Chapter 4

Adaptive Bolted Joints

4.1 Introduction

Many practical issues need to be addressed before the self-healing bolted joint can become a reality. One of the primary issues is the heating of the SMA washer. Initial experiments performed at CIMSS by Muntges et al (2001) successfully demonstrated that a SMA washer could be used to restore preload in a bolted joint. In each of their successful experiments the washer was heated by placing the entire structure into an oven. Ideally, the washer would make use of SMA's relatively high resistivity and would be activated by resistive (Joule) heating. This method is often employed when SMA wires are used as actuators. In that case a small amount of power is usually sufficient to heat the SMA to its activation temperature because of the small mass of the wires. Also, the primary means of heat transfer away from the wire is convection to the surrounding medium, which in many designs is air. Unfortunately, the relatively large mass of the SMA washer and low resistance because of its short length make resistive heating particularly difficult. In addition, the large mass of the members connected by the joint can often act as a heat sink for what heat is generated. It is desired to develop a design for which minimizes the amount of power required to activate the SMA washer to make the procedure more practical. A series of models were developed to assess the viability of resistive heating and provide an estimate for the power requirements during experiments. In order to decrease the amount of heat loss ceramic washers have been included as insulation in both the models and experiments.

The joint studied was the same joint used in previous experiments at CIMSS by Muntges et al. (2001). A SMA washer that was previously successfully actuated was used as well.

The SMA actuator is a standard part manufactured by Intrinsic Devices Inc. (model AHE0957-0049-0382) used for coupling pipes. The initial dimensions are 0.96 inches for the inner diameter, 1.05 inches for the outer diameter and 0.382 inches in length. The ring is coated in two places with a light blue temperature sensitive paint. Upon heating to the temperature for complete actuation, the paint should change colors to almost black.

4.2 Heating Model

In order to make an initial estimate the electrical resistance the SMA ring was represented as a solid wire. An effective wire diameter of 5.55 mm was calculated from the cross sectional area of the ring to be used in the experiments. Using a length of 9.69 mm and the following equation from Raychem,

$$Resistance/mm = \frac{1.019\times10^{-3}}{d^2}(ohm/mm)\,, \tag{4.1}$$

a resistance of 0.0018 ohm was calculated.

It was also determined that the primary mode of heat loss from the ring during heating would be conduction to the components touching the ring. This was based on previous experiments by Muntges et al. In addition a cooling time of close to 30 minutes is calculated for a 5.5 mm diameter wire, in still air with prolonged heating using a cooling equation given by Raychem (Waram 1993). This again indicates that most heat loss will be through conduction.

The following table lists the properties used in the models. The thermal conductivity (*k*) of the SMA in its austentitic state, which is conservative, is from a table of selected properties of NiTi from www.sma-inc.com. The heat capacity is as listed by Raychem.

Table 4.1 SMA ring properties

Resistance	0.0018 ohms
Mass	6.778 g
Length	0.969 cm
Inner Diameter	2.44 cm
Outer Diameter	2.68 cm
Thermal Conductivity (*k*)	18 W/m K
Heat Capacity (*Cp*)	837 J/m K

The minimum ring temperature for complete actuation (A_f) reported by Intrinsic Devices is 438 K. It is also recommended that the temperature not go above 573 K to reduce the potential for thermally activated creep.

In order to estimate the amount of power required to heat the ring and the corresponding time required, the one dimensional heat equation with energy generation was used to describe the heat generation along the length of the SMA actuator. The equation is shown below

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t}, \tag{4.2}$$

where T is temperature, x is the length along the actuator, k is thermal conductivity, ρ is density, c_p is the heat capacity, t is time and $\dot{q}$ is the rate of heat generated per unit of volume given by the following equation

$$\dot{q}=\frac{I^2R}{volume}, \tag{4.3}$$

where I is current, R is resistance and volume represents the volume of the ring. Figure 4.1 shows a schematic of the ring.

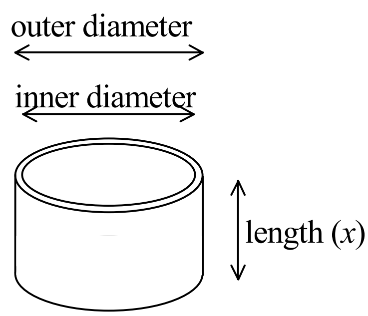

Figure 4.1 Schematic of SMA ring

The model, evaluated in Mathematica, represents the members of the joint bounding the actuator elements (aluminum members, nut, bolt and metal washers) as heat sinks and maintains the corresponding surfaces at room temperature (300 K). The Mathematica code is shown in Appendix A. A plot of the joint made using equation 4.2 showing the ring heated with 300 amps (162 W) and no additional insulation shows that the ring reaches a maximum temperature at its midlength of 413 K, 25 K less than needed for complete actuation, after approximately 20 seconds.

