Chapter 1

INTRODUCTION

1.1 Background

The bolted joint is one of the most common mechanical components in all types of engineering structures. Often these joints are critical to the function of the structure and their failure could have huge costs or endanger lives. Joints are subject to a variety of failure modes and are an area that has still not been completely explained by engineers. The goal of this research is to reduce the likelihood of failure and cost of maintenance of bolted joints and to increase the understanding of the dynamics bolted joints.

The most frequent mode of failure for bolted joints is self-loosening. To reduce this mode of failure the concept of a self-sensing and self-healing bolted joint has been developed. This concept combines health monitoring techniques with actuators to restore tension in a loose bolt. Such a device is often referred to as a “smart structure” because of its ability to sense its condition and then react to it. In general, smart structures use a combination of sensors, actuators and control systems to adaptively change to their condition or surroundings.

Smart materials have the ability to convert one form of energy to another. Examples include conversion of electrical to mechanical energy and vise versa by piezoelectric materials, heat to mechanical energy by shape memory alloys (SMA), magnetic to mechanical energy in magnetorheological (MR) fluids and a variety of other materials. The coupling of two forms of energy in intelligent materials can provide significant advantages to structures or devices incorporating them. They also come in a variety of shapes and sizes, allowing them to be used in a variety of applications and to be unobtrusively placed throughout a structure including remote or inaccessible locations. In addition smart materials can often be used as both sensors and actuators allowing them to actively monitor structures.

One of the most promising health monitoring techniques for many structures, including bolted joints, is the electromechanical impedance technique. The basic concept of the impedance technique is to use high frequency vibrations to monitor the local area of a structure for changes in structural impedance that would indicate damage or imminent damage. This is possible using a piezoelectric sensors/actuators whose electrical impedance is directly related to the structure's mechanical impedance. The impedance measurements can easily give information on changing parameters, such as resonant frequencies. Generally the measurements are made at very high frequencies (greater than 30 kHz). The short wavelengths at such frequencies allow for the detection of small changes in the integrity of a structure. However, one of the drawbacks of this method is that measurements are usually made with laboratory size impedance analyzers, which are bulky and expensive.

The impedance method will be used in conjunction with SMA actuators to develop self-monitoring and self-healing bolted joints. The actuators will be included in the joint as washers. Proof of concept experiments were completed using "off the shelf" actuators that are used primarily for coupling pipes. The axial extension, which is the important characteristic for this application, is a complex side effect of the radial compression for which they are designed. More research is needed to address practical issues such as electrically heating and sizing of the washers. It is desired to develop a model of the joint members, which incorporates the effects of SMA actuators, to provide a basic understanding of the dynamic behavior of the bolted joint-SMA washer combination and how the parameters of the SMA actuator contribute to its dynamics. The model will provide a method for selecting the size of the actuator for different configurations by examining the torque-preload relation.

1.2 Research Objectives

The ultimate goal of this research is to develop a self-monitoring, self-healing bolted joint to reduce the likelihood of failure and cost of maintenance of structures. Specifically this will require improvements making the impedance method more accessible and transportable, an increase in the understanding of the dynamics bolted joints, and solutions to practical issues of implementing relatively large SMA actuators. The work can be divided into three primary issues to be addressed: making the impedance-based technique more accessible, increasing the understanding of bolted joint dynamics so that the answer of "when to activate self-healing actions" can be determined, and solving many of the practical issues of implementing a SMA washer based adaptive joint including sizing, heating and connecting electrically.

1.3 Research Contributions

The research presented in this thesis spans a variety of technical subjects. In the area of structural health monitoring the research makes the impedance-based health monitoring technique more accessible by developing and testing a more practical method of taking impedance measurements. The device constructed allows for the measurement of impedance without the use of a typical large and expensive impedance analyzer. It will also allow significant improvements in miniaturization and portability.

The work also increases the body of knowledge concerning the dynamics of bolted joints and their diagnostics. Results for quantitative diagnostics using impedance measurements can have applications to the maintenance of many types of structures. Damping in bolted connections is addressed.

