# Influence of Stress Relaxation in Hybrid Composite/Metal Bolted Connections

**Project Report for the**

**Modular Advanced Composite Hull form (MACH) Technology Project**


Prepared by:

Keith N. Pelletier, Graduate Research Assistant

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Prepared for:

Office of Naval Research
800 N Quincy St.
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Grant No. N00014-01-1-0916
Dr. Roshdy G.S. Barsoum,
Program Manager



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January 25, 2005

Roshdy G. S. Barsoum
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Dear Dr. Barsoum:

Enclosed please find two copies of the report entitled "Influence of Stress Relaxation in Hybrid Composite/Metal Bolted Connections" including the required SF298. This report is submitted under the Modular Advanced Composite Hullform Technology (MACH) project, Grant No. N000014-01-1-0916. If you have questions or comments please do not hesitate to contact me.

Regards,

Vincent Caccese, Ph.D
Associate Professor of Mechanical Engineering

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## ABSTRACT


Hybrid composite/metal connections are susceptible to bolt load loss due to viscoelastic creep and/or environmental effects. Accordingly, the focus of this research is on experimentally quantifying temporal changes in bolt load of composite/metal hybrid connections. Stress relaxation and creep are major concerns when using bolted connections in composite materials. Hybrid composite/metal bolted connections tend to change bolt load with time primarily due to the viscoelactic nature of the matrix material. This is especially true through the thickness of the material, where the behavior of the material is dominated by the matrix. It is ultimately desired to use bolted composite/metal hybrid connections for naval applications, where it is important to maintain as much of the initial preload as possible to ensure watertight integrity. Stress relaxation in hybrid composite/metal bolted connections was studied experimentally during this effort at the sub-component scale. In so doing, EGlass/vinyl ester plates were bolted together to

aluminum with steel bolts to determine the primary stress relaxation response. Specific test plans were developed to study stress relaxation under relatively uniformly loading, the effect of retorquing the bolts, and the effect of tapered head versus protruding head bolts. A pilot study on effect of the environment was also undertaken to develop parameters and procedures for study. All tests were run for a period of at least 3-month to estimate the primary stress relaxation effects. Test results show that the load curves could be fit to a simple power law equation using the method of least squares. Reloading tests show that some of the preload in the connections could be maintained with periodic retightening of the bolts. Also, substantial temperature dependence was observed in the connections that were reloaded multiple times. Connections that are reloaded can maintain more of their initial preload, but are more sensitive to temperature shift, even at small changes in temperature of only 5 degrees Fahrenheit. In general, reloading the connections will help the connections to maintain their initial preloads, but great care must be taken in cases with large temperature changes. Tapered head bolts were tested in some connections and compared to results obtained from non-tapered head bolts. Little to no difference was seen when using tapered head bolts over non-tapered head bolts as the connections using tapered head bolts had roughly the same stress relaxation rate as the connections using non-tapered head bolts. Environmental testing has recently been started on the hybrid connections, and only preliminary results are available.

## 1. INTRODUCTION

This report summarizes the experimental study of stress relaxation in hybrid composite/metal bolted connections. It is part of an ongoing effort to investigate the response of hybrid connections in naval vessels. Bolted connections are used often in hybrid structures where the ability to easily remove structural components is required. Concern over the effect of stress relaxation in the hybrid bolted joints was the impetus for this study. Creep in the through the thickness direction of the composite material is typically experienced by bolted composite connections. A composite panel bolted in the thickness direction is highly susceptible to preload loss, due to the viscoelastic nature of the resin, which dominates the transverse direction.

The work was performed under the Modular Advanced Composite Hull-form (MACH) project where the focus was to develop and test hybrid metal/composite connections for naval ship applications. The primary motivation for this project is to provide alternatives to conventional hull construction techniques and conventional hull forms by using modular hybrid construction methods. The major effort of the MACH project is to develop a hybrid structural system that is comprised of polymer matrix composite structural panels connected to metallic supporting structure. In addition to enabling advanced hull shapes, the hybrid concept used in MACH is also expected to decrease system weight, which in turn should lead to faster and more efficient vessels. Also, due to the modularity of the system, access to the hull interior would be greatly improved. Various connection methods are being examined for the project, including adhesive bonding, embedded metallic inserts, and bolted connections. Use of bolted connections is desirable in cases where removable panels are required. Design of removable panels enables easier access for maintenance and exchanging of equipment for mission specific tasks.

Bolted connections present a problem, however, in that composites tend to creep over time, due to the viscoelastic nature of the matrix material. This creep leads to stress relaxation and potential loss of preload in bolted connections. In order to maintain watertight integrity in the bolted connections, it is desired to minimize the amount of stress and load relaxation in the bolts, and to maintain as much of the initial preload as possible. It is the goal of this effort to quantify the stress relaxation and to study the important parameters that govern stress relaxation in bolted composite/metal hybrid connections. In this way, reliable and cost effective connections can be designed with a high degree of structural and watertight integrity.

### 1.1 Objectives

The objective of this effort is to quantify the stress relaxation of transversely compressed composites in bolted aluminum/Eglass-vinyl ester hybrid connections. The intent is to study bolted hybrid connections at a sub-component level, to isolate the effects of viscoelastic creep on the stress relaxation of the bolt. The study is intended to investigate the effects of the following:

1. Stress distribution through the thickness
2. Re-applying bolt torque (Reloading)
3. Varying thickness of the constituents
4. Varying bolt size
5. Tapered vs. standard protruding head bolts
6. Temperature and moisture

### 1.2 General Creep Response

Creep in a material is defined as a time-dependent continuous deformation of the material under a constant stress. Creep can be separated into 3 different stages, namely, primary, secondary and tertiary. These three stages are shown in Figure 1.1. The first stage, primary creep, is where creep occurs rapidly as the rate decreases over time. The secondary creep stage proceeds at a nearly constant rate. The third and final stage, called tertiary creep, occurs at an increasing rate, and typically ends in fracture.

Creep in composites is due primarily to the viscoelastic nature of the resin used in infusing the composite. While not the sole phenomenon responsible for the creep in composites, the matrix of the material is the largest contributing factor. Other aspects to consider when determining the creep in a composite are the composition of the fibers and the dynamic effects of temperature and humidity.

Shen et al. [1998] made observations of viscoelastic creep at a marred polymer surface by utilizing a scanning probe microscope. The material studied was an Acrylic

Polyol/HDI Timer coating deposited on an aluminum substrate. The marring on the surface was done with a diamond tip, at five different normal force levels, 68, 133, 190, 257, and 325 micro Newtons. Utilizing the scanning probe microscope, they were able to observe the surface of this material either partially or completely recover due to creep effects. Images of the surface were taken starting at 15 minutes after the marring, and then taken continuously at increasing periods of 10 minutes, 20 minutes, and 30 minutes for a time frame of 6 hours.

It was discovered that there was a recoverable and unrecoverable aspect of the surface marring. The recoverable part was dominated by the viscoelastic creep rate, and was constant throughout the range of forces used to mar the surface, i.e. the depth of the marring. This creep rate is determined by several factors such as the components of the polymer, temperature, and humidity. The unrecoverable plastic deformation was dependent on the forces used during marring. The surface became more and more permanently deformed as the marring force was increased. Another interesting find from these tests was that the viscoelastic creep in this composite is extremely sensitive to water. Immersion in water greatly accelerated the recovery of the surface due to creep. A test was run where the results were looked at after 5 minutes, and the marred surface had recovered dramatically vs. a test that was done out of water.

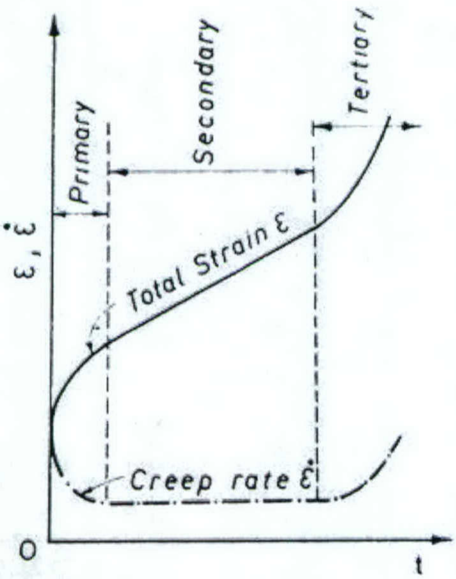



**Figure 1.1 – Three Stages of Creep [Findley et al., 1976]**

The orthotropic rate independent behavior of polymeric composites was described by Sun and Chen [1991] using a plasticity model based on a one-parameter potential function. This is given by:

$$2f(\sigma_{ij}) = \sigma_{22}^2 + 2a_{66}\sigma_{12}^2, \tag{1.1}$$

where the σ's are stresses, the subscripts 1 and 2 refer to the fiber and transverse directions, and $a_{66}$ is an unknown parameter determined from experimental results [Kim and Sun, 2002]. This lead to the rate dependent non-linear behavior in polymeric composites being modeled using viscoplasticity models. Zhu and Sun [1998] studied the loading and unloading of IM7/5260 carbon-epoxy composite under different rates of loading and unloading. It was discovered that stress decreased with time during the loading cycle when loading was kept at a constant strain level, while stress increased over time during the unloading cycle at a constant strain rate. Kim and Sun [2002] used this information to study and model stress-relaxation and stress recovery in the thermoplastic composite AS4/PEEK. The tests were performed at room temperature using an MTS machine in displacement control mode controlled by an Instron 8500 digital controller. Specimens were loaded at a given strain rate to the desired strain level and held at that level for 1,000 seconds. Stress relaxation data was recorded during this period. Stress recovery tests during the unloading were performed in a similar manner at the same strain levels. The strain rates used were 0.00001/s, 0.0001/s, and 0.01/s. Off-axis coupons were used during these tests of 20, 30, and 45 degrees. Accordingly, they were able to show that the equilibrium stress-strain curves for both loading and unloading were basically the same. A one-parameter plastic potential function was very accurate in describing the behavior of the composite during loading and unloading. It was also found that the relaxation behavior in the composite during the loading and unloading are similar. At a given strain rate, the relaxation curve during loading was almost identical to the recovery curve during unloading.

### 1.2.1 Creep Response in the Fiber Direction

Creep response in the fiber direction of composites is dependent on several factors. Creep in this direction is primarily dictated by the matrix material, and its viscoelastic properties. The type of fiber used, and the volume fraction of the fibers also contribute to the creep properties of a composite material.

Kim and McMeeking [1994] performed testing on creep in composite materials in the fiber direction. They found that the matrix followed the following power law creep:

$$\varepsilon_{ij} = \frac{3}{2}\varepsilon_0\left(\frac{\bar{\sigma}}{\sigma_0}\right)^{n-1}\frac{s_{ij}}{\sigma_0}, \tag{1.2}$$

where $\varepsilon_{ij}$ is the strain rate, $s_{ij}$ is the deviatoric stress, denoted by:

$$s_{ij} = \sigma_{ij} - \sigma\delta_{ij}, \tag{1.3}$$

$\bar{\sigma}$ is the effective stress, given by:

$$\bar{\sigma} = \sqrt{\frac{3}{2}s_{ij}s_{ij}}, \tag{1.4}$$

and $\sigma_0$ and $\varepsilon_0$ are material constants. Kim and McMeeking [1994] further developed this model by analyzing the matrix flow field in much greater depth. They showed that when there is no slip, or interface mass transport, the composite would have high creep resistance compared to the matrix material alone. The creep stress intensity, S, is defined as the ratio of the stress in the composite material divided by the stress in the pure matrix at the same strain rate.

$$S = \frac{\sigma_a}{\sigma_0}\left(\frac{\varepsilon_0}{\varepsilon}\right)^{1/n}. \tag{1.5}$$

Once slipping or interface mass transfer occurs, however, either separately or together, they can greatly reduce the creep stress intensity of the composite. If either or both occur rapidly, it can reduce the effective creep stress intensity to below that of the matrix material alone.

Raghavan and Meshii [1997] performed studies on the long-term deformation and strength of carbon-composites using short–term test data obtained for accelerated testing conditions such as higher temperature, stress, and humidity. Continuous carbon fiber reinforced polymer composite (AS4/3501-6) and the epoxy (3501-6) were used to test creep.

Five different fiber orientations of the composite were tested, 0, 10, 30, 60, and 90 degrees. The 0, 10, 30, and 60 degree orientations were made with eight plies each, while the 90 degree laminate was made with 16 layers. They found that the creep in the composite and its epoxy matrix increases with increasing stress, temperature, and time. The composite creep was discovered to be highly non-linear in behavior, and that this non-linearity increased with increasing temperature. Results also showed that the slope of the compliance curves changed with changes in stress and temperature. This indicates that the non-linearity in the composite may increase with time as well. Their results indicate that the uni-directional composite is a non-linear material, or is thermo-rheologically complex in behavior.