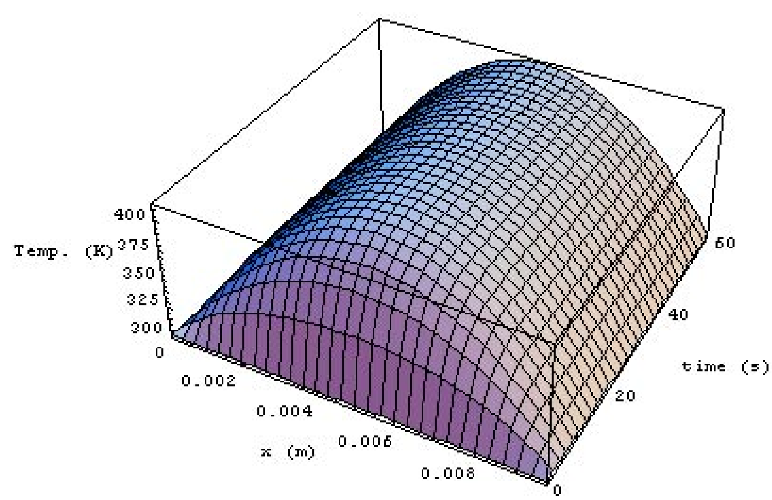

Figure 4.2 Heating model of ring with no insulation

In addition, the temperature decreases quickly away from the center in order to meet the heat sink boundary conditions at the edges of the ring. Large portions of the ring would be well under the complete actuation temperature.

In order to reduce the amount of heat loss from the ring by conduction insulation is needed. Muntges et al. originally attempted using several layers of Kapton tape sandwiched between the actuator and surrounding members. Unfortunately, the tape absorbed the expansion of the ring when actuated. The need for a hard, nonconductive material points to ceramics as a logical choice for the insulator. The addition of ceramic washers was incorporated into the model as a nonconstant density, thermal conductivity and heat capacity. This is somewhat conservative since it does not include thermal contact resistance. The ceramic washer properties are shown in table 4.2.

Table 4.2 Ceramic ring properties

Material	Alumina
Density	3970 kg/m^3
Length	0.48 cm
Thermal Conductivity (*k*)	36 W/m K
Heat Capacity (*Cp*)	765 J/m K

The temperature profile of the SMA ring with ceramic washers and 300 amps of current, again generated with the heat equation in Mathematica, is shown in figure 4.3.

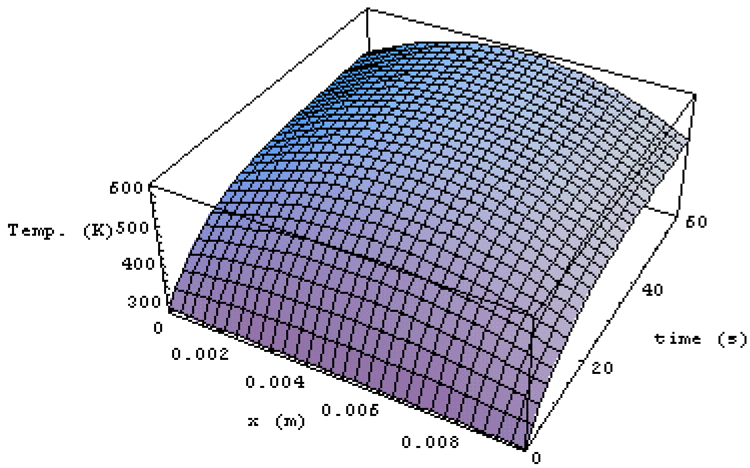

Figure 4.3 Heating model of ring with ceramic washers

The midlength temperature reaches A_f (438 K) after approximately 6.1 seconds. The heating of the SMA actuator benefits in two ways by the addition of washers. First, the lower thermal conductivity of the ceramic increases the resistance to conduction to the large members of the joints acting as heat sinks. Second, the washers distance the SMA ring from the heat sinks allowing not only a higher temperature, but also a flatter temperature profile. If copper leads are added to the model the midlength temperature reaches A_f after only 5.5 seconds due to the fact that the ring is moved even further from the components acting as heat sinks. In addition, the mid length will still reach A_f before reaching steady state with only 150 amps (40.5 W) applied.

It should be noted that a slight time delay should be added since some of the heat is absorbed during the transformation from martensite to austenite. A correction term, t_c, provided by Raychem is given by the following equation.

$$t_c = 121.23 \frac{d^4}{I^2} \left(\frac{T_{\max} - T_{abient}}{T_{\max} - A_f} \right), \tag{4.4}$$

Using the temperature for complete actuation given by Intrinsic as A_f, which is conservative, and the effective wire diameter of the ring, a correction of approximately 2.2 seconds is obtained. Additional time (approximately 5 seconds) should also be added so that either the rest of the ring or the majority of it reaches A_f.

Therefore, in order to effectively actuate the SMA washer, an insulating washer seems to be required. Heating without insulation requires power which is way too high for conventional power supply and sometimes it is even dangerous. This would hinder implementation of this technique to practical field applications.

4.3 Resistive Heating Experiment

The purpose of the first experiment was to test the effectiveness of ceramic washers, evaluate the use of copper electrodes, as well as determine a more exact amount of power required to actuate the washer. The experiments were performed in Virginia Tech's Center for Power Electronic Systems in order to utilize their HP 6680A DC power supply. The source had a maximum current of 800 amps and maximum voltage of 5 volts. One significant advantage of the HP 6680A over other sources is the ability to control the power applied via the current rather than voltage. In resistive heating the ratio of amount of heat generated to volume is independent of the length of wire or actuator for a constant current source. For constant voltage or constant power systems the amount of heat generated per unit of volume increases as the length of wire or actuator is shortened.

