation if the applied stress is extremely high above the elastic strength and below the austenite temperature. Thus, the increase in temperature generates an internal load due to the martensitic transformation, and the material returns to its initial shape of the austenite temperature, disconnecting the two conductors. Moreover, the SMA spring can produce a range of loading/unloading forces to match temperature variations [23].

3.3 The Thermo-mechanical behaviour of the SMA Actuator

Therefore, the analysis of tension-compression loading is an implied evaluation of the several ways the position should respond to a temperature change (Figure 8).

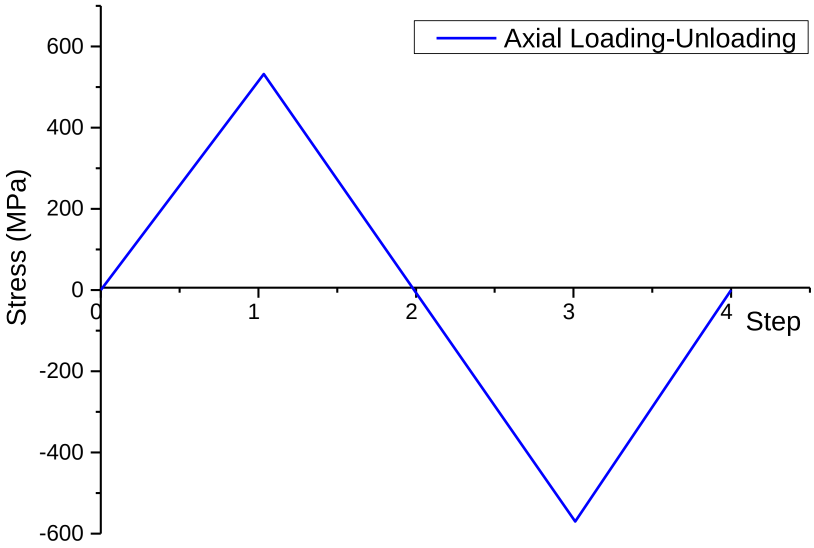

Figure. 8: *Proportional loading path*

As a result, the model can capture the thermomechanical behaviour of the SMA actuator, as shown in Figure 9:

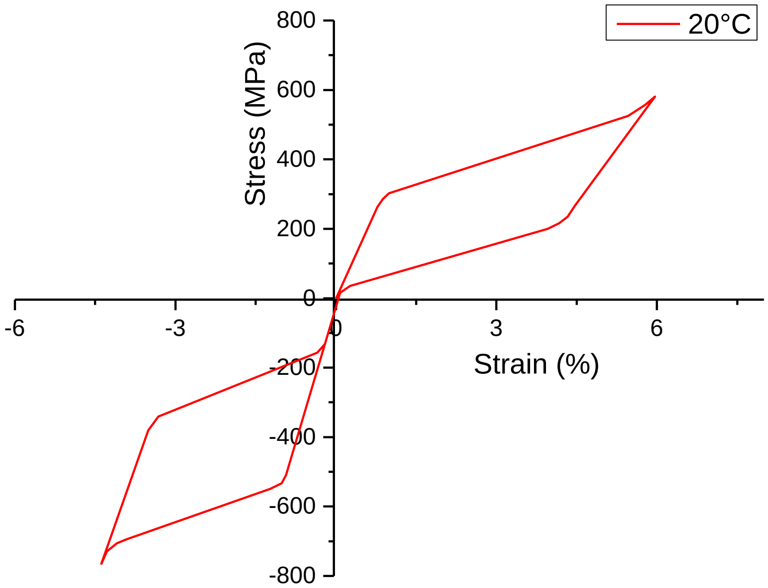

Figure. 9: *the evolution of strain as a function of stress for tensile and compression load*

Figure 9 represents the material's behaviour during tensile-compression testing as an asymmetry in the stress-strain curve. Compared to the tensile test, the compression test demonstrates a higher commencement of transformation for the compressed stress and a lower transformation strain of 3% to 4%, while the tensile test reached a strain of 6%.

The position of the shape-memory alloy change in response to the variation in temperature, and the more significant the temperature change, the greater the displacement.

The SMA spring absorbs ambient heat, and when the actuator is decompressed, the two electrical conductors separate, thereby cutting power to the electrical device.

In the last few years, researchers have proposed effective techniques which make it possible to decrease the incidents and protect the structures. Unfortunately, the electric circuit can become infected by a rise in temperature, especially in the case of a sudden fire or explosion, which can harm the alarm system or reduce its effectiveness. As a result, the building may sustain partial or whole damage, and because preventative devices are costly, it is challenging to install them in many places of large structures. On the other hand, the suggested method is an easy-to-install thermo-mechanical technique that enables temperature variation detection via an intelligent actuator, which also enables working in harsh temperature environments. Consequently, the SMA actuator can generate a preventive mechanical action before the system reaches the critical thresholds until the temperature is reduced or, if the temperature rises further, the connection systems goes off and activate the alarm.

4. Conclusion

This ambitious study aims to develop a new preventing fire system based on smart actuators. The proposed SMA actuator can detect and monitor the electronic systems when there is an observable temperature variation, which can ensure an early fire detection system. Then it can eliminate fire events or unexpected explosions. The study makes it possible to add an SMA actuator as a spring between two connectors to protect the electrical device. This functionality is acquired from the SMA, which mainly characterizes by several characteristics due to the robust thermo-mechanical coupling that reacts to temperature variation and generates a significant mechanical load. Hence, a numerical study was conducted to adjust the proposed intelligent system for fire detection and prevention, and thermo-mechanical modelling was proposed to describe the behaviour of the SMA as an actuator and intelligent sensor for the fire prevention system. 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 results show that the proposed system is auspicious, and the simulation results of the proposed fire detection system are compared with several existing methods. It is found that the proposed method has a higher fire detection rate. Comparing the current study's findings to those of previous research demonstrates a significant improvement in the temporal response and cyclic deformation, which reaches approximately 8% of the deformation. The future scope of the work will be about extending the current study of the proposed smart actuator that will be made more widely applicable in a variety of expensive electrical components in order to protect them from temperature fluctuations. Moreover, the electrical system will operate at optimum efficiency because of reducing the energy consumption caused by the Joule effect.

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