Finally, improvements on the implementation of self-sensing and self-healing bolted joints move the concept closer to implementation in operational structures. Difficulties in the heating of relatively large volumes of SMA are addressed including electrical connection and thermal insulation issues. In addition a method of size selection of SMA washer/actuators is described.

1.4 Literature Review and Technology Introduction

There are many possible approaches to health monitoring. The impedance method is in the category of vibration-based non-destructive evaluation (NDE) techniques. Many types of vibration-based NDE techniques have been developed. The next section describes the types of methods used in the in the health monitoring community. Following that is a review of the current state of impedance based health monitoring and an overview of self-repairing structures and finally shape memory alloy technology.

1.4.1 Vibration Based Non-Destructive Evaluation Techniques

A very large body of work exists in the field of vibration-based NDE. Several extensive literature reviews have been compiled in the past several years, including an extensive survey of over 300 papers by Doebling et al. (1998). Vibration based NDE has been a very active area of research for many years. The first published example of vibration characteristics being used to identify damage to a structure was by Lifshits and Rotem in 1969. Much of the early research focused on health monitoring of off shore oil platforms, nuclear power plants and rotating machinery. In the 1980's the field expanded rapidly, especially in the areas of turbo machinery, civil and aerospace structures (Carneiro 2000). More recently damage detection has become a regular focus of many conferences including SPIE's Symposium on NDE for Health monitoring and Diagnostics, Stanford's Structural Health Monitoring Conference and sessions on damage detection at the International Modal Analysis Conference in the past year alone. Specifically associated with the research presented in this thesis, Park's doctoral dissertation (2000) and Kabeya's thesis (1998) discuss vibration based NDE techniques as it relates to the impedance method.

Many health monitoring methods rely on modal parameters to detect damage. Modal analysis has become a standard practice of engineers to describe the dynamics of a structure with natural frequencies, damping ratios and mode shapes. By detecting changes in these parameters the presence and location of damage can be determined. A review of using frequency changes for damage detection was compiled by Salawu (1997). The concept of tracking natural frequency changes for damage detection was first reported by Adams et al. (1978). Damage was characterized based on the ratio of frequency changes for two modes. Farrar et al. (1994) discuss limitations of monitoring the resonant frequencies. The main drawbacks are that resonant frequencies are global characteristics and thus are insensitive to small levels of damage occurring on a local level and very precise measurements would be needed. This can be seen in the following example using a simple spring mass model from Banks et al. (1996). The change in natural frequency, ω, with respect to stiffness, k, is

$$\frac{\mathrm{d}\omega}{\mathrm{d}k} = \frac{1}{2\sqrt{km}} = \frac{\omega}{2k}, \tag{1.1}$$

and with respect to mass is

$$\frac{\mathrm{d}\omega}{\mathrm{d}m} = -\frac{1}{2}\sqrt{\frac{k}{m^3}} = -\frac{\omega}{2m}. \tag{1.2}$$

The sensitivity of ω decreases as the value of the stiffness or mass increases. For a two meter long airplane wing, the stiffness is about 116 N/m so that changes in frequency near 100 Hz corresponding to 1% changes in stiffness would be expected to be on the order of 0.4 Hz and changes near 1000 Hz would be on the order of 4 Hz. Modern analyzers often have difficulty detecting changes of a fraction of a Hertz. In addition changes in unmodeled parameters such as humidity and temperature can cause such small changes in frequency measurements taken on different days.

Mode shape changes have also been monitored to detect and locate damage. West (1984) proposed using the modal assurance criteria (MAC), correlating mode shapes between damaged and undamaged structures, to characterize damage. Other researchers looked at mode shapes (Rickles and Kosmatka 1992; Lin 1994), mode shape curvatures (Pandy et al. 1991; Pabst and Hagendorn 1993) and strain mode shapes (Chance et al. 1994). Mode shapes in general are more difficult to obtain than resonant frequency information (Doebling et al. 1997) and lack accuracy unless there are a large number of sensors. They are, however, more sensitive than resonant frequency changes (Osegueda et al. 1992). Several other methods monitor the dynamic matrices (mass, stiffness, damping and flexibility) for changes indicating damage. Unfortunately, these matrices are not always positive definite or ensure connectivity. Also, all elements change in the matrices rather than just a few changing significantly, making location of the damage difficult (Friswell 1997).

