Development and evaluation of thermo-mechanical behaviour of shape memory alloy based adaptive composite structure

M.Tech. Thesis

By

Vijay Choyal

(1502103009)

Discipline of Mechanical Engineering

Indian Institute of Technology Indore

JUNE 2017

Indian Institute of Technology Indore

Candidate's Declaration

I here by certify that work which is being presented in the thesis entitled **Development and evaluation of thermo-mechanical behaviour of shape memory alloy based adaptive composite structure** the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period July 2015 to May 2017 under the supervision of **Dr. I. A. Palani** and **Dr. M. Anbarasu** of Discipline of Mechanical and Electrical Engineering respectively.

The matter contained in this thesis has not been submitted by me for the award of any degree from any other institute.

Vijay Choyal
(1502103009)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(Dr. I. A. Palani) (**Dr. M. Anbarasu)**

Vijay Choyal has successfully completed his M.Tech. Oral Examination held on…………

Signature of the Thesis Supervisors **Signature of Convener, DPGC**

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Signature of the PSPC Member 1 **Signature of the PSPC Member 2**

Date: **Date:** -

Acknowledgement

I take this opportunity to express my deep sense of respect and gratitude for, Dr. I.A. Palani and Dr. M. Anbarasu for believing in me to carry out this work under their supervision. Their constant encouragement, friendly interactions, and constructive support have enabled this work to achieve its present form. Their innovative perspective towards things and continuous pursuit for perfection has had a profound effect on me and has transformed me majorly. I feel greatly privileged to be one of their students.

I am thankful to Prof. Pradeep Mathur, Director, IIT Indore, for giving me an opportunity to carry out the research work and providing all the facilities.

I am extremely thankful to Mr. S. S. Mani Prabu for guiding me and helping me out from the very first day I joined this project. I would also like to express my thanks to all members of Opto-Mechatronics group for their moral support and their friendly nature.

A heart-felt thanks to my entire M. Tech 2015-2017 Batch, with whom I have spent most of my time at IIT Indore. Special thanks are extended to Mr. Dhiraj Narayane chinduji for helping me in this project.

Lastly, but undoubtedly the most valued, gratitude is expressed for my parents, for letting me choose my dreams and supporting me endlessly. Your un-matched support made this work possible.

Vijay Choyal

Dedicated to my Guide –
my mother,
my father,
my brother,
my teacher,
and my friends

Abstract

Shape memory alloys (SMAs) are a type of smart materials which have unique feature diffusion less solid-to-solid phase transformation from austenite to martensite and vice versa. Composite structures embedded with SMAs have many benefits like actuation, vibration control, and damping, sensing and self-healing. However, despite substantial research in this area, a comparable adoption of SMA composites by industry has not yet been realized. Because of the material complexity that includes strong thermomechanical coupling, large inelastic deformations, and variable thermoplastic properties. SMAs are becoming increasingly accepted in engineering applications, a similar trend for SMA composites is expected in aerospace, automotive, and energy conversion and storage related applications.

The present study consists of two main parts; the first part is the manufacturing process while the second part consists of the investigation of thermo-mechanical behaviour and mechanical property of manufactured composite. The thermomechanical behaviour of composites with different diameter wire and number of wires has been investigated. Also, multicycle thermomechanical behaviour has been studied for about 100 cycles.

Contents

List of Publications

1. ***"Deflection and Thermal Analysis of Two-way Shape Memory Alloy Embedded Smart Structures",*** **IEEE** 2016 International Conference on Design and Manufacturing, at IIITDM, Chennai, India. S S Mani Prabu, Shreyas Gulhane, Vijay Choyal, S Karthick, K Akash M Anbarasu, I A Palani

2. ***"Development and Thermo-Mechanical Analysis of Shape Memory Alloy GFRP Embedded Smart Structures",*** ASFM at CSIR-AMPRI Bhopal. Vijay Choyal, Mani Prabu S S, M Anbarasu , Palani.I.A

3. **"*Shape memory alloy based adaptive composite structure ability of multiple modes of actuation*",** Rescon, IIT Bombay, March 2017. Vijay Choyal[1], Mani Prabu S S, Dhiraj Narayane C , Palani.I.A

List of Figures

Composites are materials made up of two or more different material, each material having different characteristics on the overall material behaviour. A number materials belong to this broad category, from traditional structural materials such as concrete and masonry all the way to newly devised polymers with embedded nanoparticles such as carbon nanotubes. More commonly, the term composite refers to materials constituted by a matrix, whose function is to bind together and protect the fibers, which constitute the main load-bearing elements of the composite.

Fibre-reinforced composites are becoming increasingly popular in a wide range of applications. Historically, among the first to take an interest in composites was the aerospace industry in the 1960s [1]The main reason was the reduce in weight of composites as compared to traditional materials.

In the last decades, however, composites have started to penetrate other industries, such as automotive, sporting goods and construction, where they are mainly used as reinforcement to repair and enhance the performance of existing structures[2]

As fibre reinforced composites become established, more ideas arise on how best to combine different materials to achieve variety of structural properties. The development of smart materials, such as piezoelectric materials and shape memory alloys, has paved the way to the creation of smart composites.

Smart materials exhibit coupling between the mechanical field and some other physical field (thermal, electric, pressure, etc.), thus a stimulus in one of the fields enrages a response in the coupled field and this coupling can be exploited for sensing and actuation. In sensing, a stimulus in the mechanical field enrages a response in the coupled field which can be measured, while in actuation the coupled field is used to enrage a mechanical response. By embedding a smart material in a composite, the composite itself can exhibit smart properties and the composite can be called as smart structure or adaptive composite structure.

Smart composite structures can be used for many purposes, the main idea being to control and adapt the structural properties according to a change in external conditions. If we embedded sensor they monitor the structural conditions, while actuators can change the dynamic properties or shape according to need. Even more, embedded systems can be designed with according to our applications. More important for future new technologies are smart structure or adaptive material in which SMAs can perform a very important role. Adaptive structure can be made with the help of SMAs and composite structure like Glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP).

Enhancement of existing structures, this thesis investigates several aspects of these new materials. The Thermomechanical behaviour of SMA-composites Investigate

SMAs are a group of alloys that exhibit a phenomenon known as the shape memory effect (SME). This effect gives the alloys the ability to recover their original shape after being heated above a certain transition temperature, after being pseudo-plastically deformed. There is also a large recovery strain, of up to 8%, associated with the transition. Because of this unique property, a large research effort is currently being undertaken, directed towards the use of SMAs in the actuation of smart structures for shape control, vibration control and for damage mitigation. SMAs also have a very high damping capacity due to a superelastic effect. This property of SMAs is extremely useful in vibration damping as well as reducing impact damage in structures. With the possibility of using SMA-composites in real structures such as in aviation, high speed transport industry and the automotive industry, there are increasing demands on knowing how the composites will react under everyday conditions

1.1 Reinforcement

Fibres are the main load-bearing element of the composite, thus it is mostly on the choice of the reinforcement that the composite mechanical properties depend. Choosing a reinforcement requires to define the fibre specifications their size and arrangement.

Fibres can be made of a wide variety of materials, both inorganic that is metal, glass fibre and carbon fibre and organic that is natural fibre and aramidic Because of the small size of the cross-section about 5 to 20 µm and the reduced amount of defects, fibres are generally stiffer and stronger than material in bulk form and tend to break in a fragile manner.

Glass fibre are the cheapest among the reinforcements, thus they are the most common in applications. Their elastic modulus is comparatively low, thus they are used for both structural and non-structural applications. Carbon fibres are classified as high strength and high modulus fibers. Their elastic modulus is the highest, thus they are often favoured in low-weight and high strength structural applications. However, their cost is relatively higher than that of glass fibers. Aramidic fibers are synthetic organic fibers, also known by the commercial name of Kevlar. When drawn, aramidic Fibers acquire anisotropic properties, thus their behavior in compression is significantly worse than in tension. Because of their microstructure, aramidic fibres break in a more ductile way as compared to glass or carbon fibres; for this reason they are used in applications where energy dissipation is required, such as motorcycle helmets and bulletproof vests.

1.2 Matrix

The matrix has the role of binding and protecting the fibres in a composite. Many different materials can be used as a matrix, such as metals, cement and polymers. Polymer matrices are by far the most common in composites applications and they are the only ones discussed here.

Polymers are subdivided into thermoplastic and thermoset resins. Because of differences in the microstructure, thermoplastic resins can repeatedly melt and harden when heated and cooled, whereas thermoset resins cannot be reformed once cured. Thermoplastics tend to have lower mechanical characteristics and higher viscosity than thermosets, thus they are often used for non-structural applications and will not be dealt with in details here.

The selection of a polymer matrix is determined by a variety of factors, involving both the service life of the composite (maximum service temperature, fire and corrosion resistance, mechanical properties, etc.) and the manufacturing process (duration, temperature and pressure required in the cure cycle, viscosity, etc.). As regards the composite manufacturing, the resin can be given in liquid, semi-solid and solid form depending on the chosen process. To acquire its service characteristics, it undergoes a curing process that is a chemical reaction which results in the formation of a three-dimensional cross-linked network. Depending upon the resin chemical composition and the properties which are to be achieved in the final composite, curing can be carried out in different conditions of pressure and temperature, with or without the presence of additives and catalysts.

Epoxy resins are the most widely used for structural applications because of their good mechanical properties. They are extremely versatile, as their properties and cure cycle can be tailored to meet various application needs. Their maximum service temperature goes from 90°C to 200°C. Bismaleimide and polyimide resins provide higher service temperatures than epoxies up to more than 350°C, whereas lower cost resins include polyestersand phenolic resins, the last ones providing also flame resistance and low smoking properties.

1.4 Manufacturing process

Many different composite manufacturing techniques are available, which differ in the quality of the final product, cost, production rate, achievable size and shape. Indeed, all these factors need to be taken into consideration when the process is selected. In particular, good quality of the resulting composite and high rate of production is usually contrasting needs, as the processes that yield the best results in terms of fibre quantity and placement are usually more time consuming. Composite manufacturing consists of four phases: impregnation, lay-up, consolidation and solidification.

In impregnation, fibres are thoroughly covered with matrix to ensure a good fibre-matrix interface. Naturally, in this phase matrix viscosity is a key factor. Depending upon the process, dry fibres or fibres already impregnated by the materials supplier (pre-pregs) are used.

The lay-up consists in positioning different layers of reinforcement one on top of the other to make a laminated composite. Each layer (lamina) can be made with a different or same reinforcement and the fibre orientation can vary from one layer to the other.

Consolidation is a crucial phase, which influences the quality of the final composite: a pressure is applied to remove voids and create the best possible contact between the laminate. Depending on the process, pressure can be applied by hand, with a vacuum pump, in autoclave or press.

Finally, solidification fixes the composite shape: it is achieved by resin curing and can last from less than a minute to several hours. The placement and orientation of the layers are conventionally defined by the laminate's stacking sequence, or lamination scheme. The laminate, or plies, are listed from the bottom to the top layer and defined by the fibre orientation with respect to an axis associated to the laminate.

1.4.1 Hand lay-up method

Hand lay-up is a very labour intensive technique, whose main advantage is to allow the production of good quality parts which can be large and complex-shaped. It consists in placing the layers on a lower mould by hand and then applying pressure and temperature by means of a vacuum bag or in autoclave to allow the resin curing. Two main techniques are included in hand lay-up: pre-preg lay-up and wet lay-up. In the first case, fabrics which are already impregnated with the resin are used, in the second alternate layers of dry fibres and liquid resin are applied using a roller. The use of pre-pregs allows to control more effectively the amount of resin and fibres present in the final composite, thus obtaining a material with better properties. On the other hand, pre-pregs are more expensive than dry fibres and resin, require storage below room temperature and have a limited shelf life (usually six months to one year). In both cases, the final result strongly depends upon the skills of the laminator.

1.4.2 Vacuum infusion Method

The Vacuum infusion method consists in impregnating layers of dry fibres by injecting low viscosity resin with the aid of vacuum. The described process can be carried out with a variety of resins and fibres. Particularly attractive for the SMA/GFRP Composite manufacturing is the possibility to choose resins whose cure temperature is lower than the shape memory alloy wire actuation temperature, so that the wire do not need to be restrained during composite cure. Show in the Figure 1

1.5 Smart materials

Due to their coupled behaviour, smart materials can be used for sensing and/or actuation purposes. The coupling can be related to intrinsic material characteristics, usually at the microstructural level, or to the `intelligent' combination of different traditional materials. A variety of materials display smart characteristics. Smart material is a type of materials that has inherent intelligence to react toward external stimuli such as heat, electrical field and electromagnetic field. This reaction will produce the desired functions such as changing the shape and modifying structural behaviour of a structure. Smart

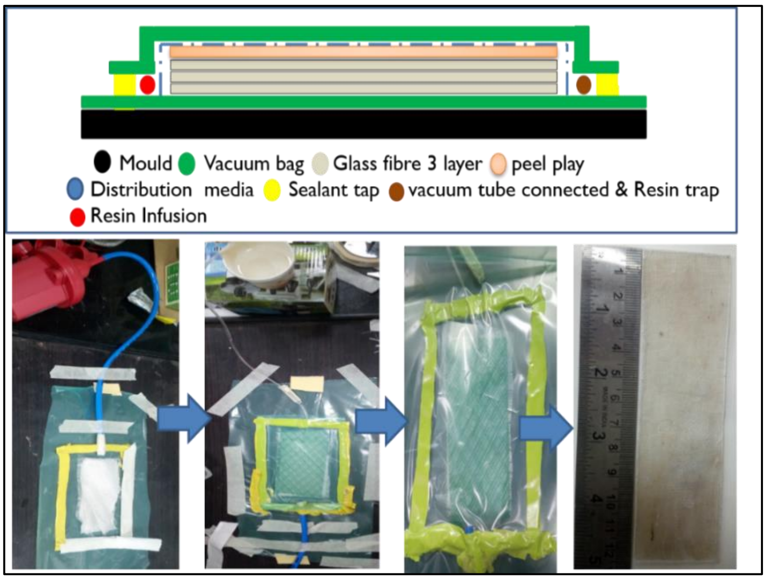


Figure 1: Vacuum infusion method for composite fabrication

materials that react by inducing an amount of strain can be classified into several types: piezoelectric material, shape memory alloys (SMA), magnetostrictive materials, electro rheological fluids, electro-optic materials, electro acoustic materials and electromagnetic materials. Mainly the smart materials are,

Piezoelectric materials are materials that produce a voltage when stress is applied. Since this effect is also applies in the reverse manner, a voltage across the sample will produce stress within the sample.

Magnetostrictive materials exhibit change in shape under the influence of magnetic field and also exhibit change in their magnetization under the influence of mechanical stress. The other types of shape memory alloys as they are, Piezo-ceramics (PZTs), Piezo-polymers (PVDFs), Electrostrictive ceramics (PMNs), Polymer gels.

Shape-memory alloys and shape-memory polymers are materials in which large deformation can be induced and recovered through temperature changes or stress changes (pseudoelasticity). The large deformation results due to martensitic phase change.[3]

Compared the actuation energy densities and the actuation frequencies of some smart materials in the Figure 2 and Figure 3. The actuation energy density that is work output per unit mass is denoted in Figure 2 with the help of dotted lines

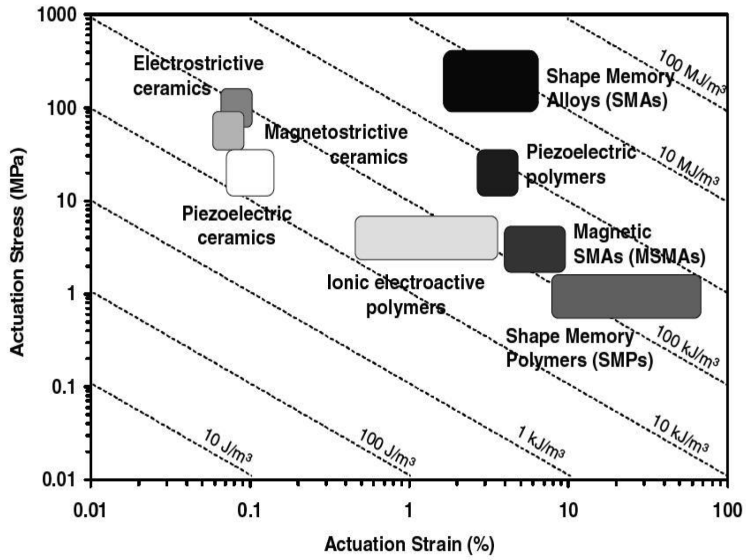


Figure 2: Actuation energy density of different smart materials[4]

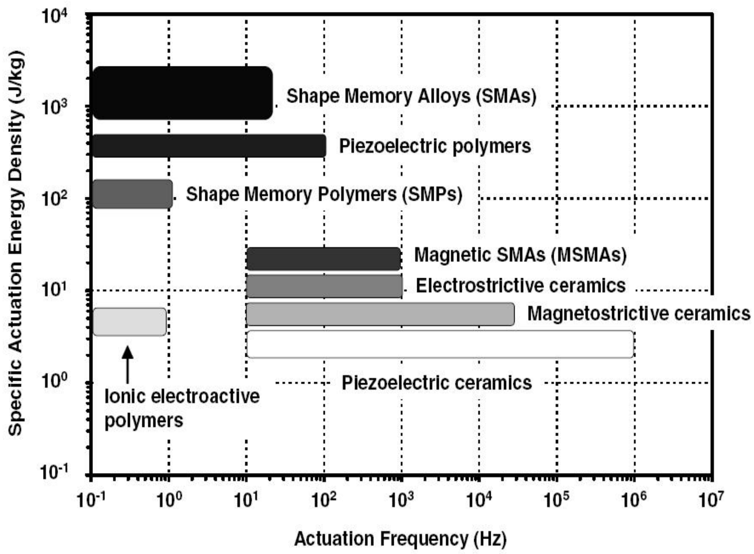


Figure 3: Actuation frequency of different smart materials[4]

and it is the product of actuation stress and actuation strain (stroke of the actuator) and we assume here that the active material is operating under constant stress. The specific actuation energy density of a specific smart material can be calculated from Figure 2 by dividing the actuation energy density by the mass density. An increase in temperature of an SMA can result in shape recovery even under high applied loads therefore resulting in high actuation energy densities as shown in Figure 2 SMAs do, however, exhibit low frequency response, as shown in Figure 3. So for high specific energy density, high strain recovery and good response time we used shape memory alloy for smart structure [4]

1.2.1 Shape memory Alloys

SMAs are a group of metallic alloys that have the unique ability to remember or to retain a shape or size prior to deformation, with the help of a heating process. They accomplish this shape memorization via a temperature dependent phase transformation process characterized by two stable phases, a high-temperature phase known as austenitic phase and a low-temperature phase known as martensitic phase. This phenomenon is known as the shape memory effect. Austenite, the high-temperature phase, is relatively hard and has a much higher Young's Modulus; whereas the martensite phase is softer and more malleable. When cool and in the martensite phase, the SMA can be easily stretched by applying a small external force. To recover its original length, the alloy is heated beyond a certain temperature, causing it to contract and transform into the austenite structure. Heating the SMA can be done via Joule heating (active control), which is resistively heating the material using electric current and hot atmosphere (passive control).