By comparing the results from the creep test on the epoxy with that of the different composite lay-ups, it was found that the creep acceleration and magnitude of strain is reduced by the fibers of the composites. It was also shown, through a comparison of the tensile and shear creep, that the creep of the composite subjected to in-plane shear loading is higher than that subjected to tensile loading.

Maksimov and Plume [2001] researched the effects of different fiber materials on the creep of the composite. This study involved examining the creep in the fiber direction of both Aramid and glass FRP (fiber-reinforced plastics). In this study the creep response was studied in the fiber direction and it was influenced more by the fiber properties than would be in the case stress relaxation in a bolted joint where creep is dominated by the matrix material in the through the thickness direction. They kept the volume fraction of fibers in the composite plates the same, 0.5, and then varied the ratio between the aramid and glass fibers. The following ratios of aramid fibers to glass fibers were used: 0.5/0, 0.4/0.1, 0.29/0.21, 0.18/0.32, 0.1/0.4, and 0/0.5. These tests were run for a period of 5.7 years and all began at a stress level of 700 MPa. What they discovered was that the pure glass FRP showed very little creep, while the pure aramid FRP showed a much greater creep over the same time period. The plates that were made from mixtures of glass and aramid fibers showed increased creep as the volume fraction of aramid fibers increased. It can thus be concluded that the partial replacement of aramid fibers with glass fibers makes it possible to reduce the creep behavior in aramid composites.

### 1.2.2 Creep Response in E-glass/Vinyl ester Composites

Scott and Zureick [1998] performed long-term testing on pultruded E-glass/vinyl ester composites under longitudinal compressive loading. These experiments were conducted at three different stress levels for a time period of up to 10,000 hours. The three stress levels used were 65-MPa, 129-MPa, and 194-MPa. These levels corresponded to 20%, 40%, and 60%, respectively, of the average value of ultimate compressive stress of short term tests performed using ASTM D3410 compression testing.

Scott and Zureick [1998] modeled their experimental results using the power law developed by Findley et al. [1976]. The simplest form of power law creep is given as:

$$\varepsilon(t) = \varepsilon_0 + mt^n \tag{1.6}$$

where $\varepsilon(t)$ is the total time-dependent creep strain, $\varepsilon_0$ is the stress-dependent and temperature-dependent initial elastic strain, $m$ is a stress-dependent and temperature-dependent coefficient, $n$ is a stress-independent material constant, and $t$ is the time after loading. The constants, m and n, are found from the experimental data by rearranging equation (1.6) and taking the natural log of both sides:

$$\log[\varepsilon(t) - \varepsilon_0] = \log(m) + n\log(t)\,. \tag{1.7}$$

Plotting the data on a logarithmic scale results in a straight line, where the intercept at $t = 1$ hour yields the value of $m$, while the slope of the line is the value of $n$. From the experimental data, they were able to develop a design equation for estimating the long-term longitudinal elastic modulus $E_L(t)$ for FRP composite materials manufactured using the pultrusion process with glass fiber reinforcement, primarily in the longitudinal direction, and a matrix similar to Dow Derakane 411™. They found $E_L(t)$ to be as follows:

$$E_L(t) = \frac{E_L^0}{1 + \frac{E_L^0}{E_t}(8760t)^n} \tag{1.8}$$

where $E_L^0$ is an initial longitudinal elastic modulus, $E_t$ is the time dependent component, and $t$ is time in hours.

## 1.3 Stress Relaxation due to Creep in Bolted Connections

Creep response in the direction perpendicular to the fibers is almost entirely dictated by the matrix material of the composite. In bolted connections, this will cause a phenomenon called stress relaxation. In bi-directional laminates the matrix is not reinforced in the through the thickness direction. Accordingly, its creep resistance is not greatly increased by the high creep resistance of the E-glass fibers.

Creep in the through-the-thickness direction is typically experienced by bolted composite connections. A composite panel bolted in the thickness direction is highly susceptible to preload loss, due to the viscoelastic nature of the resin, which dominates the transverse direction. If there is significant loss of preload due to creep, then the extent of total preload loss during the life of the joint must be established to determine whether the connection is adequate for the desired use.

Weerth and Ortloff [1986] performed extensive studies of bolted composite connections for use in military vehicles. In their tests, they sandwiched an E-glass/Vinyl ester hollow cylinder composite between 2 washers. Figure 1.2 shows the experimental setup that they used. The loss in preload over time was monitored through the use of washer load cells and a computer controlled data acquisition system.

Tests were run for periods of 1 day, 1 month, 1 year, 5 years, and 10 years. Preload losses for those time periods were 15, 28, 36, 41, and 43 %, respectively. They found that the resulting load data fit a power law form, and were able to predict the preload loss using a power law equation as follows:

$$P_{ir} = P_i t^{(1.482 \cdot 10^{-11} P_i^{2244} - 0.0497)}, \tag{1.9}$$

where $P_{ir}$ is the load in the connection at any time, $P_i$ is the initial preload, and t is the time in hours.

Adding stitching through-the-thickness of a composite can be used in bolted connections to improve its creep resistance. Pang and Wang [1999] studied the effects of

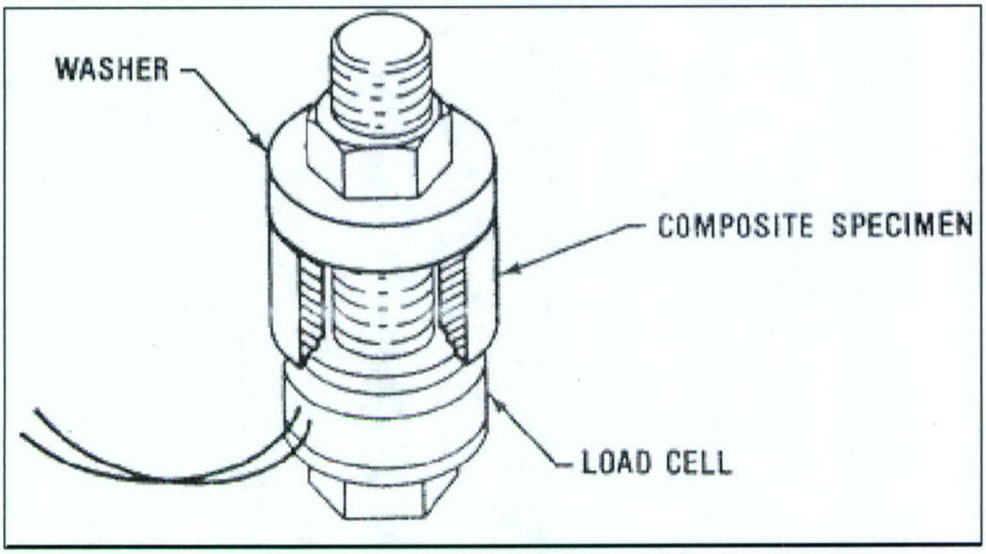



**Figure 1.2 – Bolted Composite Connection used by Weerth and Ortloff [1986]**

Through-the-thickness stitching on the creep resistance of a carbon/glass fiber/epoxy composite material. The composite was made up of 5 layers of bi-directional carbon fiber cloth sandwiched between two layers of bi-directional E-glass cloth. The matrix used was an epoxy resin under the designation of EPOCAST 50-A/946. Three types of threads were tested to determine whether thread strength had any effect The thread used in the tests was a cotton yarn (Tex = 300), a carbon yarn (Tex = 200), and a thick carbon yarn (Tex = 800). In addition, two stitch densities were considered. Spacing the stitching rows at 5 mm pitch produced high density stitching. Low density stitching was achieved using a row pitch of 10 mm. The composite was fabricated using a standard wet lay-up. Pang and Wang [1999] came to several conclusions based on their results. They found that stitching in the loading direction was very effective in reducing the creep rate. Out of the three fibers, the 800 Tex carbon fiber was the most efficient in reducing the creep response, followed by the 200 Tex carbon, and the 300 Tex cotton. They also found that the density of the stitching affects the creep rate, with the smaller stitch pitch more effective at reducing the creep response.

### 1.4 Temperature, Humidity, and Environment Effects on Creep

Chen and Kung [2002] evaluated the hygrothermal sensitivity of bolted composite joints. They used a numerical method to model a bolted double-lap T300/5205 composite joint. The joint consisted of a steel bolt, and a composite lay-up of $[\pm45/0_2]_{2S}$, with a thickness of 6.7 mm.. This was compared to experimental results from IM7/8552 specimens. The bolted connection was studied through the matrix dominated thickness direction. Both the numerical results and the experimental results showed that the clamp-up torque on the bolted connection was extremely sensitive to changes in temperature and humidity.

In order to simplify the model, only a single bolted composite joint was considered. The connection consisted of a plate of composite bolted through the center of the plate. Washers of varying thickness were used on either side to sandwich the composite and provide a relatively uniform loading condition. The following 5 assumptions were made in order to simplify the model.

1. Linear theory is applied to the bolt-axial 1-D case.
2. Washers enable the stress between them and the laminate to be treated as uniform.
3. Stress in each composite layer is considered uniform through the thickness.
4. Stress relaxation/creep is ignored.
5. Temperature and humidity effects act independently of each other.

From this analysis, Chen and Kung [2002] concluded that hygrothermal sensitivity was a large factor when dealing with bolt clamping force. They also found that the washer to bolt diameter ratio was the major geometric factor when designing a composite joint. They went on to say that long-term effects such as stress relaxation and creep could be studied to provide further design guidelines as they pertain to the hygrothermal sensitivity of bolted composite connections.

Guedes et al. [2000] investigated the long-term behavior of composite materials. The long-term behavior of composites can be influenced by both physical and chemical aging. The resin and the interface between the fiber and resin are the elements that influence the time dependant properties of the composite the most. They performed creep and creep recovery, relaxation and ramp loading tests on a T300/5208 laminate at room temperatures. A time period of about 14 months was used in the testing. They also investigated the environmental factors coupled with the mechanical loading of a composite. They used a quasi-unidirectional glass/epoxy composite for these groups of tests. The material was tested at 75 degrees Celsius, at several different humidity levels (0%, 24%, 34%, 73%, and 92%

relative humidity). Two different exposure times were used, 1600 hours and 3100 hours. They found that the stress-strain response was completely reversible after the absorption/desorption cycle, suggesting no micro-structural damage was done. They also found that the quasi-static mechanical response was very dependent on exposure time.

### 1.5 Methods of Measuring Creep and Stress Relaxation

ASTM standards contain a few methods of measuring both creep and stress relaxation. Testing can be performed in tension, compression, bending, and torsion, depending on which load case is closest to actual application. Of particular note are ASTM F1276-99 [1999], ASTM D2990-01 [2001], and ASTM E 328-02 [2002].

ASTM F1276-99 describes a method to test the creep relaxation of laminated composite gasket material. A compressive stress is applied to the material between two platens. The stress is applied using a nut and bolt. The relaxation is measured using a dial indicator. The dial indicator is set to zero when no load is applied to the bolt. The bolt is then tightened to the desired stress level and a reading is taken ($D_0$). The dial indicator is then removed, and the specimen fixture is then placed in an oven for 22 hours at 100 ± 2 °C. The fixture is then cooled to room temperature, and the dial indicator is reattached and zeroed. The nut is loosened and a reading is taken with the dial ($D_f$). The percent relaxation is then calculated by:

$$relaxation,\% = [(D_0 - D_f)/D_0]\times 100. \qquad (1.10)$$

ASTM D 2990-01 gives methods for testing tensile, compressive, and flexural creep and creep-rupture of plastics. The method consists of applying the desired load, and then measuring the extension or compression of the specimen at specific time intervals of 1, 2, 12, and 30 minutes, 1, 2, 5, 20, 50, 100, 200, 500, 700, and 1000 hours. Temperature and relative humidity is also recorded during testing to monitor environmental factors. Strain is reported for tension or compression tests by dividing the extension or compression, at given times, by the initial gage length. Maximum strain at the midspan is calculated for flexural tests.

ASTM E328-02 provides methods of testing stress relaxation in materials under tension, compression, bending, and torsion loads. The testing requires the specimens to be subjected to an increasing load until the desired initial strain is attained. Once the initial strain is reached, the specimen is constrained, and the initial stress can be calculated from the initial load. Load readings are continuously taken for the duration of the test. Plots are then made of the stress over time.

