

510
51

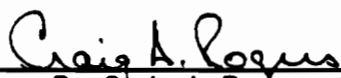
**ACTIVE DYNAMIC RESPONSE TUNING OF ADAPTIVE COMPOSITES UTILIZING
EMBEDDED NITINOL ACTUATORS**

by

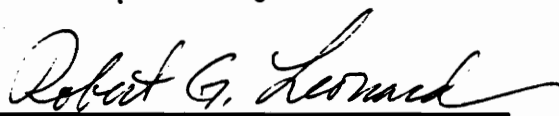
Daniel Keith Barker

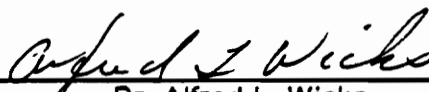
Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Mechanical Engineering

APPROVED:


Dr. Craig A. Rogers, Chairman


Dr. Harry H. Robertshaw


Dr. Robert G. Leonard


Dr. Alfred L. Wicks

July, 1989

Blacksburg, Virginia

LD
5655
V855
1989
B 2735

C.2

ACTIVE DYNAMIC RESPONSE TUNING OF ADAPTIVE COMPOSITES UTILIZING EMBEDDED NITINOL ACTUATORS

by

Daniel Keith Barker

Dr. Craig A. Rogers, Chairman

Mechanical Engineering

(ABSTRACT)

Adaptive composites utilizing embedded nitinol fibers have the unique ability to change their material properties, induce large internal distributed forces in a structure, and can modify the stress and strain distribution within a structure in a controlled manner. In this study, nitinol fibers are embedded in graphite-epoxy and are used as distributed actuators to actively tune the dynamic response of clamped-clamped beams. The natural frequencies of clamped-clamped nitinol composite beams are shown, experimentally, to increase linearly as a function of temperature. Beams with nitinol volume fractions of 5%, 10%, and 15% can increase their first natural frequency by factors of 1.7, 2.5, and 3.0 respectively.

Classical lamination theory is used to formulate a mathematical model of the dynamic response which includes the adaptive properties of the embedded nitinol fibers as a function of temperature, as well as the thermal aspects of the matrix material. Experimental characterization of nitinol for use as constrained thermosets is performed and the results are used in the mathematical model. The mathematical model is used to calculate the natural frequencies of clamped-clamped nitinol composite beams and the results are compared to experimental results.

It is clear that adaptive composites represent a new concept in active control of structural responses and may act as a catalyst for future developments in both material and structures technology. Demonstrating, experimentally and computationally, the ability to alter the dynamic response using unique adaptive qualities will hopefully inspire new material/structural interaction paradigms.

Acknowledgements

I would like to thank Dr. Craig Rogers for all his help and encouragement during my research and writing of this masters thesis. Craig is a man determined to advance the technology of smart materials and structures. His commitment and service to engineering as well as his students has made it an honor and a pleasure to work under his guidance. I would also like to thank my other committee members, Dr. Robertshaw, Dr. Leonard and Dr. Wicks for being on my committee and making it possible for me to finish this work.

Primary funding and support of this work came from U.S. Nitinol (Chuck Hovey in particular), the Center for Innovative Technology, and the Office of Naval Research under contract N00014-88-K-0566. Without the support of these groups, this research may very well have never been started.

Special thanks go to my wife Karen for her emotional support and help with this thesis. Her love never fails. Without her my life could never be complete. I also feel the need to thank the members of my family, who have been able to encourage me to

strive harder to complete the difficult tasks in life. They have instilled in me a sense of spiritual awareness and faith in God necessary to complete the tasks I would not otherwise be able to complete on my own.

Lastly, I would also like to thank my friends of the "SMSL crew" who are not only co-workers holding worthy advice and suggestions, but more importantly, good friends.

Table of Contents

- 1.0 Introduction and Literature Review 1
- 1.1 Introduction 1
- 1.2 Evolution of Smart Materials and Structures 3
 - 1.2.1 Passive Vibration Control Techniques 6
 - 1.2.2 Active Vibration Control Techniques 8
 - 1.2.3 Smart Structures 11
 - 1.2.4 Adaptive and Sensing Materials 13
- 1.3 Introduction to Shape Memory Alloys 23
 - 1.3.1 History 24
 - 1.3.2 Mechanism of the Shape Memory Effect 25
 - 1.3.2.1 Transformation 25
 - 1.3.2.2 Shape Memory Effect 31
 - 1.3.2.3 Repeatability 36
 - 1.3.2.4 Transformation Temperatures 37
 - 1.3.2.5 Effects on the Transformation Temperature 39
 - 1.3.3 Applications 40

1.4 Shape Memory Alloy Composites 45

1.4.1 Fabrication 48

1.4.2 Operating Principles 51

2.0 Nitinol Characterization 54

2.1 Introduction 54

2.2 Test Apparatus and Procedure 57

2.3 Results 64

2.3.1 Recovery Stress as a Function of Temperature 64

2.3.2 Repeatability of Shape Memory Effect 66

2.3.3 Effect of Composite Cure Cycle 72

2.4 Summary 81

3.0 Theory 83

3.1 Introduction 83

3.2 Theoretical Simulation 85

3.2.1 Formulation 86

3.2.2 Calculation of Bending Stiffness 90

3.2.3 Calculation of Stress Resultants for Clamped-Clamped Boundary Condi-
tions 91

3.3 Theoretical Results 96

4.0 Experiment 106

4.1 Introduction 106

4.2 Experimental Apparatus and Procedure 107

4.3 Experimental Results 117

4.3.1 Discussion of Experimental Technique	117
4.3.2 Boundary Conditions	121
4.3.3 Hysterisis Effects	129
4.3.4 Nitinol Volume Fraction	139
5.0 Comparison of Theoretical and Experimental Results	151
5.1 Introduction	151
5.2 Determination of Boundary Constants	153
5.2.1 Thermal Boundary Constant	153
5.2.2 Nitinol Boundary Constant	158
5.3 Natural Frequencies versus Nitinol Volume Fraction	160
5.4 Effect of Thermal Expansion	169
6.0 Conclusions and Recommendations	178
6.1 Conclusions	178
6.2 Recommendations	184
References	189

List of Illustrations

Figure 1. Phase Transformation of Nitinol [50]. 26

Figure 2. Electrical Resistivity versus Temperature of Nitinol [47]. 28

Figure 3. Young’s Modulus and Yield Stress versus Temperature of Nitinol [48]. 30

Figure 4. Shape Recovery of Nitinol. 32

Figure 5. Shape Memory Effect of Nitinol [50]. 33

Figure 6. Nitinol Tensile Recovery Stress versus Temperature as a Function of Initial Plastic Strain [48]. 35

Figure 7. Typical Transformation Curve for SMA Showing Elongation and Recovery versus Temperature under a Constant Tensile Stress [50] 38

Figure 8. Nitinol Pipe Coupling Device [71]. 42

Figure 9. Vena Cava Filter using Nitinol Alloy [73]. 44

Figure 10. Bias and Agonist/Antagonist Type Nitinol Actuators [43]. 46

Figure 11. Fabrication Schemes for SMA Reinforced Composites. 49

Figure 12. Typical Composite Cure Cycle, Temperature versus Time. 56

Figure 13. Test Apparatus for Nitinol Characterization. 58

Figure 14. Recovery Stress versus Temperature for Constrained Nitinol, first cycle. 65

Figure 15. Recovery Stress versus Temperature for Constrained Nitinol, second cycle. 68

Figure 16. Recovery Stress versus Temperature for Constrained Nitinol, third cycle. 69

Figure 17. Recovery Stress versus Temperature for Constrained Nitinol, fourth cycle. 70

Figure 18. Activated Recovery Stress versus Number of Cycles. 71

Figure 19. Recovery Stress versus Temperature for Constrained Nitinol, cycled fiber. 73

Figure 20. Activated Recovery Stress versus Time at Constant Temperature for Constrained Nitinol. 74

Figure 21. Simulated Composite Cure Cycle, Temperature versus Time. 75

Figure 22. Simulated Composite Cure Cycle, Recovery Stress versus Time. 77

Figure 23. Recovery Stress versus Temperature, immediately following composite cure cycle. 79

Figure 24. Recovery Stress versus Temperature, 24 hours after completion of composite cure cycle. 80

Figure 25. Schematic Representation of Clamped-Clamped Beam for Simulation. 87

Figure 26. Description of Boundary Conditions. 93

Figure 27. Natural Frequencies versus Inplane Stress 98

Figure 28. Natural Frequency Ratio versus Inplane Stress 100

Figure 29. Natural Frequencies versus Compressive Inplane Stress 101

Figure 30. Unactivated Natural Frequencies versus Nitinol Volume Fraction. . . 102

Figure 31. Activated Natural Frequencies versus Nitinol Volume Fraction. 104

Figure 32. Normalized Activated Frequencies versus Nitinol Volume Fraction. . 105

Figure 33. Lay-up Scheme for Nitinol Reinforced Composite Beam. 108

Figure 34. Tool Plate for Composite Fabrication. 109

Figure 35. Experimental Apparatus for Active Strain Energy Tuning. 111

Figure 36. FFT of SMA Beam at Room Temperature. 119

Figure 37. FFT of Activated SMA Beam. 120

Figure 38. ASET of "Rested" SMA Beam with Free Fibers, 15% nitinol volume fraction 122

Figure 39. ASET of "Rested" SMA Beam with Constrained Fibers, 15% nitinol volume fraction	125
Figure 40. Natural Frequency versus Temperature of Graphite-Epoxy Beam. . .	127
Figure 41. Natural Frequency versus Temperature of "Rested" 15% Volume Fraction Beam and Graphite-Epoxy Beam.	128
Figure 42. Comparison of Natural Frequencies versus Temperature of "Rested" and "Worked" Graphite-Epoxy Beam.	131
Figure 43. ASET of "Worked" SMA Beam with Free Fibers, 15% nitinol volume fraction.	133
Figure 44. Comparison of "Rested" and "Worked" SMA Beam with Free Fibers, 15% nitinol volume fraction.	135
Figure 45. ASET of "Worked" SMA Beam with Constrained Fibers, 15% nitinol volume fraction.	136
Figure 46. Comparison of "Rested" and "Worked" SMA Beam with Constrained Fibers, 15% nitinol volume fraction.	137
Figure 47. Time Hysterisis of Room Temperature SMA Beam with Free Fibers, 15% nitinol volume fraction.	138
Figure 48. Time Hysterisis of Activated SMA Beam with Constrained Fibers, 15% nitinol volume fraction.	140
Figure 49. ASET of "Rested" SMA Beam with Free Fibers, 10% nitinol volume fraction.	142
Figure 50. ASET of "Worked" SMA Beam with Free Fibers, 10% nitinol volume fraction.	143
Figure 51. Comparison of "Rested" and "Worked" SMA Beam with Free Fibers, 10% nitinol volume fraction.	144
Figure 52. ASET of "Rested" SMA Beam with Free Fibers, 5% nitinol volume fraction.	145
Figure 53. ASET of "Worked" SMA Beam with Free Fibers, 5% nitinol volume fraction.	147
Figure 54. Comparison of "Rested" and "Worked" SMA Beam with Free Fibers, 5% nitinol volume fraction.	148
Figure 55. Maximum Activated Natural Frequencies of "Rested" SMA Beams as a Function of Nitinol Volume Fraction.	149
Figure 56. Prestress at Boundaries for Graphite-Epoxy Beam.	154

Figure 57. Experimental Thermal Boundary Constant for "Rested" Beam.	156
Figure 58. Natural Frequencies versus Temperature for Graphite-Epoxy Beam.	157
Figure 59. Prestress at Boundaries for SMA Composite Beam, 15% nitinol.	159
Figure 60. Experimental Nitinol Boundary Constant.	161
Figure 61. Comparison of "Rested" Activated Natural Frequencies versus Volume Fraction	163
Figure 62. Comparison of "Rested" Activated Natural Frequency Ratios versus Volume Fraction.	164
Figure 63. Unactivated Natural Frequencies versus Nitinol Volume Fraction, "Rested" Beams.	166
Figure 64. Normalized Activated Natural Frequencies versus Nitinol Volume Fraction, "Rested" Beams.	168
Figure 65. "Worked" Thermal Boundary Constant.	170
Figure 66. Activated Natural Frequencies versus Nitinol Volume Fraction for "Worked" Beam.	172
Figure 67. Unactivated Natural Frequencies versus Nitinol Volume Fraction for "Worked" Beams.	173
Figure 68. Normalized Activated Natural Frequencies versus Nitinol Volume Fraction for "Worked" Beams.	175
Figure 69. Normalized First Natural Frequency for "Rested" and "Worked" Beams.	177

List of Tables

Table 1. Test matrix for nitinol characterization, fiber A 61

Table 2. Test matrix for nitinol characterization, fiber B 62

Table 3. Material properties for graphite-epoxy and nitinol. 97

Table 4. Test matrix for 15% nitinol volume fraction beam. 112

Table 5. Test matrix for 5% and 10% nitinol volume fraction beams. 113

Table 6. Test matrix for graphite-epoxy beam (no nitinol). 115

Table 7. Experimental results for ASET. 179

1.0 Introduction and Literature Review

1.1 Introduction

Nitinol composites have the ability to change their material properties, induce large internally distributed forces in a structure, and can modify the stress and strain distribution within the structure in a controlled manner. These adaptive characteristics can be exploited to actively tune the dynamic response of the composite.

Shape memory alloys, specifically nitinol, are unique in that they have a “memorized” shape and can recover up to 8% plastic strain upon activation. Below the phase transition temperature, a nitinol fiber can be plastically elongated from its memory shape. If the fiber is constrained from returning to its memory shape, large recovery stresses (up to 100 kpsi or 689 MPa) are possible. The shape memory effect also involves a large increase in its stiffness or Young’s modulus (about 300%) as the fiber is heated above its phase transition.

In this study, nitinol fibers have been embedded in graphite-epoxy composites and have been used as distributed actuators to actively tune the dynamic response of clamped-clamped beams. As the embedded and prestrained nitinol fibers are heated, the stiffness of the fibers increases and the fibers try to contract to their original length. This results in the dual effect of an increased overall stiffness of the composite and an increase in the stored strain energy throughout the composite. The strain in the nitinol fibers results in a distributed load throughout the composite beam along the entire length of the fibers. The increased "residual" strain in the beam is equivalent to an in-plane tensile load applied at the clamped-clamped boundaries, which results in a change in the dynamic response.

The emphasis of this work is to demonstrate the adaptive nature of nitinol composites by experimental analysis of the dynamic response of clamped-clamped nitinol composite beams as a function of the degree of activation of the embedded nitinol actuators and other design variables. The dynamic response is evaluated by experimental determination of the natural frequencies as a function of the temperature of the composite material. A first order theoretical simulation based on classical lamination theory is derived in an effort to better understand the roles of changing material properties (for both the embedded nitinol fibers and the matrix material) and the recovery stress of the embedded nitinol fibers as a function of temperature. New adaptive control techniques to prevent buckling and/or design structures with a uniform dynamic response over a large temperature range are inferred from the theoretical and experimental results. Conclusions concerning the feasibility of nitinol composites to adaptively tune the dynamic response of the composite structure are given.

Nitinol composites fall into a category of materials now referred to as smart materials and structures. Smart materials and structures are unique in that they can adapt to a changing environment in such a way to help preserve the structural integrity of the system of which it belongs. Adaptive or smart materials provide design engineers with the opportunity to design systems that will "react" to a disturbance in a predetermined and desired way. The adaptive nature of smart structures will lend themselves to new vibration control techniques based on the ability to "tune" the passive material parameters or independently generate distributed strains or stresses throughout structural members after the structural fabrication process has been completed.

The philosophy of smart materials and structures and the present state of the technology is presented below and is followed by an introduction to shape memory alloys; specifically nitinol (the smart material used in this work). Finally a review of nitinol reinforced composites is presented, outlining the current control schemes utilizing this adaptive composite system.

1.2 Evolution of Smart Materials and Structures

There are many methods of vibration control presently available to a design engineer. Passive techniques generally utilize the three dynamic design variables – mass, stiffness, and damping – to give a part or structure good dynamic response to an outside disturbance, usually defined as the operating conditions. Vibration requirements are not always satisfied during the design and production stages. Engineers

are often times left with the task of "fixing" an existing structure to meet vibration requirements. Many passive techniques incorporate a vibration control device designed to reduce the dynamic response of a specific point, or problem area, on the structure. These techniques typically have no moving mechanical parts and therefore require little or no maintenance. Conventional methods are limited, however, to generally narrow dynamic ranges. Active control techniques offer a more flexible means of vibration control when passive techniques are unable to satisfy vibration requirements over the spectral range of the operating conditions or when implementation is too costly. Present active control schemes require the use of applied external forces or motion at discrete locations to oppose the vibration and effectively dissipate the energy in the structure.

Control problems become more difficult as a flexible structure is excited by distributed forces. An example of this is an airplane encountering turbulence in flight. The problem is further complicated by the increased order of the mathematical model necessary to simulate the vibrational modes of the distributed parameter system. The large flexible booms and structural members associated with today's spacecraft and satellites are distributed parameter systems having many degrees of freedom and consequently a large number of vibrational modes requiring some form of isolation.

The traditional method of controlling the structural resonances is to increase the stiffness at "problem" locations. Low mass requirements of today's designs severely restrict this method. Active control methods have been proposed utilizing discrete sensors and actuators. Vibration isolation can usually be achieved at the sensor and actuator locations, but undesirable vibration levels may still exist at other locations

along the structure. Constrained layer damping is one example of a distributed parameter control technique which has been utilized effectively in a variety of applications. The ability to actively tune inherent material or structural properties or apply a distributed control force along a flexible structure would offer an excellent opportunity to control a distributed parameter system.

With recent advances in composite technology, materials with unique properties may now play a significant role in new active control concepts. Materials such as optical fibers, piezoelectric ceramics or polymers, electro-rheological fluids, and shape memory alloys all have the unique ability to respond or react to various stimuli or inputs. These materials can be embedded in composite laminates and can be used as integral sensors and/or actuators. "Smart", "Intelligent", "Sense-able", and "Adaptive" have all been used to describe structures with the ability to respond or react to a certain stimuli or input in a desired fashion. Each term has its own implied definition and has generated a great deal of dialogue on how this new science should be titled. This research has generated a new way of thinking and has given engineers another way to model nature and her adaptive systems.

Smart structures incorporate the advantages of both passive and active control techniques in the same system. Passive design variables integral to the structure (i.e., stiffness, damping, strength, etc.) traditionally cannot be modified or changed to increase the dynamic range of operation after the structure is in operation. Smart materials can be integrated within the 'skeletal' structure of a system to give adaptive-passive characteristics that can be controlled using an active control scheme. Instead of using discrete actuators to control a distributed parameter system, the inherent or characteristic physical properties of the system can be altered

in a controlled fashion to give the desired dynamic response for a particular disturbance.

What follows is a review of the present methods of vibration control, accompanied by an assessment of the current state of the technology of smart materials and structures. Accepted definitions of smart materials and structures will also be given. This review is meant to give the reader a sense of the evolution of "Smart", "Intelligent", "Sense-able", and "Adaptive" structures and an insightful look into the philosophy behind this new technology.

1.2.1 Passive Vibration Control Techniques

The conventional approach to satisfy vibration requirements has been to design a structure to meet necessary strength, stiffness, weight and other structural requirements and then to "fix" the structure to meet the vibration requirements. These methods often include tuning masses to place natural frequencies away from driving frequencies, vibration absorbers which suppress high amplitude vibration, and additional damping. The effect is to change the response characteristics of the structure after it has been designed. Structural optimization techniques are readily available [1-5] and give the designer the ability to fall back on corrective design measures. Technology advances are leading to more complicated aircraft, spacecraft, and space structures which require more innovative techniques than simply adding a device to the structure.

Viscoelastic materials have been used to establish damping as a design variable. This material dissipates the mechanical vibratory energy in the form of heat. When

viscoelastic material undergoes extensional strain, the resulting stresses will begin to relax as a result of the viscoelastic nature of the material. If the viscoelastic material is strained in a cyclic manner, the hysteresis or relaxation of the recovery stress can be used to dissipate the vibratory strain energy [6]. Constrained layers of viscoelastic damping material bonded to structural surfaces or between components can be used to form laminated skins or frames. Constrained layer damping has found use primarily in large aircraft, particularly in the area of reduction of wing flutter to improve the aerodynamic performance and acoustical vibration which contributes to fatigue. Ely [7] discusses the successful implementation of constrained layers of viscoelastic material in the redesign of the leading edge flap for the A-7 aircraft and the F-111 outboard spoiler to achieve large increases in their acoustical fatigue lives. Miles [8] reports the incorporation of constrained layer damping applied to the upper deck fuselage structure of the Boeing 747 to reduce noise levels inside the cabin.

Pritchard, et al., [9] has also investigated the possibilities of designing a structure to meet vibration requirements through the method of nodal point placement. This technique consists of modifying the mass distribution of a structure to place the node of a mode at a desirable location. A mathematical optimization procedure was developed which minimizes the sensitivity of a nodal location to a change in the design variable (usually total mass) and is referred to as the sensitivity derivative. This concept of "modal shaping" has been proposed as a method to reduce structural vibration, especially in helicopter rotor blades.

Passive control techniques have the disadvantage of being constrained to a limited range of operating conditions. Rivin [10] has suggested that judiciously-designed passive nonlinear systems have an amazing potential for self-adaptation to changing

conditions. Rivin [11] discusses the use of nonlinear engine mounts as an effective means of satisfying vibration requirements in complex vibratory environments. Nonlinear wire-mesh materials are incorporated to provide the necessary adaptation to changing environment. A hardening nonlinearity at static loading results in a constant natural frequency characteristic in a wide load range. A softening nonlinearity during vibratory loading results in an adaptive characteristic of the engine mount. Stiffness at low amplitudes is very high, and damping is very low, while at high amplitudes stiffness is reduced and damping is very high. For large amplitude shake vibrations and for passage through resonance damping is very high, while at high frequencies which usually are associated with low amplitudes, low damping results in good isolation of the vibratory energy. The ability to easily modify the stiffness or damping characteristics was an important step in the evolution of smart structures.

1.2.2 Active Vibration Control Techniques

Judiciously designed passive nonlinear systems are often times not easy solutions to obtain. Active control schemes generally dissipate the energy of vibration by opposing the vibration with the use of external and discrete actuators to impart a motion or force to the structure. Active methods become necessary when passive methods are not robust enough, are simply not feasible, or are too costly.

Engine mounts and vehicle suspension systems are traditionally passive control devices. The introduction of fast, inexpensive microprocessors has opened the doorway to using state feedback and automatic control. The current trend in engine isolation is to use fluid-filled engine supports which incorporate internal hydraulic

pathways in configurations which produce prescribed frequency filtering of the relative motion across the mount. These devices are far superior to the more conventional rubber mounts. Margolis' adaptive engine mount [12] uses a relatively slow actuator and simple measurements to maximize at all times r.m.s. deflection across the device in some optimal way. By maximizing the relative deflection across the device the transmitted force is minimized. Margolis also concedes that considerable development in sensors and high speed, low cost actuators is necessary before this approach to engine isolation becomes practical. Many active and semi-active suspension systems have been proposed and suspensions with slow load levelers and variable dampers are in widespread use. Karnopp and Margolis [13] show that active suspension schemes require both variable stiffness and damping to effectively optimize, or at least improve, the dynamic response to disturbance. These active control schemes are unique in that they implement a change in passive design parameters to make a system more robust, but these control schemes still require the use of external mechanical devices to impart this change.

Larger distributed parameter systems and structures present other problems conducive to active control techniques. Distributed parameter systems have many degrees of freedom and therefore require high order mathematical models to simulate the vibrational modes of the system. Large space structures are such distributed parameter systems. The problem of controlling the vibration of the structure at a location where both sensor and actuator can be located is a simple one. The very high order, and consequently very high bandwidth, of these systems can give rise to instabilities, however. In particular, as practical active control devices such as sensors and actuators have finite bandwidth, great care must be exercised so that control of low-frequency modes does not destabilize the intermediate and higher-order modes. Goh

and Caughey [14] consider position feedback in addressing stability problems of finite actuator dynamics in the collocated control of large space structures. The authors contend that with the addition of complicated “tuning filters” restrictive sufficient conditions (pertaining to actuator dynamics and initial conditions) can be derived like those with velocity feedback that can guarantee stability for all modes, including the uncontrolled and unmodeled modes.

If the actuator and/or sensor cannot be located at the point where control is necessary, the control problem becomes very difficult due to low structural damping and changing spacecraft stiffness and inertial values. One example of this noncollocated problem is the pointing control of a space antenna, which must be done with very high precision. Cannon and Rosenthal [15] have shown experimentally that a sudden reversal in the plant’s pole-zero sequence can occur when inertias are changed as the spacecraft configuration is changed in the course of the mission. This poses a most difficult problem for the controller. The authors contend that there are configurations for which there may be no practical alternative to adaptive control (variable control algorithms based on the configuration of the spacecraft).

Perhaps, a system or structure that could actively change its mechanical properties, such as stiffness or damping, would offer a solution to this adaptive control problem. In fact, Goh and Caughey [16] have developed, analytically, a vibration suppression technique for large space structures via stiffness modification. The authors contend that their control scheme guarantees stability no matter what the gains may be, or whether knowledge about the modal structure is accurate or not. This is verified by virtue of the positive definite rate of energy decay.

1.2.3 Smart Structures

Adaptive structures may prove to be a very effective way to approach today's complicated control problems. Adaptive structures may be thought of as structures made of materials or mechanical devices that have the ability to actively change their physical geometry, or the physical properties of the structure. Mechanical devices of this nature have been discussed in previous paragraphs. With recent advances in composite fabrication, adaptive materials can be integrated within a structure giving the structure the capability to actively adapt to changing conditions. The best analogy to this controllable structure might be the physiology of the human body. A composite system can be fabricated to form the skeletal structure and adaptive materials can be integrated within the composite during the cure or consolidation process to give the structure a nervous system capable of sensing both internal and external conditions, and a muscular system capable of reacting or responding to this sensed information. To make this analogy complete, some form of intelligence would have to be added to transform the sensed information into a desired response. Robertshaw [17] suggests that "organic" is the best prefix for structures with the inherent ability to sense, decide, and respond to some disturbance, either internal or external to the structure. Robertshaw feels the term "organic" better relates the living nature of these adaptive qualities than "smart", "intelligent", "active", or "senseable". Due to its popularity, "smart" has become the accepted prefix for these unique materials and structures.

There has been much discussion related to the definition of smart materials and structures. Rogers [18] defines smart materials as "containing distributed actuators, sensors, and microprocessor capabilities," and differentiates between smart and

adaptive materials by stating that adaptive materials and structures are but a subset of smart materials and structures. Many materials have adaptive capabilities, but are not smart unless coupled to sensor and control information. Gandhi [19] uses at least four qualifiers referring to smart materials as an “innovative class of multi-functional, dynamically-tunable, ultra-advanced, intelligent composite materials”. Rivin has defined smart structures as “judiciously designed passive nonlinear systems” which have an “amazing potential for self-adaptation to changing conditions, as well as significant adjustability” [10]. Wilkes has defined smart structures in a similar manner, stating that “smart materials” may simply be “well designed and engineered” materials [20]. The previous two definitions certainly involve the most fundamental necessary condition that is often lacking in other more sophisticated definitions. Robertshaw restates the need for smart structures to “possess the three needed attributes of integral actuators, integral sensors, and some intelligence to direct the actuator” [21]. These three attributes are necessary when we, directly or indirectly, try to mimic the musculo-skeletal processes of the human physiological process.

Although there is no accepted definition due to the evolving state of the technology, all definitions seem to have common attributes. Collecting the common attributes will begin to form the basis for an accepted definition of smart materials and structures. The common features to be included in the definition are:

1. **Sensors:** Smart structures have embedded (or bonded) or intrinsic sensor(s) which recognize and measure the intensity of the stimulus which could be stress, strain, thermal, electric, magnetic, chemical, radiation, etc.
2. **Actuators:** Smart structures have embedded or intrinsic actuator(s) to respond to the stimulus.

3. **Control Mechanism:** Smart structures have the ability to control the response to the stimulus according to a predetermined relationship. The control mechanism must be capable of selecting response if more than one option is available.
4. **Time and Nature of Response:** Smart materials have fast response in relation to stimulus. The system returns to its original state when the stimulus is removed.

It is noted that smart structures are made of smart materials having unique adaptive and/or sensing capabilities. This conglomeration of elements leaves room for further refinement in this new and evolving technology.

1.2.4 Adaptive and Sensing Materials

Many materials are available that have the unique ability to change their physical properties (i.e., stiffness, damping, viscosity, shape, etc.) due to certain stimuli or inputs. Optical fibers, piezoelectric polymers and ceramics, electro-rheological fluids, and shape memory alloys are some of these materials. Research is presently under way to investigate the potential of these materials for use as sensors and actuators in smart structures. The present state of this research is discussed in the following paragraphs.

Optical fibers are the most advanced of the recognized smart materials and have been investigated primarily for use as integrated sensors in "Smart Skins." A smart skin is the portion of a structural system capable of sensing strain and/or damage within the structure. Embedded optical fibers are distributed sensors which give integrated strain measurements over the entire length of the fiber. The ability to sense

external disturbances in a distributed fashion, as opposed to discrete locations, gives a structure a skin-like sensory system.

Fiber optic sensors can be classified into one of two types. Extrinsic sensors are the sensors where the fiber operates as a light transmitter only, it performs none of the sensing. An extrinsic fiber optic sensor is used to detect the light from a source and check for a break in the beam. Such a sensor is often used in robotics to sense the presence of a workpiece. An intrinsic sensor utilizes some intrinsic property of the fiber to detect a phenomenon or to quantify a measurement. An example of this would be the detection of radiation from radiation-induced luminescence.

Optical fibers entered the arena of sensor technology about ten years ago, making for a long list of applications. In 1979 and 1980, Claus [22] participated in the first documented distributed fiber experiments, conducted at NASA Langley, which demonstrated the use of embedded optical fiber sensors for the measurement of strain in low temperature composite materials. Since then Claus [23] has worked on the development of optical fiber interferometric, blackbody, evanescent, modal domain and time domain sensors for the evaluation of composite cure, in-service structural component monitoring, nondestructive materials evaluation, and damage detection and evaluation. Claus, Jackson, and May [24] have developed an optical waveguide embedded in composites that can be used to determine the two dimensional dynamic strain by using the optical refractometry and signal processing of the fibers. Electro-absorption phenomenon has been used by Su [25] to show magnetic field sensing capabilities. Martinelli [26] describes a fiber optic interferometer that can measure deformations and vibrations. Baumbick [27] notes the use of optical fibers and optical sensors in propulsion systems because of the severe environmental

conditions there. Bucholtz, Kersey and Dandridge [28] describe a fiber optic accelerometer based on the displacement to strain conversion suitable for use at DC and low frequencies.

Two separate sources speak of the possibilities of fiber optic actuators [29,30]. Although a brand new technology, Collier, McGlade and Stephens [29] claim that total electrical isolation can be achieved by complementing optical sensors with optical actuators – the “control-by-light” concept. Jones [31] also proposes the “control-by-light” in an article about optical fibers’ role in industry and discusses the use of intensity, wavelength, or rate modulation for multimode technology and point-source sensors. Bogue [32] addresses the use of fiber optics in accelerometers. Allan [33] and Pennywitt [34] describe the development of one of the first tactile sensors at Tactile Robotics Systems using fiber optic bundles, and further development by MIT using bundles containing 1190 fibers. An improved design was investigated that uses the fibers as both the emitter and receiver, allowing for greater resolution. The resolution of the sensor is limited by the size of the fiber.

The advantage of fiber optics, as is fast becoming evident, is that “the glass and silica fibers are themselves the basis for a broad range of sensors which utilize fiber properties to provide optoelectronic signals indicative of external parameters to be measured” [35]. These intrinsic properties of the glass and the silica are what qualify optical fibers as smart materials. Optical fibers are capable of performing as the sensor as well as performing the transmission of the sensor’s signal. They have a wide area of applications and will become more and more prevalent as new applications are developed and refined. These include measurements of temperature, pressure, displacement, magnetic fields, chemical composition, and others.

Other sensors have been incorporated into the “smart” world, and one of the most prevalent are piezoelectric ceramics and polymers. Piezoelectric sensors are made of materials that generate an electrical response to an applied strain; this is their adaptive reaction to stimuli. Piezoelectric materials can be crystals and ceramics, but because they have a brittle nature the piezoelectric sensors are generally made of one of the family of polymers, polyvinylidene fluoride, also known as PVDF or PVF₂. Because it is a polymer, it can be formed into very thin sheets and adhered to almost any surface. It outperforms many other sensors in its mechanical strength and its high sensitivity to pressure changes.

PVF₂ is a polymer that can be polarized or made piezoelectrically active with the appropriate processing during manufacture. In its nonpolarized form, PVF₂ is a common electrical insulator. In its polarized form PVF₂ is essentially a tough, flexible piezoelectric crystal. A voltage potential across the piezoelectric film is produced when the film is strained. The uniaxial film indicates the integrated, one dimensional strain over the entire surface area of the sensor. The biaxial film indicates the integrated strain in two directions over the surface area of the sensor. A disadvantage of the piezoelectric sensors is that static strain measurements are not possible. The voltage potential across the sensor will dissipate over a period of time.

Pennywitt [34] reports that Nevill and Patterson of the University of Florida have developed a piezoelectric tactile sensor that is able to recognize objects with “about 100 percent accuracy”. It is sensitive enough to distinguish the letters of the braille alphabet and different grades of sandpaper, showing great promise in exploratory sensing or object identification. Nevill and Patterson’s tactile sensor concept is based on the theory that the papillary ridges of the fingertips provide information that

is useful in the identification of objects to touch. The sensor is composed of two separate PVDF transducers. One transducer is oriented so that its direction of greatest electrical sensitivity is parallel to the direction of movement; the other is oriented transverse to that direction. The two transducers, oriented perpendicular to each other, are bonded together with nonconductive epoxy. The transducer assembly is then bonded to a silicone rubber pad made of a regular series of triangular ridges, made to simulate the ridges on the human fingertip. The construction of the sensor allows for the separate analysis of the transverse and parallel vibrations induced by moving an object across the sensor.

Allan [33] and Pennywitt [34] report that researchers at the University of Pisa are also working on a skin-like sensor utilizing piezoelectric material. Dario, De Rossi, Pinotti, Bardelli, and others are attempting to design a piezoelectric sensor capable of reproducing the sensing properties of the human fingertip. The sensor consists of an outer "epidermal" layer and an inner "dermal" layer, each of which performs distinct sensing functions. Electrodes are affixed to the top and bottom of the epidermal layer to give a distributed or integrated pressure measurement over the entire surface of the sensor. The dermal layer is bonded to a circuit board containing an 8 by 16 array of circular electrodes, allowing a more highly resolved and localized pressure or deformation measurement. In different modes of operation it can detect edges, corners, and geometric features, or it can distinguish between different grades of fabric.

Nakamura, et al., [36] propose a tactile sensor for robots using a ultra-thin film (200-300 μm) and back their claim with mathematical analysis and numerical simulation. It also exhibits response to temperature changes, which is called the

pyroelectric effect; this can be an advantage or disadvantage contingent on the application.

Piezoelectric materials are very versatile in that they can also be used as actuators. Piezoelectric materials can be utilized as actuators by applying a voltage potential across the material to induce a distributed strain over the entire surface area of the material. In this fashion a piezoelectric actuator can be used to generate a displacement or a force if the strain is opposed. The piezoelectric actuator is a true distributed actuator and can be analyzed and controlled in distributed systems using distributed control theory.

Piezoelectric usage has increased in positioning applications because piezoelectric polymers generate little heat and can conserve energy as compared to their electromechanical counterparts. High precision applications are a prevalent form of piezoelectric actuation. Tanoshima, et al., [38] performed a vibration analysis on a printer head which is position driven by piezoelectric effect. Tojo and Sugihara [39] have developed a turntable driven with the piezoelectric effect and exhibiting very high positioning accuracy – less than 4.88×10^{-7} rad. Takahashi [41] proposes two types of piezoelectric actuators, one with two piezoelectric plates stuck together and the other where a number of plates are laminated together. These actuators can be driven with low power and can be mass produced.

Piezoelectric actuators have also been proposed for vibration control of flexible structures. Bailey and Hubbard [37] of MIT designed an active vibration damper using a piezoelectric actuator and distributed-parameter control theory. A scale model of a flexible satellite was built and piezoelectric actuator films were bonded along the entire length of the long flexible beams extending from the satellite. The distributed

actuators generate strains, or forces, along the bonded surface of the vibrating beams to oppose the energy of vibration.

The force (or strain) created in these piezoelectric actuators is proportional to the voltage field put across the crystal. This simple relation makes for simplistic control algorithms and distributed analysis. The relationship is:

$$\varepsilon_p(x,t) = V(x,t) \times (d_{31}/h_2)$$

where ε_p is the strain, V is the applied voltage, d_{31} is the appropriate piezoelectric constant, and h_2 is the thickness of the PVF₂ layer [37]. The equation is valid for both actuator and sensor applications. It is clear that piezoelectric crystal/polymers have a vast assortment of applications. They can be used both as actuators and sensors. Perhaps more important is that they are distributed devices, and can be readily used in control schemes for distributed systems. The primary disadvantage of piezoelectric sensors and actuators is that they cannot be used for static measurement or actuation.

Another class of materials, electro-rheological fluids, has the inherent ability to undergo an abrupt and reversible change in viscosity when subjected to electrostatic potentials. Electro-rheological (ER) fluids are typically suspensions of micron-sized hydrophilic particles suspended in suitable hydrophobic carrier liquids. When an electric potential is applied across the ER fluid, these hydrophilic particles arrange themselves in particle "trains" and cause an increase in the viscosity of the fluid. ER fluids can be implemented within a structure, allowing for variable internal damping [19].

Vibration control using ER fluids has been demonstrated using hollow graphite-epoxy cantilever beams filled with various electro-rheological fluids [19]. By applying a voltage across the beam, the internal damping can be increased and vibrations can be suppressed. Gandhi proposes that ER fluids can be used to suppress vibrations in such distributed parameter systems as aircraft wings and helicopter rotors.

The variable viscosity characteristics, if exploited properly, can be used to create a structure with variable stiffness. An adaptive engine mount system which has a low dynamic stiffness over a wide frequency range is described by Duclos [42]. This system uses electro-rheological fluids and valves to tune a dynamic stiffness "notch". The system improves on the already existing fluid filled motor mounts. The operating principle is based on the fluid in the motor mount being forced through an orifice or notch to give the system inherent damping and stiffness characteristics. Duclos' motor mount incorporates electro-rheological fluid. The viscosity of the fluid can be tuned to give the appropriate dynamic response to external disturbances. As the engine speed changes, the system adapts itself to tune the notch to the dominant vibration frequency. The system has been demonstrated on a test car at Lord Corporation and the commercialization of tunable mounts is proceeding in several products.

Shape memory alloys are another class of materials that have adaptive characteristics. A shape memory alloy (SMA) has the inherent ability to remember a specific "memorized" shape. Below the transition temperature the SMA can be plastically deformed from its memory shape. When the SMA is heated above the transition temperature, the SMA will return to its "memorized" shape, if not constrained from doing so. The large recovery force associated with the return to memory shape has

typically been the mechanism exploited to create distributed SMA actuators. There are a number of alloys that exhibit the shape memory effect, but the most popular is the Nickel-Titanium (Ni-Ti or nitinol) alloy. Nitinol has a relatively high electrical resistivity which lends itself to easy and uniform heating via electric current.

Shape memory alloys have been applied to a number of items including connectors and heat engines, but have usually found application in bang-bang type actuators. This has begun to change. Recently in Japan, SMAs have been developed into robot manipulators. The shape memory alloy has only recently begun to attract serious attention as an actuator. Most of the work presently being done seems to be occurring in Japan. Because of Japan's dominance in the SMA research and since little of that work has been documented in English, it is hard to know where the Japanese have taken the technology. Hashimoto, et al., [43] show the use of SMAs in robotic actuators. Two types are discussed, biased and differential. Biasing uses a spring to obtain the bias force against the unidirectional force of the SMA. In the differential type, the spring is replaced with another SMA and the opposing forces control the actuation, similar to the way biceps and triceps control the motion of the human forearm. Yeager [44] has developed a one-pound three-quarter-inch-stroke linear actuator using a spring made of nitinol wire. This design includes prevention from ancillary jams. A more thorough discussion of early applications of nitinol is presented below.

Rogers has developed a new class of adaptive materials implementing nitinol actuators [17]. Adaptive materials using shape memory alloys have the capability of changing their physical geometry, or of altering their physical properties. The basic concept behind the adaptive structure developed at VPI&SU is that SMAs are inte-

grated in a bulk material (i.e., laminated fiber-reinforced composite) as an actuator for force, motion, and/or variable stiffness. Rogers states many possible applications for his adaptive structures, to include: active shape control of large antenna reflector surfaces, active vibration control of large flexible structures, and attenuation of noise transmitted through a structure.

With advances in the control algorithms, biasing with springs or opposing SMAs, active cooling techniques, and the creation of SMA composites, the shape memory alloys have improved their range of applications and are becoming more reliable and promising actuators.

Duclos, Coulter, and Miller give many possibilities for the application of smart materials in the field of vibration control [46]. Engine mounts and suspension systems are good examples of control schemes in which smart materials could be used to best make use of adaptive passive characteristics in a control system. Space structures, aircraft wing surfaces, helicopter rotor blades, and submarine surfaces are all examples of distributed parameter control problems that would lend themselves to the use of smart materials as distributed sensors and actuators. Duclos, Coulter, and Miller warn, however, researchers must be careful not to increase system complexity which contributes to the difficulty of the control problem and manufacturing costs, and that distributed parameter control algorithms must be further developed before smart materials can be used to solve today's vibration problems. These authors are encouraged by the promising potential of smart materials' ability to integrate adaptive passive characteristics into the control strategy, necessary to minimize system complexity. It is the belief of this author that the innovative nature of this technology will generate new control schemes that are less complicated than present active control

schemes. Emulating nature's control systems can certainly lead to better control systems.

1.3 Introduction to Shape Memory Alloys

This Introduction to shape memory alloys describes the unique trends and characteristics common to all shape memory alloys, although the magnitude of a particular trend may be different for each alloy. The shape memory alloy used in the theoretical and experimental portions of this work is the Nickel-Titanium alloy, nitinol. References to specific material properties and other constants therefore refer to nitinol and should not be considered common to all shape memory alloys, unless otherwise specified.

This Introduction is intended to provide a basic understanding of the material properties and shape memory effect of shape memory alloys (specifically nitinol) exploited for structural control of nitinol composites. The following information is sufficient to understand the operating principles of the structural control schemes involving nitinol described in this work, as well as future research activity concerning nitinol at the Smart Materials and Structures Laboratory at Virginia Polytechnic Institute and State University. More detailed information concerning shape memory alloys is available in the literature [47-65].

1.3.1 History

Beginning in the 1950's, certain alloys were observed to recover large plastic deformations and return to a "memorized shape" when heated. This phenomenon was first observed in AuCd and in 1963 it was also found in NiTi. Before 1970 this was thought to be a characteristic peculiar only to these three alloys. In 1970, however, the same phenomenon was observed in CuAlNi, and it became clear that this behavior was common to alloys which underwent thermoelastic martensitic transformations. Following this initiative, subsequent researchers have discovered the shape memory effect in a large number of alloys. They include the copper alloy systems of Cu-Zn, Cu-Zn-Al, Cu-Zn-Ga, Cu-Zn-Sn, Cu-Zn-Si, Cu-Al-Ni, Cu-Au-Zn, Cu-Sn, and the alloys of Au-Cd, Ni-Al, Fe-Pt, and others. The most common of the shape memory alloys or transformation metals is the NiTi alloy.

In 1965, Buehler and Wiley of the U.S. Naval Ordnance Laboratory received a United States Patent on a series of engineering alloys that possess a unique mechanical (shape) "memory" [57]. The generic name of the series of alloys is 55-Nitinol, derived from Ni (Nickel) - Ti (Titanium) - NOL (Naval Ordnance Laboratory now known as the Naval Surface Warfare Center). These alloys have chemical compositions in the range of 53 to 57 weight percent nickel. A great deal of effort was expended over the next ten years in characterizing the material and developing new applications to exploit its remarkable shape memory effect and its unusual mechanical properties. The Naval Ordnance Laboratory (now known as the Naval Surface Warfare Center) was and still is the leader in characterizing nitinol. Several other laboratories have made significant contributions to the understanding of the nitinol, in particular is Battelle Memorial Institute and NASA.

Substantial progress has been made in understanding the nature of the shape memory effect (described in detail below). A great deal of literature has been published over the past twenty years presenting detailed thermal, electrical, magnetic, and mechanical characterizations of this unusual alloy [58-65]. However, there is still much to be learned about the influence of high temperatures, used in composite fabrication and processing, on the extent, duration and repeatability of the SME as well as the dynamic actuator and sensing characteristics of nitinol.

1.3.2 Mechanism of the Shape Memory Effect

1.3.2.1 Transformation

A shape memory alloy (SMA) undergoes a change in crystalline form (a phase change) at a specific transformation temperature. In nitinol alloys the transformation involves the change from an ordered cubic crystal phase above the transition temperature (austenite) to a monoclinic crystal phase below the transition temperature (martensite). The material resides in either the austenite or martensite phase in an effort to achieve thermodynamic stability. The martensite phase has no right angles in the cell structure. In order for the martensite phase to form as the material in the austenite phase is cooled below the transition temperature, the crystalline arrangement must form alternating bond angles. The martensite and austenite crystalline arrangements can be seen in Fig. 1. One band of the crystal structure tilts one way while the next tilts the other, and so on, in an alternating fashion. This arrangement is called the twinned martensite phase and allows a change in phase of the nitinol without any diffusion and large latent heat requirements.

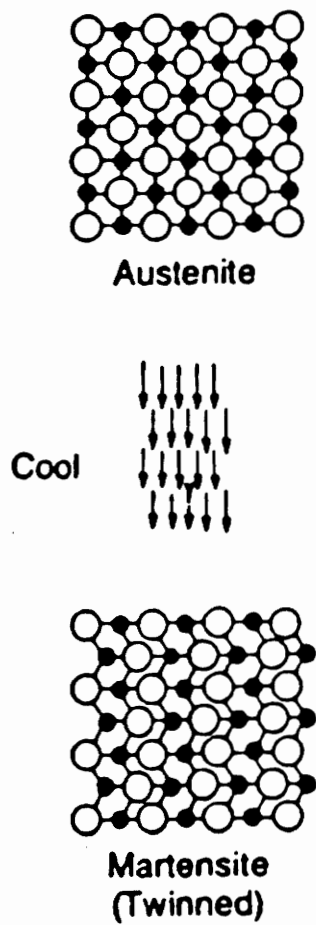


Figure 1. Phase Transformation of Nitinol [50].

