3-10-2010

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Recommended Citation

Jee, Soo-Chan, "Development of Morphing Aircraft Using SMP" (2010). *Theses and Dissertations*. 2148.
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DEVELOPMENT OF MORPHING AIRCRAFT STRUCTURE USING SMP

THESIS

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DEVELOPMENT OF MORPHING AIRCRAFT STRUCTURE USING SMP

THESIS

Presented to the Faculty

Department of Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering

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March 2010

AFIT/GSE/ENV/10-M02

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AFIT/GSE/ENV/10-M02

Abstract

The U.S Air Force needs new aircraft which provide longer flight time, less fuel consumption, better aerodynamics in order to perform Air Force missions successfully as the mission environment changes rapidly. A morphing wing aircraft is considered as a potential new aircraft for those missions. This thesis explores Shape Memory Polymer (SMP) properties test results and its applicacation for morphing wing skin. Several SMP composite laminates were considered for investigating shape changing characteristics required for morphing skin. The braided composite preforms used in making SMP composites were explored in morphing wing operating system based on the results of property tests. The system definition, life cycle of system, user analysis, and some architecture for identifying systems effectively formed the basis for the generic system engineering process presented. Further, this thesis explores initial geometric deformability, recovery characteristics, material property estimates, and develops the system using morphing material in order to present a concept for emerging morphing wing aircraft as a potential future Air Force's alternative. Based upon this research, the material system considered here does not meet the morphing requirements for such aircraft.

Acknowledgments

I would like to express sincere appreciation to my faculty advisor, Dr. Som Soni, and Dr. Joseph Carl, for their brilliant and insightful guidance and steadfast support throughout the course of this thesis effort. I would also like to thank my academic advisor, Dr. Jacques, for his great support during coursework. In addition, I would like to thank Mrs. Annette Robb, director of IMSO in AFIT, for sacrifices supporting international officers. Finally I would like to thank the USAF .I learned a lot from USAF and AFIT. I would like to apply everything I studied here for development of R.O.KAF.

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- Captain. Soo-chan Jee

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List of Abbreviations

AF – Air Force

AFIT – Air Force Institute of Technology

AFRL – Air Force Research Laboratory

AOA – Angle of Attack

ASCA– Automated System for Composite Analysis

CLAP – Composite Laminate Analysis Program

CONOPS – Concepts of operations

DARPA – Defense Advanced Research Projects Agency

DoD – Department of Defense

DoDAF – Department of Defense Architecture Framework

FESAP – Free Edge Stress Analysis

MWOS–Morphing Wing Operating System

MWMS– Morphing Wing Mechanism System

RCS – Radar Cross Section

SEP - System Engineering Process

SMP – Shape Memory Polymer

USAF – United States Air Force

R.O.KAF – Republic of Korea Air Force

TST – Time Sensitive Target

TMF –Thermo-mechanical fatigue

DEVELOPMENT OF MORPHING AIRCRAFT STRUCTURE USING SMP

I. Introduction

1.1 Problem Statement and Objective

The way the United States Air Force uses aircraft needs to be changed. New targets have emerged and new enemy's strategies have been developed. As most people already know, enemies make their targets smaller and hide them to prevent detection. We also face difficulty in attacking those targets because of complexity and proliferation of air control in certain areas. In this situation the aircraft need more time, information and energy to detect and attack targets. In other words, the United States Air Force needs to make aircraft that provide flexibility and versatility to deal with these kinds of targets in a cost effective manner [1]. These new changing warfare environments require new concepts of aircraft in warfare. To meet the new requirements, many scientists have researched many kinds of new aircraft. Among them, morphing aircraft is a promising alternative. Generally, a morphing aircraft changes its external shape to adapt to a changing mission environment during its flight. Research on morphing aircraft is popular and proliferating all over the world. NASA, DARPA and other labs have already developed their morphing aircraft test models and have been conducting different experiments on morphing aircraft. To make morphing aircraft, we face several difficulties in transforming wings. There are some transforming wings so far; however, we need wings that can change their shape with various motions and agility in a cost effective manner. This thesis deals with the Shape Memory

Polymer (SMP) for making formable wing skin. SMPs are promising materials with properties offering literate stiffness and geometric changes at temperature changes. Thus, SMP can be deformed or keep its shape as temperature changes. Using this property this thesis deals with challenges involved in making the morphing aircraft wing skin. We integrated the effect of retaining shape of the polymer with cyclic deformation under thermo mechanical loading. At about 50 cycles, we observed that plastic deformation has taken place. This shows that the material considered does not meet the morphing requirements of an aircraft.

1.2 Thesis Proposal

AFRL and DARPA have sponsored this research leading to a morphing aircraft mechanism. They have already made enormous progress in this technology; however, there is still a lot more to be done in creating a morphing wing and transforming wing system. This situation drives this thesis proposal because AFIT laboratory facilities, faculty, and students can help explore other more effective alternatives from mechanical based design to material based (e.g. SMP based) designs.

1.3 Outline of Thesis Content

Chapter 2 deals with background consisting of approaches to make morphing wings and create appropriate material for developing morphing wings. This background lays down the foundation in chapter 3 for experimenting with SMP laminates. Chapter 4 includes results of material experiments. Finally, chapter 5 includes conclusions and recommendations based on the research conducted during thesis study.

II. Background

This section introduces morphing and SMP materials with a brief introduction to the morphing wing and SMP. The section includes system engineering review.

2.1 The Benefit of Morphing

Morphing has numerous benefits, including better aerodynamics and less fuel consumption. The benefit morphing wings provides includes improved aerodynamics of the aircraft in variable flight environments. Flying below transonic speed, the lift to drag ratio (L/D) is estimated as [2] :

$$\left(\frac{L}{D}\right)_{\max} = \frac{b}{2}\sqrt{\frac{\pi e}{S_{wet}C_f}}$$

Where b is the wing span, C_f is the skin friction coefficient, S_{wet} is the total wetted space (wings, tails, fuselage), and e is a parameter called the Oswald efficiency factor for the wing. Maximum L/D is an important parameter which determine aerodynamics and fuel consumption in designing aircraft, A comparison of L/D ratio between unmorphed (fixed wing) and morphed (*) is shown below assuming C_f and e are equal.

$$\left(\frac{L}{D}\right)_{\max} \Bigg/ \left(\frac{L}{D}\right)^{*}_{\max} = \frac{span}{span^{*}}\sqrt{\frac{S^{*}_{wet}}{S_{wet}}}$$

This ratio shows that smaller Swet or larger wing span(b) increase the ratio. Another important parameter, aerodynamic drag is presented below.

$$Drag = thrust\ \ required = qC_{f}S_{wet} + \left(\frac{1}{q\pi e}\right)\left(\frac{W}{b}\right)^{2}$$

Aerodynamic drag for an airplane with weight W, operating at a subsonic flight speed V at an altitude with an air density is . q = ½ V^2 and Cf is the skin friction coefficient[2] . The first term concerns the parasite is drag which includes the effect of skin friction. This term doesn’t include wave drag or pressure drag. The second term induced drag caused by the lift force. Parasite drag results from friction in the thin boundary layer surrounding the aircraft surface. In high speed flight, the parasite drag caused by S_{wet} is very important. We can decrease parasite drag effectively by making smaller wing area to minimize S_{wet}. NextGen Company tried to assess the potential benefit of wing morphing. The results of this study in terms of system-level performance improvements are illustrated in the spider plot in Figure 2-1. In this figure, flight performances are shown for fixed and morphing wing geometry. The outmost points represent the theoretically best performance at each of the designated flight conditions [3].

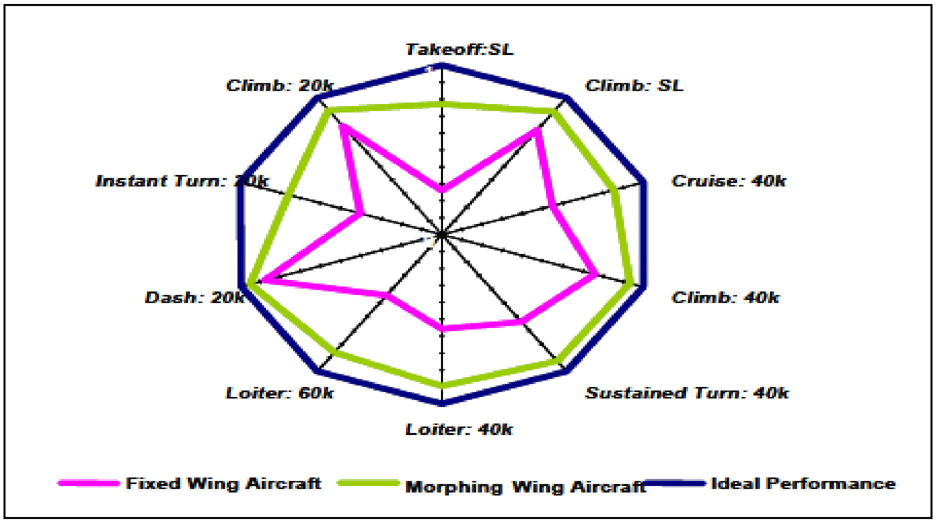


Figure 2-1 Spider plot comparison of fixed and morphing wing aircraft

A morphing wing also has an advantage of fewer exposed edges. Exposed edges produce more Radar Cross Section (RCS) during the flight. An aircraft with higher RCS due to edge are more prone to radar detection. If morphing wings are implemented, wings could be shaped with fewer edges. The last benefit of a morphing wing is manufacturing cost effectiveness due to fewer components. Current variable sweep aircraft have many components to make the sweep angle change. Such aircraft consist of many actuators, frame and lines that are complex and heavy. These complex and heavy parts make the variable sweep aircraft undesirable. Morphing wings are very simple and have very few components compared to conventional aircraft and variable sweep aircraft. This makes aircraft lighter and more reliable and easier to maintain.

2.2 Ideal Morphing Aircraft Scenario

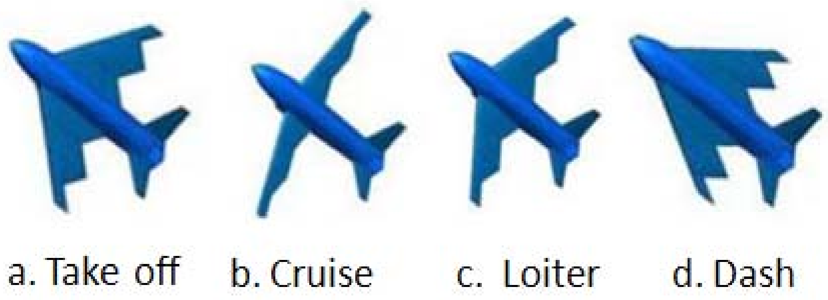


Figure 2-2 Four different sweep angles for the morphing aircraft

a. Take off

Morphing aircraft find the most optimal lift coefficient over drag coefficient ratio(C_L/C_D) for takeoff to get the shortest distance for takeoff. After takeoff, the aircraft sets up the wing to climb up to 30,000 feet with changing Angle of Attack (AOA) and wing shape.

b. Cruise

After climbing up to 30,000 feet, morphing aircraft change their wing again. To get the effective fuel consumption and low drag for cruising long distance, morphing wings transform to longer span and smaller surface to get high C_L/C_D ratio.

c. Loiter

The morphing aircraft loiter to get enemy information and detect the enemy. Morphing aircraft maintain longer wing span and a larger surface to save fuel consumption during the loiter. Morphing aircraft can spend more time loitering because they can change wing shape in a fuel effective manner.

d. Dash

During loitering the morphing aircraft transform their wings with more sweep back angle to dash in order to get high speed and handling control.

2.3 Morphing Aircraft Type

This section briefly reviews the history and current effort in the development of morphing air craft, variable sweep angle aircraft, active (folding) wing aircraft and morphing skin air craft. These aircrafts are tested and some of them performed missions in the wars.

2.3.1 Variable sweep air craft

A well known morphing air craft is the F-14, which has variable sweep wings (Figure 2-3). It has performed multi-role successfully. The variable sweep wing or swing wing uses kinetic and mechanical principles to change sweep angle in the wing. By decreasing sweep angle, wetted surface becomes bigger. It produces more lift force with less fuel consumption. On the other hand, by increasing sweep angle, wetted surface is getting smaller. It reduces drag, so aircraft can dash faster than conventional air craft. These variable sweep air craft have the advantage that it is easy to change the sweep angle with an easy mechanism. But this way still has some disadvantages. One of the critical problems is that it is very complex to use a hinge to make a variable wing. The wing needs more components and control to move the hinge of the wing. It causes more components in the wing, and it results in a heavier wing that prevents lighter aircraft.

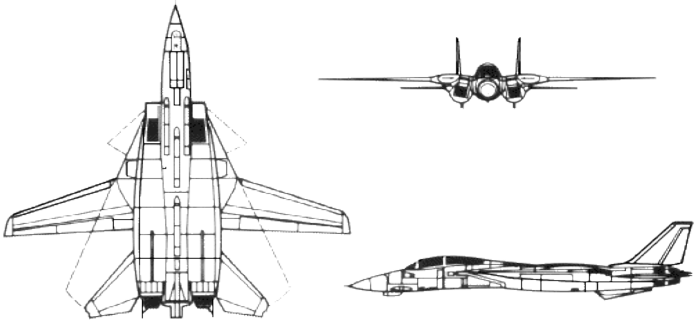


Figure 2-3 Variable sweep aircraft, the F-14

2.3.2 Active wing air craft

Another method is folding wing. Many scientists devised wings that twist or fold during flight. This method is still researched as a promising approach. Folding the wing uses the actuator or active skin material. These aircraft fold their wing to speed up during the flight (Figure 2-4). The effect is like a larger sweep angle. On the other hand, morphing air craft unfold their wings when they need more lift to minimize fuel consumption. This expands wetted area to get more lift. However, this way can only transform its wing through a restricted shape that is implemented by a mechanical actuator. Active wing aircraft lack variability in changing the wing platform.

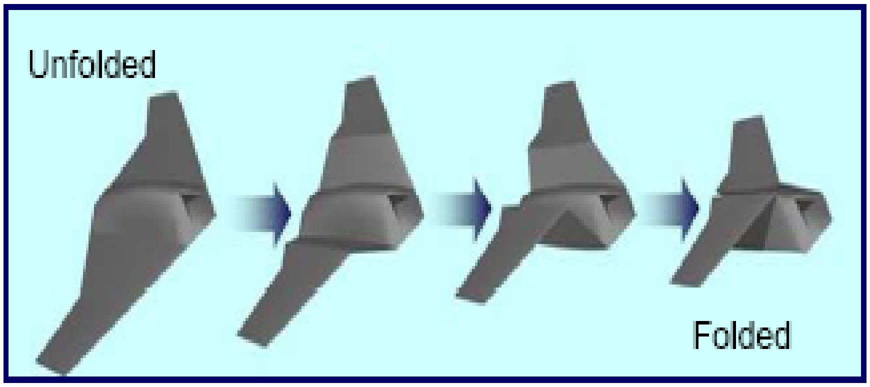


Figure 2-4 Active wing aircraft

2.3.3 Morphing skin aircraft

The last method that can transform wing shape is using flexible skin that consists of composite and fibers. Using flexible material has been researched in the AFRL and NASA as an effective alternative [4]. The goal of this method is creating a morphing wing like that of birds using different material. Flaps and fuselage sometimes split or move together using actuators in this method. The main barrier and key point of this method is how to make new material that is transformable and rigid to maintain the load of the aircraft during flight. If we achieve that, we will acquire the desired morphing effect, minimizing total gross weight without other added components. The author will explore this approach. The following section discusses the candidacy of morphing material.

2.4 Morphing Skin Material Requirement

Morphing wing material requires certain properties to satisfy requirements. First, the material should be rigid to sustain aerodynamic load during flight. Combat mobility causes a lot of G-forces. If the material is not rigid enough to withstand g-force, the material may be deformed, it might transform wing shape. The material should have rigidity to withstand any aerodynamic load during flight. Second, the material should be transformable in the desired condition. This property is the basic function of morphing material. After the material is stretched, it should recover its original shape, provided the temperature or actuator condition is changed. If this property doesn’t perform properly, it may make the wing asymmetrically twisted. Third, it should be transformed in a short time with little energy. Morphing aircraft can’t wait for a long time to transform wings, and can’t spend a lot of energy only for changing wing shape. Material should be changed in shorter time using an actuator to keep these properties. Fourth, material should withstand large in-plane and shear strains. Morphing wings are apt to produce a lot of strain because of transition, which may cause a lot of cracks. This could cause catastrophic failure. Thus, to keep the reliability of the wing, the material should sustain strains [4].

2.5 Morphing Wing Skin Candidacy: SMPs

SMP are an emerging class of active polymers that have dual-shape capability. They can transform their shape in a pre-programmed way from shape A to shape B when the material is exposed to an appropriate stimulus.

2.5.1 General concept of shape-memory polymers

The shape-memory effect is not an intrinsic property. Polymers do not transform by themselves. This means that shape memory results from a combination of polymer morphology and specific processing. By conventional processing, for example(figure 4) extruding or injection molding, the polymer is formed into its initial, permanent shape B. Afterwards, in a process called programming, the polymer is deformed and fixed into the temporary shape A. Under application of an external stimulus, the polymer recovers its initial shape B. This cycle of programming and recovery can be repeated several times, with different shapes in subsequent cycles. In comparison with metallic shape-memory alloys, this cycle of programming and recovery can take place in a much shorter time interval and polymers allow a much higher deformation rate between shapes A and B [6].

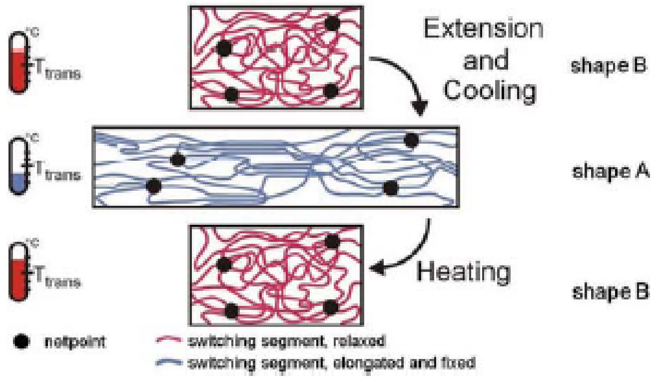


Figure 2-5 Principle of Shape Memory Polymer

The polymer network consists of molecular switches and net points. The net points determine the permanent shape of the polymer network and physical characteristics. If the working temperature is higher than T_{trans} then the switching domains are flexible, resulting in an elastic behavior of the polymer network above T_{trans}. If the sample has been previously deformed by application of an external stress, it snaps back into its initial shape once the external stress is released. During the course of this study, we concentrated on investigating the shape changing capability of SMP composite as a function of thermo mechanical load. We have observed that the SMP composite loses its capability of recovering its original shape at about 50 cycles. Thus this material is not suitable for morphing wing aircraft application. It may be useful for munitions application where lesser number of morphing cycles may be required to meet the mission objective.

2.6 Systems Engineering Process

Many people define system engineering as an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed. Issues such as logistics, the coordination of different teams, and automatic control of machinery become more difficult when dealing with large, complex projects. Systems engineering deals with work-processes and tools to handle such projects, and it overlaps with both technical and human-centered disciplines such as reliability maintainability, logistics support and human factors [7].

In this thesis the author will apply system engineering to define an appropriate wing morphing system. The reason why system engineering is useful can be explained using the following Figure 2-6 [8]. Many materials and control methods are advancing rapidly. Some of them are tested and used in other structures. New materials often are different from conventional materials in that they have more complex properties with which to deal. As a candidate for morphing wing material, SMPs has very complex properties as temperature changes. These new complex challenges create a rising need for an interdisciplinary system approach. We have to involve other engineering approaches such as mechanical and industrial engineering. We also involve new failure modes and strategies for managing them. In these kinds of work, System Engineering Process (SEP) will help us analyze processes and integrate all the solutions for the system.

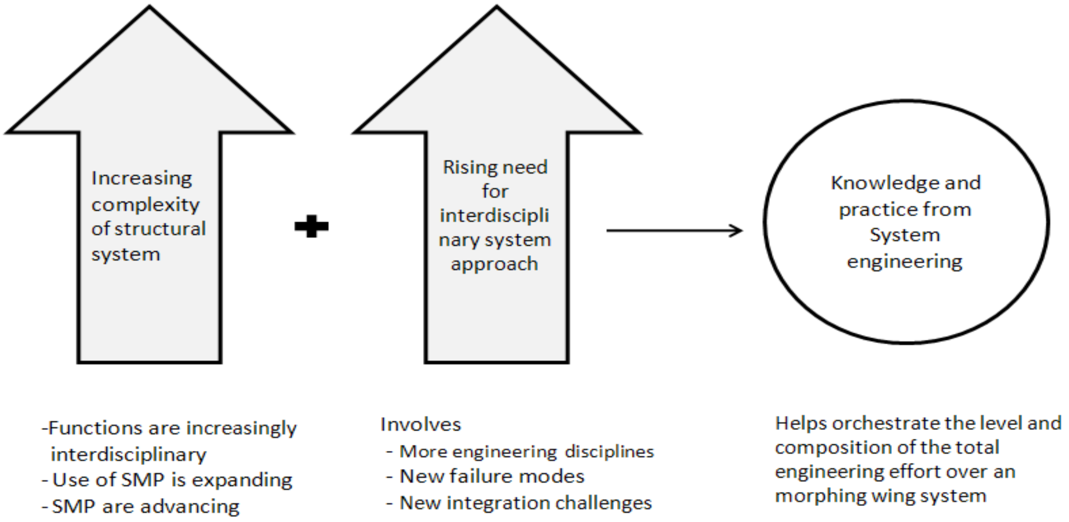


Figure 2-6 Recent trend in structural design and a way ahead for overcoming the challenges

In system engineering the stake-holders of the system influence the objectives of the system against which the success of the system is measured. These objectives usually include cost, schedule, and technical performance. In applying system engineering, the system engineer has to resolve conflicting objectives. To apply the interdisciplinary approach for the required system design, a systems engineering approach is depicted by the Vee model (Figure 2-7). The system engineering Vee model starts with understanding the stakeholder requirements to develop the system concept and the validation plan. In this step the system engineer decomposes user's requirements and develops the system concept. The engineer considers many engineering views from many stakeholders and thinks about an overall system concept. Once this first step is accomplished, the engineer starts to develop the system performance specification, system requirements, and the system verification and validation plan. In this step, engineers have to facilitate the design and system tradeoffs due to the complexity of the issues and the multitude of stakeholders involved [1]. The design engineers then expand the system concept or configuration and prepare a Configuration Item (CI) verification plan. In this step, the engineers consider many kinds of engineering views (e.g. mechanical, industrial, electrical, etc) to evolve the design in compliance with specifications and to build documentation and inspection plans. By using logical engineering principles to decrease life cycle cost, the system engineer can justify spending the required amount of money to incorporate systems engineering into the total system design and function [9].

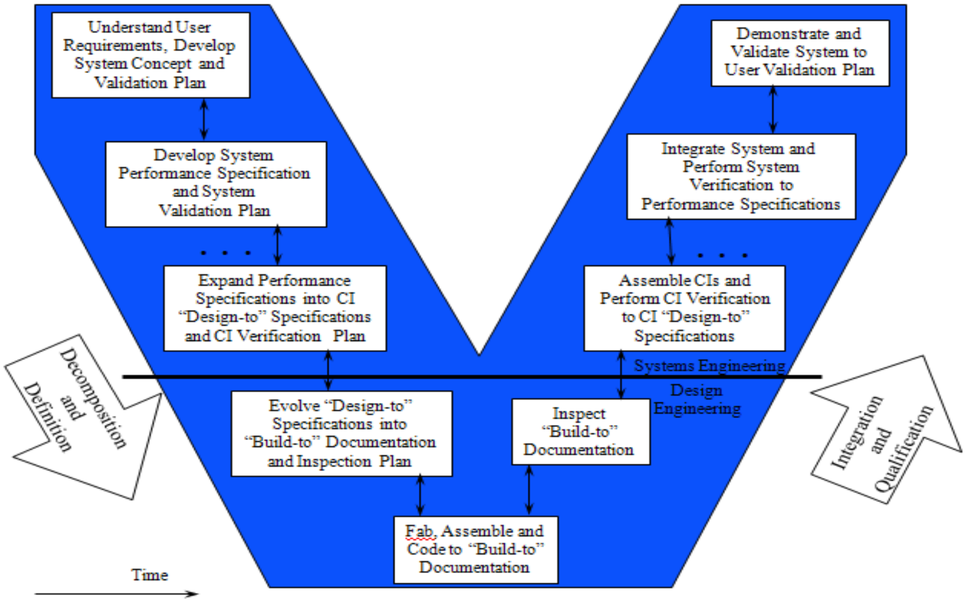


Figure 2-7 Vee model

The right hand side of the Vee model describes the integration and qualification activities of the system. Integration involves the assembly of the CIs into components, the assembly of lower level components into higher-level components and the system. This involves testing of the newly assembled system components to determine whether the assembled components will meet the set of requirements or specifications that the design phase had established for that component. This qualification is called verification. Verification addresses the question; did we build the system right? Once the system is verified against the system requirements, the system must be validated. Validation answers the questions: Did we build the right system? Or does the system meet the user requirements? After validation, the stakeholders decide whether the system is acceptable or not.

