SHAPE MEMORY ALLOYS AND THEIR APPLICATIONS IN WING MORPHING TECHNOLOGY

SEMINAR PROJECT

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by

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The project report entitled “SHAPE MEMORY ALLOYS AND THEIR APPLICATIONS IN WING MORPHING TECHNOLOGY” submitted by Mr. Daniel Joel Gracias (Roll No. 200110029) may be
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ABSTRACT

A notable set of ‘smart materials’, Shape Memory Alloys (SMAs) provide the potential for a variety of applications. They have the ability to regain their original shape even after apparent plastic deformation or ‘memorise’ when they are subjected thermomechanical or magnetic variations. The same materials, in a certain temperature range, can undergo recoverable up to approximately 8.5%. These effects are called thermal shape memory and superelasticity (elastic shape memory) respectively. These phenomena occur due to a reversible phase change known as the thermoelastic martensitic transformation. The shape memory effect can be used to generate motion and/or force while superelasticity can store deformation energy.

Since the discovery of superelasticity exhibited by an Au-Cd alloy by Arne Ölander in 1932, SMAs have been implemented in a broad range of applications due to their unique properties. These include consumer products and industrial applications: structures and composites, automotive, aerospace, mini actuators, micro-electromechanical systems (MEMS), robotics, biomedical and even in fashion [1]. Iron-based and copper-based SMAs, such as Fe– Mn–Si, Cu–Zn–Al and Cu–Al–Ni, are low-cost and commercially available, but are not ideal for most applications due to their instability, brittleness and poor thermomechanical properties. Therefore, Ni-Ti alloys are preferred in most cases. [1] This report covers the thermomechanical shape memory behaviour of nitinol, a Ni-Ti shape memory alloy. It also conducts a brief case study on a wing morphing design involving shape memory alloys.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 HISTORY

Shape Memory Alloys (SMAs) are a group of metallic alloys that have the ability to regain their original shape after deformation when subject to particular thermomechanical or magnetic stimuli. This behaviour is termed as Shape Memory Effect (SME). The same materials exhibit superelasticity (also known as pseudoelasticity), which is the ability to undergo recoverable deformation up to about 8.5% in a certain temperature range. SME is useful in actuation applications and pseudoelasticity is employed for applications such as vibration isolation and dampening.

The shape memory effect was first discovered in the Au-Cd system by Arne Ölander in 1932. Later in 1938, the same effect was observed by Greninger and Mooradian in Cu-Zn and Cu-Sn alloys. The fundamental phenomenon behind shape memory behaviour was reported in 1949 by Kurdjumov and Khandros and in 1951 by Chang and Read. Practical and industrial applications of SMAs could never be fully realised because of the associated high costs, manufacturing complexity and unattractive mechanical properties. This was changed with the discovery of SME in the Ni-Ti system, which provided a superior combination of material properties for commercial applications. In 1962, Beuhler at the Naval Ordinance Laboratory (NOL) first reported the shape memory behaviour in Ni-Ti alloys and hence the name Nitinol (Ni-Ti NOL) is used to describe this alloy. Nitinol alloys are cheaper to produce and safer to handle leading to their popularity in industrial applications such as structures and composites, automotive, aerospace, mini actuators, micro-electromechanical systems (MEMS), robotics, biomedical and even in fashion [1]. Iron-based and copper-based SMAs, such as Fe–Mn–Si, Cu–Zn–Al and Cu–Al–Ni, are low-cost and commercially available, but are not ideal for most applications due to their instability, brittleness and poor thermomechanical properties. Therefore, Ni-Ti alloys are preferred in most cases. [1]

This report will deal with the properties, behaviour and applications of Nitinol.