This change in phase is different from ordinary metals in that the change in phase in most metals involves the diffusion or large movements of atoms. In SMAs, and specifically nitinol, the transformation involves a simple shearing motion of the atoms within the crystal structure. Because diffusion or large movements are not required resulting in a low latent heat of transformation, the transformation can take place very quickly. The transition from one phase to the other can take place as fast as heat can be introduced or removed from the material.

Along with the change in phase, SMAs undergo a change in material properties as temperature of the material is heated above or cooled below the transition temperature. These include electrical resistivity, mechanical damping and stiffness, thermal conductivity, as well as others. These properties, as they apply to nitinol are discussed below.

A great deal of information is available on the electrical resistivity of nitinol and the effect of temperature and the amount of plastic deformation in the low temperature, martensitic phase. A typical resistivity versus temperature curve is shown in Fig. 2. Hanlon, et al., [58] in 1969 measured the electrical resistivity of nitinol over the composition range from 48 to 52 atomic percent Ti at temperatures from -450°F to $+1652^{\circ}\text{F}$ (-268°C to $+900^{\circ}\text{C}$). Wang [60] performed an experimental study with specimens of 51 atomic percent Ni that were free of deformation and compressive stresses. Wang's study showed the effect of annealing temperatures and thermal cycling on the characteristic resistivity versus temperature curves. Buehler and Wiley [61] measured the electrical resistivity of nitinol alloys containing 54.5 and 55.1 weight percent Ni in order to obtain some indication of the structure of variously quenched specimens. Cross, et al., [48] found that the shape of the resistivity versus

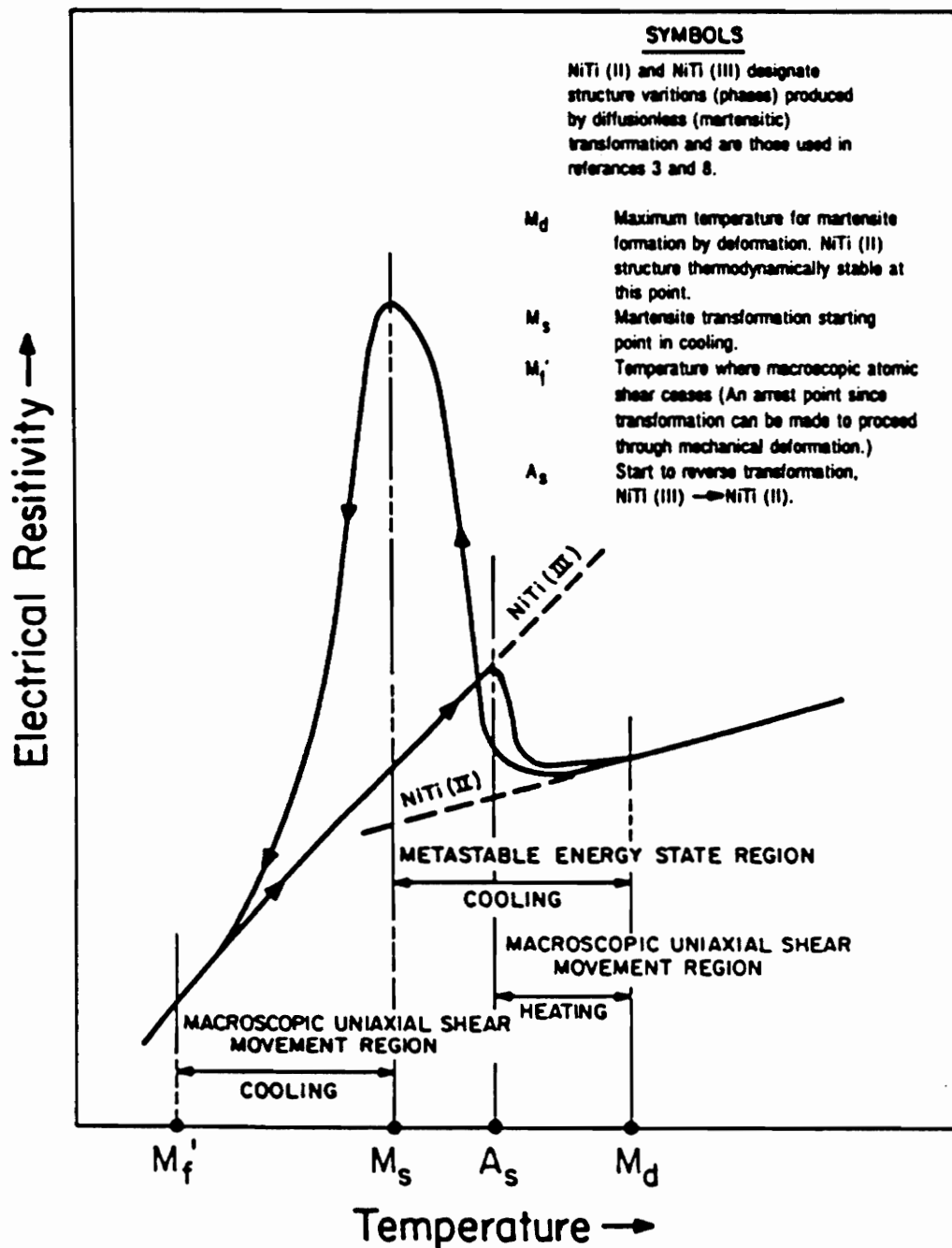


Figure 2. Electrical Resistivity versus Temperature for Nitinol [47].

temperature curve for drawn wire depended strongly on the heat-treatment temperature used for giving the wire a straight memory. The resistivity-temperature curves also varied with the chemical composition of the alloy, form (wire or strip), and dimensions (diameter and thickness). It was also found that the electrical resistivity is highly correlated with the bend-recovery behavior of the wire heat treated at various temperatures.

Buehler and Wiley [59,61] first noticed the unique mechanical vibration-damping property of nitinol by striking a bar of the material at room and elevated temperatures. At room temperature, a dead sound was produced by the blow whereas at about 135°F (57°C) the bar exhibited a metallic ring which became even more brilliant at about 171°F (77°C). Buehler and Wiley made quantitative measurements of damping by the low-frequency (0.4 Hz) torsion-pendulum method, using 0.0206 inch (.523 mm) and 0.0360 inch (.914 mm) diameter drawn wire. Wasilewski [62] investigated the dynamic elastic modulus and damping of stoichiometric NiTi. Spinner and Rozner [63,64] made a very thorough study of the internal friction and elastic modulus of NiTi using nonconsumeable-arc-cast material prepared from high-purity carbonyl nickel and sponge titanium.

Mechanical stiffness is also observed to increase as nitinol transforms from one phase to the other. The relationship for the Young's modulus and yield strength versus temperature for nitinol is shown in Fig. 3. The Young's modulus increases by a factor of three from the low temperature to high temperature phases. Also, the yield strength increases by a factor of ten. These properties will be examined in greater detail in the following section.

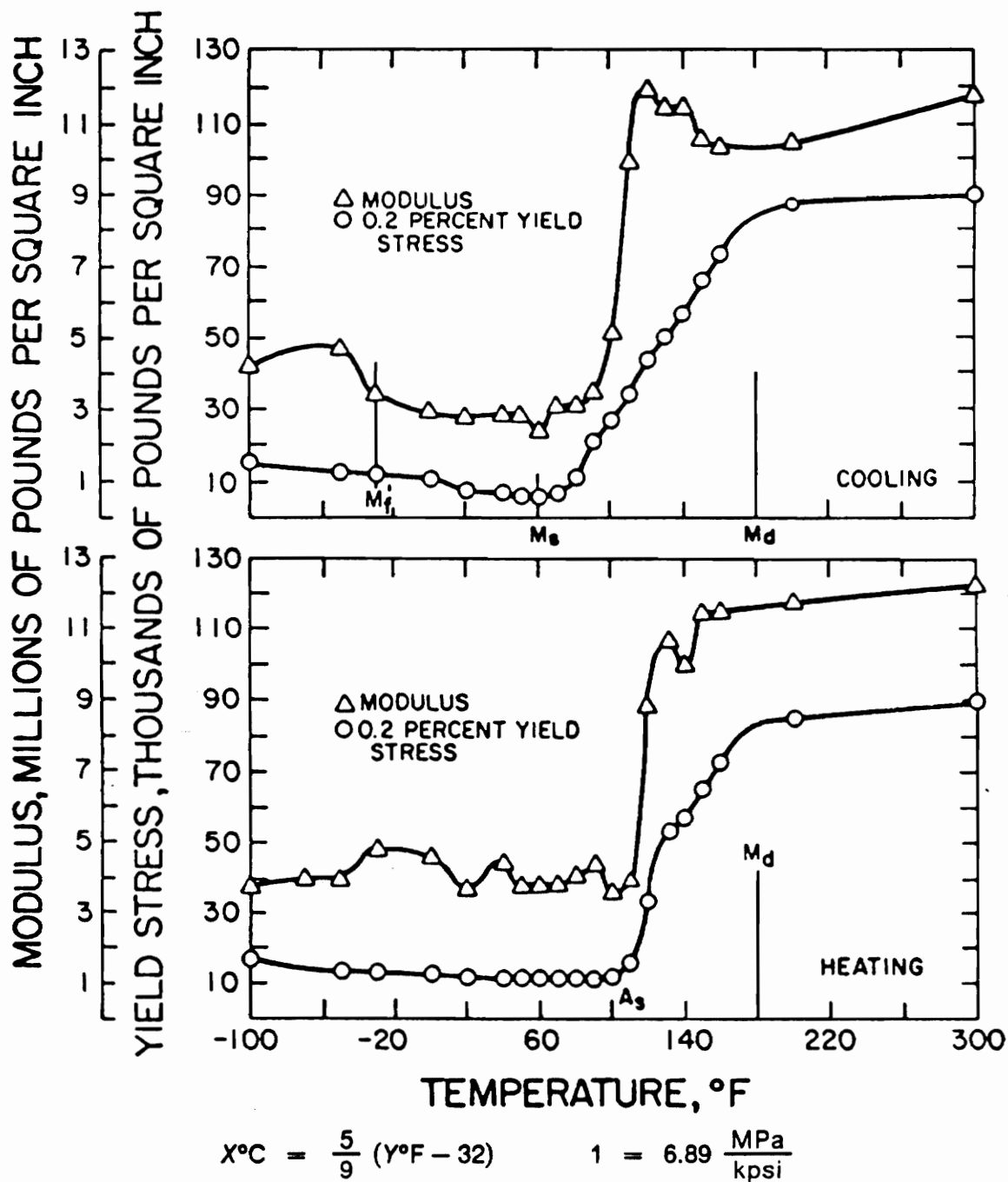


Figure 3. Young's Modulus and Yield Stress versus Temperature for Nitinol [48].

The thermal conductivity of nitinol and alloys of NiTi with copper or nickel was measured by Goff [65] again showing the dependance on temperature and composition.

These changes in material properties can be exploited within a mechanical structure to allow the structure to adapt to changing conditions. The changing resistivity suggests the potential use of nitinol as a temperature sensor integral to the structure itself. The unique hysteresis of the resistivity versus temperature would enable the sensor to detect whether the structure was heating up or cooling down. The temperature dependence of the mechanical damping and stiffness suggests the potential of nitinol for use as actuator integral to the structure. Nitinol actuators have been embedded in composite beams and their potential as internal actuators has been demonstrated. This is discussed in greater detail below.

1.3.2.2 Shape Memory Effect

The process of shape recovery for a nitinol wire is shown in Fig. 4. As nitinol is deformed in its low temperature, martensite phase the alternating bond angles of the monoclinic crystalline structure are flipped to the opposite tilt. This deformation, or change in shape, can cause all or only some of the alternate bond to tilt in the opposite direction. As the nitinol is heated above the characteristic transition temperature, the crystalline structure undergoes a simple shearing motion to arrive at the ordered cubic crystalline structure of the high temperature austenite phase. This process can be seen in Fig. 5. This change in phase recovers the simple shearing motion induced by the deformation of the low temperature martensite. Nitinol will

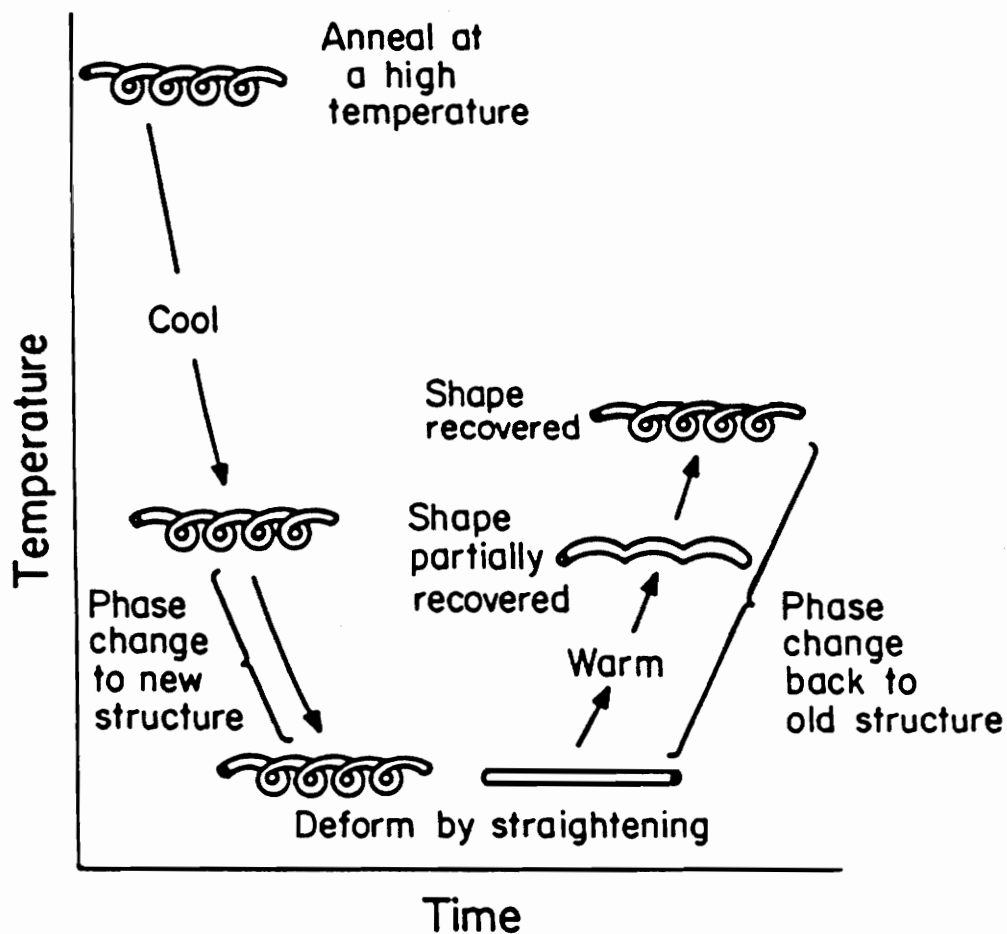


Figure 4. Shape Recovery of Nitinol.

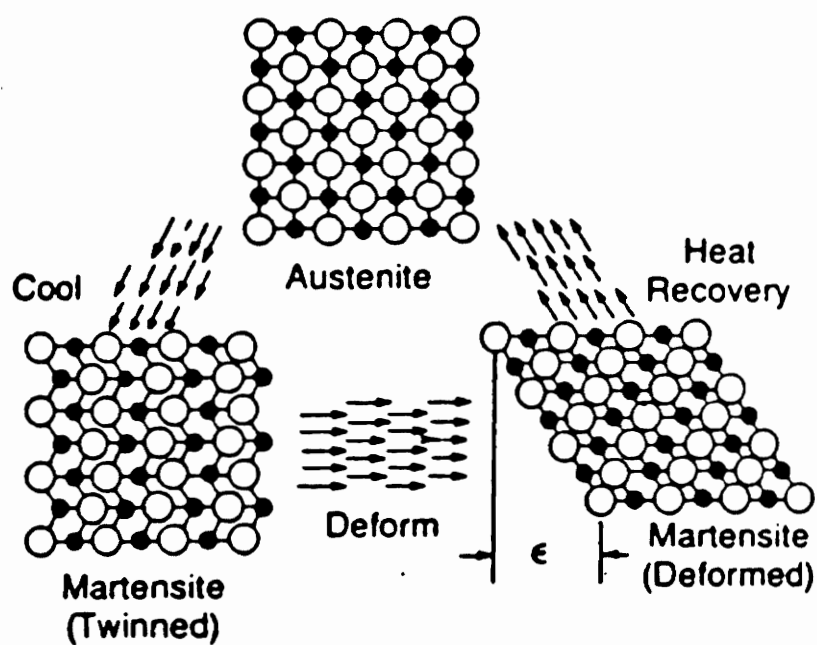
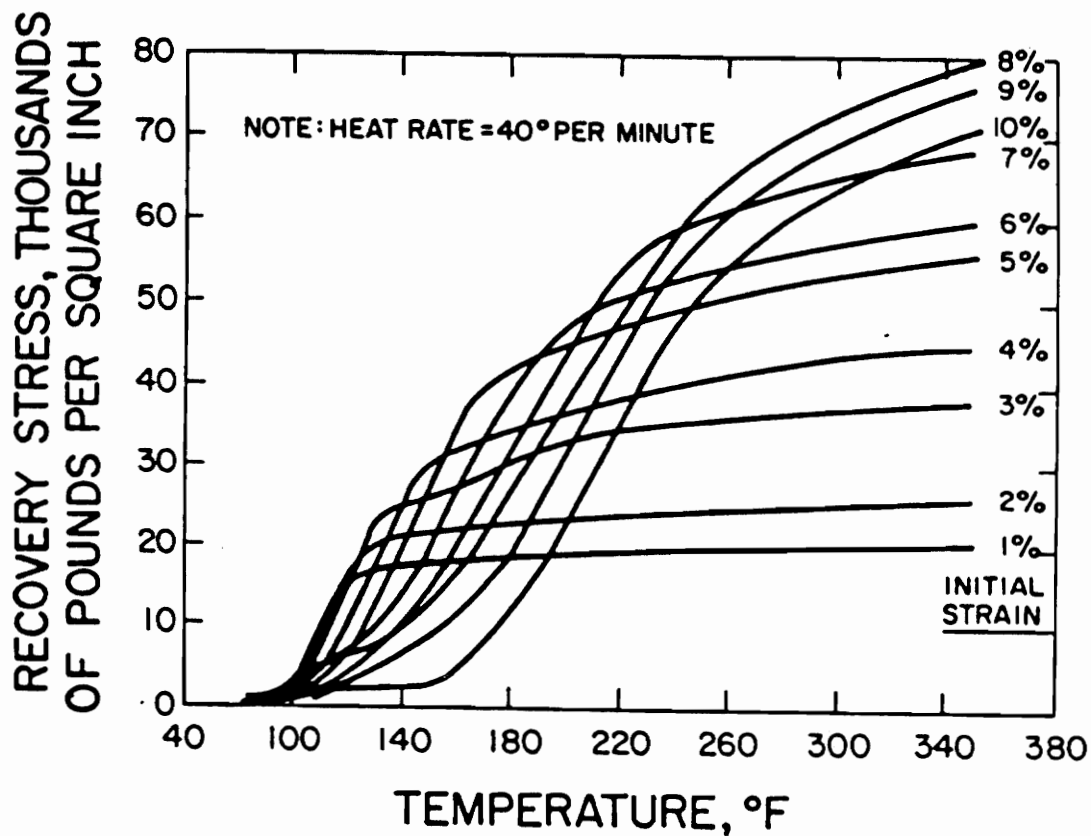


Figure 5. Shape Memory Effect of Nitinol [50].

recovery its original shape if the plastic deformation below the transition temperature does not involve diffusion or large movements of the atoms within the crystal structure. SMAs in the martensitic phase can sustain up to 8% plastic deformation without any large movements of the atomic structure. Strain in the high temperature austenite phase results in the forced formation of the martensite phase. Because the material thermodynamically prefers to be in the austenite phase, a force is required to hold the material in the strained state. This process is often referred to as strain induced martensite. A SMA in the high temperature form can be utilized as a superelastic spring able to undergo a 6% deformation without any permanent plastic deformation.

The characteristic “memorized” shape is defined, or redefined, by an annealing process. The shape memory alloy is plastically deformed to the desired memory shape and constrained. The material is then annealed at a temperature in the range of 752°F to 1472°F (400°C to 800°C). The high temperature of the annealing process relieves the residual stresses within the crystal structure due to the shape memory effect. As the shape memory alloy is slowly cooled through the high temperature parent phase (austenite for nitinol) the constrained shape of the material is memorized and a new shape memory is defined.

The thermodynamic driving force of the martensite to high temperature parent phase transformation is stronger than the yield stress of the martensite phase of the alloy. If plastically deformed nitinol is constrained from returning to its memory shape, large recovery forces can be realized during the phase transformation, and are a strong function of the amount of initial plastic deformation of the SMA in the martensite phase. This trend is shown in Fig. 6. These forces can be much larger



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 6. Nitinol Tensile Recovery Stress versus Temperature as a Function of Initial Plastic Strain [48].

than the force required to deform the material below the transition temperature. Restraining the material from regaining its memory shape can yield stresses of 100,000 psi (689 MPa). The yield strength of martensitic nitinol is approximately 12,000 psi (82.7 MPa), refer to Fig. 3. The large recovery force associated with the SME can be exploited to convert heat to work, either as a one cycle element or as a cyclic engine.

1.3.2.3 Repeatability

Deformations to the martensitic phase due to simple shearing motions in the monoclinic crystal lattice are non-damaging to the crystal structure. In normal metals, deformation occurs by the motion of dislocations and atomic planes actually slide over one another and assume a new crystal position. These large motions of the atomic planes do not allow the material to have a “memory” of its original shape before deformation. Forcing the material to return to its original shape only causes more tangles of atomic dislocations and will lead to work hardening. In SMAs deformation by changing the “tilt” of a twin orientation does not cause any dislocation motion. This shearing motion allows the material to sustain the deformation. The deformation can be recovered simply by inducing the high temperature parent phase through the addition of heat.

Although the martensitic crystal structure has the unique ability to absorb a plastic deformation for subsequent recovery upon heating, the relative amount of recoverable deformation decreases with the amount of plastic prestrain to the material in the low temperature form. Cross, et. al., [48] has shown this trend by imparting an initial plastic prestrain to a 0.020 inch (0.51 mm) diameter nitinol wire and measuring the percentage of the prestrain the nitinol was able to recover upon heating. It was

shown that the amount of recoverable prestrain continued to decrease over a period of 100 cycles. After 60 cycles the amount of recoverable prestrain remained a constant value. This trend suggests the requirement for a break in period for “virgin” nitinol.

1.3.2.4 Transformation Temperatures

The temperature at which the SMA in the martensitic phase prefers, thermodynamically, to exist in the high temperature parent phase is defined as the transition temperature. For nitinol, the transition temperature is determined by the composition of the nitinol and can be anywhere from -58°F to +311°F (-50°C to +155°C). The phase transformation associated with the SME is driven specifically by heat, therefore the rate of transformation is determined specifically by the rate heat is delivered to the structure.

There are actually four different characteristic temperatures which define the transformation from martensite to the high temperature parent phase and back to martensite. The elongation versus temperature for a nitinol sample loaded with a constant tensile stress is shown in Fig. 7. At low temperature the tensile stress is large enough to deform the shape memory alloy in the martensite phase. As the temperature is increased to the austenite start temperature (A_s) the material thermodynamically prefers to be in the austenite phase and begins to contract back to its memorized shape. The transformation is complete when the temperature reaches the austenite finish temperature (A_f). Upon cooling, the transition temperatures are different than those for heating. As the temperature is decreased to the martensite start temperature (M_s) the material thermodynamically prefers to be in the

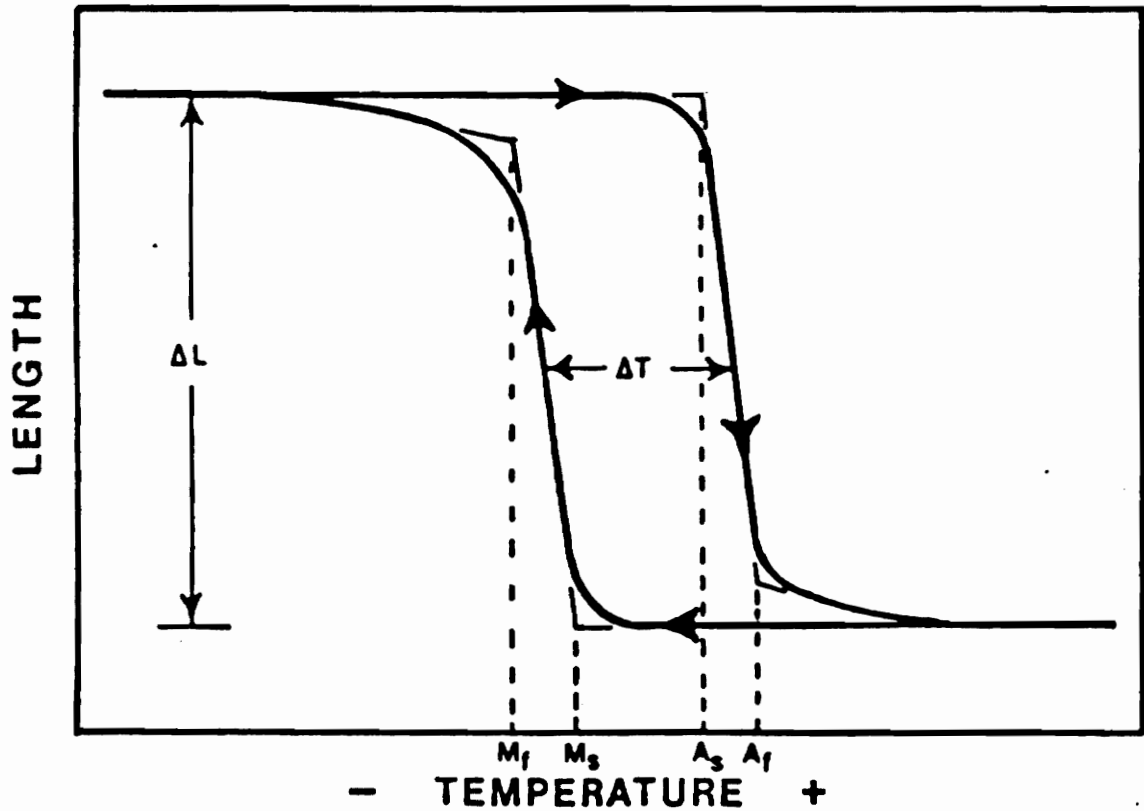


Figure 7. Typical Transformation Curve for SMA Showing Elongation and Recovery versus Temperature under a Constant Tensile Stress [50]

martensite phase and the constant tensile stress is large enough to elongate the material. The transformation is complete when the temperature reaches the martensite finish temperature (M_f).

1.3.2.5 Effects on the Transformation Temperature

Alloy composition has the largest effect on the transition temperature. An applied stress can also have an effect on the transition temperature. If an applied stress (large enough to deform the SMA in the low temperature martensite phase) is not removed as the alloy is heated, the SME can not occur until the material has gained enough heat energy to transform into the high temperature parent phase. The net effect is an increase in the transition temperatures, A_s and A_f – 1°C for every 1000 psi (6.89 kPa) applied to nitinol [50]. A reverse effect is seen upon cooling. As the temperature of the SMA is decreased the material begins to elongate and the martensite phase is induced by the applied stress. The applied stress acts as an aid to the formation of the martensite phase and the process is referred to as stress induced martensite.

If the temperature of the SMA remains above the A_f temperature, a superelastic form of the alloy exists. As the alloy is deformed from its memorized shape with an applied stress, the stress induces the martensite phase through the simple shearing of the monoclinic crystal structure. As long as no dislocations are seen by the crystal structure, the shape memory alloy will thermodynamically prefer to exist in the high temperature parent phase and the deformation will be recovered when the applied stress is relieved. If the transition temperature is defined (through alloy composition)

to be below the operating conditions, the shape memory alloy can be utilized as a superelastic material able to recover up to 6% deformation.

1.3.3 Applications

The unique characteristics of the martensitic transformation of SMAs has been exploited for use in a variety of tasks and applications. Early applications made use of SMAs as bang-bang type actuators and coupling devices. These applications focused primarily on the SMAs ability to return to its memory shape rather than its ability to achieve large recovery forces when constrained from returning to its memorized shape.

One of the first applications was a latching device for a British satellite in which a torsion tube of nitinol triggered the release of three instrument booms. The release had to be rapid and reliable in order to avoid any dynamic imbalance that might affect the stability of the spinning satellite [66].

The Raychem Corporation, having wide experience in heat shrinkable plastics, have developed coupling devices made of nitinol. One particular device solved the problem of coupling hydraulic-fluid lines in the F14 jet fighter built by the Grumman Aerospace Corporation. The coupling had to maintain its gripping integrity down to -184°F (-120°C), so the alloy had to have a transformation temperature in the cryogenic region. The couplings are expanded approximately four percent in the martensitic condition at liquid-nitrogen temperature, then placed around the tubes to be joined. During warming to room temperature, they contract, producing a tight seal. The use of such fittings avoids metallurgical degradation which can result from

welding or brazing and avoids damage to the aircraft "skin." Over 300,000 such high-performance connectors have been used in U.S. Navy aircraft with no reported failures [71].

Raychem has also produced a line of Cu-based alloy heat-shrinkable fittings in addition to other fasteners and devices. These devices can be provided in the field in the (deformed) martensitic condition at room temperature and applied simply by heating them with a propane torch [71]. A coupling of this sort is shown in Fig. 8.

SMA's have also been examined for use in the medical arena. Nitinol "butterflies" can be used to attach artificial limb joints to the existing limb. An artificial joint incorporating a nitinol butterfly can be attached to the existing limb by inserting the nitinol portion into the central hollow of the bone. The butterflies are inserted cold and expand to form a tight lock on reaching body temperature [66].

This same technique can also be used for short term healing processes. Typically severely broken bones and fractures are set with plates and screws. This process is slow and tedious. Nitinol clasps can be used to hold the damaged portion of the bone together during the healing process. Nitinol clasps are inserted cold and as the clasps reach body temperature they shrink to hold the break or fracture firmly together. It has also been shown that nitinol does not react adversely with living tissue [72].

A rather different medical application of the shape memory effect has the goal of filtering blood clots out of the circulatory system before they can do serious harm. Most clots of dangerous size form in the legs and lower trunk and travel through the veins to the heart and lungs, where they can block a vital blood vessel. Anticoagulant

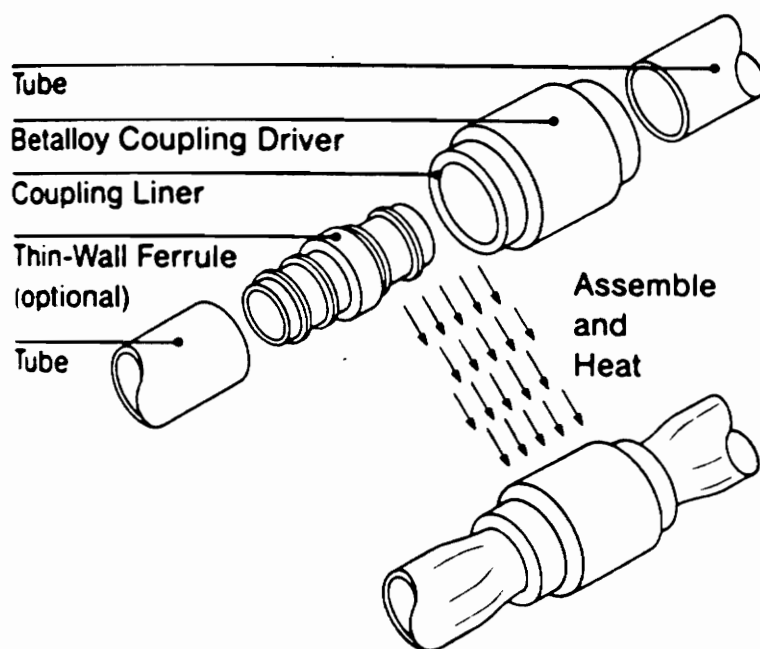


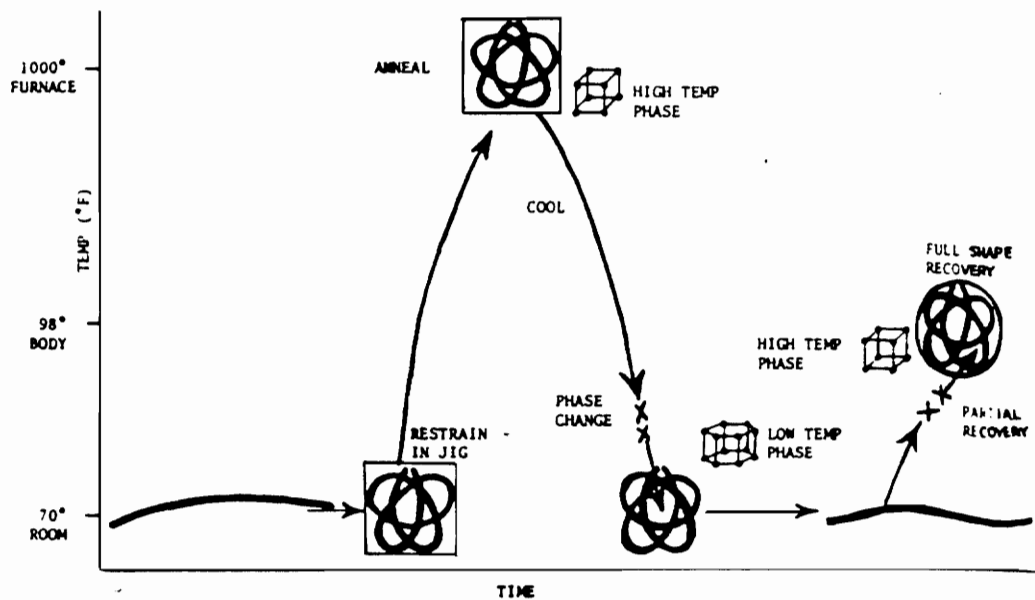
Figure 8. Nitinol Pipe Coupling Device [71].

substances, although they are extremely useful, carry risks of their own. Morris Simon of Beth Israel Hospital in Boston and the Harvard Medical School conceived the idea of fabricating a screen-like filter with a continuous length of nitinol wire. The wire can be straightened out when it is cooled below the martensite transformation temperature, chosen to be well below body temperature. As the wire is chilled to maintain its straightened condition, it can be inserted through a catheter in an arm vein into the vena cava, the large vein that feeds into the heart. As the wire warms up it assumes the screen-like form. Experiments on dogs have been encouraging [73]. The filter is shown in Fig. 9.

SMA's can also be used as both a temperature sensor and actuator device. Europa Manor Engineers Ltd. in the UK have developed and produced a greenhouse ventilator actuated by a SMA. The temperature at which the valve opens can be set by turning a knob that alters the compression on a spring acting against a spring made of the memory alloy. The characteristic of the memory spring is such that the force it exerts increases as its temperature rises [71].

A similar memory spring can regulate the clutch system that couples and uncouples the radiator fan in an automobile cooling system. Present devices operate through a viscous-fluid clutch controlled by a bimetallic spring. The memory alloy clutch eliminates the need for fluid seals and provides a more flexible speed control [66].

The Japanese have also devoted a great deal of effort to developing applications for shape memory alloys. A minimum of this work has been documented in English making it difficult to know the extent to which their developments have advanced. Some of the most notable applications involve SMA's for use as robotic actuators. Hitachi has developed a highly dextrous robot hand having nitinol joints which can



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 9. Vena Cava Filter using Nitinol Alloy [73].

flex. The SMA which forms the joints will flex and bend under the heat generated when an electric current is applied to it, emulating the human nervous system's control of the muscles in a hand [66].

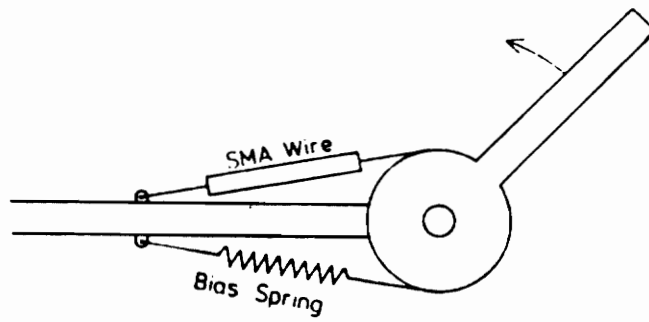
Hashimoto, et al., has also demonstrated the use of SMAs for robotic actuators [43]. The actuator can be either a biased or differential type. The biased actuator uses a spring to obtain the bias force against the unidirectional force of the SMA. The differential actuator involves the use of two opposing SMA actuators to control the actuation in an agonist/antagonist fashion, as shown in Fig. 10.

As cooling schemes are developed and higher actuation frequencies are achieved, SMAs will surely lend themselves to many new and innovative applications.

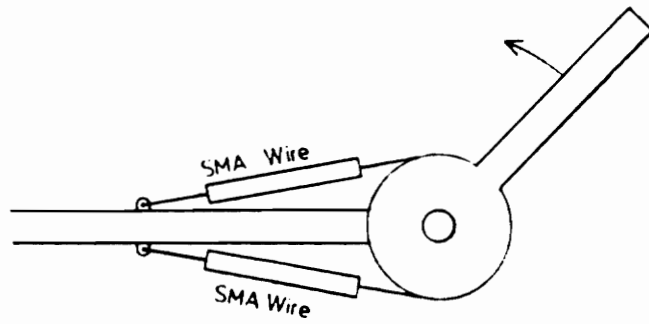
1.4 Shape Memory Alloy Composites

SMAs as fiber reinforcement can give structures numerous adaptive capabilities. Adaptive and/or smart materials, which contain distributed actuators, sensors, and microprocessor capabilities, can be used in many applications requiring a high degree of adaptability to changing external and internal conditions. External conditions may consist of environment, loads, or the desire to change the scope, purpose, or geometry of the structure after it has been built and is in service. Internal conditions may be damage or failure to isolated portions of the material or structure.

The number of applications requiring or desiring such adaptability is increasing rapidly and more are sure to follow as the technology is more readily transferred to the



(a)



(b)

Figure 10. Bias and Agonist/Antagonist Type Nitinol Actuators [43].

production level. One of the current needs is for long-duration unattended materials and structures that can be used in isolated environments (i.e., submarines, Naval vessels, defense vehicles, and the space station) or in biomedical applications. Using adaptive/intelligent materials may result in structures with self-inspection and self-identification capabilities which can direct the adaptive response based on the environment and/or damage to the structure.

The ability to adaptively alter the mission, scope, objectives, and geometry of a structure will have tremendous impact on the design philosophy of structures in the future. For example, a structural member made of SMA reinforced composites can compensate for deterioration in absorptivity and thermal expansion properties that result in excessive change in length of that or other members as well as control the motion and vibration of the structure. The same material can be used to change load paths in a structure or within the material so that the component can be replaced or repaired before it causes catastrophic failure of the system or unacceptable degradation of performance.

Applications for adaptive/intelligent SMA composites include:

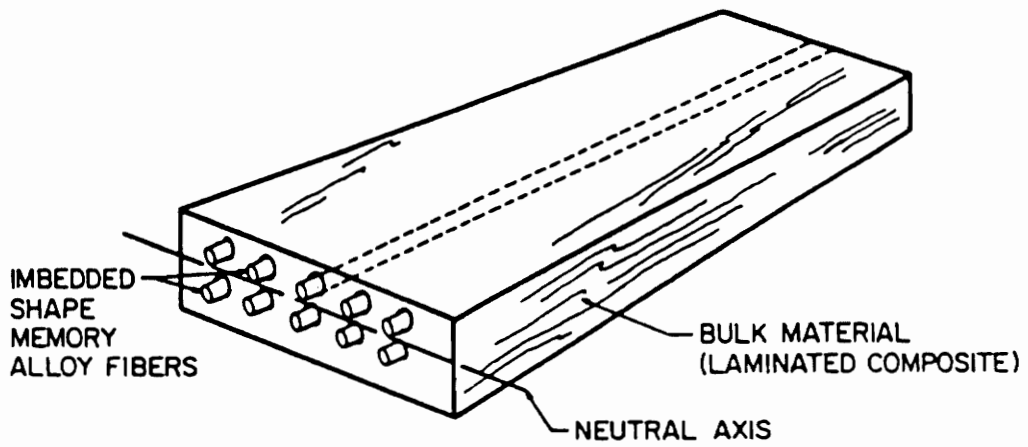
- Failure detection/prevention of structures (i.e., bridges, walkways, phone and electric cables, and mechanical components).
- Active vibration control and structural suppression for acoustic enclosures, propeller aircraft, large flexible structures, etc.
- Active vibration control of helicopter rotor blades.
- Thermal expansion balancing.
- Robot manipulators (fingers).
- Thermally activated valves and ducts.

- Thermal switches.
- Structural dimension adjustment and environment adaptation for large reflector antennas.

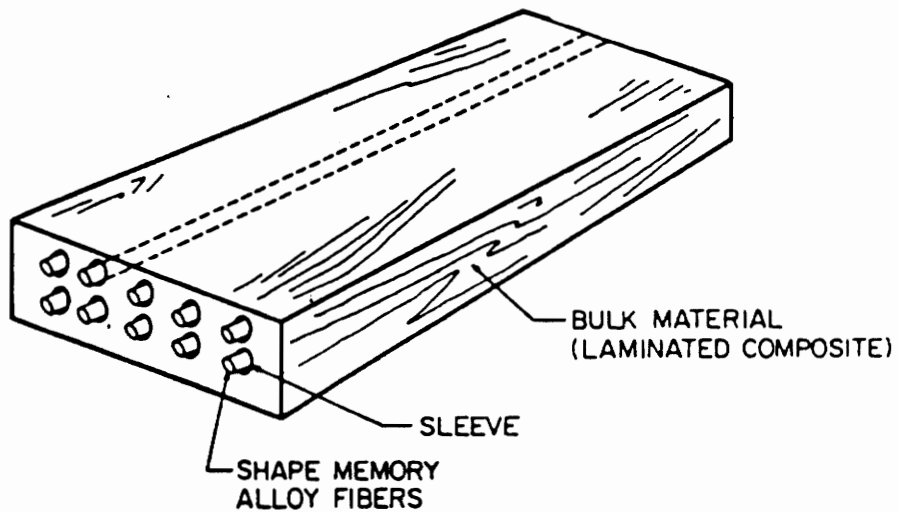
The development and subsequent production of this class of materials could have deep influence on several diverse technological fields, i.e., material science, vibrations and controls, ocean and aerospace structures, biotechnology, and may act as a catalyst for the development of many new devices and technologies. Brief descriptions of some the applications and the corresponding basic operational modes of the shape memory alloy reinforced composites appear in Ref. [67].

1.4.1 Fabrication

The class of the material referred to as SMA reinforced composites in this paper is simply a composite material that contains shape memory alloy fibers (or films) in such a way that the material can be stiffened or controlled by the addition of heat (i.e., apply a current through the fibers) [57,67]. One of the many possible configurations of the SMA reinforced composite material is one in which the SMA fibers are embedded in a material off of the neutral axis on both sides of the structure in agonist-antagonist pairs. This configuration is shown in Fig. 11. Before embedding the fibers, the SMA fibers are plastically elongated and constrained from contracting to their "normal" or "memorized" length upon curing the composite material with high-temperature. The plastically deformed fibers are therefore an integral part of the composite material and the structure. When the fibers are heated, generally by passing a current through the SMA, the fibers "try" to contract to their "normal" or



Shape Memory Alloy Fibers Laminated within a Fiber Reinforced Composite



Shape Memory Alloy Fibers Inserted in a Fiber Reinforced Composite

Figure 11. Fabrication Schemes for SMA Reinforced Composites.

"memorized" length and therefore generate a uniformly distributed shear load along the entire length of the fibers. The shear load offset from the neutral axis of the structure will then cause the structure to bend in a known and predictable manner.

There are numerous other configurations, such as creating "sleeves" within the composite laminate which the plastically elongated SMA can be inserted into and then clamped to both ends. When the SMA is heated, the fibers try to contract in the same fashion as explained above. When one end of the beam is free, the fibers in a sleeve will exert a concentrated force on the ends of the structure in a direction that is always tangent to the structure at the point where the fibers are clamped to the structure. When both ends of the beam are fixed, heating the SMA results in "fibers" with a significantly increased stiffness and applied tension that will resist any transverse motion. The difference between the embedded fibers and the fibers in a sleeve is that in the first case the force of the SMA is distributed over the length of the fiber and in the later case the force is concentrated at the end of the structure.

SMA reinforced composites have tremendous potential for creating new paradigms for material-structures interaction [17,69,70]. The list of scientific areas that can be influenced by novel approaches possible with SMA reinforced composites is quite large. For example, vibration control can be accomplished by using the distributed force actuator capabilities similar to the common piezoelectric systems. However, two unique approaches to active control are possible with a material that can change its stiffness, physical properties and in the second case, apply large distributed loads throughout the structure; i) active strain energy tuning, and ii) active properties tuning. The term active modal modification is sometimes used instead of the term active properties tuning, although the method is the same for each. The term active modal

modification is used when the approach is designed to specifically modify the dynamic or modal response of the structure.

1.4.2 Operating Principles

SMA, and nitinol in particular, have many unique characteristics and behaviors. One of the two most important characteristics from a structural control standpoint is the large change in the Young's modulus when the material transforms from the austenite to the martensite phase. The other is the characteristic shape recovery effect, which manifests itself in a remarkable restoring force and/or recovery of a tremendous amount of plastic strain. From these two basic material characteristics, two structural control schemes can be classified. The names active properties tuning (APT) and active strain energy tuning (ASET) are given to the structural control schemes which rely on embedded SMA fiber actuators or reinforcement.