In analyzing SMP properties and implementing a morphing wing control system, Vee model is the most appropriate. The Vee model provides benefits for the planning and realization of this system:

(1) The Vee model is considered a standardized process model.
(2) Management of system risk: The Vee model improves project transparency and project control by specifying standardized approaches and describing the corresponding results and responsible roles. It permits an early recognition of planning deviations and risks and improves process management.
(3) Improvement of communication between all stakeholders: The standardized and uniform description of all relevant elements and terms is the basis for the mutual understanding among all stakeholders. Thus, the Vee model can reduce frictional loss between user, acquirer, supplier and developer [10].

III. Methodology

The morphing aircraft wing requires complex sub systems. The thesis deals with the mechanics of materials associated with shape changing aspects. These materials are the most important part in the development of morphing aircraft wings. Composites made with shape memory polymer, matrix and bi-axial braids and fibers are used. Further details follow:

3.1 Experimental Investigation

3.1.1 Overview

The material used to fabricate all test specimens for this investigation is Shape Memory Polymer using the Veriflex E2 resin system. Lay-up and manufacturing was performed at CRG Industries in Beavercreek, OH. Specimens are prepared by CRG industries. Deformation tests were performed in the AFIT system engineering laboratory.

3.1.2 Equipment set up

The testing system is designed to provide an affordable and easy to use platform for mechanical testing of shape memory polymers and shape memory polymer matrix composites. The system is designed to apply a maximum of 500 lbs tension loading to a wide range of specimen geometries and dimensions. The heating unit is made out of a transparent acrylic box and heat is applied to the specimen using forced hot air generated using an industrial heat gun. The temperature in the box is digitally regulated using a high accuracy temperature controller and a phase-fired power supply. The testing frame has a built in load cell that can measure loads up to 1000 lbs. It can be connected to a computer through a DAQ (Data acquisition) card which works with data acquisition software such as Labview.

3.1.3 Component list

a. Metallic frame

The frame is made out of 14 gauges; 1.5” x 1.5” galvanized steel slotted angle material and is designed to withstand a maximum load of 500 lbs.

b. Temperature controller unit

The temperature controller unit runs on 110V / 60Hz AC power. On/off toggle switches on the front of the box control the functions (Figure 3-1).

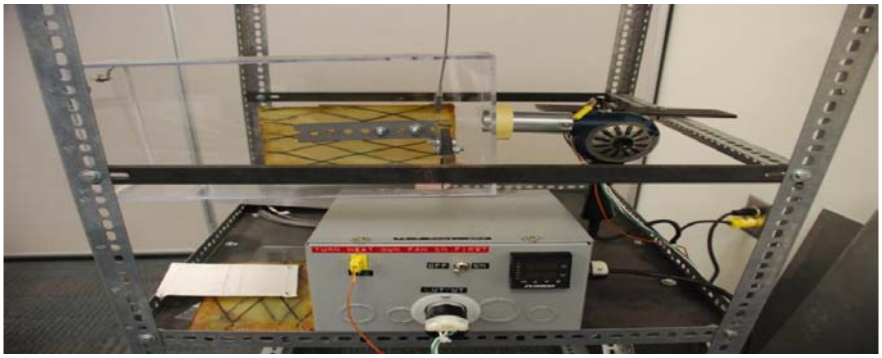


Figure 3-1 Temperature controller unit

c. Ratcheting puller for loading

Figure 3-2 Puller

The ratcheting puller used in the test frame is model 4LY45 from Grainger Inc (Figure 3-2).

d. Heating unit/furnace

The heating unit consists of a modified Bosch 1942 industrial heating gun and transparent acrylic box to house the specimen and retain hot air for heating the specimen. The heat gun is modified to separate the input power for the fan and the heating element. The fan is powered through a 110V wall outlet. It is highly recommended to turn the fan on before connecting the heating element to prevent burning the heating element out from excessive heat without circulating air (Figure 3-3).

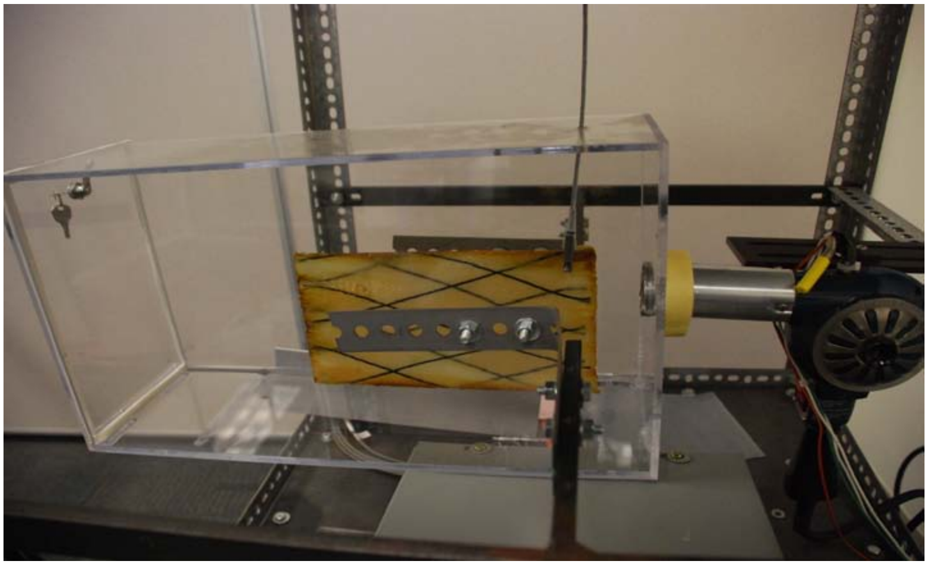


Figure 3-3 Specimen in the furnace and heat gun

e. Load cell

The load cell is constructed of stainless steel and can measure loads up to 1000 lbs. The load cell is linearly calibrated to output 21mV at 1000 lbs.

3.1.4 Veriflex E2 resin

Cured Veriflex E2 has unique “shape memory” properties. When heated above its glass transition temperature (Tg), Veriflex E2 (figure 3-4) changes from a rigid plastic to an elastic rubber. In this elastic state it can be twisted, pulled, bent, and stretched, reaching over 100% elongation. If cooled while constrained in this new shape, the polymer hardens and can maintain its deformed configuration indefinitely. When heated above Tg this polymer returns to the shape in which it was cured. This process can be repeated indefinitely without loss of the memory shape or degradation of the material. Veriflex E2 resin is engineered with a glass transition temperature (Tg) of 217 ºF(103ºC). The uncured resin has a low viscosity that makes it easy for processing composite fabrication. The SMP composites used by Veriflex E2 have common features and benefits. These have unique shape memory properties, and they can be deformed and recover repeatedly. This property makes them transform reversibly from rigid polymer to soft elastomeric. It also provides over 100% elongation in its elastic state with increased durability [11].

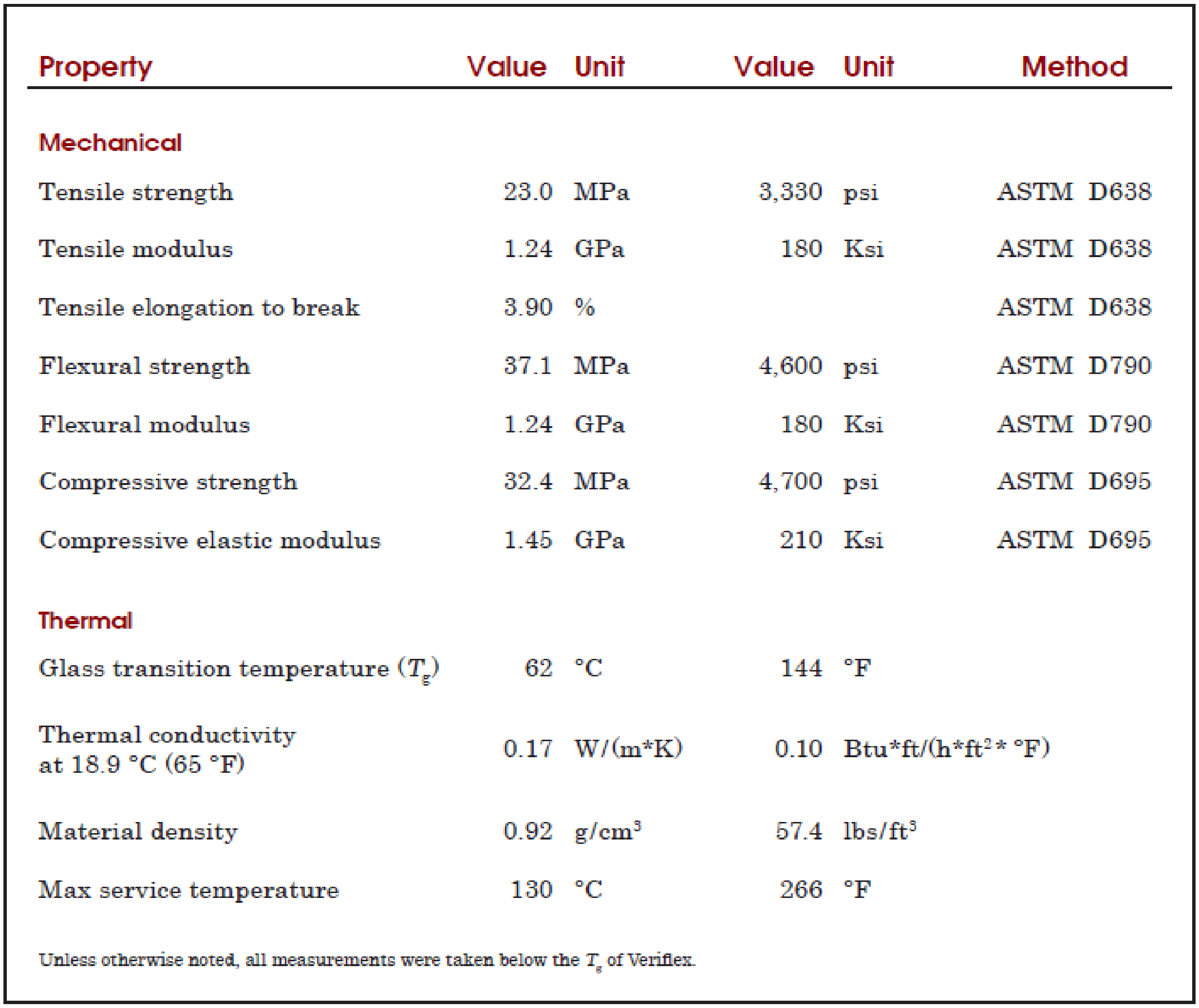
Figure 3-4 Veriflex E2 resin

- Curing conditions :

  Veriflex E2 (Table 3-1) should be cured in a closed system mold. Here is a suggested cure cycle:

- Ramp from room temperature to 257 ºF over a half hour
- Soak at 257 ºF for 4 hours
- Ramp form 257 ºF to 302 ºF over a half hour
- Soak at 302 ºF for 4 hours

Table 3- 1 Cured material properties



Property	Value	Unit	Value	Unit	Method
Mechanical					
Tensile strength	23.0	MPa	3,330	psi	ASTM D638
Tensile modulus	1.24	GPa	180	Ksi	ASTM D638
Tensile elongation to break	3.90	%			ASTM D638
Flexural strength	37.1	MPa	4,600	psi	ASTM D790
Flexural modulus	1.24	GPa	180	Ksi	ASTM D790
Compressive strength	32.4	MPa	4,700	psi	ASTM D695
Compressive elastic modulus	1.45	GPa	210	Ksi	ASTM D695
Thermal					
Glass transition temperature (T_g)	62	°C	144	°F	
Thermal conductivity at 18.9 °C (65 °F)	0.17	W/(m*K)	0.10	Btu*ft/(h*ft^2* °F)	
Material density	0.92	g/cm^3	57.4	lbs/ft^3	
Max service temperature	130	°C	266	°F	

Unless otherwise noted, all measurements were taken below the T_g of Veriflex.

3.1.5 Manufacture SMP steps

At first, we got two clean plates and put mold release on the surface of them. We wiped the mold release with long strokes over the entire surface using a paper towel, going over it several times to ensure the entire plate had been covered (Figure 3-5). Then, we let the plates dry for 5 minutes before continuing

Figure 3-5 Cleaning plates

1. Cut a length of wooden bar to match the length of the specimen. Bar should be long enough to go around the edges of mold. We have to fasten the wooden bars in desired positions with tape or molding bond. The bars will keep the resin from falling or slipping (Figure 3-6).

Figure 3-6 Fastening wooden bar

2. We activated resin for impregnating the braid prefom to make composite panels. Veriflex E2 resin consists of part A and part B. Both parts should be mixed in specified ratio. We weighed part A and B of the resin in prescribed proportions, and, we prepared them to be applied to the prefom (Figure 3-7).

Figure 3-7 Preparing resin

3. We poured resin in the center of the frame to be the bottom of the laminates. The poured resin should be spread out evenly. If it is not spread, it could result in uneven or irregularly soaked laminates.
4. We put the fiber in the center of the frame made by the wooden bars. We have to make sure the fiber is fully soaked by the resin and enclosed with bars (Figure 3-8).

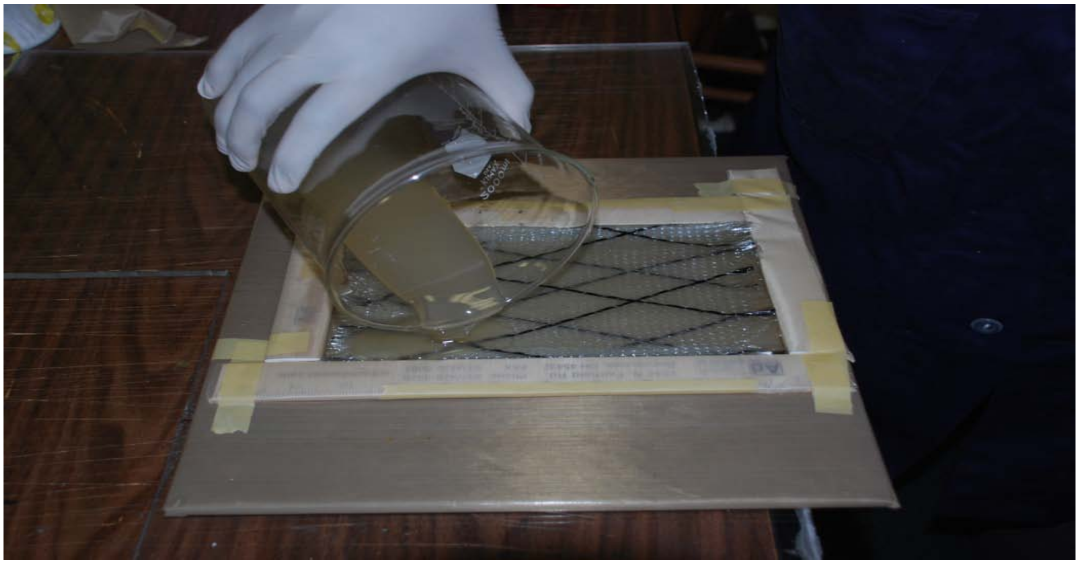


Figure 3-8 Pouring resin

5. Then we placed the second sheet on top of the first on which we already made the frame and soaked the fiber (Figure 3-9).

Figure 3-9 Placing second sheets on top of the first plates

6. We used a vacuum plastic bag to prevent external contaminants. We kept the vacuum state in the plastic bag.
7. We placed the plates on the temperature 254 ºF for 10 hours (Figure 3-10).

Figure 3-10 Keeping temperature

8. We took the specimen from the temperature keeping equipment. Then we trimmed edges of the specimen (Figure 3-11).

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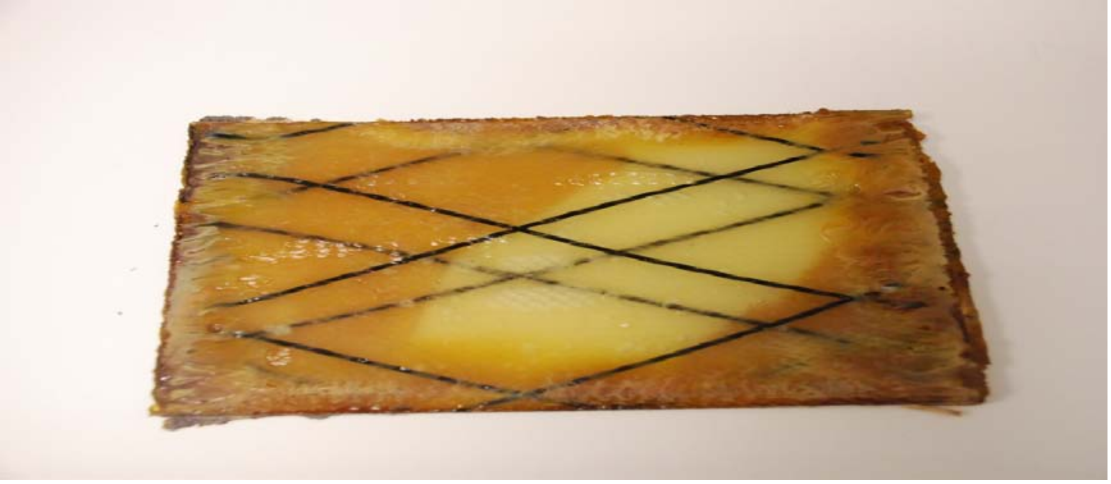


Figure 3-11 Completed specimen

3.2 System Engineering Application

3.2.1 Scope

In order to apply system engineering application to establishing a morphing wing operating system (MWOS) that can be applied to any morphing wing, the thesis had to be adequately scoped to provide specific values. Currently many research teams are trying to devise a morphing wing aircraft with various wing materials. Because of the relatively immature technology, it is hard to anticipate how to control the wing. Another uncertainty is that each morphing wing characteristic varies the propertes of each wing material. This uncertainty makes it difficult to generalize the property of every morphing wing. This thesis deals with conceptual system engineering application of morphing wing operating system. All the results from this application will be in appendix A

3.2.2 Assumptions

There are a number of assumptions that were required to develop the system engineering approach to develop MWMS (Morphing Wing Operating System). They are:

(1) SMP has been made appropriately and will show reliable shape changing property in every test;
(2) Morphing will be operated instantly during flight;
(3) The actuator can be developed to exactly load the wing material; and
(4) The morphing wing section has similar functions and properties to a conventional wing section.

3.2.3 Stakeholder's Perspective of the System

Identifying the stakeholders is a very important step at the beginning of the conceptual design of a system using the system engineering methodology. Stakeholders can be the bill payer, the developers, the operators, the trainers among others. We need to identify all the stakeholders who are involved with this system under development in order to communicate with them. This is an important step for a system engineer to reflect the requirement from the stakeholders and implement them. Identifying stakeholders might be difficult in some cases like this: The system domain is so large that it is impossible to identify all the stakeholders. In this thesis, the author will restrict attention to stakeholders who are involved with MWOS closely. The author will describe the MWOS system and its life cycle phases to identify the stakeholders for each phase. Potential stakeholders can be identified in each phase without any omission. The final product will include stakeholders in each phase.

3.2.4 Operational Concept of the System

An operational concept describes how a system will be utilized. Its interactions with external systems and the main functions of the system are included in that description. The author tried to represent how to use the system and the needs it is going to serve with various stakeholders. It will include a vision of the system and mission requirements mentioned by the stakeholders using informal language.

This thesis creates the operational concept using two different ways. The first way produces a set of scenarios. These scenarios have both inputs and outputs to the system. The view of stakeholders about the production, use and maintenance of the system is shown in each scenario. The second way to establish the operational concept is to monitor similar existing aircraft wing operating systems. There are a lot of wings currently being used in various airplanes. They are made of many kinds of composites and alloys. Various wings have different operating systems depending on the material properties. For example, a wing made of lighter composite can be light and easy to control. However, it is weak in sustaining environmental effects such as hail or foreign objects. Thus it needs to be controlled in different ways compared to other wings. This thesis referred to a lot of different wings currently existing in various airplanes. These references helped to produce an operational concept of the system.

3.2.5 Architectures

System engineers have the tools to understand and deal with complex system interactions. It is the architecture that provides clarity and simplifies complex systems. Architecture in system engineering means the formal representation used to display information about a system in a comprehensive way that facilitates decision making. Architecture also plays an important role in communicating between developers and stakeholders. There are a lot of architecture frameworks being used currently. Each architecture frame has its own purpose and properties. Fortunately, the DoD has its own architecture framework. It is the DoDAF (Department of Defense Architecture Framework), which is widely used in many system designs for the Air Force [12].

3.2.5.1 DoD architecture framework

DoDAF version 2.0 was signed on May 2009. This updated DoDAF serves as the overarching, comprehensive framework and conceptual model enabling the development of architectures to facilitate the ability of Department of Defense managers at all levels to make key decisions more effectively through organized information sharing across the Department, Joint capability areas, Mission, Component, and Program boundaries[12]. DoDAF 2.0 has multiple viewpoints compared to DoDAF 1.5. DoDAF 1.5 has only three views – The operational views, the system/service views and the technical views. DoD 2.0 includes new views – capability view, standards views, data/info views, service views, projects [12].

The all views (AV) deal with overarching aspects of architecture context that relate to all models. The operational views (OV) contain graphical and textual descriptions of operational activities or functions and information exchanges. These views articulate operational scenarios, processes, activities and requirements. The system views (SV) also use graphical and textual products; however, these views emphasize actual system components and interconnections in support of the functions and capabilities described in the OV. The services views (Svc) articulate the performers, activities, services, and their exchanges providing for or supporting, DoD functions. The capability views (CV) articulate the capability requirements, delivery timing, and deployed capability. The standards view (StdV) renames the technical view (TV). It articulates applicable operational, business, technical, and industry policy, standards, guidance, constraints, and forecasts. The data and information view (DIV) reveals the data relationships and alignment structures in the architecture. Finally, the project views describes the relationships between operational and capability requirements and the various projects being implemented; Detailed dependencies between capability management and the defense acquisition system process. Appendix B table shows the DoDAF V 2.0 views and a general description of each product.

3.2.6 Architecture Building Process

The author followed several steps for creating architecture as learned through system engineering classes.

3.2.6.1 Step one: generating related questions

The first step was to generate important questions. This step provided a lot of brain storming ideas. The author identified problems and solution approaches through questions and answers.

- What is the most different thing between conventional aircraft and morphing wing aircraft?
- Of what does the MWOS is consists of?
- Who is interested in developing morphing wing aircraft?
- What will be the life cycle of the MWOS?
- How can we validate performance of the MWOS?
- What activities should be considered importantly?
- What is the relationship between maintenance and deformation?

Generating questions allowed the author to understand user’s perspectives. Obviously, the objective of this system must be more reliable and better than conventional wing operating systems in terms of many aspects such as aerodynamics, cost, strength, reliability, etc. The system architectures were built with these objectives in mind.

3.2.6.2 Step two: determining the architecture description scope, and context with any assumption.

As described above the architecture scope was constrained to the morphing wing made of SMP. It also described many properties of wing control systems in life cycle terms. The morphing wing material system also dealt with the following assumptions.

(1) SMP has been made appropriately.
(2) Morphing will be operated instantly during flight.
(3) The actuator can be developed to exactly load the wing section.
(4) The morphing wing section has similar function and properties to conventional wing sections.

The level of detail in this architecture was left intentionally broad because morphing wings are currently being developed. Moreover, the architecture was quite easily affected by properties of the wing material. These limiting factors made it impossible to go deeper into defining detailed system architectures.

3.2.6.3 Step three: determining what information the architecture description needs to capture

There was a lot of information related to this architecture. The author generated a lot of candidate architectures through articles and library data. How to organize them is an important role of a system engineer. Step three makes sure that the information contained in the architecture is relevant and correlates with the information collected from the previous steps.

