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Design Considerations for Shape Memory Alloy-Based Control Applications

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Abstract

Shape memory alloy (SMA) is one of the classes of smart material with high power to weight ratio, small size, and silent actuation. This has an ability of external actuating and also as a sensing element facilitating the dual functionality in the inhabited system, thereby minimize the weight and number of devices. SMA possesses an ability to remember its parent shape (austenite) and recover to it from its deformed state (martensite) at a characteristic transformation temperature. It has an unparalleled energy and power density and delivers large force and displacement. The work density of SMA is high enough to make it a very vital design factor for control applications. This chapter features the important parameters that are neccesery to be consider for designed to build an efficient control mechanism for an SMA instrumented system. This gives a broad spectrum of basic elements that are to be fixed before the developing stage, and the factors are meant to be necessarily quantified.

Keywords: Sensors, actuators, self-sensing actuation, shared sensing and actuation, variable impedance actuator

2.1 State of the Art in Shape Memory Alloy—An Introduction

Current technology has certain common desires for actuators designed for automotive, aeronautics, biomedical, robotics, and spatial applications,

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which is in requisite of compact and lightweight with integration compatibility, high efficient operation of force and power, and low cost. As today's technology aims towards designing of micro scales for mechanical as well as electromechanical devices. On miniaturization, classical actuators like electrical, pneumatic, and hydraulic affect a large debility power loss. These limitations led to the development of intelligent materials like piezoelectric, magnetostrictive, and shape memory alloy (SMA). When compares to these materials, SMA posseses the benefits of high strain and the highest power density enhanced with a significant amount of actuation with an extremely small envelope volume. Other dynamic inherent characteristics of SMA devices are their compliance in harsh environments, the simplicity of their actuation mechanisms, their silent and smooth motion, and their bifunctionality of sensing and actuation. These features make SMA a capable candidate among the actuators dominate in the field of aerospace and robotics.

However, it took about remarkable years for SMA from the discovery in the 1960s period to get prominent and well-known functional material, the current development could only be recognized by functional applications of SMA into medical technology (orthodontic wires, guide wires, stents) which is now commercialized widely.

2.1.1 SMA Actuators in a Feedback Control System

An SMA element operates counter to a biasing element to facilitate fixed or variable force to produce work. On actuation, the one-way SMA combined with biasing element that generates work done can be harnessed for actuator applications. SMA actuators can be used in different types of biasing configurations using either passive elements including dead mass, helical springs, cantilever strips, torsion springs, etc., or by an active element using SMA wire. By Kohl [1], it has been stated that SMAs display maximum work densities at 10^7 Jm^{-3}, i.e., 25 times more than that of the work density of electric motors when compared to conventional motors scaled to micro-size. Chaudhuri and Fredericksen [5] in the domain of robotics built a hand-actuated by SMA wires as it exhibits forces more than that of human muscle. A sigma-shaped pulley system to enhance the performance of an actuator is proposed by Hirose *et al.* (1986). Kuribayashi [2] proposed a control technique for the hysteresis by limiting the range of displacements and thus abridged the problem to a linear one. Hysteresis can also be reduced by employing an antagonistic SMA configuration. Further, it can be reduced by engaging direct sensors like temperature in feedback control loop. Ikuta *et al.* [3], proposed on estimating electrical resistance as a sensing signal for position control and experimental results revealed that the stiffness of an SMA spring is a linear function to normalized electrical resistance which led to experimenting with direct stiffness control.

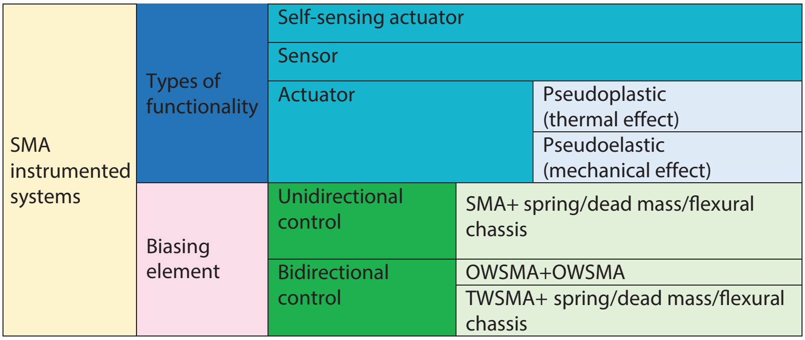
2.1.2 Factors to be Considered

Assembling an SMA-based system involves the identification of three factors at the initial stage.