The joint consisted of two 1/4 x 2 x 9 inch sections with an overlap of 3.5 inches and connected by a 1/2 inch bolt with washers. A 7/8 x 3/4-inch PZT sensor, cut from 0.01 inch thick sheet of PZT material supplied by Piezo Systems, Inc. was bonded 7 inches from the bolt. A qualitative analysis using the impedance method would be relied upon to evaluate the effectiveness of the actuation. A schematic of the beam is shown in figure 4.4.

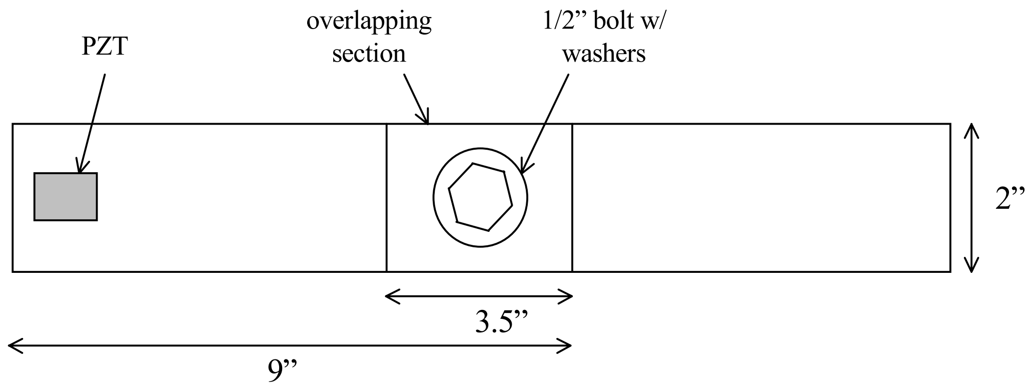

Figure 4.4 Schematic of beam used in heating experiments

The SMA washer was bounded by two 1/8 inch thick copper electrodes. These were then sandwiched between two 3/16 inch thick alumina (AlO_2) washers, provided by Bolt Technical Ceramics, to electrically and thermally isolate the SMA actuator system while not absorbing the actuation. This was then enclosed by steel plate washers, and finally, the nut and members of the joint. The bolt was also wrapped in electrical tape in the area of the electrodes and SMA to ensure that it was electrically isolated when power was applied. The configuration can be seen in figure 4.5.

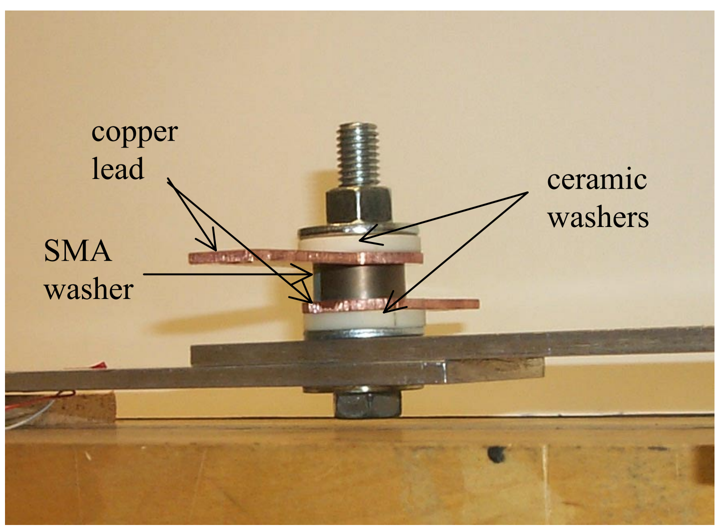

Figure 4.5 Self-healing by resistive heating configuration

The impedance was monitored over several ranges of frequencies from 2.8 kHz to 35 kHz using the HP4194A. The joint was initially tightened to 25 ft-lbs and the impedance recorded. The joint was loosened to 10 ft-lbs and impedance recorded again. The joint was never completely loosened to ensure that components did not shift. After the impedance measurements of the "loose" joint were made, power cables from the HP 6680A power source were connected to the leads. The voltage and current were initially set to a maximum of 5 V and 10 A respectively. The circuit required approximately 0.1 V to produce 10 A of current. The current was gradually increased over a period of several minutes to a maximum of 400 A, at which the smaller of the power cables became warm and the power was turned off. At the maximum power 0.6 V was required to draw 400 A of current. The temperature sensitive paint on the SMA actuator never changed color however, some cracking and flaking of the paint did occur. The joint was not handled until approximately one minute after the power was removed. The leads and actuator were still warm to the touch at this point. The power cables were removed and impedance measured a final time. A check of resistance from the leads to the bolt was made to confirm that the actuator had remained electrically isolated. Results are shown in the figures 4.6 through 4.11.