According to the DoDAF description, “if pertinent information is omitted, the architecture description may not be useful; if unnecessary information is included, the architecture effort may prove infeasible given the time and resources available, or the description may be confusing and cluttered with details that are superfluous to the issues at hand[12].

The author investigated similar architectures that show many kinds of aircraft systems, control systems and flight control systems. Some of them were effective and became the backbone of the thesis. However, it was difficult to get sufficient data to show properties of future morphing wing because SMP is a relatively new material.

3.2.6.4 Step four: determining the products to be built

DoDAF has many architecture products to choose from depending on the needs and preferences of the architecture. After discussion with advisors, the author decided that the goal of architecture in this thesis is to define and identify possible system requirements and estimate the interaction and function of MWOS. Thus, the author concluded that architecture products should be useful for showing this. DoDAF suggests the following products for integrated architecture: AV-1, AV-2, OV-1, OV-2, OV-5, SV-1, SV-5, and TV-1. All the architecture products will be presented in appendix A.

3.2.6.5 Steps five and six: gathering the architecture data and using the architecture description for its intended purpose

The last two steps for building architecture are applying architecture products. Step five is gathering the architecture data and building the requisite products. Step six is using the architecture description for its intended purpose. Both of these steps have been briefly discussed in this section, and will be elaborated in appendix A. The author follows the product sequence from DoDAF 1.5 (Figure 3-12)

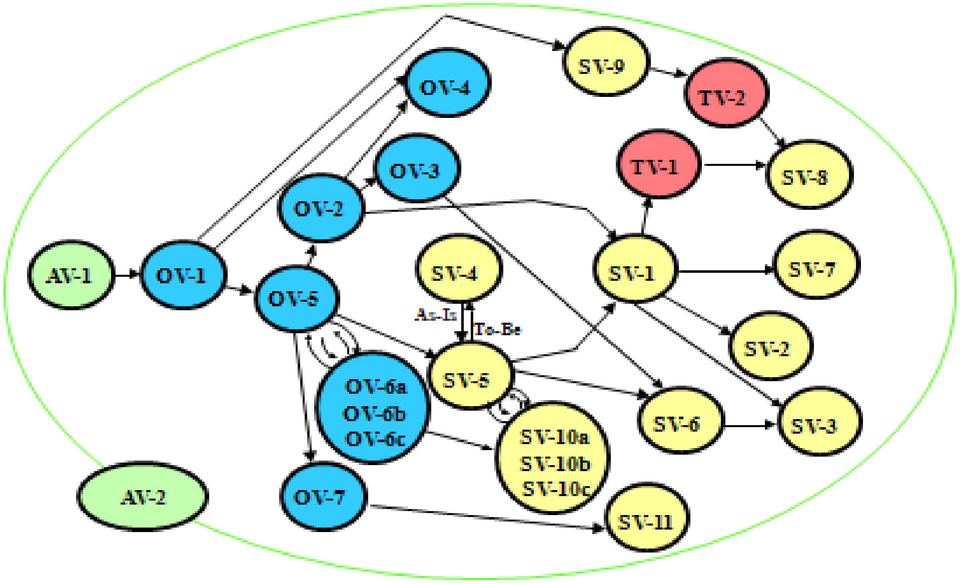


Figure 3-12 DoDAF products relationships

Resulting products using DoDAF are included in appendix A

IV. Result of Property Test

There are many attempts to develop morphing wing aircraft [3].The present work is an attempt to understand the response characteristics of available SMP composites. Since morphing wing structure needs to demonstrate repeated shape change in flight, an attempt was made to understand the effect of cyclic thermal and mechanical loadings on response characteristics of SMP composites. For that purpose, we used both analytical and experimental approaches. This chapter shows the results of preliminary material property tests and system engineering application using *material properties data*.

4.1 Material Property Test

The author selected a black colored specimen to monitor the process of how the SMP softens at glass transition temperature, Tg. As the specimen is heated, it changes its color because resin in the SMP is softening as it is heated. With the heat transfer through the specimen, the white part (resin is activating) increases its area in the black specimen. The author applied tensile force in an axial direction with the puller after the SMP specimen softens. The specimen was deformed in the axial direction, as desired. Microscopically, the specimen consisted of fiber and resin, the polymer chains can undergo rotational conformational changes, allowing the polymer chains to be uniaxially strained. As the material is strained, the alignment of the chains increases, which increases the stored energy in the material as the configurational entropy of the chain decreases. This energy is subsequently locked into the polymer chains when the material is cooled below Tg and the chains are restricted from freely rotating via interactions with their neighbors. When the polymer is reheated above Tg without constraint, an increase of entropy serves as a driving force for the material to recover its initial shape [13].

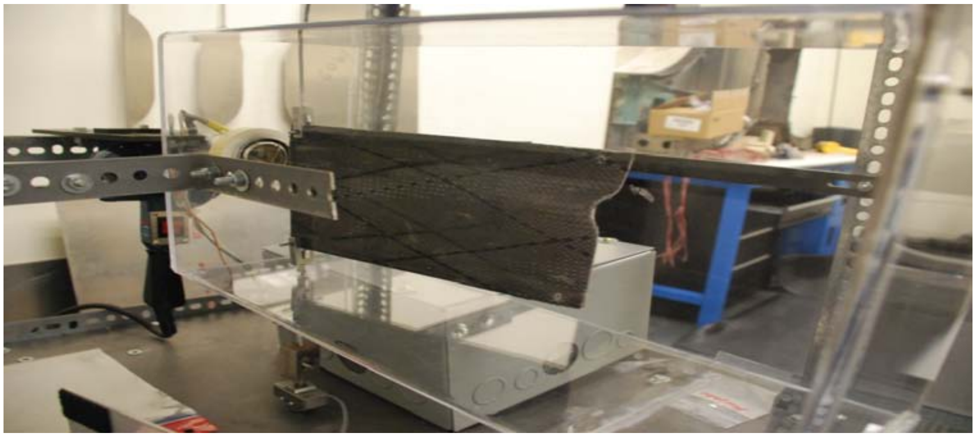


Figure 4-1 Origin Specimen in the furnace

Original SMP specimen was black fiber and resin. It was firm and opaque (Figure 4-1).

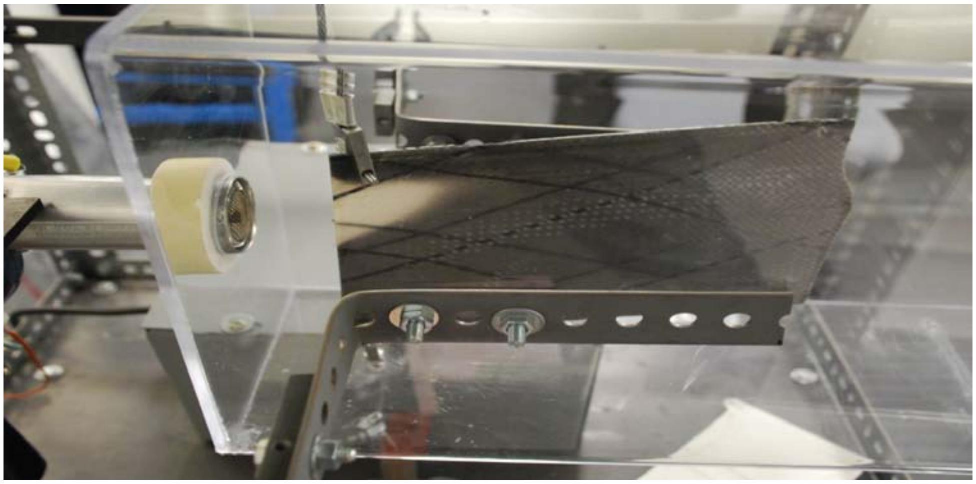


Figure 4-2 Changing color of specimen

The specimen is losing its black color as the specimen is being heated by the heat gun. The part closer to the heat gun started to change color and soften as the specimen get heated (Figure 4-2).

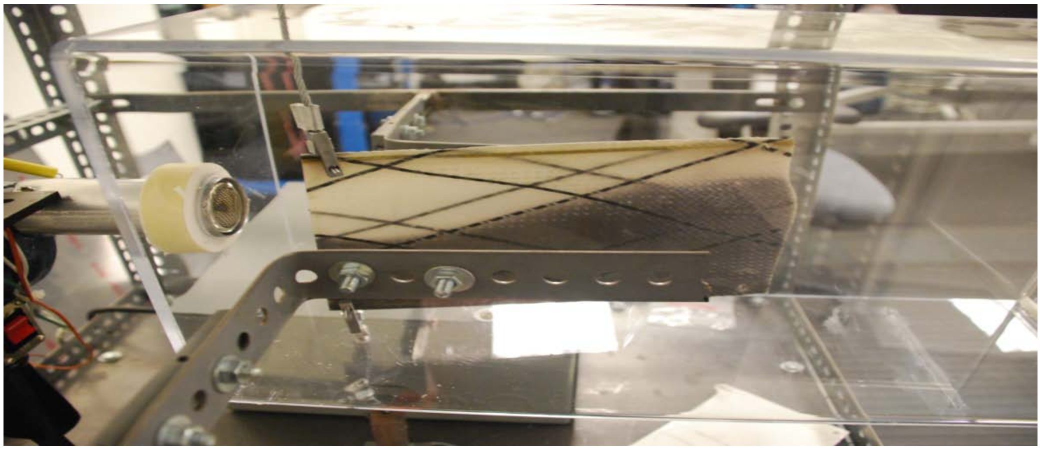


Figure 4-3 Heated specimen

Almost half of the specimen turned its color from black to white. The specimen was heated and softened continuously (Figure 4-3).

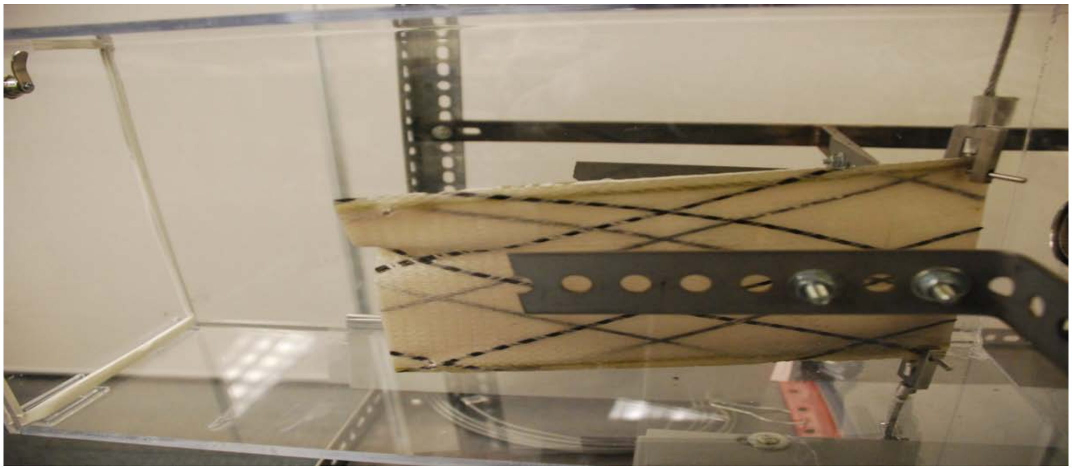


Figure 4-4 Soften specimen

While the SMP is being softened, the author loaded the tensile force in an axial direction. The load made deformation in the specimen easy (Figures 4-4, 5).

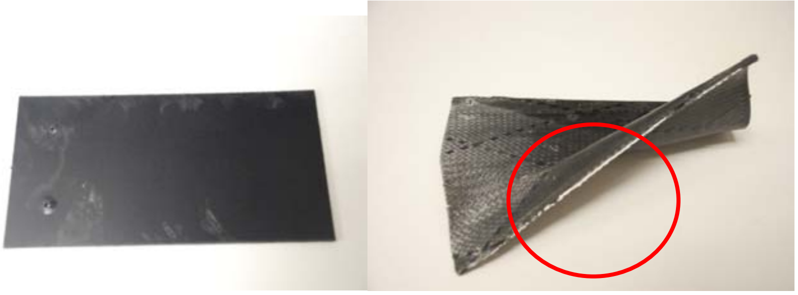


Figure 4-5 Deformed specimen

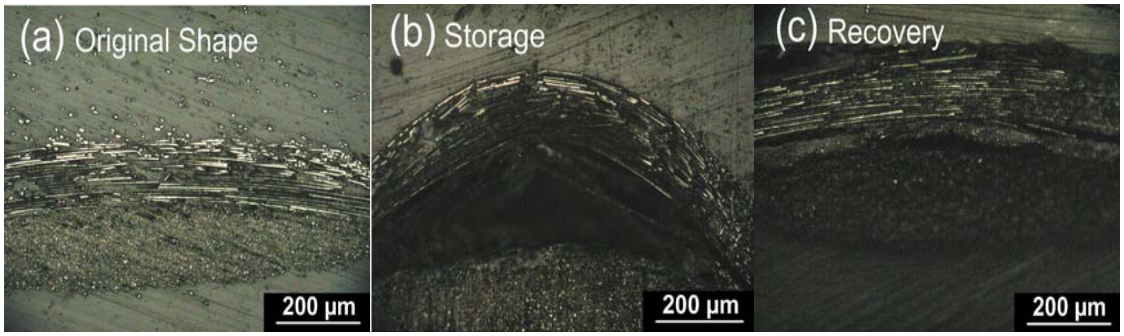


Figure 4-6 Optical microscopic images of SMP composite specimen [14]

Microscopic figures (Figure 4-6) from Liu's article shows an optical microscopic image of an SMP specimen. By referring to these figures, the author could clearly understand how the SMP deformation process happens while the SMP is being heated [14]. The image of original shape (left) shows the longitudinal fibers and the SMP matrix is pretty good, namely there is no failure or delaminating in the composite. The image of storage (center) shows large delaminating gap between the transverse fiber and the longitudinal fiber. The image of recovery (right) shows the recovered configuration of fiber micro buckling at the same location of the previous image. A small recovered delaminate gap also can be observed between the transverse fiber and the longitudinal fiber.

4.2 Micromechanics Analysis

4.2.1 Purpose of Micromechanics Analysis

Micromechanics of material is the analysis of composite or heterogeneous materials on the level of the individual phases that constitute these materials [15]. It deals with mechanical properties of the constituent materials of the composite. The author could understand basic principles of SMP deformation and properties of it by applying micromechanics analysis. Figure 4-7 shows the constituent properties of fiber and matrix materials are used to calculate the ply properties using rule of mixture. Ply properties are used to calculate the laminate properties. In this section mechanics of composites is used to understand the response characteristics of SMP composites

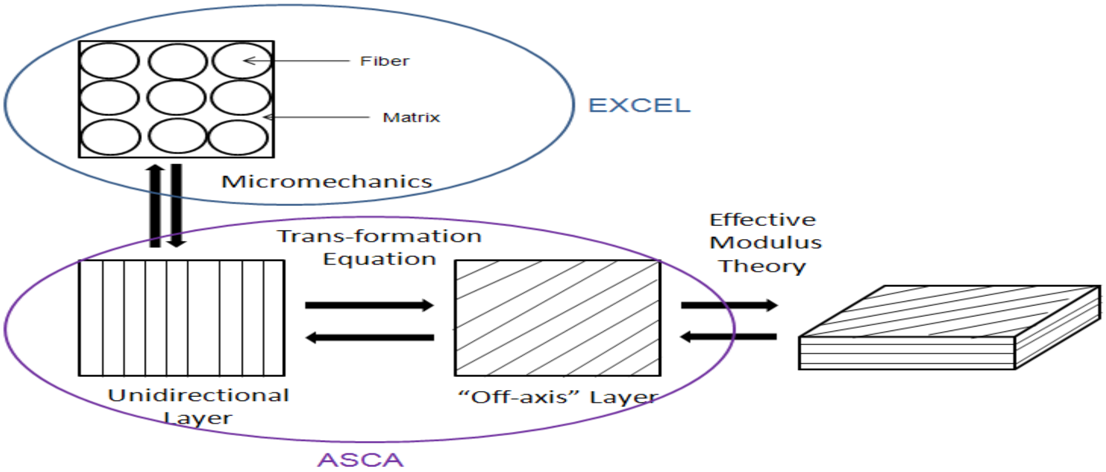


Figure 4-7 Analyzing composites

4.2.2 Procedures of Micromechanics Analysis

4.2.2.1 Determining effective lamina properties

In order to analyze the lamina properties we used micromechanics using the rule of mixture $E11=E_f*V_f + E_m*V_m$. The volume fraction of fiber V_f and the volume fraction of matrix V_m satisfy the total volume relation $V_f+V_m=1$. E_f and E_m are Young's modulus for fiber and matrix materials and are obtained using experiments. We can obtain the ply Young's modulii E11 and E_{22} for the ply as given below [16]:

$$E11=E_f*V_f+E_m*V_m\,,\quad 1/E_{22} = V_f/E_f+V_m/E_m\,,$$

In order to apply this method, the author decided to select one of SMP specimen made using Veriflex resin. From the given basic data, the specimen material has $V_f=0.66$, $V_m=0.33$ (weight of fiber = 60.29g, weight of matrix = 30.84g). Figure 4-8 is the specimen representing the SMP composite laminate. The analysis is done by micromechanics and the laminate analysis modules given in the Automated System for Composite Analysis (ASCA).

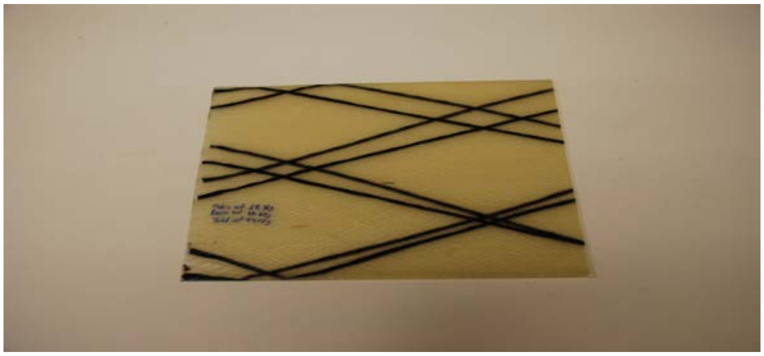


Figure 4-8 Specimen sample

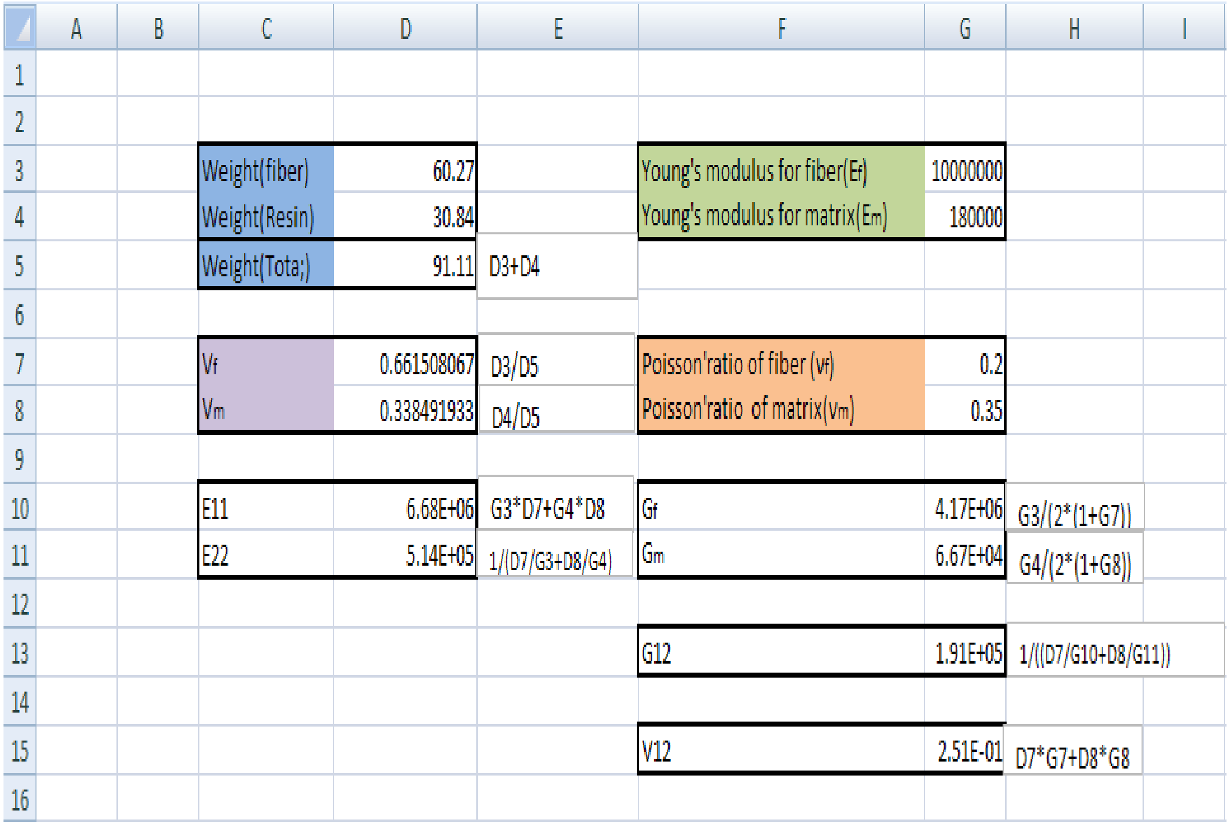
The author could get the various values for starting micromechanics analysis by using the basic equations and an EXCEL program (Figure 4-9). With the help from EXCEL sheet we determined the effective shear modulus given by the equation $1/G_{12}=V_f/G_f+V_m/G_m$.

Where $G_f=E_f/[2(1+\nu_f)]$; ν_f is Poisson's ratio of fiber and ν_m is Poisson's ratio of matrix;

$G_m=E_m/[2(1+\nu_m)]$

From known equation in TSAI's book[16], we can get Poisson's ratio $\nu 12 = V_f*\nu f+ V_m *\nu_m$

Using this equation and Excel program, the author can get the lamina properties of interest.



	A	B	C	D	E	F	G	H	I
1									
2									
3			Weight(fiber)	60.27		Young's modulus for fiber(E_f)	10000000		
4			Weight(Resin)	30.84		Young's modulus for matrix(E_m)	180000		
5			Weight(Tota;)	91.11	D3+D4				
6									
7			V_f	0.661508067	D3/D5	Poisson'ratio of fiber (ν_f)	0.2		
8			V_m	0.338491933	D4/D5	Poisson'ratio of matrix(ν_m)	0.35		
9									
10			E11	6.68E+06	G3*D7+G4*D8	G_f	4.17E+06	G3/(2*(1+G7))	
11			E22	5.14E+05	1/(D7/G3+D8/G4)	G_m	6.67E+04	G4/(2*(1+G8))	
12									
13						G12	1.91E+05	1/((D7/G10+D8/G11))	
14									
15						V12	2.51E-01	D7*G7+D8*G8	
16									

Figure 4-9 Automated SMP analysis using EXCEL

By substituting the values for E_f, E_m, ν_m, we can determine the G_f and G_m values

$G_f=E_f/2[(1+\nu_f)]= 4.17$Msi , $G_m=E_m/[2(1+\nu_m)]=0.06$Msi.

By substituting the values for G_f and Gm, we can determine G_{12} :

$1/G_{12}=V_f/G_f+V_m/Gm$; G12=0.19 Msi

By using these values, we can analyze the specimen using an ASCA program.