Many other issues limit the use of vibration-based detection methods. Low order global modes do not show early damage since incipient damage is not generally global in nature. Changes in mass and loading are normal in many structures. Changes in boundary conditions often cause considerable changes in the dynamics of the structure that can be difficult to distinguish from a damaged structure. To solve this problem Farrar and Doebling (1998) have developed bounds for modal parameters based on the statistical variations caused by boundary condition changes. Also, the use of a laser Doppler vibrometer can provide enhanced accuracy for obtaining modal data.

Several methods exist utilizing time responses rather than modal data (Banks et al. 1996; Cattarius and Inman 1997). These methods avoid model expansion or reduction found in modal approaches, however, generally require large amounts of computations or a precise model. In addition, for linear systems, the loss of information is negligible when transferring data in the time domain to the frequency domain.

Other vibration-based health monitoring techniques include applying wavelet transformations (Staszewski 1999), artificial neural networks monitoring a variety of types of data (Spillman et al. 1993; Tsou et al. 1993; Worden et al. 1993) and the electromechanical impedance technique, which is discussed in the next section.

1.4.2 Impedance-based Health Monitoring Technique

The impedance-based health monitoring method is made possible through the use of piezoelectric patches bonded to the structure that act as both sensors and actuators on the system. When a piezoelectric is stressed it produces an electric charge. Conversely when an electric field is applied the piezoelectric produces a mechanical strain. For a linear piezoelectric material, the relation between the electrical and mechanical variables can be described by linear relations (Crawley and Anderson 1987):

$$\begin{aligned} S_i &= s_{ij}^E T_j + d_{mi} E_m \\ D_m &= d_{mi} T_i + \varepsilon_{mk}^T E_k \end{aligned} \tag{1.3}$$

or

$$\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} s^E & d_t \\ d & \varepsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} , \tag{1.4}$$

where S is the mechanical strain, T is the mechanical stress, E is the electric field, D is the charge density, s is the mechanical compliance, d is the piezoelectric strain constant, ε is the permittivity, and the subscripts i , j , m and k indicate the direction of stress, strain or electric field. The superscripts E and T indicate that those quantities are measured with electrodes connected together and zero stress, respectively and the subscript t indicates transpose. The first equation describes the converse piezoelectric effect and the second one describes the direct piezoelectric effect.

The process to be used with the impedance-based monitoring method utilizes both the direct and converse versions of the piezoelectric effect simultaneously to obtain an impedance signature for the structure. The PZT is driven by a sinusoidal voltage sweep. Since the patch is bonded to the structure, the structure is deformed along with it and produces a local dynamic response to the vibration. The area that one patch can excite depends on the structure and material. The response of the system is transferred back to the piezoelectric patch resulting in an electrical response. The electrical response is then analyzed where, since the presence of damage causes the response of the system to change, damage is shown as a phase shift or magnitude change in the impedance. A more detailed explanation of the technique can be found in the references (Liang et al. 1994; Park, et al. 2000; and Peairs et al. 2001).

Figure 1.1 shows a model used to represent a PZT-driven dynamic structural system. The PZT is considered to be a thin bar in axial vibration due to an applied alternating voltage. One end is fixed and the other is attached to the structure, which is consistent with the way force is transferred from the PZT to the structure.