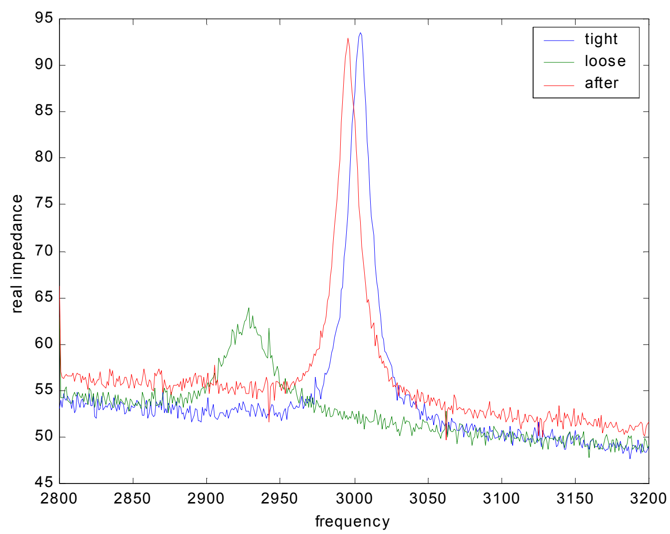

Figure 4.6 Resistive heating experiment impedance from 2.8 kHz to 3.2 kHz

The peak in this frequency range exhibits the expected behavior, shifting to the left upon loosening, indicating a reduction in stiffness, then shifting back to the right after power was applied. The peak moved back towards its original position, but not all the way, indicating that actuation was partially successful in restoring the lost preload in the joint. Also, the magnitude of the peak decreased when loosened and increased after actuation, indicating that damping increased in the loose joint as expected.

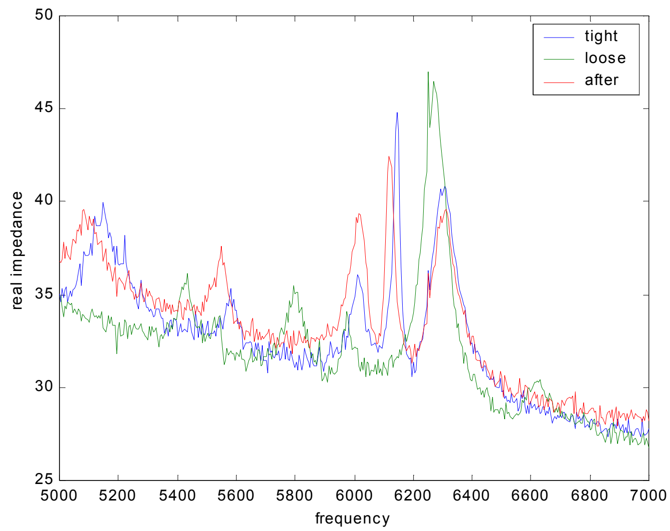

Figure 4.7 Resistive heating experiment impedance from 5 kHz to 7 kHz

Similar results were seen in the 5 kHz to 7 kHz frequency range. In this plot the first results that do not follow the expected decrease in magnitude and shift to the left pattern with loosening are found. The magnitude of large peak initially at 6.3 kHz increased at the loose state, however did shift to the left. These departures from the expected movement of the peaks can be explained by the fact that the PZT excites all modes of the structure, some of which may be affected differently than the typical bending modes by the loosening and subsequent retightening by lengthening of a component of the joint. Also, the higher frequency peaks in this plot move larger distances upon loosening, but return almost completely to the original frequency position of the tight joint.

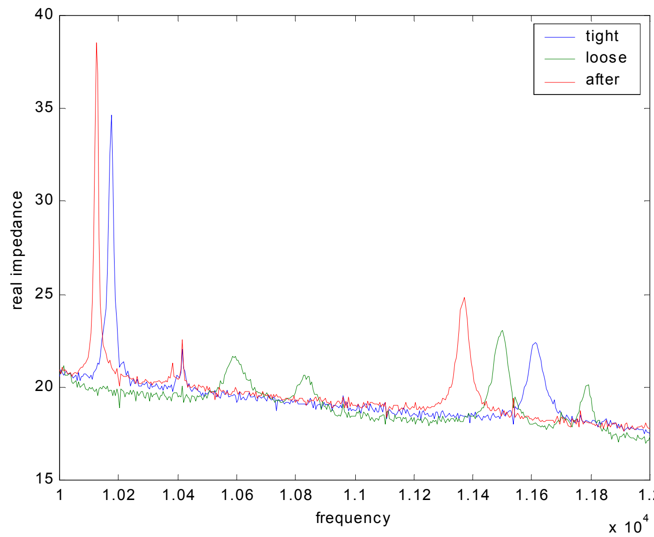

Figure 4.8 Resistive heating experiment impedance from 10 kHz to 12 kHz

At this frequency range the information obtainable from the impedance plot diminishes greatly. The large peak initially at 10.2 kHz moves out of the frequency range recorded, but then returns after actuation to just slightly left of the original location. Similar phenomena can be assumed to occur with the double peak initially at 10.4 kHz, however, the left peak of the double peak does not return as far as the right peak, causing them to separate slightly. The peak at 10.6 kHz may be shifted from the initial peak at 11.6 kHz, or may just be a new mode formed upon loosening. Assuming the former, it returns most of the way back to its original frequency position ending up at 11.4 kHz after actuation. The remaining peaks in this frequency range could be peaks shifted from peaks outside of this frequency range, or new peaks formed upon loosening. Another possibility for the peaks at 11.6 kHz (tight), 11.5 kHz (loose) and 11.4 kHz (after) could be that these are all the same peak and it is actually shifted further to the left after actuation.

Similar results were found in the remaining frequency ranges. At higher frequencies the peaks after actuation moved increasing further to the right, eventually being further to the right than the initial tight joint. Also, it becomes difficult to determine which loose peak corresponds to the same tight peak and peak after actuation, due to the large shifts which move the loose peaks past one or several other tight peaks. The following figures show several of the remaining frequency ranges recorded. A particularly good example of the demonstrating that the actuator restored the lost preload is the peak at 31.6 kHz (tight) in figure 4.10. The very large peak either completely disappears from the frequency range, a shift of at least 1.6 kHz, or is so diminished that it no longer resembles the original peak, then returns after actuation to its original position and magnitude.