For active properties tuning, a relatively large volume fraction of SMA fiber actuators are embedded in a "matrix", (which may be fiberglass, graphite/epoxy, or any other structural composite or constituents thereof). The embedded fibers are actuated by resistive heating, i.e., passing an electrical current through the fibers. Once the temperature of the fibers exceed the transition temperature, the Young's modulus of the SMA fibers may be increased in a controlled manner from 4 Mpsi to 12 Mpsi (27.6 GPa to 82.7 GPa) [64]. This change of the Young's modulus occurs over a range of approximately 9°F to 36°F (5°C to 20°C) depending on several material parameters and processing history. The temperature range is characteristic of the hysteresis associated with the twinning mechanism of the phase change. To simplify calculations,

and provide a means for assessing the authority of control, the material properties are assumed to change linearly with respect to temperature, and when appropriate are proportional to the restoring stress.

Active strain energy tuning uses the same mechanisms as described above for active property tuning but adds another important control parameter, the restoring stress associated with embedded plastically-elongated SMA fiber actuators “trying” to regain their original shape by contracting.

The SMA fibers are plastically elongated and constrained in a fixture so as not to contract during the consolidation of the “matrix” composite material that occurs typically at a temperature much higher than the phase transformation of the actuators. When the embedded actuators are heated, the fibers try to contract and therefore place the structure in a “residual” state of strain. The resulting stored strain energy (tension or compression) changes the energy balance of the structure and modifies the modal response much like tuning a guitar string or much like the variable stiffness of the human muscle.

For different boundary conditions of a SMA reinforced composite structure, i.e. a plate, the recovery force will result in quite different effects. If the plate is free at the edge, thereby allowing in-plane displacement, the recovery force caused by the SMA fibers could be modelled as a compressive in-plane load acting along the edge. If the in-plane displacement of the boundary is restrained, the result of the SMA fiber recovery force can be modelled as an in-plane tension load.

Using either active properties tuning or active strain energy tuning can result in significant control of the structural response of a composite structure. The difference

between these two concepts is that APT changes the structure response by varying the stiffness of the structure alone while ASET depends primarily on the recovery force of the plastically elongated fibers to change the structural response. ASET also relies on, to a lesser degree, the change in the Young's modulus of SMA actuators as described above in reference to APT.

2.0 Nitinol Characterization

2.1 Introduction

Active strain energy tuning (ASET) of nitinol composites utilizes plastically prestrained nitinol fibers embedded in a composite matrix. These nitinol actuators are constrained force actuators with the ability to create a distributed in-plane load within the composite in the direction of the nitinol fiber. Studies of the shape memory effect of constrained nitinol available in the literature are limited, leaving many questions unanswered. If ASET of nitinol reinforced composites is to advance past the research stage and proceed to the production stage, questions concerning the repeatability of the shape memory effect of constrained nitinol must be answered. Also, the effect of high temperatures (common to composite cure cycles and other consolidation processes) on the shape memory effect must be investigated.

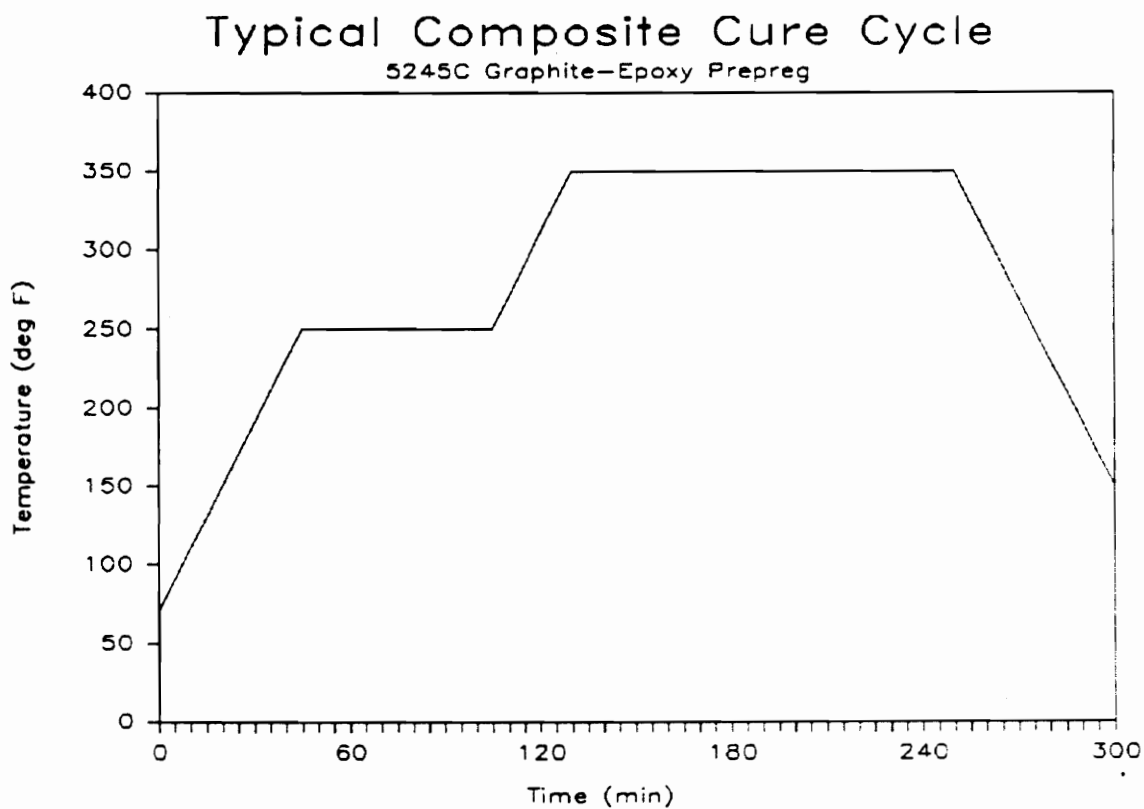
Information on the repeatability of the shape memory effect (SME) of nitinol is available in the literature [43-44], as discussed in Chapter 1. Many tests have been per-

formed to demonstrate the repeatability of shape recovery of nitinol strained from their original memory shape (i.e., tension, bending, etc.). The results of these works show that a "break-in" period is necessary to bring about a repeatable shape recovery and that the break-in period is dependent on the amount of strain from the memory shape. Extensive testing, however, has not been performed to quantify the repeatability of recovery stresses of constrained nitinol. The effect on the maximum recovery stress as a function of the length of time at temperatures above the austenite start, A_s , and below the austenite finish, A_f , has not been characterized either.

Composites must undergo a cure cycle during the fabrication process. Many composites demand cure cycles with temperatures reaching 350°F (177°C) for extended periods of time (up to two hours), as shown in Fig 12. Annealing (re-defining the memory shape) of nitinol specimens has been successful at temperatures as low as 750°F (399°C) [44]. Although annealing temperatures are much greater than temperatures seen by composite cure cycles, the effect of cure temperatures greater than the austenite finish temperature, A_f , must be investigated. The permanence of the change in maximum recovery stress as a result of composite cure temperatures must be evaluated as well.

The intent of the testing and characterization that follows is to demonstrate the changes in the maximum recovery stress and the unrecoverable residual stress of constrained nitinol fibers as a result of:

- number of cycles that the fiber is heated to, or above, the austenite finish temperature, A_f , and then cooled below the austenite start temperature, A_s
- length of time at, or above, the austenite finish temperature, A_f



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

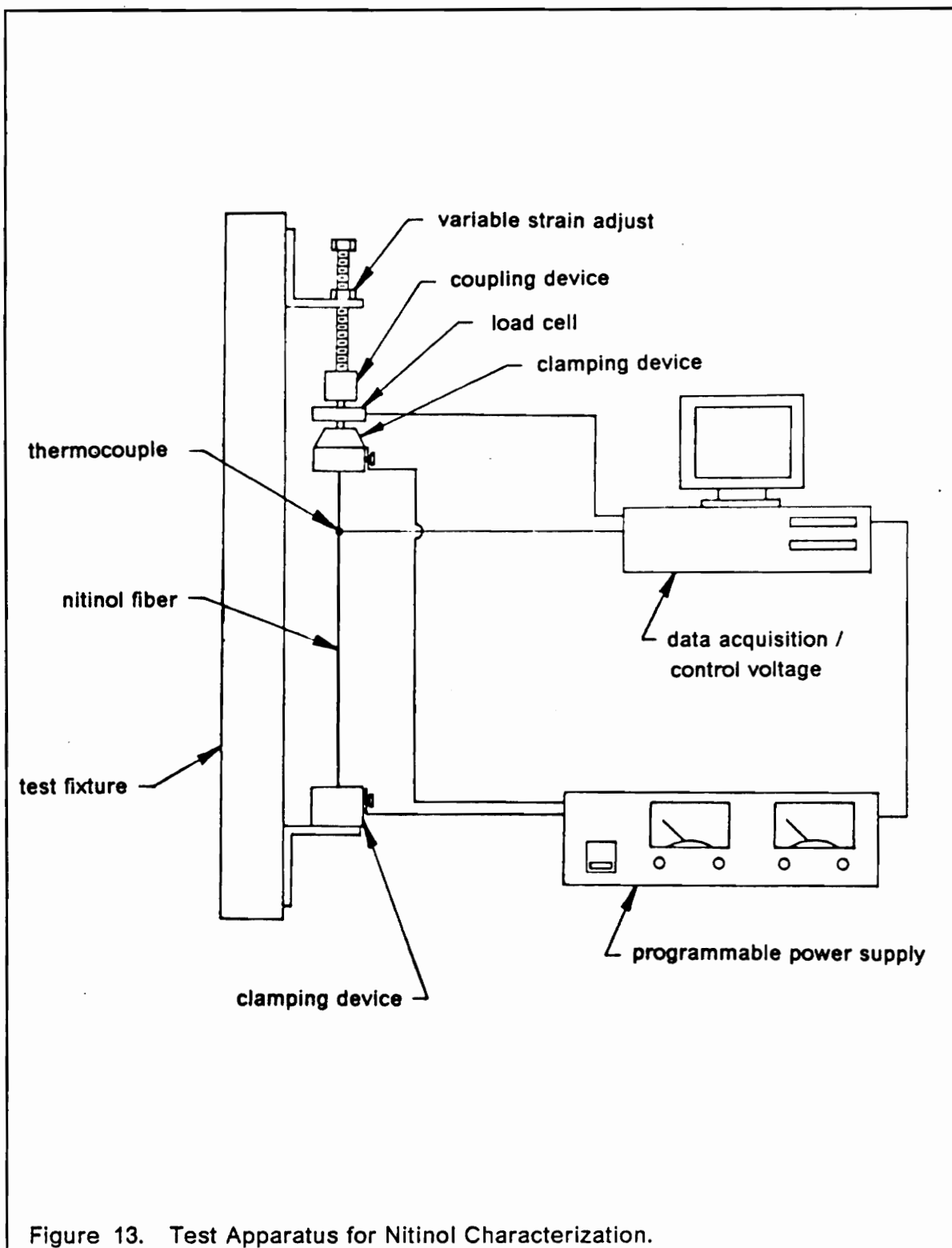
Figure 12. Typical Composite Cure Cycle, Temperature versus Time.

- high temperatures of the composite cure cycle
- length of time at a temperature below the austenite start temperature, A_s , after the composite cure cycle.

The results of the following characterization are used to determine the available range of recovery stress in a nitinol composite. The available range is defined by the difference between the maximum recovery stress and the unrecoverable residual stress. This range of available recovery stress is used in the simulation of active strain energy tuning. The results discussed below also show the need for a more thorough investigation of the shape memory effect of plastically prestrained and constrained nitinol fibers and provides useful insight and suggestions for the direction of future research.

2.2 Test Apparatus and Procedure

The test fixture and apparatus used to characterize the recovery stress of constrained nitinol fibers is shown in Fig. 13. A nitinol fiber is constrained at both ends between the clamping devices. The fiber is strained by adjusting the distance between the clamping devices using the variable strain adjust. The variable strain adjust is simply a bolt and nut. The distance is determined by pulling the bolt axially until the required distance is obtained. The nut is then positioned against the upper constraint as shown to maintain the required distance. A load cell (A. L. Design, Inc., 10 lb load cell, S/N 890313) is located between the nitinol and the upper constraint. The load



cell is used to measure the recovery force of the nitinol fiber. Conversion to stress is made by dividing the force measurement by the fiber cross-sectional area. A thermocouple (Omega, E-type, Chromel-Constantan thermocouple) is used to measure the temperature of the nitinol fiber. A programmable power supply (HP-6268B programmable DC power supply) is used to apply a current through the nitinol fiber, thus heating the fiber utilizing the high resistance of the nitinol. The power supply is controlled using a PC-AT computer and appropriate control logic with D/A conversion (Data Translation, Inc., DT2801 A/D and D/A board). The computer and A/D board are also used to store temperature and corresponding force data.

A brief discussion on the accuracy of the thermocouple measurement is necessary. The nitinol fiber is heated by applying an electric current through the fiber. Because the thermocouple measurement is based upon a voltage difference at the junction, the thermocouple must be isolated from voltage potentials and electric current external to the thermocouple. This is achieved by coating the entire length of the nitinol fiber with teflon tape. Coating the entire length of the nitinol fiber insures uniform heating. The measured temperature is actually the temperature of the surface of the teflon tape. One would expect a thermal time constant and temperature difference to exist between the temperature of the nitinol fiber and the surface of the teflon tape. These variables are not quantified because the intent of this work is only to determine trends and the extreme recovery stress of nitinol fibers for use as constrained force actuators. Therefore the thermal time constant, temperature difference, and corresponding discrepancy in the apparent and actual temperatures is merely stated as an inherent factor in the data. The nitinol characterization studies that follow should not be used to relate recovery stresses to a specific temperature, but should be in-

terpreted as extreme values of residual and recovery stress that can be exploited for use as a constrained force actuator.

Test matrices for the characterization of constrained nitinol fibers are shown in Tables 1 and 2. Each matrix represents one fiber and associated tests performed in the order shown in the tables. Detailed descriptions of the test procedures are given below.

Testing proceeds as follows. A length of unstrained nitinol fiber – 0.015 inch (0.38 mm) diameter; transition temperature, A_s , of 100°F (38°C); and 22.50 inches (57.2 cm) unstrained memory length – is constrained in the test fixture and given a 5% strain from the memory length using the variable strain adjust. This gives a final constrained length of 23.63 inches (60.0 cm).

Recovery stress versus temperature cycles are characterized by heating the fiber to a desired temperature and then cooling back to near room temperature. Heating occurs by applying a current through the fiber. The magnitude of the current is determined by computer and a command algorithm. The command signal from the computer is a ramp function. Current from the power supply is therefore a ramp function as well. The rate at which the fiber is heated is controlled by defining the slope of the command signal, dV_0/dt ; where V_0 is the control voltage to the power supply. The fiber is cooled by decreasing the magnitude of the current across the fiber using a ramp function of decreasing magnitude. The fiber therefore cools by natural convection. The rate of cooling is also controlled by defining the slope of the command signal. Heating and cooling occur at a rate of approximately 15°F/min (8°C/min).

Table 1. Test matrix for nitinol characterization, fiber A

0.015 inch (0.38 mm) diameter, A _s = 100°F (38°C), 5% strain from memory length	
Test	Description
1	recovery stress versus temperature cycles 1 through 4
2	maximum recovery stress versus no. of cycles cycles 5 through 40
3	simulated composite cure cycle
4	recovery stress versus temperature immediately following cure cycle
5	recovery stress versus temperature 24 hours after completion of cure cycle

Table 2. Test matrix for nitinol characterization, fiber B

0.015 inch (0.38 mm) diameter, A _c = 100°F (38°C), 5% strain from memory length	
Test	Description
1	maximum recovery stress versus temperature cycles 1 through 3, hold at fully activated temperature for 30 minutes
2	maximum recovery stress versus no. of cycles cycles 4 through 40
3	recovery stress versus temperature immediately following completion of cycle no. 40
5	recovery stress versus temperature 24 hours after completion of cycle no. 40

Temperature and corresponding restoring stress data are stored at a sample rate of approximately 8 samples/sec during both the heating and cooling process. Stress and temperature are sampled over time, so the data must first be manipulated to allow stress to be characterized as a function of temperature. This is required for both the heating and cooling process. A simple algorithm collects all values of stress corresponding to a specific temperature plus or minus 0.05°F (0.03°C). These values of stress are then used to compute an average value of stress for the specific temperature. Temperature is indexed through the range of the sampled data to give stress versus temperature data with a resolution of 0.10°F (0.06°C). This process is then repeated for the cooling data. Average recovery stress versus apparent temperature, for both heating and cooling, is characterized in this fashion.

Cycle testing continues by heating the fiber to the fully activated (austenite) phase and then cooling back to near room temperature over 40 cycles. Heating and cooling occurs as described above. The fully activated recovery stress is recorded for each cycle and the fully activated recovery stress is characterized as a function of number of cycles. The recovery stress versus temperature of the cycled nitinol is then characterized as described above.

A variation on the cycle testing procedure is performed by holding the temperature of a new uncycled fiber at the fully activated state for 30 minutes for each cycle. This allows the fully activated recovery stress to be characterized as a function of length of time in the fully activated state as well as a function of number of cycles.

A composite cure cycle is simulated by subjecting the constrained nitinol fiber to a typical temperature versus time characteristic shown previously in Fig. 12 on page 56. The temperature is raised to 250°F (121°C) at a rate of approximately 3°F (2°C)

per minute and held for one hour. The nitinol fiber is then raised to a temperature of 350°F (177°C) at a rate of approximately 3°F (2°C) per minute and held at that temperature for two hours. The nitinol fiber is then cooled to 150°F (66°C) at a rate of approximately 3°F (2°C). At this point the fiber is allowed to cool to room temperature by natural convection. Heating and cooling is performed as described above. Temperature and corresponding stress measurements are stored at a rate of one sample per minute. The recovery stress versus temperature of the cured nitinol is then characterized as described above.

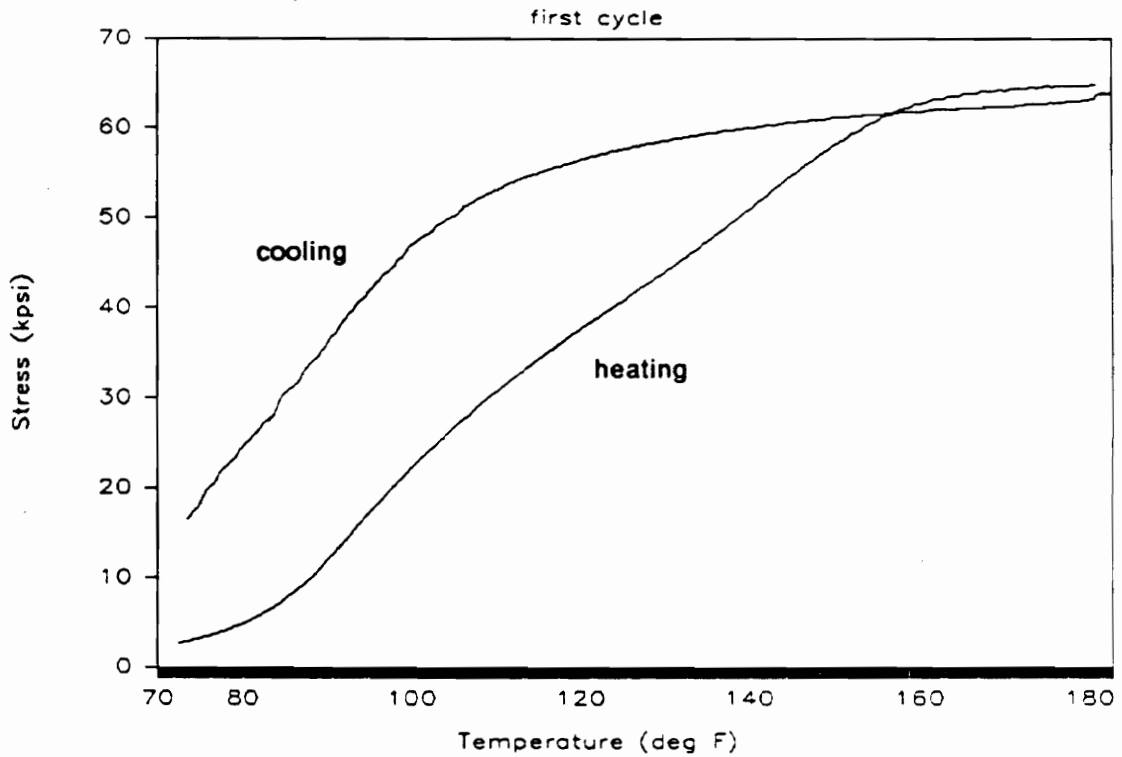
2.3 Results

2.3.1 Recovery Stress as a Function of Temperature

The recovery stress versus temperature of the first cycle of a constrained nitinol fiber – 0.015 inches (0.38 mm) diameter and transition temperature, A_s , of 100°F (38°C) – is shown in Fig. 14. Stress is calculated by dividing the measured force by the fiber cross-sectional area.

At the start of the test, the temperature of the nitinol fiber is 72°F (22°C). This temperature is below A_s , therefore the the fiber is in the fully martensitic phase and there is no stress in the fiber as a result of the shape memory effect. The stress at this temperature is caused by the unrecovered elastic prestrain introduced during the 5% strain from the memory length. As the constrained nitinol fiber is heated, the stress

Recovery Stress of Constrained Nitinol



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 14. Recovery Stress versus Temperature for Constrained Nitinol, first cycle.

within the fiber increases with increasing temperature to a maximum of 65 kpsi (448 MPa).

The nitinol fiber is allowed to cool to room temperature through natural convection. The recovery stress upon cooling involves a hysteresis effect, not following the path taken upon heating. Instead, the recovery stress for corresponding temperatures is higher upon cooling than upon heating. It should also be noted that the stress at room temperature at the end of the test is higher than at the start of the test. This residual stress corresponds to the true unrecoverable elastic strain due to the 5% strain introduced to the memory length of the nitinol fiber during the set-up procedure. One would expect the unrecoverable residual stress to increase for the first activation cycle. As the nitinol fiber is heated for the first time, the SME allows the fiber to contract to a completely taut position, thus regaining any slack in the fiber introduced during the set-up procedure. This first activation cycle can be thought of as an initialization cycle.

It should also be noted that the measured temperature does not correspond to the temperature of the nitinol fiber. As discussed above, this is caused by the thermal time constant and temperature difference between the nitinol fiber and the surface of the teflon tape where the temperature is measured. It is stated again that references to a specific temperature should not be made.

2.3.2 Repeatability of Shape Memory Effect

Testing proceeds by heating a prestrained and constrained nitinol fiber to the fully activated (austenite) state and then cooling back to room temperature over a number

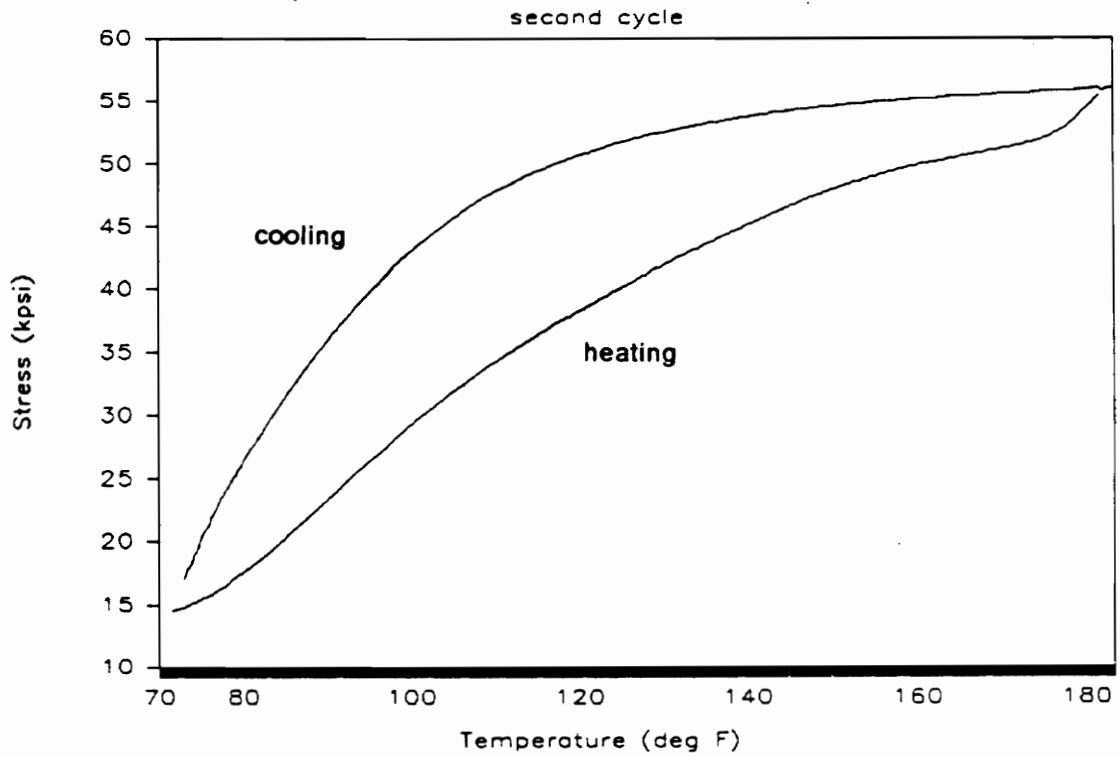
of cycles. Temperature and stress measurements are made in the fashion described above. The first four activation cycles of the constrained nitinol fiber discussed above are shown in Fig. 14 on page 65 and Figs. 15-17.

It should immediately be noticed that the maximum recovery stress decreases dramatically over the first four cycles from 65 kpsi (448 MPa) for the first cycle to 51 kpsi (352 MPa) for the fourth cycle. The residual stress in the unactivated (martensite) state remains constant at 15 kpsi (103 MPa) after the first cycle. Another trend apparent in the first four activation cycles is that the hysteresis effect tends to decrease as a function of the number of cycles. These trends suggest the existence of a break-in period similar to that for displacement type nitinol actuators.

A new unstrained nitinol fiber, having the same diameter, transition temperature, and unstrained memory length, is constrained and given a 5% strain as described above. The fiber is cycled to its activated (austenite) state and back to its unactivated (martensite) state 40 times. The activated state is determined by referring to the recovery stress versus temperature curves for the previous fiber, Figs. 14-17. The nitinol fiber is at or near its fully activated state (or austenite phase) at a temperature reading of 160°F (71°C) which corresponds to the austenite finish temperature, A_f , of the nitinol fiber. The fiber is heated to this "activated" temperature and then allowed to cool to near room temperature. The recovery stress is recorded at 160°F (71°C) for each cycle. The activated recovery stress for each cycle is shown in Fig. 18. The maximum recovery stress for the first four cycles of the previous fiber are also shown for comparison.

The activated recovery stress decreases from 61 kpsi (421 MPa) to a repeatable value of 44 kpsi (283 MPa) after 6 cycles. The activated recovery stress for the first cycle

Recovery Stress of Constrained Nitinol

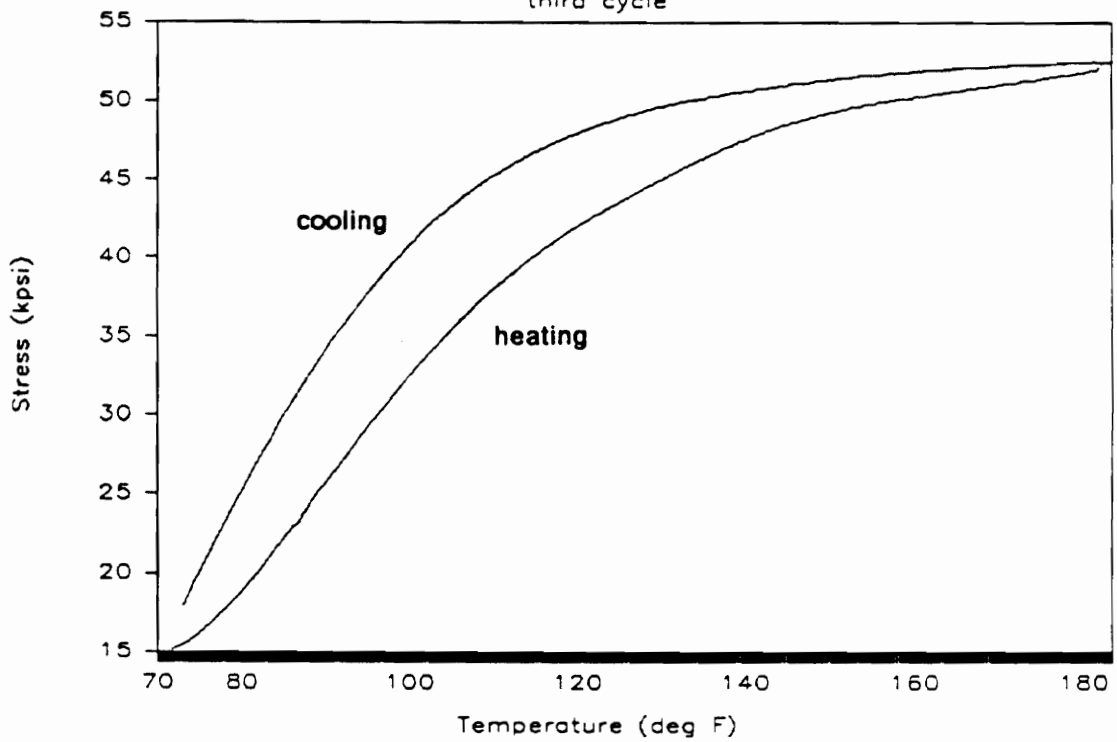


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 15. Recovery Stress versus Temperature for Constrained Nitinol, second cycle.

Recovery Stress of Constrained Nitinol

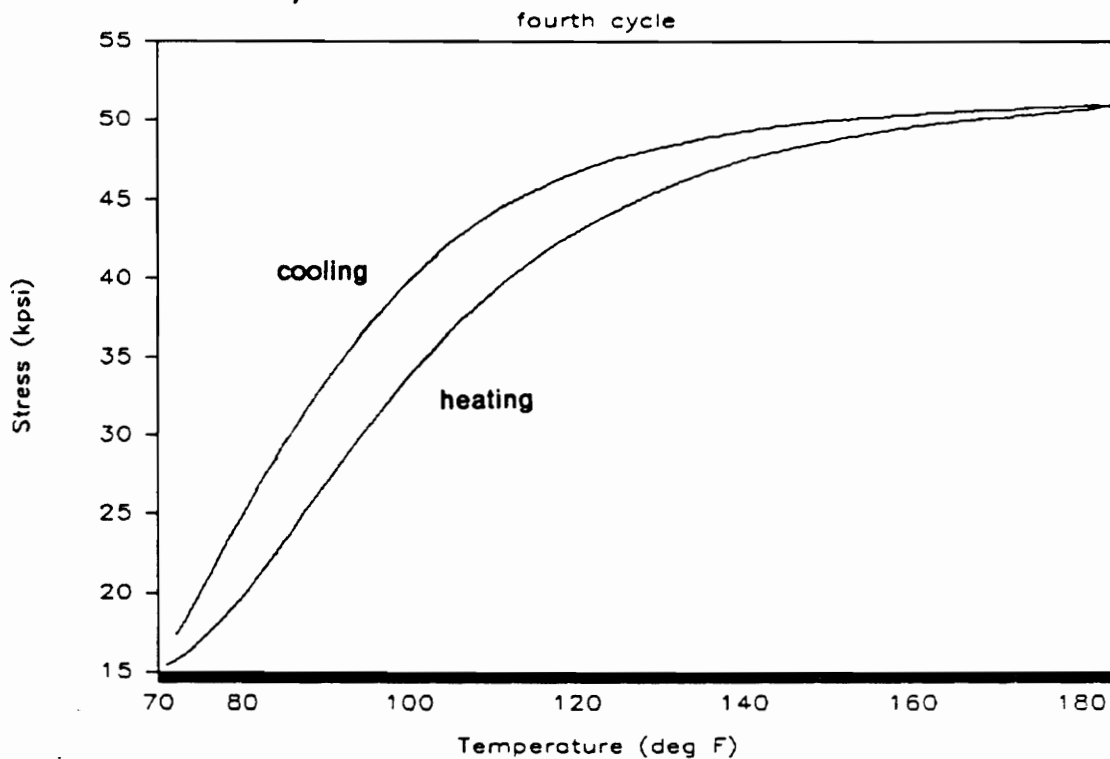
third cycle



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 16. Recovery Stress versus Temperature for Constrained Nitinol, third cycle.

Recovery Stress of Constrained Nitinol

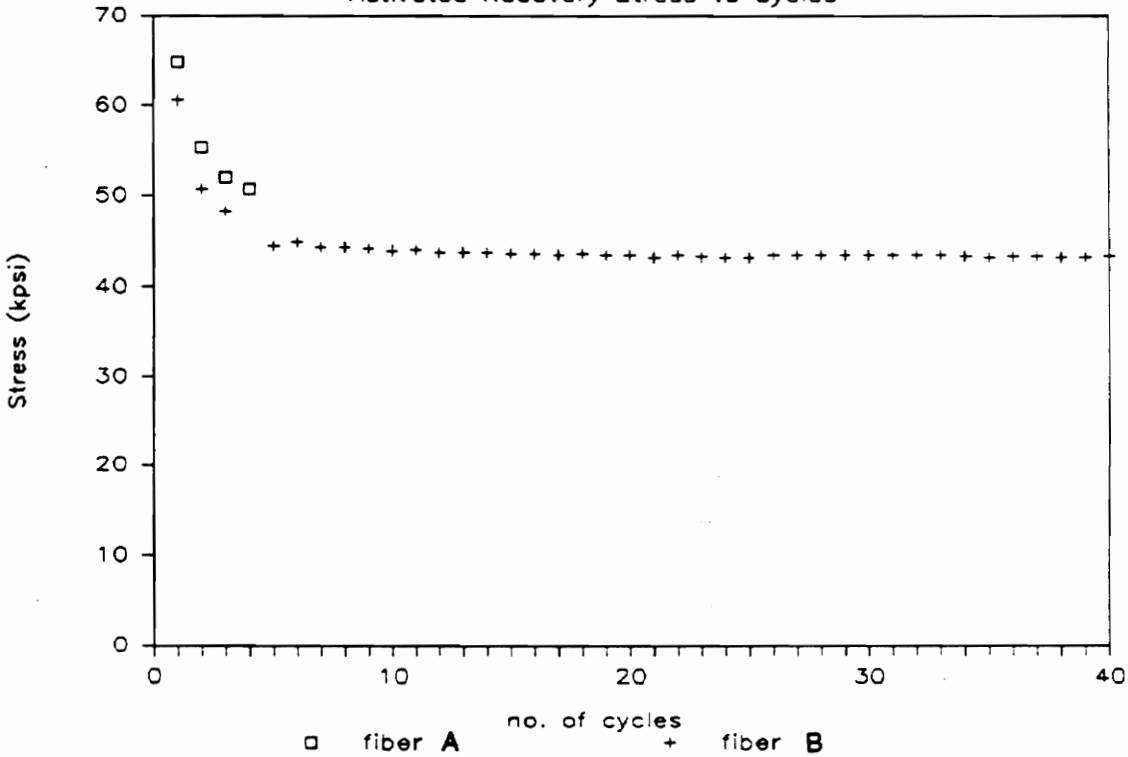


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 17. Recovery Stress versus Temperature for Constrained Nitinol, fourth cycle.

Cycle Test of Constrained Nitinol

Activated Recovery Stress vs Cycles



$$1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 18. Activated Recovery Stress versus Number of Cycles.

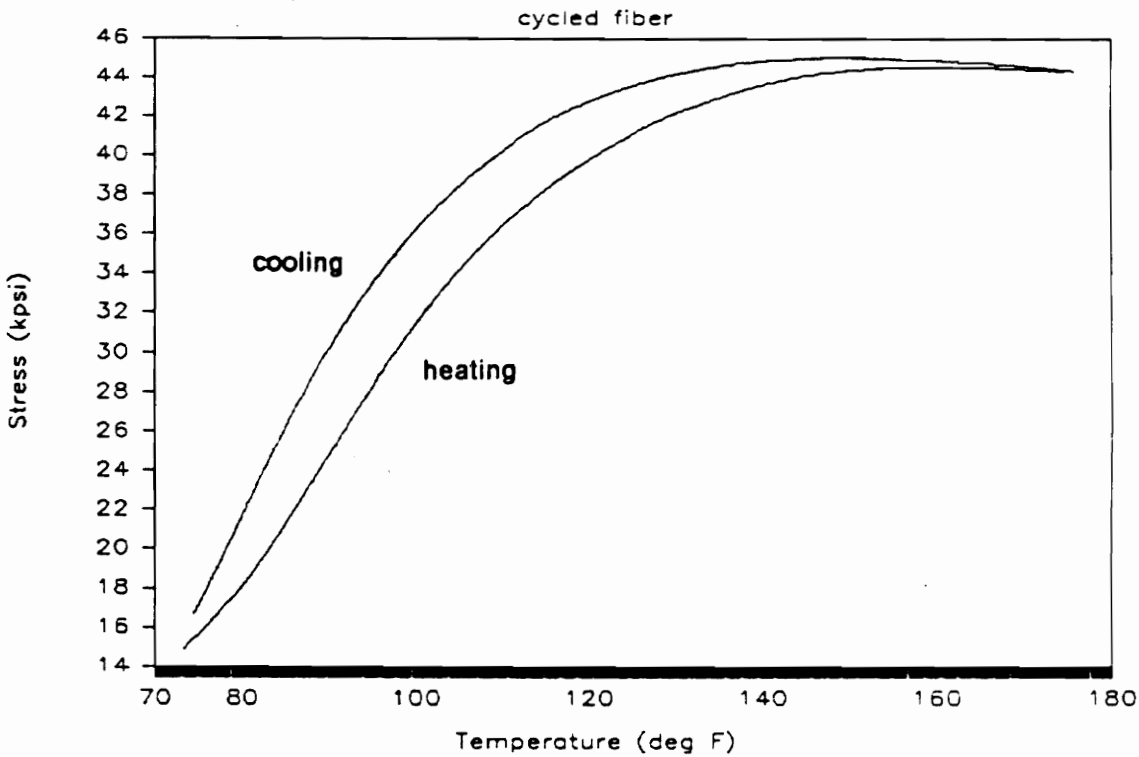
of the previous fiber (fiber A) is higher than that for the first cycle of the present fiber (fiber B). This is because of the choice of the "fully activated" temperature of 160°F (71°C). The recovery stress continues to increase by a small amount at temperatures above 160°F (71°C). This is shown in the recovery stress versus temperature curve for fiber A (refer to Fig. 17 on page 70). Although the present fiber is not heated to the fully activated level, it is heated to a near fully activated level. The recovery stress versus temperature for the cycled fiber is shown in Fig. 19. The maximum recovery stress has decreased from 65 kpsi (448 MPa) for the first cycle (refer to Fig. 14 on page 65) to a repeatable value of 44 kpsi (303 MPa) after 6 cycles.

The first three cycles of the cycled fiber are held at the activated temperature for a period of 30 minutes. The temperature is held constant at 160°F plus or minus 2°F (71°C plus or minus 1°C). The recovery stress versus time for the third cycle is shown in Fig. 20. The recovery stress remains constant with time once it has reached its activated level. This suggests that the break-in period for nitinol is due to the number of cycles and not the length of time at an activated temperature. The results of these tests indicate the recovery stress of a constrained nitinol fiber will reach a repeatable level after the fiber has been cycled 6 times.

2.3.3 Effect of Composite Cure Cycle

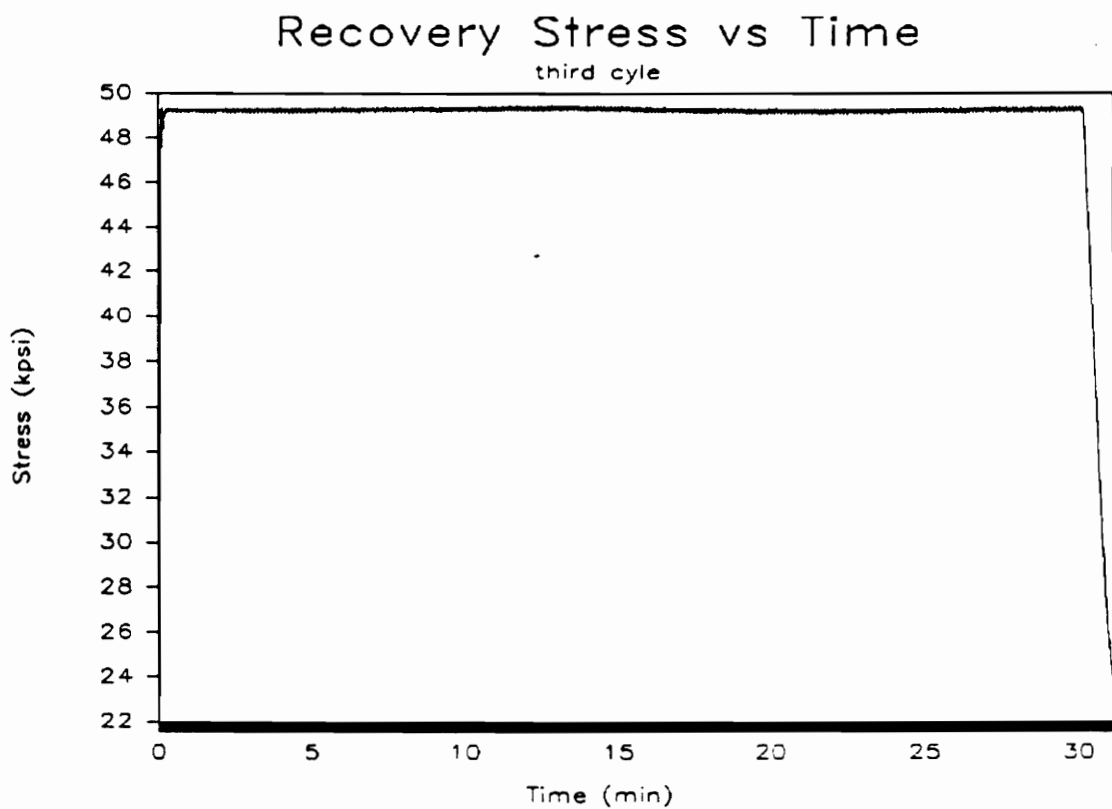
A nitinol fiber – 0.015 inch (0.381 mm) diameter, austenite start temperature, A_s , of 100°F (38°C), and unstrained memory length of 22.5 inches (57.2 cm) – is constrained in the test fixture and given a 5% strain from the unstrained memory length. A composite cure cycle is simulated as shown in Fig. 21. Temperature is maintained

Recovery Stress of Constrained Nitinol



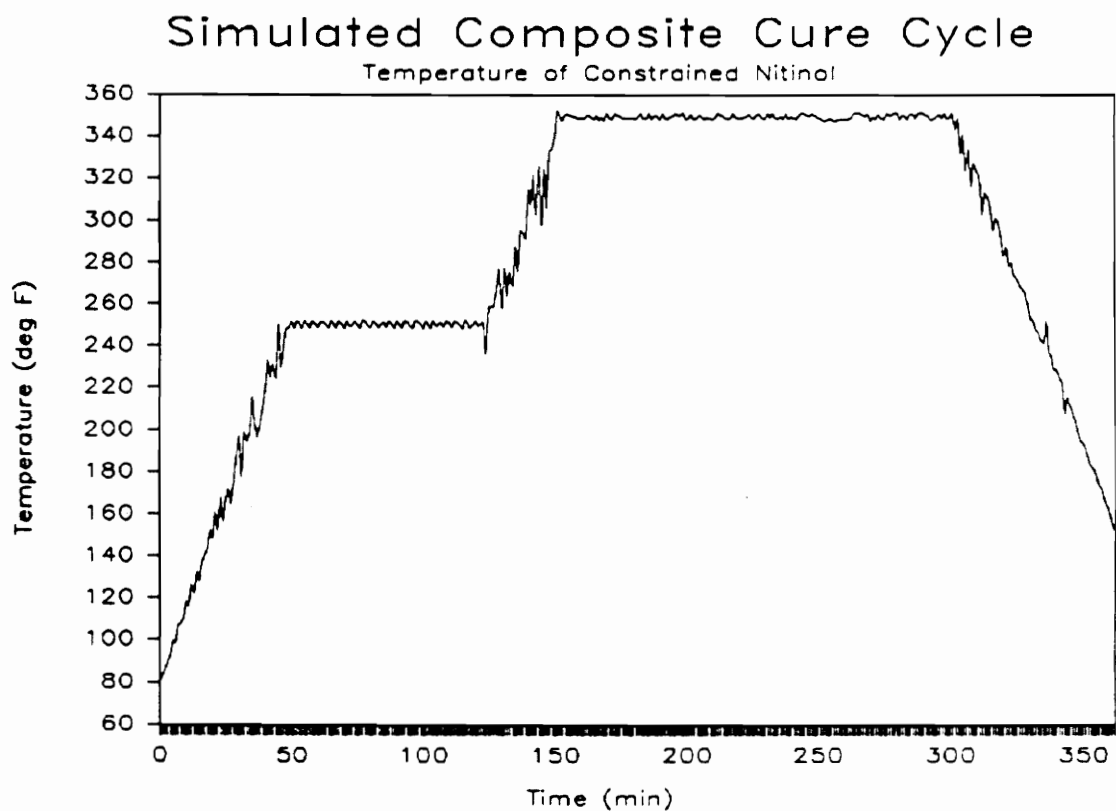
$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \qquad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 19. Recovery Stress versus Temperature for Constrained Nitinol, cycled fiber.



$$1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 20. Activated Recovery Stress versus Time at Constant Temperature for Constrained Nitinol.