- Functionality in which the SMA element is employed.
- Classifying the behavioural region to operate.
- Choosing the appropriate biasing element for repetitive and cyclic operation.

2.1.2.1 Different Types of Functionality—Actuator

Having attracted property like shape memory effect and superelasticity/pseudoelasticity of SMAs got its attention in various fields of industry. There are also few insights on interesting factors that attract SMA to be a potential candidate for a wide range of applications.



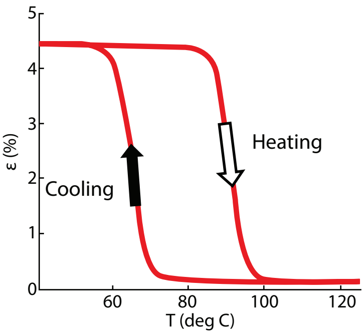
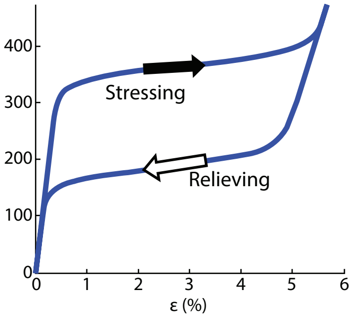
SMA instrumented systems	Types of functionality	Self-sensing actuator	
		Sensor	
		Actuator	Pseudoplastic (thermal effect)
			Pseudoelastic (mechanical effect)
	Biasing element	Unidirectional control	SMA+ spring/dead mass/flexural chassis
		Bidirectional control	OWSMA+OWSMA
			TWSMA+ spring/dead mass/flexural chassis

With high intrinsic strength of the SMA actuators, there is an advantage of being able to implement direct drive devices with smooth and noiseless operation. SMA actuated systems are made “intelligent” and their shape or stiffness is dynamically modified by embedded/bonded SMA; this helps shock absorption, which had been the primary weakness of traditional actuators. For micromanipulation control, many sensors were employed in order to achieve accuracy with the fast response time. Unfortunately, the usage of many sensors for the micro and nanodevices/systems is restricted due to their sizes, performances, and restricted degrees of freedom.

Hence, an alternative method is to use the actuators in sensing mode by capturing the variation in electrical resistance on its actuation by the concept of self-sensing method.

There are several advantages in using the self-sensing actuation (SSA) technique is that it allows a reliable reduction in expenditures and is made to be compact by eliminating expensive sensors. As the actuator is an integral part of the system, the resolution is relatively good equivalent to that of external sensors sensing signal.

This idea of recovering plastic deformation to dissipate energy in SMA by hysteretic cycles finds a broad scope in structural health monitoring systems. The presence of R-phase (Twinned martensite) is the main cause of the hysteric feature. The pseudoelasticity and damping ability of SMA is developed as a supplemental restoring element and energy dissipation actuators. The vital capability lies in the transformation from the parent phase, microstructurally symmetric cubic austenite, to the less symmetric martensitic product phase and revert back either by removing heat or by removing the load in case of pseudoelastic behavior or the evolution of R-phase in phase transformation, respectively. The austenite finish temperature is set based on the fabrication process and also the alloy composition of SMA will lead to the behavior of pseudoelastic.

Pseudoplasticity	**Pseudoelasticity**
Exhibits Shape memory effect	Exhibits Superelastic effect
Thermal induced phase transformation	Stress-induced phase transformation
This transformation involves M_S, M_f, A_S and A_f	This transformation occurs above A_f
	

In pseudoelastic, on removal of applied stress, the martensite cannot stay stable in that phase and thus reverts back to austenite. So, at low-temperature, austenite state is stable in pseudoelastic wires on contrary to the SME wires. This property is employed to develop dampers, absorbers, fasteners, clampers, and so on.