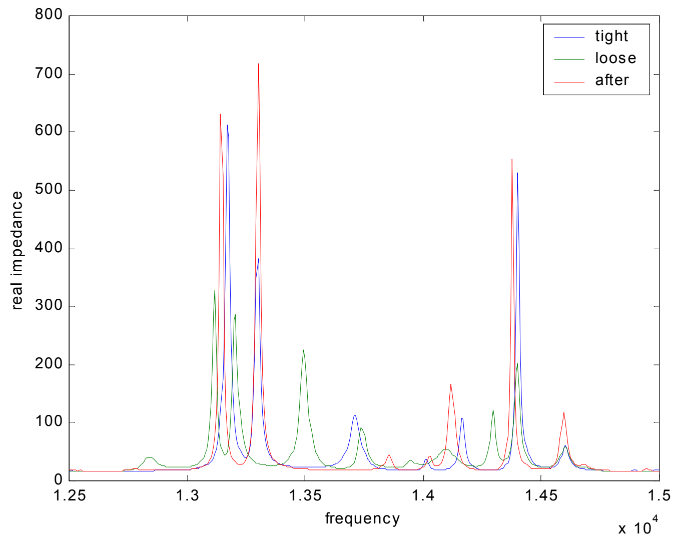

Figure 4.9 Resistive heating experiment impedance from 12.5 kHz to 15 kHz

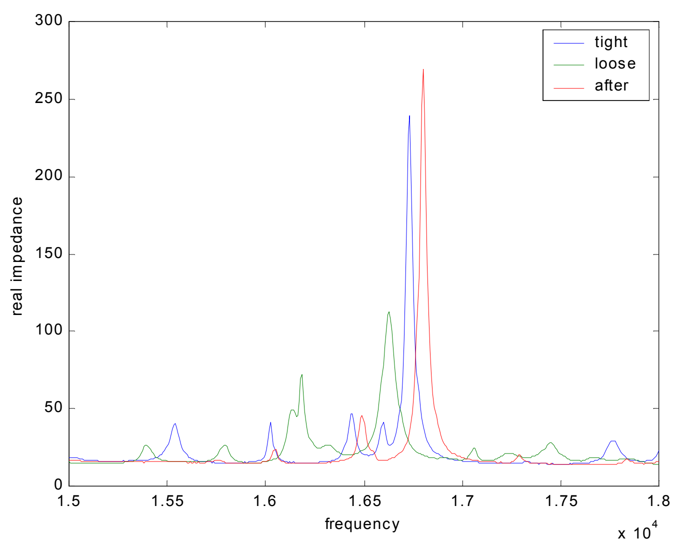

Figure 4.10 Resistive heating experiment impedance from 15 kHz to 18 kHz

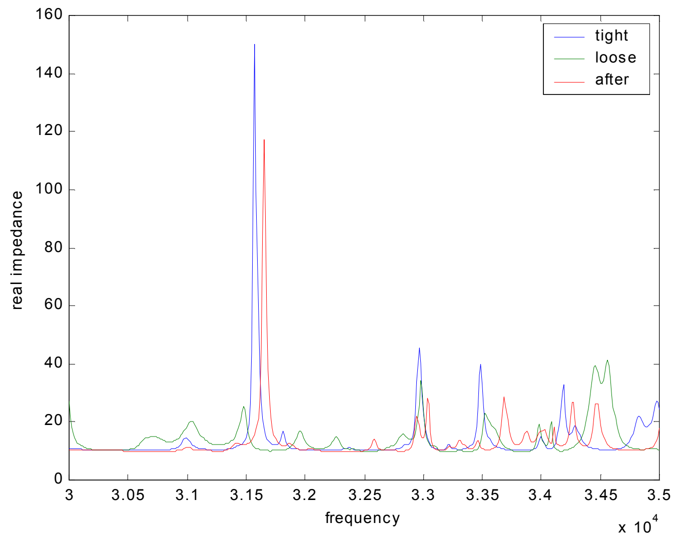

Figure 4.11 Resistive heating experiment impedance from 30 kHz to 35 kHz

The results of the impedance method analysis indicate that the SMA actuator was successfully activated even though the temperature sensitive paint did not change color. This was further supported by heating the ring with a car battery as the power source, which provided enough heat to cause the SMA to tarnish, but still did not cause a change in the color of the temperature sensitive paint. The failure of the paint prevents an accurate determination of required power for activation. One explanation for this may be that the paint blistered off when current levels were high, but before the activation temperature was reached. In future experiments it would be useful to monitor the temperature via another method. Since transducers or monitoring equipment may be damaged by high current, an infrared thermometer (available at CPES) would be appropriate for monitoring. Also, it may be desirable to utilize another method of electrically heating, if the power requirements for direct resistive heating of the actuator prove to be impractical. Contributions, of the experiment include demonstrating that actuation via resistive heating was possible without sparking or danger of explosions, an upper bound of the power required is now known for this size of actuator, which can possibly be scaled to other sizes of actuators, and it is now possible calculate a more accurate resistance of the actuator, which can also be scaled.