Many SMAs that have been discovered so far, NiTi shape memory alloys, also known as Nitinol, have proven to be the most flexible and successful in engineering applications because of good mechanical property compare to other SMAs. SMAs are commonly used is in the form of wires, sheet and ribbon. In our research, NiTi, has been used in wire form for all the experiments.

The term NiTiNOL in honor of its discovery at the Naval Ordnance Laboratory (NOL). In aforementioned two phases of SMAs, each with a different crystal structure and therefore different properties. One is the high temperature phase called austenite (A) and the other is the low temperature phase called martensite (M). Austenite (generally cubic) has a different crystal structure from martensite (tetragonal, orthorhombic or monoclinic). The transformation from one structure to the other does not occur by diffusion of atoms, but rather by shear lattice distortion. Such a transformation is known as martensitic transformation. Each martensitic crystal formed can have a different orientation direction, called a variant. The assembly of martensitic variants can exist in two forms: twinned martensite (M^t), which is formed by a combination of self-accommodated martensitic variants, and detwinned (M^d) or reoriented martensite in which a specific variant is dominant. The reversible phase transformation from austenite (parent phase) to martensite (product phase) and vice versa forms the basis of the unique behaviour of SMAs. Upon cooling in the absence of an applied load, the crystal structure changes from austenite to martensite. The phase transition from austenite to martensite (forward transformation) results in the formation of several martensitic variants. The arrangement of variants occurs such that the average macroscopic shape change is negligible, resulting in twinned martensite. When the material is heated from the martensitic phase, the crystal structure transforms back to austenite, and this transition is called reverse transformation, during which there is no associated shape change. We remark that the martensitic transformation in SMAs consists mainly in a shear, without volume change. [5] The crystal structures of twinned martensite and austenite for an SMA and the transformation between them is shown in Figure 4 There are four temperatures related with the phase transformation. During the forward transformation, austenite, under zero load, begins to transform to twinned martensite at the martensitic start temperature (M_s) and completes transformation to martensite at the martensitic finish temperature (M_f). And during heating, the reverse transformation start at the austenitic start temperature (A_s) and the transformation is completed at the austenitic finish temperature (A_f).

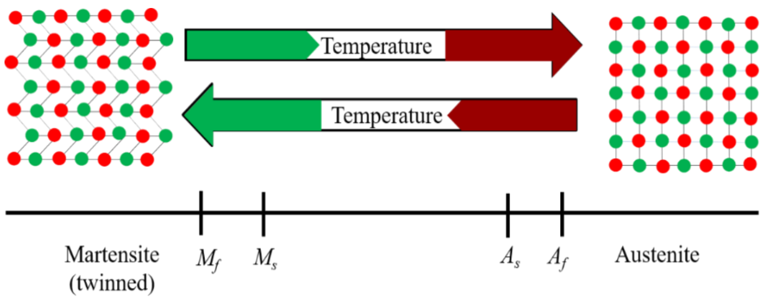


Figure 4: Phase transformation of SMAs due to heating without mechanical loading

Show in the Figure 5[5] If at low temperature a mechanical load is applied to the material when material in the twinned martensite phase, then possible to detwin the material from twinned to detwin martensite by organising a variants. The detwinning process results in shape change, where the deformed SMA is retained when the load is removed. In Figure 6[5] showing A consecutive heating of the SMA to a temperature above A_f will result in a reverse phase transformation form Detwinned martensite to austenite, lead to complete shape recovery. Cooling back to austenite will result formation of twinned martensite with no shape change called shape memory effect.

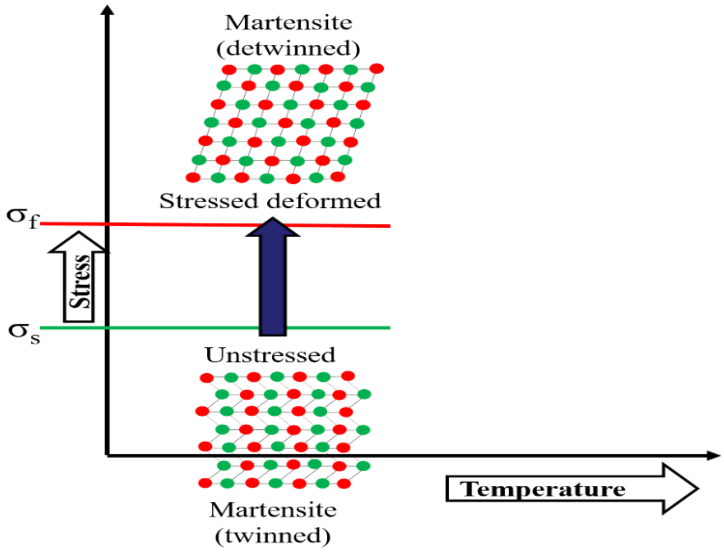


Figure 5: Shape memory effect of SMA detwining with applied load

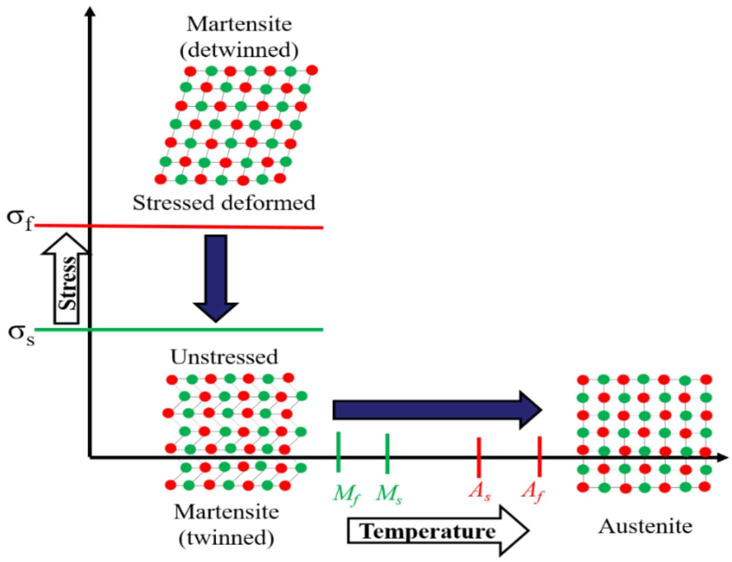


Figure 6: Shape memory Effect of SMA during loading and consecutive heating at no load

When the SMA is cooled with a mechanical load greater then σ_s applied to the austenitic phase, the phase transformation will result in the direct creation of detwinned martensite phase, producing a shape change. Then again heating the SMA will result in retaining the shape that is shaped recovery, while the load is still applied show in the Figure 7.[5] Transformation temperatures depend strongly only on the applied load i.e. higher values of the applied load result in higher transformation temperatures. Under an applied load with a relevant stress σ, the new transformation temperatures are represented in Figure 7 for martensitic finish, martensite start, austenite start and austenite finish temperatures. [6]

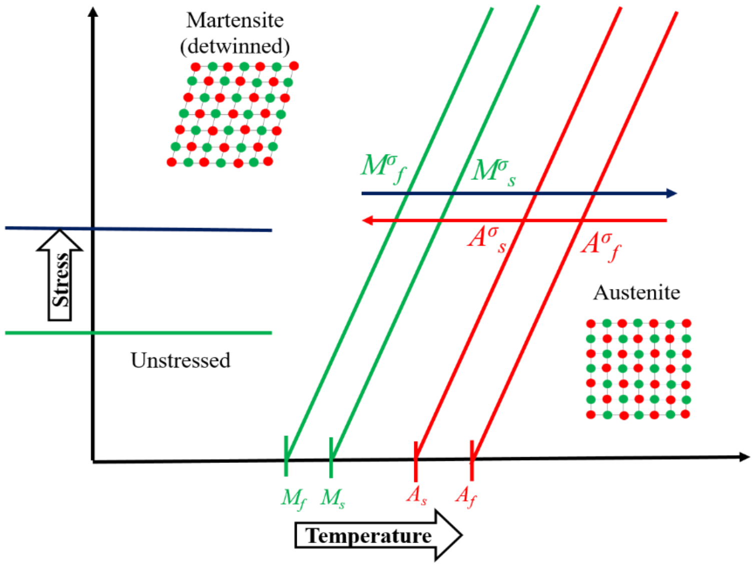


Figure 7: Phase transformation during heating when load is applied

Transformation can also be done by applying a required high mechanical load to the SMA in the austenitic phase. The result of this SMA fully detwinned martensite created from austenite. If the temperature of the material is greater than A_f, a complete shape recovery will done upon unloading to austenite. This phenomena is called the pseudo-elastic effect [6], show in the Figure 8. And represented the macroscopic shape change due to the applied load in stress-strain diagram, as shown in Figure 9.

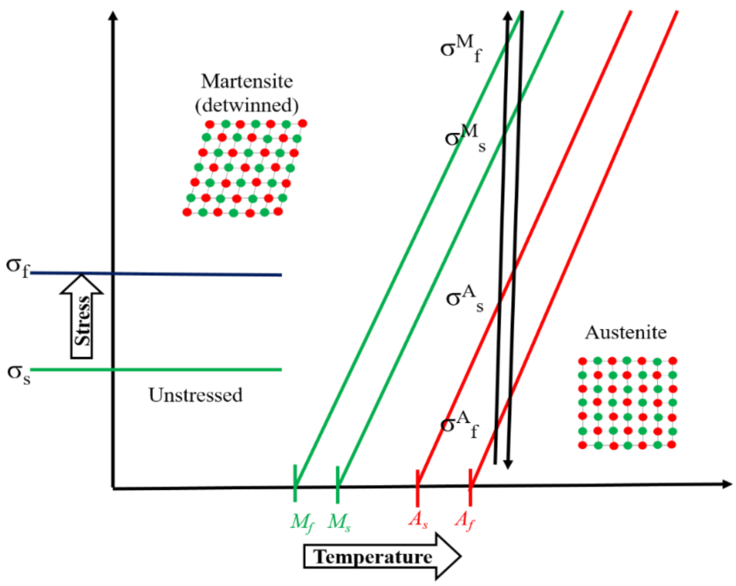


Figure 8: pseudo-elastic effect loading curve

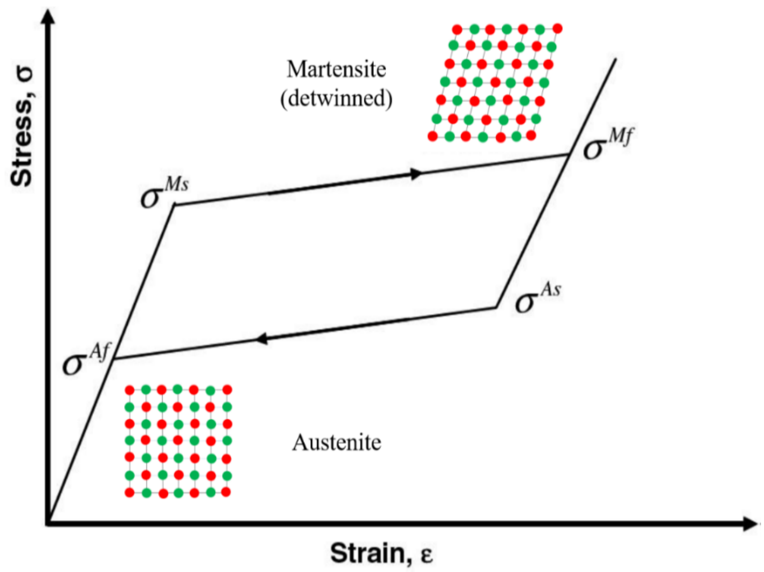


Figure 9: Pseudo-elastic stress strain curve

1.6 Motivation

Minor deflection in structure with conventional technologies requires expensive heavy motors, hydraulics and many moving parts. Nevertheless, using SMA embedded adaptive smart structures, deflection can be easily attained and it is simple in design, light weight, no moving parts and scalable.

This project focuses on the development of smart structure with SMA via applied electrical pulse. Prior to insertion in the polymeric structure, the SMA will be shape trained through a series of heat treatment, enabling blade deflection on heating.

No researcher has addressed the multicycle issues for the actuation of SMA composite structures. Here, it is planned to investigate the multicycle thermos-mechanical behaviour to stimulate the SMA integrated adaptive structure with respect to the required deflection and the adaptability and the repeatability behaviour of SMA adaptive structures

1.7 Research Objectives

- ❑ Material suitability analysis and fabrication of glass and carbon fibre reinforced composites (GFRP and CFRP) embedded with shape memory alloy (SMA).
- ❑ Fabrication of glass fibre reinforced composites with various diameter and different number of SMA wires and with different training methods.
- ❑ Investigations of stress strain behaviour of SMA embedded smart composites with GFRP without SMA wire.

- Thermomechanical analysis of smart composites

  Active mode: Electrical energy based Joule heating method at different heating and cooling time and at different ambient temperature.

  Passive mode: In house developed passive heating setup with hot air blower.

- Multicycle thermomechanical analysis of smart composites using active mode.

The design of an adaptive flap system based on smart material embedded composite is a multidisciplinary problem. The challenge is to design a structure that is capable of withstanding not only the prescribed loads, but also to changes its shape precisely on requirement. To meet these demands, the actuation system consisting of active materials such as piezoelectric, shape memory alloy and dielectric elastomers can be utilized. The limited tensile stress levels to fracture of the piezo electrically driven actuators pose a threat of much deflection that may lead to catastrophic failure of the structure .[7] So it's a need to adopt an smart material without the hazard of self-destruction. This crucial feature can be exploited by the SMA reinforced polymeric composite structures. [8]showed a reliable tip deflection of 7.5 mm of smart composite beam developed by embedding SMA wires. In the last decade, few researches showed the SMA wire embedded composite as adaptive flapper system for aircraft wings for better flight control and less power consumption [9].

Main idea behind this work is to obtain a better understanding of the effects that embedded SMAs have on the material properties of composite structures, as well as to determine the benefits of embedding the SMAs. Composite structures embedded with SMAs have many applications including shape control for use in changing the camber of aircraft wings [10]–[13] as well as in vibration control [14] in order to enhance the performance of structures.

Internal stresses induced by actuation of a thin SMA ribbon embedded in a polymer matrix. The SMA ribbons were sandblasted to increase the adhesion to the polymer matrix. A room temperature cure polymer was used in order to be rid of any residual stress effects produced from the actuation of the SMA. The composites were then studied using photoelastic methods and the resulting photoelastic fringes were found to be due entirely to the actuation of the SMA ribbons.[15] To develop smart adaptive structural components by controlling their shapes in bending, SMA actuators in general need to be integrated with the host components such as composite structures, though some non-embedding approaches have also been investigated.[16]

One common manufacturing technique for SMA composites was discussed in [17]. In this paper the manufacture of an SMA composite used for impact resistance was discussed. The SMA composites in this paper consisted of a vinylester resin reinforced with superelastic SMA wires and glass or carbon fabric. To manufacture these composites, specialized frames were built to secure the SMA wires and ensure correct wire spacing. Sheets of fabric reinforcement were then placed between the layers of SMA reinforcement and the process was repeated until the composite had a total of 4 layers of SMA wire reinforcement. To create a composite between these two reinforcing materials vinylester resin was added using vacuum assisted infusion.

A woven type smart soft composite (SSC) was fabricated and implemented as a soft morphing spoiler by Min-Woo Han et al [18] in order to adjust its aerodynamic performance by transforming its shape using a compact mechanism. The woven type SSC which consists of SMA wires for actuation and anisotropic materials to obtain directional properties were embedded together in a flexible polymeric matrix was designed for application in a trailing edge for the rear-spoiler. The structure was implemented as the trailing edge of the spoiler of a small-scale car (1 /8-scale). Also, the embedded SMA wires were divided into two different current channels to generate a bend-twist deformation intended to increase the yawing moment. To find the effects of the airflow on the generated forces by the morphing spoiler, wind tunnel tests were conducted in an open-circuit bowing-type wind tunnel. Test results showed that the proposed structure is capable of large deformations, self-recovery to its original shape, and withstanding the external forces applied through the airflow surrounding the morphing spoiler shown in the Figure 10.