1.2 THE Ni-Ti SYSTEM

Nitinol alloys generally have a composition of around 50 at.-% or 55 wt.-% Ni. The shape memory phenomena generally involve two phases: the austenitic parent phase at higher temperatures and the metastable martensitic phase at lower temperatures. The austenitic phase has a CsCl-type $B2$ superlattice ($Pm\overline{3}m$) while the martensitic phase displays a close-packed $B19'$ monoclinic structure ($P2_1/m$) as shown in Fig. 1 [2]. There also exist some other phase transformations involved with shape memory, such as rhombohedral, bainite and rubber-like martensite, which will not be discussed in detail.

The austenite-martensite phase transformation involves a solid-phase diffusion-less lattice distortion. Due to the absence of diffusion in the mechanism, this change takes place practically instantly. In order to minimise strain energy, the martensitic transformation originates from an invariant (undistorted and unrotated) plane that is common to both lattice structures. The austenitic lattice undergoes a shearing parallel to the crystallographic to the invariant plane in a particular crystallographic direction, resulting in up to 24 possible martensitic variants characterised by shear direction. This shear is generally enabled by reversible twinning in shape memory alloys [1]. These twins are termed as 'self-accommodating' as they maintain the bulk shape of the austenitic phase, ensuring there is no bulk deformation in this process [2]. The various characteristic properties of SMEs are enabled by this phase transformation mechanism.

Some of the alloy's mechanical and thermal properties also vary between the two phases: for example, Young's modulus, electrical resistivity, thermal conductivity and thermal expansion coefficient [1]. The austenitic structure is relatively hard, whereas the martensitic structure is soft and easily deformable.

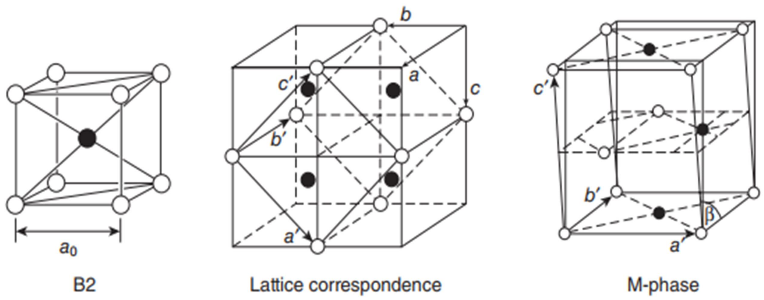

Fig. 1: Lattice structure of austenitic and martensitic phases [2]

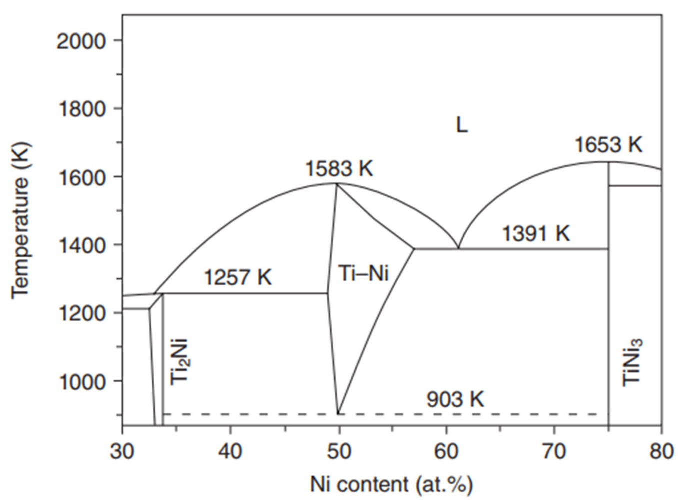

Fig. 2: Equilibrium phase diagram of Ti-Ni binary system [2]

2 THERMOMECHANICAL BEHAVIOUR

2.1 DEFORMATION BEHAVIOUR

The martensitic phase transformation exhibits hysteresis as shown in Fig. 3. On cooling of austenite the formation of martensite starts at temperature M_s. The transformation is complete at the martensitic finish temperature M_f. Similarly, on reheating austenite starts forming at temperature A_s and finishes at A_f , where $M_f < M_s < A_s < A_f$ as can be observed in the figure. An important implication of the presence of hysteresis is that the current state of the system depends on its previous state and not just state variables, which manifests as a 'memory'-like effects.