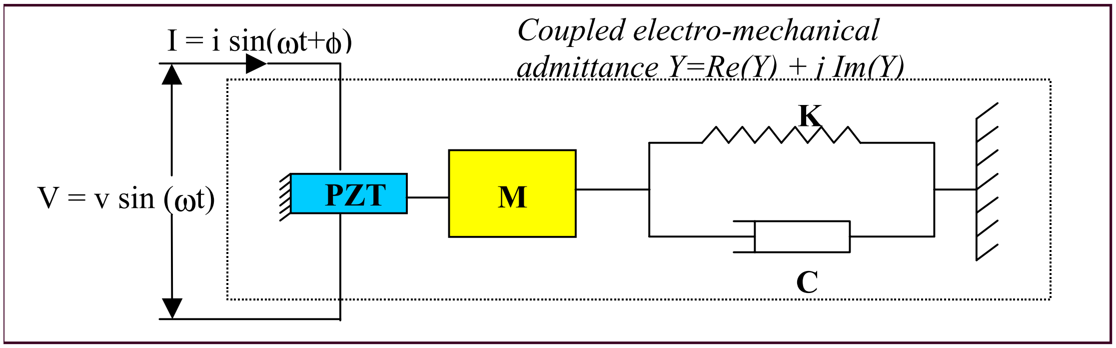

Figure 1.1 1-D model representing a PZT-driven dynamic structural system

The solution to the wave equation gives the following equation for electrical admittance (Liang et al. 1994)

$$Y(\omega) = i\omega\, a(\bar{\varepsilon}_{33}{}^{T}(1-i\delta) - \frac{Z_s(\omega)}{Z_s(\omega)+Z_a(\omega)} d_{3x}{}^{2}\hat{Y}_{xx}{}^{E}) \qquad (1.5)$$

In equation (1), Y is the electrical admittance (inverse of impedance), Z_a and Z_s are the PZT material's and the structure's mechanical impedances, respectively, $Y_{xx}{}^{E}$ is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero stress, $\varepsilon_{33}{}^{T}$ is the dielectric constant at zero stress, δ is the dielectric loss tangent of the PZT, and a is a geometric constant of the PZT. This equation indicates that the electrical impedance of the PZT bonded onto the structure is directly related to the mechanical impedance of a host structure.

The impedance method has many advantages compared to global vibration based and other damage detection methods. Low excitation forces corresponding to less than 1 V, combined with high frequencies (typically greater than 30 kHz), produce power requirements in the range of micro Watts. The small wavelengths at high frequencies also allow the impedance method to detect minor changes in structural integrity and in some cases detect imminent damage.

A substantial amount of previous work has been published related to impedance-based health monitoring. Liang et al. (1994) analytically explained the dynamic characteristics and electromechanical coupling properties of PZT systems. Sun et al. (1995) showed that impedance frequency response functions represent the structural dynamics of a system by completing modal testing using transfer impedance.

Experimental tests have been conducted on a variety of structures including: a four bay space truss by Sun et al. (1995), aircraft structures by Chaudry et al. (1995) and Zagrai and Giurgiutiu (2002), a massive bridge joint by Ayres et al. (1996) and Park (2000), a built in pipeline structure by Park et al (2001), and a composite reinforced masonry wall by Raju et al. (1998). Overviews of the impedance-based health monitoring and experimental studies have been compiled by Rogers and Lalande (1996) and Giurgiutiu and Rogers (1998). Raju (1998) discussed many issues affecting the impedance method, including actuator excitation level, test wire length, using multiple sensor/actuators for a single signal (multiplexing) and boundary conditions. Park et al (2001) and Lopes et al (2000) integrated the impedance method with the spectral element methods (Park) and neural networks (Lopes) in order to establish somewhat quantitative health monitoring using the impedance method.

Previous work has also been done to define the parameters of the impedance technique. Estaban (1996) developed a theoretical determination of the sensing region of the impedance sensors using wave propagation techniques. The sensing region can vary significantly depending on the material and density of the structure. Experiments have shown sensing regions of 0.4 m for composite reinforce concrete structures, up to 2 m for simple metal beams (Park 2000). The sensing region can be extended even further using transfer impedance between two PZT patches (Castanien and Liang 1996; Kabeya 1998).