4.4 External Heater Experiment

A second heating experiment was done using an external heater attached to the SMA washer. First a Thermofoil^{TM} heater from Minco Products, Inc., model HR5208R6.4L12B, was tested on an already actuated ring outside the joint configuration. The flexible, silicone encapsulated heater was approximately 0.04 in. x 0.3 in. x 3.1 in. and rated to 60 W/in.^{2}. It had a resistance of 6.4 ohms and was powered with a Alinco model DM340MV DC power supply with a maximum voltage of 15 V and current of 35 A. The ring was easily heated to above 165 C without insulation after several minutes using 9 V (12.7 W).

To test the heater in the joint configuration the same joint was used minus the copper leads used for the direct current heating. A Thermofoil^{TM} heater was bonded to the outer surface of the SMA ring. A portion of the ring with the thermally sensitive paint was not covered. Also the base of the heater where the leads are attached is thicker than the rest of the heater and would not remain attached to the ring. The configuration can be seen in figure 4.12.

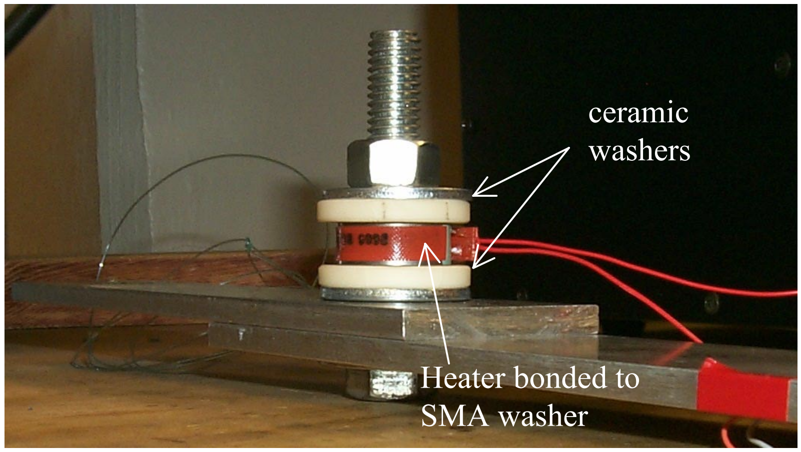

Figure 4.12 Bolted joint with heater

The joint was initially tightened to 25 ft-lbs and the impedance measured for several ranges from 2.8 kHz to 35 kHz. During tightening, the ceramic washers developed several radial cracks, however, no part dislocated. The joint was then loosened (though it never became slack), retightened to 10 ft-lbs and impedance measured again. The joint was then heated with the maximum power that the Alinco source could provide (approximately 15 V at 3 A) for several minutes. The temperature sensitive paint never changed color, but the bolt became very hot and aluminum members became warm. The joint was then allowed to cool and the impedance measured again. On inspection of the joint after heating it was discovered that a small section of the heater had become disbonded and the silicone had burnt at that point. Results from the test are shown below.

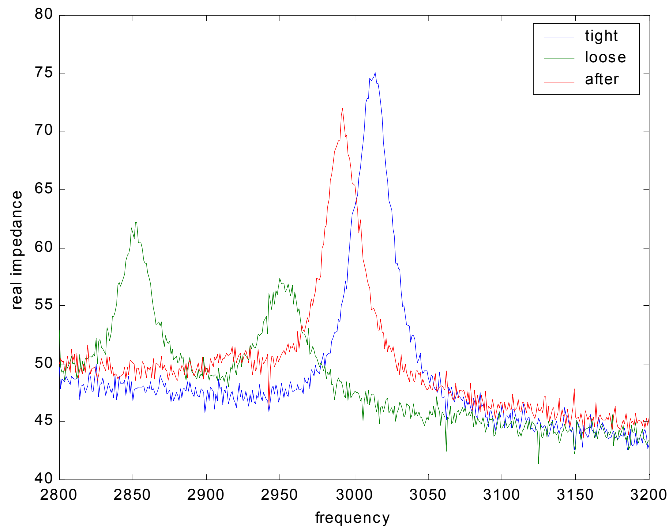

Figure 4.13 External heater experiment impedance from 2.8 kHz to 3.2 kHz

The results are similar to the first experiment. The peak in the frequency range from 2.8 kHz to 3.2 kHz exhibits the expected behavior, shifting to the left upon loosening, indicating a reduction in stiffness, then shifting back to the right after power was applied. The peak moved back towards its original position, but not all the way, indicating that actuation was partially successful in restoring the lost preload in the joint. Also, the magnitude of the peak decreased when loosened and increased after actuation, indicating that damping increased in the loose joint as expected. This reaffirms the damping model seen in the third chapter. A loose joint would allow larger amounts of microslip, and thus increased damping.