The deformation behaviour is strongly temperature sensitive, because of the difference in the deformation mechanisms in the austenitic and martensitic phases. The austenitic phase undergoes plastic deformation by means of slip. On the other hand, the martensitic phase undergoes recoverable deformation by means of 'detwinning', which is shearing of unfavourably oriented twin neighbours into a single variant. It is this detwinning mechanism that gives the characteristic softness to martensite. The deformation behaviour in various temperature ranges is shown in Fig. 4.

At temperatures below M_f deformation occurs purely through twinning. On heating such a deformed sample to A_f, the martensite transforms to austenite phase. As mentioned in section 1.2 , the macroscopic shape of austenite is almost identical to twinned martensite, due to the self-accommodating nature of the twins. This means that heating to the austenite phases results in a reversion to previous un-deformed state. On cooling, twinned martensite is formed again, having the original shape. This phenomenon is known as the (one-way) shape memory effect.

At higher temperatures but still below M_s some slip deformation also takes place due to the increasing austenitic content. When $M_s < T < A_s$, deformation occurs via stress induced martensitic transformation. This stress induced martensite does not revert upon unloading since the temperature is still under the austenitic start temperature. In temperatures between A_f and T_s , the austenite deforms via stress induced martensitic transformation, but reverts on unloading since the austenite is the stable phase in this temperature range. This results in the phenomenon of superelasticity, which is the ability to recover large deformations (up to 8.5% in some cases). The temperatures between A_s and A_f exhibit a mixed behaviour: partial recovery and partial shape memory.

T_s is the temperature above which deformation occurs via slip as opposed to martensitic transformation. Fig. 5 represents the same loading conditions as Fig. 4 in a temperature-stress phase diagram. σ_M is the critical stress required for stress induced martensitic transformation while σ_S is the critical stress required to initiate slip. When $T > T_s$, $\sigma_M > \sigma_S$ resulting in slip being favoured as mentioned earlier. [3]

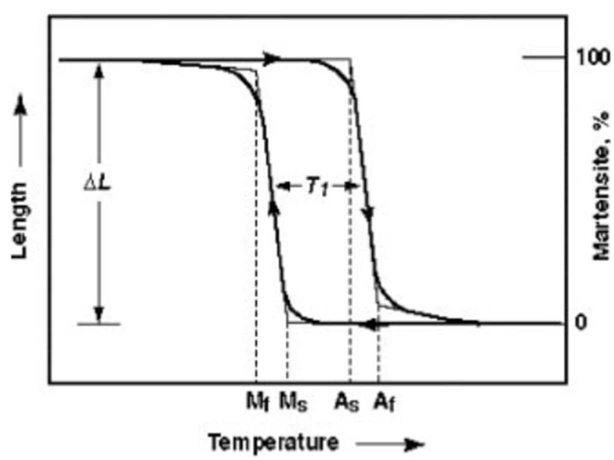

Fig. 3: Schematic of evolution of volume fraction of martensite as a function of temperature under constant stress loading [3]

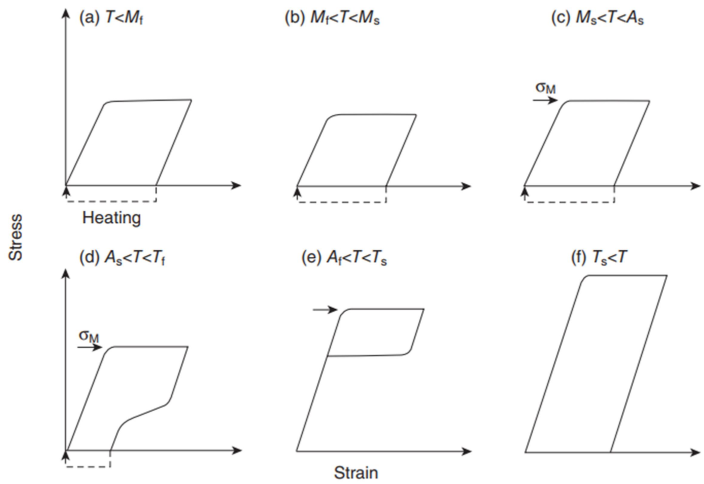

Fig. 4: Schematic stress strain behaviour of SMAs at various temperatures [3]