Stain gages may be used to measure the strain in the specimen over time during experimentation, but they present problems when working with plastics. The major concerns are local heating due to the current in the gage, and the difficulty in aligning the axis of the gage so that different components of the strain are completely separated. Strain gages are also a concern in long-term testing due to creep of the adhesive used to bond the gage to the specimen. For these reasons, using an extensometer is usually the best way to measure the strain during creep tests.

## 1.6 Analytical Creep Models

Several methods have been used over the years to model the creep behavior of materials. According to Findley et al. [1976], Andrade studied the creep of lead wires under constant load, and developed the first creep law as follows:

$$l = l_0(1 + \beta t^{1/3})e^{kt}, \tag{1.11}$$

where $l_0$ and $l$ are initial and current lengths of the specimen, $t$ is the time under load, and $\beta$ and $k$ are stress dependent constants.

Steady state creep, in particular, has been studied in great detail. Bailey and Norton [Findley et al, 1976] developed an empirical equation to describe steady state creep under low stresses,

$$\dot{\varepsilon} = k\sigma^p, \tag{1.12}$$

where $\dot{\varepsilon}$ is the steady state creep, $\sigma$ is the applied stress, and $k$ and $p$ are material constants. This equation is known as the power law or Norton creep law. An exponential law to describe the steady state creep proposed by Ludwick was also described in Findley et al. [1976] given as:

$$\dot{\varepsilon} = ke^{\sigma/\sigma^+}, \tag{1.13}$$

where $k$ and $\sigma+$ are both material constants. This equation, however predicts a finite strain rate when the stresses vanish, whereas equation (1.12) predicts it to be zero. To resolve this, Soderberg [Findley et al., 1976] proposed the following equation

$$\dot{\varepsilon} = c(e^{\sigma/\sigma+} - 1), \tag{1.14}$$

where $c$ and $\sigma+$ are material constants.

Creep in polymers has also been examined at great length. Leaderman [Findley et al., 1976] found the following relationship for the creep of bakelite under constant torque:

$$\varepsilon = \varepsilon^0 + A\log t + Bt, \tag{1.15}$$

where $\varepsilon^0$, $A$, and $B$ are functions of stress, temperature, and material. Phillips [Findley et al., 1976] found that creep could be described by:

$$\varepsilon = \varepsilon^0 + A\log t, \tag{1.16}$$

if the strain rate goes to zero as $t$ approaches infinity. The power law given in equation (1.6), yields very good agreement to experimental results, over most other models [Findley et al, 1976]. This is due in part to the fact that the creep of polymers starts at a very rapid rate after loading, and then proceeds at a decreasing rate. Findley's model accurately describes this behavior, whereas equations (1.15) and (1.16) do not. For this reason, Findley's creep model is often used to describe creep of most plastics.

## 2. TEST OVERVIEW AND FIXTURES

A series of tests were conducted to study the effects of stress relaxation on E-Glass/vinyl ester composite/aluminum hybrid connections. Operational procedures and results of these tests are discussed in this section. The goal is to develop a database, which quantifies the stress relaxation in hybrid connections. One group of tests was performed utilizing a compression block fixture to quantify the stress relaxation of the composite subjected to a relatively uniform stress state through the thickness of the composite material. The other testing consisted of a composite plate bolted to an aluminum plate using a single bolt passing through the center of the plate. The objectives are to study the effects of stress concentrations and bolt re-torquing on stress relaxation, the effects of tapered versus non-tapered bolts and the effects of temperature and humidity. All test specimens were cut from E-glass/vinyl ester composite panels, fabricated at the University of Maine Crosby Laboratory, using a VARTM (Vacuum Assisted Resin Transfer Molding) process. Tests were run for a period of at least 3 months to study the primary stress relaxation effects.

### 2.1 Test Methodology

A summary of the tests performed in this study is given in the test matrix shown in Table 2.1. Tests include a compression block series, where the composite material alone is studied at two different preload levels of 10,000 and 5,000 pounds, as summarized in Table 2.1a. A series of reloading tests were performed on single, isolated bolt composite/aluminum hybrid connections for three different panel thickness, ½", ¾", and 1". Six different reloading cases were run for this group, as presented in Table 2.1b. Two preload levels were examined on the ½" and the 1" thick laminates. Another series of tests, summarized in Table 2.1c are done on single, isolated bolt composite/aluminum hybrid connections using tapered headed bolts at two different preload levels, to compare their response to non-tapered bolts. Single bolt composite/aluminum hybrid connections are also examined under various temperature and humidity conditions (see Table 2.1d). Three different humidity conditions were used, as shown in the test matrix, where C1 is at 150°F, 90% RH, C2 submerged in water, and C3 is at room temperature and 50% RH. The temperature study involves heating and cooling a specimen at certain intervals, with one at 50% RH and the other submerged in water. These environmental tests are discussed in greater detail in Section 2.5.

**Table 2.1 - Test Matrix**

2.1a

| | 1/2 inch | | |
|---|---|---|---|
| | Preload (lbs) | Stress (psi) | # of Tests |
| Compression Block | 10000 | 2500 | 1 |
| | 5000 | 1250 | 1 |

2.1b

| | | Panel Thickness | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1/2 inch | | | | 3/4 inch | | 1 inch | | | |
| | tightening cycle | Preload (lbs) | # of tests | Preload (lbs) | # of tests | Preload (lbs) | # of tests | Preload (lbs) | # of tests | Preload (lbs) | # of tests |
| Single Bolt, Reloading, caphead bolt test | no reloading | 5000 | 2 | 2500 | 1 | 10000 | 2 | 15000 | 1 | 7500 | 1 |
| | 3 days | 5000 | 2 | 2500 | 1 | 10000 | 2 | 15000 | 1 | 7500 | 1 |
| | 1 week | 5000 | 2 | 2500 | 1 | 10000 | 2 | 15000 | 1 | 7500 | 1 |
| | 2 weeks | 5000 | 2 | 2500 | 1 | 10000 | 2 | 15000 | 1 | 7500 | 1 |
| | 3 days twice | 5000 | 2 | 2500 | 1 | 10000 | 2 | 15000 | 1 | 7500 | 1 |
| | 3 days thrice | 5000 | 2 | 2500 | 1 | 10000 | 2 | 15000 | 1 | 7500 | 1 |

2.1c

| | | 3/4 inch | |
|---|---|---|---|
| | Preload (lbs) | tapered | caphead |
| Single Bolt, tapered vs. caphead bolts | 10000 | 3 | 1 |
| | 5000 | 2 | 2 |

2.1d

| | | 3/4 inch | |
|---|---|---|---|
| | Conditioning Cycle | Preload (lbs) | # of tests |
| Environmental Tests using caphead bolts | Control at C3 | 10000 | 1 |
| | C1, tighten, C2 | 10000 | 1 |
| | C1, tighten, C3 | 10000 | 1 |
| | Tighten, creep for 1 week at C3, then C2 | 10000 | 1 |
| | Tighten, C2 for 1 month, C3 for 1 month, then repeat | 10000 | 1 |
| | Temperature Study | 10000 | 1 |

All tests were run for at least 3 months, with test data being collected and analyzed periodically. All four groups of tests were conducted at the same time through the use of a data acquisition system. Analysis of the data from the reloading test is used to determine if retorquing the bolts helps to lower the stress relaxation in the composite over time. Analysis of the tapered versus non-tapered tests is used to ascertain the effect tapered bolts have on the stress relaxation, as compared to non-tapered bolts. Environmental tests were performed to assess the effect of temperature and moisture content on the stress relaxation.

### 2.2 Compression Block Test and Fixture

Compression block tests are used to quantify the transverse stress relaxation of the E-glass/vinyl ester composite under relatively uniform stress. The test fixture consists of two large steel blocks, with a composite sample being compressed between the two, as shown in Figure 2.1. A photograph of the fixture and various components is shown in Figure 2.2. The fixture has a square cross-sectional area, with dimensions of 6" by 6". The bottom half is 2.9 inches high, while the top half is 1.8 inches high. Bolts at its four sides impart the compression load. ½" diameter load washers (Omega, LC900 series) are used to read the applied load on each of the four bolts. A Blackhawk dial torque wrench with a maximum capacity of 175 ft lb, is used to tighten the bolts to the desired preload.

### 2.2.1 Compression Block Test Article

The compression block test article is a square 2 x 2 inch specimen with constant thickness, t, of ½ inch. It was cut from a 2 x 4 foot panel of E-glass/vinyl ester with a quasi-isotropic lay-up; $([(\pm\ 45)_f,(0/90)_f]_4)_S$. More details regarding material constituents are presented in Section 2.5.2.

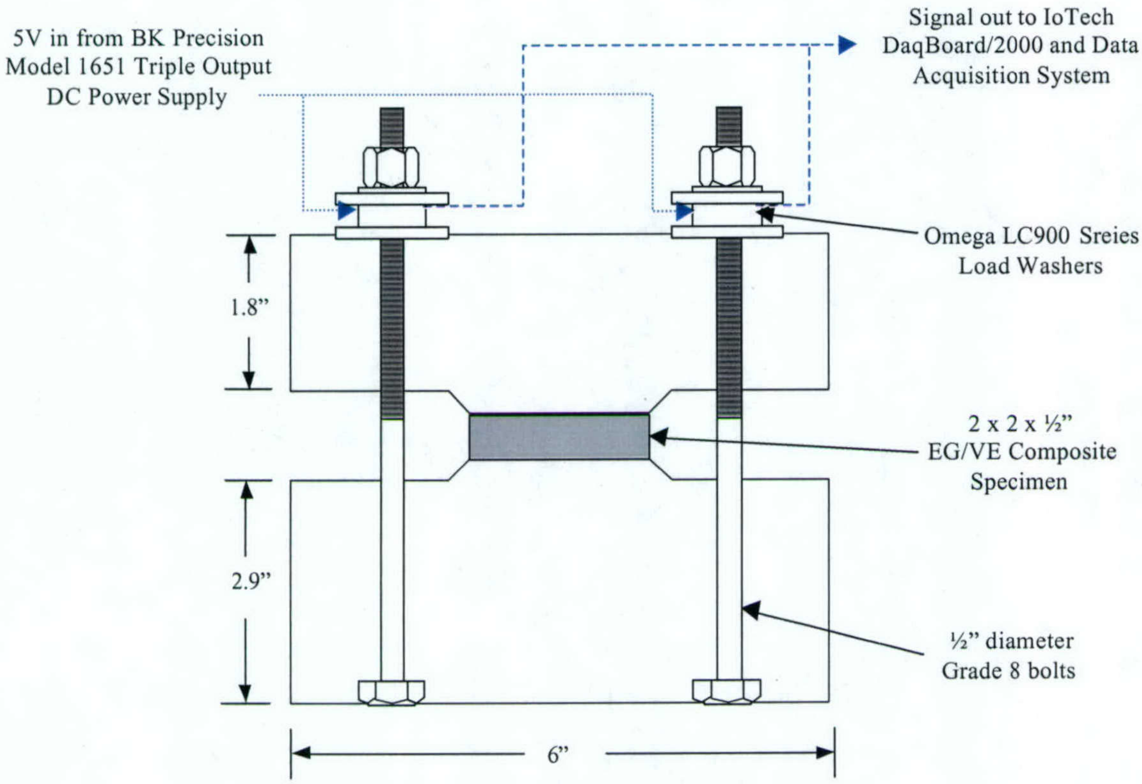



**Figure 2.1 - Compression Block Test Schematic**

### 2.2.2 Compression Block Test Procedures

Compression block tests were automated using an IOTech data acquisition system with a 16-bit resolution and a computer code called DAQFI. The DAQFI program was created at UMaine, and a module was written specifically to run the stress relaxation tests. The configuration interface of the program is described in more detail in Section 2.8.8. The load washers were calibrated through the data acquisition system to allow direct recording of the output in pounds of preload.