Figure 10: Morphing spoiler attached with small scale car

Chapter 3 Fabrication of adaptive composite structure

Fabrication of adaptive composite structure divided into two parts; first part is the Shape training of SMAs and the second part is manufacturing of the composite structure as shown in the Figure 11.

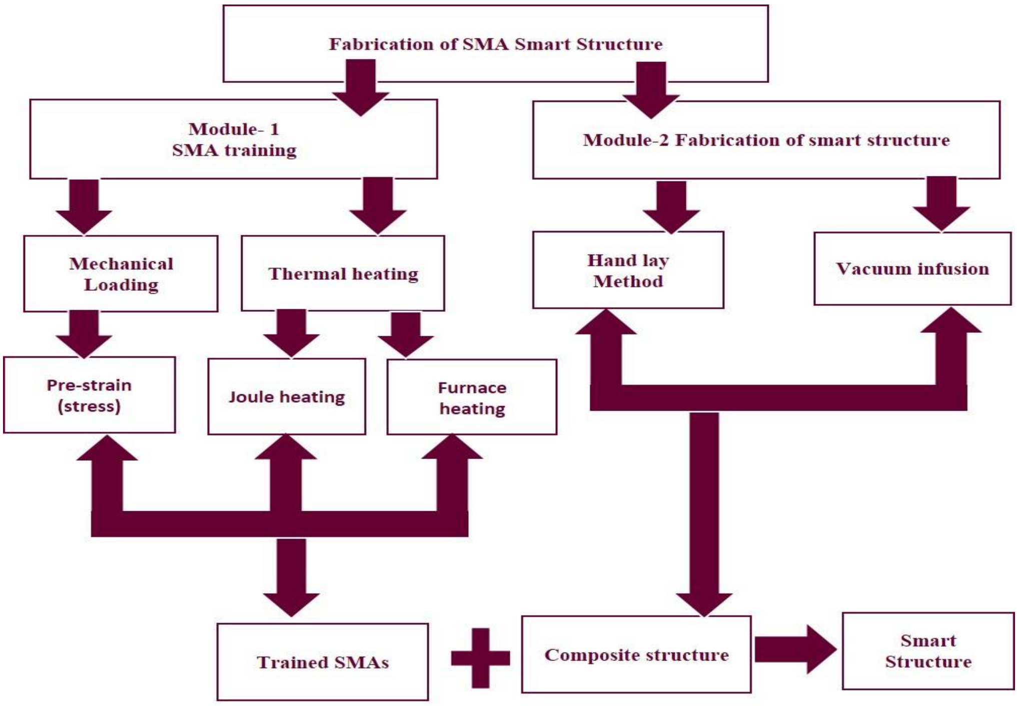


Figure 11: Fabrication process of adaptive structures

3.1 Design Consideration

3.1.1 SMA wire property

The design and manufacture of adaptive composite structures require considerations and selection of a significant number of performance and actuation parameters. These include SMA wire material, wire cross-sectional profile and dimension, prestrain level, volume fraction and through-the-thickness location, host composite material and lay-up, a level of applied current, and structures dimensions for the given performance requirements in terms of bending strain. A comprehensive experimental investigation of treating all these parameters as equal variables will be prohibitively expensive. Thus the current study has focused on the variation of just four selected parameters, namely, composite host material, applied current level, beam length and actuation cycle. There are three major SMAs such as Cu–Zn–Al, Cu–Ni–Al and binary Ni–Ti (Nitinol) used for adaptive structural applications. And Nitinol is selected here because of its greater strain recovery capacity, excellent corrosion resistance, and stable transformation temperatures with a relatively high electrical resistance and compatibility with cure temperatures of the present host composites [19]. So that is why in this work Flexinol wires are commercially produced NiTi alloy wires. Nitinol (55% Ni-45% Ti) SMA wires of diameter 300 µm, 375 µm and 500µm were used for SMA/CFRP Composite. These Nitinol wires has an austenite temperature A_s=68 °C, and an austenite finish temperature A_f = 78°C, and a martensite start temperature M_s = 42°C and martensite finish temperature M_f = 52°C.

3.1.2 Reinforcement and matrix

The reinforcements made up of unidirectional glass fibre fabric. Glass fibres are chosen both for their relatively low stiffness as compared to carbon fibres and for the electrical insulation they provide. Indeed carbon fibres conduct electricity, thus Joule heating of the embedded shape memory alloy wires would be difficult to achieve. The laminate is composed of three layers with the fibres perpendicular to the shape memory alloy wires direction. This way, the bending stiffness in the wires direction is minimum and the maximum actuation should be achieved. Eight wires are placed between the first and second fibres layer, thus giving the maximum possible offset from the plate mid plane.

3.2 SMA training

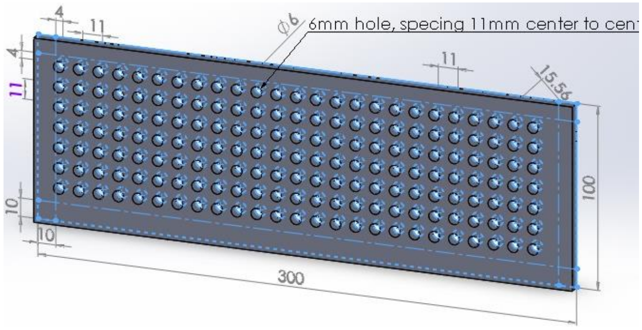
In most of case, SMAs are supplied as raw material that is without shape memory. To memorise the certain shape, training of the wire is required. *Training* an SMA refers to a process of repeatedly loading the material following a cyclic thermo-mechanical loading path until the hysteretic response of the material stabilizes and the inelastic strain saturates.

In this work shape memory alloy wire was used are first trained with the help of different available method like mechanical loading and thermal heating.

In mechanical loading fixed SMA wire at one end and applied the according stroke of the wire the maximum strain recovery the nitinol wire is 8% but for the safety purpose used strain in this work is 4%.

Flexinol wires are commercially produced NiTi alloy wires which have been trained to exhibit the shape memory effect over millions of cycles without fatigue, provided the working strain is limited to 4%. We used Flexinol wires with an austenite finish temperature (A_f) of 90 °C and a diameter of 300µm, 375μm and 500μm. In thermal heating shape-setting of SMA is a thermally-induced process that occurs when the alloy is heated to temperatures of approximately 450-500°C for 10 to 25 minutes. The heating can be done with the help of furnace and joule heating. If resistive or joule heating will be used for shape-training, then a power source capable of at least 5 Amperes and 20 Volts is needed. In most literature, shape-setting occurs in a furnace because in resistive heating thermal induced in the SMAs is gradually, the result was a brittle wire that weakly exhibited the shape memory effect.[20]. Designing the fixtures for shape training (Shown in the Figure 12) the freedom in choosing the shape we want to create. Fixture should be like that in which SMA wires must be clamped down on the fixture rather than tied in any way, bolts will be used to clamp the ends of the wires, holding them in place.

a.



b.

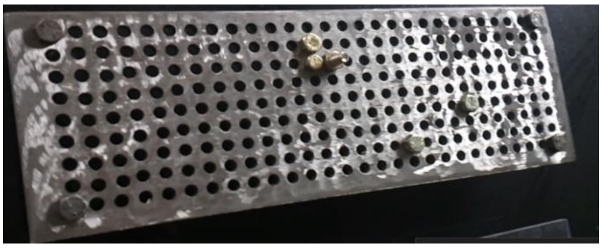


Figure 12: a. Design Fixture b. Actual fixture

Shape setting of SMAs through furnace heating Shown in the Figure 14. In order to delete any residual stress of previous deformation history, the wire was first placed in furnace at 700°C For 20 min followed by cooling to room temperature.

Step 1: Choose SMA (Nitinol) wire of required dimensions.

Step 2: Fix the SMA wire on the fixture in which shape we want (shown in the Figure 13).

Step 3: Reach the temperature of the Muffle furnace up to 450°C then put the fixture in to the furnace.

Step 4: At 450°C up to 20 min SMA reach to austenite phase and remember the shape setting according to our requirement.

Step 5: After 20 min remove the fixture and place in the water for quenching the SMA.

Step 6: Straight the SMA wire and perform the process repeatedly up to number of cycle. If number of cycle increases, recovery level will also increase but we used 5 Cycle.

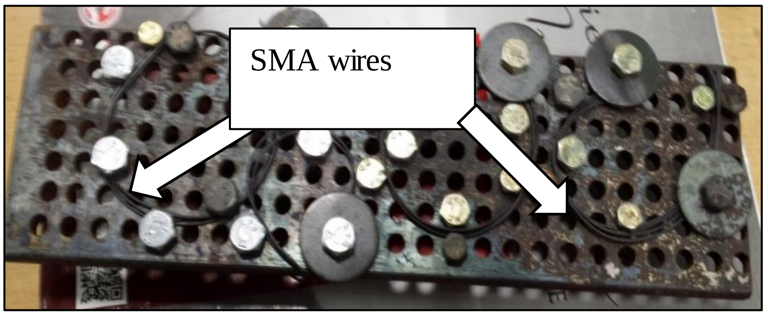


Figure 13: Fix the SMA wire on the fixture

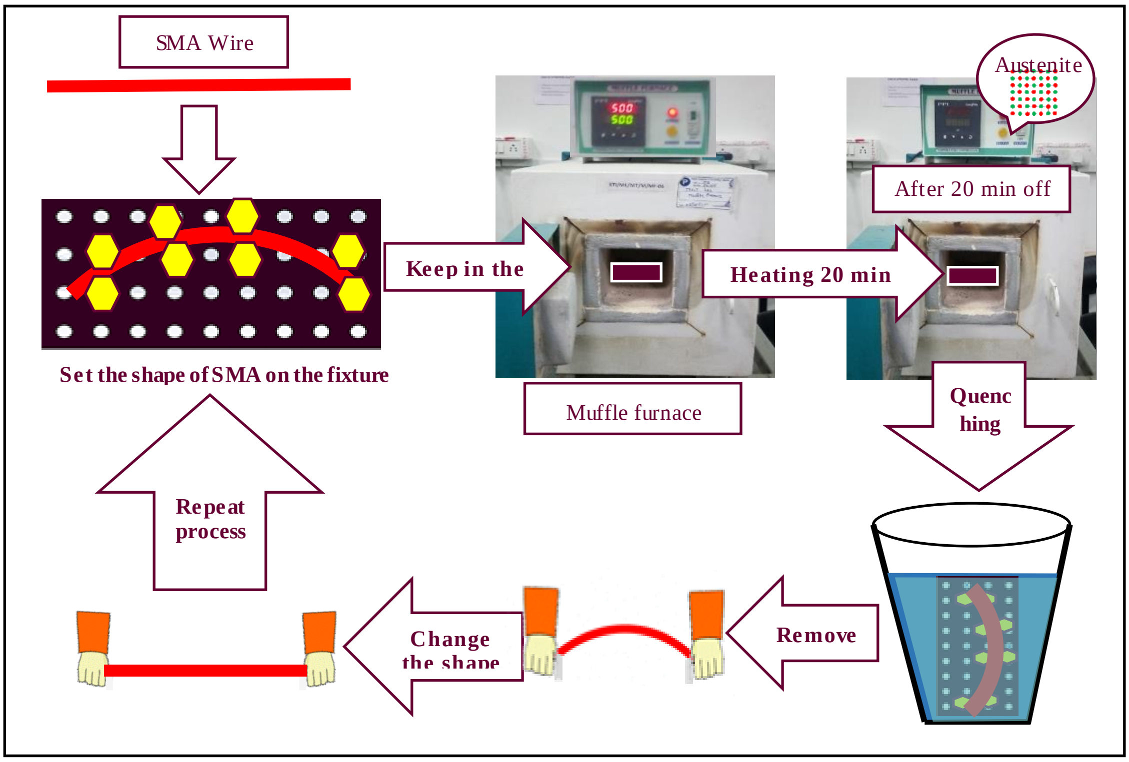


Figure 14: Thermal induce shape training of shape memory alloys

The wire can also be trained by Joule heating. Shape setting of SMAs through Joule heating is shown in the figure 15 where the wire is placed in a fixture and 16-18 Ampere current is supplied for 5 minutes and then allowed to cool for 2 min. This is done for 5 cycles. However, furnace heating is more effective than Joule heating as it shows shape remembrance property for more number of cycles.

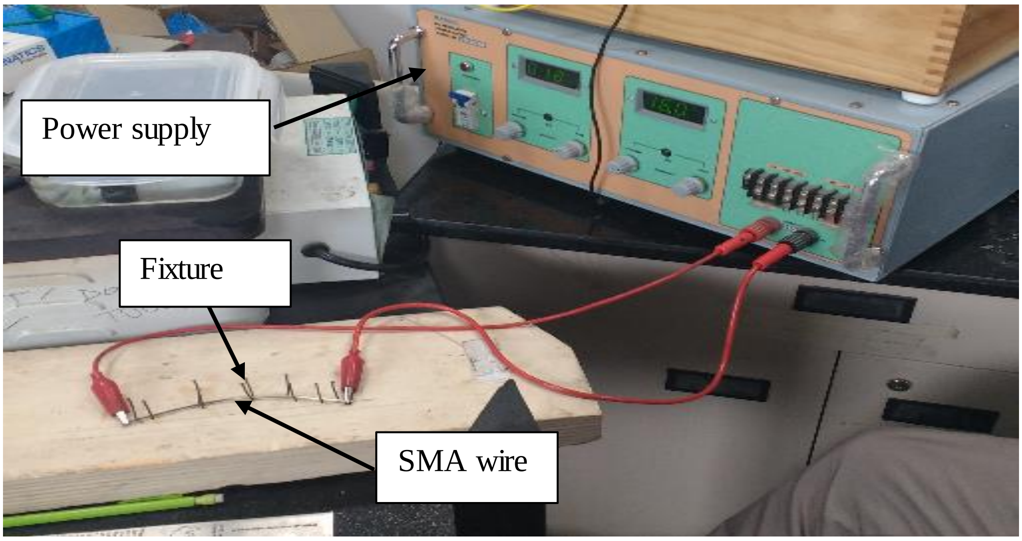


Figure 15: Shape setting of SMA through joule heating

3.3 Fabrication of smart structures

The present experimental investigation on shape memory alloy hybrid composites focuses on shape control applications. Indeed, the shape control configuration is highly sensitive to the material parameters of both shape memory alloy wires and host structure, thus it requires careful design.

The adaptive composite structure is the glass fibre reinforced polymer (GFRP) embedded with SMA wires longitudinally.

The SMA/GFRP adaptive structures were fabricated by hand lay method and cured at room temperature. In order to prepare shape memory alloy based adaptive composite structure an alignment frame device shown in Figure 16 was used to ensure that during composite manufacturing cure the pre-strained and trained wires should be kept in straight with the some specified same distance between the wire to wire with desired thickness of the overall composite structures. The alignment device is made with base plate of wooden and acrylic sheet with proper alignment of all the hole as shown in the Figure 17. Then prepare the mould with proper spacing hole between the each wire as shown in the Figure 18 in which both side hole is given so distance between the wire will be maintain and the hole size is bit greater than the diameter of the wire wires were threaded through easily without being damaged and made a pair of wire tension tightening strip and two arrays of wire fixers or wire connector for fixing the wire in both side. Wires were threaded through easily without being damaged.

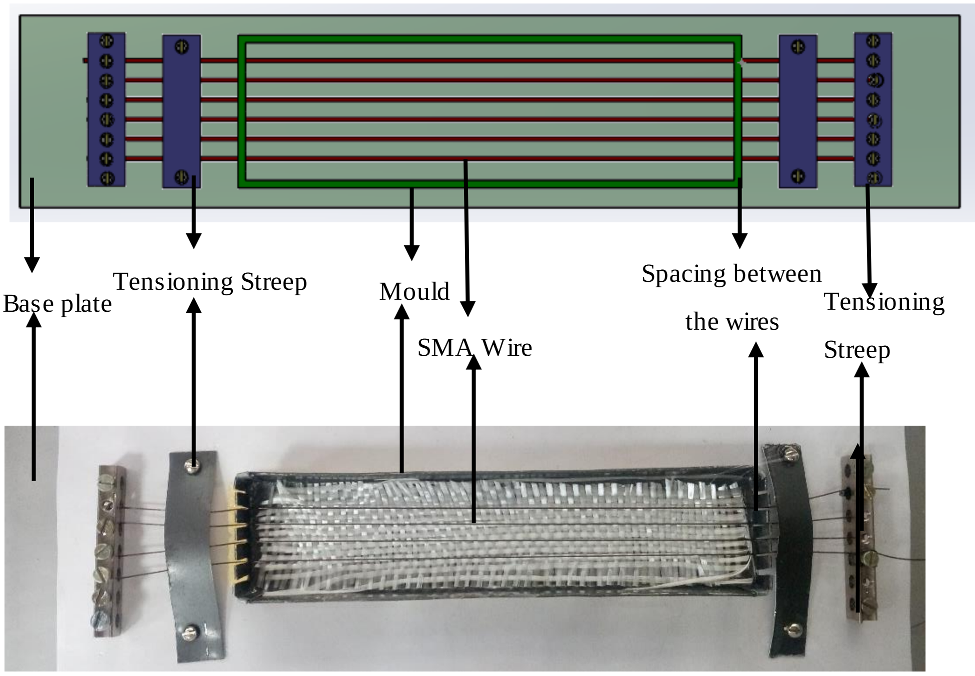


Figure 16: SMA wire alignment device for development of adaptive composite structure

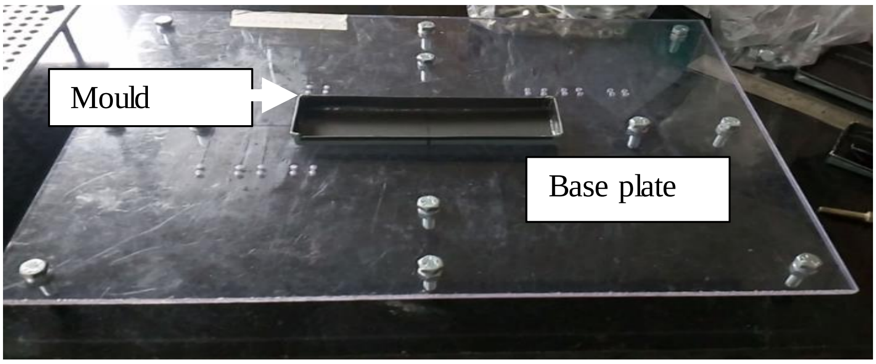


Figure 17: Base plate for Specimen manufacturing

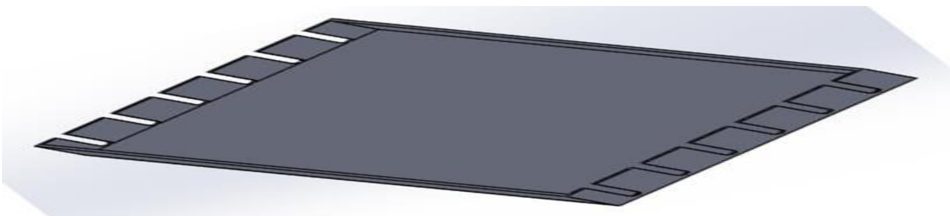
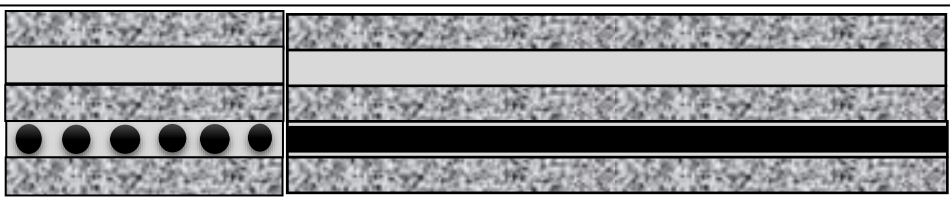


Figure 18: Mould for SMA composite structures

The step by step process of making composite structure with embedded with SMA wire.