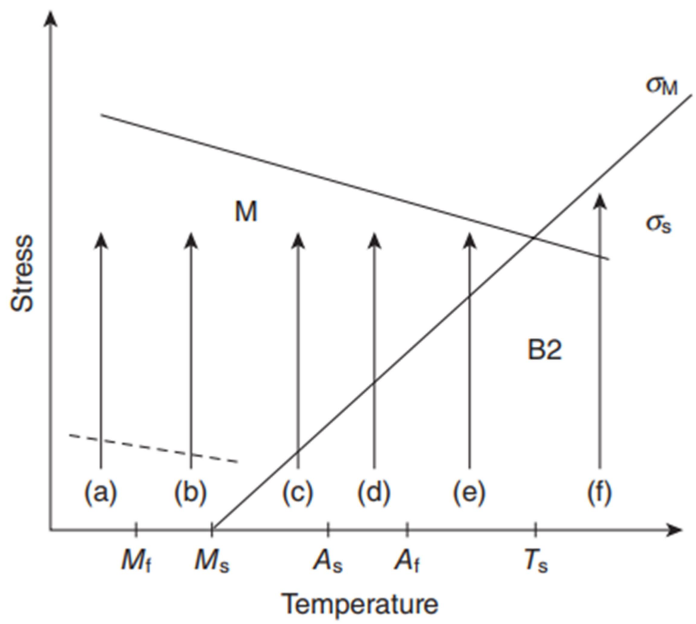

Fig. 5: Schematic critical stresses required for martensitic transformation (σ_M) and slip (σ_S) as a function of temperature[3]

2.2 STABILIZATION OF MATERIAL RESPONSE

In polycrystalline SMAs, the loading history also plays a role in the temperature-response. A permanent recoverable strain is induced during a transformation cycle which is termed as TRIP or Transformation-Induced Plasticity. The amount of irrecoverable strain is higher in the initial cycles and then reduces with the number of cycles, eventually stabilizing to zero. The repeated cycling to result in such stabilization is also known as 'training'. Apart from stabilizing the material's thermomechanical response, training also effectively eliminates the Austenite to twinned Martensite transformation. By bypassing the twinned state, the material deforms to the detwinned Martensite state on cooling Austenite without the application of stress. This results in the two-way shape memory effect, a phenomenon by which the SMA ‘remembers’ two different shapes and switches between them depending on temperature. Such a response is ideal for actuator applications, where the SMA is heated (usually by application of current) to achieve desired motion [8]. Training via isobaric thermal cycling is depicted in Fig. 6. The one way SME, two way SME and SE are summarized in Fig. 7

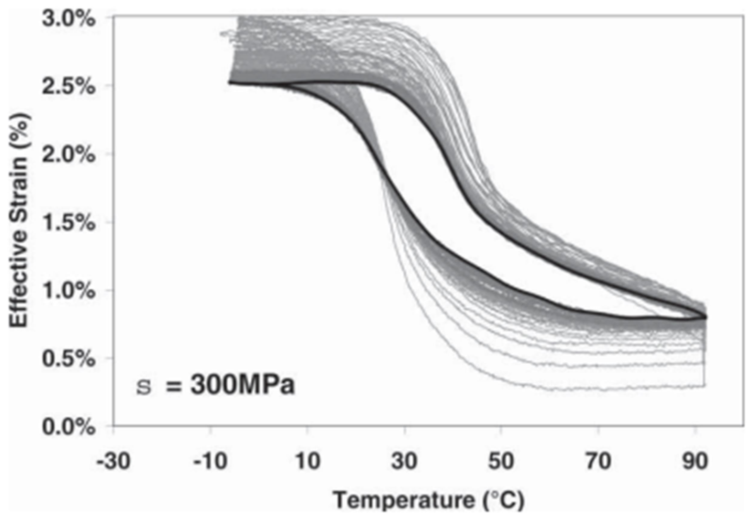

Fig. 6: Experimental results for training via isobaric thermal cycling [8]