2.1.2.1.1 Variable Impedance Actuator

Actuators are a prime element for generating force and motion is a vital element of any mechatronics system. The variable compliance or variable stiffness are required in many robotic fields where human and machine interacts, unlike in classical stiff electrical drives used in industrial robotics, which demands accuracy and precision for tracking. Variable impedance actuator (VIA), depending on the external forces and the mechanical properties of the actuator, varies the stiffness from its set equilibrium position, in an unknown and dynamic environment for human-machine interaction. The adaptability of compliance in the interface with the human operator is important in applications which demand continuous force exchange. This bilateral force control needs to deliver the force continuous with accuracy for any force feedback devices for the human to exactly project the scenario on the robot slave site.

2.1.2.2 Self-Sensing Actuation

The traditional sensors are not ideally suitable to the micro and nano world because of their sizes, performances, and limited measurement of degrees of freedom. Henceforth, an alternative method is to use the actuators in sensing mode by capturing the variation in electrical resistance on its actuation by the concept of self-sensing method. Self-sensing is the inherent ability of a material/element to sense its own displacement/strain. SSA systems are compact as they configure a single element to sense any voltage signal preferably electrical resistance while in its actuated state.

Figure 2.1 demonstrates the SSA approach in a general control application. Apart from piezoelectric or SMA, SSA is possible with materials that intrinsically contain information about varying mechanical quantities on its actuation such as force and displacement in addition to electrical quantities like charge and electric field. In self-sensed–based control, the mechanical quantities are reconstructed by acquiring electrical quantities and the model of the transducer. So, in a generic closed-loop system, the final control element (actuator) and the transducer for feedback control

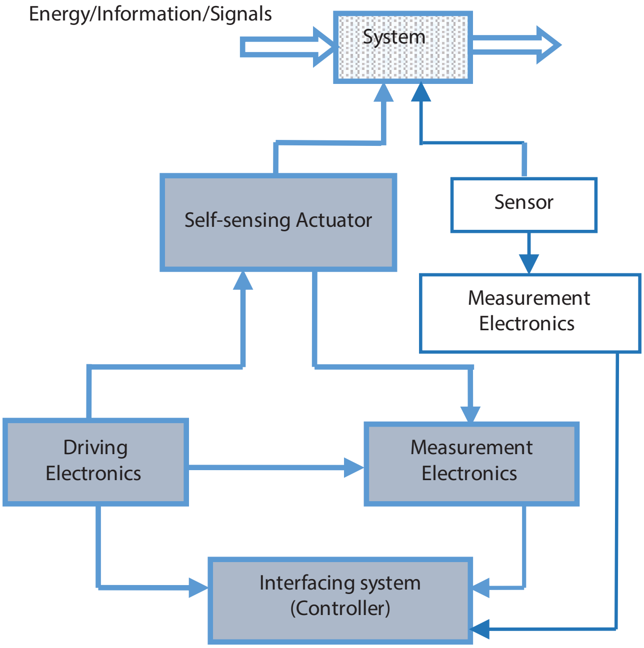


Figure 2.1 Schematics of external sensed and self-sensed actuators control.

(sensor) are the same elements performing bi-functionality. Therefore, self-sensing control application works without the necessity of any external sensor, as it is determined based on the knowledge of the model of the self-sensing actuator.

SMA actuators are a potentially viable choice for actuators that are used in a various broad spectrum of applications. SMA actuators are advantageous over piezoelectric for some applications for being able to generate larger forces, though at low frequencies and they can be made up into different shapes, like wires, tubes, sheets, and thin films Sun *et al.* [18]. SMA wires are normally used, can be embedded into the face sheet of a structure of interest, such as a helicopter blade, and can actively alter the shape of the structure in the controlled fashion (Song *et al.* [19]).