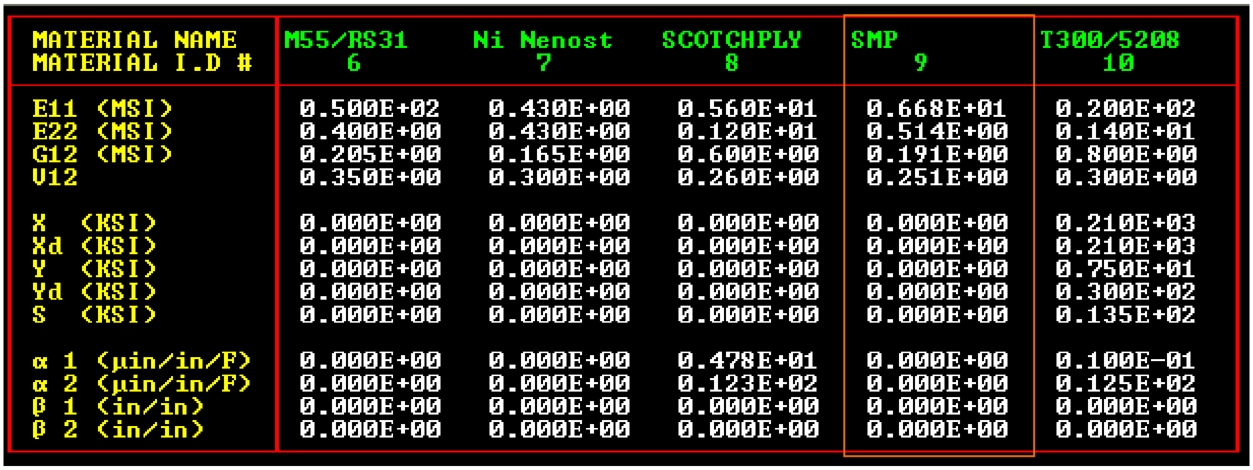
4.2.2.2 Automated system for composite analysis (ASCA) program

ASCA has four modules. We have used two modules namely, Composite Laminate Analysis Program (CLAP) and Free Edge Stress Analysis Program (FESAP). The details are given in reference [17].

a. Composite Laminate Analysis Program (CLAP) analysis

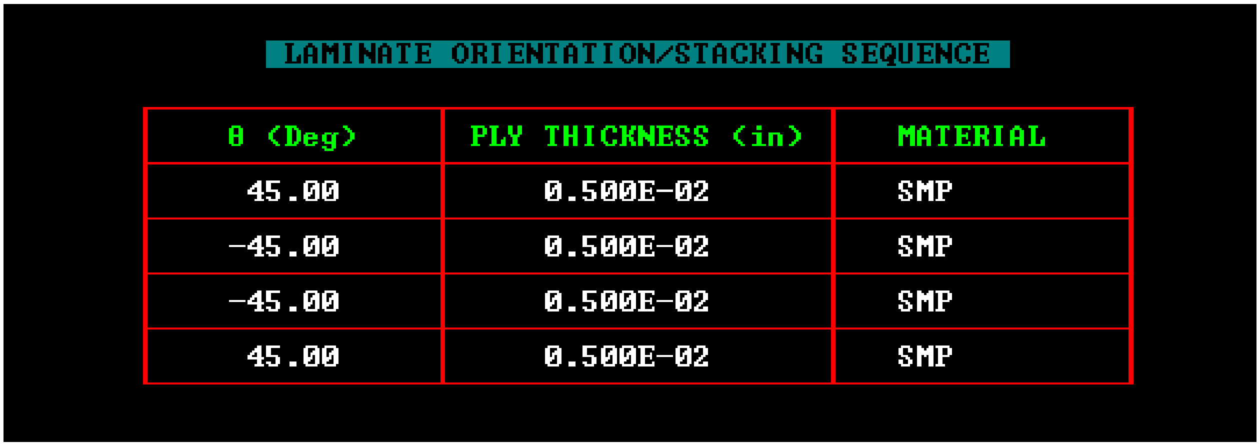
CLAP is an interactive program which conducts point stress and failure analyses of general laminates. CLAP can determine the overall modulus and compliance matrices of the laminate along with its effective modules, poisson's ratio and hydrothermal properties [17].

Figure 4-10 shows the lamina data used in ASCA for a representative SMP specimen composite (±45)s laminate.



MATERIAL NAME MATERIAL I.D #	M55/RS31 6	Ni Nenost 7	SCOTCHPLY 8	SMP 9	T300/5208 10
E11 (MSI)	0.500E+02	0.430E+00	0.560E+01	0.668E+01	0.200E+02
E22 (MSI)	0.400E+00	0.430E+00	0.120E+01	0.514E+00	0.140E+01
G12 (MSI)	0.205E+00	0.165E+00	0.600E+00	0.191E+00	0.800E+00
V12	0.350E+00	0.300E+00	0.260E+00	0.251E+00	0.300E+00
X (KSI)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.210E+03
Xd (KSI)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.210E+03
Y (KSI)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.750E+01
Yd (KSI)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.300E+02
S (KSI)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.135E+02
α 1 (μin/in/F)	0.000E+00	0.000E+00	0.478E+01	0.000E+00	0.100E-01
α 2 (μin/in/F)	0.000E+00	0.000E+00	0.123E+02	0.000E+00	0.125E+02
β 1 (in/in)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
β 2 (in/in)	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Figure 4-10 Specimen property

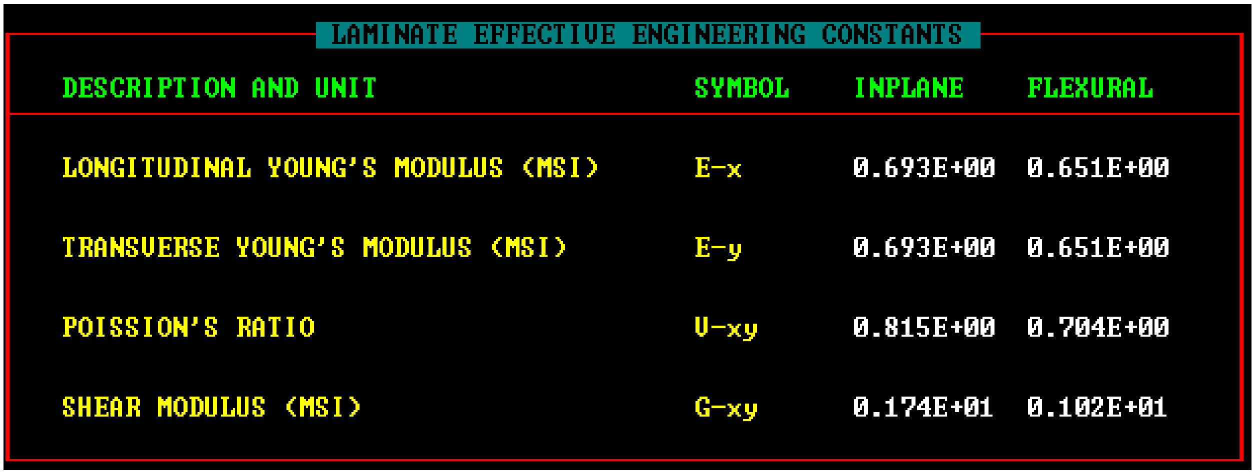


LAMINATE ORIENTATION/STACKING SEQUENCE

θ (Deg)	PLY THICKNESS (in)	MATERIAL
45.00	0.500E-02	SMP
-45.00	0.500E-02	SMP
-45.00	0.500E-02	SMP
45.00	0.500E-02	SMP

Figure 4-11 Specimen orientation and stacking sequence

Figure 4-11 shows the stacking sequence of a representative SMP composite (±45)s laminate. Based on the ply properties through micromechanics analysis and CLAP program, the effective engineering constants for the SMP specimen sample are shown in Figure 4-12.



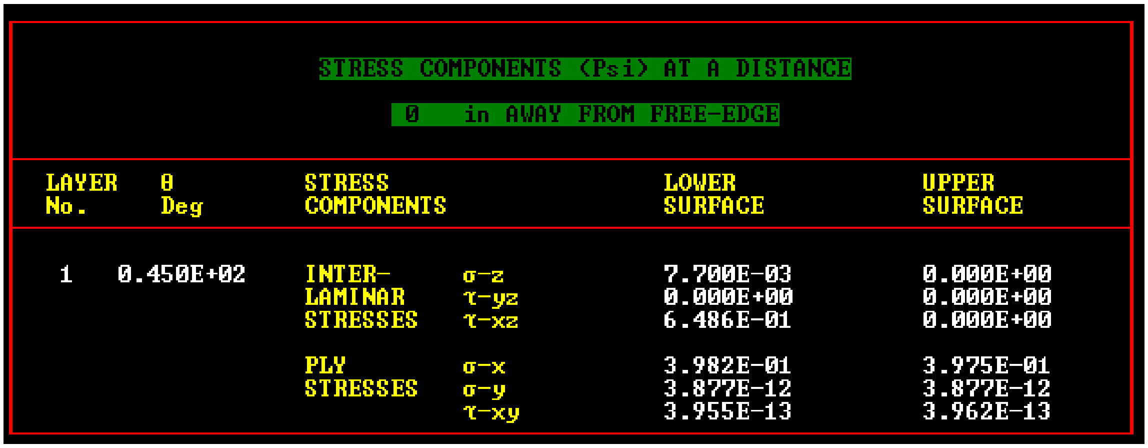
```
                    LAMINATE EFFECTIVE ENGINEERING CONSTANTS

  DESCRIPTION AND UNIT                      SYMBOL    INPLANE     FLEXURAL

  LONGITUDINAL YOUNG'S MODULUS (MSI)        E-x       0.693E+00   0.651E+00

  TRANSVERSE YOUNG'S MODULUS (MSI)          E-y       0.693E+00   0.651E+00

  POISSION'S RATIO                          V-xy      0.815E+00   0.704E+00

  SHEAR MODULUS (MSI)                       G-xy      0.174E+01   0.102E+01
```

Figure 4-12 Laminate effective engineering constants

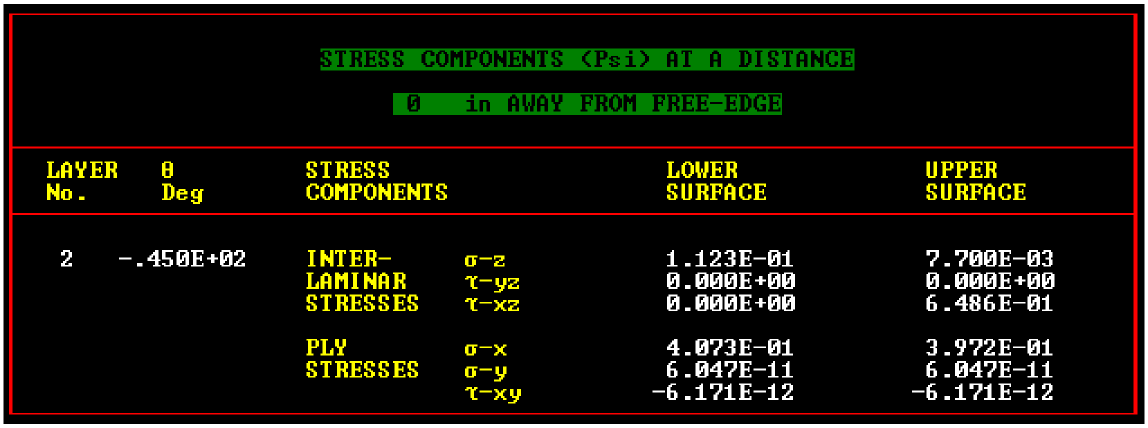
b. Free Edge Stress Analysis (FESAP)

FESAP is an interactive program that does free edge stress analysis of symmetric composite laminates. This program, also written in FORTRAN and basic, has various libraries of material properties, it determines the ply stress, and interlaminar stress [17]. We have executed FESAP in the ASCA program to analyze the SMP specimen composite (±45)s laminate.

Stress components at different locations (0, 0.01, 0.02, 0.03 inch) distance from free edge were computed for applied mechanical axial stress (σ_{-x}=0.5psi). The outputs are given in the following figures 4-13, 14, 15.16

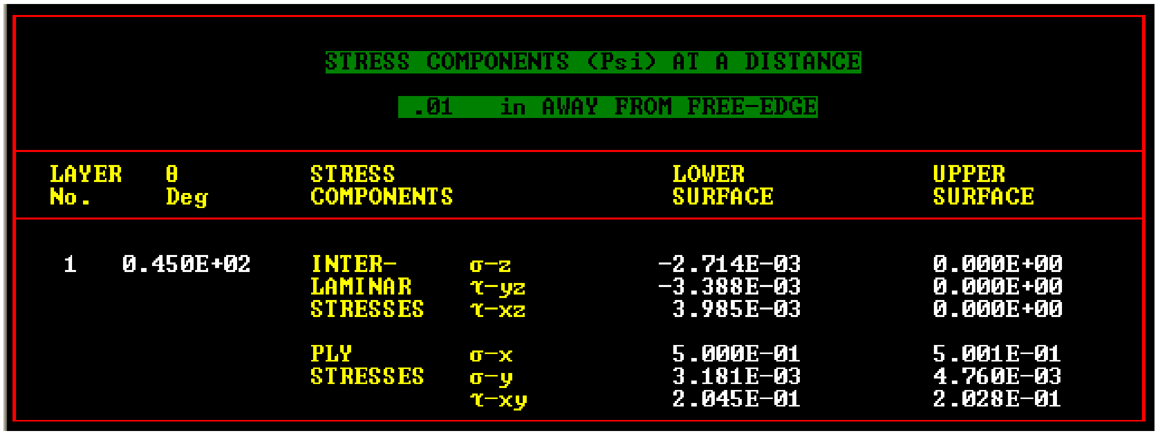


```
                    STRESS  COMPONENTS  (Psi)  AT  A  DISTANCE

                         0    in  AWAY  FROM  FREE-EDGE

LAYER    θ         STRESS                        LOWER          UPPER
No.      Deg       COMPONENTS                    SURFACE        SURFACE

 1    0.450E+02    INTER-      σ-z               7.700E-03      0.000E+00
                   LAMINAR     τ-yz              0.000E+00      0.000E+00
                   STRESSES    τ-xz              6.486E-01      0.000E+00

                   PLY         σ-x               3.982E-01      3.975E-01
                   STRESSES    σ-y               3.877E-12      3.877E-12
                               τ-xy              3.955E-13      3.962E-13
```

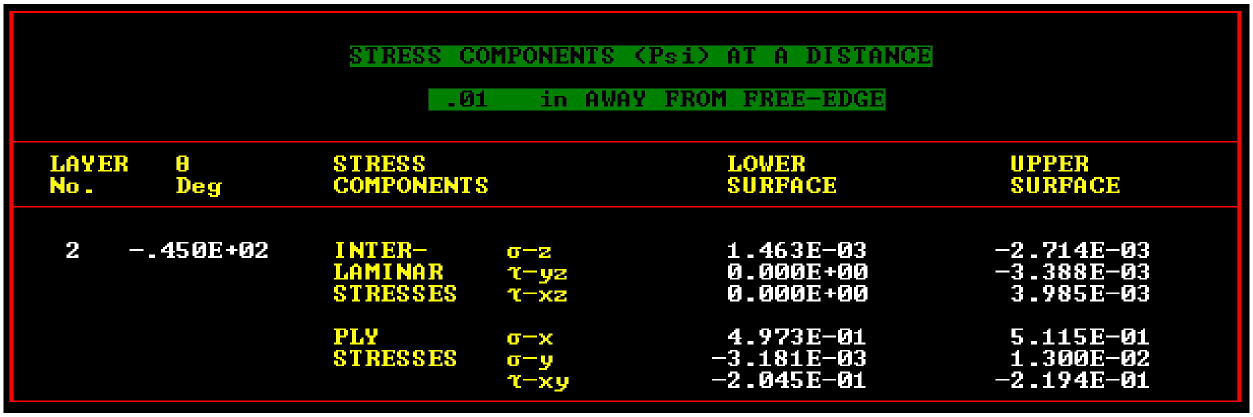


```
                    STRESS  COMPONENTS  (Psi)  AT  A  DISTANCE

                         0    in  AWAY  FROM  FREE-EDGE

LAYER    θ         STRESS                        LOWER          UPPER
No.      Deg       COMPONENTS                    SURFACE        SURFACE

 2    -.450E+02    INTER-      σ-z               1.123E-01      7.700E-03
                   LAMINAR     τ-yz              0.000E+00      0.000E+00
                   STRESSES    τ-xz              0.000E+00      6.486E-01

                   PLY         σ-x               4.073E-01      3.972E-01
                   STRESSES    σ-y               6.047E-11      6.047E-11
                               τ-xy             -6.171E-12     -6.171E-12
```

Figure 4-13 Stress components from free edge

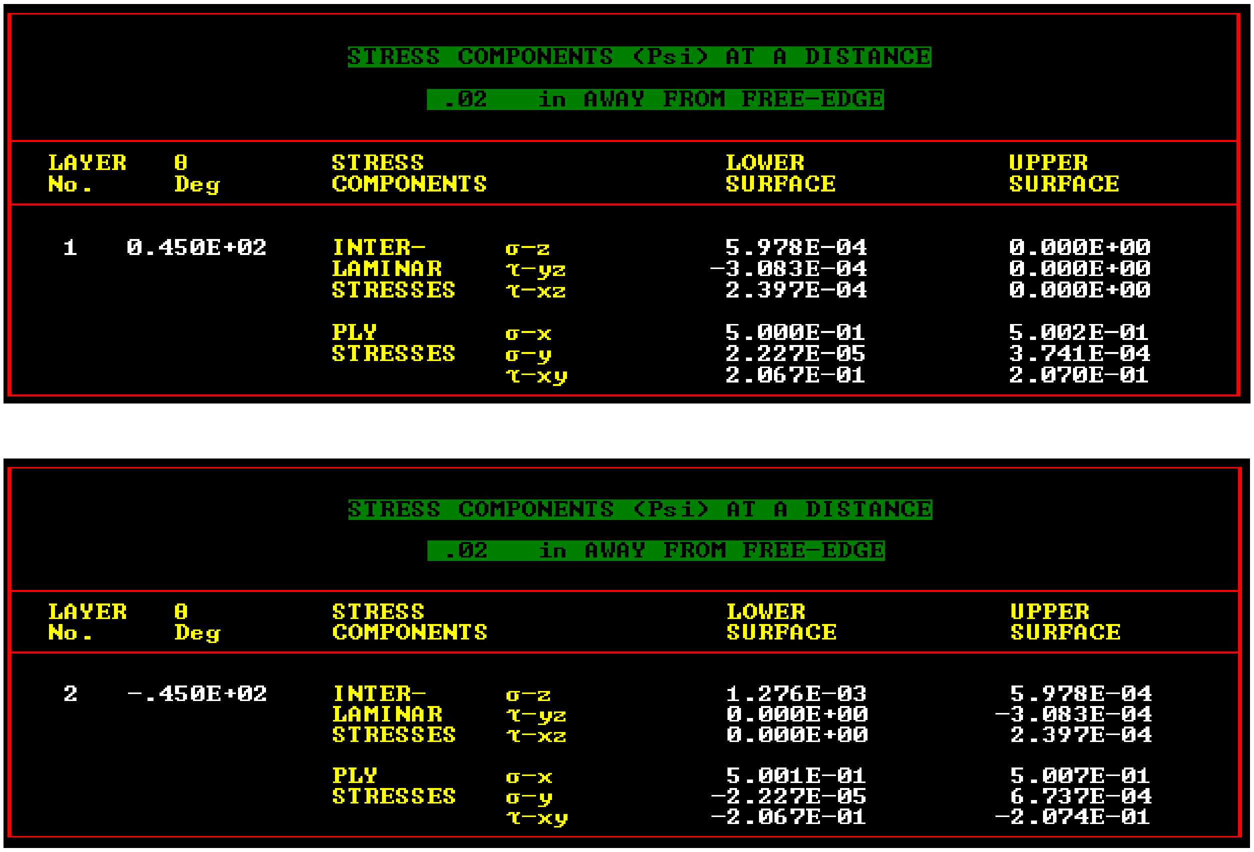


```
                    STRESS  COMPONENTS  (Psi)  AT  A  DISTANCE

                         .01    in  AWAY  FROM  FREE-EDGE

LAYER    θ         STRESS                        LOWER          UPPER
No.      Deg       COMPONENTS                    SURFACE        SURFACE

 1    0.450E+02    INTER-      σ-z              -2.714E-03      0.000E+00
                   LAMINAR     τ-yz             -3.388E-03      0.000E+00
                   STRESSES    τ-xz              3.985E-03      0.000E+00

                   PLY         σ-x               5.000E-01      5.001E-01
                   STRESSES    σ-y               3.181E-03      4.760E-03
                               τ-xy              2.045E-01      2.028E-01
```



```
STRESS COMPONENTS (Psi) AT A DISTANCE
.01    in AWAY FROM FREE-EDGE

LAYER    θ          STRESS                     LOWER             UPPER
No.      Deg        COMPONENTS                 SURFACE           SURFACE

 2     -.450E+02    INTER-       σ-z           1.463E-03        -2.714E-03
                    LAMINAR      τ-yz          0.000E+00        -3.388E-03
                    STRESSES     τ-xz          0.000E+00         3.985E-03

                    PLY          σ-x           4.973E-01         5.115E-01
                    STRESSES     σ-y          -3.181E-03         1.300E-02
                                 τ-xy         -2.045E-01        -2.194E-01
```

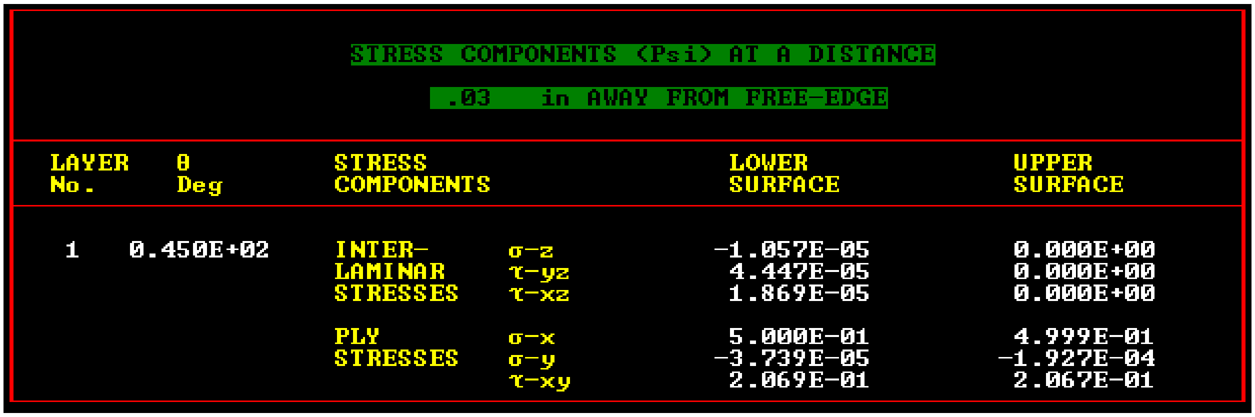
Figure 4-14 Stress components at 0.01 inch



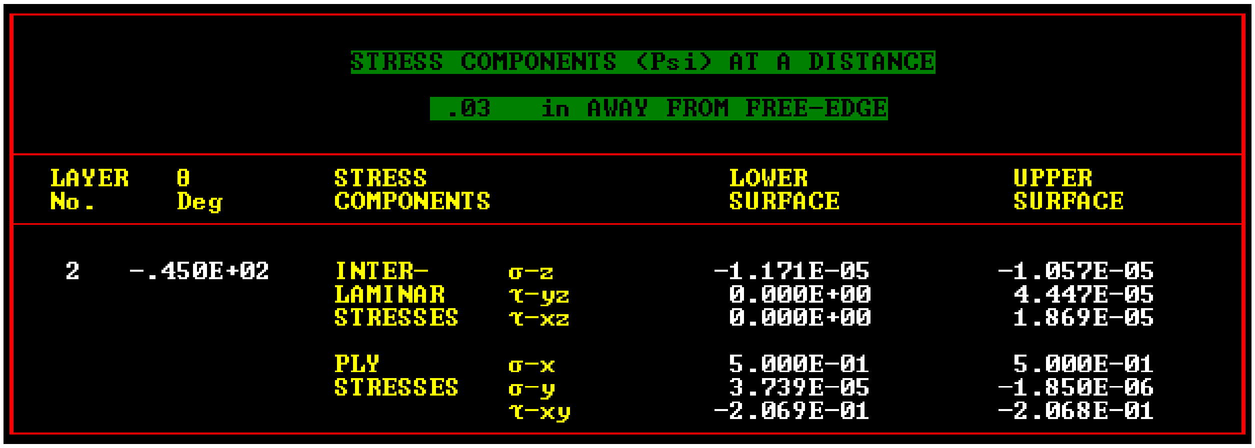
```
STRESS COMPONENTS (Psi) AT A DISTANCE
.02    in AWAY FROM FREE-EDGE

LAYER    θ          STRESS                     LOWER             UPPER
No.      Deg        COMPONENTS                 SURFACE           SURFACE

 1     0.450E+02    INTER-       σ-z           5.978E-04         0.000E+00
                    LAMINAR      τ-yz         -3.083E-04         0.000E+00
                    STRESSES     τ-xz          2.397E-04         0.000E+00

                    PLY          σ-x           5.000E-01         5.002E-01
                    STRESSES     σ-y           2.227E-05         3.741E-04
                                 τ-xy          2.067E-01         2.070E-01
```

```
STRESS COMPONENTS (Psi) AT A DISTANCE
.02    in AWAY FROM FREE-EDGE

LAYER    θ          STRESS                     LOWER             UPPER
No.      Deg        COMPONENTS                 SURFACE           SURFACE

 2     -.450E+02    INTER-       σ-z           1.276E-03         5.978E-04
                    LAMINAR      τ-yz          0.000E+00        -3.083E-04
                    STRESSES     τ-xz          0.000E+00         2.397E-04

                    PLY          σ-x           5.001E-01         5.007E-01
                    STRESSES     σ-y          -2.227E-05         6.737E-04
                                 τ-xy         -2.067E-01        -2.074E-01
```