The frequency range monitored is usually set by trial and error. In general, it is desired to have many peaks (high modal density) so that the response will be more sensitive to damage because of the higher density of dynamic information (Sun et al. 1995). Frequencies are generally somewhere in the range of 30 kHz-250 kHz. The wavelength of the excitation must be smaller than the characteristic length of the damage to be detected. Higher frequencies are generally better at locating the damage, while lower frequencies have larger sensing areas since damping is more efficient at high frequencies.

Damage metrics are generally used for the assessment of damage. A variety of damage metrics exist. One of the more simple damage metrics is defined as

$$M = \sum_{i=1}^{n} \left[\mathrm{Re}(Y_{i,1}) - \mathrm{Re}(Y_{i,2}) \right]^2 , \tag{1.6}$$

where *M* represents the damage metric, $Y_{i,1}$, is the impedance of the PZT when measured at healthy conditions, $Y_{i,2}$ is the impedance of the structure for the comparison with the base line measurement at frequency interval *i* (Park et al. 2000). This is sometimes modified by subtracting the difference of the means of the two data sets from $Y_{i,2}$. in order to account for shifts in the entire curve and not a change in shape that would indicate damage. An alternative damage metric is the correlation between two functions (Raju 1998). The damage metric simplifies the interpretation of impedance variations and provides a summary of the information obtained from the impedance response curves. Using a damage metric in conjunction with a damage threshold value, this technique can warn inspectors in a green/red light form, whether or not the threshold value has been reached.

It is evident that much research has been conducted on the impedance method and it is becoming an established method of health monitoring. Its benefits include: (Park 2000)

- The method uses non-intrusive sensors/actuators that can be placed in inaccessible locations.
- The sensors have a large range of linearity, fast response, high conversion efficiency and long term stability.
- The method is not based on models so complex structures can be monitored.
- The data can be easily interpreted.
- Because the frequency range monitored is high, the impedance method is sensitive to small amounts of damage.
- The method can be adapted for continuous online health monitoring.

These attributes make the impedance-based health monitoring technique a suitable method for the sensing aspect of the self-sensing and self-healing bolted joint.

1.4.3 Self-Repairing Structures

Much research has been done on the development of intelligent material systems and structures using a wide variety of the smart materials available. However, most applications are for either the detection of damage or for shape and vibration control (Zako and Takano 1999). A new class of smart structures is self-repairing structures. These structures or devices react to damage and some action is produced to restore it to its undamaged condition. These are often referred to as biomimetic structures because they take inspiration from living organisms. An overview of biomimetic systems including information on self-healing systems is presented by Siochi et al. (2002).

One type of self-repairing structure is a self-healing polymer composite developed by White et al. (2001) at the University of Illinois. This composite autonomically heals cracks as they develop in a structure. When a crack forms it ruptures embedded microcapsules that release a healing agent. The agent flows into the crack through capillary action and is polymerized by a catalyst in the matrix of the composite. The researchers report a 75% recovery in toughness and a 20% increase in critical load over a control sample. The researchers also believe that the concept will continue to evolve until it is truly a biomimetic system that contains a circulatory system. A similar system has been developed by Zako and Takano (1999), but requires heat, such as from a laser to heat the damage location for epoxy particles to melt to heal delaminations in composites. Another example is self-healing concrete. Krstulovic-Opara et al. (1994) have developed a slurry infiltrated fiber concrete. The concrete is initially made with very little water allowing some of the cement powder to remain inactive. When damage develops in the form of small, disconnected hairline fractures water seeps in through the cracks mixes with the inactive cement and causes it to activate and seal the crack.

Another self-healing system in development is a self-sealing bladder for use in pressurized inflatable structures such as a space suit or inflatable satellite. The current space suit in use allows only 30 minutes for an astronaut to get back to safety in the event of a tear of less than 4 mm in the suit. The self-healing concept would include a viscoelastic bladder sandwiched between other layers. The challenge of researchers is to design a self-healing bladder that is flexible, durable and yet similar to current materials in use and lightweight (Ware et al. 2001).