SMA can be actuated by either joules heating effect or by thermoelectric heaters. NiTiNOL (named after NiTi, which was discovered at the Naval Ordnance Laboratory). When the temperature increases in the SMA wire, the inherent properties like electrical resistance, the volume fraction of martensite and austenite, stiffness various along the phase transformation cycle. Different phase transformation mechanisms involved in heating and cooling may subsequently influence the correlation between the electrical resistance and strain output of the SMA actuator. On heating, the wire's electrical resistance first decreases due to temperature rise and vice versa. On reaching the safe heating current/transformation temperature, the wire gets contracted (increase in diameter) and the resistance decreases correspondingly, and on cooling, the SMA wire gets expanded by its biased element thereby increases the resistance. The variation of resistance in the actuation cycle can be used to specify the amount of contraction force as in Lin *et al.* [20]. The self-sensing property is the correlation between the driving voltage and the voltage drop (resistance) across the SMA wire. Electrical current is applied to the SMA wire, to contract and, hence, operated as an actuator. The change in resistance will be mapped to the consistent change in the voltage drop, as well as the structure's displacement when the wire contracts. This can be measured by using the wheat stone bridge or voltage divider method, the current is driven between the two outer points and the voltage is measured between the inner points. The voltage drop is then correlated into electrical resistance and corresponds to the SMA structure's displacements. The electrical resistance variation or the voltage drop variation signals across the SMA wire is utilized as the feedback sensing signal. This allows the determine the location of SMA-based structures in space without the need for any other external additional sensors.

2.1.2.2.1 Self-Sensing Techniques

There are three different self-sensing schemes to acquire the variation of electrical resistance in the SMA wire during actuation. Resistance feedback control is reported in kinds of literature and is focussed on SMA-spring or SMA- fixed force pairs. In unidirectional control, the operation involves opposite pulling units with sufficient stiffness element which affects the range of displacement. The range of motion can be increased using antagonistic SMA wire actuators or multi-wire actuators with self-sensing capabilities for miniaturized applications, thereby reduces the hardware complexity of placement and cost introduced by additional sensors and this is bi-directional control.

2.1.2.2.1.1 MAPPING APPROACH

Among mapping methods, there are two approaches: polyfit approach and neural network (NN)–based approach using measurement feedback. This method involves intense open-loop experimentation.

In polyfit technique, the electrical resistance variation/resistivity/volume fraction (an inherent property as a sensing signal) is calibrated

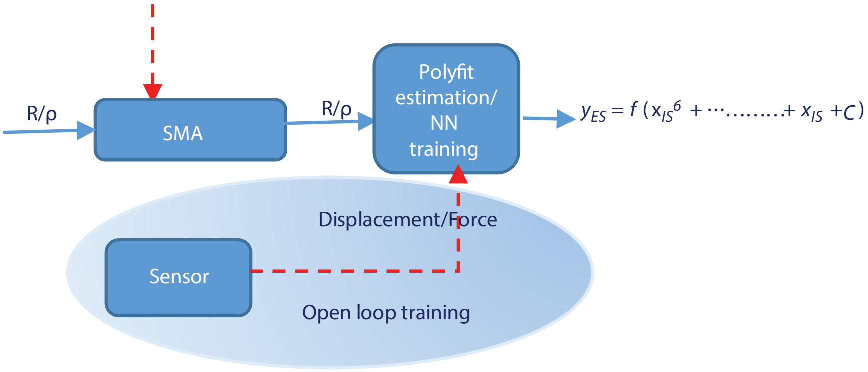


Figure 2.2 Schematics of the mapping technique.

with an external physical sensor as in Figure 2.2. The accuracy of this method is greatly reliant on the accuracy of the calibrator used and the polyfit equation is normally limited to six degrees due to software computation. Simply, it is represented as a polyfit equation of the form

$$y_{ES} = f\left(x_{IS}^{6} + \cdots\ldots\ldots\ldots + x_{IS} + C\right) \tag{2.1}$$

where x_{IS} is the electrical resistance/resistivity, any internal sensor variation in the SMA wire which is mapped to get value same to that of an external sensor signal (y_{ES}). So it needs open-loop experimentation in different loading, temperature, and initial conditions to exactly get the genuine signal variation, which makes the process a tedious one.