1. Preparation of Mould using mild steel sheet or wood, transparent poly sheet, and wires clamps.

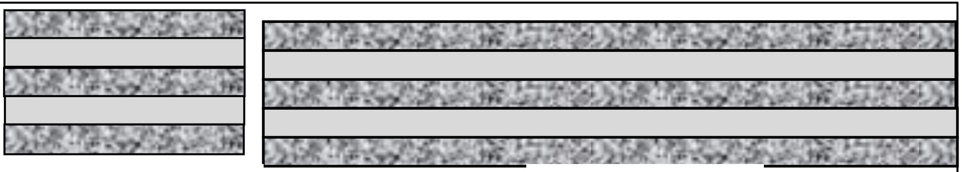
2. On top of the fibre layers, a number of other layers were placed: a release film, which ensure easy detachment of the final composite from the mould.
3.
4. Place the wire in the setup and clamp them in tension.
5. Provide the extra tension both side with the help of tensioning Strip.
6. Preparation of epoxy hardener mixture in the ratio 100:30.
7. Apply a layer of epoxy mixture using hand layup process and place a layer of glass fibre reinforcement on it.
8. Apply more alternative layers of epoxy mixture and glass fibres to get the epoxy structure of required thickness (shown in the Figure 19).
9. Apply sufficient weights on the fixture to keep the wires tight during curing process. Allow the mixture to cure for 24 hours. Take out the weights and separate the clamps to get the SMA embedded epoxy plate.



Side view Front view

1. Reinforcement fibre 2. Epoxy resin 3.reinforcemet fibre 4. SMA wires+epoxy resin 5. Reinforcement fibre

Figure 19: hand layup layer configuration of reinforcement, matrix, epoxy resin and wire



Side view Front view

1. Reinforcement fibre 2. Epoxy resin 3.reinforcemet fibre 4. Epoxy resin 5. Reinforcement fibre

Figure 20: Glass Fibre composite without SMA

3.3.1 Glass Fibre reinforced polymer (GFRP) composite structure without SMA

Initially in this work composites were fabricated without SMA for understanding the process. Three fibre layer of 130X30X0.25 mm were used and follow the manufacturing process of composite structure process describe in the **Chapter 3 Fabrication of adaptive composite structure** and which structure glass fibre and epoxy resin configuration is shown in the Figure 20 and actual step and final product shown in the Figure 21.

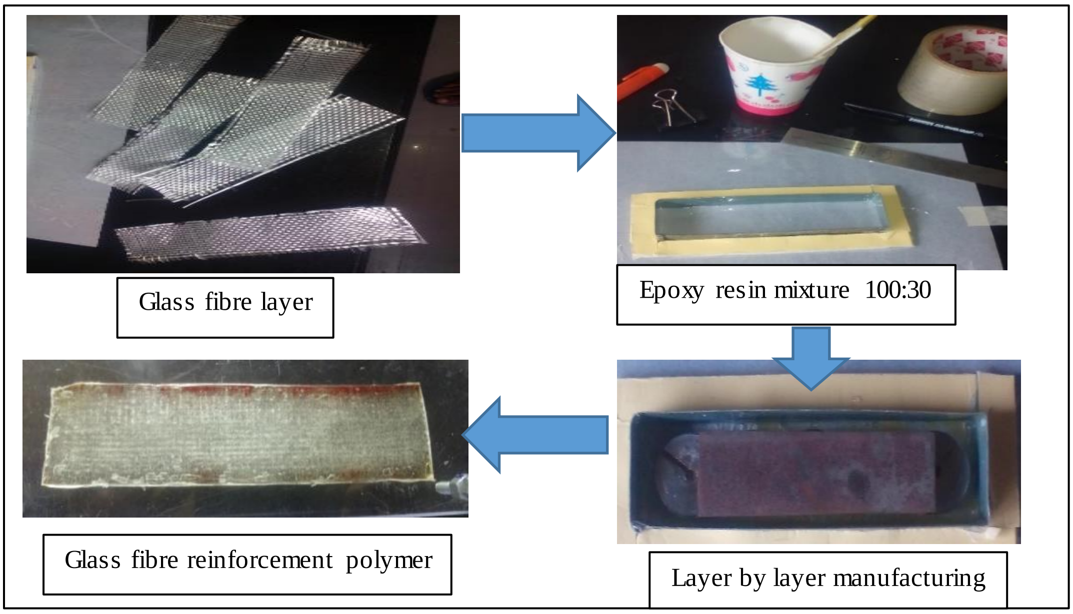
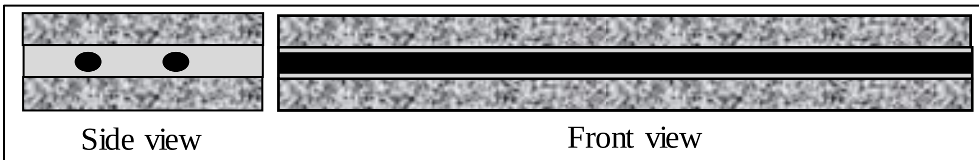


Figure 21: fabrication process of manufacturing of GFRP composite



1. Reinforcement fibre 2. Epoxy resin 3.reinforcemet fibre 4. Epoxy+SMA resin 5. Reinforcement fibre

Figure 22: SMA/GFRP Configuration

In SMA/CFRP, since the nitinol wires were not shielded to prevent potential contact with semi-conductive carbon fibres so due to that deflection in lower time is not possible so in this work only for evaluation of thermo-mechanical behaviour focused only on the SMA/GFRP Composite structures.

Specimen: 3 SMA/GFRP 100X30X.75, D=250 µm, Wire=6

In this above manufactured composite only two symmetric layer in both side of the wire, outer of the SMA wire so because of that direction of bending will not be able to notice. So in the next experiment shape memory alloy wires embedded at a distance from the plate neutral axis and also increased the number of wire to get maximum deflection. SMA/GFRP structure developed with dimensions 130 mm long, 30 mm wide, 0.75 mm thick (130X20X0.75) and 6 wires of 250 µm diameters embedded side by side with a wire to wire

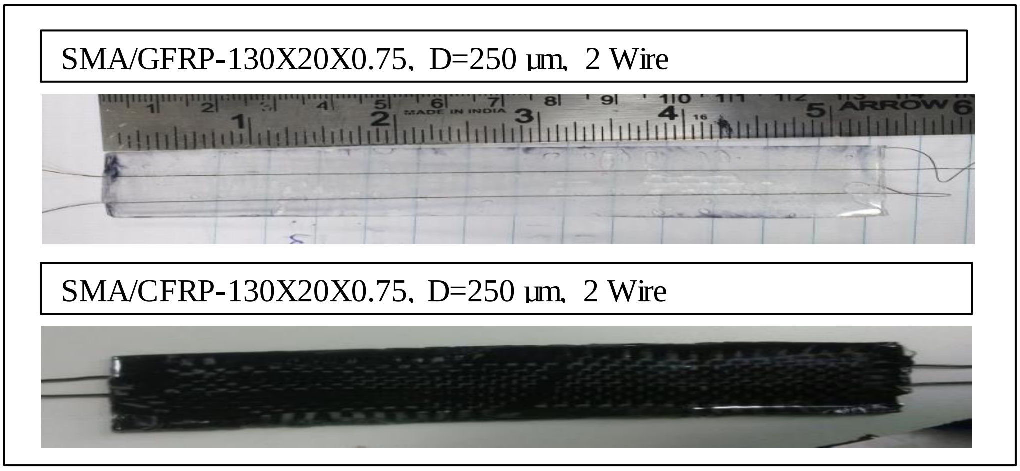


Figure 23: SMA/GFRP and SMA/CFRP Final Product

spacing of 4.3 mm configuration shown and follow the process of manufacturing explained in the **Chapter 3 Fabrication of adaptive composite structure**. The shape memory alloy wires are perfectly visible under the first glass fibres layer. A visual inspection reveals non perfect bonding between the shape memory alloy wires and the composite layers: the light grey areas around the wires, which are evident in particular in the zones marked by the arrows, denote the presence of some air between the composite layers.

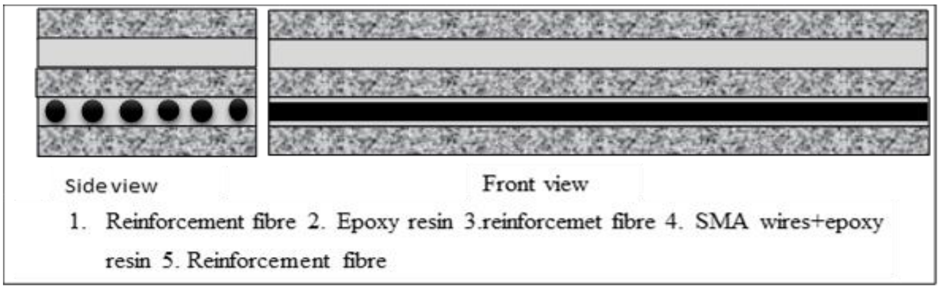


Figure 24: Configuration of specimen 3

The presence of bonding defects is mainly related to the size of the wires as compared to the laminae thickness and not sufficient pressure applied on the composite structure while curing. The bonding could be improved by

- Using small diameter of shape memory alloy wires so maximum contact will be happened between the layers
- Using less viscous resin which may better penetrate the gaps between the shape memory alloy wires and the composite fibres

- Applying more pressure may improve the bonding between the shape memory alloy wires and the composite fibres.

But due to less flexibility in manufacturing, unable to use small diameter and less viscous resin but pressure can be applied more. So in the improvement in the composite structure is explained in the next section.

Figure 25: Defected specimen 3

3.3.3 Improved glass fibre reinforced composite structure with SMA wire for end deflection

In the specimen 3 due to non-perfect bonding between the shape memory alloy wires and the composite layers and due to that some air bubble, specimen failed during further heating. So to overcome this problem, in the next specimen through sufficient pressure applied on the composite structure. The bonding could be improved.

Specimen: 4 SMA/GFRP 100X30X.75, D=250 µm, Wire=6

So in this, SMA/GFRP structure were developed with the dimensions 100 mm long, 30 mm wide, 0.75 mm thick (100X30X0.75) and 6 wires of 250 µm diameters embedded side by side with a wire to wire spacing of 4.3 mm and following the process of manufacturing explained in the **Chapter 3 Fabrication of adaptive composite structure** with sufficient pressure.

Defect of air bubble removed in the specimen 4 and the results are quite good. So in pre-trial of fabrication of composite structure is done and got all good condition and moving towards the comparison study between the structure specification and deflection, 4 different specimen manufactured with same dimension with different wire diameter and different number wires.

Specimen: 6 SMA/GFRP or CFRP 130X35X1, D=350 µm, Wire 6

SMA/GFRP structure developed with the dimensions are 130 mm long, 35 mm wide, 1 mm thick (130X20X1) and 6 wires of 375 µm diameters embedded side by side with a wire to wire spacing of 5 mm and follow the process of manufacturing explained in the **Chapter 3 Fabrication of adaptive composite structure**.

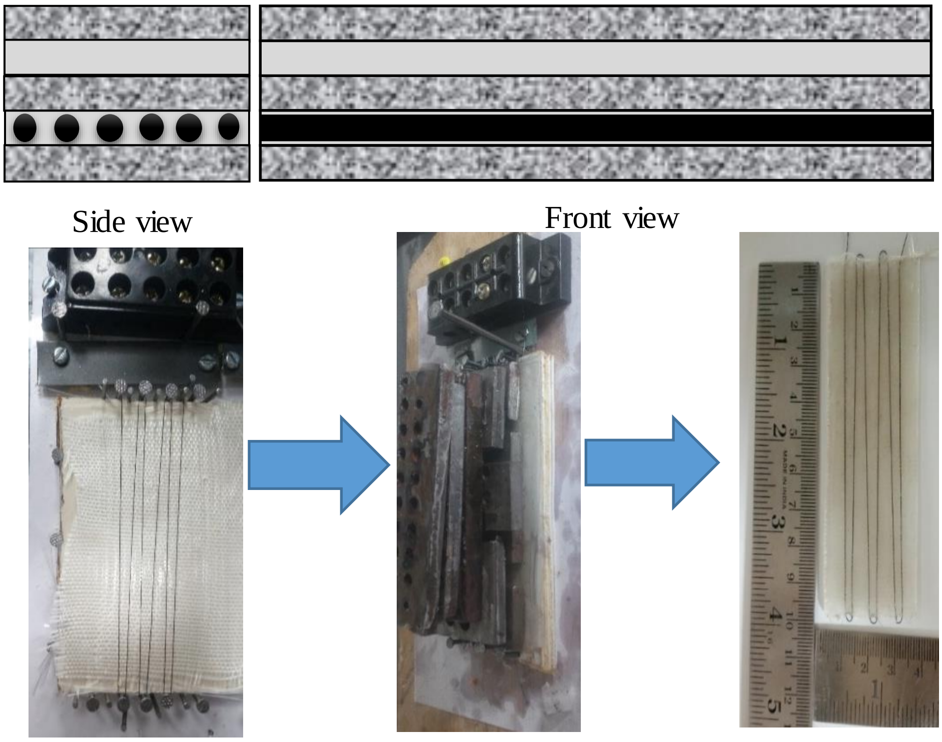


Figure 26: Specimen 3 Configuration

Specimen: 7 SMA/GFRP 130X35X1, D=500 µm, Wire 4

SMA/GFRP structure developed with the dimensions 130 mm long, 35 mm wide, 1.25 mm thick (130X35X1.25) and 4 wires of 500 µm diameters embedded side by side with a wire to wire spacing of 5 mm and follow the process of manufacturing explained in the **Chapter 3 Fabrication of adaptive composite structure**.

Specimen: 8 SMA/GFRP 130X35X1, D=500 µm, Wire 6

SMA/GFRP structure developed with the dimensions 130 mm long, 35 mm wide, 1.25 mm thick (130X35X1.25) and 6 wires of 500 µm diameters embedded side by side with a wire to wire spacing of 5 mm and follow the process of manufacturing explained in the **Chapter 3 Fabrication of adaptive composite structure**.

Specimen: 4 SMA/GFRP or CFRP 130X30X1, D=500 µm, Wire 8

SMA/GFRP structure developed with the dimensions are 130 mm long, 35 mm wide, 1.25 mm thick (130X35X1.25) and 8 wires of 500 µm diameters embedded side by side with a wire to wire spacing of 5 mm and follow the process of manufacturing explained in the **Chapter 3 Fabrication of adaptive composite structure**.

3.3.4 Glass fibre reinforced composite structure with SMA wire for twisting angle

Specimen 10: SMA/GFRP 130X35X1, D=250 µm, Wire 8

In order to get twisting angle, glass fibre reinforced polymer embedded with 8 SMA wire are manufactured. 4 SMA wires are located near the top surface and 4 SMA wires near the bottom surface with all wires maintaining a constant eccentricity form the middle place across the thickness. Each of the 8 wires starts in one corner of the matrix and cross the width of the matrix along the length of the structures. The position of the SMA wires in the matrix and the notation for each wire is shown in the Figure 27. One layer used when they cross each other at the middle point of the matrix. The structure is manufactured by using process explained in the **Chapter 3 Fabrication of adaptive composite structure**.