Figure 4-15 Stress components at 0.02 inch



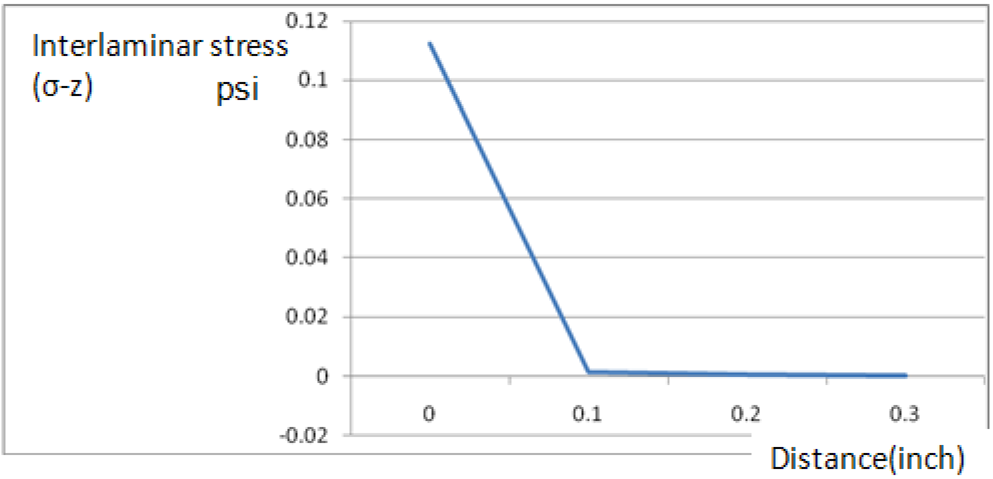
```
            STRESS  COMPONENTS  (Psi)  AT  A  DISTANCE
                 .03    in  AWAY  FROM  FREE-EDGE

LAYER    θ          STRESS                      LOWER            UPPER
No.      Deg        COMPONENTS                  SURFACE          SURFACE

  1   0.450E+02     INTER-        σ-z          -1.057E-05        0.000E+00
                    LAMINAR       τ-yz          4.447E-05        0.000E+00
                    STRESSES      τ-xz          1.869E-05        0.000E+00

                    PLY           σ-x           5.000E-01        4.999E-01
                    STRESSES      σ-y          -3.739E-05       -1.927E-04
                                  τ-xy          2.069E-01        2.067E-01
```



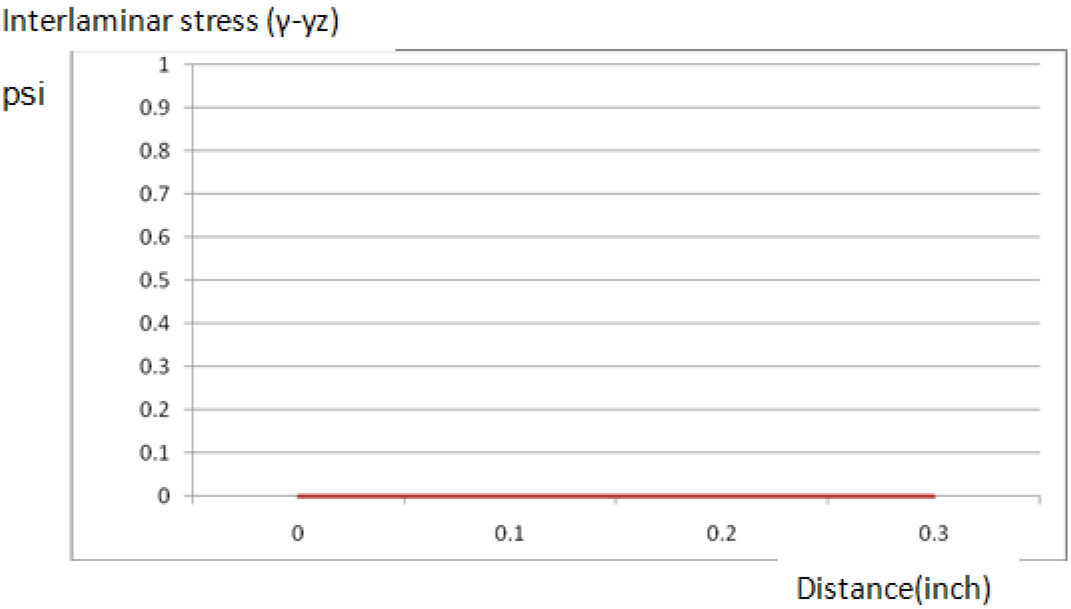
```
            STRESS  COMPONENTS  (Psi)  AT  A  DISTANCE
                 .03    in  AWAY  FROM  FREE-EDGE

LAYER    θ          STRESS                      LOWER            UPPER
No.      Deg        COMPONENTS                  SURFACE          SURFACE

  2   -.450E+02     INTER-        σ-z          -1.171E-05       -1.057E-05
                    LAMINAR       τ-yz          0.000E+00        4.447E-05
                    STRESSES      τ-xz          0.000E+00        1.869E-05

                    PLY           σ-x           5.000E-01        5.000E-01
                    STRESSES      σ-y           3.739E-05       -1.850E-06
                                  τ-xy         -2.069E-01       -2.068E-01
```

Figure 4-16 Stress components at 0.03 inch

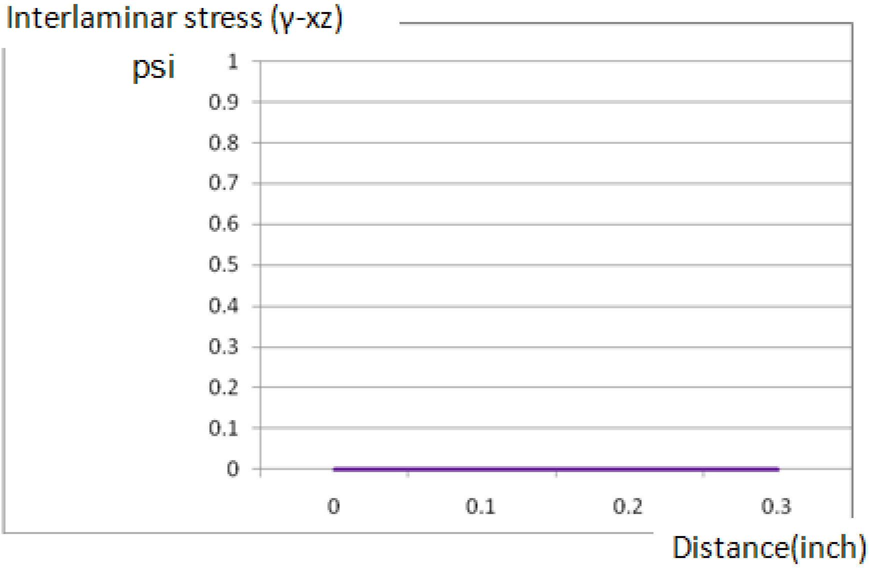
Graph 4-1,2,3, given below are based on FESAP analysis against layer No.2 They show how the transverse stress and shear stresses vary with respect to distance.



Graph 4-1 Interlaminar stress (σ-z)



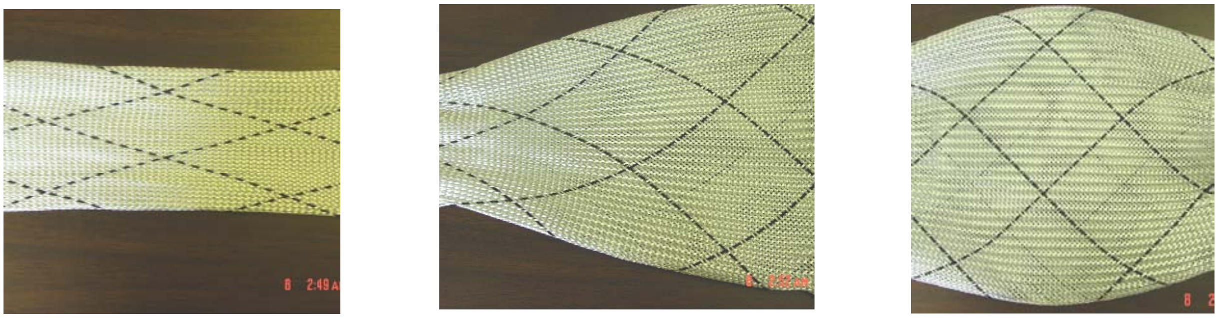
Graph 4-2 Interlaminar stress (γ-yz)



Graph 4-3 Interlaminar stress (γ-xz)

4.2.2.3 Analysis using braids:

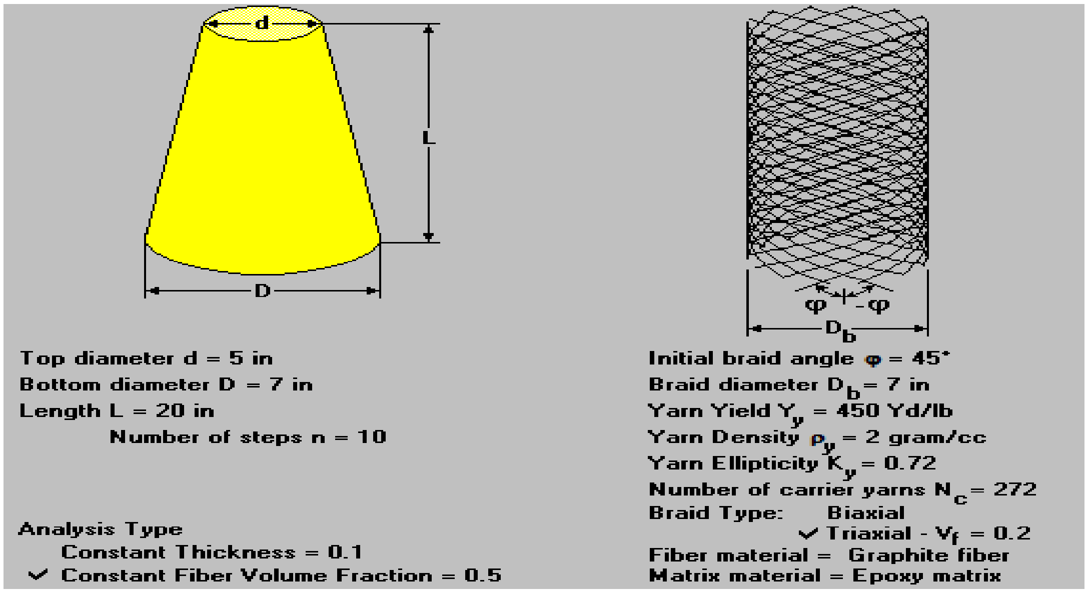
Braids can be used as a preform for making SMP composite laminates (Figure 4-17)



a) Undeformed shape b) Deformed shape 1 c) Deformed shape 2

Figure 4-17 Braided preform in undeformed and deformed shapes

As shown in Figure 4-17, preform fiber orientation can be represented by braid shown in software cover sheet given in Figure 4-17a. The change of properties with the change of fiber angle at different location can be shown similar to a deformed shape as a conical shape of this figure. With the help of the braids program, which is developed by Adtech Inc for analyzing braided composites, we easily show the variability of properties as we change the fiber direction along the braided cone. The specimen deformed by tensile load in the experiment could be assumed to be a cone in this program. To show the variability in stiffness properties ,Young's modulii ,calculated using braids are given in Figure 4-18. Additional results using the braids program are presented in Appendix B.

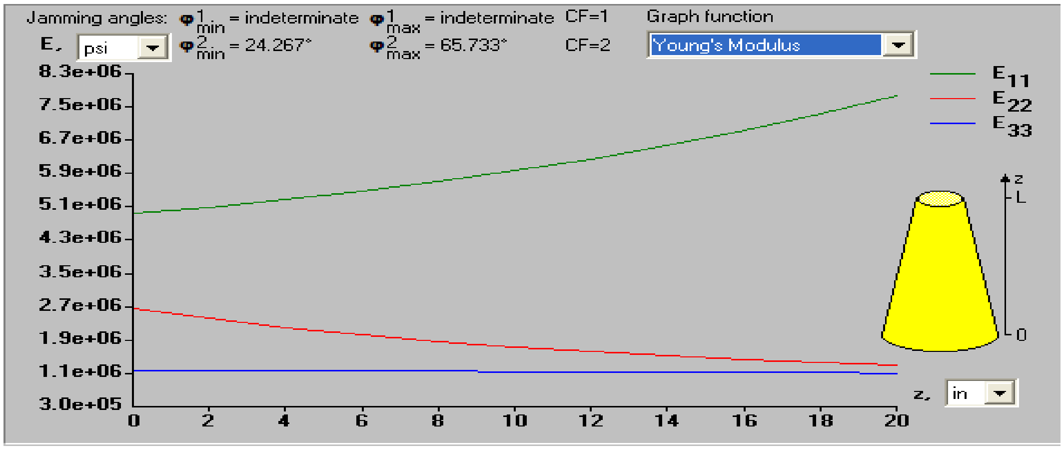


Top diameter d = 5 in
Bottom diameter D = 7 in
Length L = 20 in
Number of steps n = 10

Analysis Type
Constant Thickness = 0.1
✓ Constant Fiber Volume Fraction = 0.5

Initial braid angle φ = 45°
Braid diameter D_b = 7 in
Yarn Yield Y_y = 450 Yd/lb
Yarn Density ρ_y = 2 gram/cc
Yarn Ellipticity K_y = 0.72
Number of carrier yarns N_c = 272
Braid Type: Biaxial
✓ Triaxial - V_f = 0.2
Fiber material = Graphite fiber
Matrix material = Epoxy matrix

Figure 4-17a General information about the SMP composite using the Braids program



Jamming angles: φ^{1}_{min} = indeterminate φ^{1}_{max} = indeterminate CF=1

E, psi φ^{2}_{min} = 24.267° φ^{2}_{max} = 65.733° CF=2

Graph function: Young's Modulus

z, in

Figure 4-18 Young modulus of specimen

4.3 Thermo-Mechanical Fatigue Testing

4.3.1 Purpose of Thermo-Mechanical Fatigue Testing

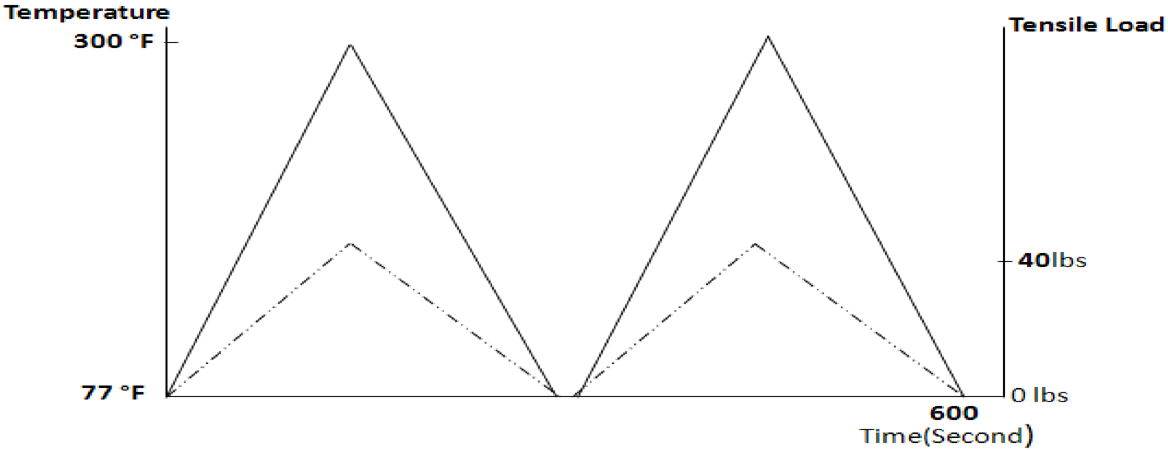
SMP are expanding its usefulness in a wide variety of applications, however the stress strain response and failure mechanisms of SMP are still not well understood because it is a relatively new structural material. The fact that SMP are being used in a variety of temperatures is another challenge for understanding the properties of SMP. In order to get the properties of SMP in various temperatures, new test methods are essential like a thermo-mechanical fatigue test. The idealized thermo mechanical fatigue test, with loading patterns is usually used in a material characterization test. The mechanical loading and thermal loading are applied to the test specimens either in-phase or out of phase [18]. By experimenting with this TMF test, we can identify how TMF would affect SMP. This test will also show how morphing wing based on SMP should be maintained and fixed as temperature changes.

4.3.2. TMF Testing Procedure

a. Preparing SMP composite specimen made with resin and fiber.

b. A hole in the center of the specimen monitors how thermo-mechanical fatigue will affect the hole in the specimen

c. The author applied thermal the fatigue load shown in Graph 4-4 , below.



Graph 4-4 Graph of thermo mechanical load

d. The author used C-SCAN against the specimen in order to identify differences between the original and thermo-mechanical loaded specimen (Figure 4-19, 20)

e. After C-SCAN, X-ray inspection was executed in order to monitor the difference among specimens (Figure 4-21).

Throughout the C-SCAN we conducted nondestructive inspection for composites in which short pulse of ultrasonic energy is incident on a sample. The thermo-mechanical loaded specimen shows that it has more gray colored part. It means that this part has the possibility of such as the delaminating, transformed fiber, and any foreign inclusions present. X-ray inspection (Figure 4-21) shows that fracture happened in the side hole of thermo mechanical loaded specimen compared to original specimen because repeated thermo mechanical load acted on the hole.

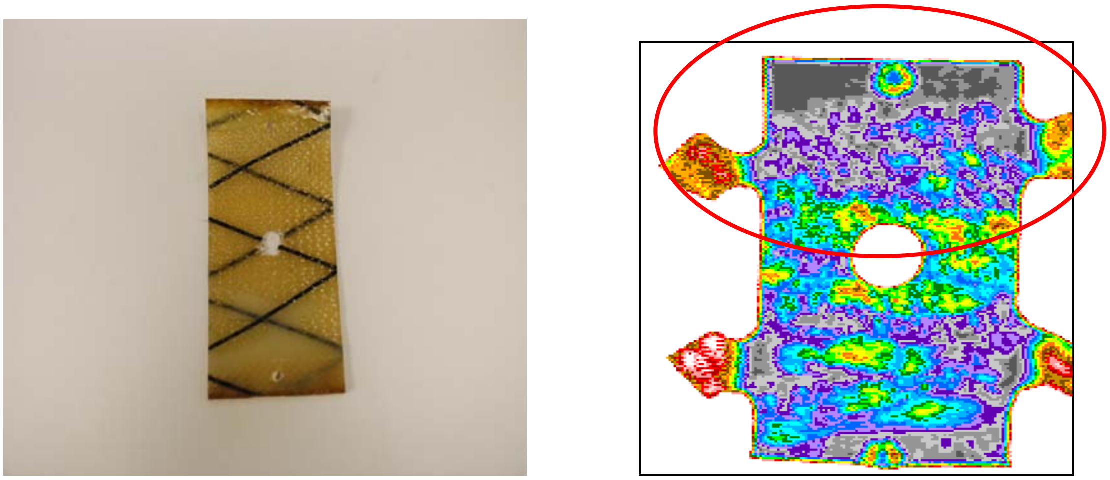


Figure 4-19 Original specimen

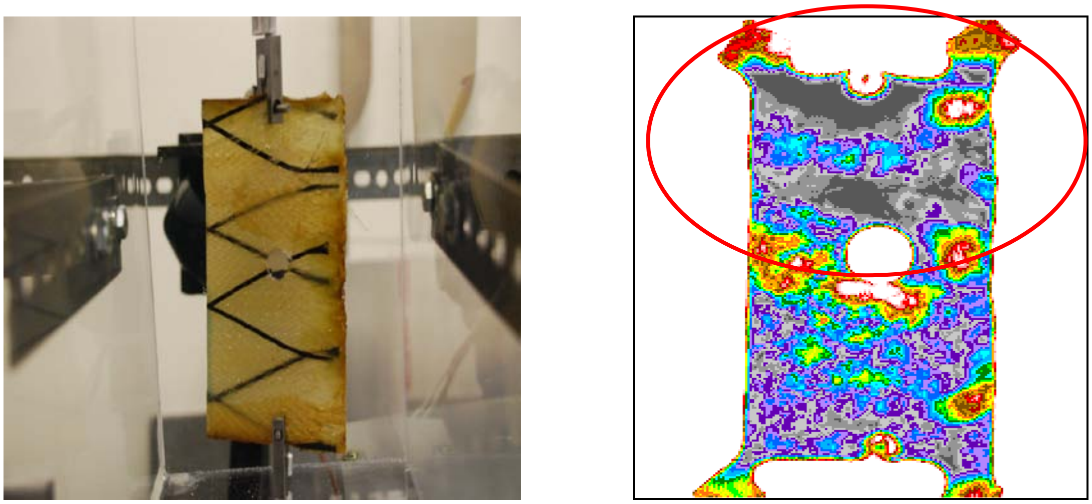


Figure 4-20 Thermo-mechanical loaded specimen

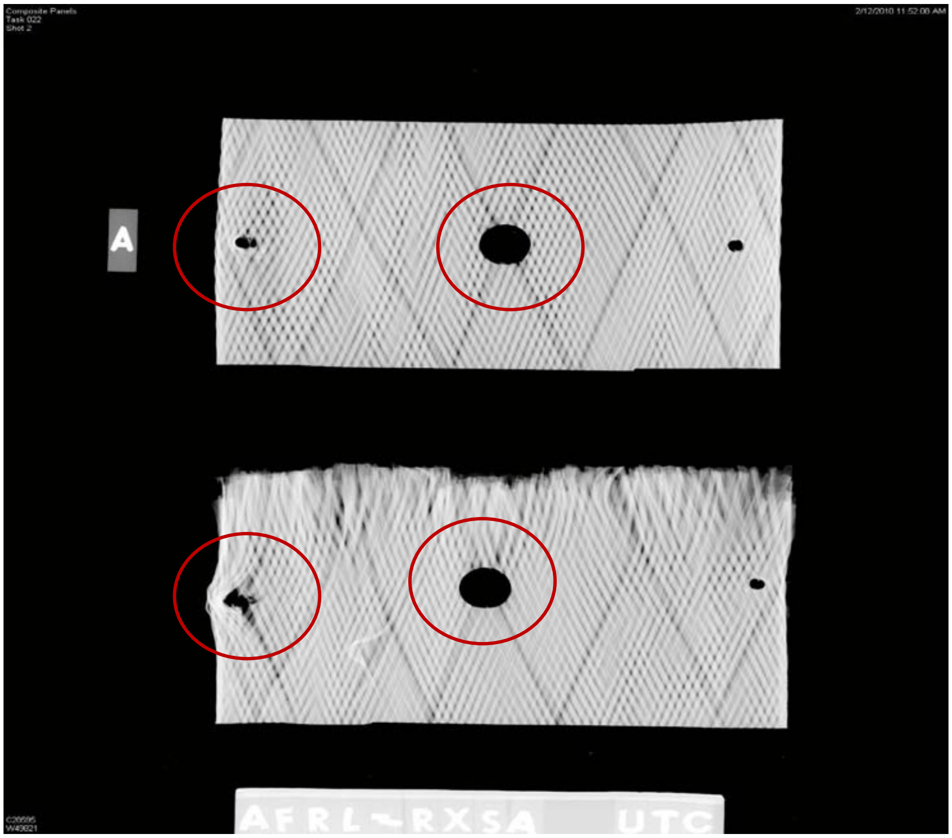


Figure 4-21 X-ray inspection of specimens

4.4 Fracture of Specimens

For testing the SMP specimens, given in table 4-1, two holes were drilled at two corners. A pin was used at each hole to apply load. In most of the case, we observed the shape could change after removing the load and temperature. In some cases, we observed that shape does not recover to its original shape. It indicates that the development of plastic deformation (Figures 4-22, 23) has taken place in loaded specimen.