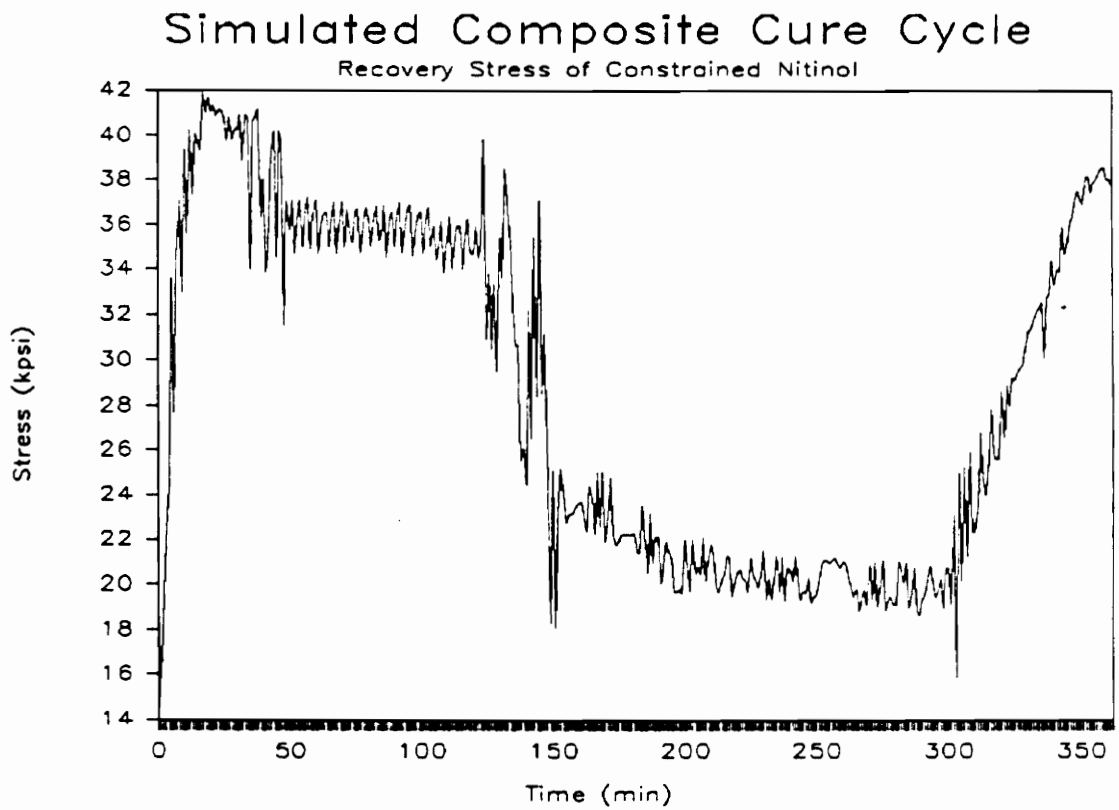
$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 21. Simulated Composite Cure Cycle, Temperature versus Time.

at a specific level using a closed loop control algorithm based upon feedback of the thermocouple measurement. The temperature is raised to 250°F (121°C) at a rate of approximately 3°F (2°C) per minute. The temperature is held at 250°F (121°C) plus or minus 2°F (1°C) for one hour. The nitinol fiber is then raised to 350°F (177°C) at a rate of approximately 3°F (2°C) per minute. A large amount of scatter in the temperature is present during the rise to 350°F (177°C). The error between the command temperature and the actual temperature is as high as 10°F (4°C). The temperature is held at 350°F (177°C) plus or minus 2°F (1°C) for two hours. The nitinol fiber is then cooled to 150°F (66°C) at a rate of approximately 3°F (2°C). At this point the fiber is allowed to cool to room temperature by natural convection.

The recovery stress versus time can be seen in Fig. 22. The fluctuation in the recovery stress is a result of the fluctuation of the temperature. Large fluctuation in the temperature between the one hour hold at 250°F (121°C) and the two hour hold at 350°F (177°C) results in a large fluctuation in the recovery stress. The recovery stress is very sensitive to temperature in this region.

The recovery stress increases as a function of temperature up to approximately 170°F (77°C) and then decreases as a function of temperature. At the point where temperature is held at 250°F (121°C) for one hour, the recovery stress remains relatively constant. As the temperature is increased towards 350°F (177°C), the recovery stress continues to decrease with increasing temperature. During the two hour hold at 350°F (177°C), the recovery stress does not remain constant. The recovery stress decreases as a function of time to a relatively stable level after approximately one hour. The drop in recovery stress over the two hour hold amounts to about 4 kpsi (28 MPa). As the temperature is decreased towards room temperature, the recovery



$$1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 22. Simulated Composite Cure Cycle, Recovery Stress versus Time.

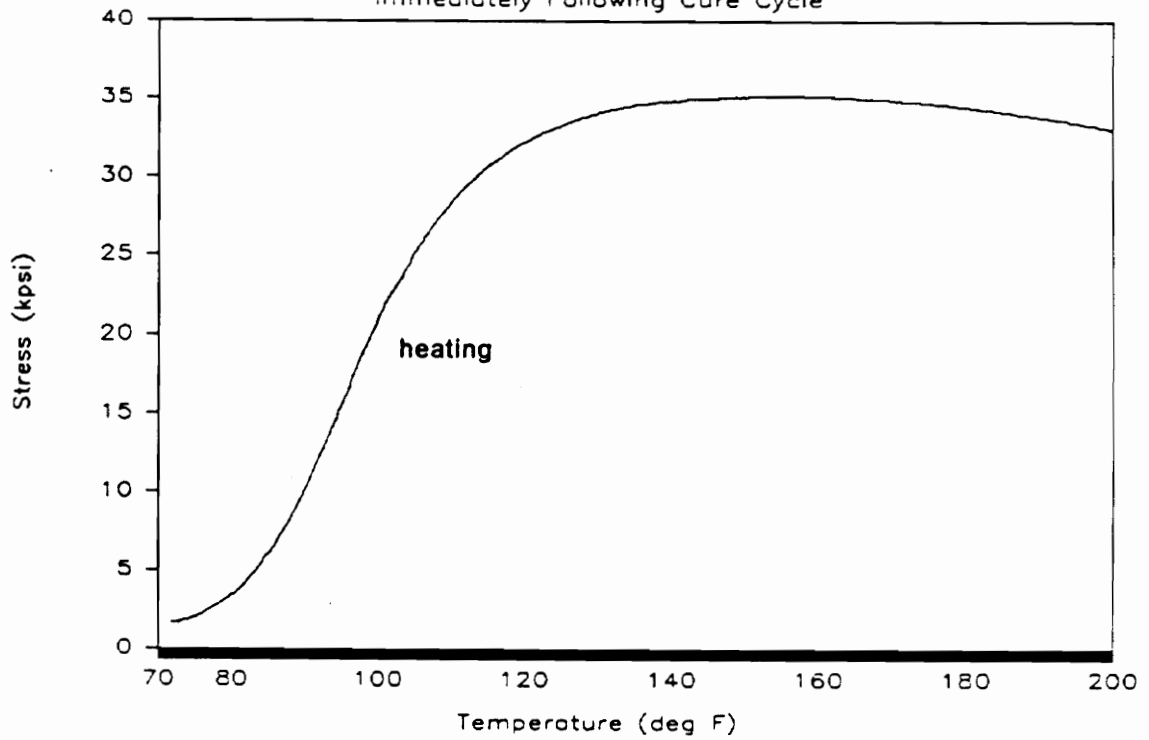
stress increases with decreasing temperature down to 160°F (71°C). It is interesting to note that the difference between the maximum recovery stress upon heating and the maximum recovery stress upon cooling amounts to about 4 kpsi (28 MPa) which is the same amount lost during the two hour hold at 350°F (177°C). As the temperature continues to decrease, the recovery stress decreases.

A recovery stress versus temperature curve is shown for the nitinol fiber immediately following the simulated composite cure cycle in Fig. 23. The recovery stress has decreased from 44 kpsi (303 MPa) for a cycled fiber (refer to Fig. 19 on page 73) to 35 kpsi (241 MPa) for the fiber immediately following the composite cure cycle. Another interesting note is that the residual stress has decreased from 15 kpsi (103 MPa) for a cycled fiber to 1.6 kpsi (11 MPa).

A strange phenomenon is noticed. The fiber is left constrained in the fixture at room temperature for a period of approximately 24 hours. After this period of time, the recovery stress versus temperature is again characterized. The results of this test are shown in Fig. 24. The recovery stress has increased from 35 kpsi (241 MPa) immediately following the cure cycle to 44 kpsi (303 MPa) which is the same value found after cycling (refer to Fig. 19 on page 73). The recovery stress has somehow been restored to its previous value before the composite cure cycle. This author has no reasonable explanation for this interesting phenomenon. It should also be noted that the residual stress has not regained its value before the cure cycle. In fact, the residual stress has decreased from 1.6 kpsi (11 MPa) immediately following the cure cycle to 1.0 kpsi (6.9 MPa) 24 hours after the completion of the cure cycle. This has interesting implications as to the potential of nitinol as a constrained force actuator. By subjecting the constrained nitinol fiber to the high temperatures of the composite

Recovery Stress of Constrained Nitinol

Immediately Following Cure Cycle

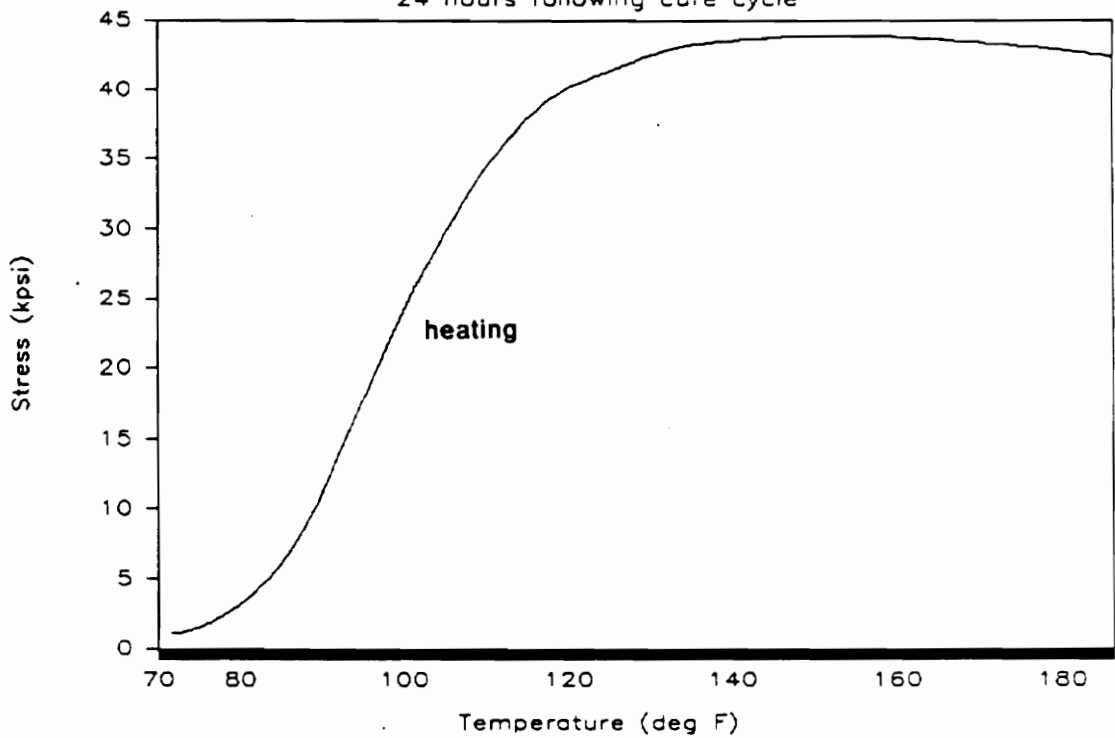


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 23. Recovery Stress versus Temperature, immediately following composite cure cycle.

Recovery Stress of Constrained Nitinol

24 hours following cure cycle



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 24. Recovery Stress versus Temperature, 24 hours after completion of composite cure cycle.

cure cycle, the range of actuation has been increased from 29 kpsi (200 MPa) for a cycled fiber (refer to Fig. 19 on page 73) to 43 kpsi (296 MPa). Subjecting a constrained force actuator to high temperatures (in comparison to A_r and well below the annealing temperature) may prove to be an effective means of maximizing the potential of the actuator.

2.4 Summary

Constrained nitinol fibers typical of those used as embedded actuators in nitinol composites have been investigated. Maximum values of the recovery stress and the residual stress at room temperature for a constrained fiber have been determined. The repeatability of the recovery stress and the residual stress has also been shown. The effect of high temperatures (typical of composite cure cycles) was shown to have a limited effect on the SME of constrained nitinol fibers. The results of this study are used in the theoretical simulation of nitinol composites.

The intent of this characterization is to show the changes in the maximum recovery stress at the A_r temperature and residual stress below the A_r temperature due to the number of cycles the fiber was heated and cooled, length of time at the A_r temperature, and high temperatures of composite cure cycles. These effects were demonstrated and the results are summarized as follows:

- A break-in period of six or more cycles is required to achieve a repeatable maximum recovery stress.

- Cycling does not have any effect of the residual stress.
- The length of time at a temperature above A_s and below A_f does not have any effect on the maximum recovery stress.
- The composite cure cycle does not have a lasting effect on the maximum recovery stress.
- The composite cure cycle reduces the residual stress dramatically.

This experimental study has shown that the available range of recovery stress in a nitinol reinforced composite is 43 kpsi (296 MPa). This range of recovery stress is the range used in the theoretical simulation of ASET of the nitinol reinforced composites presented below.

The results of this study indicate the need for a more thorough investigation of the shape memory effect of plastically prestrained and constrained nitinol fibers and provides useful insight for the direction of this research. Recommendations for future research are presented in Chapter 6.

3.0 Theory

3.1 Introduction

A theoretical simulation is derived to predict the dynamic response of a nitinol composite beam clamped at both ends. The simulation incorporates the adaptive nature of the composite system and its ability to alter its dynamic response. The dynamic response is evaluated by calculating the fundamental natural frequencies as a function of the "unactivated" or "activated" state of the beam.

Active Strain Energy Tuning (ASET) of a composite structure utilizes embedded shape memory alloy (SMA) fibers to create a state of residual strain within the composite. Nitinol fibers are plastically elongated prior to embedding the fibers in the composite structure. As the embedded nitinol fibers are heated, the fibers try to contract (regain the memorized shape or length) as defined by the shape memory effect (SME). The matrix material opposes the recovery force of the embedded nitinol fibers and prevents the fibers from returning completely to the memory shape or length. The state

of strain of the activated nitinol fibers and the matrix material results in a state of 'residual' stress throughout the composite in the direction of the embedded fibers. If the in-plane displacement of the boundary is restrained, the recovery stress acts as an in-plane tension load. The in-plane load has the effect of increasing the flexural stiffness of the beam and results in a significant increase in the fundamental natural frequencies.

The in-plane load is a function of the nitinol recovery stress, the thermal expansion of the matrix material, and the prestress on the beam. Clamping at each end constrains only the surface of the beam in contact with the clamping device. The clamped-clamped boundaries do not prevent localized strain of the matrix material in the area of the embedded fibers. As the nitinol fibers are activated, the matrix material strains at localized areas near the fibers. The recovery stress is therefore balanced by the coupled reaction of the strained matrix material and the clamped boundaries. The portion of the recovery stress opposed by the clamped boundaries is modeled as a distributed in-plane load. The thermal expansion of the matrix material results in a distributed in-plane load as well. The thermal expansion of the matrix material is opposed by both the clamped boundaries and the embedded nitinol fibers. The clamped boundaries prevent thermal expansion at the surface of the beam in contact with the clamping device while the recovery stress of the embedded nitinol fibers opposes thermal expansion near the nitinol fibers. The thermal expansion of the matrix material opposed by the clamped boundaries is modeled as a compressive in-plane load distributed over the entire beam. A mathematical model is derived to calculate the resulting in-plane load as a function of the recovery stress and the thermal expansion of the matrix material. Any stress on the "unactivated" beam immediately after clamping is modeled as a prestress and is assumed to be

constant over time. The prestress is simply added to the in-plane load resulting from the nitinol recovery force and the thermal expansion of the matrix material.

A theoretical analysis is formulated to calculate the natural frequencies of a clamped-clamped SMA beam based on the degree of activation of the embedded nitinol fibers. The adaptive variables included in this analysis are the recovery stress of the embedded nitinol fibers, thermal expansion of the graphite-epoxy matrix and change in the Young's modulus of the nitinol fibers. All these adaptive variables are a function of temperature. The dynamic response is evaluated only at the "unactivated" and "activated" states because the recovery stress has only been determined at these two extremes (refer to Chapter 2). The change in the directional moduli of the matrix material (graphite-epoxy) as a result of increased temperature is not included for lack of technical data. The moduli at room temperature are used in the simulation of the activated beam. This simulation requires the experimental characterization of the boundary conditions before results can be related to specific nitinol fiber loads. The theoretical results in this chapter are intended to give the reader an understanding of the effect of the stress resultant at the boundary and the nitinol volume fraction on the natural frequencies. Theoretical results for ASET are shown for unactivated and activated beams.

3.2 Theoretical Simulation

ASET of a clamped-clamped nitinol reinforced composite beam is presented by evaluating the free vibration response of an orthotropic graphite-epoxy beam with nitinol

fibers, strained from the memory length, embedded along the neutral axis. The free vibration response is predicted by tuning the material properties and resulting recovery forces of the deformed nitinol fibers. Investigating the effect of ASET on an orthotropic beam constrains the following formulation and discussion to midplane symmetric laminates ($B_{ij} = 0$) with the distributed "fiber" loads assumed to "in-plane loads".

3.2.1 Formulation

A schematic representation of the clamped-clamped beam is shown in Fig. 25. The beam is clamped at $x = 0$ and a . Theoretical analysis of a clamped-clamped special orthotropic beam proceeds by reducing the differential equation of motion for an orthotropic rectangular plate as given by Whitney [74].

$$D_{11} \frac{\partial^4 w}{\partial x^4} + 4D_{16} \frac{\partial^4 w}{\partial x^3 \partial y} + 2(D_{12} + 2D_{66}) \frac{\partial^4 w}{\partial x^2 \partial y^2} + 4D_{26} \frac{\partial^4 w}{\partial x \partial y^3} + D_{22} \frac{\partial^4 w}{\partial y^4} \quad [1]$$

$$+ \bar{N}_x \frac{\partial^2 w}{\partial x^2} + \bar{N}_y \frac{\partial^2 w}{\partial y^2} + 2\bar{N}_{xy} \frac{\partial^2 w}{\partial x \partial y} + \rho \frac{\partial^2 w}{\partial t^2} = 0$$

The assumed solution for a clamped-clamped beam is not a function of y , the spatial variable, ($w = f(x,t)$), therefore the differential equation of motion reduces to

$$D_{11}^* \frac{\partial^4 w}{\partial x^4} + \bar{N}_x^* \frac{\partial^2 w}{\partial x^2} + \rho \frac{\partial^2 w}{\partial t^2} = 0 \quad [2]$$

where D_{11}^* is the bending stiffness at a given activated temperature, $\bar{N}_x^*$ is the resultant stress in the x -direction for a given activated temperature, and ρ is the mass per unit

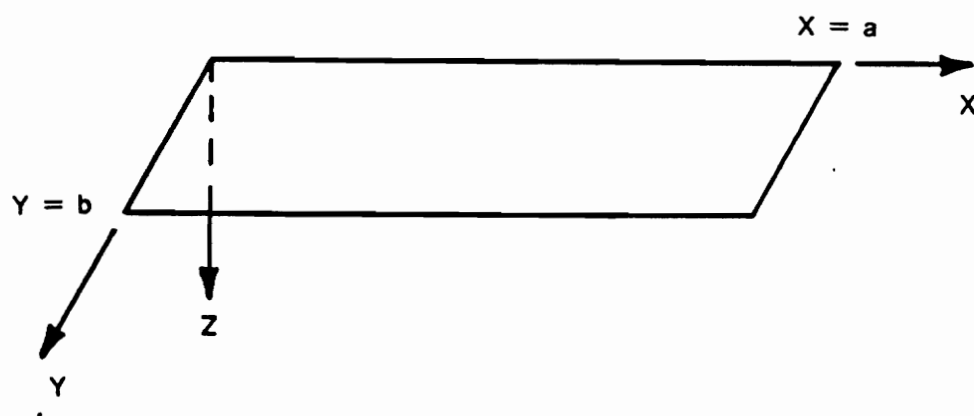


Figure 25. Schematic Representation of Clamped-Clamped Beam for Simulation.

area. The equations used to calculate the bending stiffness and the in-plane load are presented below. The mass per unit area, is calculated by integrating the density over the thickness of the beam. The assumed solution for the governing equation of motion is

$$w = \sum_{m=1}^M A_m X_m(x) \quad [3]$$

The boundary conditions for clamped-clamped ends are

$$\text{at } x = 0 \text{ and } a : \quad w = \frac{\partial w}{\partial x} = 0 \quad [4]$$

For a clamped-clamped beam, the following displacement characteristic, in conjunction with the assumed series solution given by Eq. 3, meets the prescribed boundary conditions.

$$X_m(x) = \gamma_m \cos \frac{\lambda_m x}{a} - \gamma_m \cosh \frac{\lambda_m x}{a} + \sin \frac{\lambda_m x}{a} - \sinh \frac{\lambda_m x}{a} \quad [5]$$

$$m = 1, 2, \dots, M$$

where

$$\cos \lambda_m \cosh \lambda_m = 1$$

and

$$\gamma_m = \frac{\cos \lambda_m - \cosh \lambda_m}{\sin \lambda_m + \sinh \lambda_m}$$

The resulting M linear simultaneous equations are then rewritten in matrix form as

$$([B_{m,l}] - \omega^2 [C_{m,l}]) \{A_l\} = 0 \quad [6]$$

where $B_{m,l}$ and $C_{m,l}$ are coefficients resulting from the Rayleigh-Ritz approximation of the governing energy expression [74] and given by

$$B_{m,l} = D_{11}^* \int_0^a \frac{d^2 X_l}{dx^2} \frac{d^2 X_m}{dx^2} dx + \bar{N}_x^* \int_0^a \frac{dX_m}{dx} \frac{dX_l}{dx} dx \quad [7]$$

and

$$C_{m,l} = \rho \int_0^a X_l X_m dx \quad [8]$$

Equation 6 is further reduced to

$$([B_{m,l}] [C_{m,l}]^{-1} - \omega^2 [I]) \{A_l\} = 0 \quad [9]$$

Since the resulting M simultaneous equations are homogeneous, a nontrivial solution can be obtained only if the determinant of the resulting coefficient matrix, $[B] [C]^{-1}$, is zero. Therefore, the eigenvalues of $[B] [C]^{-1}$ are determined which are directly related to the natural frequencies of free vibration.

The formulation must be further expanded for nitinol reinforced composites as the bending stiffnesses, D_{ij}^* , is a function of temperature and can be tuned by activating the embedded nitinol fibers resulting in a change of the fiber modulus by as much as a factor of three.

3.2.2 Calculation of Bending Stiffness

The bending stiffness in the x-direction, D_{11}^* , is calculated using Eq. 10, where N is the number of plies in the laminate, z_n and z_{n+1} is the location of the n^{th} ply in the z-direction, and $Q_{11}^{(n)}$ is the reduced stiffness for plane stress of the n^{th} ply.

$$D_{11}^* = \sum_{n=1}^N \int_{z_n}^{z_{n+1}} Q_{11}^{(n)} z^2 dz \quad [10]$$

The reduced stiffness is calculated using Eq. 11.

$$Q_{11} = \frac{E_{11}}{(1 - \nu_{12}E_{22}/E_{11})} \quad [11]$$

The directional moduli for the plies with nitinol fibers embedded in the 11-direction are calculated using the rule of mixtures

$$E_{11}^{(n)} = E_a^* \nu_f^{(n)} + E_{11,m} (1 - \nu_f^{(n)}) \quad [12]$$

$$E_{22}^{(n)} = \frac{E_{22,m}}{(1 - \nu_f^{(n)}) + \nu_f^{(n)}(E_{22,m}/E_a^*)} \quad [13]$$

where E_a^* is the Young's modulus of the embedded SMA fibers (nitinol) as a function of temperature, $E_{11,m}$ and $E_{22,m}$ are the elastic moduli of the matrix material, and $\nu_f^{(n)}$ is the nitinol volume fraction of the n^{th} ply. The modulus of the nitinol fibers is a function of temperature, therefore the bending stiffness, D_{11}^* , is also a function of temperature.

3.2.3 Calculation of Stress Resultants for Clamped-Clamped Boundary

Conditions

The stress resultant in the x-direction, $\bar{N}_x^*$, is calculated using Eq. 14, where N is the number of plies in the laminate, z_n and z_{n+1} is the location of the n^{th} ply in the z-direction, and $\sigma_x^{(n)}$ is the stress applied to the n^{th} ply at the clamped boundary.

$$\bar{N}_x^* = \sum_{n=1}^N \int_{z_n}^{z_{n+1}} \sigma_x^{(n)} dz \quad [14]$$

The stress for each ply is assumed to be constant over the ply thickness, therefore Eq. 14 reduces to

$$\bar{N}_x^* = \sum_{n=1}^N \sigma_x^{(n)} (z_{n+1} - z_n) \quad [15]$$

The stress, $\sigma_x^{(n)}$, is the distributed in-plane load for each ply, applied to the beam at the clamped boundaries. The stress, $\sigma_x^{(n)}$, is the result of three independent variables:

- in-plane stress as a result of nitinol recovery, σ_r^B
- in-plane stress as a result of thermal expansion, σ_a^B
- prestress applied at the clamped boundary, σ_0

The in-plane stress acting on the beam is simply the sum of these three stresses.

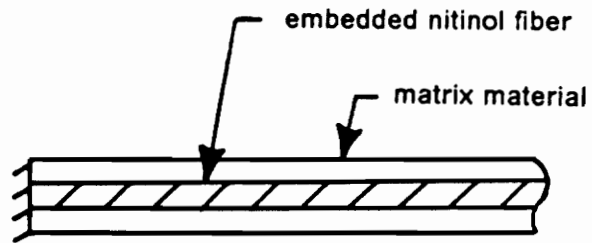
$$\sigma_x = \sigma_r^B + \sigma_a^B + \sigma_0 \quad [16]$$

The superscript B indicates that the stress is the in-plane load as a result of the clamped boundaries. All of the stress resulting from the embedded nitinol fibers and thermal expansion is not opposed by the boundaries. Some portion of these stresses is balanced within the beam and the rest is opposed by the boundary. The prestress at the boundary represents the stress introduced during experimental setup.

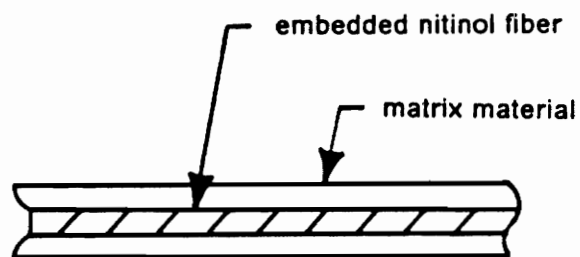
The in-plane stress as a result of the recovery stress, σ_r , of the embedded nitinol fibers is best described by considering the nature of the clamped-clamped boundary condition. The clamping devices constrain the beam from motion only at locations along the surface of the beam in contact with the clamping devices. The clamped boundaries do not prevent localized strain of the matrix material in the area of the embedded nitinol fibers, especially at the end of the beam. The calculation of the in-plane stress as a result of the recovery stress, σ_r , of the embedded nitinol fibers proceeds by considering the two extreme boundary conditions at the end of the beam ($x = 0$ and a) shown in Fig. 26. The constrained end condition allows no strain of the matrix material. The resulting recovery force of an activated nitinol fiber must be transferred entirely to the constraint. The free end condition allows strain within the matrix material. Because there is no constraint, the resulting recovery force of an activated nitinol fiber must be transferred entirely to the matrix material. Actual clamped boundary conditions fall somewhere between these two extremes.

From these extreme boundary conditions, a formulation can be derived which describes all boundaries that fall between the constrained end and free end conditions. A force balance of the constrained end condition results in Eq. 17, where σ_r is the recovery stress of an activated nitinol fiber, and v_f is the nitinol fiber volume fraction.

$$0 = \sigma_r v_f - \sigma_r^B \quad [17]$$



Constrained End Condition: $\sigma_m = 0$



Free End Condition: $\sigma_m = \sigma_r$

Figure 26. Description of Boundary Conditions.

A force balance of the free end condition results in Eq. 18, where $\sigma_m^{(f)}$ is the matrix stress for the free end condition.

$$0 = \sigma_r v_f - \sigma_m^{(f)}(1 - v_f) \quad [18]$$

By introducing the nitinol boundary constant, K_r , all boundaries between the two extremes can be characterized. The nitinol boundary constant, K_r , is a measure of the amount of the nitinol recovery force transferred to the matrix material. Therefore $K_r = 1$ for the free end condition and $K_r = 0$ for the constrained end condition.

$$\sigma_r^B = \sigma_r v_f - K_r \sigma_m^{(f)}(1 - v_f) \quad [19]$$

where

$$0 \leq K_r \leq 1$$

The equation to calculate the in-plane load caused by the recovery stress of an embedded nitinol fiber is found by combining Eq. 18 and Eq. 19

$$\sigma_r^B = \sigma_r v_f(1 - K_r) \quad [20]$$

where

$$0 \leq K_r \leq 1$$

Formulation of the in-plane stress caused by thermal expansion of the matrix material, σ_x^s , proceeds by assuming that the boundary conditions prevent all thermal expansion of the matrix material. This compressive stress for an individual ply is formulated in Eq. 21, where n is the particular ply, α_n represents the coefficient of thermal expansion in the x-direction, and E_{x_n} is the Young's modulus in the x-direction.

$$\sigma_{\alpha}^{(n)} = -\alpha_n(\Delta T)E_{x_n} \quad [21]$$

The temperature difference, ΔT , is determined by the difference in the temperature of the beam and the temperature at which the beam was clamped. In this work, beams are considered to be clamped at room temperature, 70°F (21°C).

The stress at the boundaries as a result of thermal expansion is calculated by introducing the thermal boundary constant, K_{α} . The thermal boundary constant, K_{α} , is a measure of the amount of the stress caused by thermal expansion balanced within the matrix material. Therefore $K_{\alpha} = 1$ for the free end condition and $K_{\alpha} = 0$ for the constrained end condition. The derivation is equivalent to the derivation of the nitinol boundary constant, K_n , shown above. The thermal expansion stress at the boundaries is formulated in Eq. 22.

$$\sigma_{\alpha}^B = \sigma_{\alpha}(1 - \nu_p)(1 - K_{\alpha}) \quad [22]$$

where

$$0 \leq K_{\alpha} \leq 1$$

The equation for the stress resultant in the x-direction for a clamped boundary is derived by combining Eqs. 15, 16, 20 and 22.

$$\begin{aligned} \bar{N}_x^* = & (1 - K_r) \sum_{n=1}^N \sigma_r^{(n)} v_f^{(n)} (z_{n+1} - z_n) + (1 - K_\alpha) \sum_{n=1}^N \sigma_\alpha^{(n)} (1 - v_f^{(n)}) (z_{n+1} - z_n) \quad [23] \\ & + \sigma_0 \sum_{n=1}^N (z_{n+1} - z_n) \end{aligned}$$

Both the nitinol and thermal boundary constants can be determined experimentally. The procedures and results are discussed below.

3.3 Theoretical Results

All simulations in this section are for a $[90^\circ, 0^\circ, 90^\circ]_T$ graphite-epoxy beam with nitinol fibers embedded along the neutral axis in the x-direction. The beam is clamped at both ends and has a length of 32.25 inches (81.92 cm), a width of 0.86 inches (2.18 cm) and a thickness of 0.034 inches (8.6 mm). The material properties are listed in Table 3.

Figure 27 shows the first three natural frequencies versus the in-plane stress, σ_x , for a 15% nitinol volume fraction beam. The slope ($df_n/d\sigma_x$) decreases as the in-plane stress increases. A small change in a small in-plane stress (below 250 psi or 1.72 MPa) causes a sizeable change in the natural frequencies. The same change in a large in-plane stress (above 750 psi or 5.17 MPa) causes a much smaller change in the natural frequencies. This trend suggests that any prestress introduced to the

Table 3. Material properties for graphite-epoxy and nitinol.

nitinol:		
density:		0.233 lb/in ³ (6.45 gm/cm ³)
Young's modulus:	Austenite	12 Mpsi (82 GPa)
	Martensite	4 Mpsi (28 GPa)
Poisson's ration:		0.33

graphite-epoxy: 5245C prepreg system

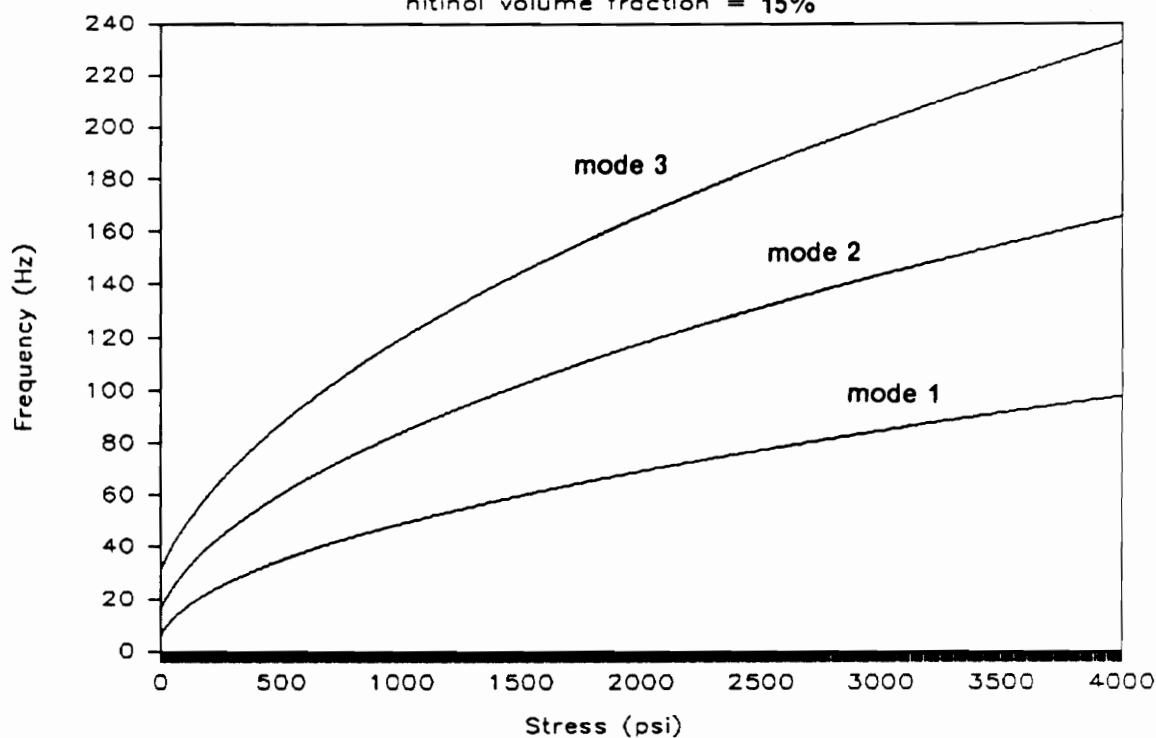
density:	0.055 lb/in ³ (1.53 gm/cm ³)
Young's modulus:	E _x = 24.0 Mpsi (165 GPa)
	E _y = 1.45 Mpsi (10.0 GPa)
Shear modulus:	0.73 Mpsi (5.0 GPa)
Poisson's ratio:	0.33
coefficient of thermal expansion:	
	α _x = not measurable
	α _y = 13.0 × 10 ⁻⁶ in/in/°F (23.4 × 10 ⁻⁶ mm/mm/°C)

* x - parallel to graphite fibers
y - perpendicular to graphite fibers

laminate:		
Theoretical Bending Stiffness, D ₁₁ (lb/in)		
v _f	unactivated	activated
0%	25.3	
5%	23.9	24.5
10%	22.6	23.7
15%	21.2	22.9

Natural Frequencies vs Inplane Load

nitinol volume fraction = 15%



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 27. Natural Frequencies versus Inplane Stress

beam during the experimental setup will have a deteriorating effect on the ability of ASET to increase the natural frequencies.

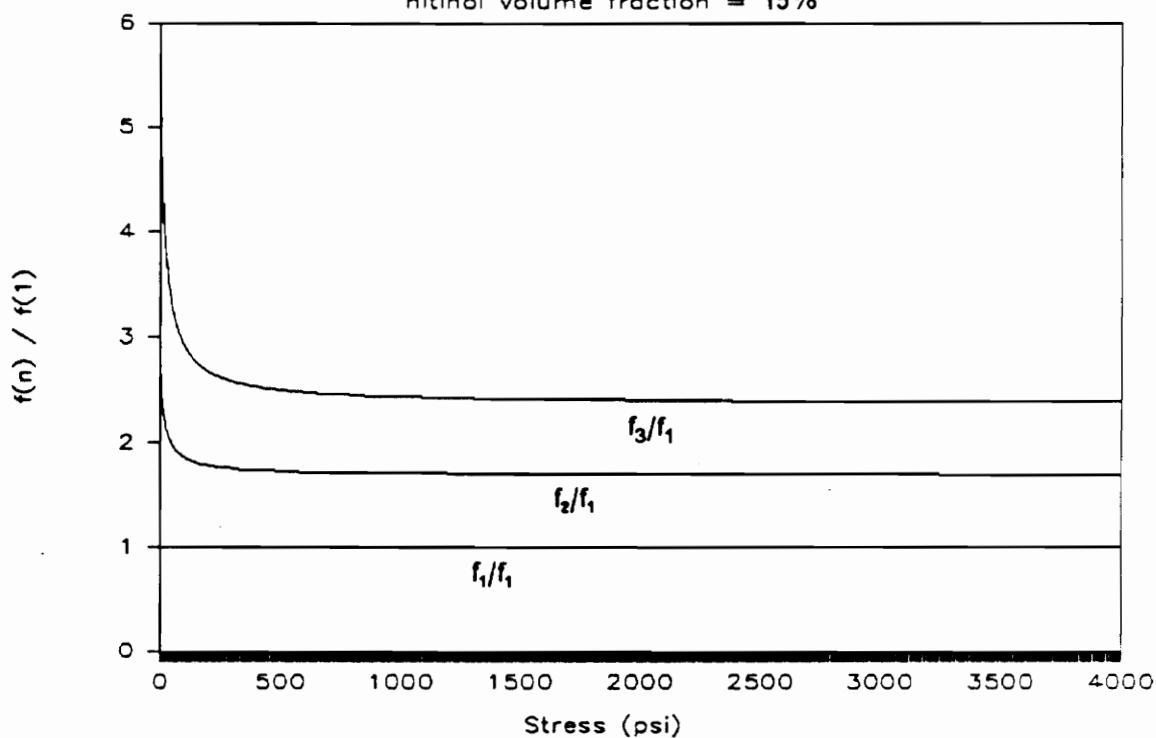
Figure 28 shows the ratio of the first three natural frequencies to the first natural frequency. An increasing in-plane stress at the boundaries has the effect of moving the natural frequencies closer together. The ratios decrease dramatically in the first 500 psi (3.45 MPa). For in-plane stresses greater than 1000 psi (6.89 MPa), the natural frequency ratios remain constant.

The first three natural frequencies versus compressive in-plane stress are shown in Fig. 29. The natural frequencies decrease as the compressive stress increases. As the compressive load approaches the critical buckling load, the first natural frequency decreases sharply towards zero. The critical buckling load for the beam described above is only 14 psi (97 KPa) as compared to the thermal expansion stress for an activated beam of 52 psi (358 KPa). This suggests that nitinol composite beams may buckle upon activation if the compressive stress caused by thermal expansion dominates the in-plane stress at the boundary. A minimum volume fraction may be required to prevent buckling caused by thermal expansion.

Table 3 on page 96 shows that the Young's modulus of elasticity for nitinol is smaller than that for graphite-epoxy. Therefore, as the nitinol volume fraction of the composite beam increases, the unactivated flexural stiffness term, D_{11}^* , decreases. It is also apparent that the mass of the beam increases as the volume fraction increases. The combination of decreased stiffness and increased mass will cause the the natural frequencies to decrease. This trend is shown in Fig. 30.

Nat. Frequency Ratio vs Inplane Load

nitinol volume fraction = 15%

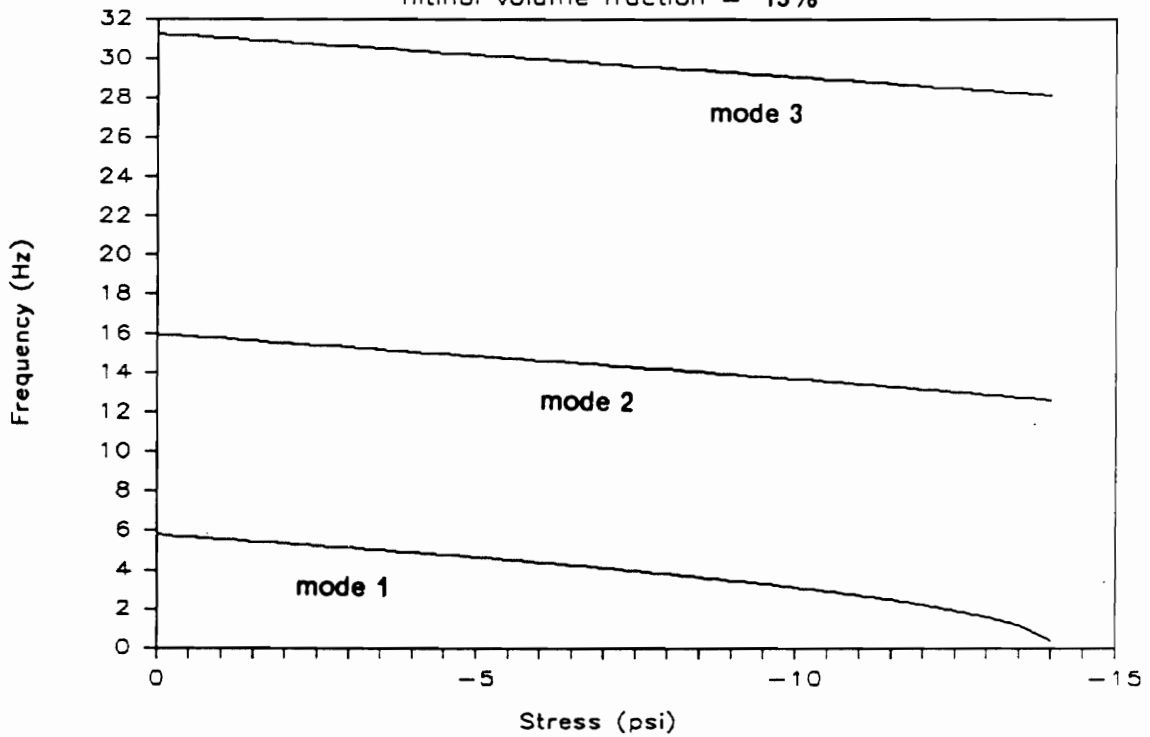


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 28. Natural Frequency Ratio versus Inplane Stress

Natural Frequencies vs Compressive Load

nitinol volume fraction = 15%

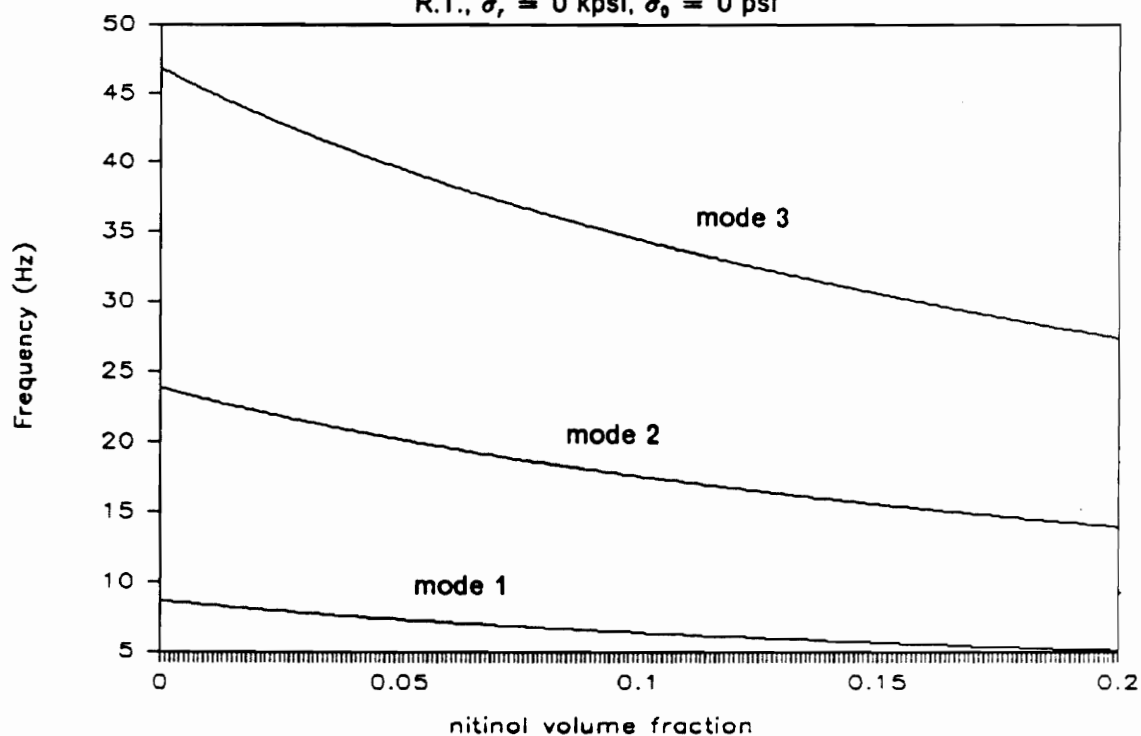


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 29. Natural Frequencies versus Compressive Inplane Stress

Unactivated Frequencies vs Vol Fraction

R.T., $\sigma_r = 0$ kpsi, $\sigma_0 = 0$ psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 30. Unactivated Natural Frequencies versus Nitinol Volume Fraction.