3.3.5 Improved Glass fibre reinforced composite structure with SMA wire for twisting angle

Specimen 11: SMA/GFRP 130X35X1, D=250 µm, Wire 8

In order to get twisting angle specimen 10 have a problem to when activated the SMA wire through joule heating other side SMA wire also try to activated so in the result uneven deformation getting to overcome this problem to manufactured specimen 11 Two layer used when they cross each other at the middle point of the matrix. 4 SMA wires are located near the top surface and 4 SMA wires near the bottom surface with all wires maintaining a constant eccentricity form the middle place across the thickness. Each of the 8 wires starts in one corner of the matrix and cross the width of the matrix along the length of the structures. The position of the SMA wires in the matrix and the notation for each wire shown in the Figure 28. The structure is manufactured by using process explained in the **Chapter 3 Fabrication of adaptive composite structure**.

3.3.6 Glass fibre and carbon fibre reinforced composite structure with or without SMA for tensile testing

In order to obtain its mechanical properties, composite laminate plates, with the dimensions of shown Figure 29 were fabricated with hand lay method. A unidirectional glass fibre and carbon fibre was used for the host structure manufacturing. A specimen with three layers placed in the unidirectional with or without embedded shape memory alloy wires was made and tested in order to obtain the strength property of the structures.

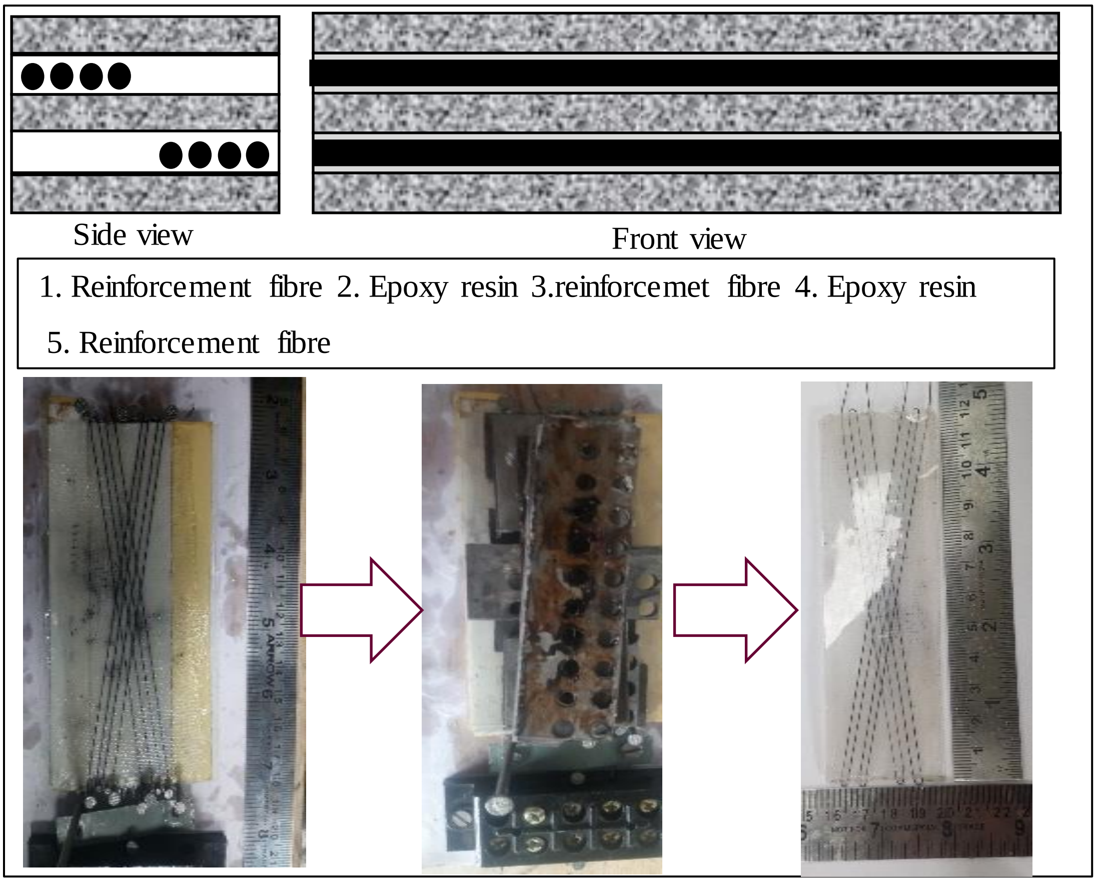


Figure 27: Position of the SMA wires within the GFRP

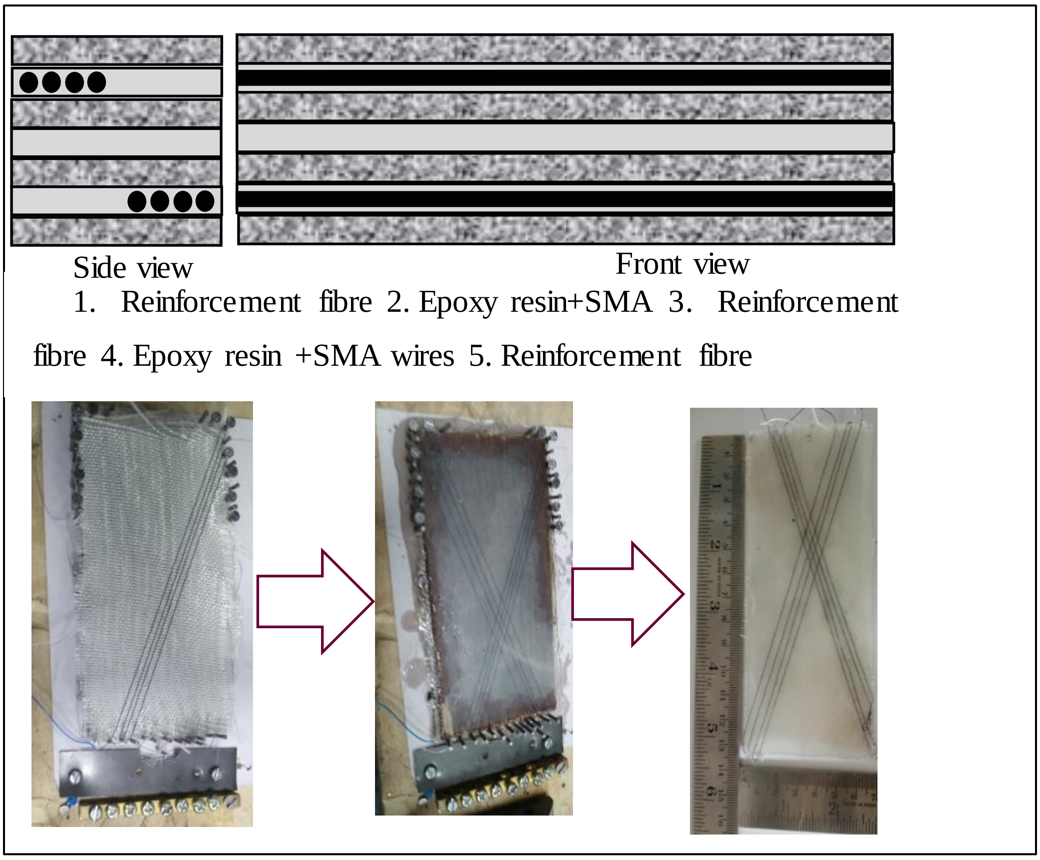


Figure 28: Improved structure fabrication for twisting angle

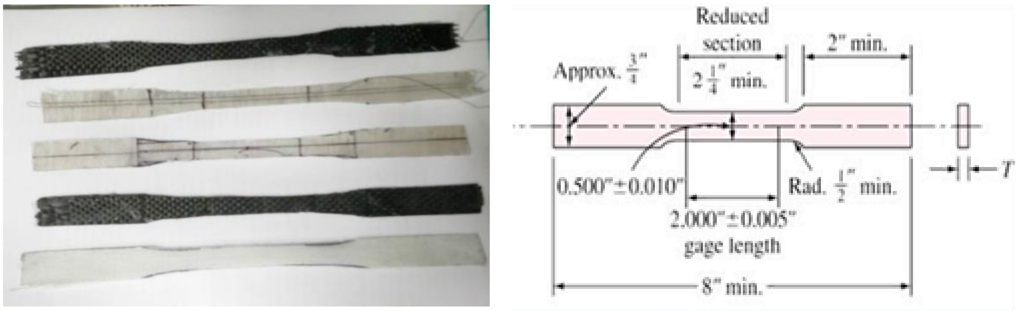


Figure 29: fabricated tensile testing specimen

Chapter 4 Thermomechanical behaviour of adaptive structures

Experimental investigation of SMA/GFRP composite making is completed. Different materials and manufacturing techniques are tested and their behaviour are discussed. As a result, a Composite made of glass fibre and epoxy resin with embedded shape memory alloy wires is built and tested. In this case, the shape memory alloy wires are heated via Joule heating, as it would be the case in most applications. Temperature and displacement data are recorded and compared.

4.1 Experimental set up and procedure

4.1.1 Setup for active control

The SMA/GFRP composite was clamped at one end, leaving a free length of different dimensions shown in the Figure 31 The shape memory alloy wires were actuated using Joule heating, couples of wires, each couple connected in parallel, were connected in series and attached to the programmable power supply (Rigol Dp 1308A) and on/off heating cooling cycle control by the program run in the Matlab. In order to measure the exact deflection of the tip of the structure. The deflection analysis was performed by using the Laser Displacement Sensor (LDS). Laser displacement sensor uses the triangulation method to measure the displacement. The composite plate is fixed in the cantilever setup and the vertical deflection of the blade is measured by the LDS. Temperature readings were obtained from the one embedded thermocouple attached to the wire just outside the epoxy layer. The thermocouples and the LDS were connected to a USB data acquisition system by Agilent 34970A Data Acquisition / Switch Unit. The data was recorded on a Computer equipped with the Matlab software shown in the Figure 30

4.1.3 Setup for passive control

The SMA/GFRP composite was clamped at one end, leaving a free length of different dimensions shown in the Figure 2 The shape memory alloy wires were actuated using hot air dryer, On/off heating cooling cycle control by the manual. In order to measure the exact deflection of the tip of the structure. The deflection analysis was performed by using the Laser Displacement Sensor (LDS). The composite plate is fixed in the cantilever setup and the vertical deflection of the blade is measured by the LDS. The LDS were connected to a USB data acquisition system by Agilent 34970A Data Acquisition / Switch Unit. The data was recorded on a Computer equipped with the Matlab software shown in the Figure 32

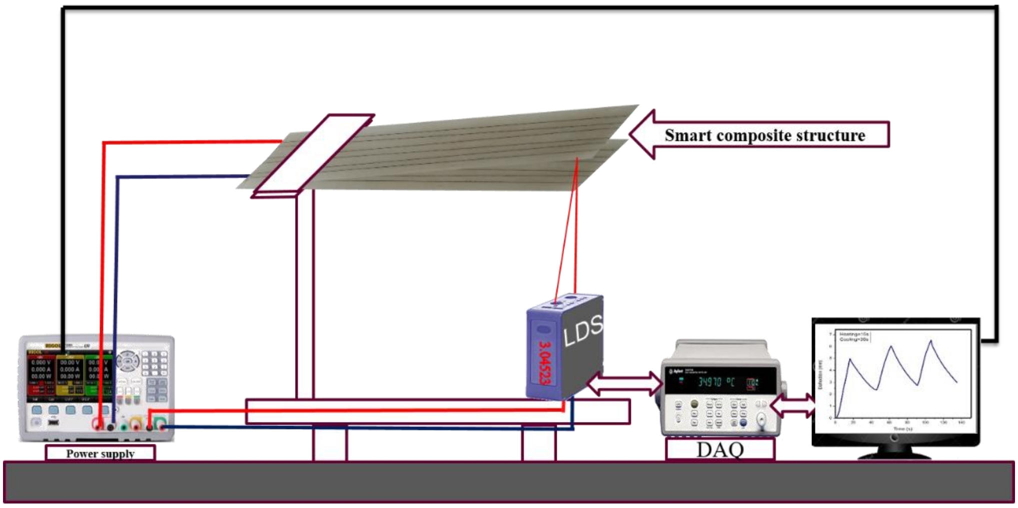


Figure 30: Active control setup block diagram

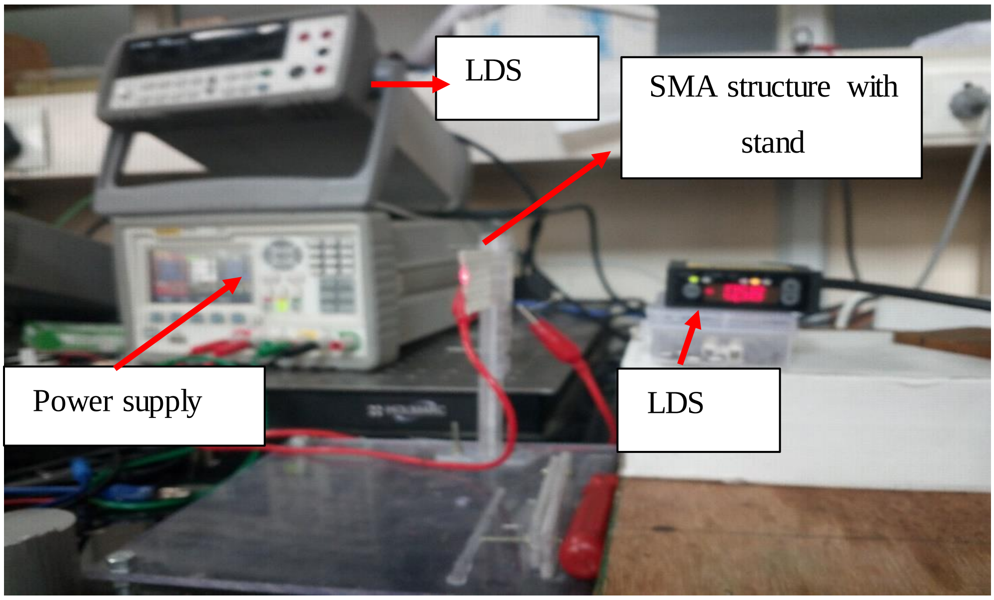


Figure 31: Active control testing of SMA/GFRP Composite

4.1.3 Setup for low tempereture testing of composite

The SMA/GFRP composite was clamped top of the roof of the chamber, in which low temperature produce with help of putting ice of 0°C inside chamber and low temperature air induced by the fan containing ice box as shown in the Figure 33 The shape memory alloy wires were actuated using Joule heating, couples of wires, each couple connected in parallel, were connected in series and attached to the programmable power supply (Rigol Dp 1308A) and On/off heating cooling cycle control by the program run in the Matlab. In order to measure the exact deflection of the tip of the structure. The deflection analysis was performed by using the Laser Displacement Sensor (LDS). Laser displacement sensor uses the triangulation method to measure the displacement. The composite plate is fixed in the cantilever setup and the vertical deflection of the blade is measured by the LDS. Temperature readings were obtained from the one embedded thermocouple attached to the wire just outside the epoxy layer. The thermocouples and the LDS were connected to a USB data acquisition system by Agilent 34970A Data Acquisition / Switch Unit. The data was recorded on a Computer equipped with the Matlab software shown in the Figure 31.

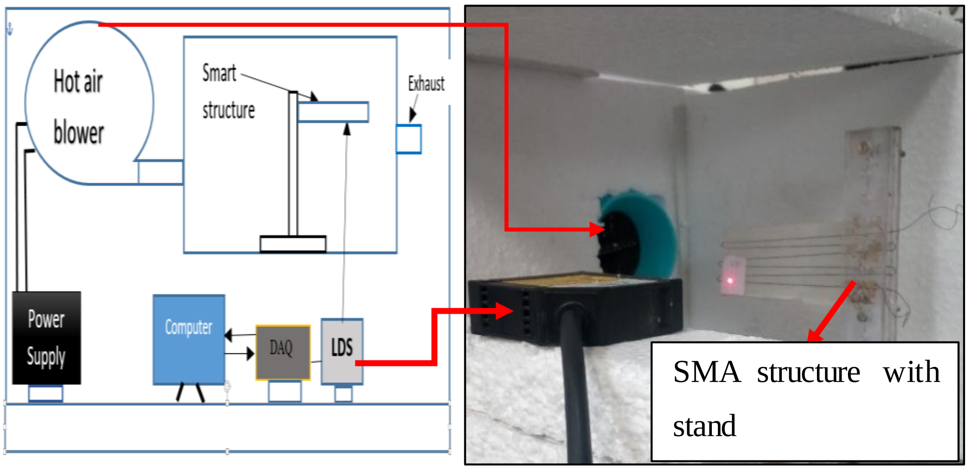


Figure 32: Passive control setup

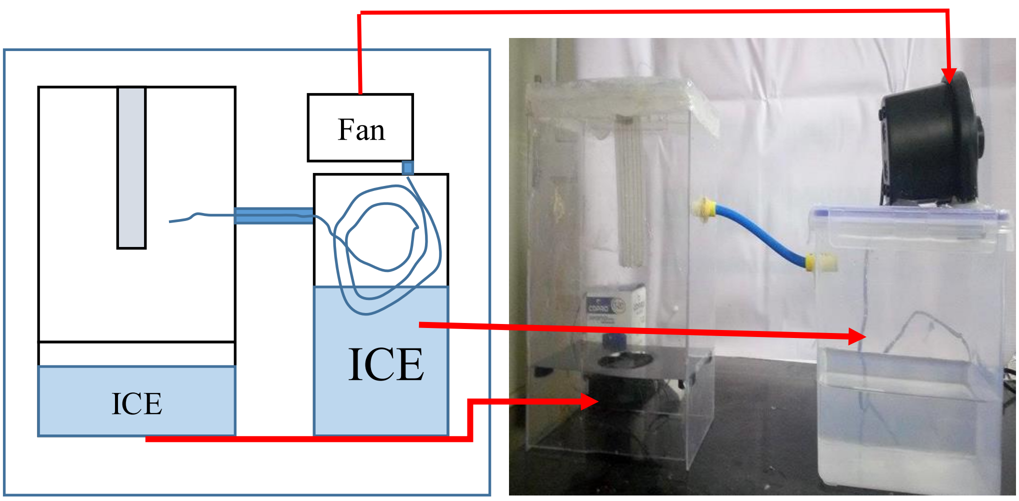


Figure 33: low temperature testing setup

4.2 Result and discussion

4.2.1. Thermomechanical behaviour adaptive composite structures

Specimen: 1 SMA/GFRP 130X20X.75, D=250 µm, Wire=2

The tip displacement is plotted against the deflection reading for different loading cycles depicts the first thermal cycle. The graph starts from A and follows the direction of the arrow from A→B shown in the Figure 34. Upon heating the displacement increases, first slowly due to a different coefficient of thermal expansion between the wires and the laminate, then more quickly as the $M \rightarrow A$ phase transformation starts. At 68°C the tip displacement is 0.20 mm. Upon cooling, the displacement decreases from B → C again due to the $A \leftarrow M$ phase transformation. However, a residual tip displacement is present when the specimen reaches room temperature Figure 34 shows again the As it can be noted in the graphs, the heating branch of the first cycle is quite different from that of the following cycles, which are stable. Then after first follows the path of the stabilized cycles. In this experiment deflection measure at two voltage 5V and 6V observe that at 6V getting major deflection then after all the experiment perform only at 6V. In this composite only two symmetric layer, outer of the SMA wire so because of that direction of bending will not be able to find so in the next experiment shape memory alloy wires embedded at a distance from the plate neutral axis.