The 2 x 2 inch composite specimen is placed between the two steel plates of the compression block, and the bolts are tightened using a dial torque wrench. All four bolts are loaded to the same value, as much as practically possible. Precise loading is difficult,

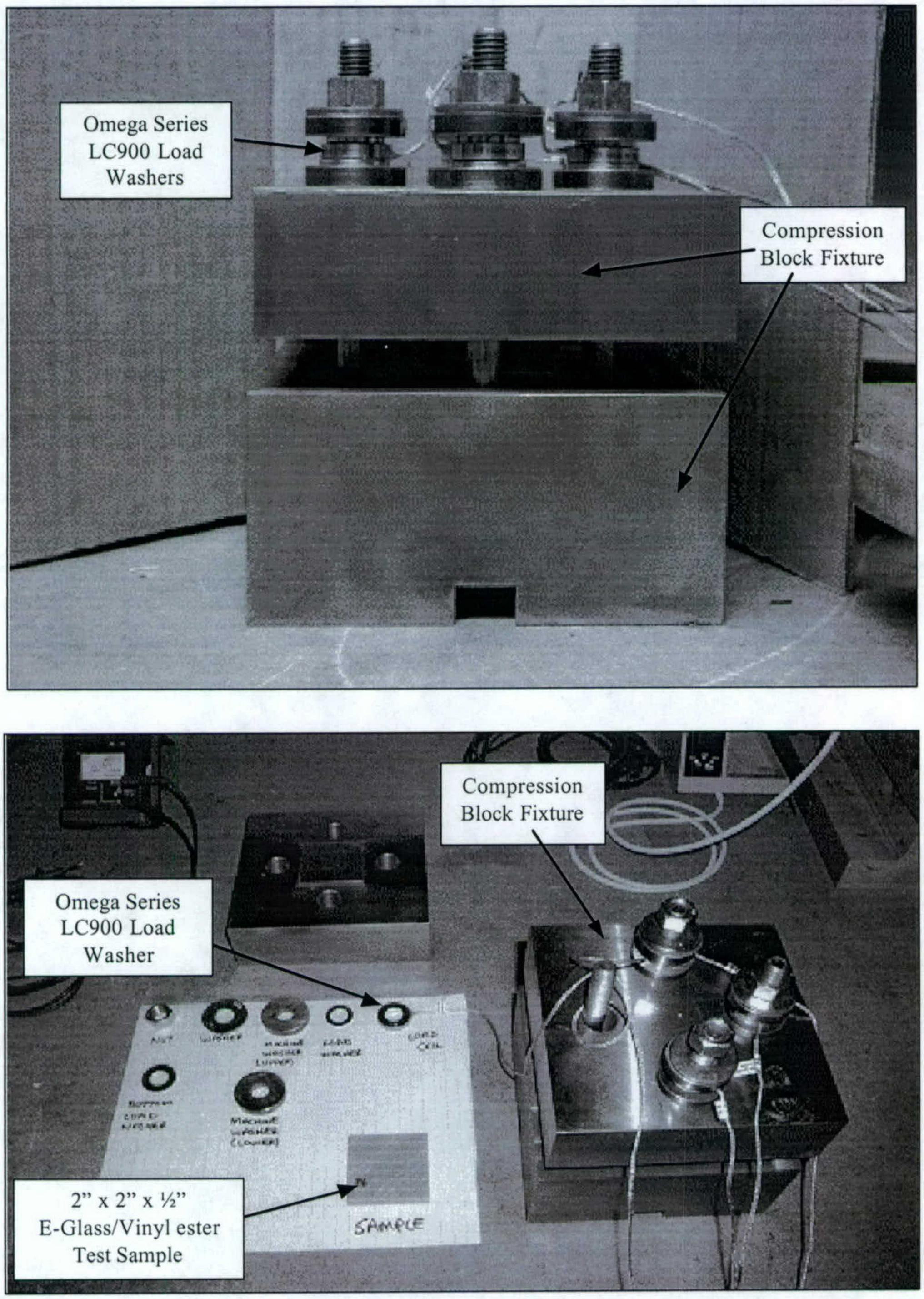



**Figure 2.2 - Photographs of the Compression Block Fixture and various Components.**

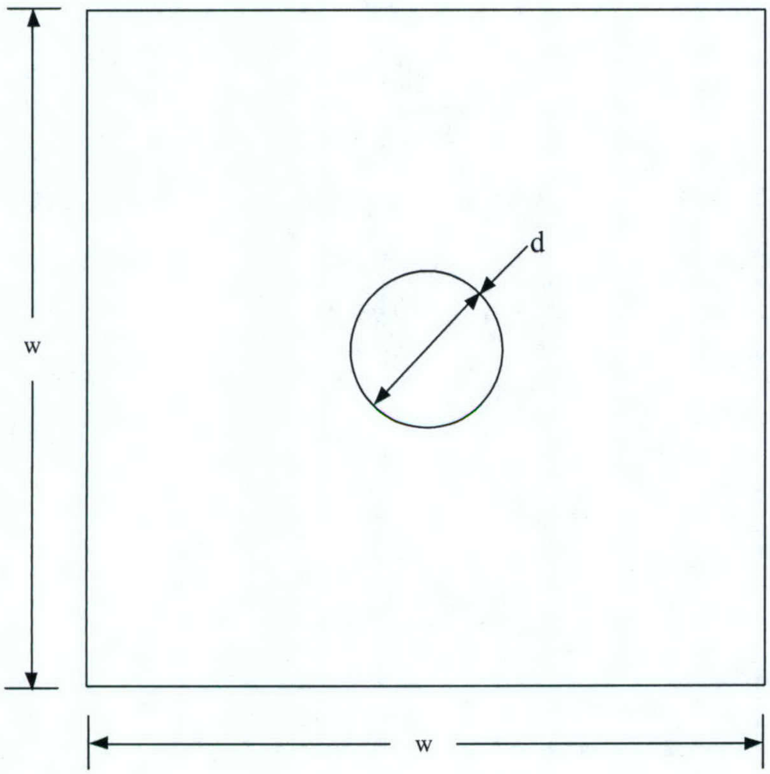
however, due to the geometry of the fixture, and as one bolt is tightened it affects those around it, either increasing or decreasing the load in the other bolts. The bolts are therefore tightened in a systematic manner to minimize this difficulty. The tightening procedure starts as one bolt is tightened to approximately ¼ of the desired preload. The bolt on the opposite side from the first bolt is then tightened to approximately ¼ of the preload. After this, the two remaining bolts are tightened to ¼ of the preload. This process is repeated by tightening each bolt incrementally until all bolts read the desired load within a few percent. A single data point indicating the starting load in each bolt is logged into the data file, and the data acquisition program is started and left to record the data over the 3 month time period. The data acquisition program is set to take data according to the schedule given in Table 2.2.

**Table 2.2 - Data Acquisition Recording Schedule**

| Test Time | Sampling Period |
|---|---|
| Start to 1 hr. | every minute |
| 1 hr. to 24 hrs. | every 10 minutes |
| 24 hrs. to 30 days | every 30 minutes |
| 30 days to 4 weeks | every 7 days |
| 4 weeks to end | every 14 days |

### 2.3 Single Bolt, Reloading Hybrid Connection Test

Single bolt hybrid connection tests are used to study the effects of reloading the composite/aluminum connection on the stress relaxation of a hybrid connection. Figure 2.3 shows an overview of the test specimen, as well as a schematic of the fixture used for testing. The maximum pressure distribution encountered during the life of the test was determined by placing a piece of pressure sensitive film at the composite/aluminum plate interface as shown in Figure 2.3. This data is used to assess the stress distribution due to the bolt load and can be used to evaluate the watertight integrity of a seal in the connection for applications on ship hulls.




**Specimen Dimensions**

| d | t | w |
|---|---|---|
| 1/2" | 1/2" | 5" |
| 3/4" | 3/4" | 7.5" |
| 1" | 1" | 10" |

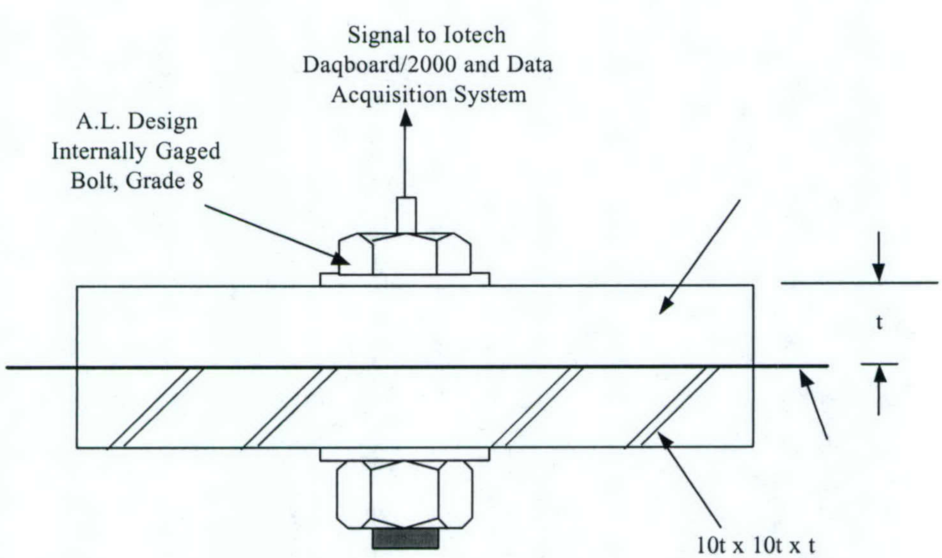



**Figure 2.3 - Single Bolt Test Specimen and Fixture Schematic**

The test article geometry was the same for both the reloading tests, and the tapered bolts vs. non-tapered bolts tests. A photograph of this test fixture is shown in Figure 2.4. Three different specimen thicknesses were tested during this group of tests, ½, ¾, and 1 inch thick. The composite specimens have a quasi-isotropic lay-up, a length equal to 10 times the thickness, and have a hole in the center equal to the bolt diameter, d. The lay-up for the ½", ¾", and 1" thick panels are $([(\pm 45)_f,(0/90)_f]_4)_S$,$([(\pm 45)_f,(0/90)_f]_6)_S$, and $([(\pm 45)_f,(0/90)_f]_8)_S$ respectively. The plates are bolted together using internally gaged bolts (AL Design Models ALD-BOLT-.5" X 2" LONG, ALD-BOLT-.75" X 2.5" LONG, and ALD-BOLT-1" X 3.5" LONG), used to monitor the load in the connection.

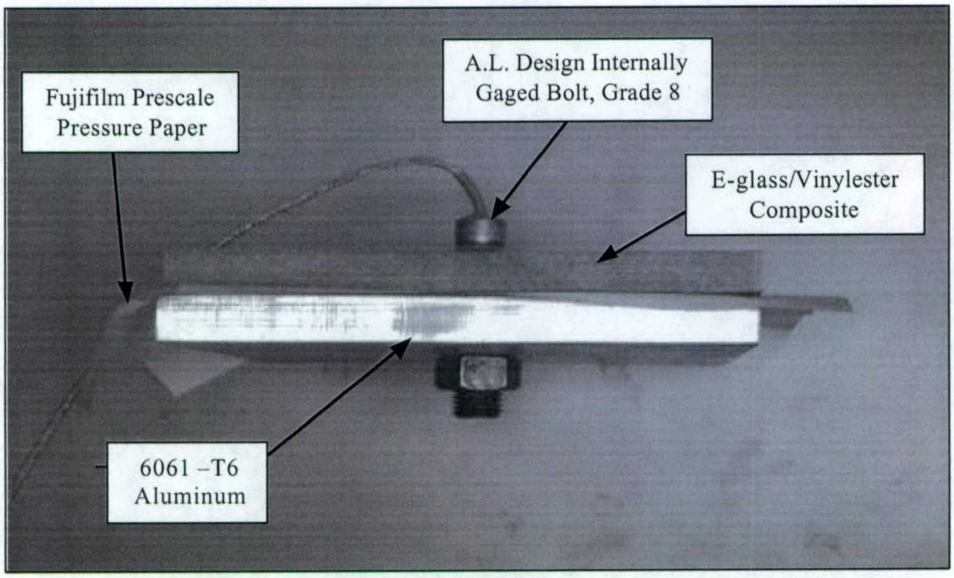



**Figure 2.4 - Single Bolt Hybrid Connection Fixture**

Six separate test fixtures were run simultaneously for panel thickness of ½", ¾", and 1". One fixture is used as a control test, with no reloading of the connection. The other five fixtures are loaded, and then reloaded according to the schedule given in Table 2.3.

**Table 2.3 - Bolt Reloading Schedule**

| Re-torquing Schedule |
|---|
| 1: control, no reload |
| 1:reload after 3 days |
| 1:reload after 3 days twice |
| 1:reload after 3 days thrice |
| 1:reload after 1 week |
| 1:reload after 2 weeks |

The internally gaged bolts, supplied by A.L. Design Inc., are used to measure load during the reloading tests. Three sizes of bolts are used in these tests, ½ inch diameter, ¾ inch diameter, and 1-inch diameter. The bolts are described in more detail in Section 2.8.2. Prescale pressure paper, supplied by Fujiflim, is inserted between the aluminum plate and the E-glass/vinyl ester composite. The pressure paper has a center hole cut out that is the same diameter as the bolt being used. More details regarding the pressure paper can be found in Section 2.8.7.