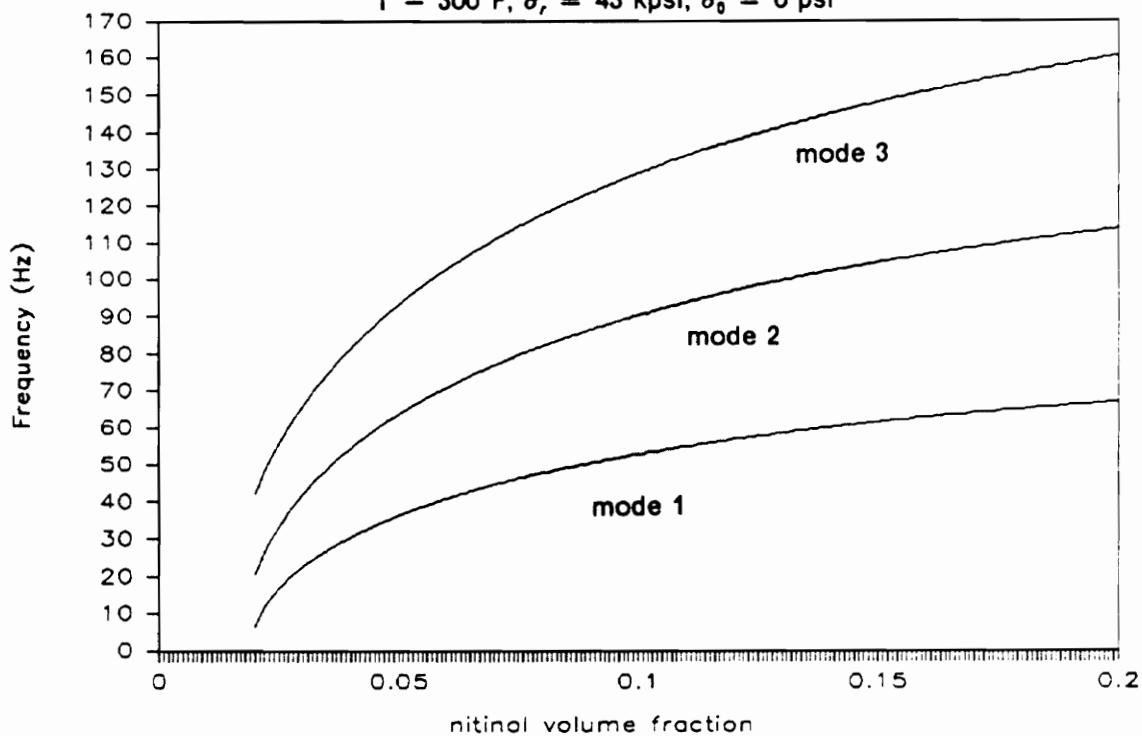
Fig. 31 shows the activated natural frequencies versus volume fraction for the nitinol composite beam described above. Typical values for the boundary constants are used for this calculation. The value used for the nitinol boundary constant, K_n , is 0.71. The value used for the thermal boundary constant, K_t , is 0.77. Experimental determination of the boundary constants is discussed in Chapter 5. The beams are assumed to have zero prestress.

The theoretical simulation does not calculate a first natural frequency for beams with nitinol volume fractions less than 20%. This corresponds to a buckled beam and indicates that the compressive stress caused by thermal expansion is greater than the recovery stress. Beams with nitinol volume fractions greater than 20% show a dramatic increase in the natural frequencies as a function of increasing volume fraction.

The potential of ASET to increase the natural frequencies is evaluated by normalizing the activated frequencies of a particular beam to the unactivated first natural frequency for the same beam. The normalized frequencies are shown in Fig. 32. First natural frequencies are shown to exhibit changes from the unactivated to activated frequencies by as much as 938% for a 15% nitinol volume fraction beam.

Activated Frequencies vs Vol. Fraction

$T = 300^{\circ}\text{F}$, $\sigma_r = 43 \text{ kpsi}$, $\sigma_0 = 0 \text{ psi}$

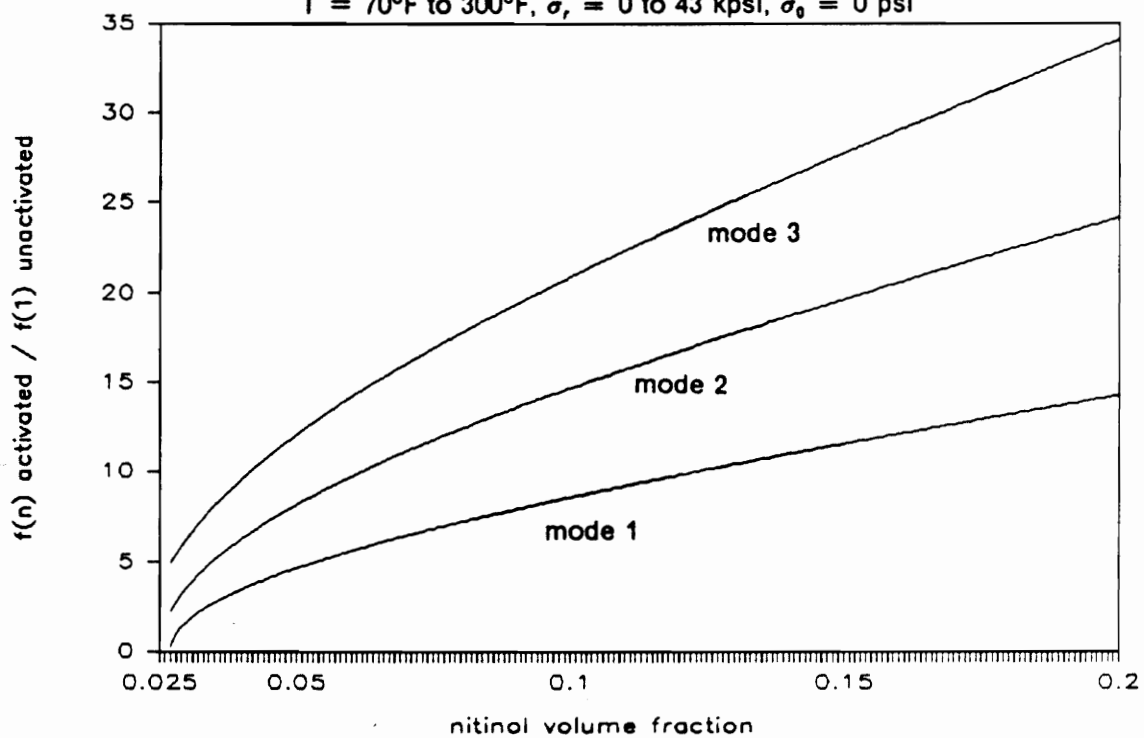


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 31. Activated Natural Frequencies versus Nitinol Volume Fraction.

Normalized Frequency Increase

$T = 70^{\circ}\text{F}$ to 300°F , $\sigma_r = 0$ to 43 kpsi, $\sigma_0 = 0$ psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 32. Normalized Activated Frequencies versus Nitinol Volume Fraction.

4.0 Experiment

4.1 Introduction

The potential of Active Strain Energy Tuning (ASET) to alter the dynamic response of a composite with embedded Shape Memory Alloy (SMA) fibers is demonstrated experimentally below. Nitinol reinforced composite beams are clamped at both ends to provide a constraint against the recovery of the embedded nitinol fibers. The recovery stress of a heated nitinol fiber appears as a tensile load throughout the beam as a result of the clamped boundaries. The tensile load on the beam has the effect of increasing the flexural stiffness of the beam and causes an increase in the natural frequencies of the clamped-clamped beam, as well as a decrease in the maximum deflection due to a transverse load [18]. The potential of ASET to alter the dynamic response of a SMA reinforced composite in a controllable fashion is evaluated by quantifying the change in the natural frequencies of a clamped-clamped beam caused by heated nitinol fibers embedded on the neutral axis along the length of the beam.

4.2 Experimental Apparatus and Procedure

Nitinol reinforced graphite-epoxy beams were fabricated at the Composite Materials and Structures Fabrication Center at VPI&SU. The nitinol fibers have an austenite finish temperature of 100°F (38°C) , a diameter of 0.015 inches (0.38 mm), and were given a 5% strain from the memory shape prior to embedding. Beams with nitinol volume fractions of 5%, 10%, and 15% are fabricated by embedding nitinol fibers along the neutral axis of the beams. The lay-up scheme for 15% nitinol volume fraction is shown in Fig. 33. Similar schemes are used for the 5% and 10% nitinol volume fractions, the only difference being the number of embedded nitinol fibers. A 10% beam is fabricated by decreasing the number of embedded fibers, shown in Fig. 33, from 24 fibers to 16 fibers. A 5% nitinol volume fraction beam is fabricated by embedding only 8 nitinol fibers.

A special tool plate was designed to constrain the nitinol fibers from returning to their memory shape during the high temperatures of the composite cure cycle. The tool plate is shown in Fig. 34. Graphite epoxy prepreg (5245C carbon fiber prepreg system) and strained nitinol fibers are laid on the tool plate using the lay-up scheme shown in Fig. 33. The appropriate spacing between nitinol fibers is maintained by the alignment pins. Spacing can be defined by rotating the rotary disk until the desired spacing is achieved. The disk is then clamped to prevent any further rotation and consequent change in spacing. The fibers are constrained from motion during the cure cycle by clamping each fiber to the tool plate with the allen screws as shown.

Specifications

Graphite epoxy: 5245 prepreg system

Dimensions: Length (L) = 32.25 in (81.92 cm)
 Width (W) = 0.860 in (2.18 cm)
 Spacing (S) = 0.031 in (0.79 mm)
 Thickness = 0.034 in (0.86 mm)

No. of actuators = 24 x .015 in dia
Nitinol volume fraction = 15%

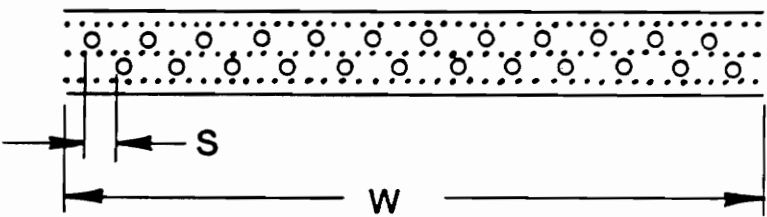


Figure 33. Lay-up Scheme for Nitinol Reinforced Composite Beam.

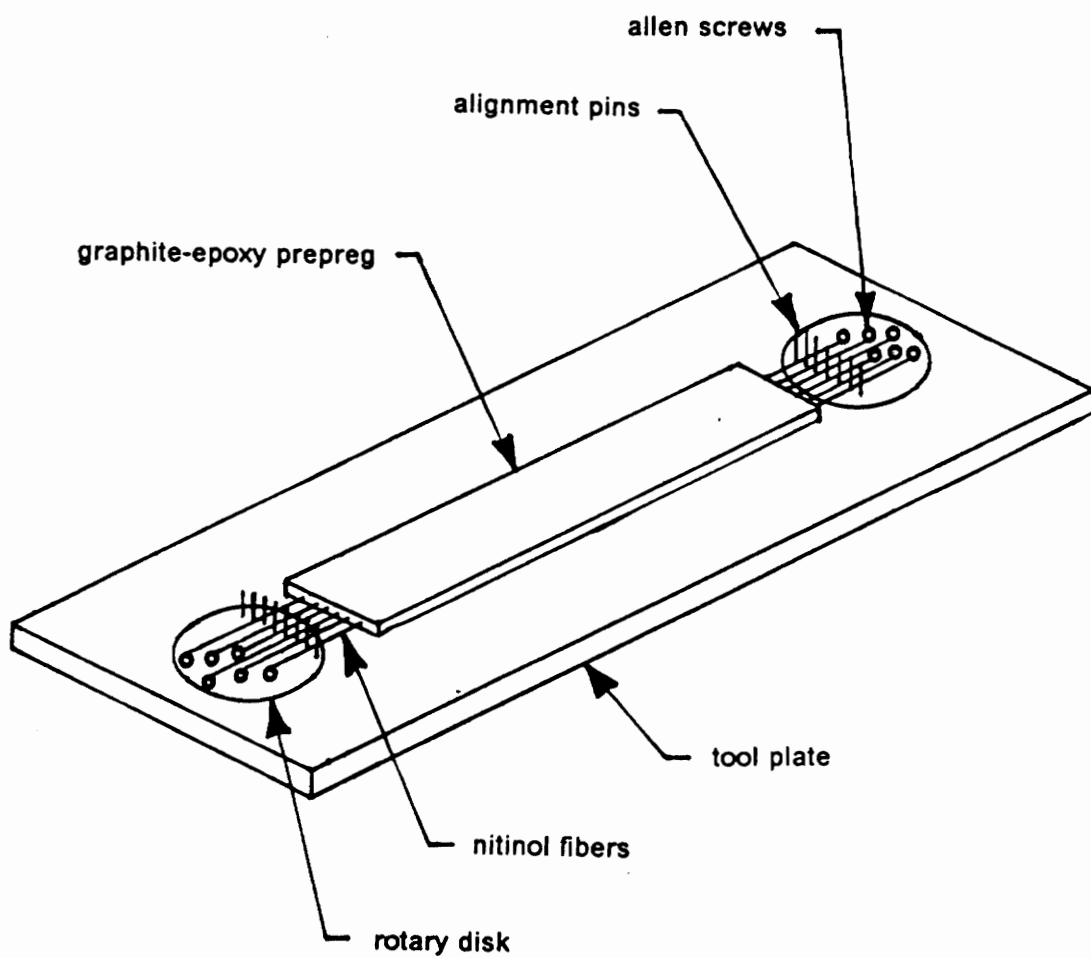


Figure 34. Tool Plate for Composite Fabrication.

The cured composite beam is removed from the tool plate and clamped at both ends in the test fixture so that the transverse vibrations occur normal to the gravitational field. Screws are used to clamp the embedded nitinol fiber to the test fixture if desired. A thermocouple (Omega, E-type, Chromel-Constantan thermocouple) is located on the surface of the beam to allow the nitinol reinforced composite to be tuned to a specific temperature. The nitinol fibers are activated by applying an electric current through the beam. Heating therefore occurs as a result of the electrical resistance of the nitinol fibers. A constant current power supply (HP-6268B programmable DC power supply) is controlled manually to bring the temperature of the beam to the desired temperature. An electro-magnetic displacement transducer (Electro Corporation, Electro-Mike EMDT #85003) is used to sense the dynamic response of the composite beam. A PC-AT computer and A/D board (Data Translation, Inc., DT2801 A/D board) are used to store temperature and displacement measurements. The experimental apparatus is shown in Fig. 35.

Test matrices are shown in Tables 4, and 5. Table 4 describes the test procedure for the 15% nitinol volume fraction beam. Table 5 describes the test procedure for the 5% and 10% volume fraction beams. In all tests, the beams are clamped to give a length between the clamping devices of 32.25 inches (81.92 cm). Nitinol fibers extending outside both ends of the beam are either clamped to the test fixture or left free depending on the requirement for the particular test. Testing is performed at steady state temperature to insure the a constant set of material properties (material properties do not change with time). Vibration of the beam is initiated by striking the beam with a hard object. Strong resonant frequency components are induced using this method. Data is sampled in real time for the vibrating beam and a Fast Fourier Transform (FFT) is performed on the discrete data points to extract the resonant fre-

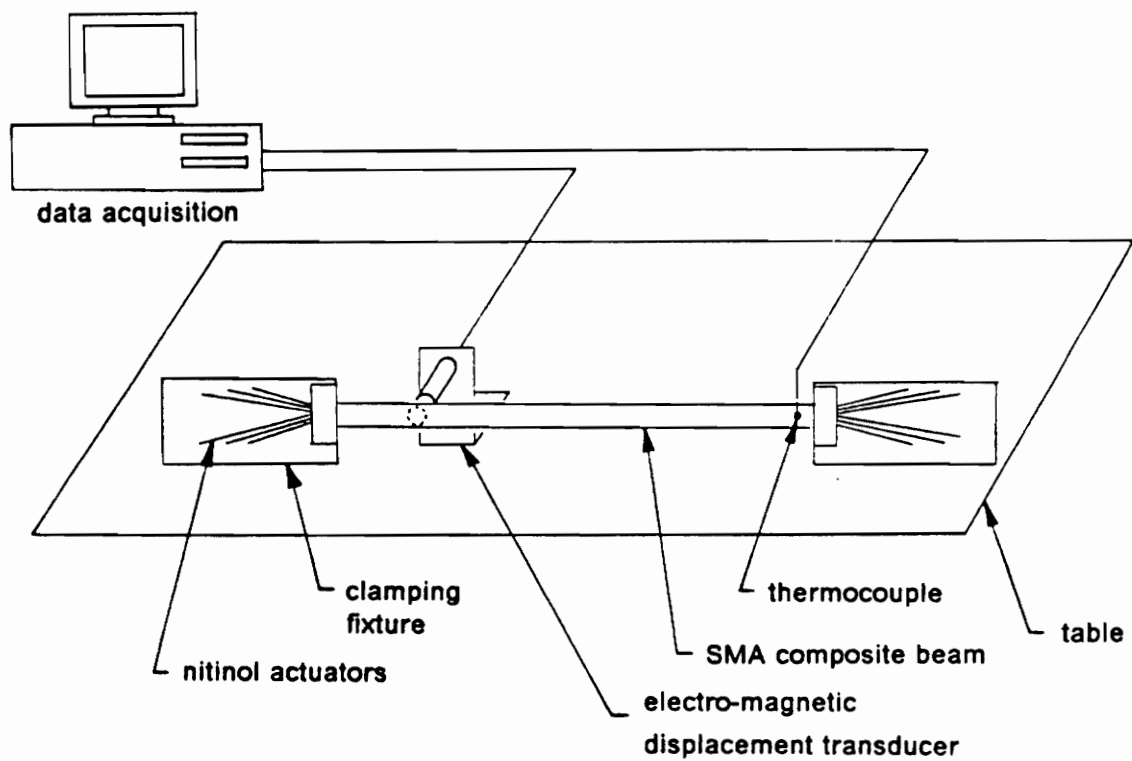


Figure 35. Experimental Apparatus for Active Strain Energy Tuning.

Table 4. Test matrix for 15% nitinol volume fraction beam.

Test	Description
1	Natural Frequency versus Temperature, original beam
2	Natural Frequency versus Time of room temperature beam immediately following test 1
3	Natural Frequency versus Temperature, rested beam six hours after completion of test 1
4	Natural Frequency versus Temperature, worked beam immediately following test 3
constrain nitinol fibers heat to fully activated temperature then cool to induce residual stress	
5	Natural Frequency versus Temperature, worked beam immediately following set-up
6	Natural Frequency versus Temperature, rested beam 13 hours after test 5
7	Natural Frequency versus Time at 250°F, worked beam immediately following test 6

Table 5. Test matrix for 5% and 10% nitinol volume fraction beams.

Test	Description
1	Natural Frequency versus Temperature, original beam
2	Natural Frequency versus Temperature, worked beam immediately following test 2

quency components of the vibrating beam. Testing is also performed on a graphite epoxy beam without embedded nitinol fibers in an effort to characterize the effect of temperature on the graphite-epoxy and the corresponding effect on the dynamic response. The same lay-up is used except that there are no embedded nitinol fibers. A test matrix for this beam is shown in Table 6.

Three terms are used to describe the state of the beam prior to the test performed. "Original" refers to a beam that has never been heated or "activated." Testing of an "original" beam therefore refers to the first time the beam is activated after being clamped at both ends in the test fixture. The term "rested" refers to a beam that has been allowed to "rest" at room temperature for the length of time necessary to relieve residual stresses as a result of thermal expansion of the graphite-epoxy matrix incurred during the activation process. The necessary "rest" time and the nature of the residual stresses are further discussed below. The term "worked" refers to a beam that has not been "rested" for the necessary length of time to relieve the residual stresses incurred during the activation process.

Natural frequency versus temperature testing is performed by determining the first three natural frequency modes at different temperatures between room temperature and 300°F (149°C). The maximum continuous service temperature of the graphite-epoxy (5245C carbon fiber prepreg system) is 300°F (149°C). Short term service is rated at 400°F (204°C). Because of the large recovery stresses of embedded nitinol fibers the maximum temperature of the natural frequency versus temperature testing is limited to 300°F (149°C) to prevent any permanent change in the dynamic behavior of the beams. The beam is heated to the desired temperature by manually increasing the magnitude of the current through the nitinol fibers. When the desired steady state

Table 6. Test matrix for graphite-epoxy beam (no nitinol).

Test	Description
1	Natural Frequency versus Temperature, original beam
2	Natural Frequency versus Temperature, worked beam immediately following test 1
3	Natural Frequency versus Temperature, worked beam immediately following test 2

temperature is reached, vibrations are induced in the clamped-clamped beam. Data is sampled in real time and a FFT is performed on the discrete data points to extract the resonant frequencies of the vibrating beam. Three data sets are taken at each temperature and the resulting FFT's are averaged. The temperature is measured after each data set is sampled. Three averages are taken in this fashion to verify that steady state temperature is achieved.

A test procedure designed to examine the natural frequencies of an activated beam or an unactivated "worked" beam as a function of time is also required. Natural frequency versus time testing for an activated beam is described first. The beam is heated to the activated temperature (determined from the natural frequency versus temperature testing) and maintained at the activated temperature for the duration of the test. Natural frequencies are determined every 30 minutes using the FFT method described above. The beam is then cooled to room temperature. Natural frequency versus time testing for an unactivated "worked" beam is then performed. Natural frequencies of the room temperature beam are determined every 30 minutes using the FFT method. The results of this testing show the hysteresis effects between the "worked" and "rested" beams.

4.3 Experimental Results

4.3.1 Discussion of Experimental Technique

The fundamental tool and basis for analysis of the dynamic response of nitinol reinforced beams presented in this work is a fast fourier transform performed on displacement measurements taken at discrete points in time. The effectiveness of this analysis is examined below.

The dynamic response of a clamped-clamped beam is quantified by experimentally determining the natural frequencies. Displacement measurements of the vibrating beam are sampled at a specified frequency and a specified number of samples are taken. The displacement transducer is not physically attached to the beam, therefore the dynamic response of the beam is not altered by the measurement system. The displacement transducer operates by inducing eddy currents in the target area (the portion of the beam where the transducer is located). The eddy currents produce a magnetic field which is sensed by the transducer. The magnitude of the magnetic field sensed by the transducer is proportional to the distance between the transducer and the target area. The beam does not make contact with the transducer and therefore the dynamic response of the beam is not effected. The resolution of the displacement measurement technique is good enough to sense the vibrational amplitudes for the first three natural frequencies. The temperature is stored after each series of samples is taken. Temperature can be measured with a resolution of 0.1°F (0.06°C).

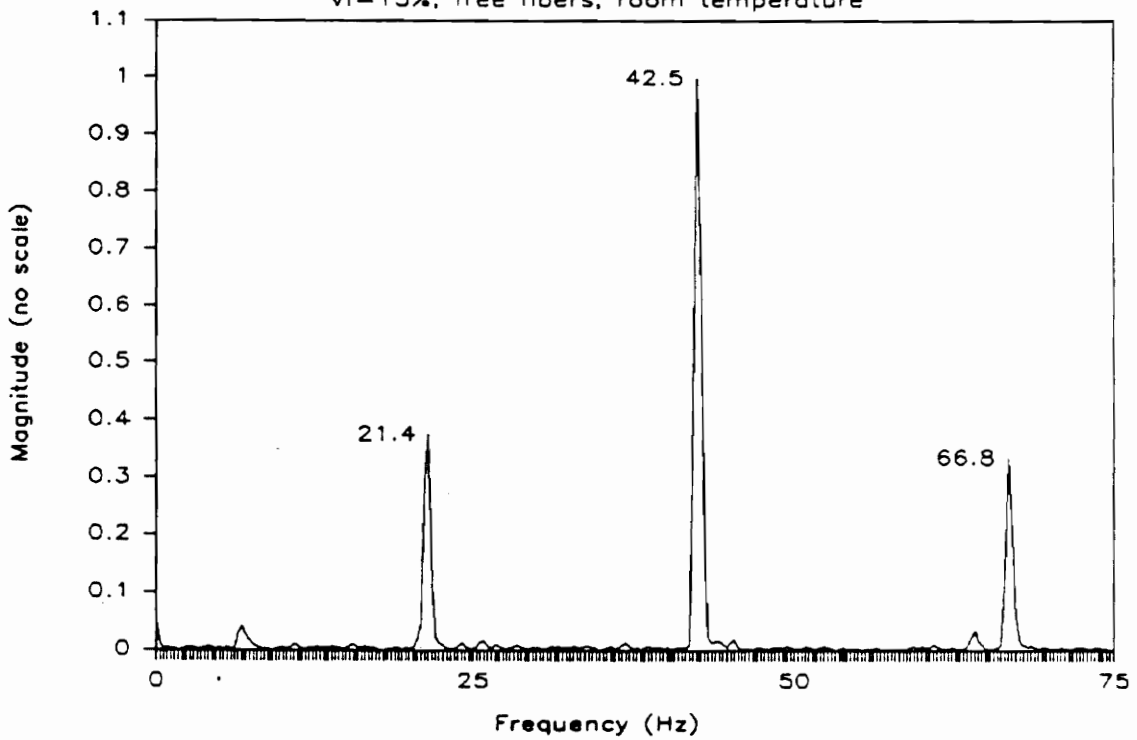
The range and resolution of the frequencies calculated by the FFT are a function of the number of samples and the sample rate. The range is simply the sample frequency divided by two. The resolution is the sample frequency divided by the number of samples. The number of samples used in each of the tests presented in this work is 512. The sample rate is chosen to give the appropriate range to allow for the correct calculation of the first three natural frequencies. The resolution of the calculated frequencies of each test is therefore different.

The magnitude of the FFT, or the power density spectrum, is shown for the 15% nitinol volume fraction beam at room temperature and 300°F (149°C) in Figs. 36 and 37. The resulting FFT of the vibrating beam at room temperature is based upon 512 displacement samples taken at a rate of 150 samples/sec. This gives a resolution of 0.3 Hz. The resulting FFT of the vibrating beam at 300°F (149°C) is based upon 512 displacement samples taken at a rate of 400 samples/sec. This gives a resolution of 0.8 Hz. All tests presented in this work have resolutions between the extreme values of 0.3 Hz and 0.8 Hz.

Three FFT's are calculated and averaged for each test in effort to i) reduce the magnitude of frequencies calculated due to random noise and ii) verify that the beam is at steady state temperature. As demonstrated by Figs. 36 and 37, the magnitude of the frequencies calculated due to the resonant frequencies of the vibrating beam are well above those calculated due to random noise in the displacement measurement. The measured temperature of the room temperature test remains constant at 72.6°F (22.6°C). This is expected since the temperature of the beam is the same temperature of the surrounding air. The measured temperatures of the three sample sets for the activated beam are 297.4°F (147.4°C), 297.6°F (147.6°C), and 298.1°F (147.8°C).

FFT of Unactivated SMA Beam

$\nu_f=15\%$, free fibers, room temperature

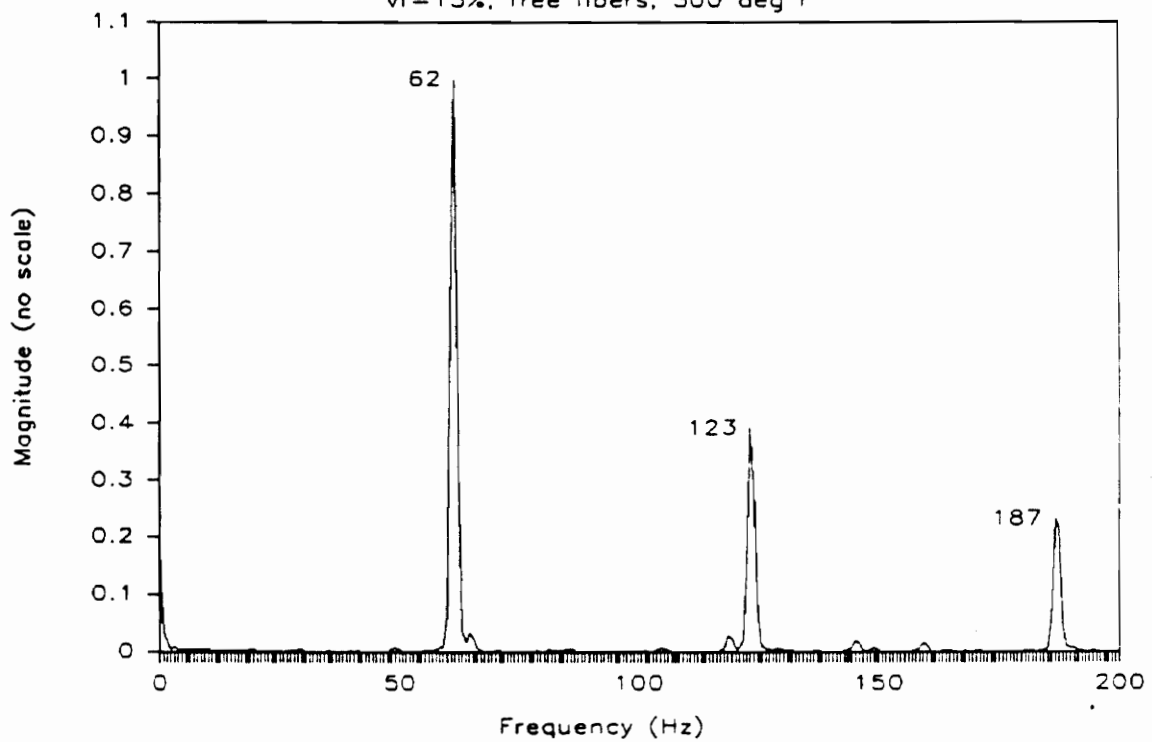


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 36. FFT of SMA Beam at Room Temperature.

FFT of Activated SMA Beam

vf=15%, free fibers, 300 deg F



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 37. FFT of Activated SMA Beam.

A fluctuation is expected because of the large temperature difference that exists between the surface of the beam and the air. Changes in natural frequencies due to the change in temperature are less than the resolution of the FFT as indicated by the sharp peaks calculated by the FFT shown in Fig. 37 on page 120. This is a consistent trend throughout the testing presented in this work.

The FFT, or the power density spectrum, of each test is not presented. The results of the FFT, that is, the first three natural frequencies, are presented. It is important to realize that the accuracy of the experimentally determined frequencies is at worst plus or minus 0.8 Hz. The signal to noise ratio of the displacement data is also shown to be acceptable.

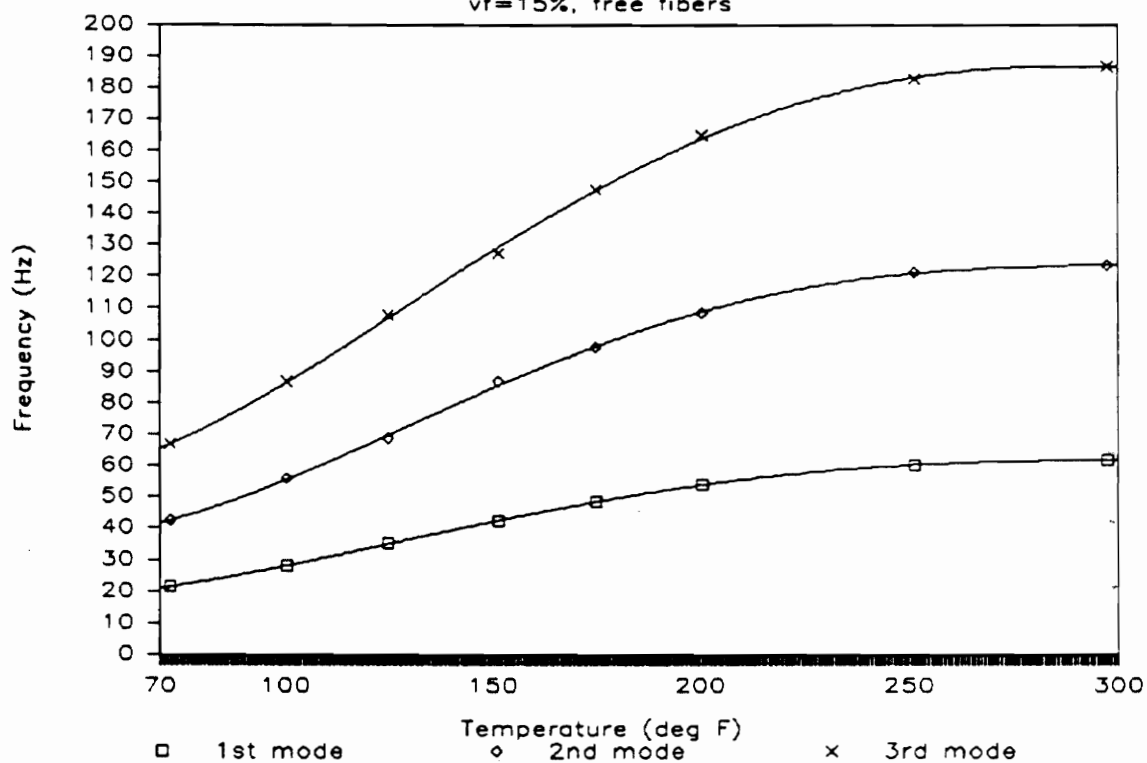
4.3.2 Boundary Conditions

The amount of the recovery stress balanced by the clamped-clamped boundaries determines (to a large degree) the increase in the natural frequencies and is a function of the boundary conditions. The effect of the boundary conditions is discussed below. The potential or effectiveness of particular boundary conditions is evaluated by calculating the percent change in the first natural frequency at room temperature to the maximum activated first natural frequency. Second and third natural frequencies are shown for qualitative comparison but are not evaluated in this section. Second and third natural frequencies are compared to theoretical results in Chapter 5.

The natural frequencies versus temperature of a "rested" nitinol reinforced beam having a 15% nitinol volume fraction are shown in Fig. 38. A least squared

ASET of "Rested" SMA Beam

vf=15%, free fibers



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 38. ASET of "Rested" SMA Beam with Free Fibers, 15% nitinol volume fraction

polynomial curve fitting procedure is performed on the experimental data points using the least squares method and is shown with the experimental data. Nitinol fibers extending outside each end of the clamped-clamped beam are not constrained. This allows the nitinol fibers to contract to some degree within the matrix material. The nitinol fibers are able to cause a strain within the matrix material and the recovery stress of the nitinol fibers is balanced within the the matrix material as well as the clamped boundary. Some portion of the recovery stress is applied to the matrix and the remainder is applied to the boundary. The first natural frequency increases from 21 Hz at room temperature to 62 Hz at 300°F (149°C). ASET yields a change of nearly 200% in the first natural frequency for the 15% nitinol volume fraction beam. The change in frequencies occurs over a large temperature range – approximately 70°F (21°C) to 250°F (121°C). This range is very linear up to 200°F (93°C).

A lower nitinol boundary constant, K_n , (less recovery stress absorbed by the graphite-epoxy matrix, refer to Chapter 3) is demonstrated by constraining the nitinol fibers. The nitinol fibers extending outside the ends of the beam are clamped to the test fixture using the clamping screws shown in Fig. 35 on page 111. The constraints tend to resist the contraction of the embedded nitinol fibers within the graphite-epoxy matrix and corresponding strain to the matrix material. Because there is less strain in the matrix material, and consequently less force, a greater portion of the recovery stress, σ_n , is applied to the boundaries. The overall effect is an increase in the activated natural frequencies.

The boundary constant of the 15% nitinol volume fraction beam discussed above is lowered by clamping the nitinol fibers extending outside the beam to the test fixture. The beam is then heated and cooled to introduce any residual stress that may occur

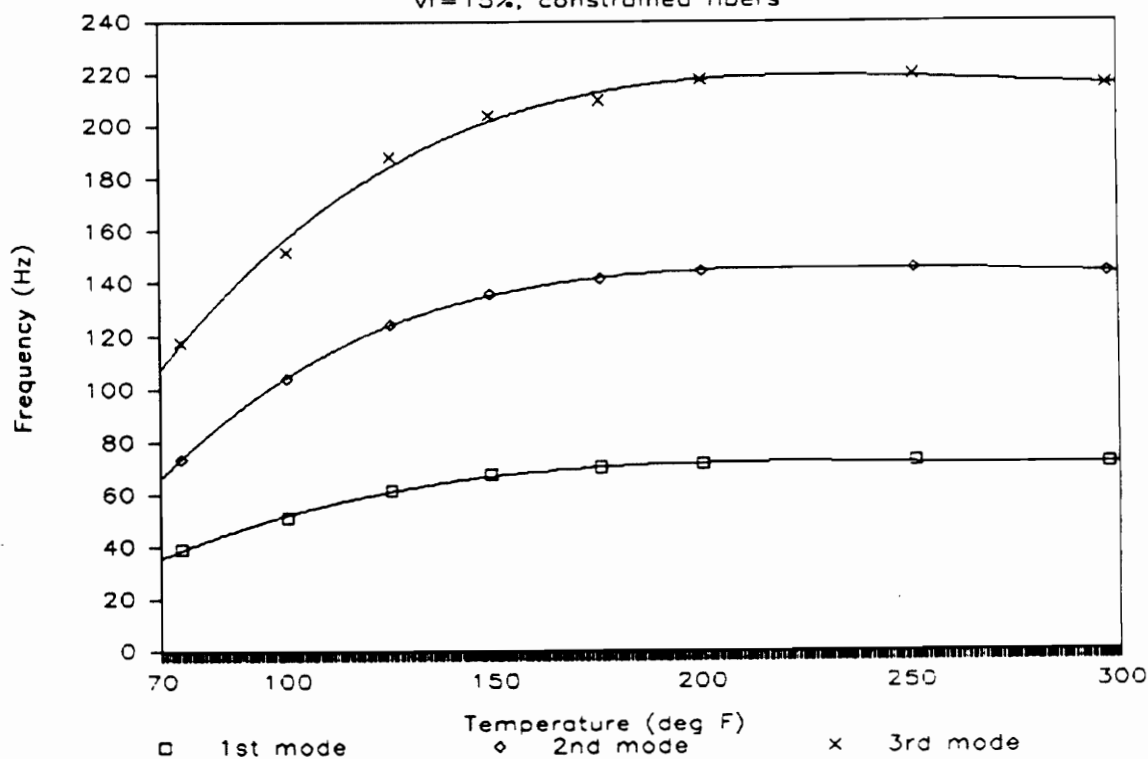
as a result of the constrained nitinol. The beam is then "rested" at room temperature for approximately 13 hours. This allows the residual stress introduced to the matrix material during heating to be relieved. The only stress that remains is assumed to be the residual stress due to the nitinol fibers at the constraints.

The natural frequencies versus temperature of a "rested" beam having a 15% nitinol volume fraction and constrained fibers are shown in Fig. 39. The natural frequency at room temperature has increased from 21 Hz for the beam with free fibers to 39 Hz for the beam with constrained fibers. This is a result of the residual stress in the nitinol fibers extending outside of the beam to the clamping screws. The constraining process introduced some strain to the portion of the nitinol fibers extending outside of the beam and therefore, as the beam is heated and cooled, residual stress is introduced to the portion of the fibers extending outside of the beam. Chapter 2 has shown that this residual stress is not relieved unless the fibers are subjected to a temperature of 350°F (177°C) for two hours. The residual stress acts as a prestress on the beam at room temperature.

Because the nitinol fibers are clamped to the test fixture, the fibers are prevented to some degree from contracting within the matrix material resulting in an increase in the activated frequencies. The first natural frequency has increased from 62 Hz at 300°F (149°C) for the beam with free fibers to 71 Hz at the same temperature for the beam with constrained fibers. Although the activated first natural frequency has increased by constraining the nitinol fibers, the controllable range has decreased. The beam with constrained nitinol fibers allows only a change of 80% in the first natural frequency as compared to the change of nearly 200% for the beam without constrained fibers. If the nitinol fibers could be constrained without introducing a resi-

ASET of "Rested" SMA Beam

vf=15%, constrained fibers



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 39. ASET of "Rested" SMA Beam with Constrained Fibers, 15% nitinol volume fraction

dual stress within the fibers, the beam with constrained fibers would have a larger percent increase in the unactivated to activated frequencies.

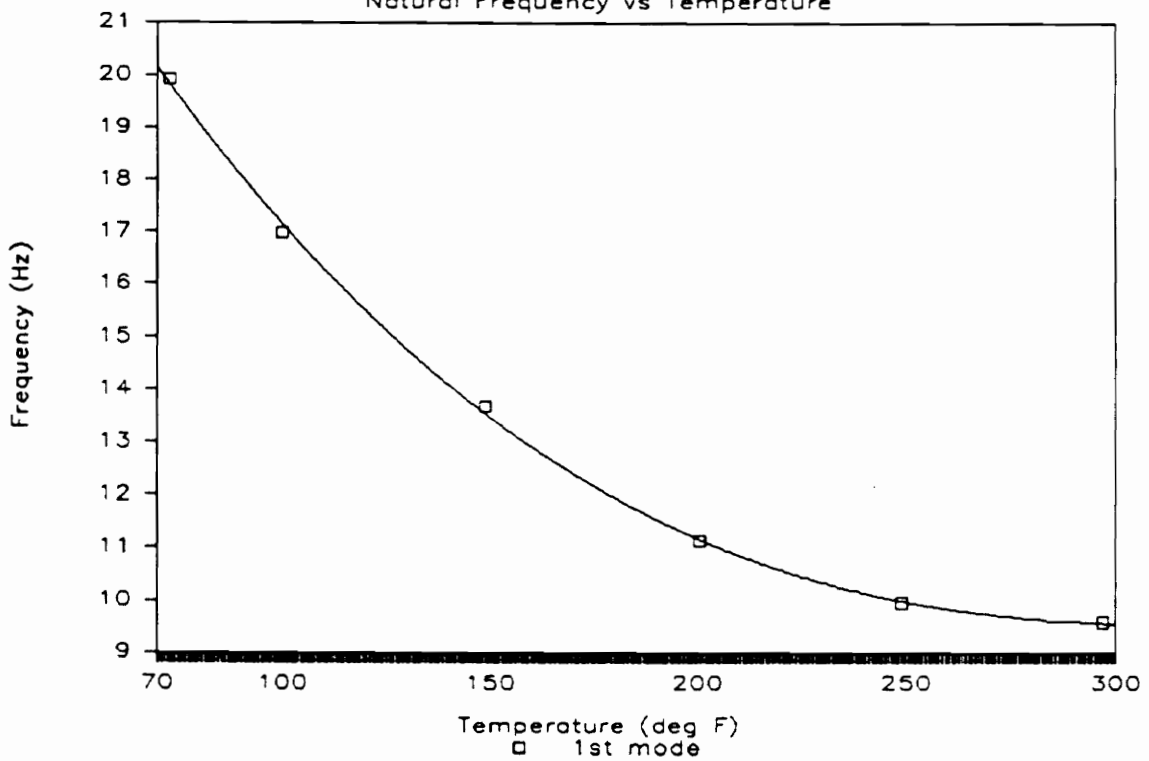
It is also interesting to note that the controllable range with respect to temperature has also decreased. The beam with constrained fibers is near its maximum activated natural frequencies at 175°F (79°C) while the beam without constrained fibers reaches its maximum activated natural frequencies at 250°F (121°C). The change in natural frequency with respect to temperature is no longer a linear relation as compared to the beam without constrained fibers.

The natural frequency versus temperature of a graphite-epoxy beam without embedded nitinol fibers is also determined. These results for the first natural frequency are shown in Fig. 40. As expected the natural frequency decreases as a function of temperature as a result of both a decrease in stiffness and thermal expansion of the graphite-epoxy matrix. Buckling is apparent as the beam approaches 300°F (149°C). This indicates that thermal expansion and the corresponding compressive load play an important role in the change in natural frequencies of the graphite epoxy beam. Considering ASET, one would expect the thermal expansion of the matrix material to have a cancelling effect on the tensile recovery stress of the embedded nitinol fibers. This means that even larger increases in the natural frequencies can be achieved if nitinol composites are tailored to have a smaller coefficient of thermal expansion in the direction of the embedded nitinol fibers.

The first natural frequency versus temperature for the graphite-epoxy beam (without embedded fibers) is compared to the "rested" 15% nitinol volume fraction beam in Fig. 41. Both beams have similar first natural frequencies at room temperature. As the beams are heated, the graphite-epoxy beam shows a decreasing frequency as a

Graphite-Epoxy Beam (no nitinol)

Natural Frequency vs Temperature

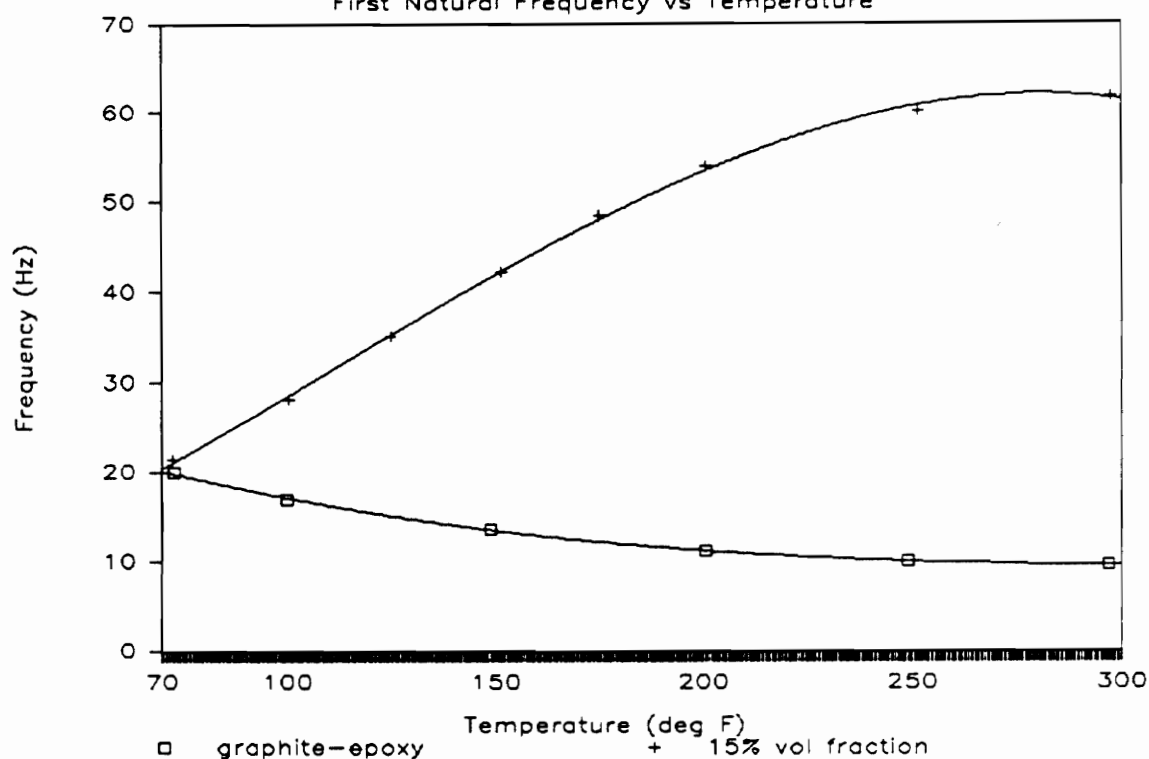


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 40. Natural Frequency versus Temperature of Graphite-Epoxy Beam.