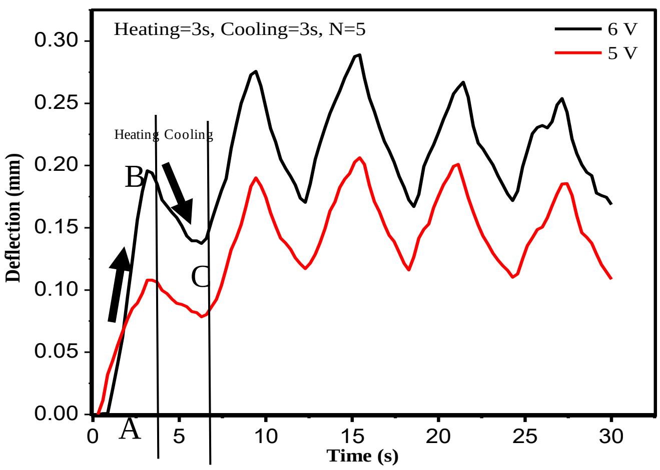


Figure 34: Deflection -time curve for different Voltage

Specimen: 3 SMA/GFRP or CFRP 100X30X.75, D=250 µm, Wire=6,

In this above manufactured composite only two symmetric layer in both side of the wire, outer of the SMA wire so because of that direction of bending will not be able to find so in the next experiment shape memory alloy wires embedded at a distance from the plate neutral axis show in the also increase the number of wire to get maximum deflection. Plotted the graph between the displacement and time. Time controlled by the programmable power supply for 5s heating and 8s cooling at 5V. The tip displacement is plotted against the deflection reading for one loading cycles. The graph show in the Upon heating the displacement increases, first slowly due to a different coefficient of thermal expansion between the wires and the laminate, then more quickly as the $M \rightarrow A$ phase transformation starts. At 68°C the tip displacement is 0.30 mm. Upon cooling, the displacement decreases due to the $A \leftarrow M$ phase transformation. However, a residual tip displacement is present when the specimen cooled up to 8s so in which proper cooling not done and again next cycle started heating and further displacement increase up to 1.2 mm and after 5s further cooling start for 8s but due to non-perfect bonding between the shape memory alloy wires and the composite layers explain in the **Error! Reference source not found.** specimen failed during further heating due to air bubble present in the specimen.

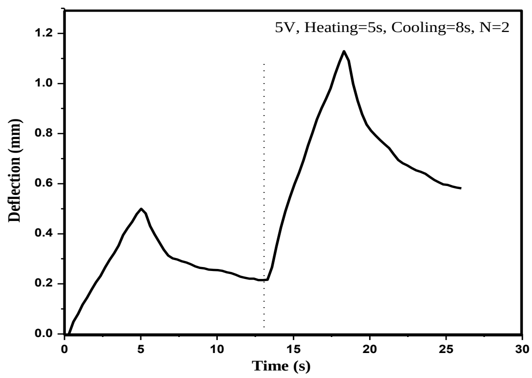
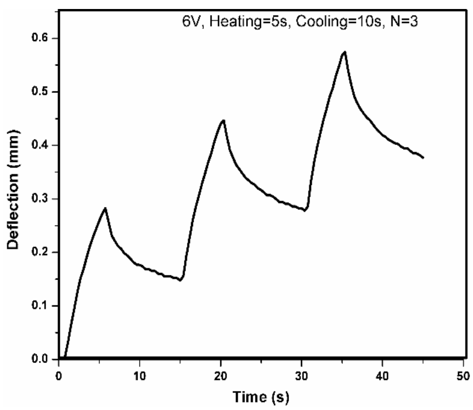


Figure 35: Deflection- Time curve for specimen 3

Specimen: 4 SMA/GFRP or CFRP 100X30X.75, D=250 µm, Wire 6

In the specimen 3 due to non-perfect bonding between the shape memory alloy wires and the composite layers and due to that some air bubble specimen failed during further heating. So overcome this problem in the specimen 4 through sufficient pressure applied on the composite structure. The bonding could be improved and tested again with on/off control through programmable power supply, but seen in the specimen 3 result 8s cooling is not sufficient to bring the specimen to the original position so in next experiment of specimen 4 increased the cooling time and Plotted the graph between the displacement and time. Time controlled by the programmable power supply for 5s heating and 10s cooling and in the experiment of specimen 1 already seen that 6V gives more deflection so in that experiment used 6V. The graph shown Figure 36 in the Upon heating the displacement increases, first slowly due to a different coefficient of thermal expansion between the wires and the laminate, then more quickly as the $M \rightarrow A$ phase transformation starts. At 68°C the tip displacement is 0.4 0 mm. Upon cooling, the displacement decreases due to the $A \leftarrow M$ phase transformation. However, a residual tip displacement is present when the specimen cooled up to 10s so in this specimen also proper cooling not done and again next cycle started heating and further displacement increase up to 1.0 mm and after 5s further cooling start for 10s but graph shows that 10s cooling is not sufficient and further increased the cooling time 15s, 20s and seen that 20s show in the is sufficient to bring the SMA/GFRP to bring at original position. Than after number of experiment perform and got the result for the experiment that 20s heating and 40s cooling will be gives very good result than perform the experiment for 10 cycle show in the maximum deflection reached to 1.3 mm about every cycle shown in the Figure 36 Figure 37



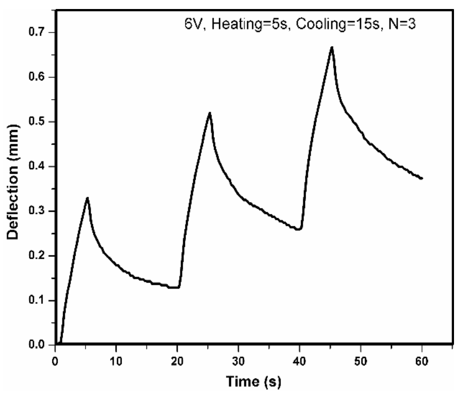


Figure 36: Deflection- Time curve for specimen 4

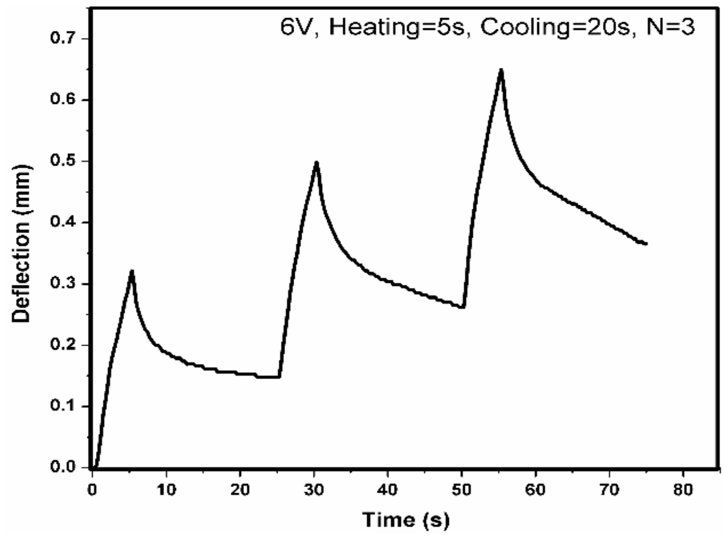


Figure 37: Deflection-Time curve for specimen 5s heating and 20s cooling

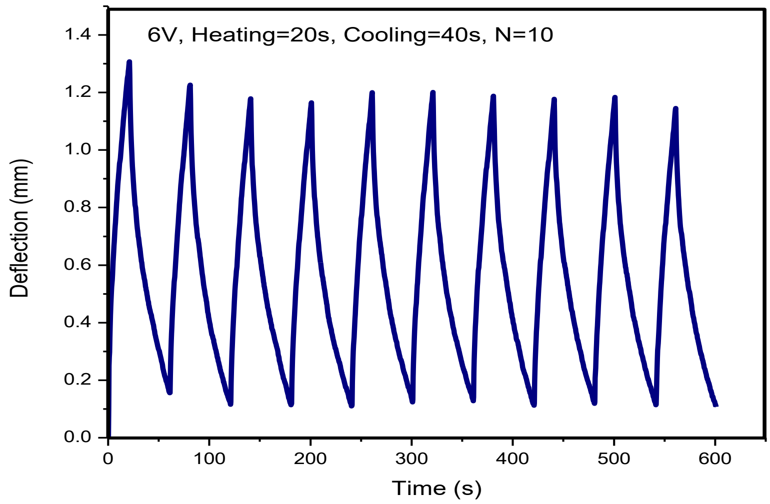


Figure 38: Deflection-Time curve for specimen 4 20s heating and 40s cooling

In specimen 3 defect of air bubble removed in the specimen 4 and seen the result are quite good. 5 deferent specimen manufactured with same dimension with deferent wire diameter and deferent number wires. Perform the experiment with various condition.

Specimen: 5 SMA/GFRP 130X30X1, D=350 µm, Wire 4

When in this experiment when joule heating is applied SMA wire shrink due to martensite to austenite. Result shown in the Figure 39 . In order to obtain maximum deflection increase the heating time and seen in the 5 mm deflection are getting.

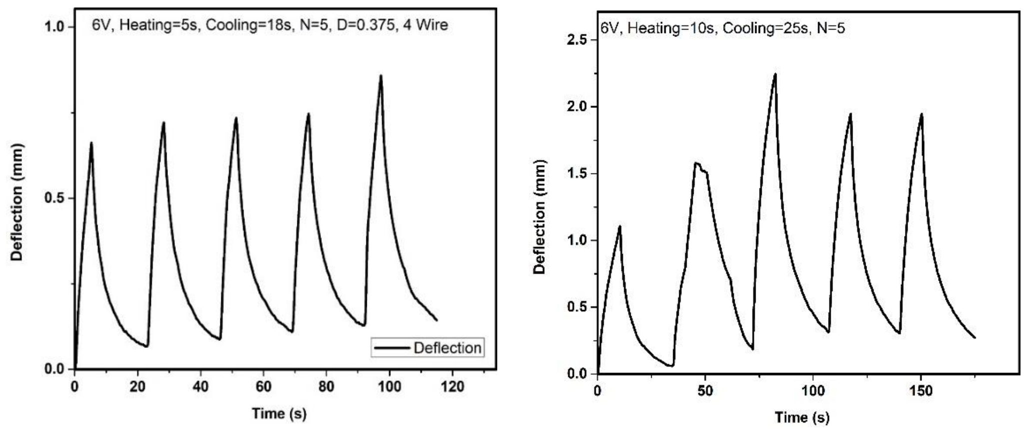


Figure 39: Deflection- time curve for specimen 5,

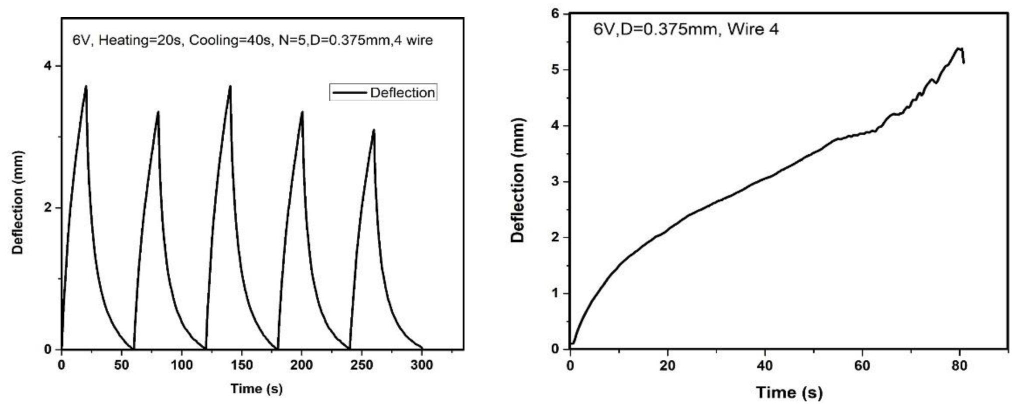


Figure 40: Deflection-Time curve for specimen 5 and maximum deflection

Specimen: 6 SMA/GFRP 130X30X1, D=350 µm, Wire 6

When in this experiment when joule heating is applied SMA wire shrink due to martensite to austenite and Result shown in the Figure 41

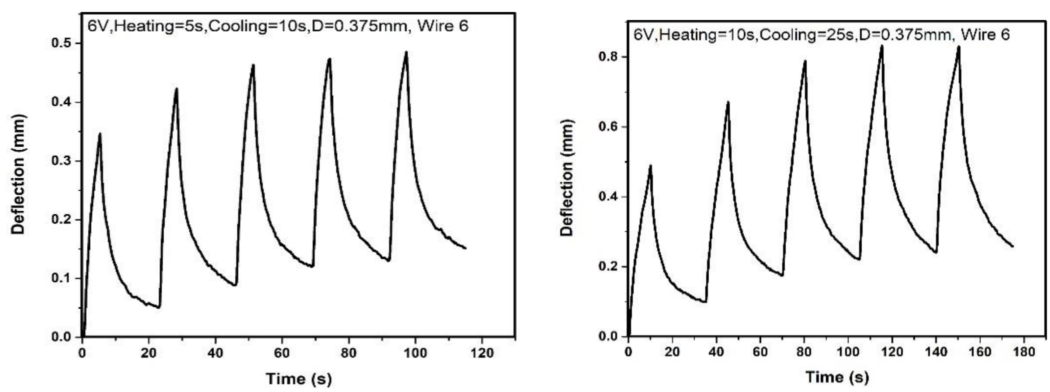


Figure 41: deflection-Time Curve for specimen 6

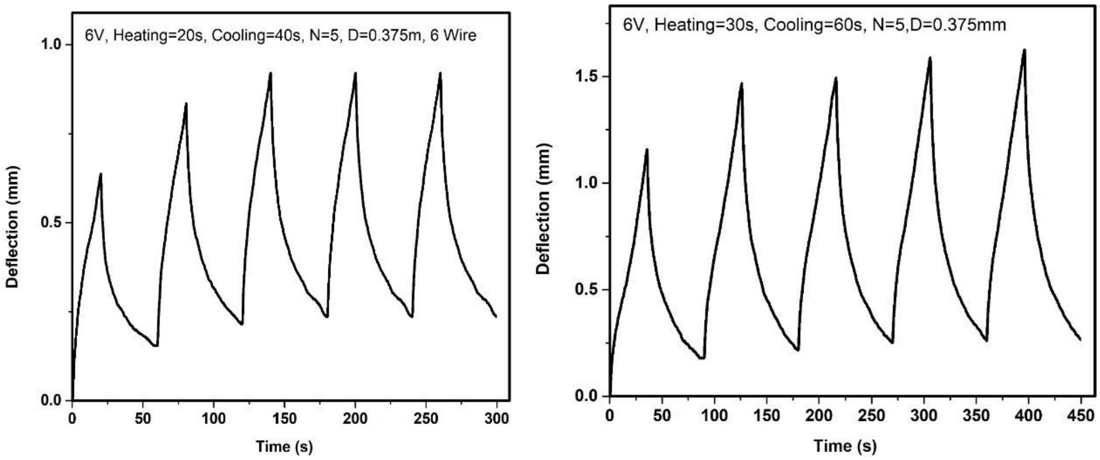


Figure 42: Deflection-Time curve for specimen 6

In order to get maximum deflection perform the experiment and obtain maximum of 2 mm deflection shown in the Figure 43