Table 4-1 Table of specimen

Vf	Specimens	Tested specimens	Cycles
0.59	2	1	5
0.65	2	1	10
0.66	2	1	15
0.67	2	1	50

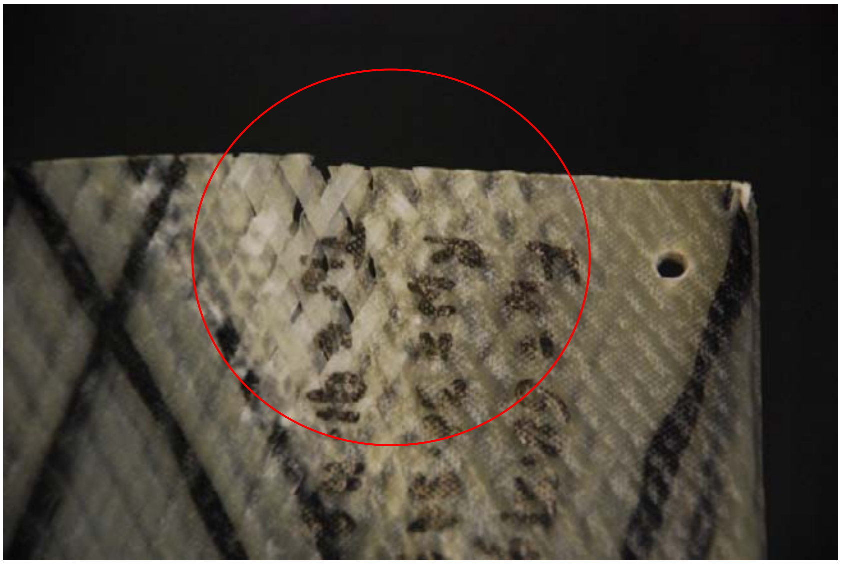


Figure 4-22 Fracture of Specimen

Figure 4-23 Fracture of specimen

4.5 Ideas for development of morphing wing

This area of research is in initial stage of development. Lot more research work needs to be done before SMP materials can be used in morphing wing aircraft. Some of the relevant areas are:

1. Effective properties with different volume fractures of fiber, matrix, location development and fiber angles
2. Heat transfer in SMP composites
3. Thermo mechanical fatigue and relevant mechanisms

The SMP analyzed does not seem to have adequate shape retaining capability for use in morphing wing aircraft. This material may be useful for application requiring shape retaining capability of up to 50 cycles such as munitions applications.

4.5.1 SMP composite having heat tube

According to the SMP material deformation test, the transforming rate of a morphing wing is up to the heat source and the actuator. How soon the wing is heated and how soon the actuator transmit load to the wing material determine the transforming rate of the morphing wing. To get the quicker and more reliable heating and actuating method, many scientists are still studying this issue. Researchers have explored the possibility of a SMP composite with a heat source tube. The devised SMP composite (Figure 4-24) has its own heat tube inside of the composite. The heat can be transferred from heat tube to the fiber and resin in the morphing wing material. If the morphing wing can be made with this composite, the aircraft would need less actuator and heat. This will make the wing system and its components simple. Simplified heating and transforming the wing will increase the response rate of the morphing wing and the agility of the system.

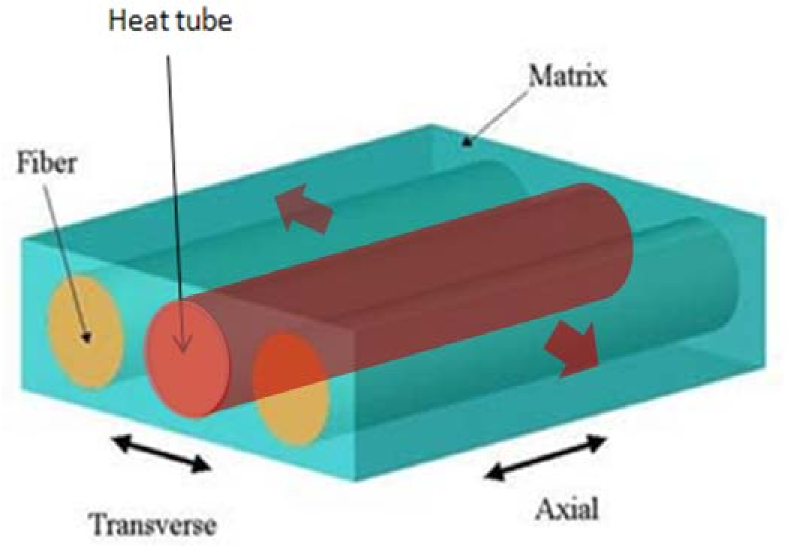


Figure 4-24 SMP composite having a heat tube

4.5.2 Heat transferring method

Morphing wing needs heat to activate the wing skin. Placing main heat source in the center of wing section will save energy and increase transforming speed because this heat source position offers the shortest distance from heat source to wing tip (Figure 4-25). In this method, heat generated in the center of the wing will be transferred to the wing section side. This heat transferring method also will be implemented through heat tube inside SMP composite.

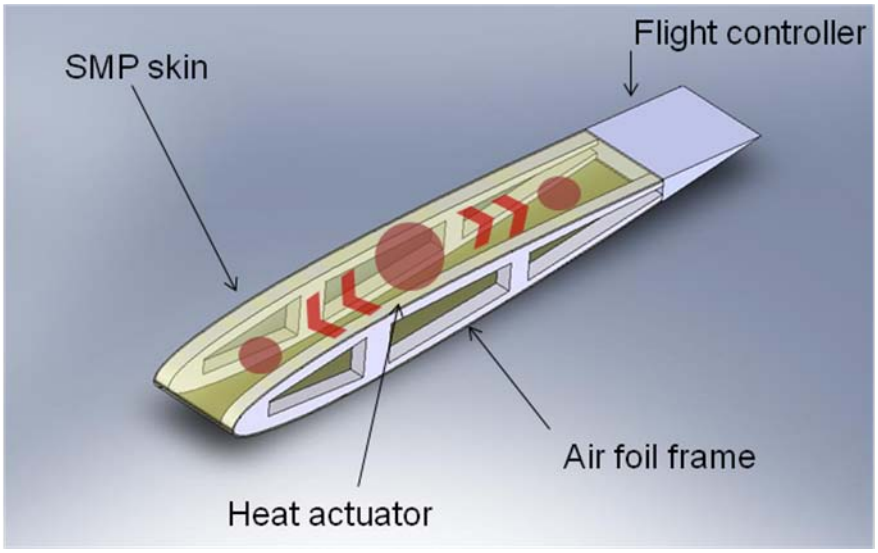


Figure 4-25 Heat transferring method in the wing section

V. Conclusions and Recommendations

Finally the author can make several conclusions about the research conducted for this study. Each conclusion can be a recommendation for near or long term for other researches. The author wants the accomplishment and results of this research to further develop an integrated system that provide directions for manufacturing, maintaining, and operating morphing wing aircraft, and advancing the MWS concept to implementation.

5.1 Morphing Wing Aircraft – Potential Air Force's Future Alternative

Current warfare is changing rapidly. The U.S Air Force needs new aircraft to provide longer flight time, less fuel consumption, and better aerodynamics in order to perform Air Force missions successfully. Currently morphing wings are developing all over the world; some of them are deployed like on UAV (Unmanned Aerial Vehicle). Throughout this thesis, we tried to make sure that morphing wing aircraft based on SMP wing skin is implementable, and to estimate how they will be operated in the Air Force. Thus, US Air Force should be more concerned about developing new alternatives for future wars.

5.2 Properties of SMP

This thesis provides mechanical characterization for SMP composites under consideration. The mechanical properties found in the research can be used in various fields in case of SMP application. This thesis has done several experiments using SMP in order to identify its unique characterization. The author showed how SMP composite has formed its various shape when axial load was applied and heated. This thesis also explored micromechanics analysis in order to analyze the material on the level of the individual phases with the help of the ASCA program. Finally this thesis showed how thermo mechanical fatigue would affect morphing material throughout the thermo mechanical test. From the results and data of the experiment, the author and advisor observed several issues with morphing material which are essential for successful implementation

- Morphing material skin needs additional sub systems to activate morphing material. It needs a heat source and actuating equipment. This equipment is essential for activating morphing material.
- Morphing material skin takes some time to form its shape, because it take some time to softening material and actuate for the desired shape.
- Morphing material skin should be monitored regularly because it could produce thermo mechanical fatigue while it is heated and cooled.
- Managing morphing material skin means monitoring a lot of data and values at the same time, because each morphing wing skin need to be transformed as each actuator directs various controls and management are needed on each morphing wing skin airfoil.

Throughout the property test, the author and advisor concluded that US Air Force should develop different systems from conventional aircraft wings in order to deploy morphing wing because morphing material has very unique properties compared to other fixed material. The SMP composite system tested has limitations with regard to retaining its shape changing capability beyond 50 cycles. Thus this material is not suitable for morphing wing aircraft.

5.3 Directions for Future Works

The author and advisor conducted research with emerging morphing material. There is still a lot more to be studied in various properties of morphing material. Some of the areas of focus for future work follow:

- Study the difference between SMP and SMP Alloy when applied to morphing wing skin
- Perform experiments to study the repeatability of SMP memory effect, then, compare them to other morphing material
- Improve the loading mechanism by inventing better ways to affect shape and dimension change in specimens with greater repeatability and reliability
- Study the effect of different types and sizes of braids on the strength and shape of composites
- Develop a heat transferring system in the wing skin with less heat loss

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Appendix A

System engineering application for morphing aircraft

A.1 Morphing Wing Operating System (MWOS) SE Design Process

The MWOS design process is begun with the problem statement. The author tried to include all the possible aspects of problem. The problem statement converged to a system engineering application for practicality, cost-effective morphing wing system, and improving the safety of flight parameters. The problem statement detail follows:

- Practicality, realization

Practicality in MWOS means operating the morphing wing should be practical for various missions and compatible with other US Air Force systems. MWOS is a developing system, so it is hard to specifically identify entire behaviors of MWOS. Thus the author tried to make a blue print of MWOS focused on the main function of the system.

- Cost effective

Determining cost related issues was difficult for this thesis because a morphing wing system is a developing system, so it is hard to estimate a budget to pay for components of wing and maintenance cost in operation. The MWOS life- cycle cost includes cost from cradle to grave following six steps (Table A-1).

Table A-1 Description of various costs

Phase	Step	Description
1	Cost of design	The expense for designing MWOS and supporting facilities
2	Cost of acquisition	The expense for purchasing morphing wings and facilities for operating it
3	Cost to install the MWOS	The expense for operating the MWOS after purchase step. This cost includes expense for software and manpower to operate morphing wings
4	Cost for operational adoption	All the expense for making morphing wing aircraft perform all the missions successfully required from that installed state.
5	Cost to maintain MWOS	The expense for maintaining morphing wings regularly according to maintenance plans
6	Cost of disposal	The cost for disposing the morphing wing according to its life cycle

A.2 MWOS Life Cycle Phases

System engineering considers the life cycle of a system important because the system is not a present condition but is a developing condition for the future. Life cycle means a series of stages through which a system passes from its inception to its retirement. The start of any system happens with the emergence of a need for new capabilities. Then, all the needs from various stakeholders are considered to design the system. This step is the beginning of the development period where the system engineers and the stakeholders work together. Following the completion of the design phase is the integration phase, the production phase, the operational phase, and finally the retirement, disposal or replacement phase [8]. These five phases involve five kinds of activities. First is the conceptual phase, where the requirement, architecture and models are developed. Second is the integration phase where various concepts and models are integrated. Third phase is the production phase where designed system is produced. Fourth phase is the operational phase where system is fully deployed. Fifth period includes all the disposal and retirement of system. The life cycle phases of system are shown below (Figure A-1). All the life cycle phases have their own value. Although the life cycle phases are shown as distinct and separate items in figure A-1, each figure is a continuation of the previous one. This continuation is very important. The author used this representation of life cycle to produce architecture for MWOS.

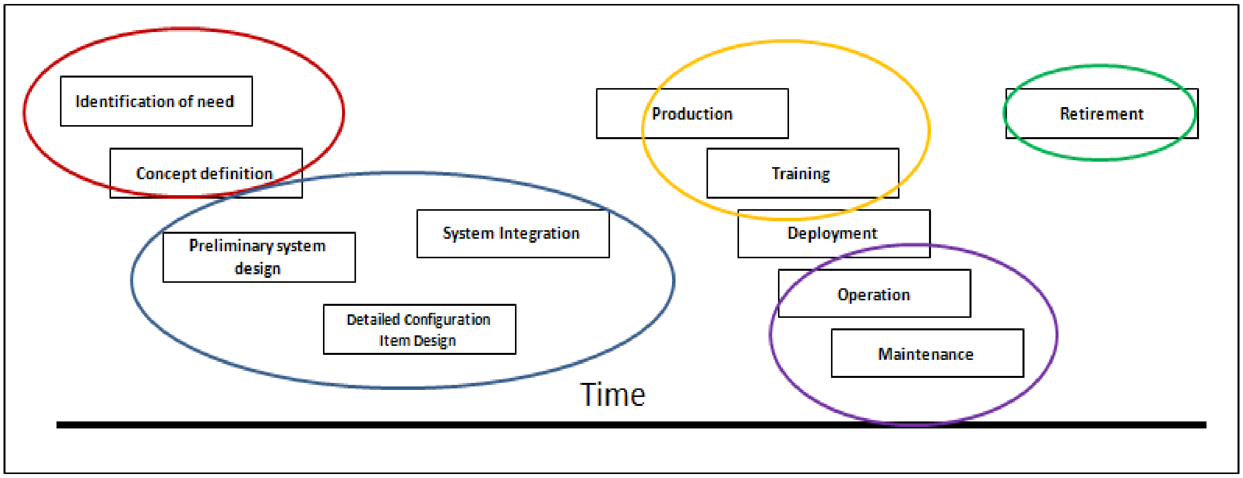


Figure A-1 Life cycle of MWOS

A.3 MWOS Stakeholders

The process which creates a list of MWOS life cycle phase and identifies the stakeholders for each phase is also an important step in system engineering. The author tried to understand and describe the viewpoint and the requirements of each category of stakeholders. This process also helped the author identify each phase which related to each stakeholder and from where system requirements should be derived. According to Buede, the author should answer the critical question “who has the right to have a requirement for the system?” in order to identify stakeholders.

A.3.1 Conceptual/design phase

This phase sets up initial concepts and develops technology development strategies. Stakeholders in various fields initiate the concept of desired system, and other stakeholders provide the realm of the possible given available technology.

A.3.2 Integration/Development phase

For the second phase, development stage, the author identified two major stakeholders. They are Office of the Security of Defense(OSD) , Air force. These stakeholders are mutually related to each other and work together sometimes. The OSD and US Congress is the main bill payer. They restrict the budget to purchase morphing wing aircraft and its system. Because they decide on the initiation and continuance of the project, OSD should consider many aspects of MWOS from other stakeholders.

The OSD might compare the advantage of MWOS to the conventional aircraft. They also evaluate the operational adoptability of morphing wing aircraft to other services such as Army, Navy in order to improve joint operational capability. They might express various opinion based on their aspect. For example, the Army specialist might evaluate the adoptability of Morphing wing aircraft in case it is deployed to the Close Air Support mission. They might analyze the good and bad of morphing wing aircraft in terms of their operational achievement. OSD is controlling the finance. They have to analyze all the cost of MWOS in each phase of system. Then, they should make a plan for controlling the budget throughout the life cycle. Another concern of the OSD stakeholder is acquisition work. The OSD oversees the entire system acquisition plan. They check the entire system acquisition duration and test plan, entire budget etc. They manage all the process during system acquisition.

Another stakeholder in the development phase is the Air Force. Actually the Air Force is the main actor who use and maintain this system. Requirement for implementing this system should be collected from many Air Force staffs who would participate in this system. Air force stakeholder can be divided in to three major parts. First part controls the operational capability. They should analyze operational effectiveness of Morphing wing aircraft when it comes to apply for various air force missions. The second part controls maintenance. They should present the entire requirement in managing maintenance system for morphing wing aircraft. Morphing wing aircraft have different wings consisting of different material compared to conventional aircraft. This unique fact needs more different subsystems in maintenance aircrafts. These differences of the system should be fully considered by the Air Force stakeholder. The Air Force stakeholder controls acquisition. Acquisition officers in the air force deals with the entire acquisition budget and plan. They should consider cost and duration when they acquire the system.

A.3.3 Production/Training phase

This phase deals with producing the system and training users. The system is produced as designed in previous phase. At the same time the training phase happens. Training phase has two kinds of stakeholders. The first is trainer and another is trainees. The trainers also consists of two parts; contractor’s training department and Air force Training Agencies. Contractor Company produces morphing wing aircraft with the manual for maintenance and flight control. The developers and contractor’s training department who produced morphing wing aircraft in the contract company should train the pilot and maintenance agencies who are supposed to take over morphing wing aircraft for the training phase.

A.3.4 Operational phase stakeholders

Deployment is the stage which has the longest time among five phases. Air force is the main stakeholder in this phase. Air force deploys MWOS to attain the operational concept. Air Force stakeholder can be divided into three specific stakeholders. The first stakeholder is operational operators. They actually control and use the morphing wing aircraft in various Air Force missions. The second stakeholder is maintenance operators. They perform maintenance against morphing wing regularly according to the maintenance plan. They also fix abrupt functional failure and report mechanical failures to headquarters and contractor's company. The third stakeholder is logistics teams. They first take over logistics of MWOS from contractor's company. They provide logistics in order to maintain current equipments as planned by system designers. Some of them should plan for the replacement of system. Morphing wing is not permanent wing. It loses its capability as time goes by or by the accident. The logistic stakeholder should provide appropriate substitution for the parts need to be replaced.

A.3.5 Retirement phase stakeholders

In the final phase of the system's life cycle, the main stakeholder is DoD and Air force. Both these stakeholders will need to develop a plan for the retirement of the MWOS system. If the system has still remaining useful advantage, MWOS will be adopted to other system. If the system is useless and need to be discarded, the MWOS will be disposed as planned [1].

A.4 Operational Concepts

Initially operational concepts are abstract; however, concepts can be evolved over time. Some CONOPS describe how a mission is to be carried out. The author tried to identify how CONOPS describes the ways (sequenced actions) we use to employ mean (military capabilities) to accomplish desired end (effects) in MWOS.

A.4.1 Problem

As science develops, potential adversaries become increasingly camouflaged and agile. Traditionally, US military operations have relied on the ability to deploy superior power close to an adversary using time constrained capabilities in the air. To take advantage of such a deployment of forces, potential adversary's targets are getting smaller and harder to detect. Adversaries emphasize camouflage and anti-access action, the required friendly flight time in the target area is increasing. The fundamental resolution of this problem requires a lot of transitions to current systems. One of these transitions is developing morphing wing aircraft and operating them in this mission environment [20].

A.4.2. Objectives

The objective of MWOS is to gain improved mission capability using morphing wing aircraft, which provides advanced aerodynamic performance.

A.4.3 Desired effects

To achieve the desired goal for the US forces, MWOS CONOPS requires the ability to achieve three overarching effects. First the defined capabilities used to execute the MWOS CONOPS will be adapted to the battle space. Second, MWOS will work for improving mission success rate by improved aerodynamic wings. Third, MWOS will establish required sub systems to maintain its own functions.

A.4.4 Capabilities

The capabilities within the CONOPS will be described by creating sets of scenarios for the life cycle phase of the system. The system engineers identify the stakeholders in the conceptual/design phase, system engineer find out the needs from customers and integrate and present them with system engineering tools. Agreement is achieved among the stakeholders on the proposed concept. The next sub phase is integration/development phase. The purpose of this phase is creating a System Engineering Plan (SEP) and define “who, what, when, where, why, and how the applied SE approach” They organize system engineering, design and define detailed roles for their members. System engineers develop CONOPS from the user’s requirements and develop the MWOS system architectures. The system design team develops the configuration item (CI) list and the design for each item. The integration plan and verification-validation requirements are defined. The CI includes the requirements set by the manufactures. The system engineer and developer create a prototype of the system. This prototype will go through validation testing. During the testing the designer validate if CIs and requirements from customer are reflected satisfactorily. The design team reviews unsatisfactory CIs. If the validation is successful, the prototype design of MWOS is approved for production. In the production phase, the manufactures get into a contract with the DoD, AF acquisition stakeholders. They produce required equipments for MWOS system. When production of system is completed, the operational/deployment phase starts in earnest. Deployment plan is arranged between AF stakeholders. The locations of the system installation, equipments required, and schedules are defined. As the first MWOS is installed, the problems are revealed. The designer find a solution to the problem with stakeholders, then make feedback in order to prevent the problems in the following system production. In the operational phase, the MWOS will be operated in the battle place. MWOS will perform various air force missions such as air to air mission like an Interdiction and air to ground such as close air support. As many MWOS are operated, more experience from the system's operation is accumulated; the need for some improvements/modification may arise. The data collected from the MWOS are analyzed and feedback is sent to the manufacturers and the designers. By this repeated process, MWOS will be operating. As the MWOS is approaching to the end of its design life, system designer and operator should evaluate the situation and make a plan for the retirement of the system. They have to cooperate with the stakeholder in the headquarters to make final decision. If they decide to agree retirement plan, system engineer and engineers have to retire MWOS with less pollution.

A.5 MWOS Operational Objectives Hierarchy

The system should be intuitive and easy to operate. To make the system feasible as desired, the development of the weighted objectives hierarchy and performance is helpful. This hierarchy defined cost, and performance goals stakeholders required for an acceptable system design. Using this objectives hierarchy provides great help to originate system requirement. The MWOS operational objectives hierarchy consists of two major parts (Figure A-2). The first part is system operating cost. It includes cost of acquisition, development, installation, operation, and disposal of the MWOS. The author classified the system operating cost with weight. The author set the weight portion based on the estimation. The other part is about the performance. This part includes deformation success rate, speed of deformation, available degree of sweep angle, fix rate, increased flight time. These factors are the essential part to measure performance of morphing wing. The author set the required criteria considering conventional aircraft performance, property of SMP. This work also was classified by the weight portion.

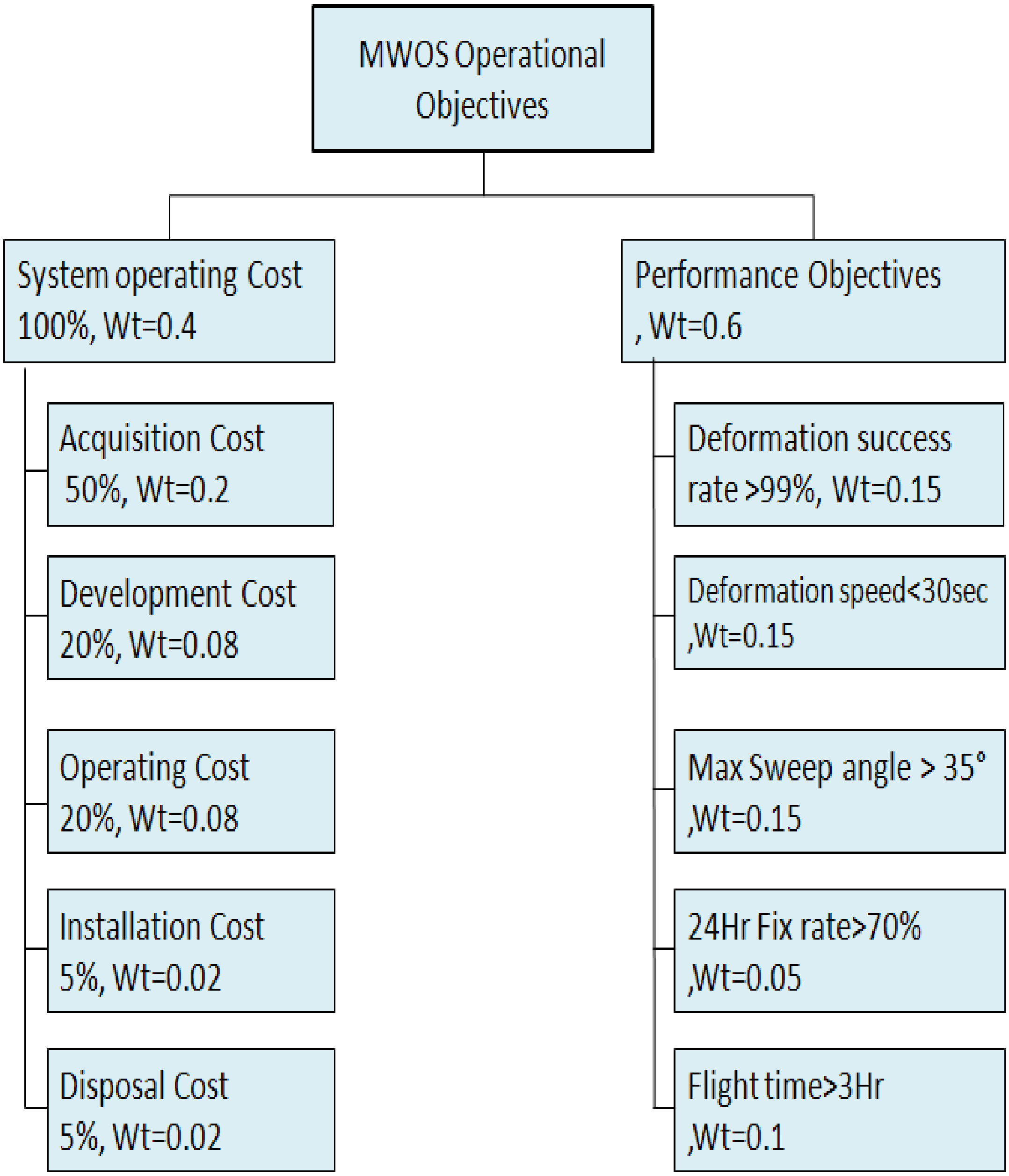


Figure A-2 Operational objective hierarchy

A.6 DoDAF Architectures for MWOS

In chapter 3, the author discussed what system architectures, their importance, are and the methodology used to develop the architecture product. In this section, architecture framework using DoDAF 2.0 is presented along with a brief description on the development process for each view.