A similar concept is used in many self-healing coatings. One example is paint that never fully dries used on structures such as the landing gear of tractor trailers. When the inevitable stones thrown at it by the road mar the paint, it flows into the damaged area, continuing to provide a barrier against corrosion. Other self-healing coatings rely on the contact of the base material with the surrounding medium to generate a new corrosion resistant surface. This is the principal behind stainless steel where the chromium creates a protective chromium oxide layer on its surface.

One method of self-healing is to design a system to reconfigure itself when it is damaged. Reconfigurable control systems require three separate functions: failure detection and isolation to determine which components are no longer useful, parameter identification to provide a model of the damaged structure and online control design that uses information from the other two to reestablish control of the modified structure. The design of reconfigurable controls is centers around two concepts: dynamic inversion and receding horizon optimal control, which can be modified for changing nonlinear dynamics. This approach has been applied to flight control systems for fighter aircraft (Bacon and Ostroff 2000) and similarly to magnetic bearings (Chen 1999).

Another very active area of research is reconfigurable circuits. There have been several conferences and symposiums on this topic including a series of NASA/DOD workshops on evolvable hardware. Much work has been done by NASA JPL's Evolvable Systems group. Such circuits would be able to adapt to unexpected conditions including damage. This would be highly valuable for long term space missions into harsh environments. It is even envisioned that circuits could evolve into new uses once their initial function had been completed. Evolving in the hardware rather than the software ensures validity of the repair, and speeds up the evolution (Keymeulen et al. 2000).

Related to the self-healing systems is the concept of damage control systems. Although the systems do not attempt to return the structure to the undamaged state, they still react to damage and try to prevent further degradation. One such project by Hanagud et al. (1992), proposes a method of detecting and controlling delaminations in composite structures. Delamination is detected in cantilever beams by comparing mode shapes and time responses of damaged and undamaged beams. The growth of delaminations is a result of high interlaminar or shear stresses, which depend on the axial force or corresponding axial stress. PZT actuators then reduce axial stresses using a constant gain feedback controller, thus retarding the growth of the delamination.

Another damage control system using smart materials was developed by Rogers et al. (1991). SMA fibers were used as an induced strain actuator imbedded in a composite structure made with photoelastic epoxy. When a crack formed the SMA was actuated through resistive heating. By examining the fringe patterns of the specimen before and after actuation it was found that the resulting compressive stress at the crack tip reduced the stress concentration by approximately 24 percent. The authors state that the most important conclusion from the research was that embedded induced strain actuators can greatly change the stress and strain distribution of a structure.

1.4.4 Shape Memory Alloy Technology

As stated earlier, the damage control portion of the self-healing bolted joint will utilize SMA technology. The shape memory effect is the ability of certain alloys to have their shape changed at low temperatures and stay in their new form until they are heated. There are several alloys that possess the shape memory effect. The most common of these are Nickel-Titanium, often referred to as NiTi or Nitinol (from Nickel Titanium Naval Ordinance Laboratory where it was first developed), Copper-Zinc-Aluminum and Copper-Aluminum-Nickel. Most applications of SMA use NiTi because it has the most recoverable motion, as well as excellent corrosion resistance, stable transformation temperatures, high biocompatibility and the ability to be heated electrically.

The shape memory effect occurs as a result of a phase transformation when cooled from austenite, its high temperature cubic structure, to martensite, with a monoclinic lattice structure, which looks like a parallelogram in two dimensions. One accepted explanation of atomic movement allowing the shape memory effect is that instead of the parallelograms aligning in the same direction, alternating rows of atoms tilting either right or left are formed. This is referred to as a twinning because the atoms form mirror images of each other. When the material is deformed it detwins and the parallelograms all lie in the same direction. Upon heating the SMA returns to its austenitic crystal structure and predeformed shape. If the SMA is restrained during this process stress will be generated in the material. Figure 1.2 shows a graphical representation of this process.