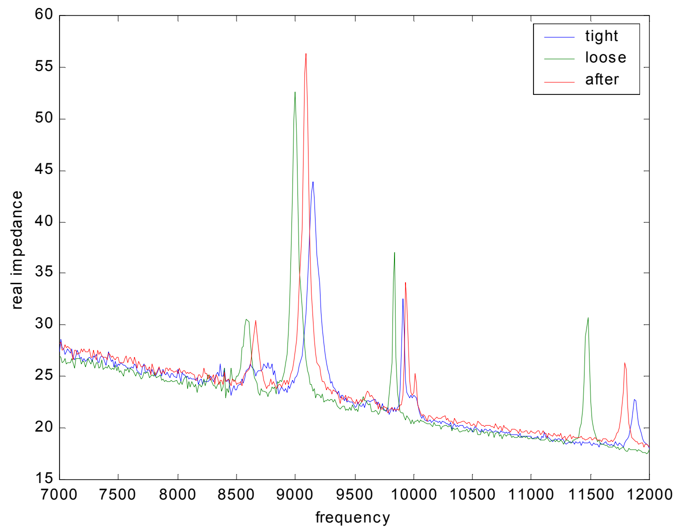

Figure 4.14 External heater experiment impedance from 7 kHz to 12 kHz

Again similar results were seen in remaining frequency ranges. The sensitivity to the loosening and tightening varies for different modes. This is demonstrated by the difference in position and magnitude change for the peaks originally at 9.91 kHz and 11.88 kHz (figure 4.14). The 11.88 kHz peak shifts 410 Hz, a 3.5 % shift, when loosened compared to the 9.91 kHz peak, which shifts only 70 Hz, less than 1 %, when loosened. In addition, the 9.91 kHz peak returns to a location slightly to the right of its original position, whereas the 11.88 kHz peak follows a more typical pattern of moving back to a position slightly left of the original. Also a trend seen in most of the peaks for the second experiment is seen in figure 4.14. The peaks after actuation become much narrower than either the loose peak or the original peak. This is also seen in figure 4.15 showing the impedance from 15 kHz to 18 kHz. The plot of the 15 kHz to 18 kHz frequency range shows higher frequency peaks moving further to the right than the original peak upon tightening as was seen in the first experiment.

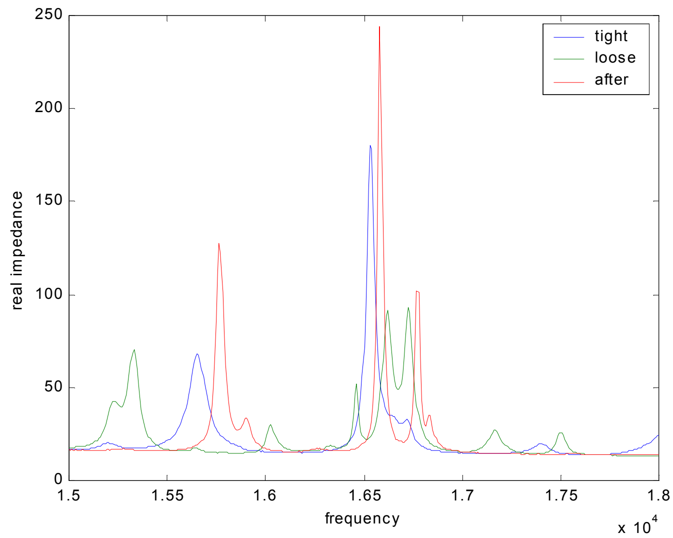

Figure 4.15 External heater experiment impedance from 15 kHz to 18 kHz

After the experiment was completed the ring and heater were wrapped in with several layers of Minco self-adhering silicone insulation tape (while still in the joint) and reheated to see if the ring could then be heated completely to its full actuation temperature. Minimal, if any, additional actuation was observed. Upon disassembly of the joint it was found that the ring was heated unevenly, resulting in a non-circular shape as seen in figure 4.16.

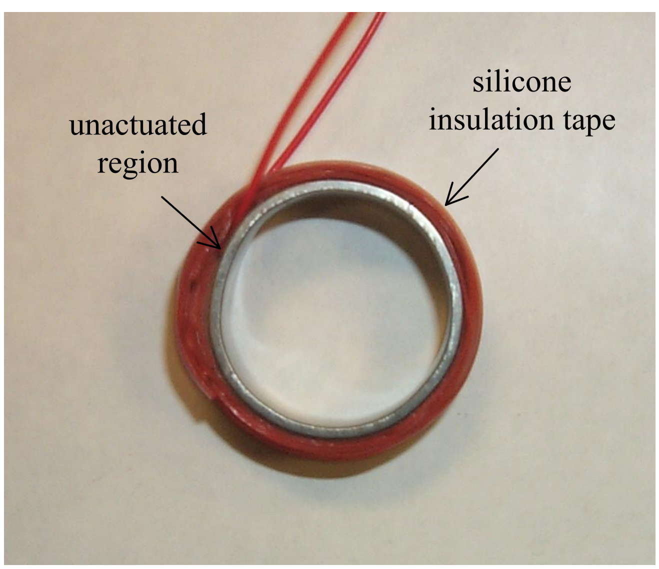

Figure 4.16 Ring showing uneven actuation

Areas where the heater disbonded or were not attached had a larger radius of curvature indicating that they were not heated. This demonstrates the importance of the heater being in contact of the entire circumference of the actuator. Furthermore, this indicates that conduction, even with the ceramic washers, is the primary mode of heat transfer since the ring heated outside the joint did not show such a phenomena even without the silicone tape. The silicone tape does, however, help hold the entire heater in contact with the ring, especially important for the actuation of rings provided by Intrinsic, which contract radially to provide the axial extension.