The bolts were tightened using the Blackhawk dial torque wrench. The 1 inch thick specimens used a torque multiplier with the torque wrench to load the bolts to torques over 175 ft lbs. The torque multiplier used is a Williams No. Tm-750 LW x 4. It is capable of a maximum torque output of 1000 ft. lbs. with a maximum torque input of 275 ft. lbs. The load relaxation data is collected through the DAQFI data acquisition system similar to the procedure described in the compression block tests.

### 2.3.1 Single Bolt, Reloading, Test Articles

The geometry of the single bolt test specimen was chosen to insure that the plate was wide enough to observe the entire pressure distribution at the composite/metal interface of the bolts due to the stress intensification below the bolt head. It was determined using a finite element model of the geometry used in these tests, that pressure effects can be seen at a radial distance of, at most, 3 times the bolt diameter from the center of the bolt line. Choosing a test article that is 10 times the bolt diameter along its length enables the entire pressure distribution to be seen with the use of pressure paper. 6061-T6 aluminum plates, of the same dimensions as the composite plate, are bolted to the composite specimens. The material properties of the metal and composite are discussed in detail in the material section, Section 2.6.

Parameters in this group of tests include varying preload, composite thickness, and the time between retightening bolts, as given in the test matrix, Table 2.1b. All 6 specimens for each series of tests were cut from the same panel of E-glass/vinyl ester composite. All specimens were cut and drilled using diamond coated, water lubricated tooling.

### 2.3.2 Single Bolt, Reloading Test Procedures

Similar to the load washers, the internally gaged bolts also contain full bridge strain gages that are used to read the applied load. They are connected in the same manner as the load washers so that the data can be read through the DAQFI data acquisition system. Details of the instrumentation are given in Section 2.8.

As with the compression block test, all the bolts were calibrated to allow direct reading of the bolt load by the data acquisition system. Pressure paper is then cut to the approximate dimensions of the specimens. A hole is cut in the center the same size as the bolt hole in the composite. The pressure paper is inserted between the E-glass/vinyl ester composite and the aluminum in the connection.

Once the specimens have been cut, holes drilled, pressure paper cut, and the bolts connected to the power supply and data acquisition system, the test articles are finally ready to load to the desired preload. In order to load a bolted connection, the connection is held relatively stationary during tightening. The torquing fixture is shown in Figure 2.5.

The specimens are tightened in the following manner. The first specimen is placed in the tightening fixture to hold it in place. Nickel based Locktite anti-seize is applied lightly to the end of the bolt. The dial torque wrench is then used to apply load to the bolts. A data file is opened, and the load is monitored through the monitoring feature of the DAQFI software. Once the bolt is tightened to the desired preload, the log button is hit in the software, and a single data point is logged. This process is repeated for each test article. Once all bolts have been tightened, the run button is activated in the DAQFI software, and the computer is left to collect data at the prescribed increments.

The test procedure includes periodic retorquing of the bolts, according to Table 2.3, in the same manner they were initially tightened. The computer program is stopped before the reloading process is started, and the load monitoring section of the program is activated before any reloading. A single data point is then logged after reloading by activating the log button in the program. This same process is repeated during each reloading process.

Once all bolts have been reloaded and data points have been logged for each, the run button is activated and the software is left to automatically collect data. The software is written to append the new data set to the previous data set, unless the program is completely shut down and restarted.

At the end of the 3 month period, the final data set is collected and reduced. For each single bolt connection fixture, a plot of load vs. time is made. The reloading cycle is also recorded. This data is analyzed to determine the effects of periodic reloading on the stress relaxation in the hybrid connections. The relaxation parameters are modeled according to a power curve fit to the data. This is described in details in the results, Section 3.

### 2.4 Single Tapered Head Bolt Tests

The single tapered head bolt tests are designed to study the effects of tapered bolts vs. non-tapered bolts on the stress relaxation in the bolted hybrid connections. The test fixtures used for this group of tests are the same type as those used for the single bolt reloading tests. Figure 2.6 shows a side view and a top view of the tapered bolt fixture. They consist of a square plate of aluminum bolted to a square plate of the E-Glass/vinyl ester composite. Load washers were used in this case to monitor the applied load, since instrumented tapered head bolts were not available. Four test fixtures were run at once, two bolted with tapered bolts, and two bolted with non-tapered bolts.

Only the ¾" panel thickness was used for this group of tests. This thickness was chosen because it is the average thickness of the test articles being studied in the reloading tests.

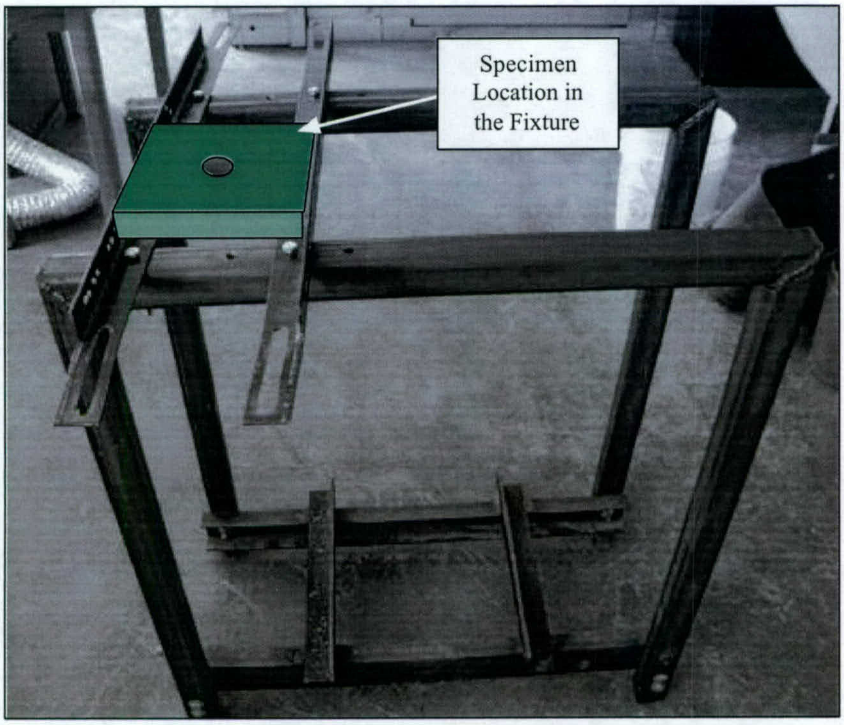



**Figure 2.5 - Photographs of Torquing Fixture**

This group of tests utilizes ¾" load washers (Omega series LC900) to monitor the bolt load in the connection. The biggest disadvantage of the load washers is that the lead wires are very fragile.

These tests are set up in exactly the same manner as the reloading tests, presented in Section 2.3. As with the other tests, the load is applied by using the dial torque wrench. Pressure paper was again used between the aluminum and the E-glass/vinyl ester composite to monitor the stress distribution.

### 2.4.1 Single Tapered Head Bolt Test Article

The test article geometry for this group of tests is very similar to that used for the single bolt reloading test. The countersunk hole, required for the tapered bolt, has an included angle of 82 degrees, as shown in Figure 2.7. The lay-up is quasi-isotropic, as before, and material specifications are provided in Section 2.6. These test articles were bolted to aluminum plates, with the same dimensions as the E-glass/vinyl ester composite plates, but without the countersunk hole.

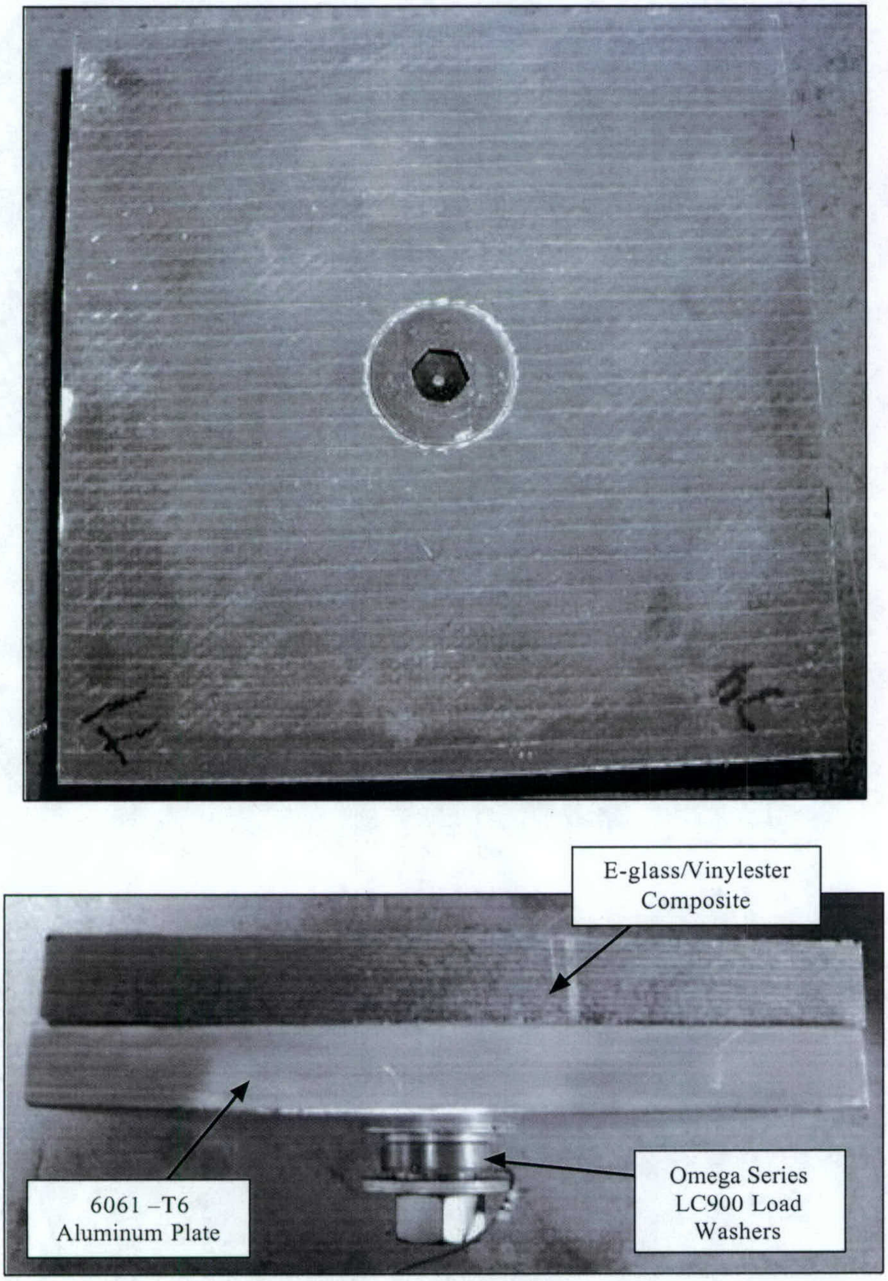



**Figure 2.6 - Tapered Bolts Fixture (Top and Side Views)**

### 2.4.2 Single Tapered Head Bolt Test Procedure

The procedure for this group of tests is very similar to that of the single bolted, reloading tests. There was no reloading of these fixtures however, during this series of tests. For this group of load washers, the recommended 5-volt excitation is used. As with the other tests, the load washers were calibrated to make them direct reading of the applied load through the data acquisition system Once all four load washers are connected to the power supply and the data acquisition system, the connections are ready to be assembled and loaded. The fixtures are placed together with the bolts, and pressure paper between the E-glass/vinyl ester composite and the aluminum. The load washers are placed at the end of the bolt, and mounted between two mounting washers so that the load applied to the washer is uniform.

The tightening fixture is used to hold the bolted connections in place while loading is being done. The load monitoring function of the DAQFI program is activated. One fixture is loaded to the desired preload and a single data point is recorded using the log button in the software. This process is repeated for each connection until all four have been loaded. At this time, the run button is activated and the DAQFI program is left to automatically collect data.