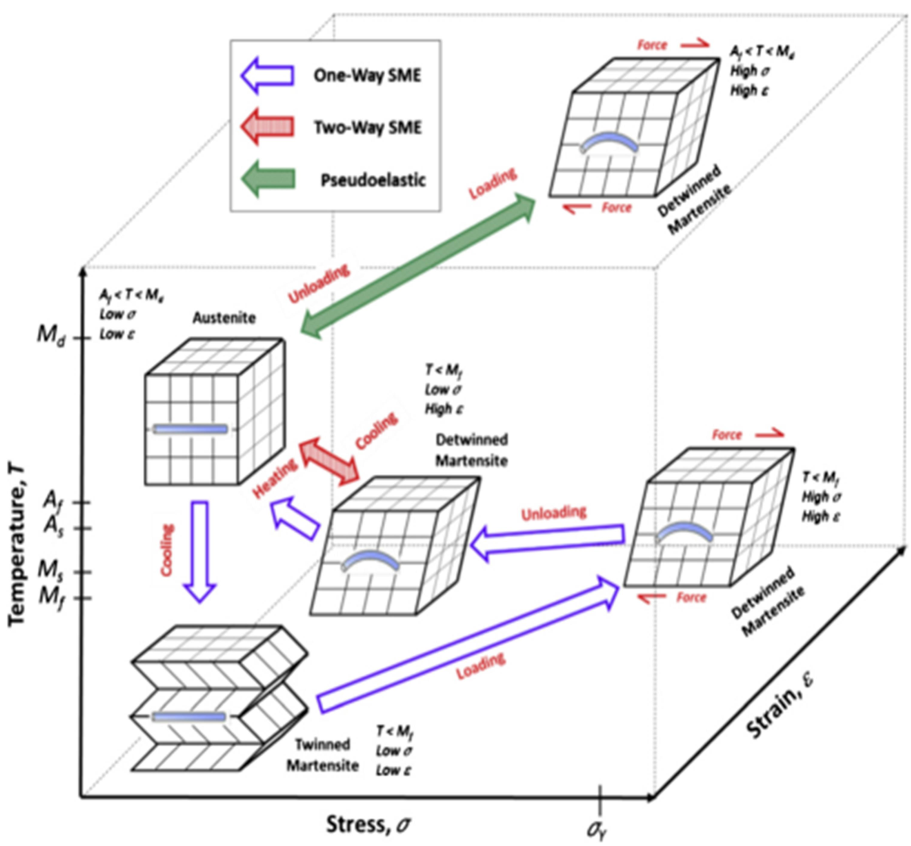

Fig. 7: Shape Memory Behaviour [1]

3 APPLICATIONS

Due to their superior work density, low mechanical complexity and biocompatibility, Ni-Ti SMAs provide an excellent option for actuation applications. They can provide significant displacement and forces, with a short response time. SMAs are also able to actuate in all three dimensions, which can be implemented into components that are required to extend, bend, twist, in isolation or in combination; and can be used in various configurations and shapes such as helical springs, torsion springs, straight wires, cantilever strips, and torsion tubes. The non-linear superelastic behaviour allows for vibration damping and isolation, while the hysteresis dissipates energy. Design challenges involved in SMA applications include low actuation frequency, accuracy, controllability and efficiency. Moreover a highly specialised and efficient heat transfer system is required to enable quick cooling.