Graphite-Epoxy and 15% Vol. Fraction

First Natural Frequency vs Temperature



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 41. Natural Frequency versus Temperature of "Rested" 15% Volume Fraction Beam and Graphite-Epoxy Beam.

function of increasing temperature. The graphite-epoxy beam has a first natural frequency of 10 Hz at 300°F (149°C). The "rested" 15% volume fraction beam, on the other hand, has an increasing frequency as a function of increasing temperature. The "rested" 15% volume fraction beam has a first natural frequency of 62 Hz at 300°F (149°C). This figure demonstrates that by including embedded nitinol fibers the activated first natural frequency of a clamped-clamped beam at 300°F (149°C) can be changed by 520%. It is apparent from these results that a nitinol composite may be tailored to give a uniform dynamic response over a large temperature range or give some other desired dynamic response as a function of temperature.

4.3.3 Hysteresis Effects

ASET of a clamped-clamped SMA reinforced composite beam utilizes a change in the state of stress on the composite to cause a change in the natural frequencies. This change in stress is induced by a change in temperature. A compressive stress caused by thermal expansion of the matrix material is also induced within the beam as a function of temperature. As the composite matrix is heated the matrix material tries to expand against the constraints. The change in natural frequency is a result of the opposing stresses as a result of embedded nitinol fibers and thermal expansion of the matrix material.

Thermal expansion of the matrix material and a reduction of the shear modulus as temperature increases results in viscoelastic shear-lag effects within clamped-clamped composite beams. The viscoelastic nature of the shear strain is demon-

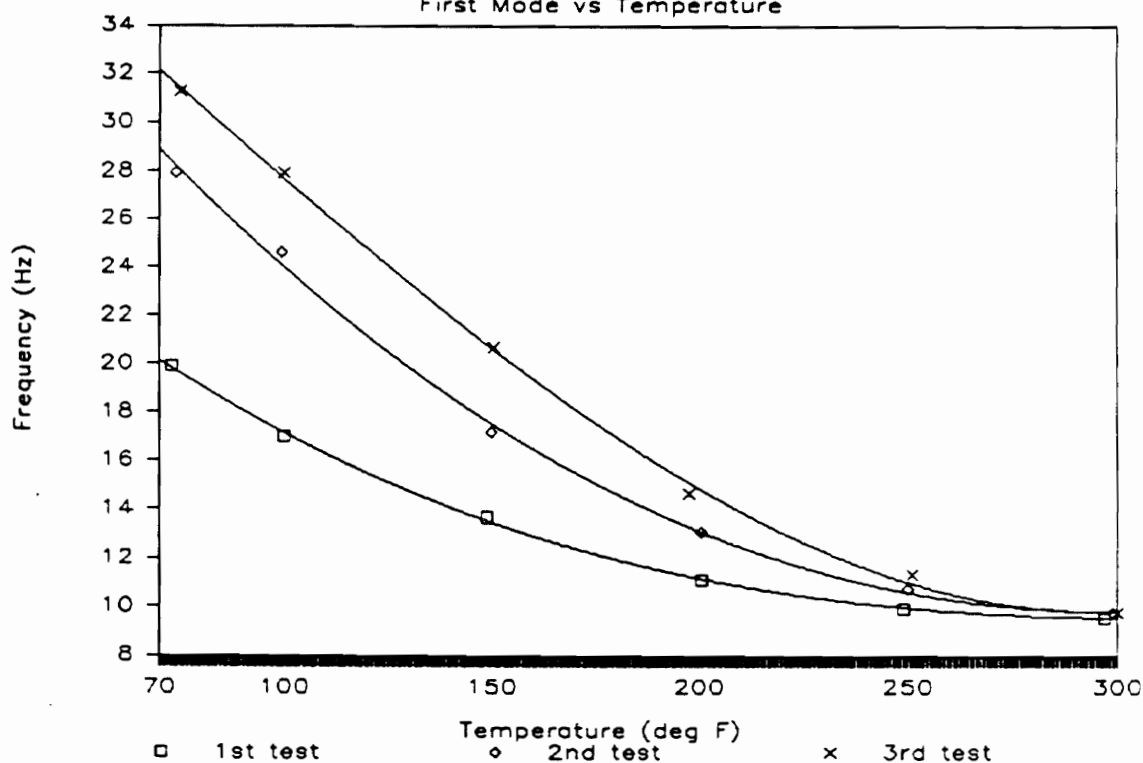
strated below. The results of these tests are used to understand the role of thermal expansion in ASET of SMA reinforced composites.

Three natural frequency versus temperature tests are performed on a graphite epoxy beam without embedded nitinol fibers. The first test is performed after clamping the beam in the test fixture. The first test represents the natural frequency versus temperature of the "original" beam. Each test is performed immediately after the previous one. The second and third tests represent "worked" beams. The results of these tests are shown in Fig. 42.

The first natural frequency at room temperature immediately after clamping is 20 Hz. The first natural frequency for the "worked" beam increases to 28 Hz for the second test and 31 Hz for the third test. The increase in the natural frequency at room temperature is a result of thermal expansion of the graphite-epoxy matrix and the clamped boundaries. The maximum temperature of the test is 300°F (149°C). At this temperature the epoxy-resin experiences a reduction in the shear modulus. The clamped boundary condition does not provide an absolute constraint against the expansion of the graphite-epoxy matrix. Clamping at each end constrains only the surface of the beam in contact with the clamping device. The end of the beam is not constrained from motion, therefore the matrix material is not constrained from expanding along the length of the beam at locations away from the surface. (Refer to Fig. 26 on page 93 and subsequent discussion of boundary conditions.) The thermal expansion of the matrix material creates a compressive stress along the length of the beam. The reduced shear modulus of the matrix material acts as a medium to relieve this compressive stress. The matrix material begins to experience a shear-lag deformation at locations away from the surface of the beam relieving the compressive

Graphite-Epoxy Beam (no nitinol)

First Mode vs Temperature



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

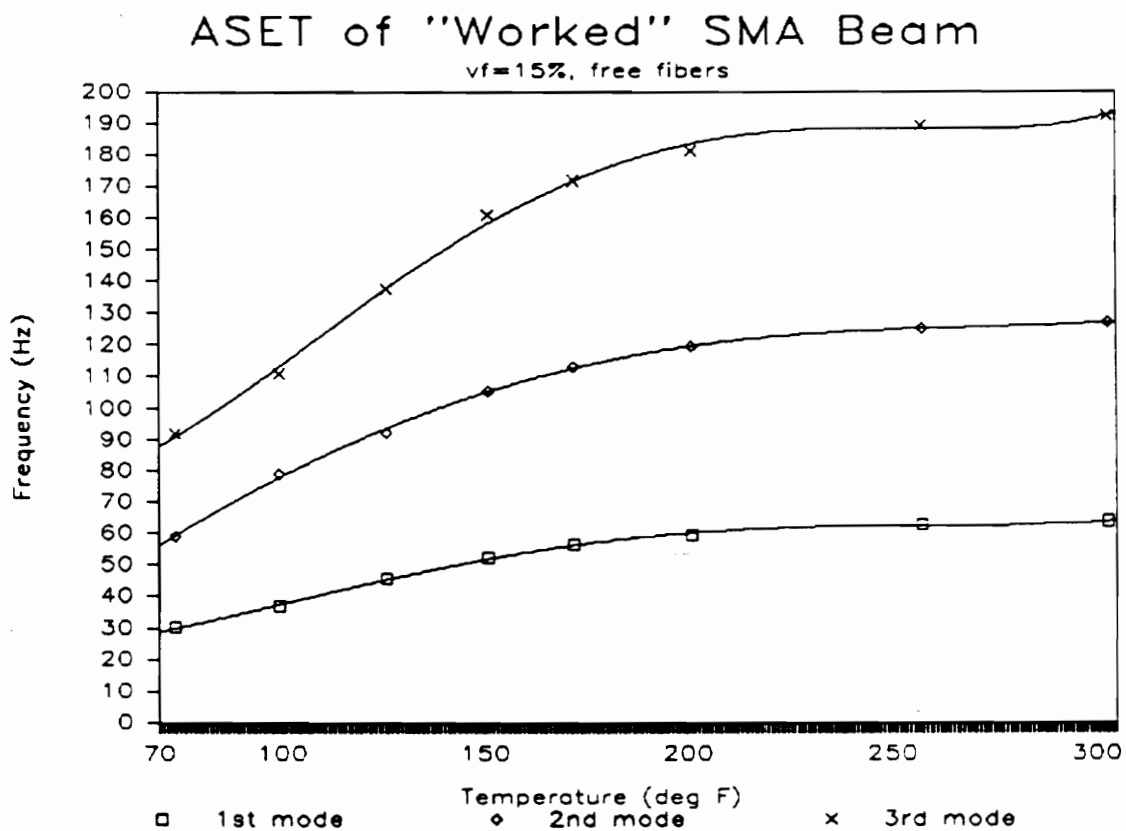
Figure 42. Comparison of Natural Frequencies versus Temperature of "Rested" and "Worked" Graphite-Epoxy Beam.

stress. As the beam is cooled to room temperature, the matrix material away from the surface of the beam tries to contract to its original length at room temperature. The shear modulus of the matrix material increases and the beam cannot recover the strain as a result of the viscoelastic nature of the shear deformation of the matrix material away from the surface of the beam. This strain in the matrix material of a "worked" beam at room temperature results in a tensile stress and a corresponding increase in the natural frequency.

Buckling is apparent as the beam approaches 300°F (149°C) for each test. The relief of the compressive stress at high temperature is not enough to relieve the buckled state of the beam. Therefore no attempt is made to quantify the decrease in natural frequency as a function of temperature. It is enough to simply state that the decrease in natural frequency is due in large part to the thermal expansion of the matrix material and resulting compressive stress along the length of the beam.

The residual stress introduced to the "worked" beams is caused by the strain introduced to the matrix material at high temperature and the inability to recover this strain as the beam is cooled. After the third test, the beam is allowed to rest for a period of 12 hours. The first natural frequency of the "rested" beam is 20 Hz, the same frequency as the "original" beam before testing. This suggests that the matrix material is able to recover a strain induced load over time, even at room temperature.

The effect of residual stress as a result of thermal expansion of the graphite-epoxy matrix and its role in ASET is demonstrated in Fig. 43. The first three natural frequencies versus temperature of a "worked" 15% nitinol volume fraction beam with free fibers is shown. (ASET of the "rested" is shown in Fig. 38 on page 122.) The first natural frequency at room temperature of the "worked" beam has increased from 20



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 43. ASET of "Worked" SMA Beam with Free Fibers, 15% nitinol volume fraction.

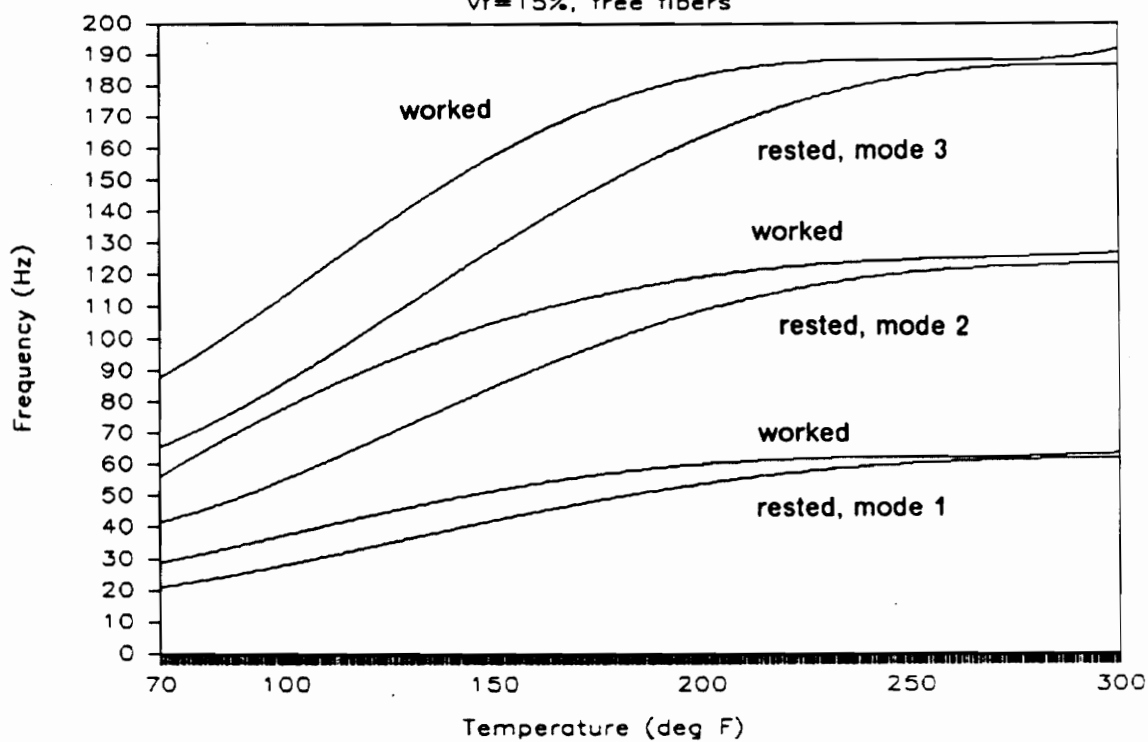
Hz to 30 Hz. The maximum activated first natural frequency has also increased from 61 Hz to 63 Hz. A comparison of the least squared polynomial curve fit for both "rested" and "worked" beams is shown in Fig. 44. The natural frequencies increase as a function of increasing temperature. The rate of increase in frequency is much larger at lower temperatures than at high temperatures. This acts as a degenerative effect in the potential of ASET. The change in the first natural frequency from room temperature to the maximum activated first natural frequency has decreased from nearly 200% for the "rested" beam to 110% for the "worked" beam.

The natural frequencies versus temperature of the "worked" 15% nitinol volume fraction beam with constrained fibers is shown in Fig. 45. (The "rested" beam is shown in Fig. 39 on page 125.) The first natural frequency of the "worked" beam at room temperature has increased from 39 Hz to 45 Hz. The maximum activated first natural frequency has also increased from 71 Hz to 74 Hz. A comparison of the least squared fits for both the "rested" and "worked" beams is shown in Fig. 46. Again, the increase in natural frequencies is a consistent trend throughout the range of temperature. The potential of ASET has also decreased from a change of 80% in the first natural frequency for a "rested" beam to a change of 60% for a "worked" beam.

Analysis of the graphite-epoxy beam without embedded nitinol fibers suggested that the residual stress of a "worked" beam is relieved over a period of time. The first three natural frequencies at room temperature versus time of a "worked" beam are shown in Fig. 47. The beam has a nitinol volume fraction of 15% and free fibers. Time is measured from the time the "worked" beam is allowed to begin cooling to room temperature. The first natural frequency 15 minutes after the beam is allowed to cool is 30 Hz. Over a period of six hours the first natural frequency decreases to

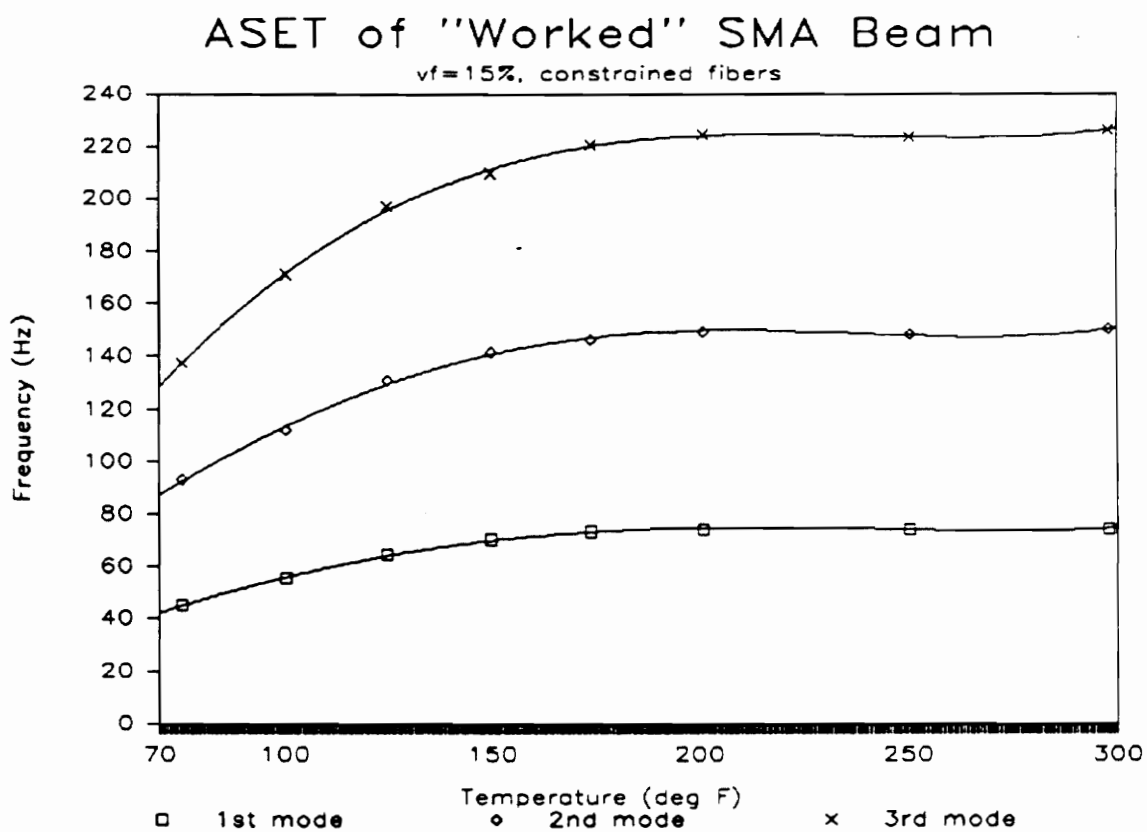
"Rested" and "Worked" SMA Beam

vf=15%, free fibers



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 44. Comparison of "Rested" and "Worked" SMA Beam with Free Fibers, 15% nitinol volume fraction.

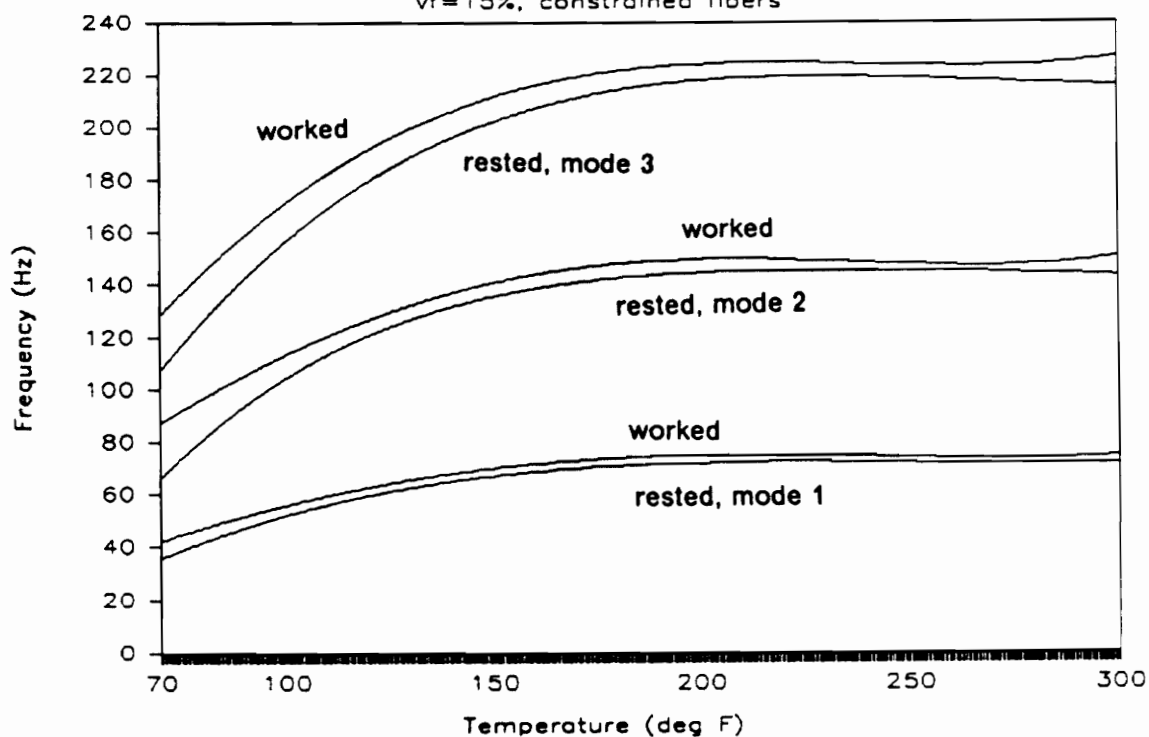


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 45. ASET of "Worked" SMA Beam with Constrained Fibers, 15% nitinol volume fraction.

"Rested" and "Worked" SMA Beam

vf=15%, constrained fibers

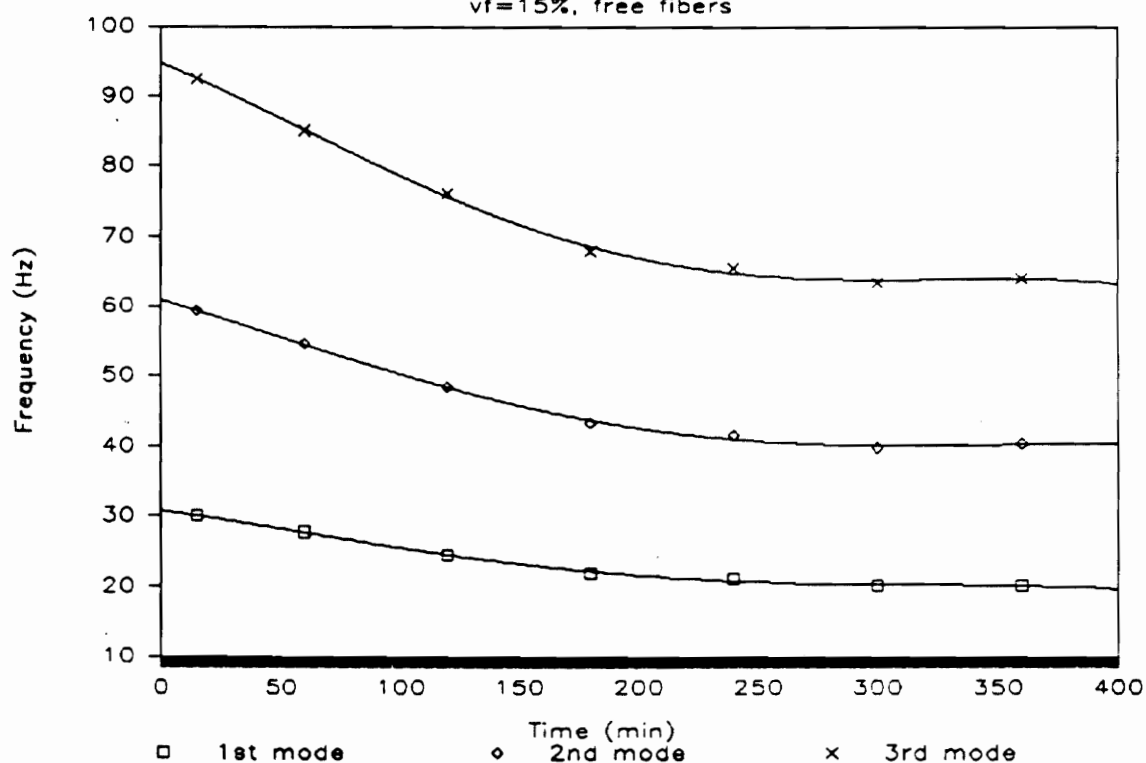


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 46. Comparison of "Rested" and "Worked" SMA Beam with Constrained Fibers, 15% nitinol volume fraction.

Time Hysterisis at Room Temperature

vf=15%, free fibers



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 47. Time Hysterisis of Room Temperature SMA Beam with Free Fibers, 15% nitinol volume fraction.

20 Hz, the same frequency of the "rested" beam at room temperature (refer to Fig. 38 on page 122).

The thermal expansion and relief of the corresponding compressive stress is also a function of time. The first natural frequency at 250°F (121°C) versus time for a "worked" beam is shown in Fig. 48. A "worked" 15% nitinol volume fraction beam with constrained fibers is heated to 250°F (121°C) and held constant for the duration of the test. The natural frequencies are determined every 30 minutes for a period of three hours. The first natural frequency increases from 73 Hz to 76 Hz after a period of three hours.

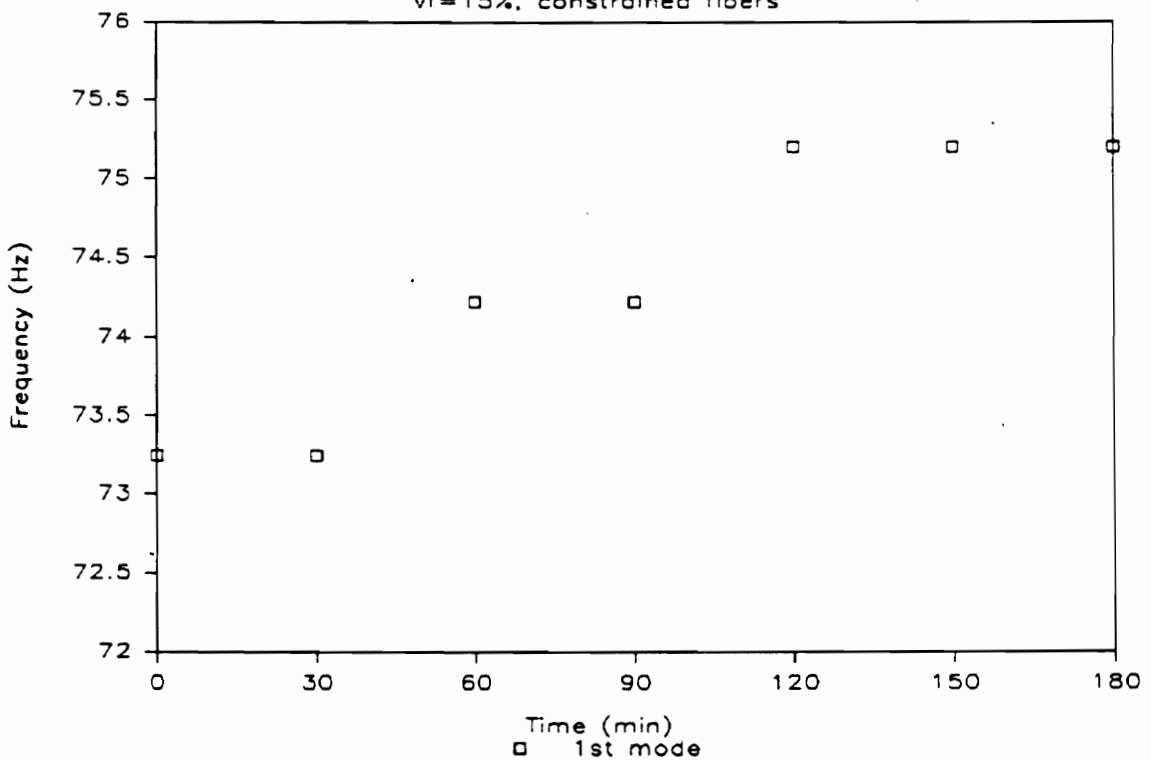
The thermal expansion of graphite-epoxy and the viscoelastic shear-lag as a result of the reduced shear modulus at the temperature of maximum activated frequencies create a residual stress within the composite matrix when the beam is cooled. This resulting tensile stress is relieved over a period of six hours. A matrix material with a lower coefficient of thermal expansion would decrease the magnitude of the residual stress in "worked" beams at room temperature. This would help to reduce the hysteresis effects of ASET of "worked" SMA composites. Another possible improvement would be to tailor nitinol composites to have a lower coefficient of thermal expansion for the overall beam. This would prevent flow of the matrix material away from the constrained surface.

4.3.4 Nitinol Volume Fraction

One would expect the potential of ASET to increase the natural frequencies of a clamped-clamped SMA beam to become more effective as the nitinol volume fraction

Time Hysterisis of Activated SMA Beam

vf=15%, constrained fibers



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 48. Time Hysterisis of Activated SMA Beam with Constrained Fibers, 15% nitinol volume fraction.

is increased. The effect of volume fraction and the role of thermal expansion of the graphite-epoxy matrix are evaluated by comparing the results of 5% and 10% nitinol volume fraction beams to the 15% volume fraction beam presented above.

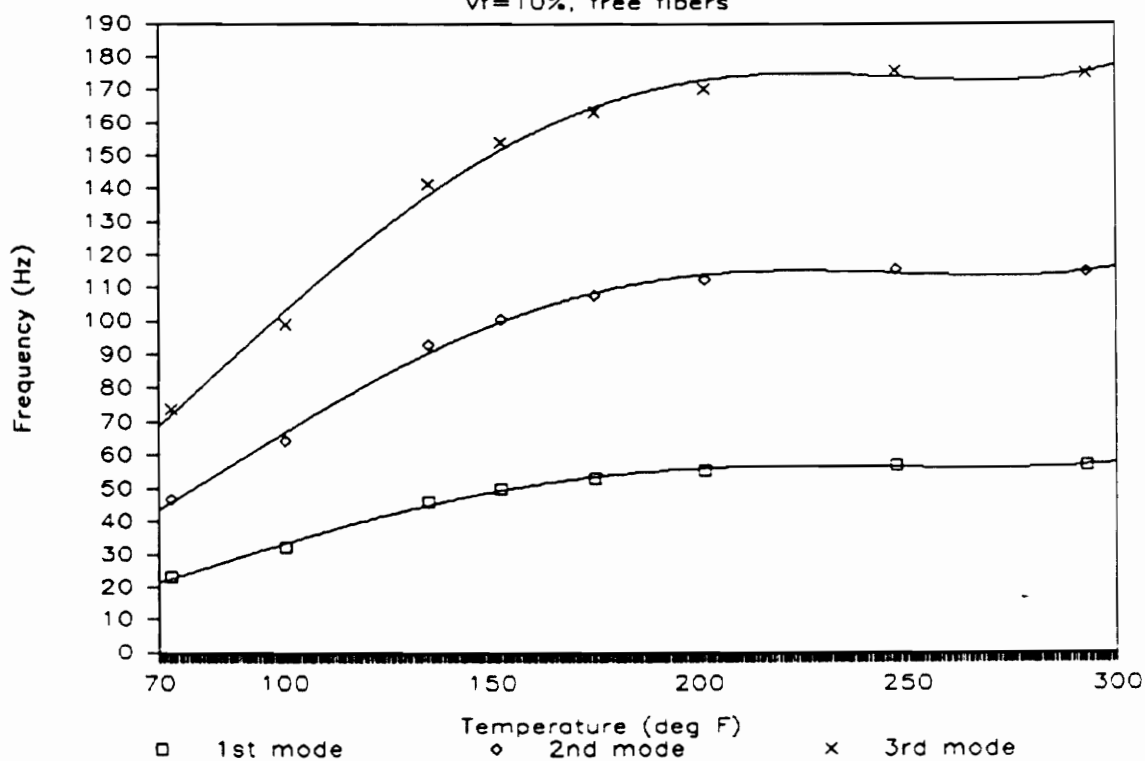
The natural frequencies versus temperature of a "rested" SMA beam with free fibers and a 10% nitinol volume fraction is shown in Fig. 49. The first natural frequency at room temperature is 23 Hz and increases to a maximum of 57 Hz. This amounts to a change of 150% in the first natural frequency. The maximum activated natural frequencies are reached at approximately 200°F (93°C). This is lower than the 250°F (121°C) required to reach maximum activated natural frequencies for the "rested" 15% nitinol volume fraction beam (refer to Fig. 38 on page 122). This gives a corresponding reduction in the linear range of activation. The 10% nitinol volume fraction beam has a linear range up to 150°F (66°C). This amounts to a reduction of 50°F (28°C) from the 15% nitinol volume fraction beam.

The natural frequencies versus temperature of a "worked" 10% nitinol volume fraction beam with free fibers is shown in Fig. 50. The first natural frequency at room temperature has increased from 23 Hz to 36 Hz. The maximum activated first natural frequency has increased from 57 Hz to 59 Hz. A comparison of the least squared fit of the natural frequencies versus temperature for the "rested" and "worked" beams is shown in Fig. 51. The overall effect is a reduction in the potential of ASET for the "worked" beam. The change in the first natural frequency at room temperature to the maximum activated first natural frequency is 64% for the "worked" beam compared to the change of 150% for the "rested" beam.

The natural frequencies versus temperature of a "rested" SMA beam with free fibers and a 5% nitinol volume fraction is shown in Fig. 52. The first natural frequency in-

ASET of "Rested" SMA Beam

vf=10%, free fibers

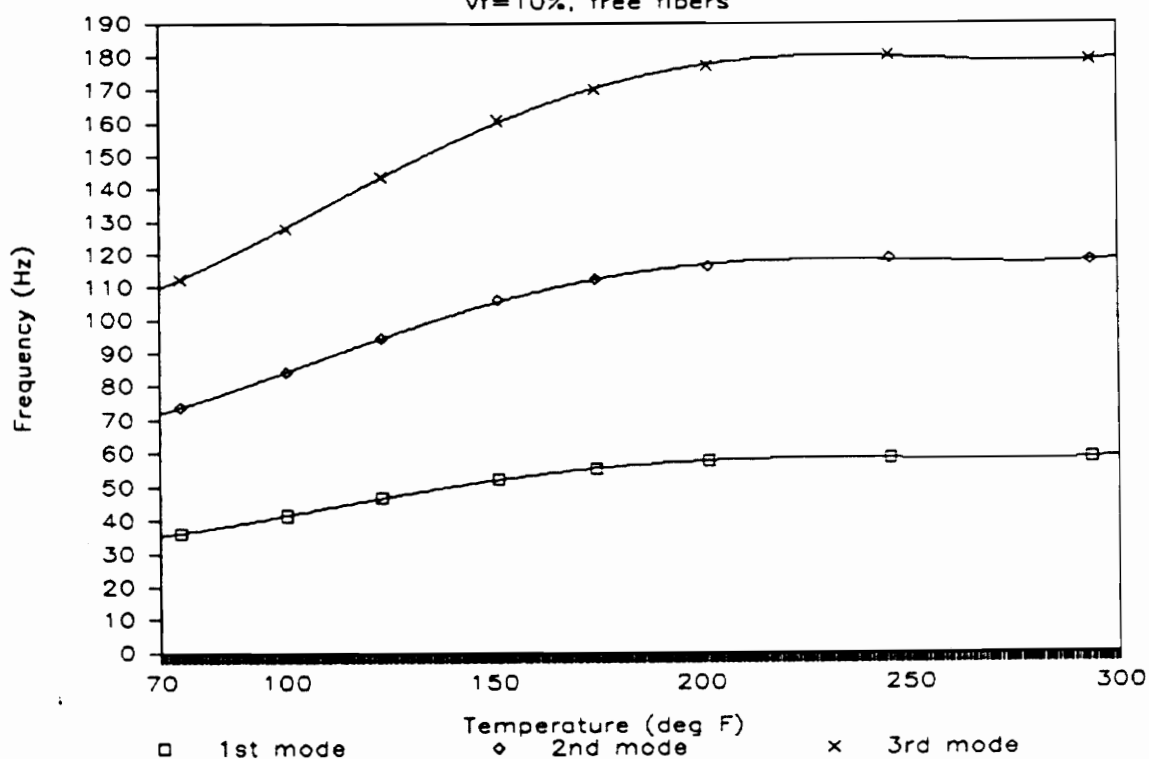


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 49. ASET of "Rested" SMA Beam with Free Fibers, 10% nitinol volume fraction.

ASET of "Worked" SMA Beam

vf=10%, free fibers

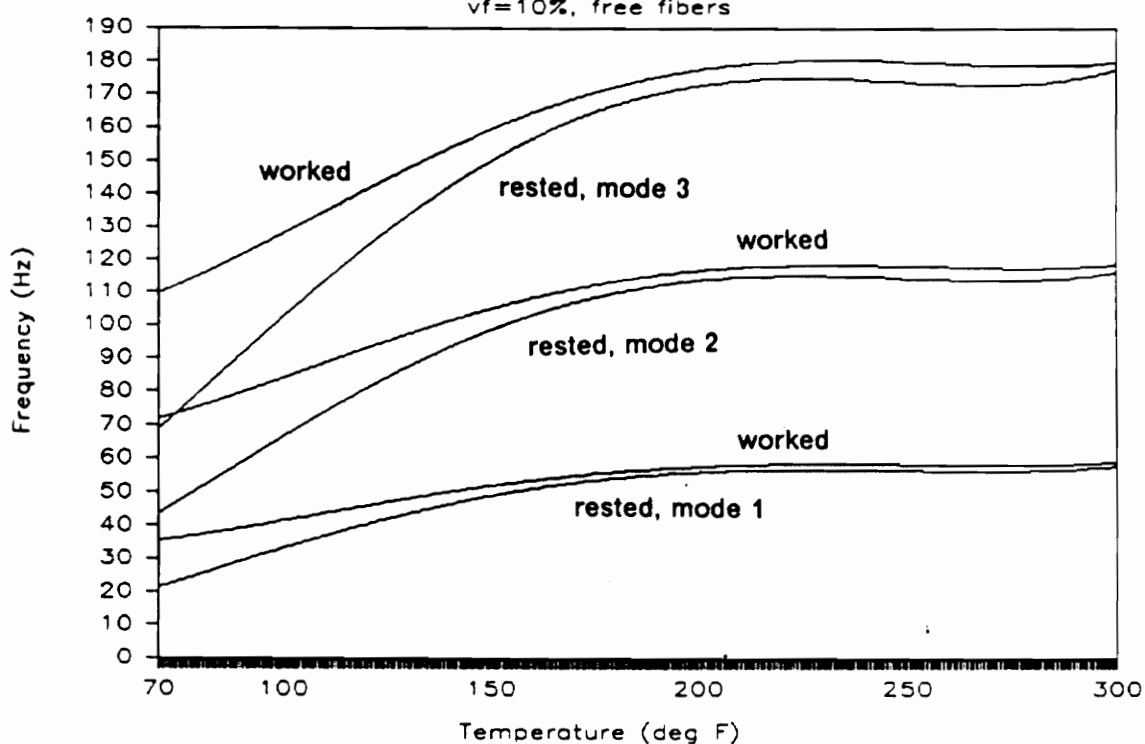


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 50. ASET of "Worked" SMA Beam with Free Fibers, 10% nitinol volume fraction.

"Rested" and "Worked" SMA Beam

vf=10%, free fibers

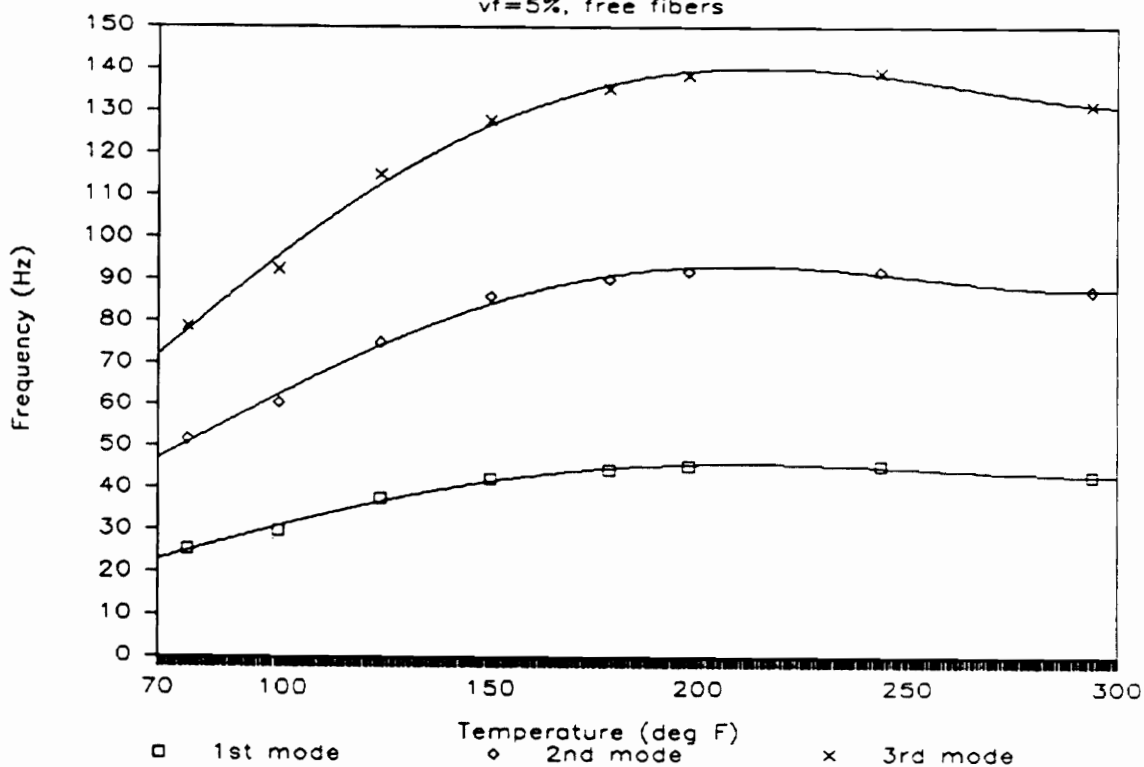


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 51. Comparison of "Rested" and "Worked" SMA Beam with Free Fibers, 10% nitinol volume fraction.

ASET of "Rested" SMA Beam

vf=5%, free fibers



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 52. ASET of "Rested" SMA Beam with Free Fibers, 5% nitinol volume fraction.

creases from 25 Hz at room temperature to a maximum of 43 Hz at the activated temperature. This amounts to a change of 72% in the first natural frequency for the "rested" 5% volume fraction beam. The maximum natural frequency occurs at a lower temperature and the linear range is smaller than the "rested" 15% nitinol volume fraction beam. The temperature at which the fully activated natural frequencies occur is approximately 200°F (93°C) and natural frequency versus temperature is fairly linear up to 150°F (66°C).

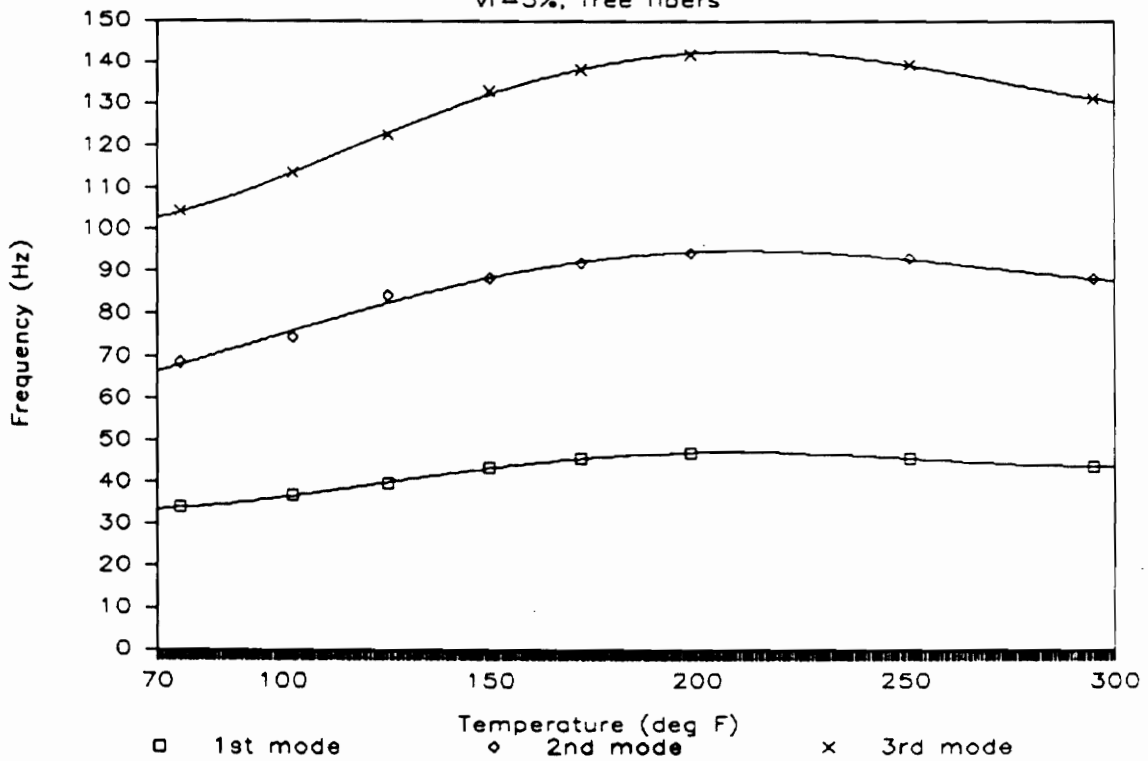
The natural frequencies versus temperature of a "worked" 5% nitinol volume fraction beam with free fibers is shown in Fig. 53. The first natural frequency at room temperature has increased from 25 Hz to 34 Hz for the "worked" beam. The maximum first natural frequency has also increased from 43 Hz to 44 Hz for the "worked" beam. A comparison of the least squared fit of the natural frequencies versus temperature for both the "rested" and "worked" 5% volume fraction beam is shown in Fig. 54. Again, the overall effect is a large reduction in the possible increase of the natural frequencies of the "worked" beam. The change in the first natural frequency to the maximum first natural frequency is reduced to 30% for the "worked" beam as compared to the change of 72% for the "rested" beam.

A comparison of the maximum activated natural frequencies for the "rested" beams with free fibers is shown as a function of nitinol volume fraction in Fig. 55. The increase in natural frequencies does not appear to be a linear function of the nitinol volume fraction.