In NN, off-line open-loop training experimentation is needed to relate the resistance-position mappings. The performance of this approach is very dependent on training the NN using several sets of input and output data obtained from the open-loop experiments. The NN controller is a hysteresis model that establishes the correlation between the applied voltage and displacement. Also, NNs, which holds nonlinear function mapping and adaptation property, are used to identify the hysteresis characteristics of mechanical systems.

2.1.2.2.1.2 Modelling Approach

This modeling approach method requires sensorless feedback but liable on mathematical modeling of SMA stress-strain relation. The one-dimensional constitutive model for the SMA actuated system is developed relating the stress to the state variables like strain, temperature, and martensitic fraction. The constraints in using these models are practicality as the required model parameters must be experimentally determined. This approach has its limitations as it operable only at ambient temperature. At ambient temperature, the material properties remain mostly constant but it becomes difficult when it experiences unexpected changes.

2.1.2.3 Sensor-Actuated Isothermal (SMA)

Active sensing is a potential concept presented in this research. When a biased SMA wire is kept in an actuated state at a constant current (sensing current) and, for a varying displacement/force (measurand) applied to it, its electrical resistance changes in a linear manner; thus, the SMA is made to function as an active sensor. The value of the electrical resistance is constant for a constant current and, while in sensing mode, when an input is applied, the ER changes (increases with increase in applied load) due to the stress-induced in the wire. The selection of the sensing current depends on the stiffness of the biasing element.

2.1.3 Configurations of SMA Employed

2.1.3.1 Agonist-Antagonist Configuration

A set of actuators acts on the same rotational/linear point but opposes each other. This means that the actuators have to be synchronized to efficiently move the attached point/shaft. This arrangement has its origin in the fact that bio-inspired actuators generate force by contracting and it takes at least one other actuators to stretch them again. The number of actuators in such an agonist-antagonist set depends on the degrees of freedom. For a single degree of freedom, a pair of actuators suffices to have full actuation of the joint.

Such a configuration with SMA can be brought in a system by using it as an agonist with either a passive or active antagonist, made to function alternately in order to oppose the other. The bias is usually the antagonist to an SMA; passive antagonist can be a dead mass or passive spring and another SMA will be the active antagonist. Though SMA is nonlinear, suitable design of the configuration can negate the hysteresis and exhibit linear movement. If the agonist-antagonist pair is active, then bidirectional active control can be achieved. Figure 2.3 picturizes the correlation of phase transformation in SMA with its configuration.

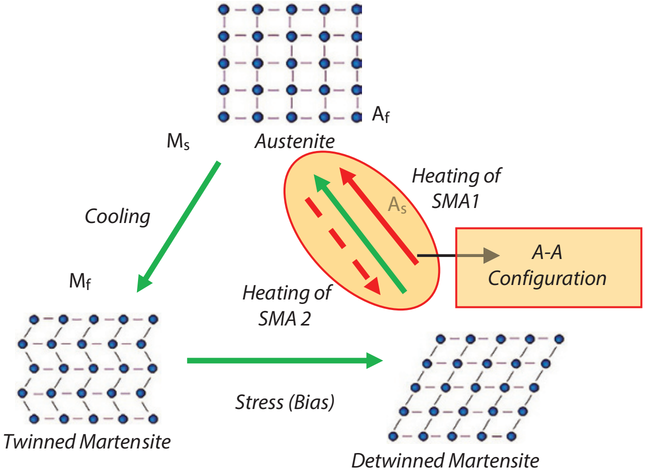


Figure 2.3 Correlation of phase transformation in SMA with its configuration.