The unique behaviour of NiTi SMAs have spawned new innovative applications in the aerospace, automotive, automation and control, appliance, energy, chemical processing, heating and ventilation, safety and security, and electronics (MEMS devices) industries. The demand for more intuitive and safe driving experience has opened the need for a variety of sensor-actuator mechanisms. These include linear actuators (e.g. rear-view mirror folding, climate control flaps adjustment and lock/latch controls) and as active thermal actuators (e.g. engine temperature control, carburetion and engine lubrication, and powertrain clutches). SMAs have also been used in robotic applications, especially as artificial muscles and micro-actuators. SMAs have also found their way into the biomedical industry- with applications in areas such as dentistry and non-invasive surgery. SMAs are used in medical equipment and devices in many fields including orthopaedics, neurology, cardiology and interventional radiology; and other medical applications include: endodontics, stents, medical tweezers, sutures, and anchors for attaching tendon to bone, implants, aneurism treatments, eyeglass frames and guide wires.

SMAs have garnered particular interest in the aerospace industry as the applications involved require handling of dynamic loads while being subject to space and weight constraints. A few examples of these are actuators, structural connectors, vibration dampers, sealers, release or deployment mechanisms, inflatable structures, manipulators, and pathfinder [1]. Aircraft wing morphing will be focused on in the following section.

3.1 WING MORPHING

As a case study, this report will study the DARPA (Defense Advanced Research Projects Agency) Smart Wing Project carried out in 1995-1999. The goal of the program was to study wings that were morphable mid-flight via the use of shape memory alloys. The primary advantage over a conventional actuation system is that the SMA system results in the wings having a continuous, hinge-less, smooth contoured wing that result in a higher efficiency. The morphable wings provide a variety of aerodynamic geometries that can be optimally selected based on the flight regime while also improving lift to drag ratio. These SMA actuated morphable wings are suitable for lightweight applications, such as unmanned aerial vehicles (UAVs). The model subject to wind tunnel tests was a 16% scaled model of an advanced military aircraft

The study involved tests of two designs, the ‘Torque Tube Design’ and the ‘Trailing Edge Control Surface Design’ The Torque Tube Design involved two SMA torque tube assemblies, effectively connecting the wing root to the tips, as depicted in Fig. 8. The SMA trailing edge control surface design involved the addition of two hinge-less control surfaces, a flap and an aileron, actuated using SMA wires in the top and bottom facesheets.

The models were both subject to wind-tunnel test providing Mach numbers ranging from 0.2 to 0.4. Data was recorded for angles of attack -4 to +16 degrees. The Torque Tube was tested for twist angles upto 5 degrees. The trailing edge provided aileron deflections upto 10 degrees. The implementation of continuous, hinge-less, smooth contoured control surfaces resulted in improved pressure distribution and reduced flow separation, as recorded by the fiber optic sensors. Significant improvements in rolling motion were recorded in the smart wing models as compared to conventional designs.

The main limitation of the test was the low actuation speed. The current design required several seconds to deploy and twice as much time to return via passive cooling. Hence this design is unsuitable for quick manoeuvres. [15] This study demonstrates one of the first tests of wing morphing designs, a field which is still undergoing active development.

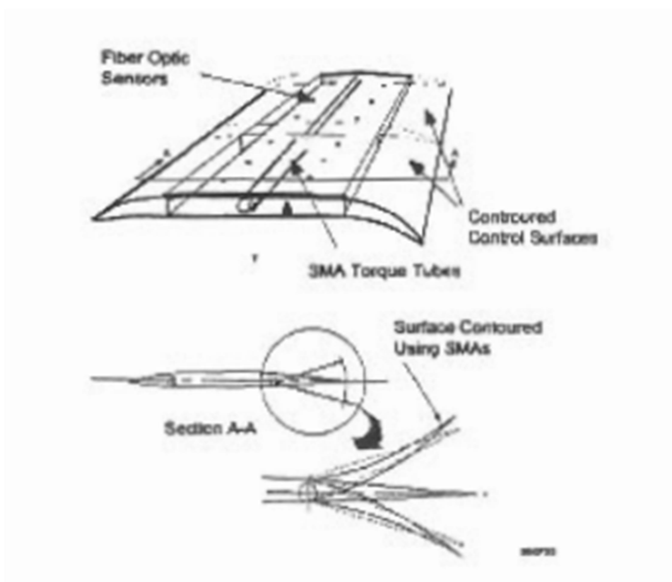

Fig. 8: Simplified schematic representing cross-section of the Torque-Tube Design[15]