Increased nitinol volume fraction has the effect of increasing the ability of ASET to change the natural frequencies of nitinol composites. The temperature at which

ASET of "Worked" SMA Beam

vf=5%, free fibers

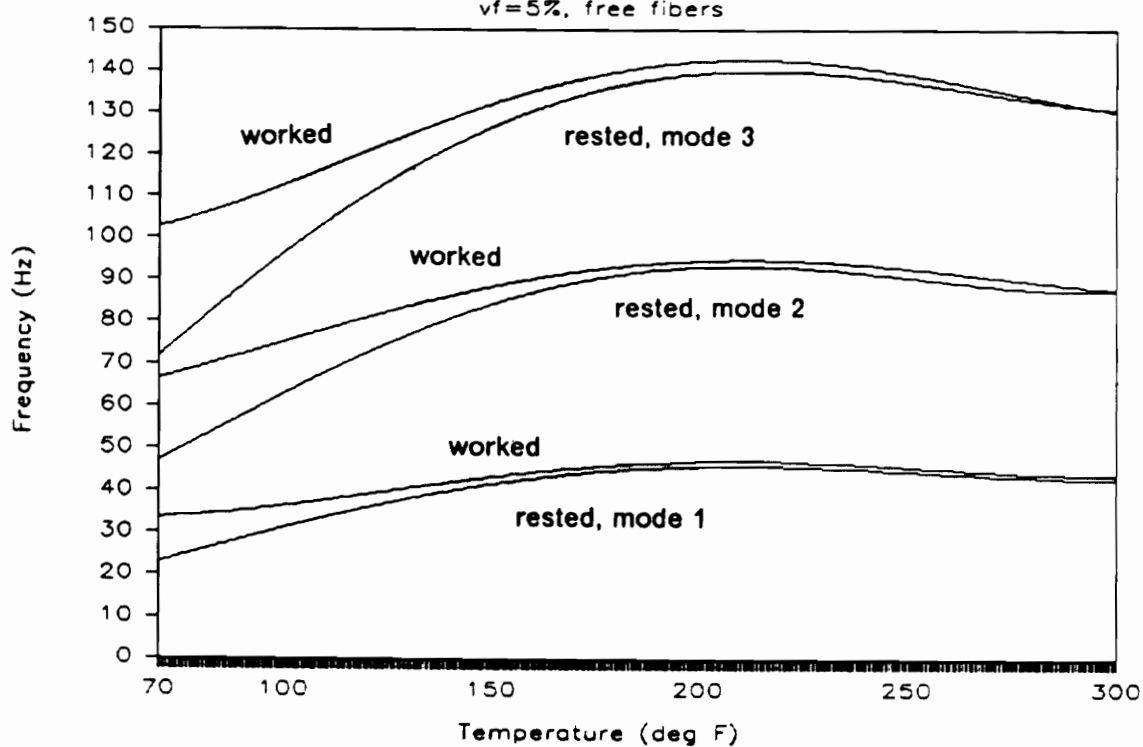


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 53. ASET of "Worked" SMA Beam with Free Fibers, 5% nitinol volume fraction.

"Rested" and "Worked" SMA Beam

vf=5%, free fibers

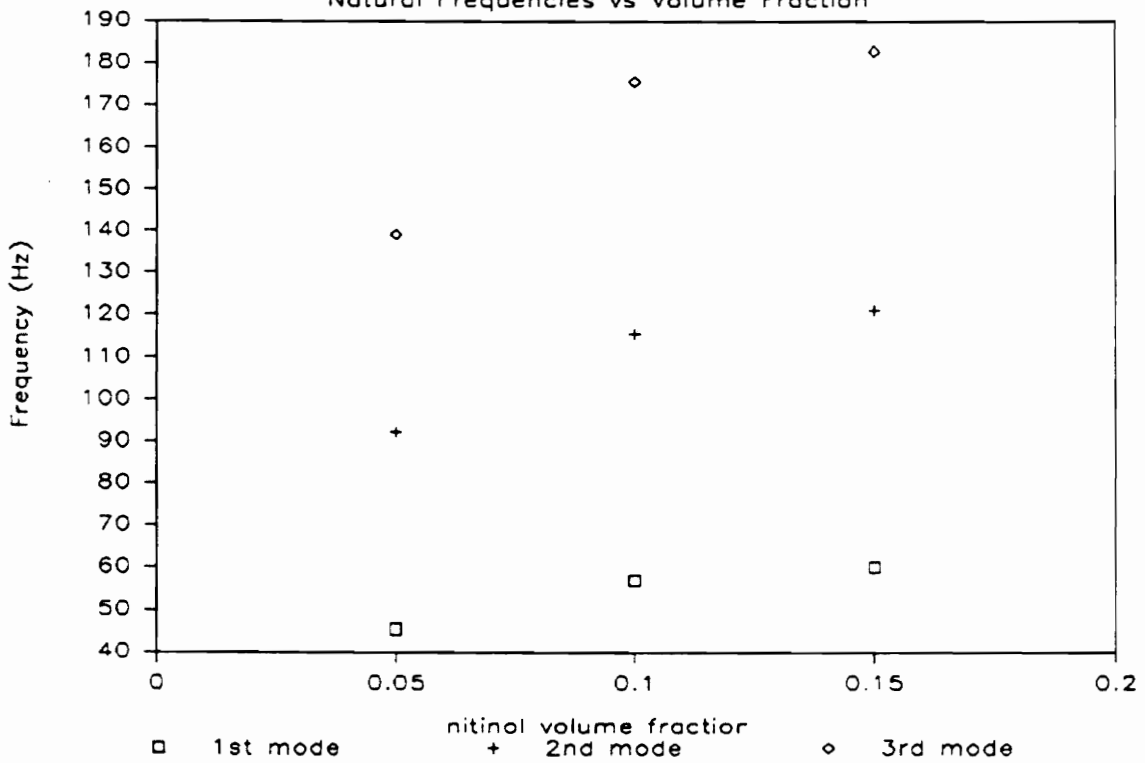


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 54. Comparison of "Rested" and "Worked" SMA Beam with Free Fibers, 5% nitinol volume fraction.

ASET of SMA Beams

Natural Frequencies vs Volume Fraction



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32)$$

Figure 55. Maximum Activated Natural Frequencies of "Rested" SMA Beams as a Function of Nitinol Volume Fraction.

maximum natural frequencies occur and the linear range of actuation are increased as well.

5.0 Comparison of Theoretical and Experimental Results

5.1 Introduction

A theoretical simulation and experimental results for Active Strain Energy Tuning (ASET) of a clamped-clamped Shape Memory Alloy (SMA) beam are presented in Chapters 3 and 4. A comparison of the predicted dynamic response and the experimental results is shown below.

The recovery stress versus temperature of the embedded nitinol fibers is not available, however the maximum recovery stress of the nitinol fiber is available. The results of Chapter 2 indicate that a maximum recovery stress for an embedded nitinol fiber is 43 kpsi (296 MPa). Because the recovery stress of nitinol as a function of temperature is not available, the theoretical simulation cannot be used to evaluate the natural frequencies for a specific temperature. Therefore, comparison of the

predicted and experimental dynamic response can be made only at the unactivated and fully activated states. The natural frequencies of unactivated and fully activated beams are predicted as a function of volume fraction and compared to the experimental results discussed above. The effect of thermal expansion of the matrix material on the performance of ASET is evaluated as well.

The theoretical simulation described in Chapter 3 requires that the boundary conditions be characterized before the dynamic response of the nitinol composite beam can be predicted. The procedure and the results for the experimental characterization of the boundary conditions are outlined and discussed below.

All beams discussed below are $[90^\circ, 0^\circ, 90^\circ]_r$ graphite-epoxy beams. Nitinol fibers are embedded on the neutral axis in the direction of the length of the beam giving 5%, 10%, and 15% nitinol volume fraction beams. The reader should refer to Fig. 33 on page 108 for the lay-up scheme and Table 3 on page 97 for the material properties. To simplify the theoretical simulation, all beams are assumed to have a clamped-clamped length of 32.25 inches (89.92 cm), a width of 0.86 inches (2.18 cm) and a thickness of 0.034 inches (8.6 mm).

5.2 Determination of Boundary Constants

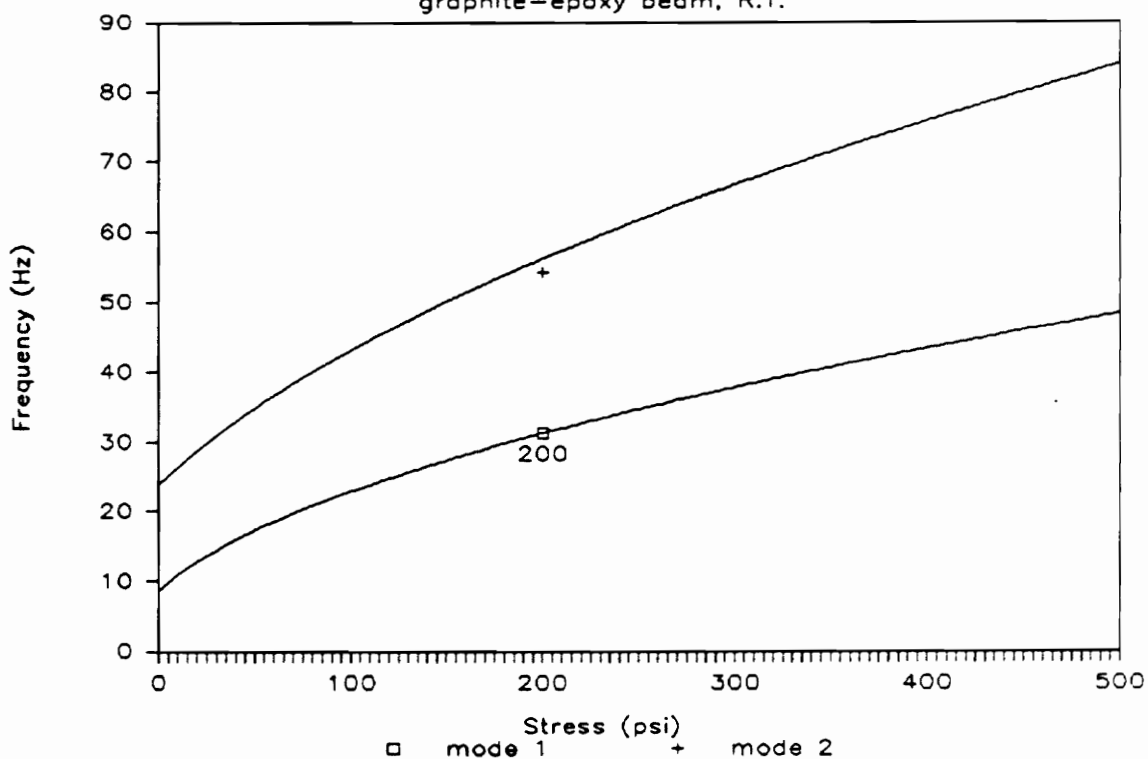
5.2.1 Thermal Boundary Constant

The thermal boundary constant is determined using the experimental results for the all graphite-epoxy beam (refer to Fig. 42 on page 131). The resultant stress used in the theoretical simulation is a function of the prestress at the boundary and the thermal expansion stress. The third test is used because a residual stress has developed at the boundaries after repeated activation. This is evident because an increase in the first natural frequency at room temperature is seen from the first test to the third test. As the beam is heated, a compressive stress at the boundaries caused by thermal expansion appears. The residual stress at room temperature for the third test can be thought of as an initial tensile prestress causing buckling to occur at a higher temperature than the first or second tests.

The thermal boundary constant is determined by calculating the prestress and thermal boundary constant necessary to calculate the theoretical first natural frequency equivalent to the experimental first natural frequency at a temperature greater than room temperature. At room temperature the stress caused by thermal expansion is assumed to be zero. The only stress at the boundary is a result of the prestress. The prestress required to calculate the first natural frequency of 31.3 Hz at room temperature is shown in Fig. 56. The calculated prestress is 200 psi (1.38 MPa). The thermal boundary constant is determined by calculating the total stress at the boundary necessary to calculate the theoretical first natural frequency equivalent to the experimental first natural frequency at 150°F (66°C). From this value and the prestress

Prestress Due to Experimental Setup

graphite-epoxy beam, R.T.



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 56. Prestress at Boundaries for Graphite-Epoxy Beam.

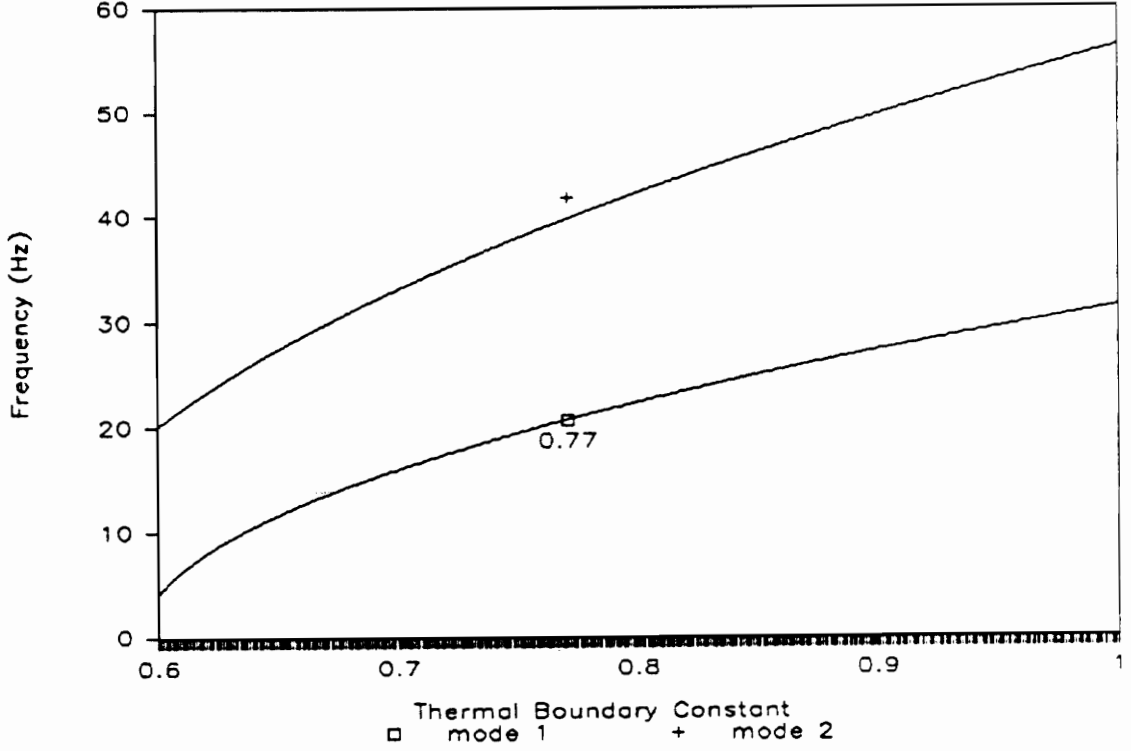
determined above, the thermal boundary constant can be determined. Fig. 57 shows the first two natural frequencies versus the thermal boundary constant at 150°F (66°C). The beam includes the 200 psi (1.38 MPa) prestress. The boundary constant is calculated to be 0.77.

The boundary constant is selected to force the theoretical first natural frequency to match the experimental first natural frequency at 150°F (66°C). The theoretical simulation can now be used to predict natural frequencies at temperatures other than room temperature and 150°F (66°C). The first natural frequencies versus temperature are calculated and compared to experimental results in Fig. 58. Good correlation between theory and experiment is seen for the first mode up to 150°F (66°C). A small error is seen in the predicted second mode. The second mode is predicted with an error of 3%. As the beam approaches 200°F (93°C), theory predicts frequencies lower than the experimental results for both first and second modes. At this temperature, the compressive thermal expansion stress begins to relax as a result of the viscoelastic shear strain of the matrix material (refer to Chapter 4). The effect is a larger resultant stress at the boundary than predicted by theory and therefore higher frequencies than predicted by theory.

The experimentally determined thermal boundary constant ($K_s = 0.77$) is used to predict the natural frequencies of "rested" nitinol composite beams. The residual stress at room temperature, as a result of relaxation of the thermal expansion stress at high temperature, is modeled as a prestress at the boundary and is not incorporated in the boundary constant. Therefore the thermal boundary constant found above should be used for "rested" beams. The thermal boundary constant is also assumed to be independent of the nitinol volume fraction.

Experimental Thermal Boundary Constant

Temperature=150 F, prestress=200 psi

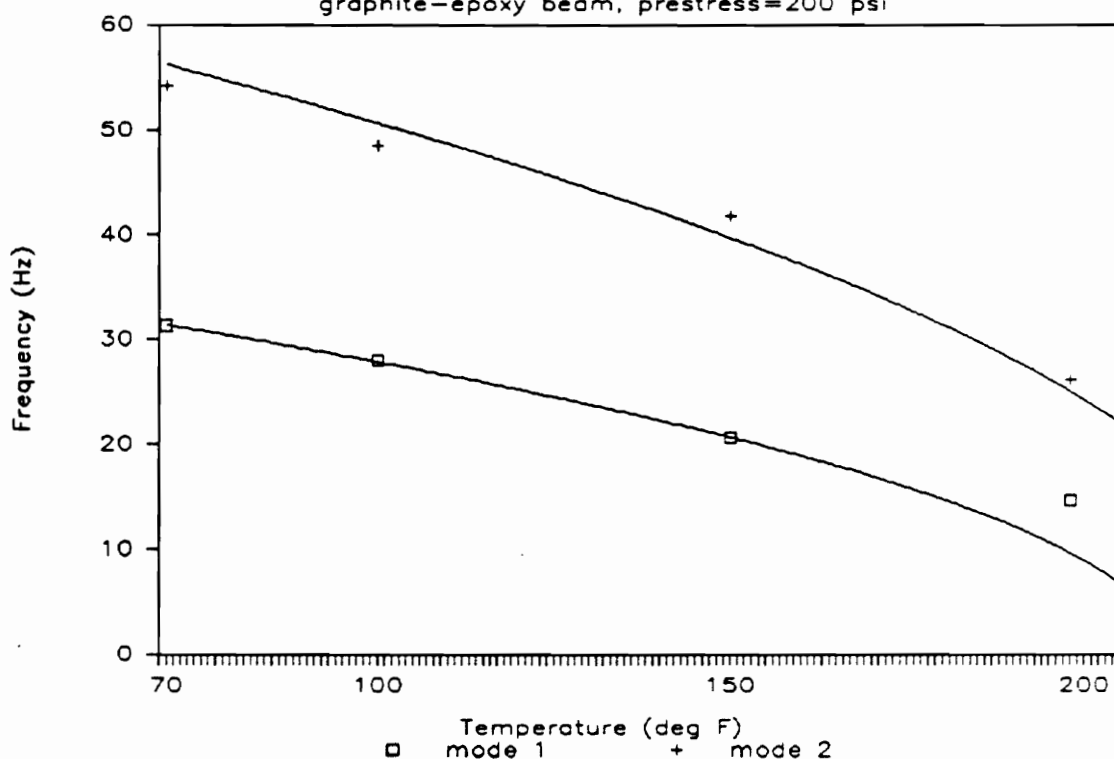


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \qquad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 57. Experimental Thermal Boundary Constant for "Rested" Beam.

Natural Frequencies vs Temperature

graphite-epoxy beam, prestress=200 psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

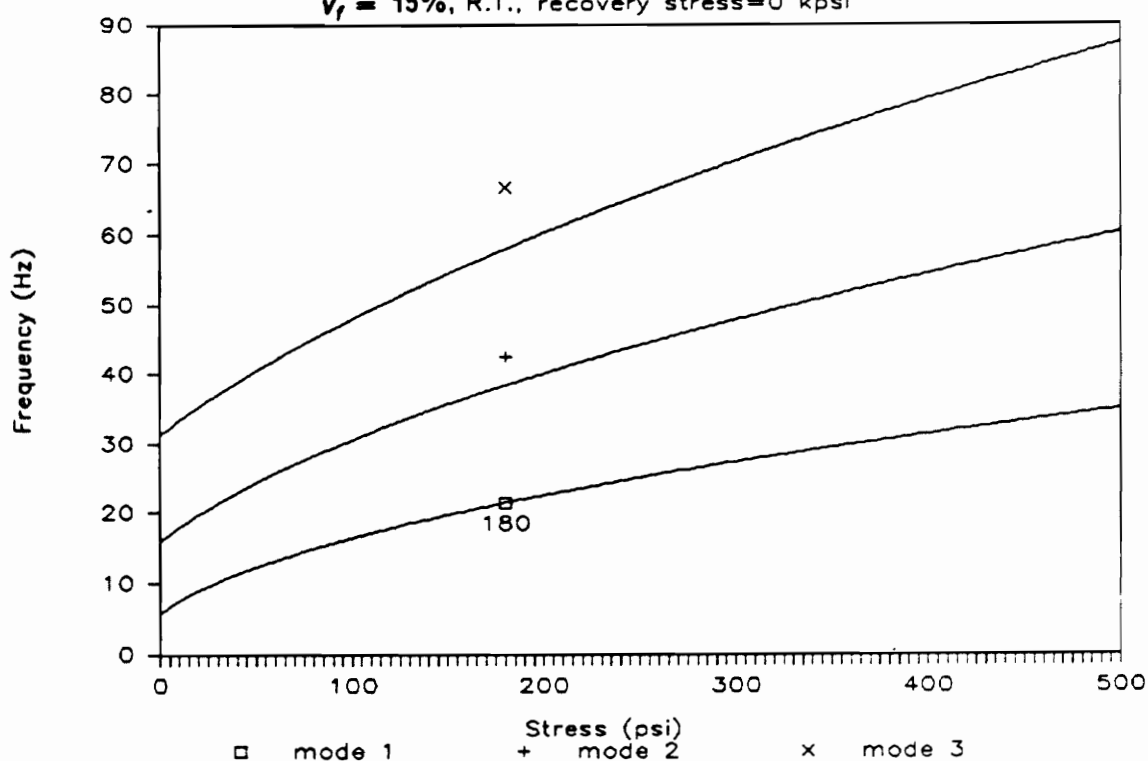
Figure 58. Natural Frequencies versus Temperature for Graphite-Epoxy Beam.

5.2.2 Nitinol Boundary Constant

The nitinol boundary constant is determined using the experimental results for the "rested" 15% nitinol volume fraction beam (refer to Fig. 38 on page 122). The resultant stress at the boundary is a function of the nitinol recovery stress (and corresponding boundary constant), the thermal expansion stress (and corresponding boundary constant), and the prestress at the boundary. The thermal boundary constant is calculated above. Two test points are required to determine the nitinol boundary constant and prestress. At room temperature the stress at the boundary as a result of the nitinol recovery stress is assumed to be zero. The prestress is the only unknown at room temperature. The necessary prestress to calculate the theoretical first natural frequency equivalent to the experimental first natural frequency is shown in Fig. 59. The prestress is found to be 180 psi (1.24 MPa). The predicted second and third natural frequencies do not fit the experimental frequencies. The second mode prediction is 10% higher than the experimental result and the third mode prediction is 13% higher than the experimental result. This is a considerable increase in the error when compared to the 3% error common to the predictions for the beam containing no embedded fibers. The increase in the error when trying to predict the natural frequencies of beams including embedded nitinol fibers is the result of residual stress within the composite, created during the fabrication process. The recovery stress of the nitinol fibers during the high temperatures of the composite cure cycle create residual stresses within the composite when the beam is cooled to room temperature and removed from the tool plate used in the fabrication process. The residual stresses as a result of the fabrication process are not included in the theoretical simulation.

Prestress Due to Experimental Setup

$\nu_f = 15\%$, R.T., recovery stress=0 kpsi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 59. Prestress at Boundaries for SMA Composite Beam, 15% nitinol.

The nitinol recovery stress is assumed to be at its maximum value at 300°F (149°C). The natural frequencies versus nitinol boundary constant are shown in Fig. 60. The nitinol boundary constant is found to be 0.71. Again the predicted second and third natural frequencies do not fit the experimental frequencies. The second mode prediction is 14% higher than the experimental result and the third mode prediction is 20% higher than the experimental result. The error in prediction for the activated modes increases even further when compared to the unactivated modes. This suggests that the theory does not correctly predict the in-plane load resulting from the nitinol fiber recovery stress and its effect on higher order modes.

The nitinol boundary constant forces the theoretical first natural frequency to match the experimental first natural frequency at 300°F (149°C). The boundary constant is assumed to be independent of the nitinol volume fraction. The theoretical simulation can be used to predict the natural frequencies of nitinol composite beams of the same thickness.

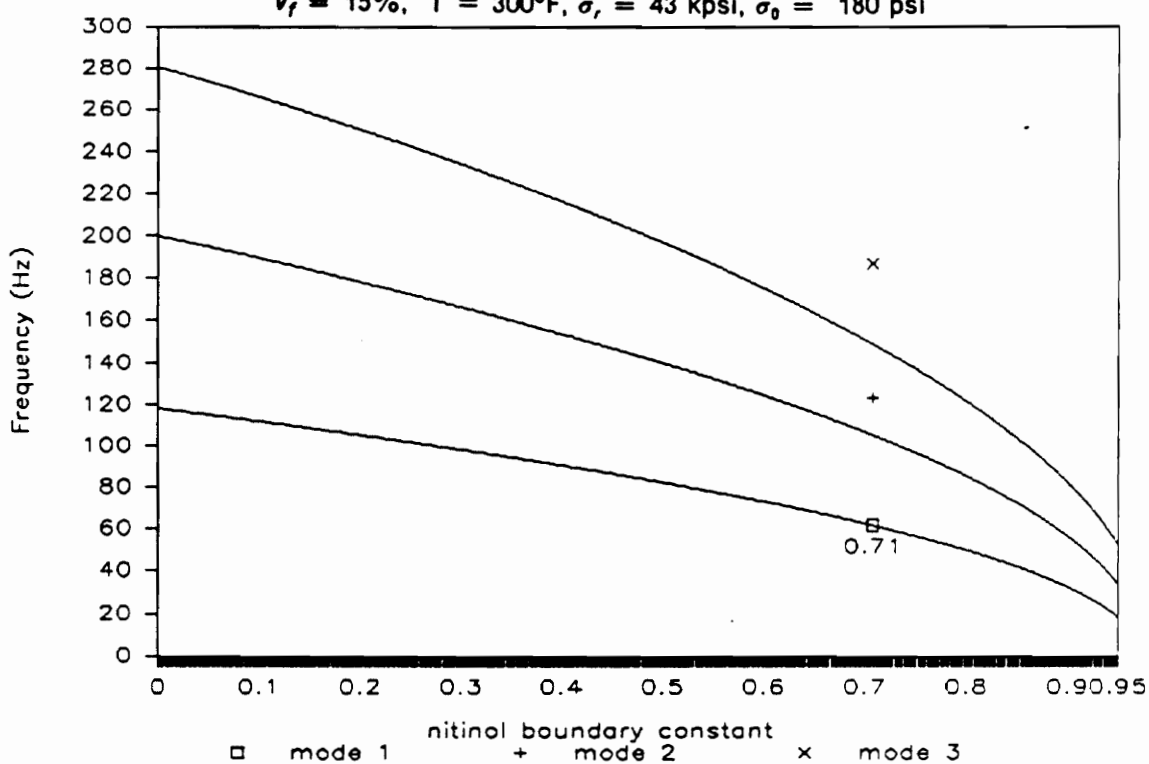
5.3 Natural Frequencies versus Nitinol Volume Fraction

The thermal and nitinol boundary constants were determined experimentally above and are listed here for reference:

- nitinol boundary constant, $K_r = 0.71$
- thermal boundary constant, $K_t = 0.77$

Experimental Nitinol Boundary Constant

$\nu_f = 15\%$, $T = 300^\circ\text{F}$, $\sigma_f = 43 \text{ kpsi}$, $\sigma_0 = 180 \text{ psi}$



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 60. Experimental Nitinol Boundary Constant.

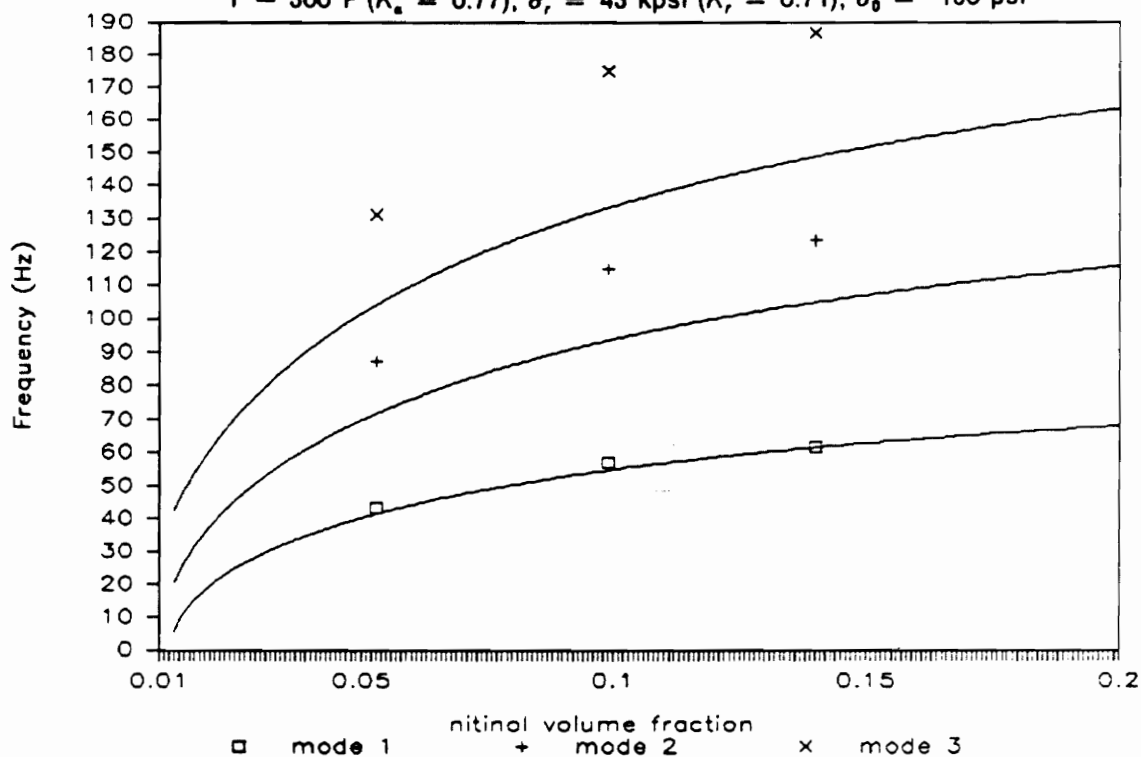
The maximum value of recovery stress for a constrained nitinol fiber is determined in Chapter 2 to be 43 kpsi. The recovery stress of plastically prestrained and constrained nitinol as a function of temperature cannot be determined using the results of Chapter 2. Therefore, comparisons can only be made for unactivated and fully activated beams. Beams are considered to be fully activated at 300°F (149°C) and embedded nitinol fibers having a 5% strain from memory shape are assumed to have a maximum recovery stress ($\sigma_r = 43$ kpsi or 296 MPa) at this temperature. A prestress of $\sigma_0 = 180$ psi (1.24 MPa) is assumed for all beams. Comparison of the theoretical and experimental results are made as a function of volume fraction for both fully activated and unactivated beams.

Figure 61 shows the activated natural frequencies for "rested" beams versus the nitinol volume fraction. The predicted first natural frequency matches the experimental frequency very well for both the 5% and 10% nitinol volume fraction beams. A constant prestress of 180 psi (1.24 MPa) is assumed for all beams. Error in the prediction of the first natural frequency is most likely due to error in the assumption of the same prestress for each experimental set-up. The predicted second and third natural frequencies for each volume fraction are lower than the actual experimental values. The theoretical results predict that buckling will occur at 300°F (149°C) for nitinol volume fractions below 1%. This suggests that properly designed structural members with embedded nitinol fibers can be used to offset effects caused by thermal expansion of the matrix material, as well as incur large changes in the dynamic response of the structural member.

The ratios of the activated natural frequencies to the activated first natural frequency for each volume fraction are shown in Fig. 62. Theory predicts that the natural fre-

Activated Frequencies vs Vol. Fraction

$T = 300^{\circ}\text{F}$ ($K_s = 0.77$), $\sigma_r = 43$ kpsi ($K_r = 0.71$), $\sigma_0 = 180$ psi

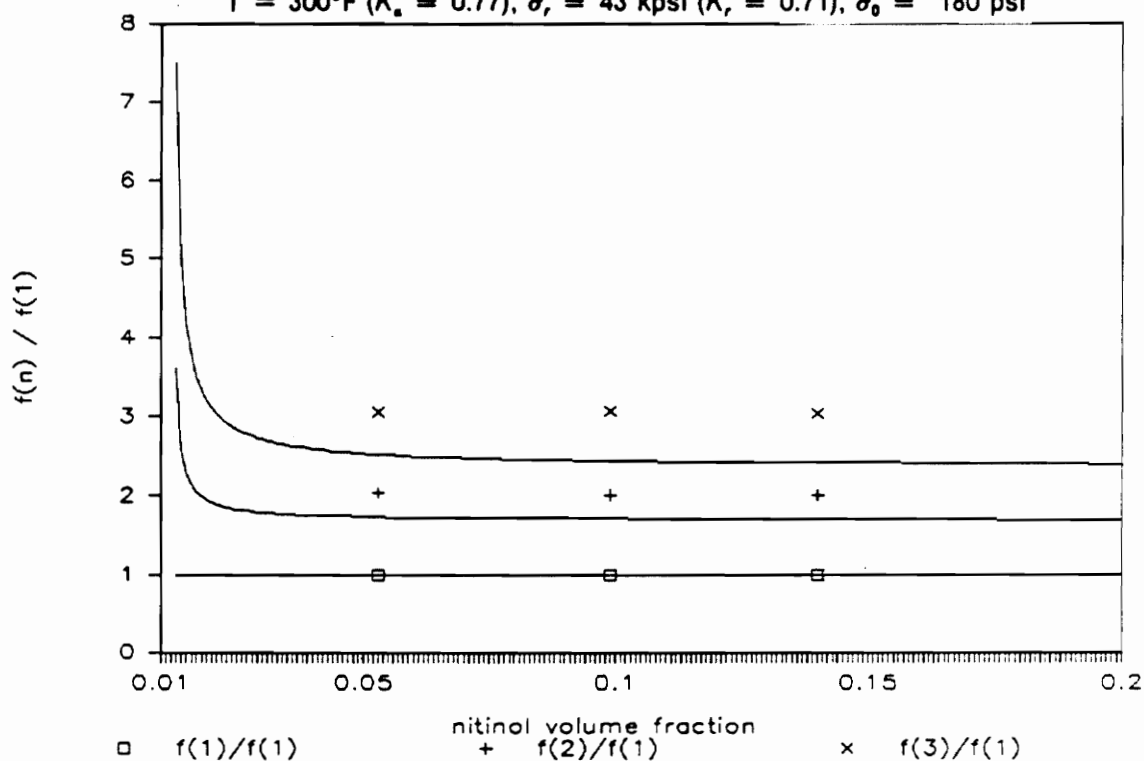


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 61. Comparison of "Rested" Activated Natural Frequencies versus Volume Fraction

Nat. Frequency Ratio vs Vol. Fraction

$T = 300^{\circ}\text{F}$ ($K_s = 0.77$), $\sigma_r = 43$ kpsi ($K_r = 0.71$), $\sigma_0 = 180$ psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 62. Comparison of "Rested" Activated Natural Frequency Ratios versus Volume Fraction.

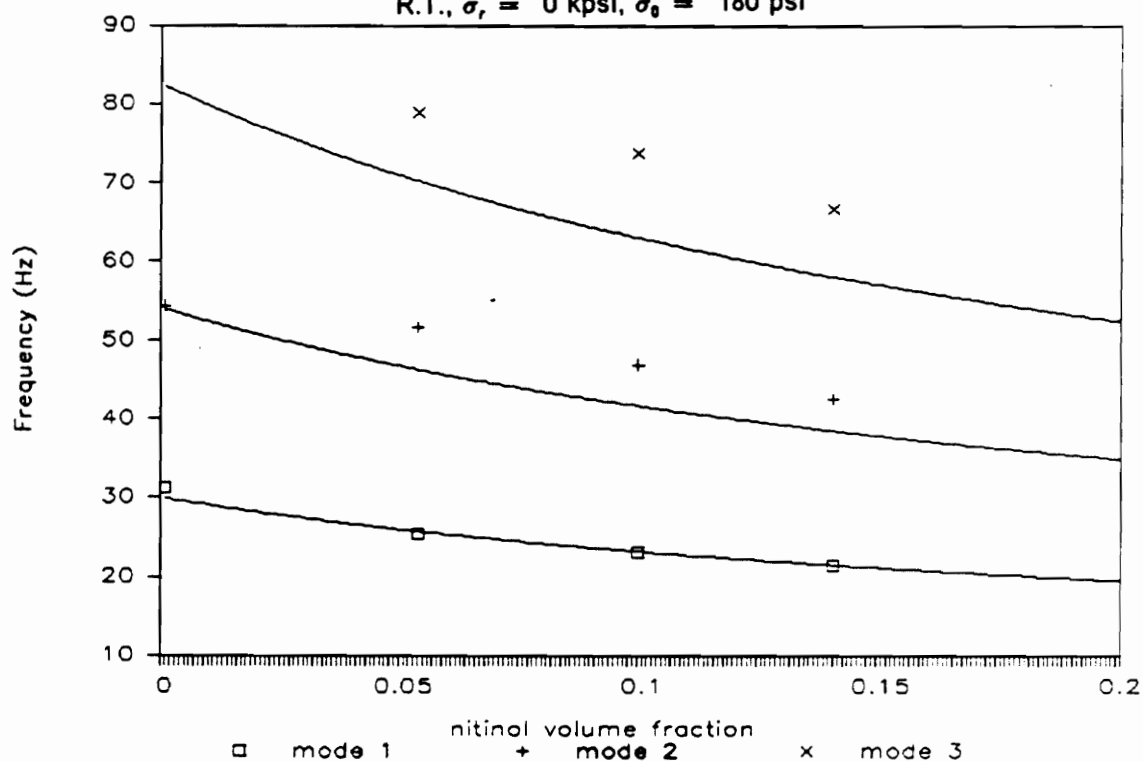
quency ratios are relatively constant for nitinol volume fractions greater than 5%. The experimental natural frequency ratios are the same for all three beams. Although the error in the second and third natural frequency ratios exist, the error is consistent for each beam. The error in the predicted second mode to first mode ratio is 15% for each beam and the error in the predicted third mode to first mode ratio is 20% for each beam.

The density of nitinol is greater than the density of the graphite-epoxy matrix (4.2 times). As the nitinol volume fraction of the nitinol composite beam increases the density of the beam increases as well. The graphite-epoxy matrix has a larger Young's modulus in the direction of the graphite fibers than the Young's modulus of the nitinol fibers (6.0 times for an unactivated beam). As the nitinol volume fraction increases, the overall stiffness of the beam decreases. Both the increasing mass and the decreasing stiffness for increasing volume fraction will cause the natural frequencies of the beam to decrease in the absence of any changing in-plane load. The only stress contributing to the resultant stress for a "rested" unactivated beam is the prestress at the boundary. One would expect the natural frequencies at room temperature to decrease as a function of the nitinol volume fraction. This trend is demonstrated in Fig. 63 and the theoretical results are compared to the experimental results. The natural frequencies of the graphite-epoxy beam (no nitinol fibers) at room temperature are included for comparison.

Theoretical first natural frequencies match the experimental first natural frequencies very well for all beams discussed above. The second and third natural frequencies for beams with embedded nitinol fibers do not correspond to the experimental results. The experimental frequencies for second and third mode are consistently

Unactivated Nat. Freqs. vs Vol Fraction

R.T., $\sigma_r = 0$ kpsi, $\sigma_0 = 180$ psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 63. Unactivated Natural Frequencies versus Nitinol Volume Fraction, "Rested" Beams.

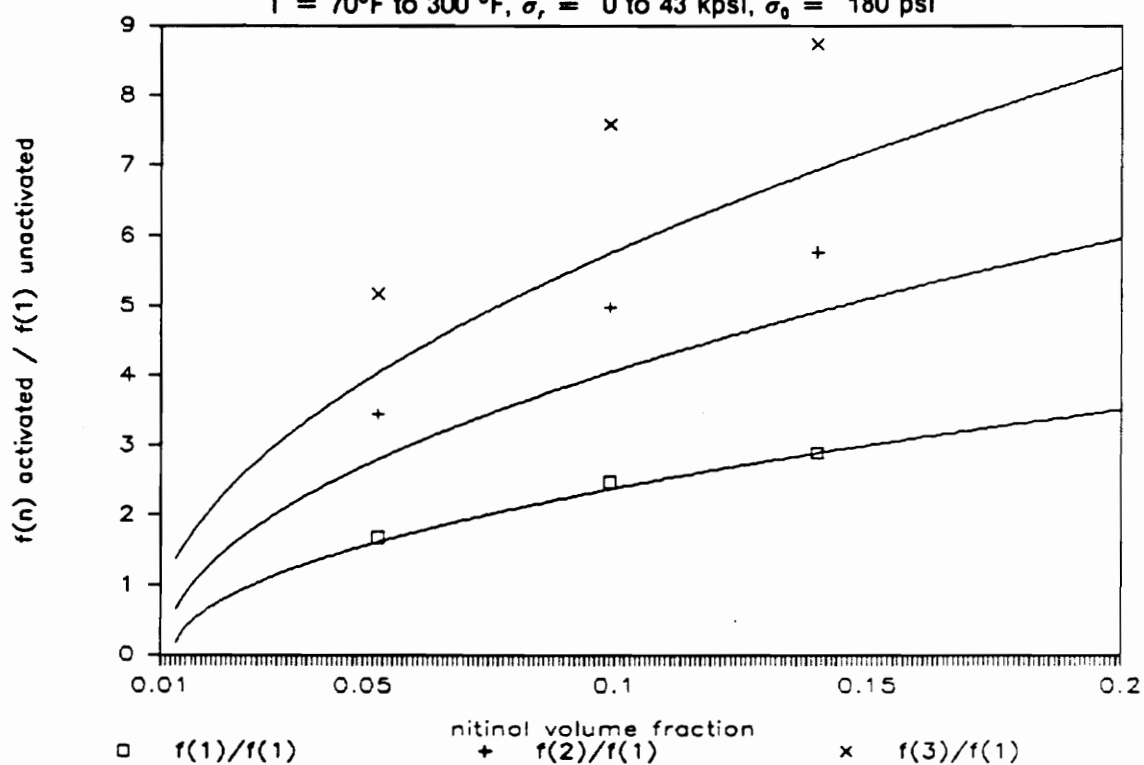
higher than the predicted results. The predicted second natural frequency for the all graphite-epoxy beam (no embedded nitinol fibers) agrees well with the experimental results with only a 3% error (experimental third natural frequency is not available for this beam). This suggests that the error in the predicted second and third natural frequencies is a result of residual stresses created within the composite during the fabrication process which are not included in the theoretical simulation.

The potential of ASET to increase the natural frequencies of nitinol composite beams is evaluated by calculating the normalized frequency increase from the unactivated to activated states. The normalized natural frequencies for a particular beam are calculated by dividing the activated natural frequencies of a particular beam by the unactivated first natural frequency of the same beam. The theoretical and experimental normalized natural frequencies are shown in Fig. 64. Simulation assumes that the all beams have a prestress due to experimental set-up of 180 psi (1.24 MPa) and that the fully activated frequencies occur at 300°F (149°C).

Correlation between theory and experiment is observed for the first natural frequency. Normalized activated first natural frequency is predicted to within 4% error. Theory consistently predicts a lower second and third natural frequency than the experimental frequencies. Normalized activated second natural frequencies are predicted to within 23% error and normalized activated third natural frequencies are predicted to within 32% error. The theoretical normalized natural frequencies do not show the existence of a point of diminishing return as a function of nitinol volume fraction. The normalized natural frequencies continue to increase as a function of nitinol volume fraction at a beneficial rate even for large nitinol volume fractions.

Normalized Activated Frequencies

$T = 70^{\circ}\text{F}$ to 300°F , $\sigma_r = 0$ to 43 kpsi, $\sigma_0 = 180$ psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 64. Normalized Activated Natural Frequencies versus Nitinol Volume Fraction, "Rested" Beams.

Theory predicts that beams having nitinol volume fractions lower than 3% will have a lower activated natural frequencies than the unactivated frequencies.

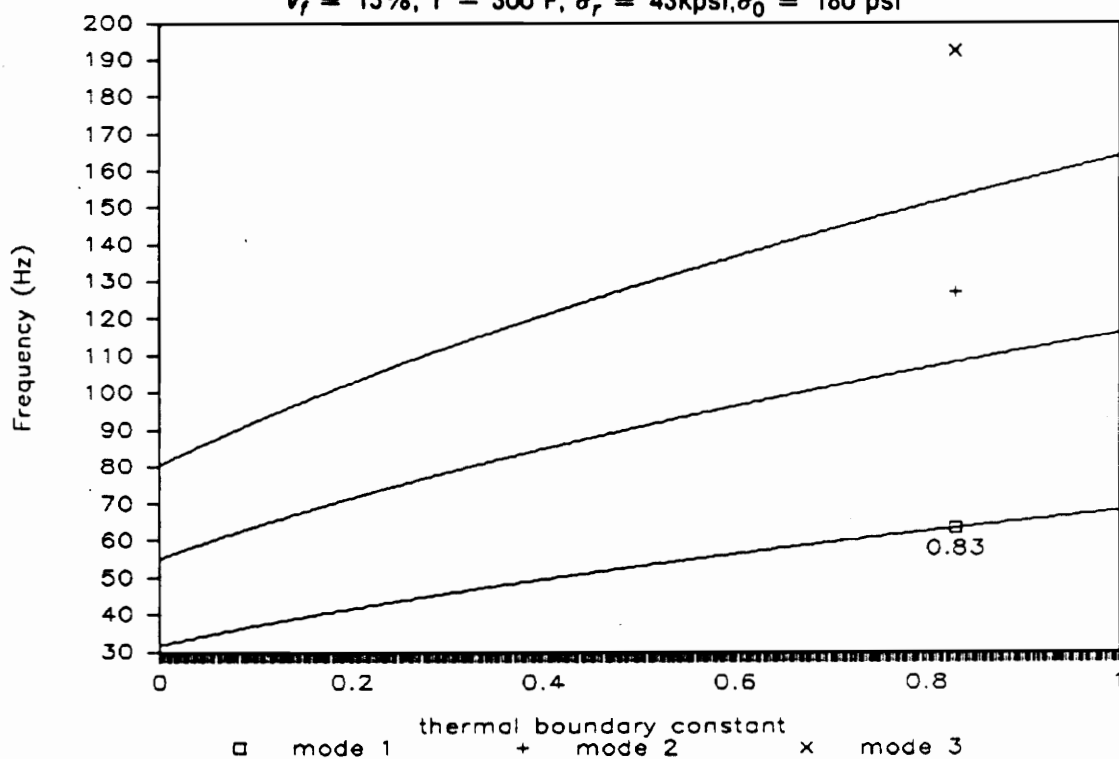
5.4 Effect of Thermal Expansion

The controllable change in natural frequencies of SMA composite beams with embedded nitinol fibers (strained from the memory shape) is primarily a result of the nitinol recovery stress and the stress due to thermal expansion. As the composite beam is heated, stresses as a result of thermal expansion appear as a compressive stress at the boundary. This compressive stress is shown to relieve itself over a period of time (refer to Fig. 48 on page 140). The relief of the thermal expansion stress at the boundary can be modeled by a change in the thermal boundary constant. As the beam is cooled, a residual tensile stress appears at the boundary as a result of the relieved thermal expansion stress at activated temperatures. This stress is also relieved as a function of time (refer to Fig. 47 on page 138). The residual tensile stress at room temperature of a "worked" beam can be modeled as a pre-stress equivalent to the portion of the thermal expansion stress relieved at the activated temperature.