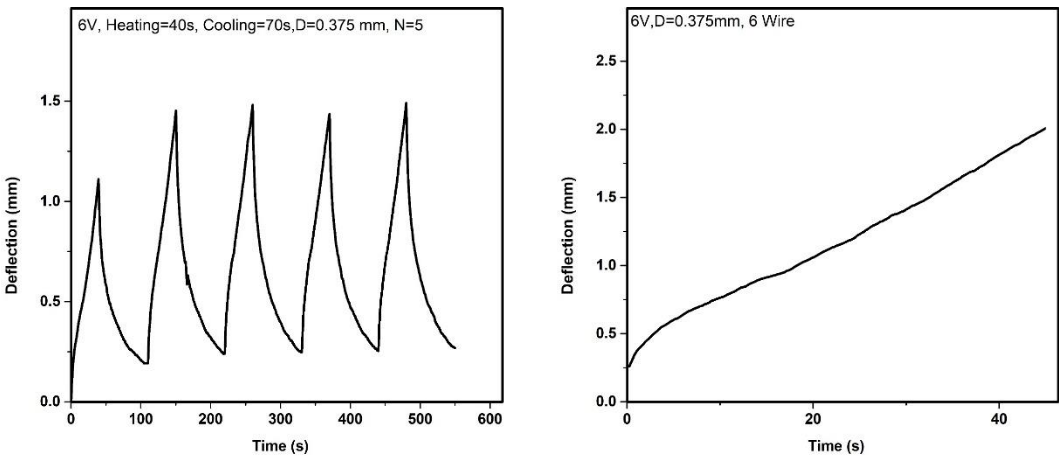


Figure 43: Deflection-Time curve for specimen 6 2

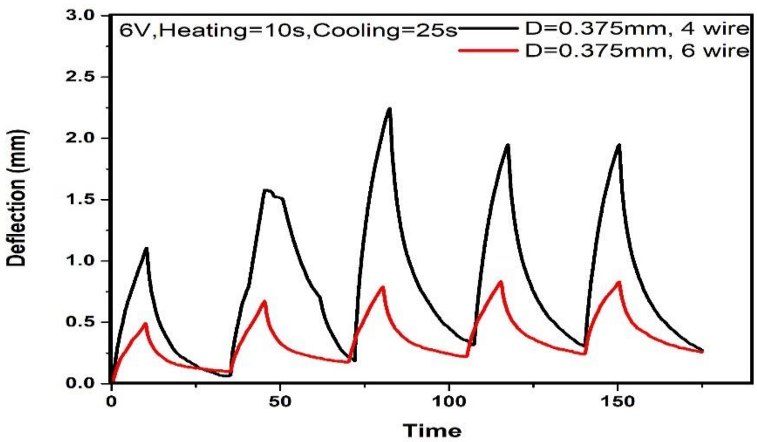


Figure 44: Deflection-time curve comparison of size of diameter

Specimen: 7 SMA/GFRP 130X30X1, D=500 µm, Wire 4

In specimen 5, 4 wire and specimen 6 6 wire but gating maximum deflection in specimen 5. So in this specimen increase the Dia of the wire and perform the experiment with low temperature, high temperature and low temperature with air blow of 15 m^3/min. setup explain in the section **4.1.3 Setup for low tempereture testing of composite**. Result shown in the Figure 45

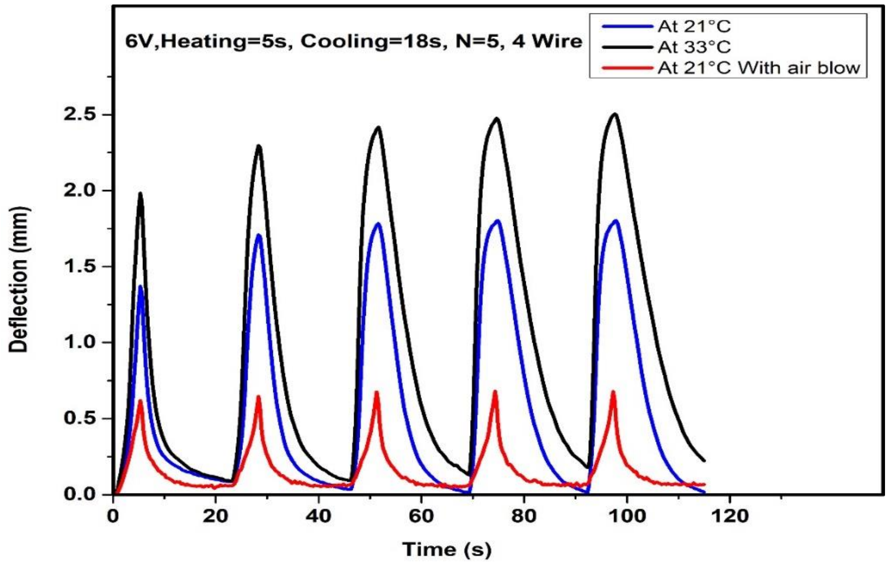


Figure 45: Deflection-time curve for deferent condition

Observe that at low temperature during joule heating required more power to change the phase form martensite to austenite so at same power at low temperature deflection is less than at high temperature and also air blow provide resistance in deflection so also in this case deflection is lower than form the all condition.

Specimen: 8 SMA/GFRP 130X30X1, D=500 µm, Wire 6

Now again specimen 8 with more wires from 4 to 6 and see the result with deferent condition. Shown in the Figure 46. Now all result are good so perform the experiment for 100 cycle and seen that all result are same so repeatability confirm shown in the Figure 47Figure 48

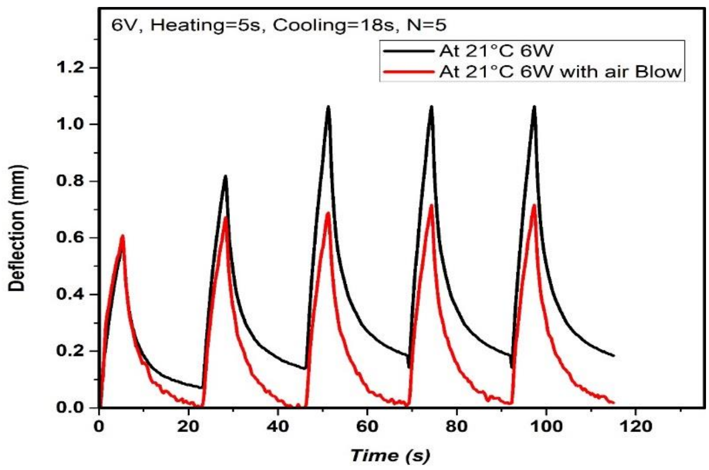


Figure 46: Deflection-time curve for specimen 8

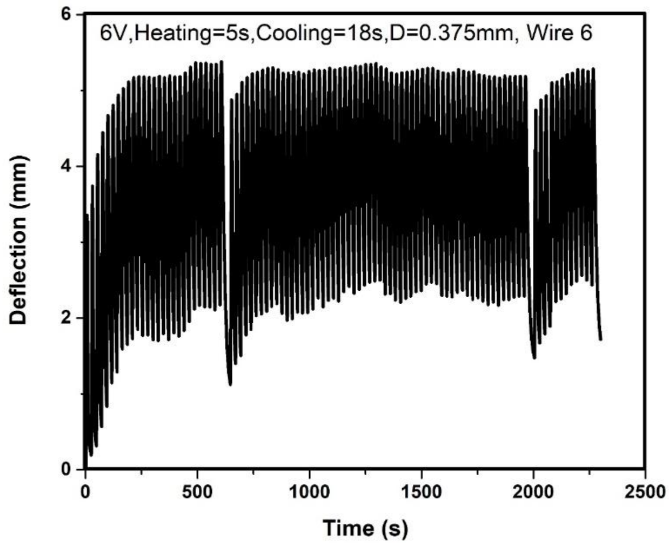


Figure 47: Deflection-time graph for 100 cycle

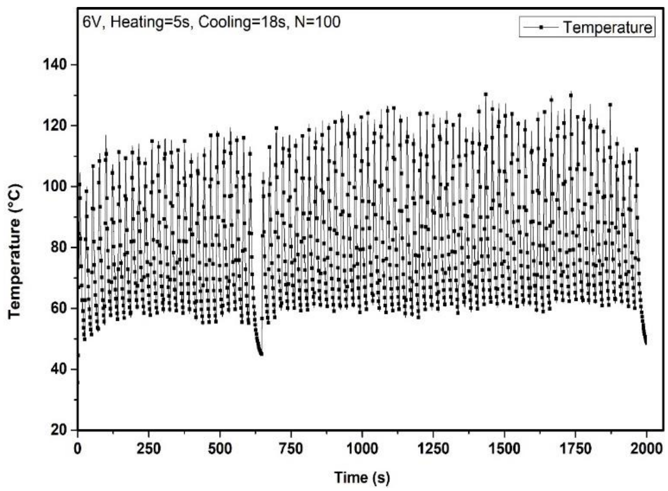


Figure 48: Temperature-time curve for 100 cycle

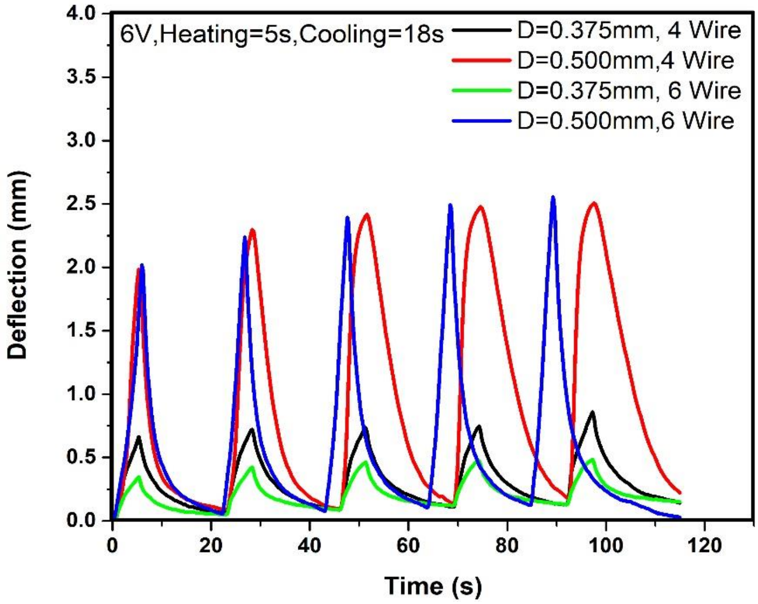


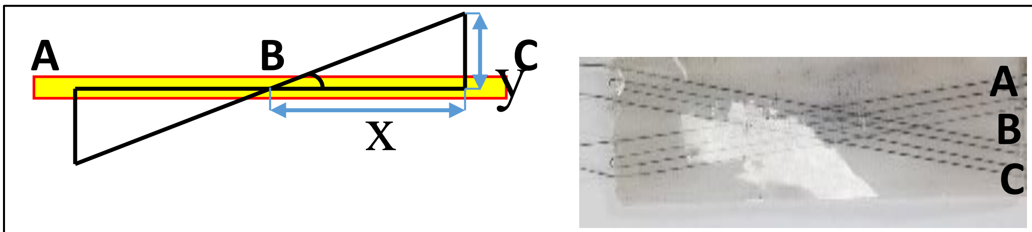
Figure 49: Comparison of the specimen

4.2.2. Twisting angle

Specimen: 10 SMA/GFRP 130X35X1, D=250 µm, Wire=8

SMA wire shrink in length when joule heating is applied and produce a high force when they change between the martensite phase at low temperature to the austenite phase at high temperature.by embedding 4 SMA wires are located near the top surface and 4 SMA wires near the bottom surface with all wires maintaining a constant eccentricity form the middle place across the thickness. Each of the 8 wires starts in one corner of the matrix and cross the width of the matrix along the length of the structures. So axial deformation of wire lead to deformation of structure can be bending, twisting of one side or both side depending on the location of SMA wire activated the structure.

In order to measure exact twisting of the specimen 10 SMA/GFRP composite was clamped at one end, leaving a free length of shown in the Figure 31 The shape memory alloy wires were actuated using Joule heating, couples of wires, each couple connected in parallel, were connected in series and attached to the programmable power supply (Rigol Dp 1308A) and On/off heating cooling cycle control by the program run in the Matlab. In order to measure the exact deflection of the tip of the structure. The deflection analysis was performed by using the Laser Displacement Sensor (LDS). LDS locate the three different position of specimen A,B, and C with one by one shown in the Figure 50 and form the deflection y with the help of formula shown in the Figure 50 angle of twisting calculated .The LDS were connected to a USB data acquisition system by Agilent 34970A Data Acquisition / Switch Unit. The data was recorded on a Computer equipped with the Matlab software shown in the Figure 30.The tip displacement and twisting is plotted against the deflection reading for different loading shown in the Figure 51 with deferent heating and cooling cycle. But in that specimen 10 used one layer between the wire so when joule heating heat is conducted to other side of the SMA wire lead to uneven deformation. So for overcome this uneven deformation used two layer between the SMA wires in the specimen 11.



$$\theta = \tan^{-1}\left(\frac{y}{x}\right)$$

Figure 50: Twisting measurement in the structure

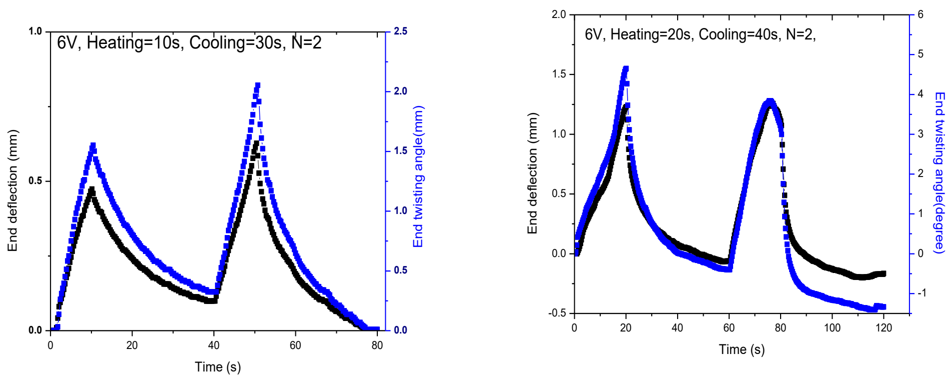


Figure 51: End deflection and end twisting with time curve for10s heating and 30s cooling

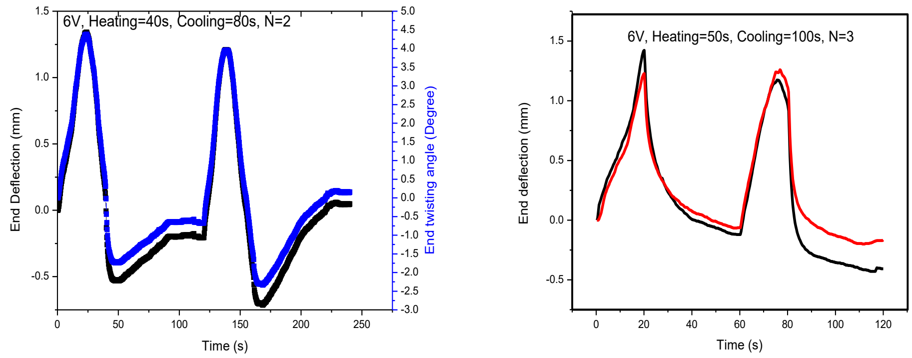


Figure 52: End deflection and end twisting with time curve for 40s heating and 80s cooling

Specimen 11: SMA/GFRP 130X35X1.25 D=250 μm, wire 8

In the specimen 10 during heating SMA wire also try to activate so in the result uneven deformation getting to overcome this problem to manufactured specimen 11 two layer used when they cross each other at the middle point of the matrix. In this specimen getting uniform deflection along with uniform

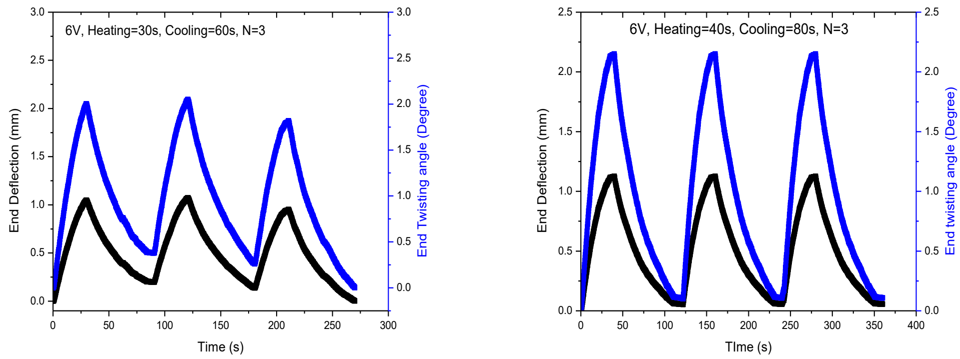


Figure 53: End deflection and End twisting with time curve for improved specimen 30s heating and 60s cooling

twisting angle. For different heating and cooling cycle perform the experiment and getting of maximum end deflection of 1.7 mm and maximum twisting angle is 3.7° shown in the Figure 55.