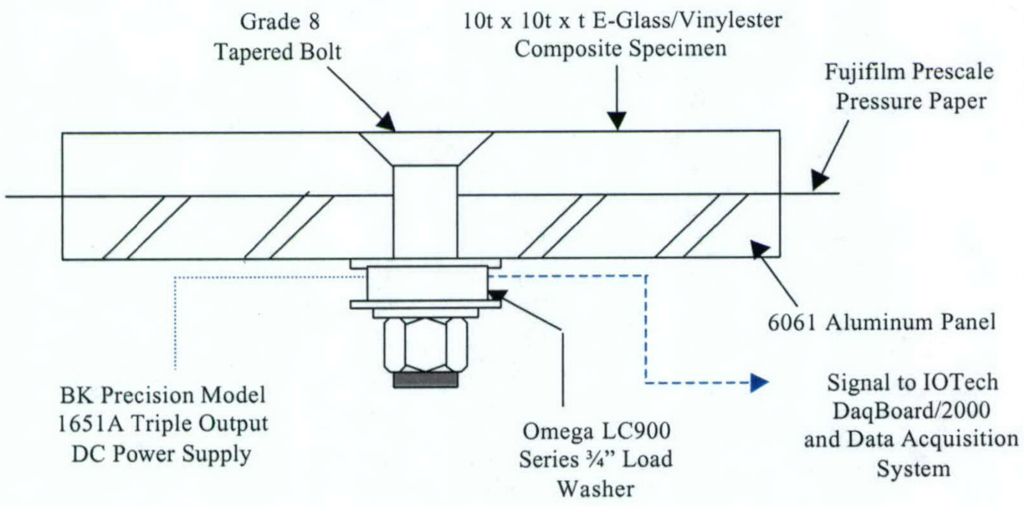



**Figure 2.7 - Tapered Bolt Test Article**

### 2.5. Environmental Testing

The environmental tests were used to study the effects of various different environmental conditions on the stress relaxation of a single bolt composite/aluminum hybrid connection. The same type of test articles used for the single bolt reloading tests were used for the environmental tests. Only one thickness, ¾", was tested. The dimensions of both the E-glass/Vinyl ester composite and the aluminum plate for these tests was 7.5 inches by 7.5 inches. A schematic and photograph of this test fixture is shown in Section 2.3, Figures 2.3 and 2.4. Internally gaged bolts were used for this series of tests.

The testing procedure for this series of tests was similar to the single bolt reloading test procedure, as described in Section 2.3.2. The only difference was that none of the test specimens were reloaded during the environmental testing. This group of tests was also run for a time period of at least three months.

Various conditioning cycles were examined, as summarized in Table 2.1d. One specimen, C1, is used as a control, and is held at room temperature and 50% RH. Another specimen, C2, is conditioned for 1 month at 150°F and 90% RH, loaded, and then held at room temperature and 50% RH. The third specimen in this group, C3, is conditioned for 1 month at 150°F and 90% RH, loaded, and then submerged in water at room temperature. The next specimen, C4, is tightened, allowed to creep at room temperature and 50% RH for 1 week, then submerged in water at room temperature. A fifth specimen, C5, is loaded, submerged in water at room temperature for 1 month, then removed and held at room temperature at 50% RH for 1 month, and then cycled. These tests are used to examine the effects of humidity on the connection, while holding temperature constant.

The final test in this group, C6, is designed to study temperature effects. The test article is loaded and allowed to creep for 1 week at room temperature. The temperature is then dropped to 40°F for half a day. It is then held at room temperature again for 1 day, and then at 90°F for half a day. This whole process is done at 50% RH. The same test is then run with the test article submerged in water with the same temperature variation and duration.

### 2.6 Material Specifications

Materials used in testing are described in this section. The composite specimens were made from Dow Derakane 8084 vinyl ester epoxy resin reinforced with E-glass fiber. The aluminum used was a standard grade 6061-T6. What follow are some of the material properties of the various materials used.

#### 2.6.1 Metallic Components

The metallic plates are fabricated of aluminum Grade 6061 – T6. The aluminum plates are used in single bolt reloading tests, tapered bolts vs. non-tapered bolts testing, and the environmental testing. Table 2.4 lists some of the properties of this alloy.

**Table 2.4 – Aluminum 6061-T6 Properties (matweb.com)**

| Physical Properties | SI | US Customary |
|---|---|---|
| Density | 2.7g/cc | 0. 0975 lb/in³ |
| **Mechanical Properties** | **SI** | **US Customary** |
| Hardness, Brinell | 95 | 95 |
| Tensile Strength, Ultimate | 310 Mpa | 45 ksi |
| Tensile Strength, Yield | 275 Mpa | 40 ksi |
| Elongation @ break | 12% | 12% |
| Poisson's Ratio | .33 | .33 |
| Modulus of Elasticity | 69 Gpa | 10008 ksi |
| Shear Modulus | 26 Gpa | 3771 ksi |
| Shear Strength | 205 Mpa | 29,733 psi |
| Fatigue Strength | 95 Mpa | 13,779 psi |

#### 2.6.2 Composite Specimens

The composite specimens used in this study were fabricated at the Crosby Laboratory, University of Maine, using a VARTM process. They consist of Dow Derakane 8084, which is an epoxy vinyl ester resin. The composite is reinforced with an E-glass knit cloth procured from Brunswick Technology, Inc. The cloth is either a 24 oz. 0/90 cross-ply, or a 24 oz. ±45 bi-axial. Properties of Dow Derakane 8084 are listed in Table 2.5, while the E-glass cloth properties are listed in Table 2.6.

The lay-up used for the test specimens is quasi-isotropic, $([(\pm 45)_f,(0/90)_f]_n)_S$, where n varies according to the panel thickness. The number of layers, n, is either 4 for the ½" thick panels, 6 for the ¾" thick panels, or 8 for the 1" thick panels. The panels were fabricated with approximate dimensions of 50" x 24". Test coupons are then mapped out of each panel and cut to the specifications given in Sections 2.2, 2.3, 2.4, and 2.5. All test coupons for one series of tests are cut out of the same panel. Figures 2.8, 2.9, and 2.10 show the general panel and specimen layout for each of the three panel thicknesses used.

**Table 2.5 - Dow DERAKANE 8084 Epoxy Vinyl ester Resin (Dow Chemical Company)**

| Physical Properties | SI | US Customary |
|---|---|---|
| Viscosity | 350 cps | 73.1 (lbf s)/ft$^2$ |
| Specific Gravity | 1.02 | 1.02 |
| **Mechanical Properties** | **SI** | **US Customary** |
| Barcol Hardness | 30 | 30 |
| Tensile Modulus | 3.17 GPa | 4.6x10$^5$ psi |
| Tensile Strength, Yield | 69 - 76 MPa | 10 – 11,000 psi |
| Elongation @ break | 10 - 12 % | 10 - 12 % |
| Flexural Modulus | 3.03 GPa | 4.4x10$^5$ psi |
| Flexural Strength | 110 - 124MPa | 16 – 18,000 psi |
| Heat Distortion Temperature | 82 °C | 180 °F |

**Table 2.6 – E-Glass Cloth Properties Isotropic**

| Physical Properties | SI | US Customary |
|---|---|---|
| Extensional Modulus $E_1^f$ | 7.24E+10 Pa | 1.05E+07 psi |
| Shear Modulus $G_{12}^f$ | 3.03E+10 Pa | 4.40E+06 psi |
| Poisson's ratio $\eta_{12}^f$ | 2.00E-01 | 2.00E-01 |
| Tensile Strength $+S_1^f$ | 1.86E+09 Pa | 2.70E+05 psi |
| Compressive Strength $-S_1^f$ | -1.10E+09 Pa | -1.60E+05 psi |
| Density $\rho^f$ | 2.55E-02 kg/ m$^2$ s$^2$ | 9.40E-02 lb/in$^2$ |
| End Area | 4.33E-07 m$^2$ | 6.71E-04 in$^2$ |

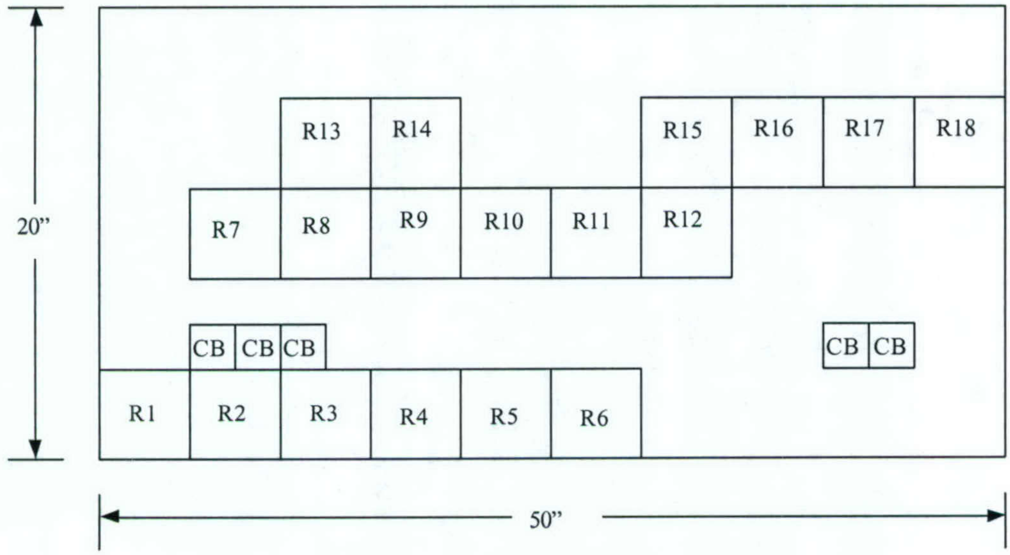



**Figure 2.8 - ½" Thick Panel Layout**

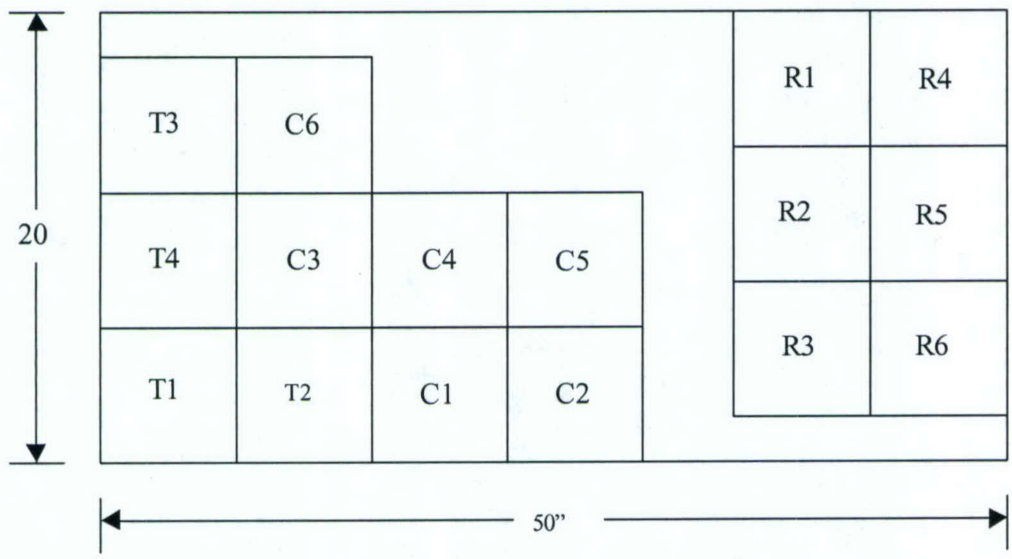



**Figure 2.9 - ¾" Thick Panel Layout**

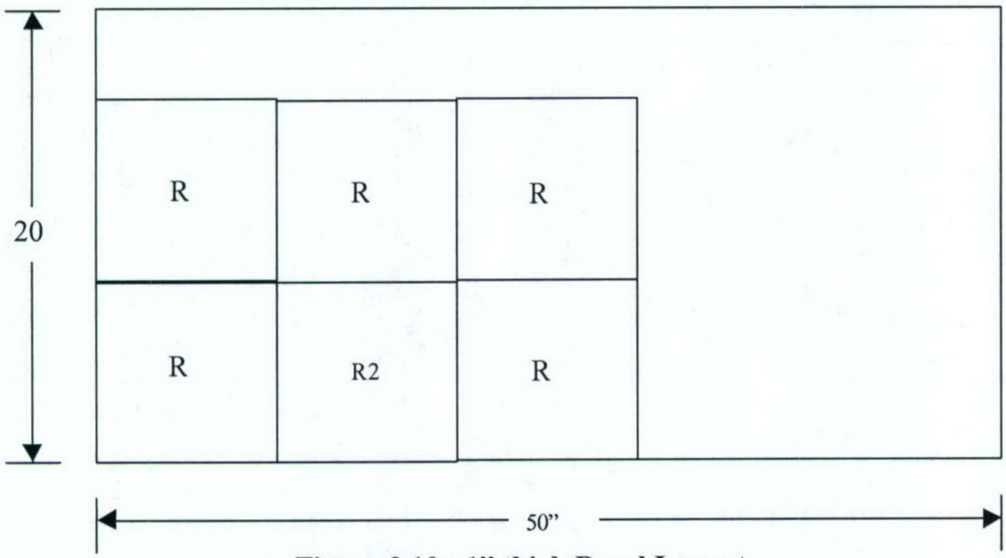



**Figure 2.10 - 1" thick Panel Layout**

A ½" thick panel is large enough to cut several groups of test articles from one panel. Panels labeled starting with R are for the single bolted reloading tests, while the ones marked with CB are for the compression block tests. Specimens 1 through 6 are for one group of tests, 7 through 12 for a second, and 13 through 18 for a third. The remaining material is put aside for material testing.