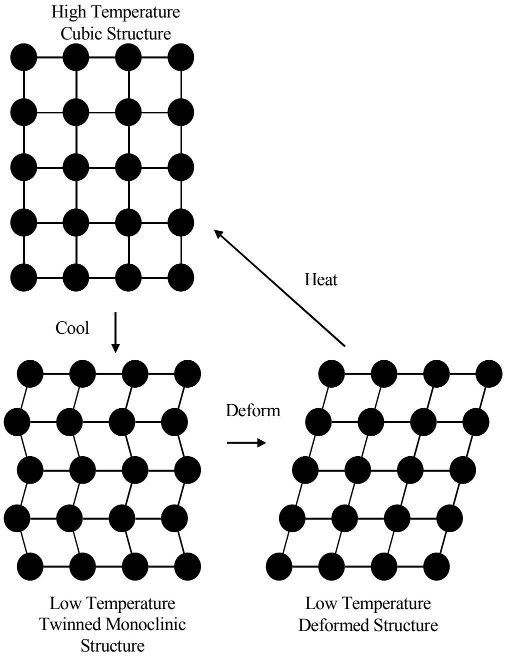

Figure 1.2 Atomic arrangements of alloys exhibiting the shape memory effect

A difference between the transformation temperatures from austenite to martensite and from martensite to austenite exists creating a temperature hysteresis as seen in figure 1.3. M_s, M_f, A_s, and A_f are the temperatures at which martensite starts forming, the part is 100 percent martensite, the austenite starts to form and the part is 100 percent austenite, respectively. The hysteresis is due to internal friction and is controlled by alloy composition and processing. In general the width of the hysteresis is 10-50 degrees C, but can be greatly increased for joining applications.

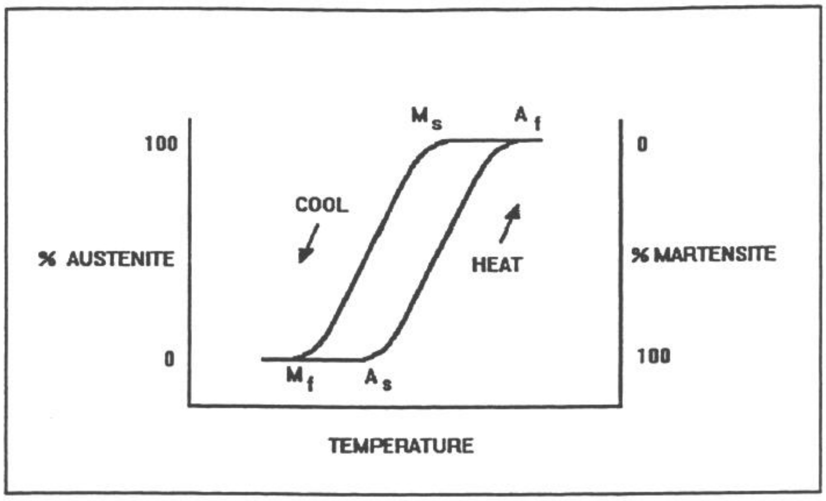

Figure 1.3 Temperature hysteresis (from Raychem, Actuator Design)

In most cases the SMA will remain in its high temperature configuration after cooling. This is referred to as the one-way shape memory effect. In order to use a SMA actuator to provide the same motion repeatedly an antagonistic or biased design must be used to provide a force to return it to its deformed position. In addition to the one-way shape memory effect, two less common behaviors, referred to as the two-way or reversible shape memory effect and all-around shape memory effect exist. As the name implies, for the two-way shape memory effect as the SMA cools it returns to its original shape without applying additional force. The all-around shape memory effect is similar to the two-way shape memory effect except that the high and low temperature shapes are exact inverses of each other and more shape change is possible.

The two-way and all-around shape memory effects are a result of several processing techniques including high deformations in various states, deformations held during temperature changes and aging. These procedures produce dislocations, stable martensite or precipitates that give the martensite twins a preferred orientation as they form on cooling. An SMA actuator employing two-way or all-around shape memory effect can not do work as it returns to its cool state. In addition the two-way and all-around effect are generally not as reliable as the one-way effect and so are normally used to reduce the amount of opposing force needed.