2.1.3.2 Synergistic Configuration

In comparison to the agonist-antagonist configuration, synergistic actuators generate force in the same direction. That doesn't mean they are exactly parallel, but their actions have a similar effect on the primitive they are actuating on. If SMA wires are configured in this fashion it has an additive effect on its displacement and one such configuration is used in the design of the smart driver assistance system (SDAS). The design should be such that the displacement generated by the SMAs should be in the same direction and at the same point.

2.1.3.2.1 Configurations of Biasing Element

SMA can perform in two modes based on the shape memory effect. They are material-based one-way and two-way shape memory effect and mechanical based. The advantages of mechanical two-way actuators have a larger range of motion and than that of material two-way actuators, whereas the advantage of the material two-way actuator is simple and compact.

Figure 2.4 shows three basic types of SMA actuators using one-way SMAs.

- Figure 2.4a shows passive-biased one-way actuator. The SMA element is actuated to move in the direction of the arrow being the dead mass (W) as the biasing element.

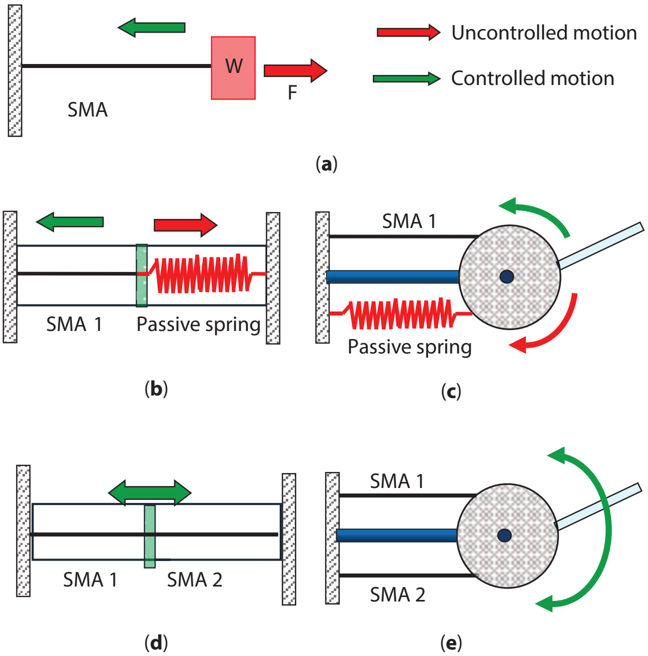


Figure 2.4 Types of SMA actuator configurations using one-way SMA wire (a) one-way actuator; (b) biased linear actuator; (c) biased rotary actuator; (d) two-way linear actuator; (e) two-way rotary actuator.

Figure 2.4b shows a spring-biased actuator, which is capable of moving the element bi-direction. The SMA element connected to the spring, and on actuation, the recovery force which is generated pull the spring, thus storing energy in it. On the removal of temperature, SMA the energy stored in the spring is released and the SMA element deforms back, thus completing the cycle. This type is configured in a rotary mode in Figure 2.4c.

On employing the passive biased actuator, only the heating of the SMA path can be controlled, whereas the cooling path is influenced by the biasing element.

- Figures 2.4d and e show a one-way shape memory effect wire that is designed to generate two-way mechanical movement with two SMA elements in antagonism. Any motion can be obtained by appropriately cooling or heating the two SMA elements. The active biased configuration involves bi-directional control.

Two-way shape memory effect-based actuator is similar to one-way actuator in shape (Figure 2.4b), while its behavior is more similar to biased actuator (Figure 2.4d).

Case Study 2.1 Governor Valve

Temperature-sensitive governor valve instrumented with NiTi thermo-variable rate spring, to control the shifting pressure in automatic transmissions by thermal actuation. This is employed in a tube with SMA spring and steel spring in a passive antagonistic configuration and which has an opening slot "S" functions to be in ON and OFF position to release pressure.

At room temperatures, the spring force of a Ni·Ti shape memory spring is lesser than that of a steel bias spring. In the martensitic state, the steel spring can compress the Ni·Ti spring, pushing the moveable piston "P" of the valve into the "closed" position. When the temperature increases, the Ni·Ti shape memory spring force is larger and it contracts, thereby making the opening slot in line with the openings and achieving the ON position. This pressure regulating valve at on and off positions are featured in Figure 2.5.