The ¾" panel was used for several different tests. Specimens marked with an R are again used for the single bolt reloading tests, those marked with a T are for tapered bolts versus non-tapered bolts, and those marked with a C are for environmental conditioning tests. Extra material is again set aside for material testing. A total of three ¾" panels were fabricated to provide test specimens for this study.

The 1" thick panel is only used for the single bolted reloading tests. A total of three 1" panels were fabricated for this study.

### 2.7 Composite Material Tests

Material verification tests are performed to quantify strength and stiffness of the composite materials used in the stress relaxation testing. These tests include:

- Composite Constituent Volume Test (Burn Off) – ASTM D2584
- Tension Test – ASTM D3039
- Compression Test – ASTM D3410

## 2.8 Instrumentation Details

Several sensors are used during testing to monitor data such as load in the bolted connection, maximum pressure distribution in the connection, ambient temperature and humidity. The data acquisition program is also used to monitor and record this data, in conjunction with the various sensors. What follows in this section is a description of the sensors and a description of the pertinent parts of the DAQFI data acquisition program.

### 2.8.1 Load Washers

Omega Engineering of Stamford, CT manufactures the series LC900 load washers used in these experiments. The load washers are compression load cells designed to measure the clamping force of a bolt. Two sizes of load washers are used in the testing; ½ inch, and ¾ inch. The ½ inch load washers are used in the compression block testing, while the ¾ inch load washers are used in the tapered bolts and non-tapered bolts testing. The load capacity is 30,000 lbs. and 65,000 lbs. for the ½" and the ¾" load washers, respectively.

The load washers have an internal full bridge strain gage mounted to their inner diameter. The corresponding wires from the strain gage are attached to the power supply and the data acquisition system in order to monitor the bolt load. Since all of the load washers could use the same power supply, they were wired to a common junction point using female banana connectors. From these common junction points, a banana cable connects to the power supply to provide bridge excitation. The load washers were all calibrated using a 5 volt bridge excitation. The power supply was a BK Precision Model 1651A Triple output DC power supply. Section 2.8.5 gives more information on this power supply.

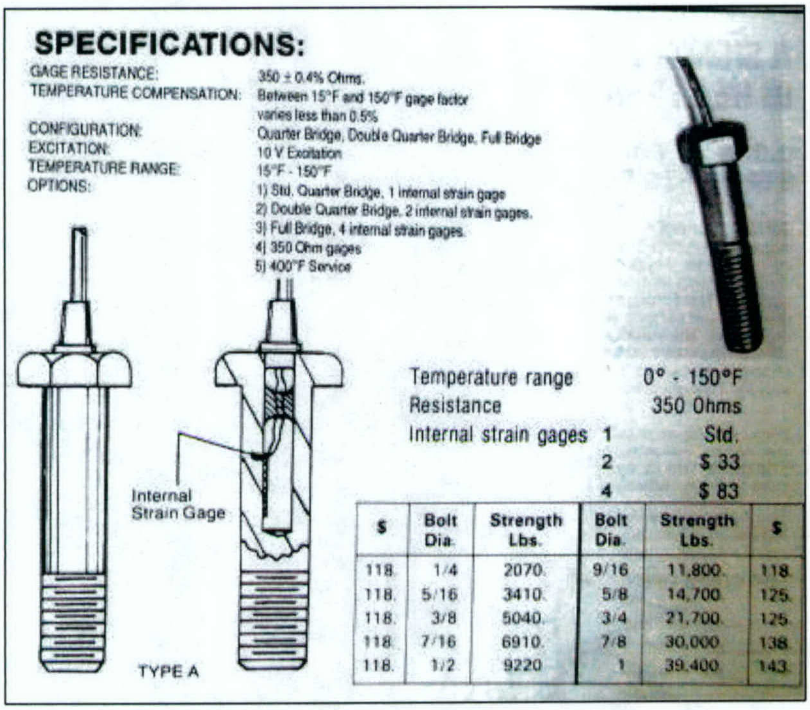
The output voltage was monitored for each of the load washers through an IoTech 16-port interface configured in differential mode. Table 2.7 contains the calibration factors for the Omega load washers.

### 2.8.2 Internally Gaged Bolts

The internally gaged bolts used are model numbers ALD-BOLT-.5" X 2" LONG, ALD-BOLT-.75" X 2.5" LONG, and ALD-BOLT-1" X 3.5" LONG, depending on the bolt diameter. These bolts are designed to measure dynamic or static tension, compression or bending loads. Three sizes of bolts are used in the testing; ½" diameter, ¾" diameter, and 1" diameter. The ½" diameter bolts have a load capacity of 9,220 lbs, the ¾" diameter bolts have a load capacity of 21,700 lbs, and the 1" diameter bolts have a load capacity of 39,400 lbs. Figure 2.11 shows a summary of the bolt specifications. As with the load washers, the bridge excitation was provided by the BK power supply and the output was connected to the IoTech interface configured in differential mode.

**Table 2.7 - Load Washer Calibrations**

| Washer Number | Size | Serial Number | Calibration Factor (lbs/mV) |
|---|---|---|---|
| 1 | 1/2" | 132402 | 3384.667 |
| 2 | 1/2" | 140203 | 3497.645 |
| 3 | 1/2" | 140204 | 3259.382 |
| 4 | 1/2" | 140205 | 3279.656 |
| 5 | 1/2" | 140206 | 3316.933 |
| 6 | 1/2" | 140207 | 3234.397 |
| 7 | 1/2" | 140213 | 3194.548 |
| 8 | 1/2" | 140215 | 3137.156 |
| 9 | 1/2" | 140217 | 3209.071 |
| 10 | 3/4" | 145773 | 6070.341 |
| 11 | 3/4" | 145775 | 6118.165 |
| 12 | 3/4" | 145776 | 6038.367 |
| 13 | 3/4" | 145777 | 5769.265 |
| 14 | 3/4" | 145778 | 5914.575 |
| 15 | 3/4" | 145779 | 6361.385 |


SPECIFICATIONS:

GAGE RESISTANCE: 350 ± 0.4% Ohms.
TEMPERATURE COMPENSATION: Between 15°F and 150°F gage factor varies less than 0.5%
CONFIGURATION: Quarter Bridge, Double Quarter Bridge, Full Bridge
EXCITATION: 10 V Excitation
TEMPERATURE RANGE: 15°F - 150°F
OPTIONS: 1) Std. Quarter Bridge, 1 internal strain gage
2) Double Quarter Bridge, 2 internal strain gages.
3) Full Bridge, 4 internal strain gages.
4) 350 Ohm gages
5) 400°F Service

Internal Strain Gage

TYPE A

Temperature range 0° - 150°F
Resistance 350 Ohms
Internal strain gages 1 Std.
2 $ 33
4 $ 83

| $ | Bolt Dia. | Strength Lbs. | Bolt Dia. | Strength Lbs. | $ |
|---|---|---|---|---|---|
| 118. | 1/4 | 2070. | 9/16 | 11,800. | 118. |
| 118. | 5/16 | 3410. | 5/8 | 14,700. | 125. |
| 118. | 3/8 | 5040. | 3/4 | 21,700. | 125. |
| 118. | 7/16 | 6910. | 7/8 | 30,000. | 138. |
| 118. | 1/2 | 9220. | 1 | 39,400. | 143. |

**Figure 2.11 - Internally Gaged Bolts Spec. Sheet (aldesigninc.com)**

A 10 volt power supply was used for the bridge excitation of the load bolts. The output wires were both connected to successive channels on the IoTech hub, and the hub is connected to the computer through the use of a DaqBoard/2000.

Each bolt has an internal 350 ohm full bridge strain gage mounted to the inside of the bolt that is used to measure the applied tension load in the bolt. The output voltage difference is read across the green and white wires of the bolt. Calibration factors for each bolt are given in Table 2.8.

### 2.8.3 Humidity Sensor

During testing, humidity was monitored using a HIH-3610 series sensor, manufactured by Honeywell. Figure 2.12 shows a diagram of the chip and mounting dimensions. This sensor has a very low current draw of 200 μA when operating at 5 Vdc. It can operate on power supplies from 4 Vdc to 5.8 Vdc. For these experiments, it is operated at 5 Vdc, since this was the voltage the sensor was calibrated at. It can operate from between –40°F to 185°F, and between 0 and 100% RH. In that range, it is accurate to ±2% RH

**Table 2.8 - Internally Gaged Bolts Calibration Factors**

| Bolt Number | Size | Serial Number | Calibration Factor (lbs/mV) |
|---|---|---|---|
| 1 | 1/2" | 20011105 | 574.7479 |
| 2 | 1/2" | 20011106 | 427.2036 |
| 3 | 1/2" | 20011107 | 456.0101 |
| 4 | 1/2" | 20011108 | 567.0741 |
| 5 | 1/2" | 20011109 | 433.3666 |
| 6 | 1/2" | 20011110 | 443.2593 |
| 7 | 1/2" | 220642 | 455.0582 |
| 8 | 3/4" | 220109 | 1045.379 |
| 9 | 3/4" | 220110 | 1055.549 |
| 10 | 3/4" | 220111 | 1039.612 |
| 11 | 3/4" | 220112 | 1026.207 |
| 12 | 3/4" | 220113 | 1005.739 |
| 13 | 3/4" | 220114 | 1205.556 |
| 14 | 3/4" | 220643 | 1039.612 |
| 15 | 3/4" | 220644 | 1050.597 |
| 16 | 3/4" | 220645 | 1052.443 |
| 17 | 1" | 220529 | 1933.889 |
| 18 | 1" | 220530 | 1887.586 |
| 19 | 1" | 220531 | 1931.333 |
| 20 | 1" | 220532 | 1945.134 |
| 21 | 1" | 220533 | 2015.657 |
| 22 | 1" | 220534 | 1868.854 |
| 23 | 1" | 220646 | 1876.19 |

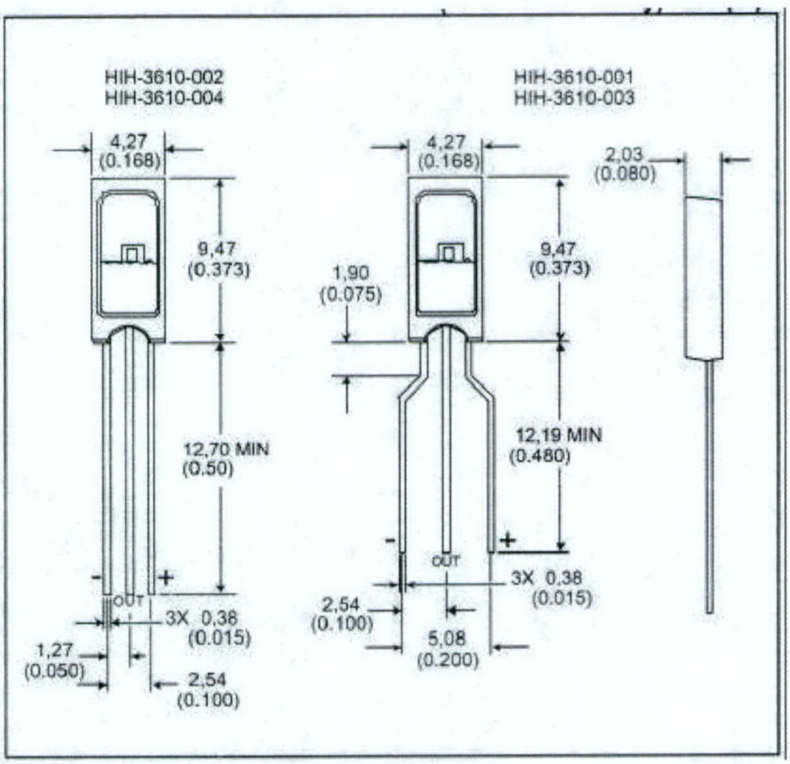



**Figure 2.12 - Diagram of HIH-3610 Series Humidity Sensor, mm (in) (Honeywell.com)**

### 2.8.4 Temperature Sensor

The temperature sensor used to monitor room temperature during the testing was a LM34CZ chip, manufactured by National Semiconductor. Figure 2.13 shows the overall layout and dimensions of the LM34CZ temperature sensor. It has a linear relationship between output voltage and Fahrenheit temperature, with a +10 mV/°F scale factor. It runs over a temperature range of –50 °F to 300 °F, with an accuracy of ±1-½°F. The sensor can operate with an excitation from 5 to 30 volts. A 15 V excitation was used during the creep study