A.6.1 All views

The first important architecture product is AV-1 and AV-2, which is a textual definition and description of the problem, and purpose and scope of the architecture products follow. AV-1 basically describes the boundaries of the architecture. AV-2 will be omitted in this thesis.

Identification

Architecture Title: Morphing Wing Operating System (MWOS) Requirement Identification.

Purpose

Problem Description: Morphing wing aircraft can be a good solution for future warfare. However, morphing wing aircraft needs smart material to transform wing shape. These kinds of materials transform their wings a lot during the operation. This unique characteristic results in a necessity for developing new operating systems for maintenance when we make aircraft with these. Users want to safely utilize the morphing wing and apply them for many kinds of missions while minimizing the downtime due to maintenance and optimizing safety of flight: MWOS that provides near-real-time feedback has been identified as the potential solution.

Purpose: to apply the system engineering approach to the process of requirements identification for the development and acquisition of the MWOS.

Scope: This architecture depicts broad MWOS requirements and information exchange.

A.6.2 Operational Architectures

A.6.2.1 OV-1

The first architecture product the author produced is the OV-1. OV-1 is the high level description of the operational concept. MWOS at the center symbolizes developed (Figure A-3). The circle around the MWOS represents system boundaries that will be affected by the development and implementation of MWOS.

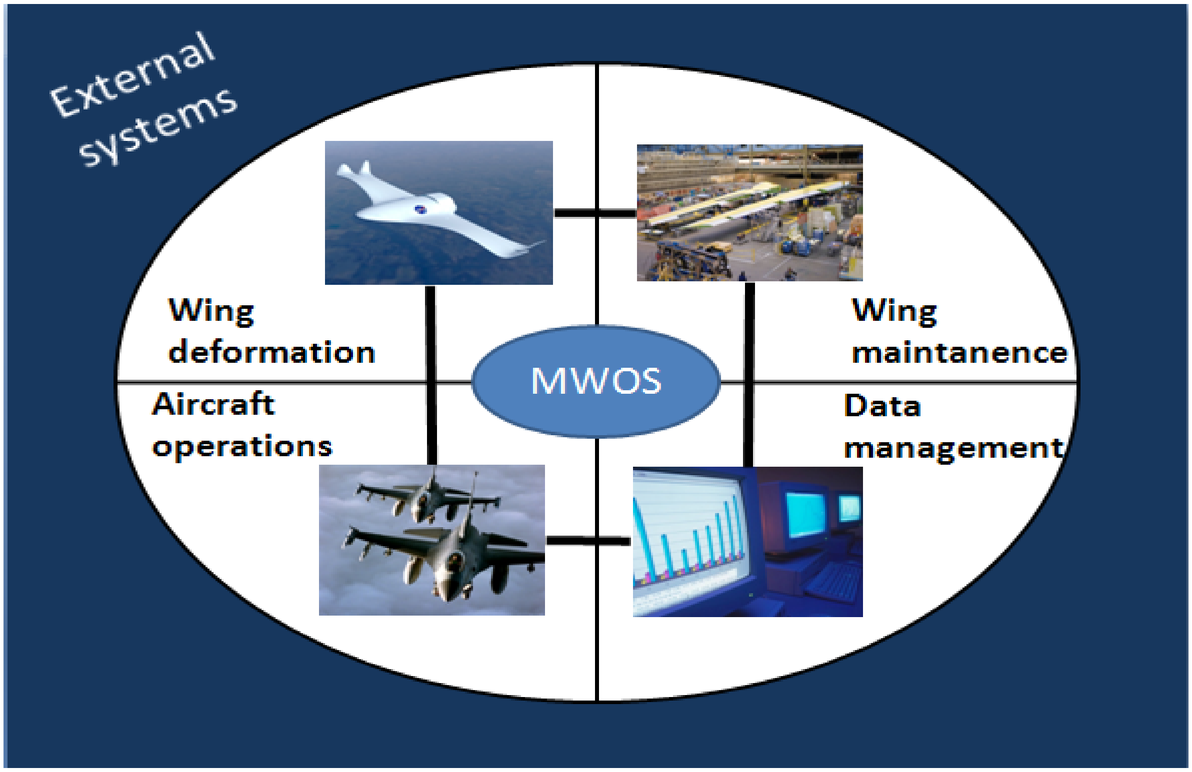


Figure A-3 MWOS OV-1

A.6.2.2 OV-5: Operational Activity Diagram

The next architecture view is the OV-5. The OV-5 has two kinds of diagrams, operational activity and node tree. By defining the main purpose of the architecture, helping identify the MWOS requirements, the author started the OV-5 development. The author monitored current wing operating systems and decomposed requirements from them. The author realized that four major requirements should be determined for MWOS. The first one determines operational requirement. This requirement relates to operational activities. This requirement can be decomposed into three sub requirements. They are analyzing mission requirement, providing necessary aircraft maintenance, and making MWOS decisions. These sub requirements control the operational requirement. The second requirement is determining the wing deformation requirement. This requirement is the unique function that does not exist in other wing operating systems. This requirement exists in order to transform the wing according to users' requests. Three major sub requirements should be determined to keep the wing deformed. They are actuator location, actuator capability, and heat source. Actuator location is important in that it determine the shape of wing. A morphing wing can change to a lot of formations. Each formation should have a different actuation location in order to make the desired shape. Actuator capability is also an important factor. Every actuator should have reliability and accurate control. The last function for determining wing deformation requirement considers heat source. SMP cannot get transformed without a heat source. Thus, keeping the heat source in proper place and time is an essential factor for determining wing deformation requirements. The third major requirement for MWOS is determining data requirements. A lot of kinds of data will be used in

MWOS like other conventional systems. These data should be organized, processed, and used for keeping MWOS operated properly. All the functions are organized throughout OV-5 node tree (Figure A-4)

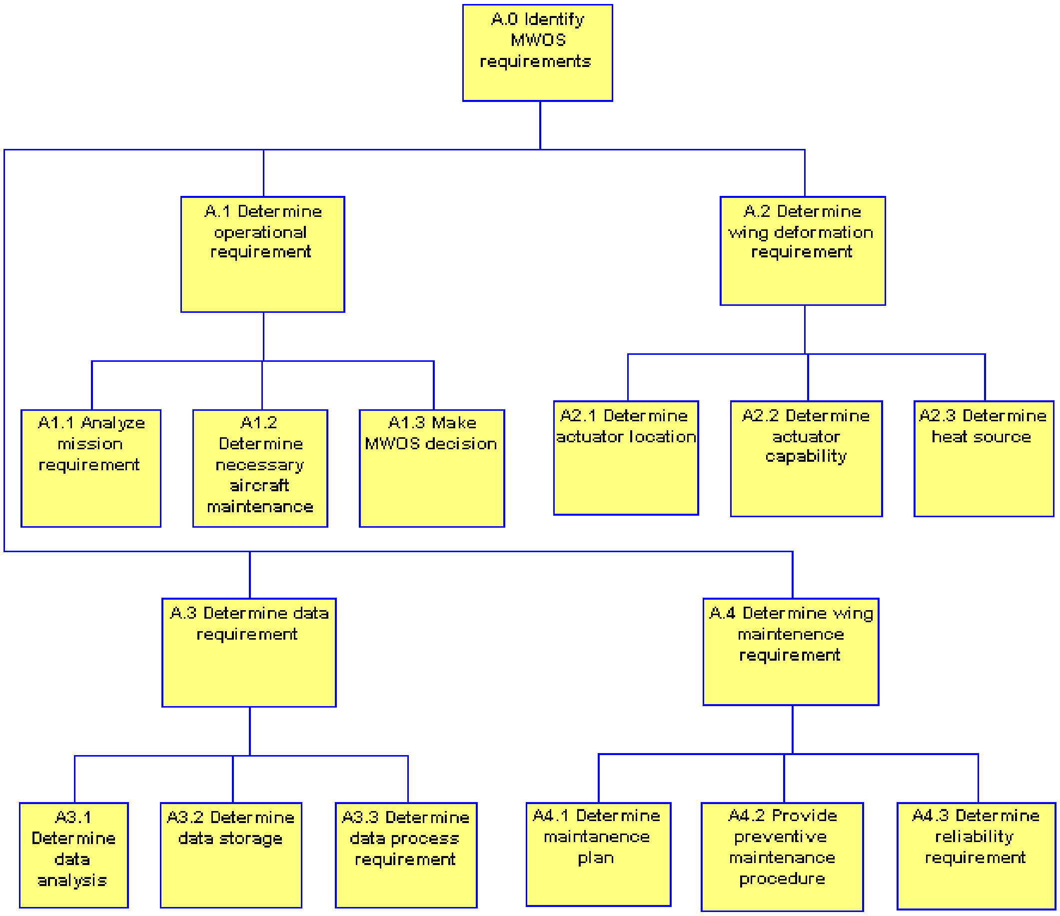


Figure A-4 OV-5 Node tree

In order to determine these data requirements, three sub requirements should be considered. They relate to analysis, storage, and processing of data. While the wing is deformed and used, a lot of records concerning its state will be collected. These data should be monitored and processed in order to maintain the condition of wings. System operators can estimate when the wing lifecycle, replacement cycle, inspection cycle will be due by viewing these data. The last requirement for MWOS is determining wing maintenance requirements. This requirement directly relates to the requirement for maintenance of a morphing wing. A morphing wing needs different inspection periods, plans, and procedures compared to conventional wings. Thus, unique maintenance requirement of morphing wings can be presented by implementing this requirement.

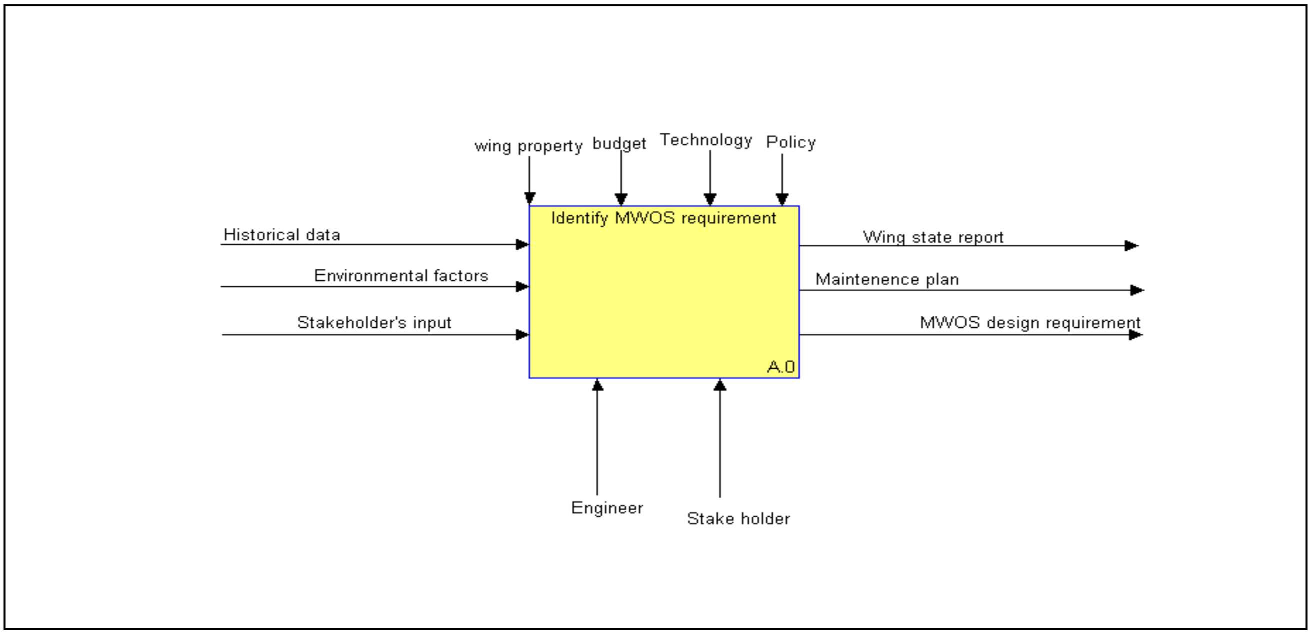


Figure A-5 AO architecture

The author also decomposed the relationship between MWOS and external systems (Figure A-5). MWOS will be controlled by several factors. They are wing property, budget, technology and policies. Wing property is general physical characteristics of SMP and its composites. The wing made of SMP will also be affected by SMP characteristics. We also found that these characteristics vary as physical condition changes throughout the experiments. Budget is the second important sub requirement. MWOS might need a lot of subsystem and equipment. However, budget is not an infinite resource. System engineers and operators should maintain the balance in managing and controlling budget in implementing MWOS. The third sub requirement factor is technology. Technology deals with how to transform, maintain, and fix morphing wings. Advanced technology can transform wings in shorter time, providing better maintainability. These technologies are still developing now. Innovative technology should be applied to operating morphing wings by the system engineer's interest. The last sub requirement is policy. This is a very basic sub requirement. Every system should be established by the guidance of AF and DoD policies. There is a possibility that some policies may conflict with required system requirements. These conflicts should be resolved.

The author identified three major inputs in MWOS. They are historical data, environmental factors, and stakeholder's input. Historical data means all the previous records of morphing wings. Environmental factors include external factors which could affect operation of morphing wing systems. For example, there will be weather, mission area terrain, and temperature of air, and so on. Stakeholder input means variety of common interest among stakeholders, who are related to MWOS. Mission requests, and inspection plans could be examples of stakeholder's input (Figure A-6).

The author identified three major outputs of this enterprise. They are wing state report, maintenance plan, and MWOS design requirements. They will be produced from MWOS through engineer and stakeholder's help. Some help will be feedback for MWOS. This makes the system more reliable and stable.

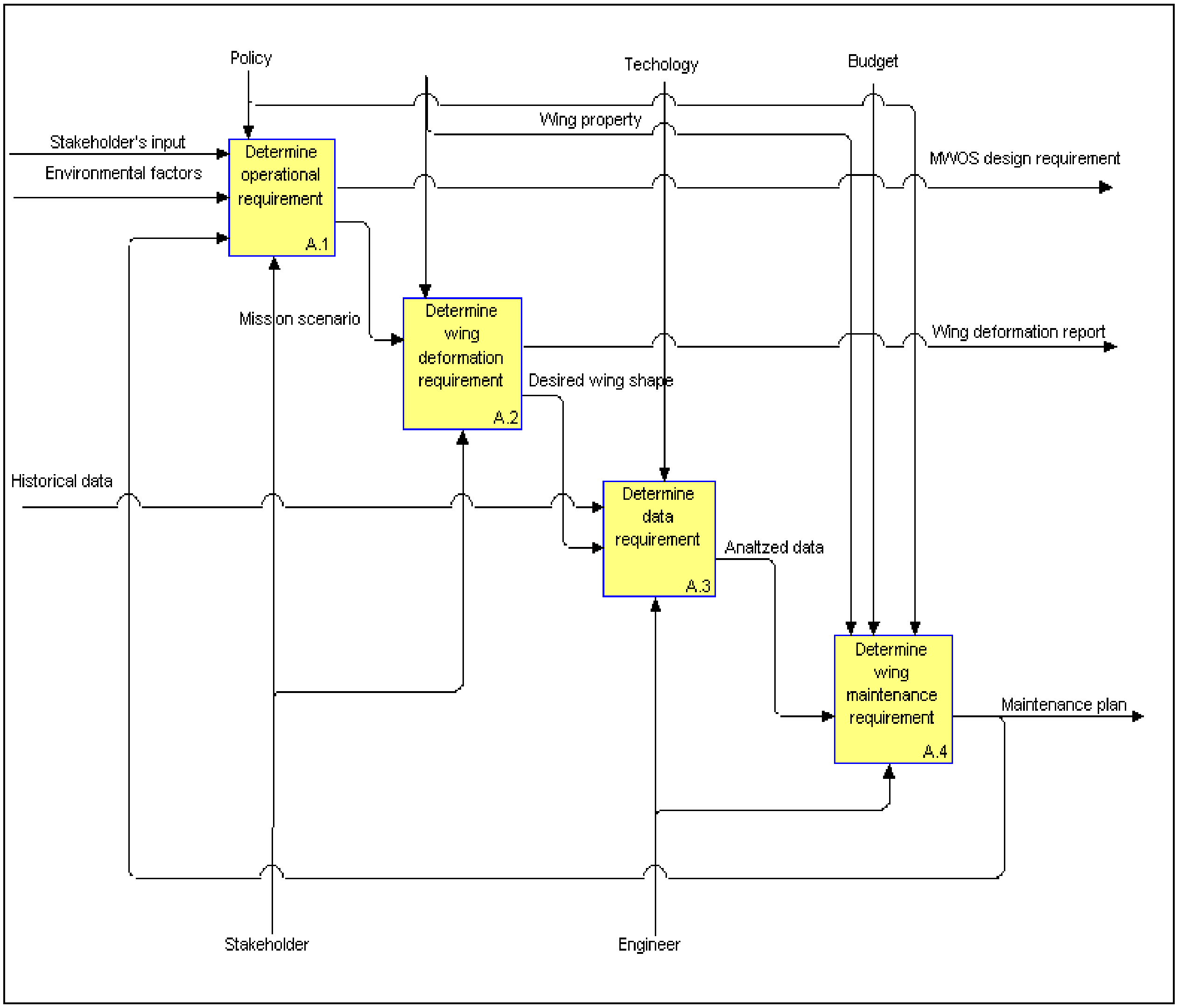


Figure A-6 OV-5 A0 architecture

The author decomposed the context diagram into four major functions or activities that a promotional MWOS should be expected to perform. Those are related to operation, maintenance, data processing, overall management. The first requirement is determining operational requirement. Operational requirement means all the requirements for performing missions in the battlefield and managing issues for operating this system. As technology develop and strategy changes, requirements in the mission should be changed. These changes will be transferred as a policy or inputs of stakeholders, environmental factors, and historical data from feedback of MWOS. After determining operational requirements optimized for morphing wing aircraft, desired mission scenario will be produced. This product includes the mission type, jobs, and even environmental factors which are considered in operating morphing wing aircraft. These scenarios will be the input to the next function. The next function is determining wing deformation requirement. This function deals with physical activity of MWOS, such as heating and forming material. SMP deforming units will perform its role to keep the wing optimized according to mission scenario. After determining this function, desired wing shape will be produced. As morphing aircrafts are deployed more and more in the combat area, desired wing shape data needs to be optimized and recorded in the MWOS. The third function deals with this necessity. All the data which are processed and organized by previous functions will be the output and feedback to the other functions. The last major function is determining wing maintenance requirements. This function directly related to the maintenance. Morphing wing needs periodical inspection, maintenance and preventive maintenance. Morphing wing needs more strict maintenance and inspection compared to conventional aircraft, because malfunction of deforming wing might be result in terrific disaster. After determining these functions, overall maintenance plan could be produced.

Appendix B

Table B-1 DoDAF 2.0 Products

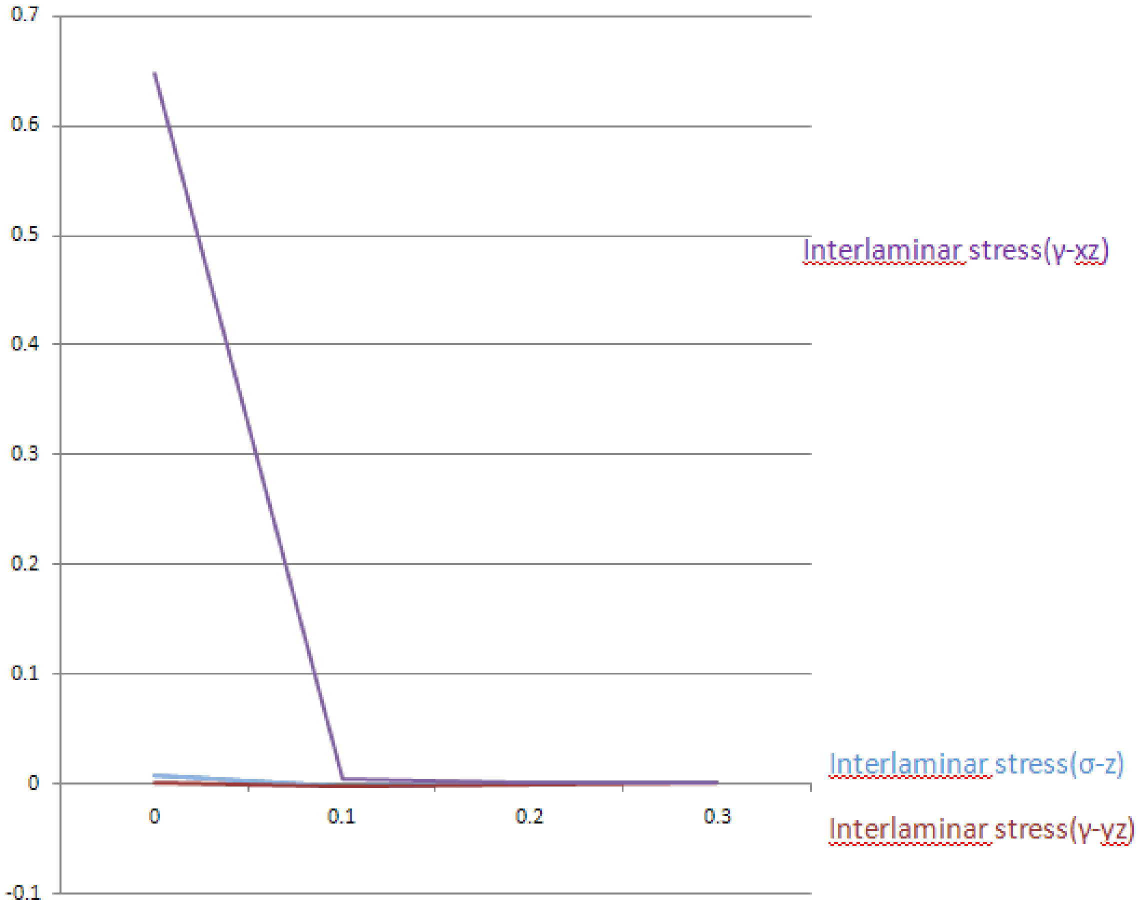
Applicable view	Model	Product name	Description
All views	AV-1	Overview and Summary information	Describes a project’s vision, goal, objectives, plans, activities, events, condition, measures, effects.
All views	AV-2	Integrated Dictionary	An architectural data repository with definitions of all terms used throughout the architectural data and presentations
Capability	CV-1	Vision	The overall vision for transformational endeavors, which provides a strategic context for the capabilities described and a high level scope
Capability	CV-2	Capability Taxonomy	A hierarchy of capabilities which specifies all the capabilities that are referenced throughout one or more architectural descriptions
Capability	CV-3	Capability Phasing	The planned achievement of capability at different points in time or during specific periods of time
Capability	CV-4	Capability Dependencies	The dependencies between planned capabilities and the definition of logical groupings of capabilities
Capability	CV-5	Capability to Organizational development mapping	The fulfillment of capability requirements shows the planned capability deployment and interconnection for a particular capability phase
Capability	CV-6	Capability to Operational activities Mapping	A mapping between the capabilities required and the operational activities that those capabilities support
Capability	CV-7	Capability to Services Mapping	A mapping between the capabilities and the services that these capabilities enable
Operational	OV-1	High Level Operational Concept Graphic	The high-level graphical description of the operational concept
Operational	OV-2	Operational Resource Flow description	A description of the resource flows exchanged between operational activities
Operational	OV-3	Operational Resource Flow matrix	A description of the resource exchanged and the relevant attribute of the exchanges
Operational	OV-4	Organizational Relationships chart	The organizational context, role or other relationships
Operational	OV-5a	Operational Activity Decomposition Tree	The capabilities and activities organized in an hierarchal structure
Operational	OV-5b	Operational Activity Model	The context of capabilities and activities and their relationships among activities, inputs, and outputs