The results of the impedance method analysis show that the tension in the joint was mostly restored after loosening. Similar trends were seen as in the resistive heating experiment including increased damping in the loose joint, shifts past the original peak position for after tightening at higher frequencies and varying degrees of sensitivity for different modes. The external heater experiment has demonstrated many of the positives and negatives to of using an external heat source. Using an external heater eliminates the need for large wires, thick leads and unconventional power sources when heating via the actuator's internal resistance. It does however increase the significance of insulation, because of the longer heating time, and add new issues such as maintaining contact with a shrinking ring and an increased possibility for uneven heating. These issues should be easily solved however. Improvements in the ceramic washers can be made by choosing a material with a lower thermal conductivity and higher fracture toughness. More exact sizing of heating elements and the addition of insulating silicon tape should aid in maintaining contact with the SMA thus preventing uneven heating.

4.5 Ring Sizing

An attempt was made at determining a method of sizing the SMA actuators provided by Intrinsic Devices, Inc. Since the rings are primarily used for their radial contraction for coupling applications, they are described by their initial dimensions and maximum diameter assuming complete recovery. For the self-healing joint application it is desirable to know the minimum length upon complete recovery so that the amount of preload restored when the ring is actuated can be determined. Since the shape change process is complex, ideally many different sized actuators would be tested to develop an empirical relationship. Unfortunately, the large cost of such an undertaking makes this impossible. Intrinsic did, however, provide a rough relationship for the free deflection of the ring, based on their own testing, that follows:

$$\varepsilon = \frac{ID_1 - ID_2}{2(ID_2 + t)}, \tag{4.5}$$

where ε is strain, ID_1 and ID_2 are the initial and final inner ring diameter respectively and t is the initial ring thickness. This can be assumed to be the strain in the axial direction and of the thickness and then be used to calculate the free deflection in the axial direction. From the free deflection, the force generated in the joint can be determined using the modulus of elasticity. This was compared with the results from the tests previously described in this chapter.

For the rings used in the proceeding experiments the nominal initial dimensions are 0.957 in., 0.049 in. and 0.382 in. for the inner diameter, thickness and length respectively. The nominal maximum recovered diameter is 0.917. Using the formula from Intrinsic, this gives a strain of 2.07 percent and corresponding free deflection length of 0.390 in.

For a typical bolt with an average coefficient of friction of 0.15 between the nut and bolt the following equation can be used to estimate the tension in the joint corresponding to various torques: (Juvinall and Marshek 1991)

$$T = 0.2Fd\ , \tag{4.6}$$

where T is torque, F is the tension in the bolt and d is the nominal diameter. Using this formula, for the fully tightened case (25 ft-lb) in the preceding experiments, the force in the joint is estimated to be 3000 lb. Upon loosening to 10 ft-lb, the tension is reduced to 1200 lb.

To calculate the blocked force of the ring the ring will be assumed to be in its martensitic state having a modulus of elasticity, E, of 4 x 10^6 psi. The area of the ring after actuation is 0.153 in^2. The length is assumed to remain approximately the same at 0.382 in. Theoretically the blocked force corresponding to a strain equal to the free deflection of the ring should be approximately 12700 lb. Since the results show that incomplete restoration of the preload occurred the blocked force model is not realistic so a new method of determining the force generated through actuation of the SMA washer, based on the equation for clamping force given by Intrinsic Devices was developed .

Intrinsic gives the clamping force in a thick walled ring as

$$F = \pi d L \sigma \ln(d/D), \tag{4.7}$$

where F is the clamping force, d is the nominal inner diameter, L is length, D is the nominal outer diameter and σ is the ring recovery stress, given by Intrinsic as 30 ksi. This is essentially the stress multiplied by the area and a thickness factor of $\ln(d/D)$.

The stress multiplied by the cross sectional area in the axial direction gives approximately 4600 lbs. Multiplying this value by the length of the ring gives a force of 1757 lbs, which, when added to the force at the loose state would be approximately 43 lbs short of full restoration. This is consistent with the results of the heating experiments.

4.6 Conclusions

Modeling and experimental testing have shown that resistive heating of an SMA ring actuator in a bolted joint is possible. Shifts in the impedance functions of the structure from 25 ft-lbs to 10 ft-lbs then back toward the 25 ft-lbs shape indicate that joint tension was mostly restored in the resistive heating experiment. SMA does not need a continuous supply of power to remain actuated, however, the amount of power required to heat an SMA washer is still an important issue. An exact value of the power required to completely heat the ring was not found, however, an upper bound of 240 W was found. Calculating the resistance of the ring using an equivalent diameter wire based on the cross sectional area of the wire was found to be accurate. The resistance, however, is very low, resulting in very large currents needed for heating. This necessitates the use of an uncommon power source, or high power device such as a car battery. The use of copper electrical leads sandwiched in the joint did, however, provide a simple means of electrical connection, without producing sparks.

A more practical method of heating is to use an external heater primarily because conventional power source can be used. In the external heater experiment the SMA actuator again mostly restored the preload in the joint. Heating with lower power does, however, increase the significance of insulation, because of the longer heating time, and add new issues such as maintaining contact with a shrinking ring and an increased possibility for uneven heating, though these issues should be easily solved. Improvements in the ceramic washers can be made by choosing a material with a lower thermal conductivity and higher fracture toughness. More exact sizing of heating elements and the addition of insulating silicon tape should aid in maintaining contact with the SMA thus preventing uneven heating.

A method of sizing the ring actuators based on a technique provided by Intrinsic Devices, Inc. has also been shown. A simple model predicts the incomplete actuation exhibited in the two experiments. This highlights the importance of effective diagnostics to determine the correct time to actuate. Additional tests with different sized actuators need to be done to verify the model's applicability to a range of joint sizes.