Another related property of SMA is superelasticity. This phenomena allows large deformations (5-10 percent) and is a result of changes in M_s, M_f, A_s and A_f with the level of stress. Since these values increase with stress, as a SMA part in its high temperature (austenite) crystalline structure is deformed and the stress is increased martensite is formed which aligns itself to the applied stress field. This creates a loading plateau in the stress strain relationship. When the part is unloaded the martensite becomes unstable and the part returns to its original shape. This process is shown in figure 1.4.

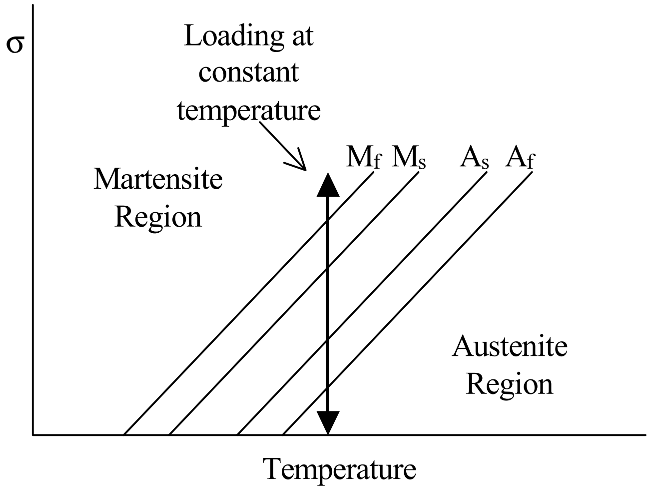

Figure 1.4 Schematic showing superelasticity of SMA

There are several good sources describing the shape memory effect and design with SMA actuators. Liang and Rogers (1990) described a unified, thermomechanical constitutive model relating the fraction of martensite in SMA to temperature. In research mentioned previously this model was used by Rogers et al. (1991) to develop a method of damage control in composite systems. Raychem Corp. has produced an extensive manual entitled "Actuator Design Using Shape Memory Alloys." The CIMSS website (www.cimss.vt.edu) contains a database of many commercial producers of SMA and devices using SMA technology. Many applications for SMA technology have been developed utilizing both the shape memory effect and superelasticity. Medical devices include catheters, orthodontics, microgrippers and angioplasty stents. Microdevices including SMA in their design are particularly promising. Because of thermodynamic efficiency may be greatly increased and removal of heat is rapid, as is the case with thin films cycle rates of over one kilohertz can be achieved (Johnson and Kramer 1998). Aerospace applications include joining devices because of the small space requirements and an application of particular interest, the Frangibolt separation system. The Frangibolt replaces explosive releasing devices in space structures by stressing a notched bolt to failure (Johnson 1992). One 1.5 cm diameter actuator can provide up to 300 kN of force.

Figure 1.5 The Frangibolt separation system

SMA is not generally used as a sensor, however some research has produced successful results employing it as such. Baz et al. (1993) utilized the changes in resistance of embedded SMA fibers to develop a modal FRF. The SMA fibers act as distributed strain gauges providing good signal to noise ratios and insensitivity to nodal points. Unfortunately, they are very limited by their low frequency bandwidth.

1.5 Outline of Thesis

The self-sensing, self-healing bolted joint concept involves two systems, health monitoring and smart materials actuators, combined into one entity. This thesis deals with many of the issues involved with each these systems. The second chapter discusses a method of making impedance measurements for health monitoring that greatly reduces the equipment cost and equipment size. Several proof of concept experiments are presented and compared to the traditional method of making impedance measurements. The experiments are based on structures that were available at CIMSS from previous research.

The question of “when to activate SMA actuators?” is considered in Chapter 3. The chapter contains a literature review of bolted joints and their diagnostics. The application of the transfer impedance method is compared to standard modal tests. An investigation of damping in bolted joints is presented. The fourth chapter discusses practical issues in adaptive bolted joints. This includes issues on activating/heating SMA actuators, connecting the actuators to the power source, size selection of SMA actuators and insulations. The last chapter presents general conclusions and provides recommendations for future work on self-sensing and self-healing bolted joints.