Applicable view	Model	Product name	Description
Operational	OV-6a	Operational Rules Model	One of three models used to describe activity. It identifies business rules that constrain operations
Operational	OV-6b	State Transition Description	One of three models used to describe activity. It identifies business process responses to events
Operational	OV-6c	Event Trace Description	One of three models used to describe operational activity. It traces actions in a scenario or sequence of events
Data/Info	DIV-1	Conceptual Data Model	The required high level data concepts and their relationships
Data/Info	DIV-2	Logical Data Model	The documentation of the data requirements and structural business process rules
Data/Info	DIV-3	Physical Data Model	The physical implementation format of the logical data model entities
Project	PV-1	Project Portfolio Relationships	Describes the dependency relationships between the organizations and projects and the organizational structures
Project	PV-2	Project Timelines	A timelines perspective on program or projects, with the key milestones and interdependencies
Project	PV-3	Project to Capability Mapping	A mapping of programs and projects to capabilities to show how the specific projects and program elements help to achieve a capability
System	SV-1	System Interface Description	The identification of system, system items, and their interconnections
System	SV-2	System Resource Flow Description	A description of resource flows exchanged between systems
System	SV-3	System-System Matrix	The relationships among systems in a given architectural description
System	SV-4	System Functionality Description	The functions performed by systems and the system data flows
System	SV-5a	Operational Activity to Systems Function Traceability Matrix	A mapping of system functions back to operational activities
System	SV-5b	Operational Activity to System Traceability Matrix	A mapping of system back to capabilities or operational activities
System	SV-6	System Resource Flow Matrix	Provides details of system resource flow elements being exchanged between systems and the attributes of that exchange

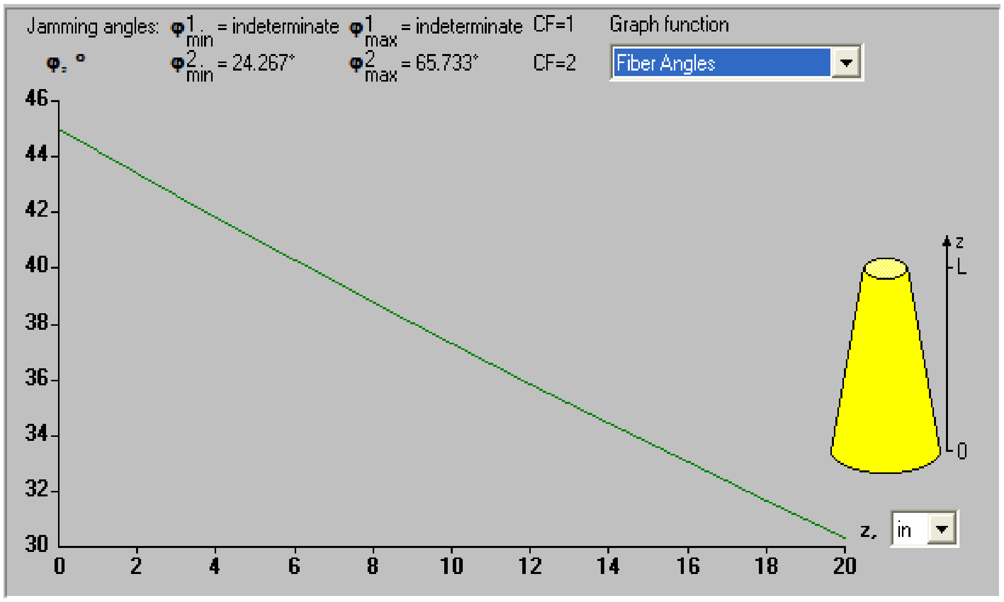
Applicable view	Model	Product name	Description
System	SV-7	System Measures Matrix	The measures of system model elements for the appropriate time frame
System	SV-8	System Evolution Description	The planned incremental steps toward migrating a suite of systems to a more efficient suite or toward evolving a current system
System	SV-9	System technology Skills forecast	The emerging technologies, skills that are expected to be available in a given set of time frame
System	SV-10a	System Rules Model	One of three models used to describe system functionality
System	SV-10b	System State Transition Description	One of three models used to describe system functionality. It identifies responses of system to events
System	SV-10c	System Event-Trace Description	One of three models used to describe system functionality. It identifies system specific refinements of critical sequences of events
Service	SvcV-1	Services Context Description	The identification of services, service items, and their interconnections
Service	SvcV-2	Service Resource Flow Description	A description of resource flows exchanged between services
Service	SvcV-3a	System-Service Matrix	The relationships among or between systems
Service	SvcV-3b	Services-Services Matrix	The relationships among services in a given architectural description
Service	SvcV-4	Services Functionality Description	The functions performed by services and the service data flows among service functions
Service	SvcV-5	Operational Activity to Services Traceability Matrix	A mapping of services back to operational activities
Service	SvcV-6	Services Resource Flow Matrix	It provides details of service resource flow elements being exchanged between services and the attributes of that exchange
Service	SvcV-7	Services Measures Matrix	The measures of services model elements for the appropriate time frame
Service	SvcV-8	Services Evolution Description	The planned incremental steps toward migrating a suite of services to a more efficient suite or toward evolving current services to a future implementation.
Service	SvcV-9	Services Rules Model	One of three models used to describe service functionality

Applicable view	Model	Product name	Description
Service	Svc-10a	Services Rules Model	One of three models used to describe service functionality
Service	Svc-10b	Services State Transition Description	One of three models used to describe service functionality
Service	Svc-10c	Services Event-Trace Description	One of three models used to describe service functionality
Standard	StdV-1	Standards Profile	The listing of standards that apply to solution elements
Standard	StdV-2	Standards Forecast	The description of emerging standards and potential impact on current solution elements, within a set of time frames

Appendix C Micromechanics analysis



Graph C-1 Stress plot of layer No.1

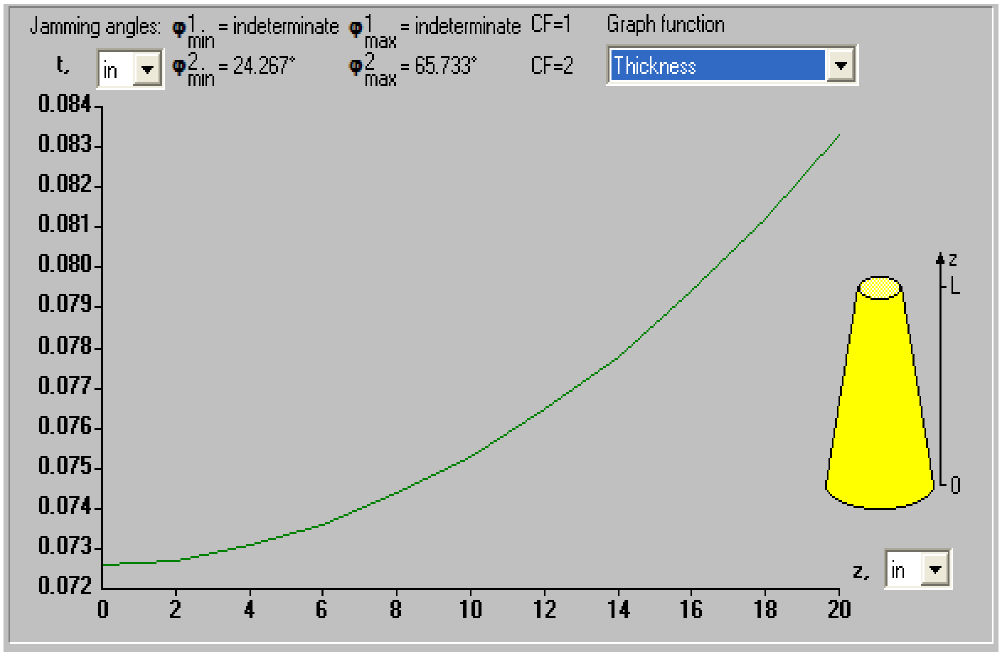


Jamming angles: φ^1_{min} = indeterminate φ^1_{max} = indeterminate CF=1

φ^2_{min} = 24.267° φ^2_{max} = 65.733° CF=2

Graph function: Fiber Angles

Figure C-1 Braids analysis of fiber angles

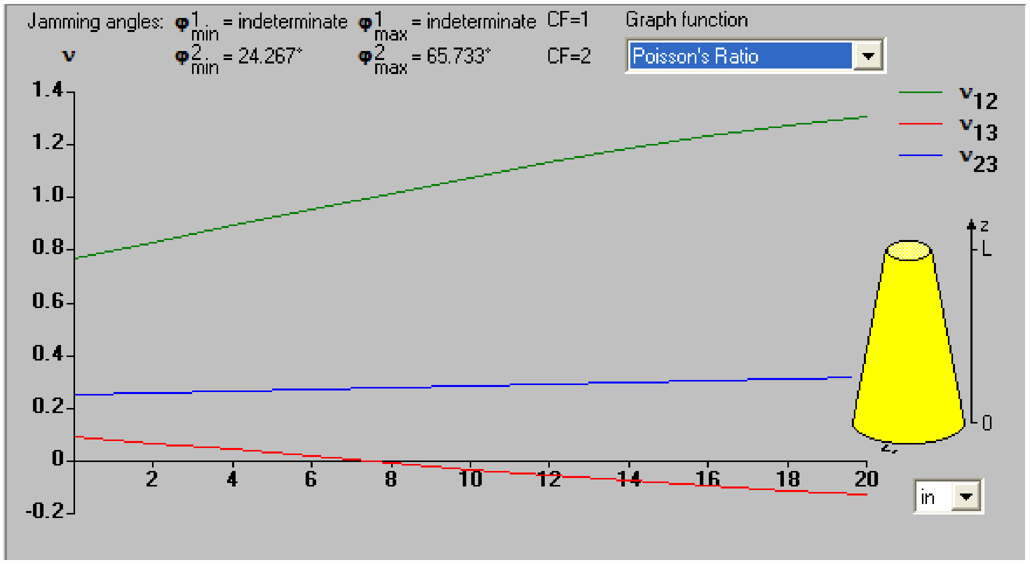


Jamming angles: φ^1_{min} = indeterminate φ^1_{max} = indeterminate CF=1

φ^2_{min} = 24.267° φ^2_{max} = 65.733° CF=2

Graph function: Thickness

Figure C-2 Braids analysis of thickness

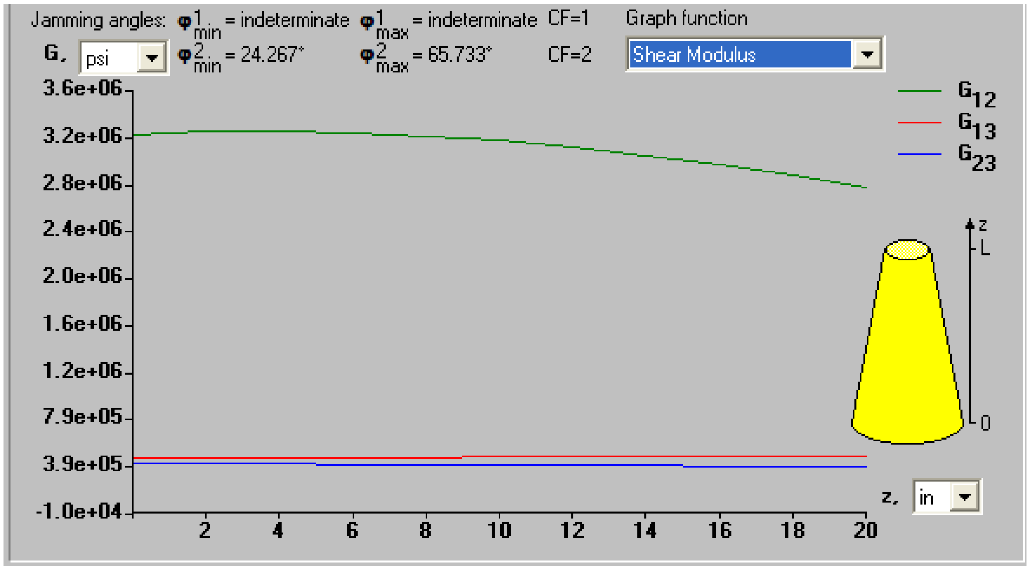


Jamming angles: φ^1_{min} = indeterminate φ^1_{max} = indeterminate CF=1

φ^2_{min} = 24.267° φ^2_{max} = 65.733° CF=2

Graph function: Poisson's Ratio

Figure C-3 Braids analysis of Poisson's **ratio**

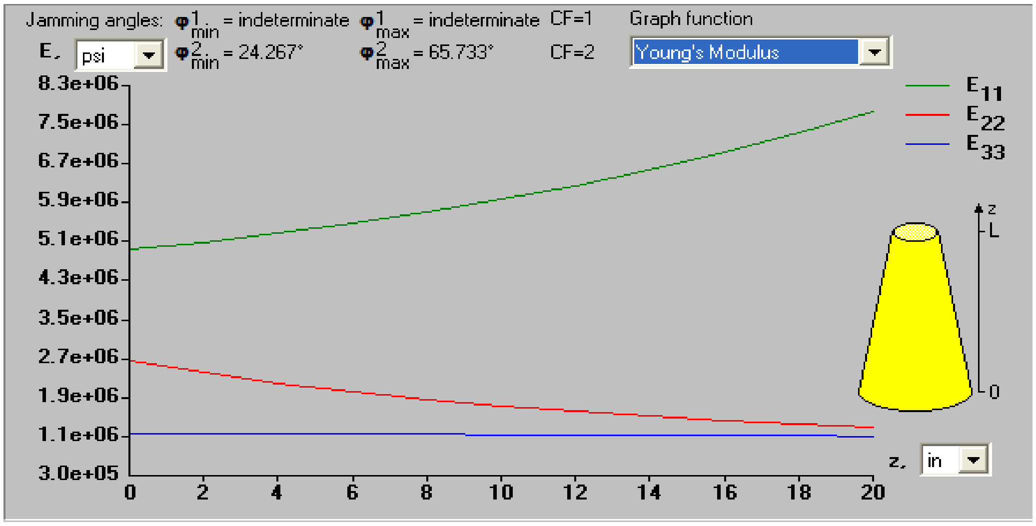


Jamming angles: φ^1_{min} = indeterminate φ^1_{max} = indeterminate CF=1

G, psi φ^2_{min} = 24.267° φ^2_{max} = 65.733° CF=2

Graph function: Shear Modulus

Figure C-4 Braids analysis of Shear modulus



Jamming angles: φ^1_{min} = indeterminate φ^1_{max} = indeterminate CF=1

φ^2_{min} = 24.267° φ^2_{max} = 65.733° CF=2

E, psi

Graph function Young's Modulus

z, in

Figure C-5 Braids analysis of Young's modulus

Appendix D OV-2, SV-5b

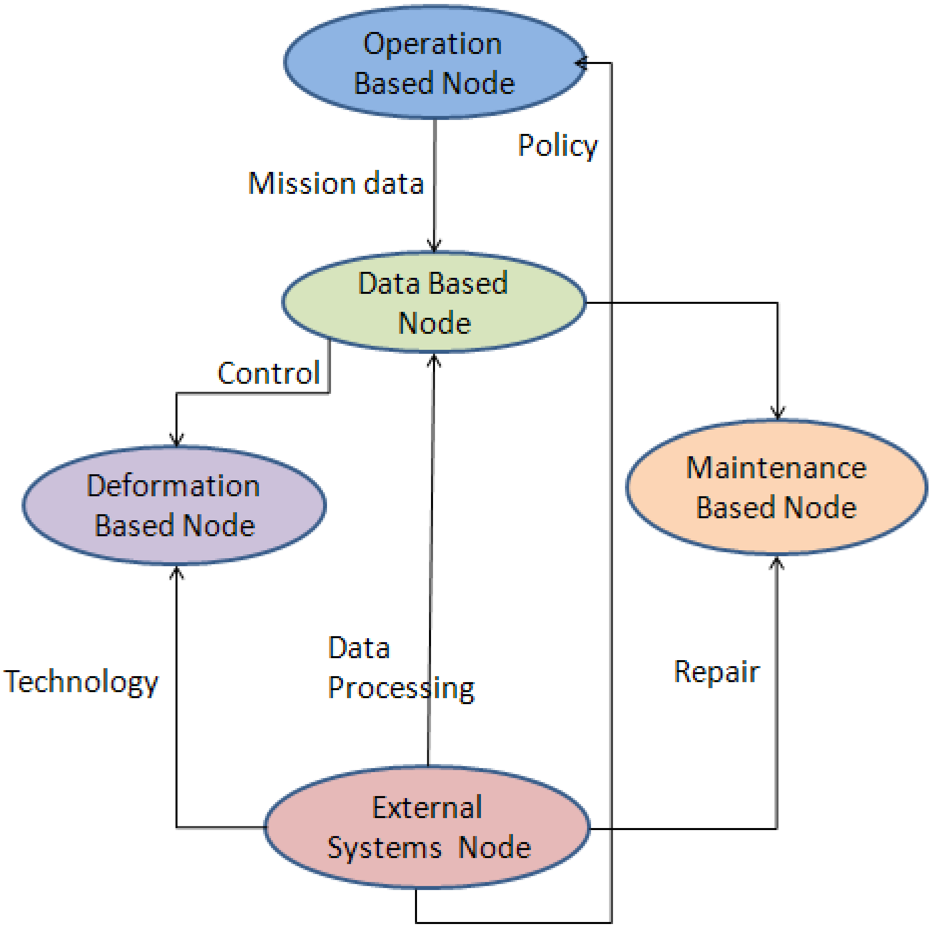
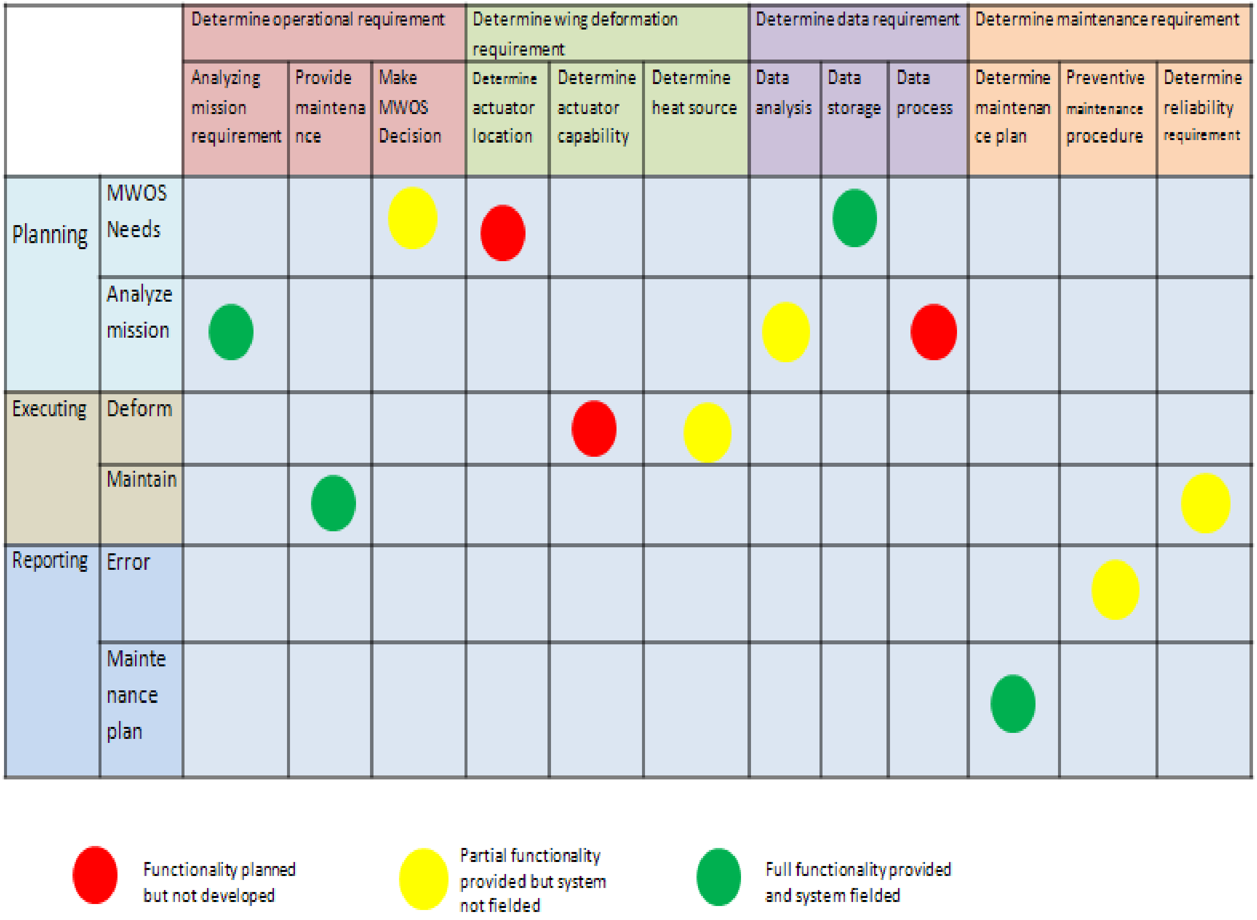


Figure D-1 MWOS OV-2

SV-5b



		Determine operational requirement			Determine wing deformation requirement			Determine data requirement			Determine maintenance requirement		
		Analyzing mission requirement	Provide maintenance	Make MWOS Decision	Determine actuator location	Determine actuator capability	Determine heat source	Data analysis	Data storage	Data process	Determine maintenance plan	Preventive maintenance procedure	Determine reliability requirement
Planning	MWOS Needs			🟨	🟥				🟩				
	Analyze mission	🟩						🟨		🟥			
Executing	Deform					🟥	🟨						
	Maintain		🟩										🟨
Reporting	Error											🟨	
	Maintenance plan										🟩		

🟥 Functionality planned but not developed

🟨 Partial functionality provided but system not fielded

🟩 Full functionality provided and system fielded

Figure D-2 MWOS SV-5b

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)* March 2010	**2. REPORT TYPE** Master's Thesis	**3. DATES COVERED** *(From – To)* June 2009 - March 2010

4. TITLE AND SUBTITLE DEVELOPMENT OF MORPHING AIRCRAFT USING SMP	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Soo-chan Jee, Capt, R.O.KAF	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GSE/ENV/10-M02
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Intentionally left blank	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S Air Force needs new aircraft which provide longer flight time, less fuel consumption, better aerodynamics in order to perform Air Force missions successfully as the mission environment changes rapidly. A morphing wing aircraft is considered as a potential new aircraft for those missions. This thesis explores Shape Memory Polymer (SMP) properties test results and its applicacation for morphing wing skin. Several SMP composite laminates were considered for investigating shape changing characteristics required for morphing skin. The braided composite prefoms used in making SMP composites were explored in morphing wing operating system based on the results of property tests. The system definition, life cycle of system, user analysis, and some architecture for identifying systems effectively formed the basis for the generic system engineering process presented. Further, this thesis explores initial geometric deformability, recovery characteristics, material property estimates, and develops the system using morphing material in order to present a concept for emerging morphing wing aircraft as a potential future Air Force's alternative. Based upon this research, the material system considered here does not meet the morphing requirement for such aircraft.

15. SUBJECT TERMS

Morphing aircraft, SMP, structure, property, Thermo-mechanical fatigue, Fracture

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Som Soni, AFIT/ENV
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** **U**	UU	116	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 785-3636 x 3420 Som.soni@afit.edu

Standard Form 298
(Rev. 8-98)
Prescribed by ANSI Std. Z39-18