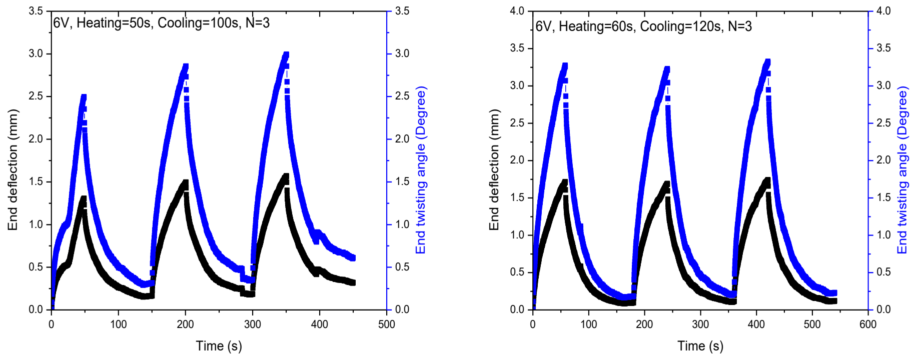


Figure 54: End deflection and End twisting with time curve for improved specimen 50s heating and 100s cooling

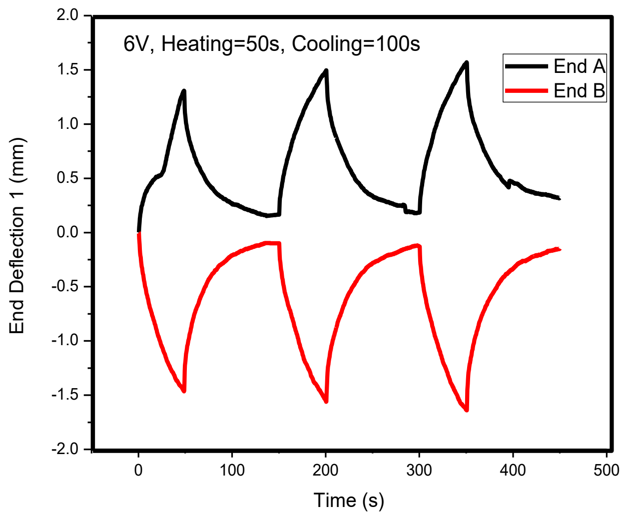


Figure 55: End deflection time curve for improved specimen 50s heating and 100s cooling

4.3.3 Tensile testing

In order to measure the strength of the structure tensile testing performed at UTM shown in the Figure 56, with deferent composition of wire and fibre structure. SMA wire embedded in GFRP the composites tensile strength increase shown in the Figure 57 also when SMA wire embedded in the CFRP also increase the tensile strength shown in the Figure 58 failure shown in the Figure 56

Figure 56: Tensile testing machine and fractured specimen

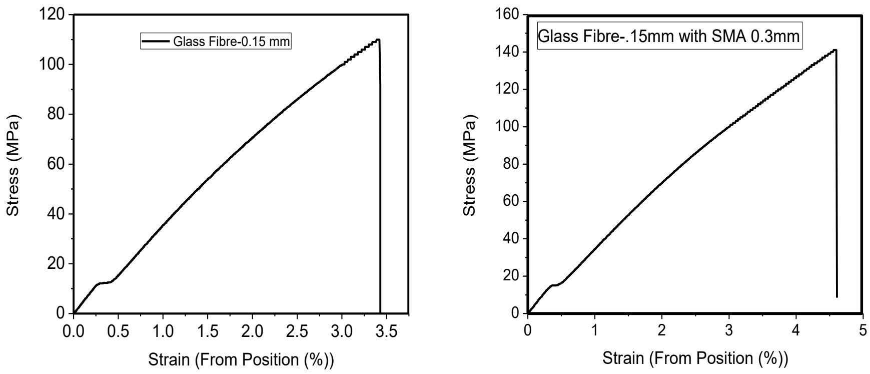


Figure 57: Stress-strain curve for structure with SMA and Without SMA

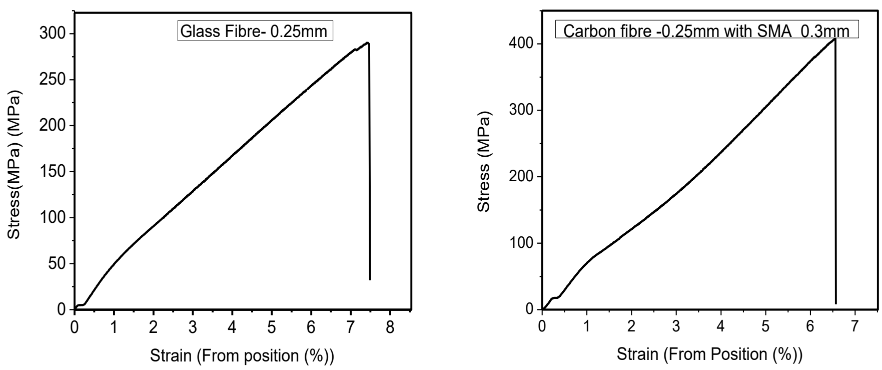


Figure 58: Stress-Strain curve for CFRP structure with SMA or Without SMA

Also when thickness of the fibre increase strength is also increase shown in the Figure 59

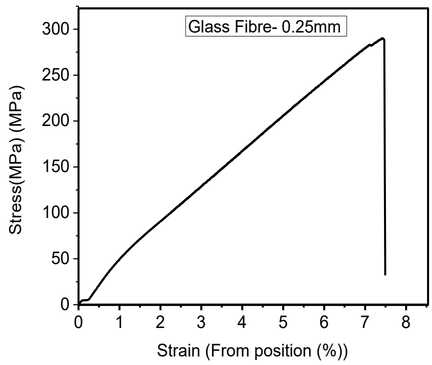


Figure 59: Stress- strain curve for GFRP structure without SMA

4.3 Consolidation of thermomechanical analysis

Specification	Temperature	Energy	Deflection	Maximum deflection
Ø 375, 4 Wire	33°C	124.8 J	3.9 mm	7 mm
Ø 375, 6 Wire	33°C	117.4 J	1.0 mm	2 mm
Ø 500, 4 Wire	33°C	120 J	8.0 mm	
Ø 500, 6 Wire	33°C	93.30 J	6.0 mm	12 mm
Ø 500, 6 Wire	21°C	93.30 J	1.1 mm	
Ø 500, 4 Wire	21°C	120 J	1.8 mm	
Ø 500, 6 Wire	21°C+a	93.30 J	0.7 mm	
Ø 500, 4 Wire	21°C+a	120 J	0.8 mm	

The bending of the SMA/GFRP composite structure show in the modelled based on a one-dimensional laminated composite, shown in the Figure 60 is revised into a three-layer laminated composite, composite, SMA wire and composite. In this section, 'three-layer composite' is used to refer to the whole composite structure.

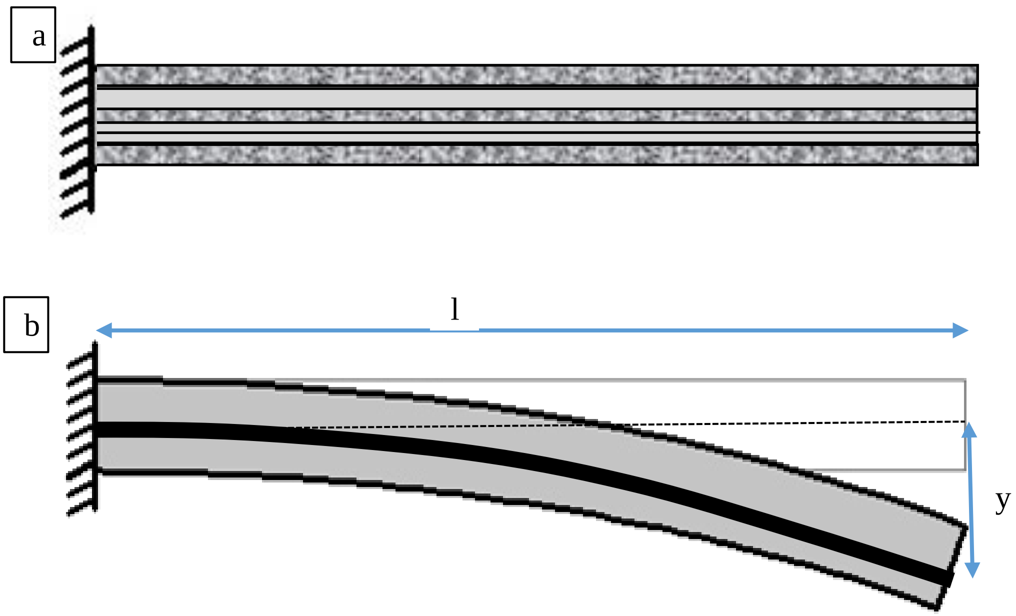


Figure 60: Structure assumption to 3 layer in b form deferent layer of composite in a.

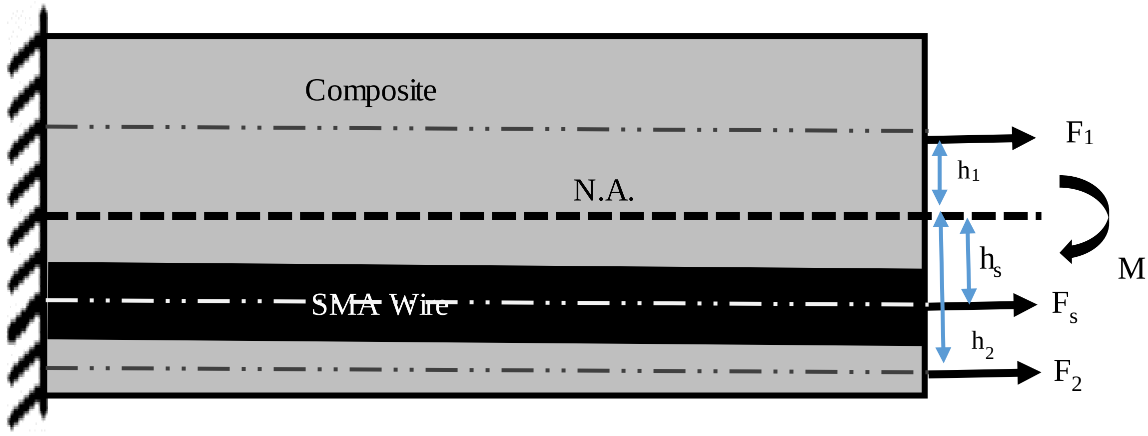


Figure 61: Model of SMA/GFRP Composite

Assumption in this model

- Composite structure assumed as cantilever beam.
- Wires are perfectly aligned and that no debonding occurs at the interface between the wires and the matrix.
- The dashed line represents the neutral axis (N.A.) passes through the mid line. Shown in the Figure 61

F_1, F_2 and F_S represent the in-plane internal forces in the Composite layer and shape memory alloy wire induced due to thermal strain. From the internal force equilibriums.[21]

$$F_1 + F_2 + F_s = 0 \qquad \text{Equation 1}$$

Due to force generated through the thermal bending moment M acting on the beam. M is the sum of all the moment generated due to individual layer force, form the moment equation...

$$M = F_1 h_1 - F_2 h_2 - F_s h_s \qquad \text{Equation 2}$$

The assumption that the section that were plane before loading remain palne after loading that means that that strain at interface layer for composite and shape memory alloy are equal

$$e_s = e_f = e_{total} = \frac{\Delta l}{l} \qquad \text{Equation 3}$$

Total strain in composite

$$e_f = e_m + e_t = \frac{\sigma_c}{E_c} + \alpha_1 \Delta T \qquad \text{Equation 4}$$

Total strain in SMA wire

$$e_s = e_m + e_t + e_{tran} = \frac{\sigma_s}{E_s} - \alpha_s \Delta T - \xi e^{\max} \qquad \text{Equation 5}$$

where e_{total}, e_s, e_m, e_f, e_t, e_{tran} are the total strain of composite, total of SMA wire, mechanical strain, strain in fiber, and thermal strain and transition strain respectively.

Force due to composite in x direction is

$$F_c = F_1 + F_2 = \sigma_1 A_1 + \sigma_2 A_2 \qquad \text{Equation 6}$$

$$F_c + F_s = 0$$

Where ζ is volume fraction of the martensite phase and e^{max} is the maximum transformation strain of the SMA wire. Here ζ can be found from the following phenomenological equations [22] depend only temperature.

$$\zeta = \begin{cases} 0 & at\ \ T > A_f \\ \frac{1}{2}\left[\cos\left(\frac{T - A_s}{A_f - A_s}\right) + 1\right] & at\ \ A_s < T < A_f \\ 1 & at\ \ T < A_s \end{cases}$$

Equation 7

Temperature time relationship in wire [23]

$$T = \frac{P}{h_c A_c}\left(1 - e^{-t/\tau}\right) + T_a$$

Equation 8

Form the equation calculate the F_1, F_2 and F_s and put in the moment equation

From the bending equation calculate the final deflection y.

$$EI\,\frac{d^2 y}{dx^2} = M$$

Equation 9

$$\theta = \frac{dy}{dx} = \int \frac{M}{EI} dx$$

Equation 10

$$y = \iint \frac{M}{EI}\, dx$$

Equation 11

Where

$$E = fE_s + (1 - f)E_c$$

Equation 12

$$E_s = E_A + \zeta(E_M - E_A)$$

Equation 13

Where f is the friction value of SMA wire in the Composite structure

$$f = \frac{V_s}{V_c + V_s}$$

Equation 14

NO.	Experiment result	Theoretical result	Simulation result
1	0.700 mm	0.400 mm	0.800 mm

- SMA based adaptive composite structure showed a two way shape memory effect. One way by the actuation of SMA wires and return stroke provided by the glass fibre reinforced polymer maximum deflection achieved 22 mm.
- No evidence of debonding or any damage to the structure due to heating and deflection of the structure.
- Adaptive composite structure shows a multiple mode of actuation, In which end deflection both side is up to 4 mm at minimum power of 3 W/180J and twisting angle of 4° both side at minimum power of 3 W/180J.
- Ultimate tensile strength of GFRP-110MPa, SMA/GFRP-140 MPa, CFRP- 350 MPa and SMA/CFRP 140 MPa.
- Passive heating maximum deflection 10 mm with 15kJ.
- Multicycle behaviour till 100 cycles without any physical damage to the composite.

Future scope

- Designing a controller for deflection control of smart composites
- Reliability testing of smart composites
- Adaptive aerofoil using SMA smart composites and its investigation

Bibliography

[1] C. Soutis, “Fibre reinforced composites in aircraft construction,” *Prog. Aerosp. Sci.*, vol. 41, no. 2, pp. 143–151, 2005.

[2] R. B. Barjibhe and B. Kumar Principal, “Study on Shape Memory Polymers and their Applications,” vol. 5, no. 3, pp. 154–158, 2015.

[3] W. M. Huang, Z. Ding, C. C. Wang, J. Wei, Y. Zhao, and H. Purnawali, “Shape memory materials,” *Mater. Today*, vol. 13, no. 7–8, pp. 54–61, 2010.

[4] D. J. Hartl and D. C. Lagoudas, “Aerospace applications of shape memory alloys,” *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.*, vol. 221, no. 4, pp. 535–552, 2007.

[5] P. K. Kumar and D. C. Lagoudas, “Introduction to shape memory alloys,” *Memory*, vol. 1, pp. 77–79, 2008.

[6] P. K. Kumar and D. C. Lagoudas, “Shape Memory Alloys,” *Memory*, vol. 1, no. 12, pp. 1307–1355, 2008.

[7] R. Barrett, R. McMurtry, R. Vos, P. Tiso, and R. De Breuker, “Post-Buckled Precompressed Piezoelectric Flight Control Actuator Design, Development and Demonstration,” *Smart Mater. Struct.*, vol. 15, no. 5, pp. 1323–1331, 2006.

[8] B. J. De Blonk and D. C. Lagoudas, “Actuation of elastomeric rods with embedded two-way shape memory alloy actuators,” *Smart Mater. Struct.*, vol. 7, no. 6, pp. 771–783, 1999.

[9] S. Barbarino, E. I. Saavedra Flores, R. M. Ajaj, I. Dayyani, and M. I. Friswell, “A review on shape memory alloys with applications to morphing aircraft,” *Smart Mater. Struct.*, vol. 23, no. 6, p. 63001, 2014.

[10] D. J. Hartl and D. C. Lagoudas, “Aerospace applications of shape memory alloys,” *Proc. Inst. Mech. Eng. Part G-Journal Aerosp. Eng.*, vol. 221, no. G4, pp. 535–552, 2007.

[11] F. Stroscher, A. Hermanutz, N. Maghaldadze, and H. Baier, “Aeroelastic tailoring of a blended wing body (BWB) aircraft structure using FSI simulation,” 2013.

[12] N. B. Kuntawala, “Aerodynamic Shape Optimization of a Blended-wing-body Aircraft Configuration,” p. 111, 2011.

[13] D. Karagiannis *et al.*, “Airfoil morphing based on SMA actuation technology,” *Aircr. Eng. Aerosp. Technol.*, vol. 86, no. 4, pp. 295–306, 2014.

[14] C. a. Rogers, “Active vibration and structural acoustic control of shape memory alloy hybrid composites: experimental results,” *J. Acoust. Soc. Am.*, vol. 88, no. 6, pp. 2803–2811, 1990.

[15] K. D. Jonnalagadda, N. R. Sottos, M. a Qidwai, and D. C. Lagoudas, “displacement measurements and numerical predictions of embedded SMA transformation,” *Smart Mater. Struct.*, vol. 9, pp. 701–710, 2000.

[16] V. Birman, “Review of Mechanics of Shape Memory Alloy Structures,” *Appl. Mech. Rev.*, vol. 50, no. 11, p. 629, 1997.

[17] S. Pappadà, R. Rametta, L. Toia, A. Coda, L. Fumagalli, and A. Maffezzoli, “Embedding of superelastic SMA wires into composite structures: Evaluation of impact properties,” *J. Mater. Eng. Perform.*, vol. 18, no. 5–6, pp. 522–530, 2009.

[18] M. W. Han, H. Rodrigue, H. Il Kim, S. H. Song, and S. H. Ahn, “Shape memory alloy/glass fiber woven composite for soft morphing winglets of unmanned aerial vehicles,” *Compos. Struct.*, vol. 140, pp. 202–212, 2016.

[19] W. Huang, “On the selection of shape memory alloys for actuators,” *Mater. Des.*, vol. 23, no. 1, pp. 11–19, 2002.

[20] L. Case, “Shape Memory Alloy Shape Training Tutorial,” *Transformation*, p. 46, 2004.

[21] M. Taya, *Electronic composites*. 2005.

[22] C. Liang and C. A. Rogers, “One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials,” *J. Intell. Mater. Syst. Struct.*, vol. 1, no. 2, pp. 207–234, 1990.

[23] E. E. Pissaloux, “Modelling and Temperature Control of,” vol. 13, no. 2, pp. 1–8, 2012.