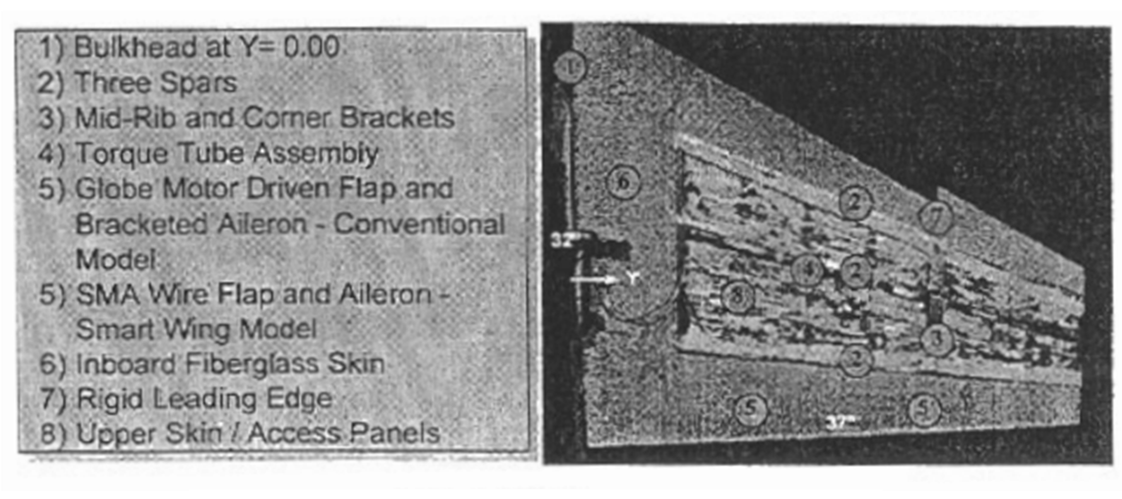

Fig. 9: Wing model of Trailing Edge Control Design [15]

4 CONCLUSION

Shape Memory alloys have the potential for complex and specialised applications due to their unique thermomechanical properties. Depending on the temperature range and loading history, SMAs exhibit three characteristic behaviours as summarised below:

1. One-Way Shape Memory Effect: Retention of deformed state on removal of load followed by recovery of original shape on heating
2. Two-Way Shape Memory Effect: 'Memorization' of two different shapes corresponding to two different temperatures
3. Superelasticity: Recovery of up to 8.5% strain on removal of load

These properties have their origin in the martensitic phase transformation, which has been explained in detail. The two-way shape memory effect can be used for actuation systems based on temperature variations, which are usually produced via Joule heating. Due to the lack of mechanical complexity, they are ideal for applications that have significant size and weight constraints. Superelasticity is useful in damping as well as applications that require high recoverable deformation. SMAs find several specialised applications in fields like automotive, aerospace, biomedical robotics and MEMS. In this report the applications of SMA in wing morphing technology have been briefly touched upon. SMA actuators can be used to effect mid-flight changes in geometric parameters such as aileron inclination, wing twist angle and airfoil camber. These SMA systems result in smooth-contoured, hinge-less continuous surfaces which result in uniform pressure distribution over the wing. Moreover, due to high actuation density and low weight, these are especially useful for lightweight UAV applications. However this technology still needs development to overcome obstacles such as low actuation frequency, low controllability and cycling fatigue.

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