The "worked" 15% nitinol volume fraction beam is used to determine the "worked" thermal boundary constant. The prestress of 180 psi (1.24 MPa) and a nitinol boundary constant of 0.71 determined above for "rested" beams is used for all "worked" beams. Figure 65 shows that a thermal boundary constant of 0.83 is necessary to predict a first natural frequency equivalent to the experimental results.

"Worked" Thermal Boundary Constant

$\nu_f = 15\%$, $T = 300\text{ F}$, $\sigma_r = 43\text{ kpsi}$, $\sigma_0 = 180\text{ psi}$



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

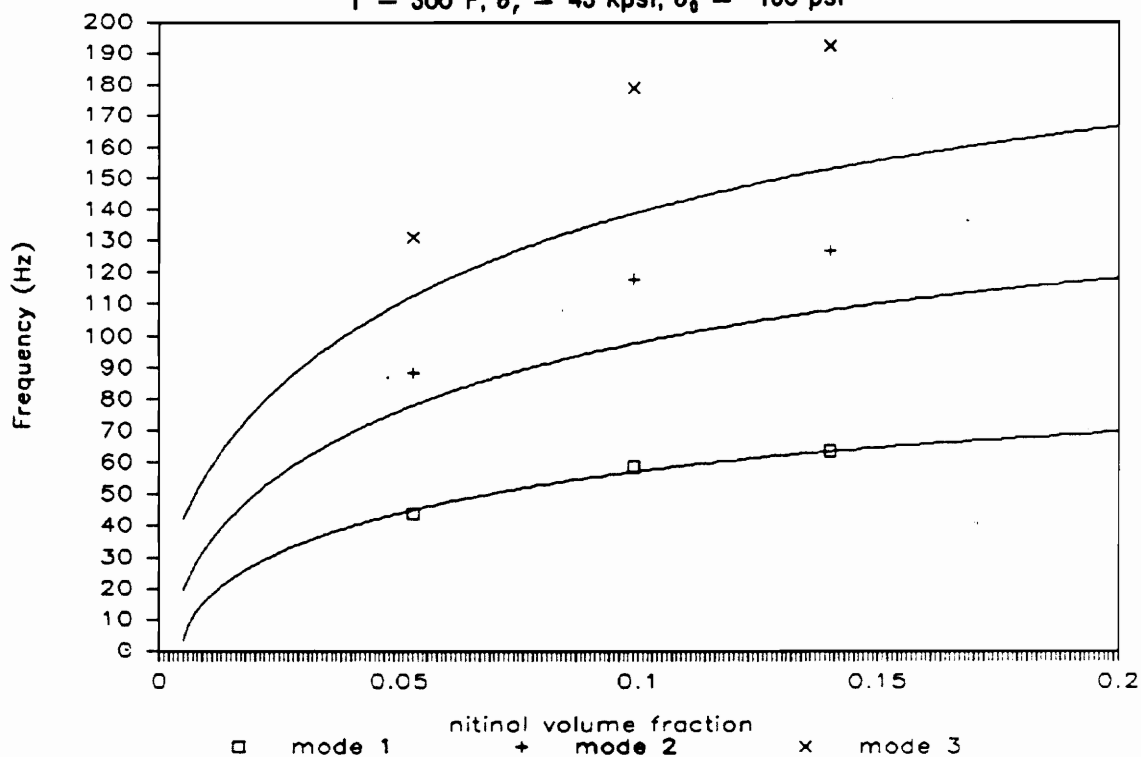
Figure 65. "Worked" Thermal Boundary Constant.

The theoretical "worked" activated natural frequencies are compared to the experimental results in Fig. 66. The first natural frequency for the 15% volume fraction beam is forced to match the experimental results. The predicted first natural frequency for the 5% and 10% nitinol volume fraction beams correspond well with the experimental results. The first natural frequency for each beam is predicted to within 3%. The theoretical second and third natural frequencies are consistently lower than the experimental frequencies. Second natural frequency is predicted to within 21% error and third natural frequency is predicted to within 29% error for each beam. Theory does not calculate natural frequencies for nitinol volume fractions less than 1%. It can be inferred that as the nitinol volume fraction decreases and the first natural frequency approaches zero, the beam will buckle. Theory predicts that buckling will occur at 300°F (149°C) for nitinol volume fractions less than 1%. This is consistent with the experimental results for the graphite-epoxy beam without embedded nitinol fibers (refer to Fig. 42 on page 131 and subsequent discussion).

The unactivated natural frequencies for a "worked" beam are predicted by including the portion of the thermal expansion stress relieved at activated temperatures as a prestress at the boundaries. The fractional portion of the thermal expansion stress relieved at activated temperatures is equal to the difference between the "worked" thermal boundary constant and the "rested" thermal boundary constant. The predicted unactivated natural frequencies are compared to experimental results in Fig. 67. Theoretical first natural frequencies do not correspond to the experimental frequencies. It is shown above that the residual stress at room temperature as a result of thermal expansion effects is a function of time (refer to Fig. 47 on page 138). Natural frequencies of a "worked" beam at room temperature decrease rapidly over the first three hours. The calculated prestress at the boundary as a result of thermal

"Worked" Activated Natural Frequencies

$T = 300^{\circ}\text{F}$, $\sigma_r = 43 \text{ kpsi}$, $\sigma_0 = 180 \text{ psi}$

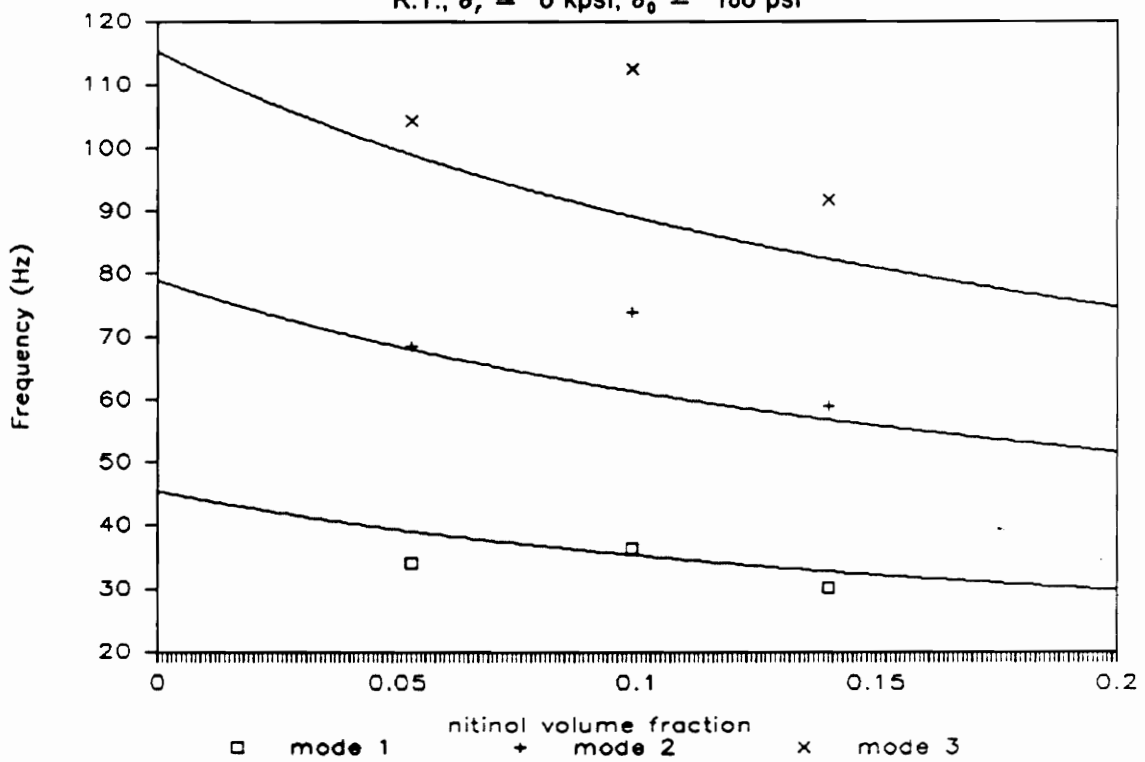


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \qquad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 66. Activated Natural Frequencies versus Nitinol Volume Fraction for "Worked" Beam.

"Worked" Unactivated Frequencies

R.T., $\sigma_r = 0$ kpsi, $\sigma_0 = 180$ psi



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \quad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

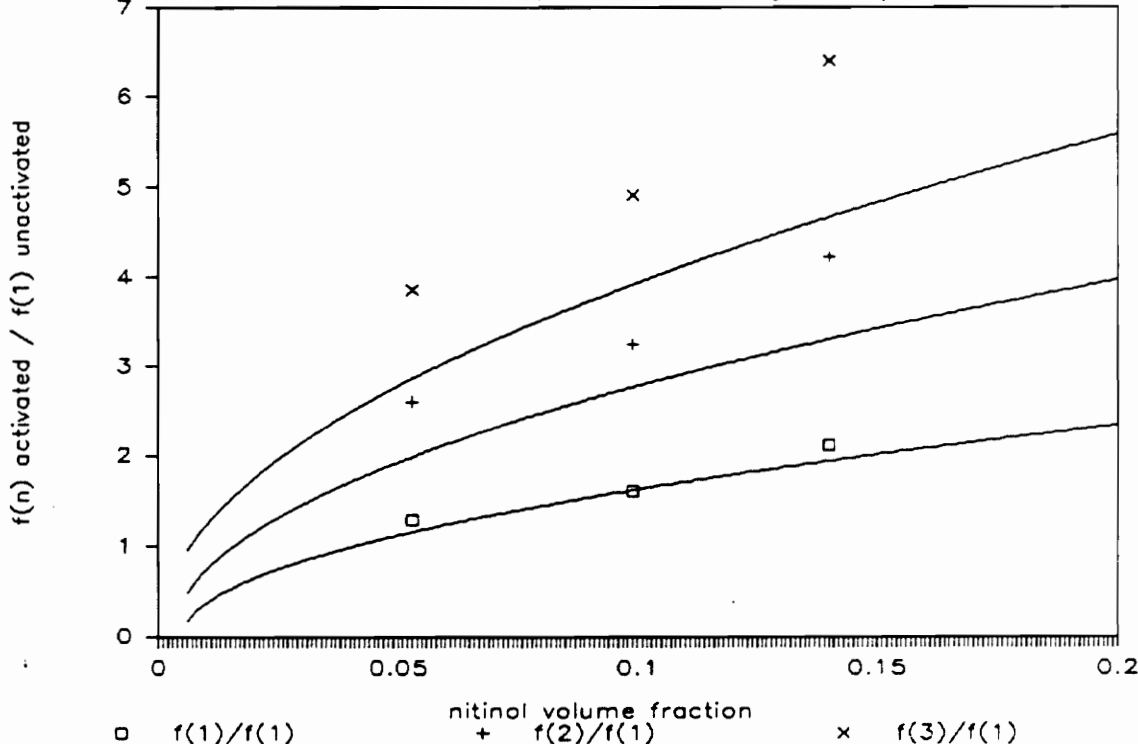
Figure 67. Unactivated Natural Frequencies versus Nitinol Volume Fraction for "Worked" Beams.

expansion and viscoelastic shear-lag effects should over-estimate the experimental residual stress due to thermal expansion effects. Theory has consistently and correctly predicted the experimental first natural frequency for "rested" beams discussed above. It is expected that the experimental first natural frequencies will fall somewhere below the predicted frequencies. This is seen for the 5% and 15% nitinol volume fraction beams. The experimental first natural frequency is slightly higher than the predicted natural frequency.

The potential of ASET to increase the natural frequencies of "worked" nitinol composite beams is evaluated by calculating the normalized frequency increase from the unactivated to activated states. The normalized natural frequencies for a particular beam are calculated by dividing the activated natural frequencies of a particular beam by the unactivated first natural frequency of the same beam. The theoretical and experimental normalized natural frequencies are shown in Fig. 68. Correlation between the theoretical simulation and the experiment is not expected because of the error in the unactivated natural frequency results. The predicted normalized natural frequencies should be thought of as a "worst" case. ASET will certainly provide at least this increase in natural frequencies for "worked" beams. The predictions for the second and third natural frequencies shown above are consistently lower than the actual experimental frequencies. Theory shows that nitinol volume fractions greater than 4% are required to give an increase in natural frequencies for "worked" beams. Beams having nitinol volume fractions lower than 4% may show a decrease in the unactivated to activated frequencies. Theory is unable to calculate the first natural frequency for beams having nitinol volume fractions lower than 1%. As the nitinol volume fraction decreases towards 1% the natural frequency decreases towards

Normalized "Worked" Frequency Increase

T = 70°F to 300°F, σ_r = 0 to 43 kpsi, σ_0 = 180 psi

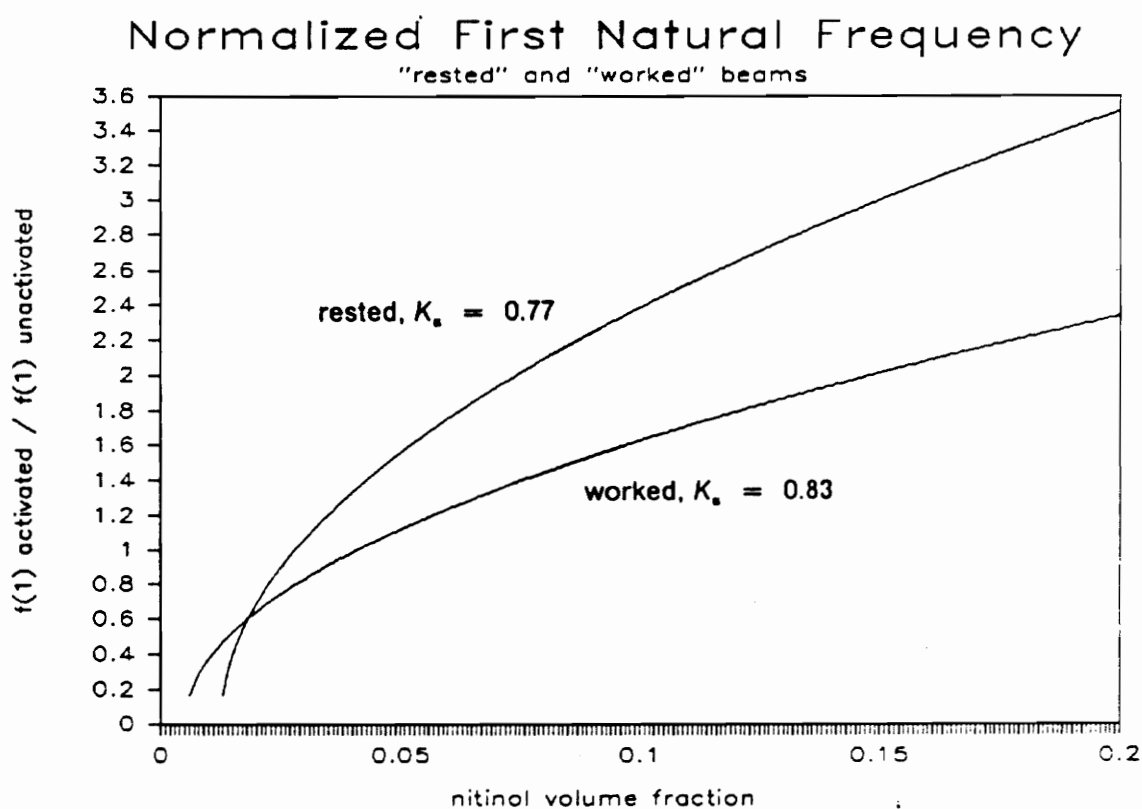


$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \qquad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 68. Normalized Natural Frequencies versus Nitinol Volume Fraction for "Worked" Beam.

zero. It can therefore be inferred that beams having volume fractions lower than approximately 1% will buckle at 300°F (149°C).

The normalized first natural frequencies for "rested" and "worked" beams are shown in Fig. 69. The region between the "rested" and "worked" curves is the range of possible increase in natural frequencies. The normalized activated frequencies move toward the "worked" curve as the time at an activated temperature increases. It has been shown above (refer to Fig. 48 on page 140) that the 15% nitinol volume fraction beam moved from the "rested" to the "worked" curve in three hours. It has also been shown above (refer to Fig. 47 on page 138) that the 15% nitinol volume fraction beam moved back to the "rested" from the "worked" curve in approximately five hours while the beam was left at room temperature. Theory predicts that nitinol volume fractions between 3% and 4% will have an increase in frequency (from unactivated to activated) for a "rested" beam, but will have a decrease in frequency for a "worked" beam. A nitinol volume fraction beam of approximately 2% will show no change in normalized activated frequencies for "rested" and "worked" beams.



$$X^{\circ}\text{C} = \frac{5}{9} (Y^{\circ}\text{F} - 32) \qquad 1 = 6.89 \frac{\text{MPa}}{\text{kpsi}}$$

Figure 69. Normalized First Natural Frequency for "Rested" and "Worked" beams.

6.0 Conclusions and Recommendations

6.1 Conclusions

Active Strain Energy Tuning (ASET) is shown to be a viable control technique to actively tune the dynamic response of an adaptive composite system. Theoretical and experimental results demonstrate the ability of ASET to change the natural frequencies with tremendous authority. Theory predicts the ability of ASET to perform other unique self-adaptive functions, such as the prevention of buckling as a result of thermal expansion. ASET can also be used to design a structure with a uniform dynamic response over a wide temperature range.

Increases in the first natural frequency from the “unactivated” state (room temperature) to the “fully activated” state (300°F or 149°C) are demonstrated experimentally and are as large as 200%. The experimental results for ASET are compiled in Table 7. A number of parameters are found to have a dramatic effect on the performance of ASET to change the fundamental natural frequencies. These parameters include:

Table 7. Experimental results for ASET.

nitinol volume fraction, v_f	rested or worked	fiber condition	increase in 1st natural frequency
15%	rested	free	200%
15%	rested	constrained	80%
15%	worked	free	110%
15%	worked	constrained	60%
10%	rested	free	150%
10%	worked	free	64%
5%	rested	free	72%
5%	worked	free	30%

$$\text{increase} = \frac{(\text{activated } f_1 - \text{unactivated } f_1)}{\text{unactivated } f_1}$$

- prestress at the clamped-clamped boundaries
- in-plane load as a function of boundary characteristics
- relaxation and hysteresis of thermal expansion stress
- nitinol volume fraction.

The prestress in the beam, either intentional or unintentional, decreases the percent change in dynamic response from the unactivated to the activated states. As the prestress increases, the magnitude of the change in the in-plane load must increase to induce the same percent change in the unactivated to activated natural frequencies. The nitinol recovery stress always results in the same change in the in-plane load and is essentially independent of the prestress. Therefore, the ratio of the activated to unactivated natural frequencies decreases as the prestress increases. Experimental results show that the first natural frequency can be changed by 200% for a "rested" 15% nitinol volume fraction beam with an estimated prestress of 180 psi (1.24 MPa). Theory predicts that ASET can change the unactivated to activated first natural frequency by as much as 938% for a "rested" 15% nitinol volume fraction beam if zero prestress is achieved.

Experimentation shows that some portion of the nitinol recovery force is balanced internally by the matrix material and that the remainder can be modeled as a distributed in-plane load applied at the boundary. The portion of the nitinol recovery force balanced by the matrix material is proportional to the integrated strain of the matrix at the clamped boundaries. Constraining the matrix material from motion (or strain) at the boundaries will decrease the portion of the nitinol recovery force balanced by the matrix material and increase the distributed in-plane load. This concept is demonstrated experimentally by comparing the activated natural frequencies of a 15%

nitinol volume fraction beam with free nitinol fibers (not constrained at the boundary) to the activated natural frequencies of the same beam with constrained nitinol fibers. The 15% nitinol volume fraction beam with free fibers has an activated first natural frequency of 62 Hz, while the same beam with constrained fibers has an activated first natural frequency of 71 Hz. The activated frequencies are larger for the constrained fiber condition indicating a larger in-plane load, as a result of the decreased matrix strain. Similar experimental results are shown demonstrating that the stress as a result of thermal expansion is balanced partly within the matrix material and the remainder modeled as an in-plane load.

Boundary constants are derived, characterizing the portion(s) of the nitinol recovery stress and/or thermal expansion stress that are modeled as in-plane loads. The boundary constants are estimated, in this work, by forcing the theoretical results to fit the experimental results for a test case. This estimation technique is undesirable, but new theoretical methods currently being used (i.e., finite element models) which are capable of predicting the boundary constants may prove to make the boundary constant a very useful tool for theoretical simulation.

A relaxation of the thermal expansion stress at the "activated" temperature (300°F or 149°C) is demonstrated experimentally. As the clamped-clamped beam approaches 300°F (149°C), the graphite-epoxy matrix experiences a reduction of its shear modulus, allowing the material to undergo viscoelastic shear deformation and thus relieve the thermal expansion stress over a period of time. As the beam is cooled, the matrix material hardens and viscoelastic shear deformation experienced at high temperature is not immediately recovered. The residual strain of the matrix material results in a tensile stress which can be modeled as a prestress. Beams having res-

idual stresses or unrecovered strain of the matrix material as a result of thermal expansion at activated temperatures are defined as "worked" beams. The residual stress associated with a "worked" beam is relieved over a period of five hours. Beams that have been maintained at room temperature for at least five hours are defined as "rested" beams. The increase in prestress for "worked" beams results in a decrease in the percent change of unactivated to activated natural frequencies. The 15% nitinol volume fraction beam in the "rested" state is capable of increasing the first natural frequency by 200% while the same beam in the "worked" state is only capable of an increase of 110% in the first natural frequency.

The ability of ASET to change the natural frequencies is also related to the nitinol volume fraction. As the nitinol volume fraction increases, the magnitude of the recovery force and thus the in-plane load increases. An increase in the nitinol volume fraction results in an increase in the percent change from the unactivated to activated frequencies. Experimental results show that "rested" 5%, 10%, and 15% nitinol volume fraction beams are capable of increasing the first natural frequency by 72%, 150%, and 200% respectively. Also, experimental results shown that "worked" 5%, 10%, and 15% nitinol volume fraction beams are capable of increasing the first natural frequency by 30%, 64%, and 110% respectively.

The nitinol volume fraction is also shown to play an important role in ASET. As the nitinol volume fraction decreases, the recovery force decreases. If the volume fraction is decreased sufficiently, the compressive stress as a result of thermal expansion of the matrix material will become the dominating stress. This results in a decrease in the natural frequencies as a function of temperature. Theory predicts that clamped-clamped nitinol composite beams can be tailored to give a uniform dynamic response

as a function of temperature or simply prevent buckling as a result of thermal expansion. Nitinol volume fractions between 2% to 5% are necessary to perform uniform dynamic response tailoring. The necessary volume fraction depends on the prestress, coefficient of thermal expansion of the matrix material, and plastic pre-strain of the nitinol fibers. Future research will probably reveal other variables that play a role in uniform dynamic response tailoring as a function of temperature. Active control schemes are possible to prevent buckling as a result of some external load. The necessary volume fraction would depend on the conditions listed above and the expected external conditions

A theoretical simulation based on classical lamination theory is used to predict the first natural frequencies very well. The simulation requires the advanced knowledge of the boundary characteristics (nitinol and thermal boundary constants) and the prestress. Boundary constants and the prestress are estimated by forcing the theory to correctly predict the first natural frequency of a "test" beam. This estimation process severely limits the usefulness of this simulation for design applications. However, the simulation has proved useful as a tool to help understand the role of prestress, boundary conditions, thermal expansion of the matrix material, and the nitinol recovery stress. Predictions of higher modes are inaccurate for beams including nitinol fibers but are accurate for beams without nitinol fibers. A higher order theory may help to better model the nitinol recovery stress.

6.2 Recommendations

Recommendations are made in an effort to improve the accuracy of the theoretical results and to generate research that will help to understand the potential of ASET and to stimulate new control techniques and applications for ASET.

An improved theoretical model will require:

- implementation of higher order theory
- constitutive models for nitinol
- material properties of matrix material as a function of temperature
- direct measurement of the temperature of embedded nitinol fibers
- measurement and/or theoretical prediction of stresses in the beam

The implementation of higher order theory may provide a better model of the residual stress of the graphite-epoxy matrix and the nitinol recovery stress. The in-plane load is presently assumed to be distributed over the cross-sectional area of the beam. The nitinol fibers create a shear stress within the matrix material, especially in the region of the nitinol fibers. Theory should also include the residual shear stress as a result of the interaction between the embedded nitinol fibers and matrix. Also the nitinol recovery stress is most likely not a distributed load. Higher order theories or even finite element models may be required to correctly model the in-plane load and the corresponding dynamic response.

Current literature does not include constitutive models for constrained nitinol fibers. The recovery stress and material properties of nitinol fibers are a function of tem-

perature and the plastic prestrain. The nitinol characterization presented in Chapter 2 provides useful data on the extreme values of recovery stress, necessary break-in periods to guarantee repeatability, and the effect of composite cure cycle on constrained nitinol fibers having a 5% plastic prestrain. This characterization must be expanded to relate the recovery stress to specific temperatures as a function of plastic prestrains. The study in Chapter 2 provides good test matrices to characterize the recovery stress for a particular plastic prestrain. The test matrices must be expanded to include different plastic prestrains, fiber diameters, etc. The experimental set-up must also be adapted to give a more accurate temperature measurement of the nitinol fiber.

The Young's modulus of constrained nitinol fibers must also be characterized as a function of temperature. It is suggested that standard tensile test methods be employed to characterize this material property for constant temperatures. Heating can be performed using an environmental chamber or passing an electric current through the fiber. Constant temperature will probably be better maintained using the environmental chamber technique to monitor the temperature of the surroundings. The resistance heating method requires maintaining a temperature difference between the nitinol fiber and its surroundings. Test procedures could be performed very quickly using resistance heating but implementation may prove to be difficult as a result of the small fiber mass and corresponding fast thermal time constant.

Characterization of the electrical resistance as a function of temperature and plastic prestrain will be of tremendous advantage to control schemes using resistance heating of nitinol composites to perform ASET. Theoretical models for the temperature of a nitinol composite can then be derived as a function of the power supplied

to the composite. Resistance as a function of temperature and plastic prestrain might best be derived by applying a voltage across the fiber and simultaneously measuring the voltage across the fiber, the current through the fiber, and the temperature over time. The resistance can then be calculated by dividing the measured voltage by the measured current for specific temperatures. This process can be repeated for different plastic prestrains.

The material properties of the matrix material must also be determined as a function of temperature. Standard tensile testing techniques for specimens with unidirectional plies are recommended to characterize the elastic moduli. An environmental chamber would prove useful to control the temperature of the test specimen. The coefficients of thermal expansion can be determined by characterizing strain as a function of temperature, using strain gages and a thermocouple attached to the surface of a unidirectional specimen. Strain should be measured in the two principle directions parallel to the ply surfaces. Slow heating to insure uniform temperature can be accomplished using any conventional oven or hot press used for composite cure and consolidation.

The constitutive relations for nitinol and the material properties for the matrix material discussed above will allow for theoretical simulation of the dynamic response of nitinol composites as a function of temperature. Present theory can only accurately predict extreme values of dynamic response. The direct measurement of the temperature of the nitinol fibers must also be accomplished to allow comparison of theory to experimental results. It is recommended that temperature be measured using an embedded thermocouple positioned next to a nitinol fiber in addition to measuring temperature at the surface of the beam.

Further information concerning the viability of ASET to actively control the dynamic response of a structure is still required. The frequency at which a nitinol composite system can be activated and then cooled to the unactivated level must be evaluated. It is expected that the frequency at which a nitinol composite can be cycled through its unactivated to activated state and back to its unactivated state will limit ASET to steady state applications where the dynamic response must be tuned to a desired level for a long period of time. Power requirements must also be evaluated. The graphite-epoxy matrix used in this work is electrically conductive. Better evaluation of the power requirements will be achieved if the nitinol fibers are electrically insulated from the matrix material.

The experimentation should be extended even further to realize new applications. Future experimentation should include a more thorough analysis of the ability of ASET to tune the nitinol composites response to external disturbances, different boundary conditions, and more advanced composite geometry.

A complete experimental modal analysis should be performed to include mode shapes. The ability to use ASET to alter the mode shape for a particular frequency will prove to be of use in modifying the acoustic transmission through a composite structure. A static deflection analysis for a constant transverse load should also be performed. The ability of ASET to increase the stiffness of the composite and its deflection to transverse load may prove useful in preventing buckling of beam-column structures.

The experimental testing should also be expanded to include the analysis of other boundary conditions such as cantilever and free-free. Difficulties are apparent when trying to make an electrical connection to a free end (or side) without altering the

dynamic response. The cantilever situation is possible if the nitinol fibers are electrically insulated from the matrix material. The embedded nitinol fibers can be oriented in a "U-type" configuration such that both electrical connections can be made at the cantilever end. More creative approaches must be considered for the free-free case.

Experimental testing must be expanded to include more advanced composite geometries such as plates and cylinders. Nitinol composite plates will allow the analysis of multi-directional embedded nitinol fibers. Natural frequencies and mode shapes can be tuned in two dimensions. Classical lamination theory for thin plates with embedded nitinol fibers already exists [18,45,69]. Experimentation in this area will provide data necessary to check the accuracy of the first order plate theory. Nitinol composite cylinders will approximate real sources for application (i.e., submarines, aircraft fuselage, etc.).

It is clear that ASET represents a new concept in active control of structural responses and may act as a catalyst for future developments in both material and structures technology. Demonstrating, experimentally and computationally, the ability to alter the dynamic response using unique adaptive qualities will hopefully inspire new material/structural interaction paradigms.

References

1. Wang, B. P., L. Kitis, W. D. Pilkey, A. Palazzolo, "Synthesis of Dynamic Vibration Absorbers," *Journal of Vibration, Acoustics, Stress, and Reliability in Design*, vol. 107, 1985, pp. 161-166.
2. Kitis, L., W. D. Pilkey, and B. P. Wang, "Optimal Frequency Response Shaping by Appendant Structures," *Journal of Sound and Vibration*, vol. 95, no. 2, 1984, pp. 161-175.
3. Juang, J., "Optimal Design of a Passive Vibration Absorber for a Truss Beam," *Journal of Guidance, Control, and Dynamics*, vol. 7, no. 6, Nov.-Dec., 1984, pp. 733-739.
4. Sobieszczanski-Sobieski, J., "Structural optimization: challenges and opportunities," *International Journal of Vehicle Design*, vol. 7, no. 3/4, pp. 242-263.
5. Sobieszczanski-Sobieski, J., B. B. James, and A. R. Dovi, "Structural Optimization by Multilevel Decomposition," *AIAA Journal*, vol. 23, no. 11, 1985, pp. 1775-1782.
6. Rogers, L., "Damping as a Design Parameter," *Mechanical Engineering*, vol. 108, 1986, pp. 161-166.
7. Ely, R. A., "Laminated Damping Fuselage Structures," *Vibration Damping 1984 Workshop Proceedings*, Long Beach, CA, Feb. 27-29, 1984, pp. OO/1-33.
8. Miles, R. N., "Beam Dampers for Skin Vibration and Noise Reduction in the 747," *Vibration Damping 1984 Workshop Proceedings*, Long Beach, CA, Feb. 27-29, 1984, pp. PP/1-18.
9. Pritchard, J. I., H. M. Adelman, and R. T. Haftka, "Sensitivity Analysis and Optimization of Nodal Point Placement for Vibration Reduction," *Journal of Sound and Vibration*, vol. 119, no. 2, 1987, pp. 277-289.
10. Rivin, E. I., "Passive Self-Adaptive Structures," *ARO Smart Materials, Structures, and Mathematical Issues Workshop Proceedings*, Virginia Polytechnic Institute and State University, Blacksburg, VA, September, 15-16, 1988.

11. Rivin, E. I., "Application of Nonlinear Mechanical Systems for Advanced Machine Elements," *Proceedings of the 7th World Congress on Theory of Machines and Mechanisms*, 1987, vol. 3, pp. 1613-1618, Pergamon Press.
12. Margolis, D. L., "Active and semi-active suspensions for engines and vehicles," *International Journal of Vehicle Design*, vol. 6, no. 4/5, pp. 571-572.
13. Karnopp, D., and D. Margolis, "Adaptive Suspension Concepts for Road Vehicles," *Vehicle System Dynamics*, vol. 13, 1984, pp. 145-160.
14. Goh, C. J., and T. K. Caughey, "On the stability problem caused by finite actuator dynamics in the collocated control of large space structures," *International Journal of Control*, vol. 41, no. 3, 1985, pp. 787-802.
15. Cannon, R. H., and D. E. Rosenthal, "Experiments in Control of Flexible Structures with Noncollocated Sensors and Actuators," *Journal of Guidance, Control, and Dynamics*, vol. 7, no. 5, Sept.-Oct., 1984, pp. 546-553.
16. Goh, C. J., and T. K. Caughey, "A Quasi-Linear Vibration Suppression Technique for Large Space Structures via Stiffness Modification," *International Journal of Control*, vol. 41, no. 3, 1985, pp. 803-812.
17. Rogers, C. A., and Robertshaw, H. H., "Development of a Novel Smart Material," *ASME Winter Annual Meeting, Chicago, Illinois*, Nov. 27-Dec. 2, 1988.
18. Rogers, C. A., C. Liang, and D. K. Barker, "Dynamic Control Concepts Using Shape Memory Alloy Reinforced Plates," *Smart Materials, Structures, and Mathematical Issues*, Technomic Publishing Co., Lancaster, PA, August 1989.
19. Gandhi, M. V., and B. S. Thompson, "A New Generation of Revolutionary Ultra Advanced Intelligent Materials Featuring Electro-Rheological Fluids," *Smart Materials, Structures, and Mathematical Issues*, Technomic Publishing Co., Lancaster, PA, August 1989.
20. Wilkes, G. L., "Materials Issues for Smart Structures," *Smart Materials, Structures, and Mathematical Issues*, Technomic Publishing Co., Lancaster, PA, August 1989.
21. Robertshaw, H. H., and C. F. Reinholtz, "Variable Geometry Trusses," *Smart Materials, Structures, and Mathematical Issues*, Technomic Publishing Co., Lancaster, PA, August 1989.
22. Rogowski, R. S., J. S. Heyman, and R. O. Claus, "The Evolution of Smart Composite Materials," *NASA Tech Briefs*, October 1988, pp. 20-22.
23. Claus, R. O., J. C. Mckeeman, R. G. May, and K. D. Bennet, "Optical Fiber Sensors and Signal Processing for Smart Materials and Structures Applications," *Smart Materials, Structures, and Mathematical Issues*, Technomic Publishing Co., Lancaster, PA, August 1989.
24. Claus, R. O., B. S. Jackson, and R. G. May, "Nondestructive evaluation of composites by optical time domain reflectometry in embedded optical fibers," *Conference Proceedings IEEE SOUTHEASTCON '85*, Raleigh, NC, USA, Mar. 31-Apr. 3, 1985, pp. 241-245.

25. Su, S. F., "Fiber-optic electric field sensors utilizing electro-absorption," *Conference Proceedings IEEE SOUTHEASTCON '85*, Raleigh, NC, USA, Mar. 31-Apr. 3, 1985, pp. 241-245.
26. Martinelli, M., "Fibre optic sensors," *Elettron Oggi. (Italy)*, no. 4, April 1984, pp. 115-116, 118, 120, 122, 124.
27. Baumbick, R. J., "Fiber optics for propulsion control systems," *Transactions of ASME Journal of Engines, Gas Turbines and Power*, vol. 107, no. 4, Oct. 1985, pp. 851-855.
28. Bucholtz, F., A. D. Kersey, and A. Dandridge, "DC fibre optic accelerometer with sub- μ g sensitivity," *Electronic Letter (GB)*, vol. 22, no. 9, Apr. 24, 1986, pp. 451-453.
29. Collier, M. J., S. M. McGlade, and P. E. Stephens, "The Optical Actuation of a Process Control Valve," *Automation and Control (New Zealand)*, vol. 15, no. 5, June 1985, pp. 52-53, 56-57.
30. Morikawa, T., "Optical Actuators," *Journal of the Society of Instrumentation and Control Engineering (Japan)*, vol. 24, no. 9, Sept. 1985, pp. 827-831.
31. Jones, B. E., *Electrotechnology (GB)*, vol. 12, no. 4, Oct. 1984, pp. 148-155.
32. Bogue, R., "Developing Science of Accelerometers," *Control and Instrumentation (GB)*, vol. 16, no. 10, Oct. 1984, pp. 69-71.
33. Allan, R., "Nonvision Sensors," *Electronic Design*, vol. 33, no. 15, June 27, 1985, pp. 103-115.
34. Pennywitt, K. E., "Robotic Tactile Sensing," *Byte*, vol. 11, no. 1, Jan. 1986, pp. 177-200.
35. Main, R. P., "Fibre optic sensors - future light," *Sensor Review, (GB)*, vol. 5, no. 3, July 1985, pp. 133-139.
36. Nakamura, Y., H. Hanafusa, N. Ueno, "A piezoelectric film sensor with uniformly expanded surface to detect tactile information for robotic end-effectors," *Proceedings of the '85 International Conference on Advanced Robotics*, Tokyo, Japan, Sept. 9-10, 1985, pp. 137-144.
37. Bailey, T., and J. E. Hubbard, "Distributed piezoelectric-polymer active vibration control of a cantilever beam," *Journal of Guidance, Control, and Dynamics*, vol. 8, no. 5, Sept.-Oct., 1985, pp. 605-611.
38. Tanoshima, K., T. Araki, and M. Tsukada, "Vibration analysis of piezoelectric actuators," *IEEE 1984 Ultrasonics Symposium Proceedings*, Dallas, Texas, Nov. 14-16, 1984, vol. 2, pp. 882-887.
39. Tojo, T., and K. Sugihara, "Piezoelectric driven turntable with high positioning accuracy," *Bulletin of the Japanese Society of Precision Engineers*, vol. 19, no. 2, June 1985, pp. 135-137.
40. Burke, T. S., C. K. Taft, *Proceedings of the 1984 American Control Conference*, San Diego, California, vol. 2, June 6-8, 1984, pp. 1026-1031.

41. Takahashi, S. "Piezoelectric ceramic actuator and its applications," *Oyo Buturi (Japan)*, vol. 54, no. 6, June 1985, pp. 587-588. In Japanese.
42. Duclos, T. G., "An Externally Tunable Hydraulic Mount which uses Electro-Rheological Fluid," *Technical Paper #870963, Society of Automotive Engineers*.
43. Hashimoto, et al., "Application of shape memory alloys to robotic actuators," *Journal of Robotic Systems*, vol. 2, no. 1, spring, 1985, pp. 3-25.
44. Yaeger, J. R., "A practical shape-memory electromechanical actuator," *ISATA 84 Proceedings, International Symposium on Automotive Technology and Automation*, Milan, Italy, Sept., 1984, vol. 1, pp. 633-642.
45. Rogers, C. A., D. K. Barker, K. D. Bennett, R. H. Wynn, Jr., "Demonstration of a smart material with embedded actuators and sensors for active control," *Proceedings of SPIE's International Symposium on Fiber Optics, Optoelectronics, and Laser Applications in Science and Engineering*, Boston, MA, Sept. 6-9, 1988.
46. Duclos, T. G., J. P. Coulter, and L. R. Miller, "Applications for Smart Materials in the Field of Vibration Control," *Smart Materials, Structures, and Mathematical Issues*, Technomic Publishing Co., Lancaster, PA, August 1989.
47. Jackson, C. M., H. J. Wagner, and R. J. Wasilewski, "55-Nitinol - The Alloy with a Memory : Its Physical Metallurgy, Properties, and Applications," *NASA-SP-5110*, 1972, 91 p.
48. Cross, W. B., A. H. Kariotis, and F. J. Stimler, "Nitinol Characterization Study," *NASA CR-1433*, Sept. 1969.
49. Goldstein, D., "A Source Manual for Information on Nitinol and NiTi," Naval Surface Weapons Center, Silver Spring, Maryland, Report NSWC/WOL TR 78-26, 1978.
50. Hodgson, D. E., *Using Shape Memory Alloys*, Shape Memory Applications, Inc., Cupertino, CA, 1988.
51. Funakubo, Hiroyasu, *Shape Memory Alloys*, 1984, Translated from the Japanese by J. B. Kennedy, Gordon and Breach Science Publishers, New York, NY, 1987.
52. Wayman, C. M., and K. Shimizu, "The Shape Memory ('Marmem') Effect in Alloys," *Metal Science J.*, Vol. 6, 1972, p. 175.
53. Perkins, J., ed., *Shape Memory Effects in Alloys*, Plenum Press, New York, 1975.
54. Schetky, L., "Shape Memory Alloys," *Scientific American*, Vol. 241, 1979, p.74.
55. Delaey, R. V., H. Tas Krishnan, and H. Warlimont, "Thermoelasticity, Pseudoelasticity and the Shape Memory Effects Associated with Martensitic Transformations," *Journal of Material Science*, Vol. 9, 1974, pp. 1521-1545.
56. Saburi, T., and C. M. Wayman, "Crystallographic Similarities in Shape Memory Martensites," *Acta Metallurgica*, Vol. 27, 1979, p. 979.
57. Buehler, W. J., and R. C. Wiley, "Nickel-Base Alloys," U. S. Patent 3,174,851, March 23, 1965.

58. Hanlon, J. E., S. R. Butler, and R. J. Wasilewski, "Effect of Martensitic Transformation on the Electrical and Magnetic Properties of NiTi," *Transactions of the Metallurgical Society of AIME*, Vol. 239, 1969, pp. 1323-1327.
59. Buehler, W. J., and R. C. Wiley, "TiNi - Ductile Intermetallic Compound," *Transactions of ASM*, Vol. 55, 1962, pp. 269-276.
60. Wang, F. E., B. F. DeSavage, W. J. Buehler, W. J., and W. R. Hosler, "The Irreversible Critical Range in the TiNi Transition," *J. Appl. Phys.*, Vol. 39, 1968, pp. 2166-2167.
61. Buehler, W. J., and R. C. Wiley, "The Properties of NiTi and Associated Phases," *Rept. NOLTR 61-75 (AD266607)*, U.S. Naval Ordnance Laboratory, Aug. 3, 1961.
62. Wasilewski, R. J., S. R. Butler, and J. E. Hanlon, "On the Martensitic Transformation in TiNi," *Metal Sci. J.*, Vol. 1, 1967, pp. 104-110.
63. Rozner, A. G., and S. Spinner, "Some Consideration of the Elastic Properties of TiNi in the Vicinity of Transformation Temperature," *Symposium on TiNi and Associated Compounds*, NOLTR 68-16, U.S. Naval Ordnance Laboratory, Feb. 20, 1968, pp. 6-1 - 6-19.
64. Spinner, S., and A. G. Rozner, "Elastic Properties of NiTi as a Function of Temperature," *J. Acoust. Soc. Am.*, Vol. 40, No. 5, 1966, pp. 1009-1015.
65. Goff, J. F., "Thermal Conductivity, Thermoelectric Power, and the Electrical Resistivity of Stoichiometric TiNi in the 3° to 300°K Temperature Range," *J. Appl. Phys.*, Vol. 35, 1964, pp. 2927-2929.
66. "Shape Memory Alloys – Metallurgical Solution Looking for a Problem," *Metallurgia*, January, 1984.
67. Rogers, C. A., and H. H. Robertshaw, "Shape Memory Alloy Reinforced Composites," *Engineering Science Preprints 25*, ESP25.88027, Society of Engineering Sciences, Inc., June 20-22, 1988.
68. Perkins, J., ed., *Shape Memory Effects in Alloys*, Plenum Press, New York, 1975.
69. Rogers, C., C. Liang, and J. Jia, "Behavior of Shape Memory Alloy Reinforced Composites - Part 1: Model Formulations and Control Concepts," *30th Structures, Structural Dynamics and Materials Conference*, Mobile Alabama, April 3-5, 1989.
70. Barker, D. K., C. A. Rogers, "Active Dynamic Response Tuning of Nitinol Reinforced Composites," *Proceedings of the Sixth Annual Review of the Virginia Tech Center for Composite Materials and Structures*, April 9-11, 1989.
71. Wayman, C. M., "Some Applications of Shape-Memory Alloys," *Journal of Metals*, vol. 32, no. 6, pp. 129-137.
72. Castleman, L. S., S. M. Motzkin, F. P. Alicandri, V. L. Bonawit, and A. A. Johnson, "Biocompatibility of Nitinol Alloy as an Implant Material," *Journal of Biomedical Materials*, vol. 10, 1976, pp. 695-731.

73. Simon, M., R. Kaplow, E. Salzman, and D. Freiman, "A Vena Cava Filter Using Thermal Shape Memory Alloy," *Radiology*, vol. 125, no. 1, 1977, pp. 89-94.
74. Whitney, J. M., *Structural Analysis of Laminated Anisotropic Plates*, Technomic Publishing Co., Lancaster, PA, 1987.

Vita

Daniel Keith Barker was born in Bethesda, Maryland, on June 23, 1965, the son of Benjamin and Janice Barker, Jr. He grew up in Fairfax, Virginia, and graduated from W. T. Woodson High School in 1983. Dan then entered the College of Engineering at Virginia Polytechnic Institute and State University and graduated with a B.S. Cum Laude in Mechanical Engineering in June 1987. Shortly afterwards, he entered graduate school at VPI&SU and received a M.S. in Mechanical Engineering in July 1989.

Dan was married to Karen Hampton Koger on June 3, 1989. Upon leaving Virginia Tech, they moved to Fort Worth, Texas, to begin work for General Dynamics.

A handwritten signature in black ink that reads "Dan K. Barker". The signature is written in a cursive style, with the first letters of each name being capitalized and prominent.