Case Study 2.2 Structural Health Monitoring

The SMA wire in pseudoelastic effect can be used as a shock-absorbing element in structural health monitoring. The SMA braces are in the frame/building structures as tendon/cables connected diagonally as in Figure 2.6. Under excitation of any vibrations, SMA braces absorb and dissipate energy through stress-induced martensite transformation (superelastic) or martensite reorientation (SME). Two designs of configurations were considered, one as in Figure 2.6a is that eight damper devices made of the

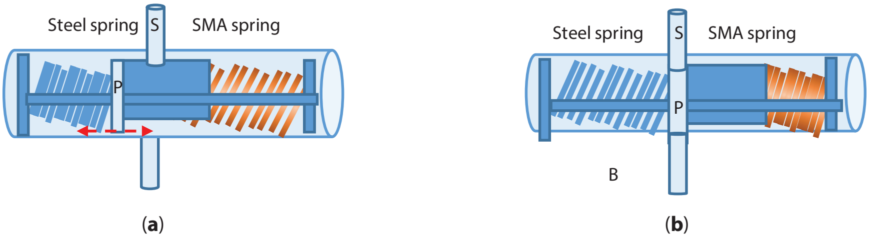


Figure 2.5 Represents valve: (a) un-actuated-martensite state "OFF"; (b) actuated-austenite state "ON".

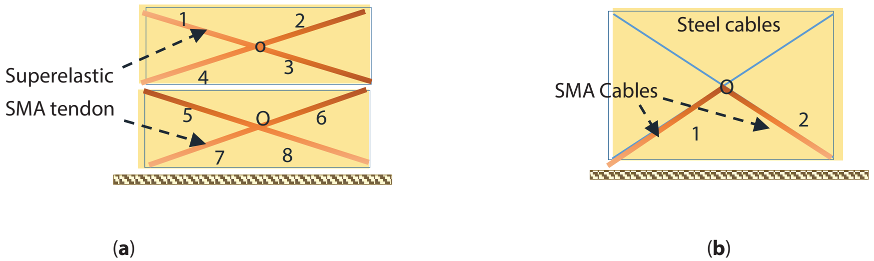


Figure 2.6 SMA braces: (a) un-actuated-martensite state; (b) actuated-austenite state.

SMA wires and steel wires are diagonal with the center "O" installed in a two-story structure. Another is to have combined steel-SMA–type braces for the frame structure with 2 of each. The dynamic characteristics and transient response hybrid tendons combinations of steel and Nitinol in the structure can be used for vibration control of coastal structures and the proper tendon geometry and there is pre-strain dependency in the dynamic response of the frame, respectively.

Case Study 2.3 Medical Staples

Shape memory orthopaedic staples are biocompatible alloys, under the shape memory effect accelerates the healing process of bone fractures. The shape memory staple, in its opened shape, OFF state in martensitic phase is driven into each side of the fractured site as represented in Figure 2.7. As the staple gets heated up to body temperature, this staple tends to contracts, compressing the separated part of bones and closes the gap between thems. This allows the stabilization with constant force accelerates healing, decreasing the time of recovery.

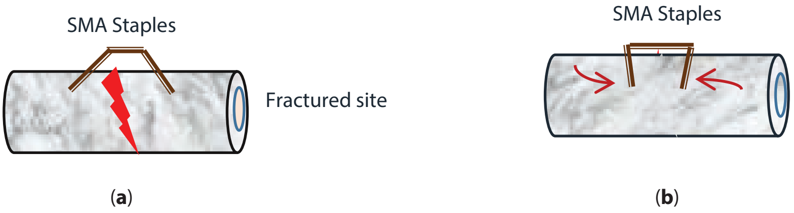


Figure 2.7 Medical SMA staple: (a) un-actuated-martensite state; (b) actuated-austenite state.

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