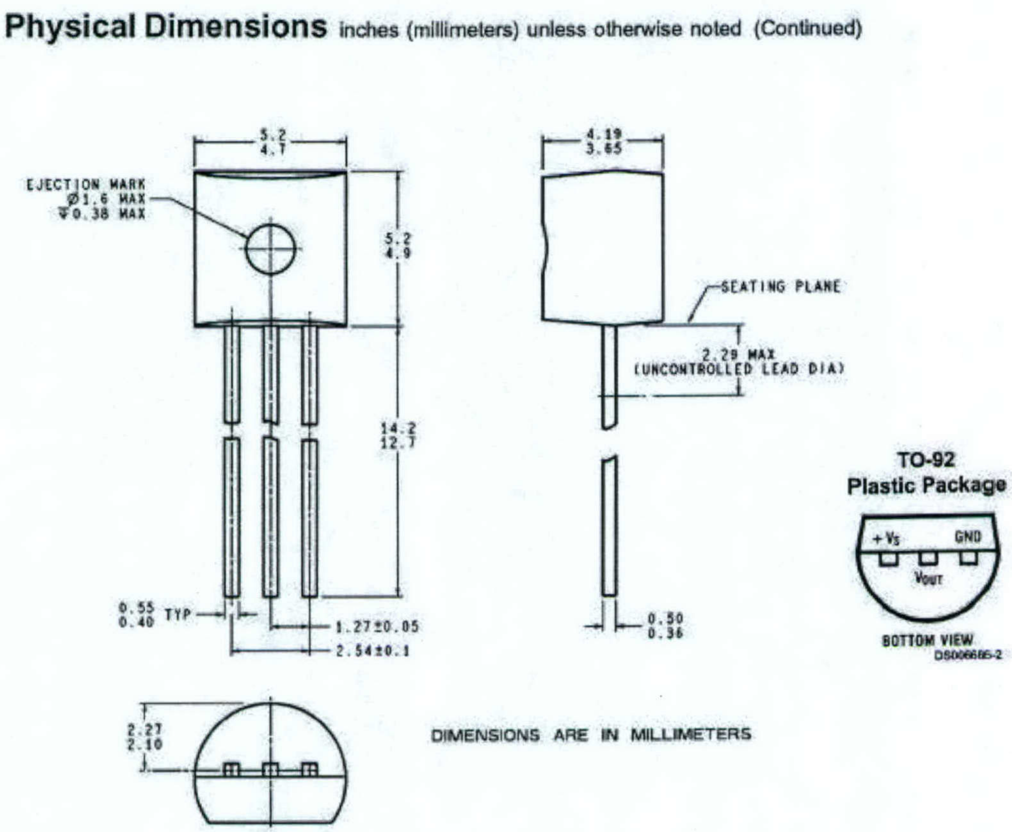



**Figure 2.13 - Dimensions of LM34 Temperature Sensor (National.com)**

### 2.8.5 Environmental Chambers

Two environmental chambers were used to obtain the environmental conditions described in Section 2.5. One is a Tenney Jr. Model THJR, and the other is a PGC (Parameter Generation & Control Inc.) SS Climate-Lab. Both these chambers are located at the University of Maine's Crosby Laboratory.

The Tenny Jr. is a bench top chamber capable of adjusting both humidity and temperature. It has a temperature range of between 10 and 200 °F, and has a standard wet bulb/dry bulb control set up to provide the temperature and humidity. It has a gravity feed system that empties the water into the heating chamber. Once the controls are set, the temperature and humidity remain constant throughout operation.

The PGC SS (steady state) Climate-Lab is a large floor model chamber, capable of varying both temperature and humidity. It is capable of a temperature range of 4.5°C to 71°C (40°F to 160°F), and can maintain the temperature to within ±0.2°C, and humidity to ±0.5% RH. This chamber does not use a wet bulb/dry bulb set up. Instead, a conditioner maintains the dry bulb temperature, while a water spray provides a mist of water to maintain the humidity. The temperature of the mist and the air temperature come to equilibrium and thus provide the desired environmental conditions

### 2.8.6 Power Supply

The power supply used in these experiments was a model number 1652, manufactured by BK Precision®. It features a triple output DC power supply, with a digital display. It has two variable power supplies, which go from 0 to 24 volts, and have a 0.5 amp current capacity. The two variable power supplies are run at a constant 10 volts, and are used as the power source for the internally gaged bolts. A fixed 5 volt supply is used for powering the load washers.

### 2.8.7 Pressure Paper

The pressure paper used during testing is made by Fujifilm and is called Prescale. This pressure paper is used to quantify the maximum pressure distribution in the single bolt connections. When pressure is applied to the Prescale, red patches appear on the film of varying color density (Density: 0.1 ~ 1.4). The varying color density corresponds to different pressure levels. The Prescale can then be analyzed using Adobe PhotoShop or a similar graphics software program. By analyzing the color density on the film, the pressure distribution in the connection can be visualized and quantified.

### 2.8.8 Data Acquisition System

A schematic of the data acquisition system currently employed is shown in Figure 2.14. It is based upon an IoTech Daqboard/2000 plug-in card. The 16-bit resolution, along with an ability to set an internal gain of 64, provided the necessary resolution with which to accurately read the loads in the internally gaged bolts and/or load washers.

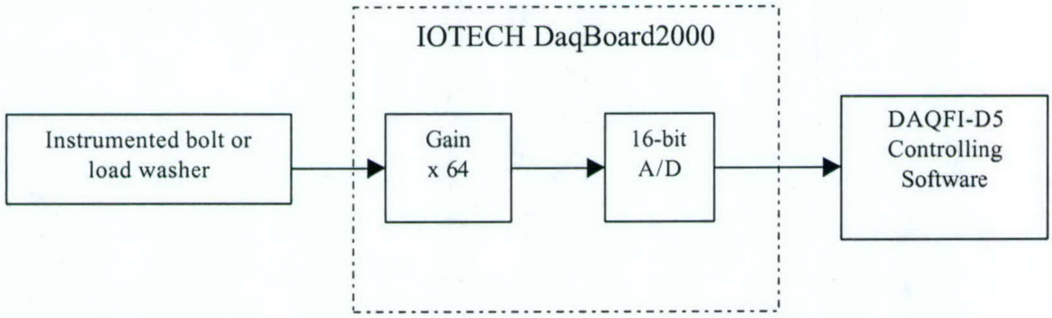



**Figure 2.14 - Data Acquisition System**

Initial tests attempted to use a Vishay 2100 strain amplifier. However, concern with drift over time lead to the use of a 16-bit A/D converter. This eliminated the need for the external amplifier, and the concern over drift of the strain amplifier.

#### 2.8.8.1 DaqBoard/2000

The DaqBoard/2000, made by IOtech, is used to collect the voltage output from the hubs, and send it to the computer. The board plugs into a PCI slot on a computer, and enables 8 channels of differential data (16 if single ended) to be read per board. Two boards are connected to each computer, enabling 16 channels to be read in differential mode by each computer. The card has a 16-bit resolution, and when used at a range of ±10 V and a gain of 64, corresponds to a voltage resolution of 0.002384 mV.

#### 2.8.8.2 Delphi 5 Data Acquisition Program

The DAQFI-D5 software, written at the University of Maine, controls the data acquisition system. A special software routine was written specifically for the stress relaxation testing. The data configuration and setup screens for the stress relaxation testing are shown in Figures 2.15 and 2.16. The screen shown in Figure 2.15 is where input data such as the number of channels being used, the number of averages, and whether the test is being run in single ended or differential mode is specified. The creep study testing was run in differential mode, as per sensor requirements. A channel can be turned on or off at this screen. The number of averages allows the user to gain more accurate data by allowing the program to record several readings at one instant in time, and average them together to obtain a single data point.

Figure 2.16 shows the configuration screen for each individual sensor. Calibration factors are entered in this section of the program. Tabulated values for these calibrations are given in Tables 2.7 and 2.8. The second area on this screen is the voltage offset. The voltage bias, taken with no load applied to the connection, is entered into the voltage offset section of this configuration screen. Accordingly, the resulting load is:

$$(V_{in} - V_{offsett}) \cdot Calibration \tag{2.2}$$

All other information on these two screens is used as a header for the data file. This is information such as a description of the data file, and a description of each channel.

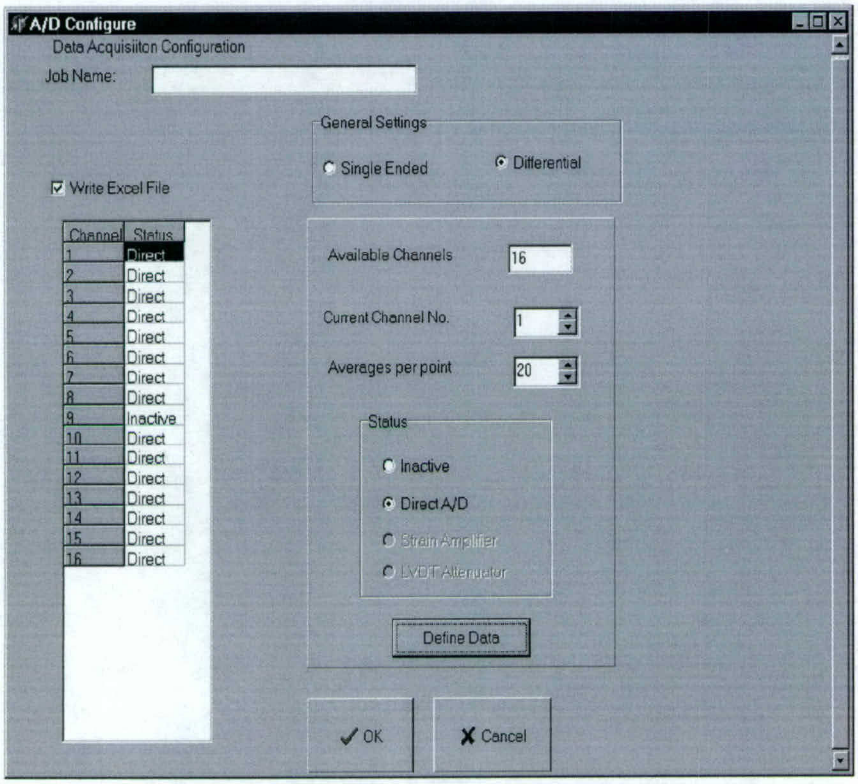



**Figure 2.15 – DaqFi-D5 Configuration A**

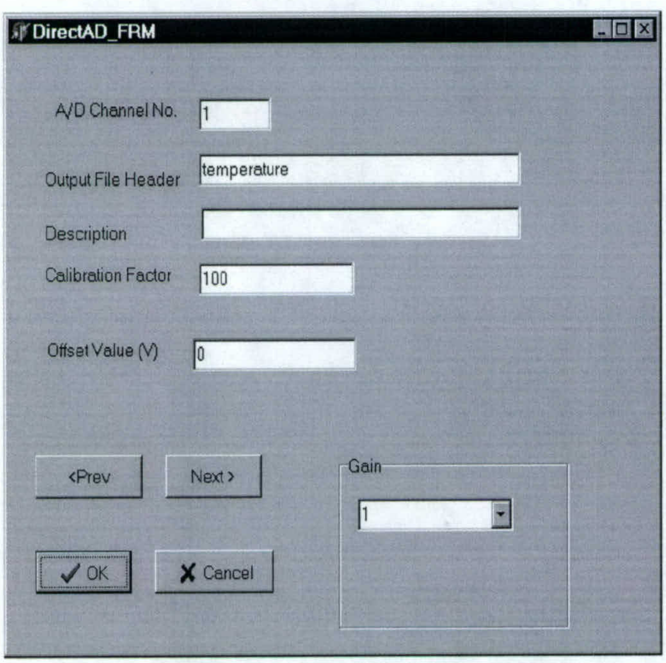



**Figure 2.16 – DaqFi-D5 configuration B**

Figure 2.17 shows the actual stress relaxation data recording program. The data recording schedule is shown on the left side of the screen, and is currently hard coded into the program. Below that is a place to select the name and location of the output data file. Under that is a box labeled Run Test. This is where the program can be started or stopped. This box also dynamically lists which data taking cycle the program is currently on.

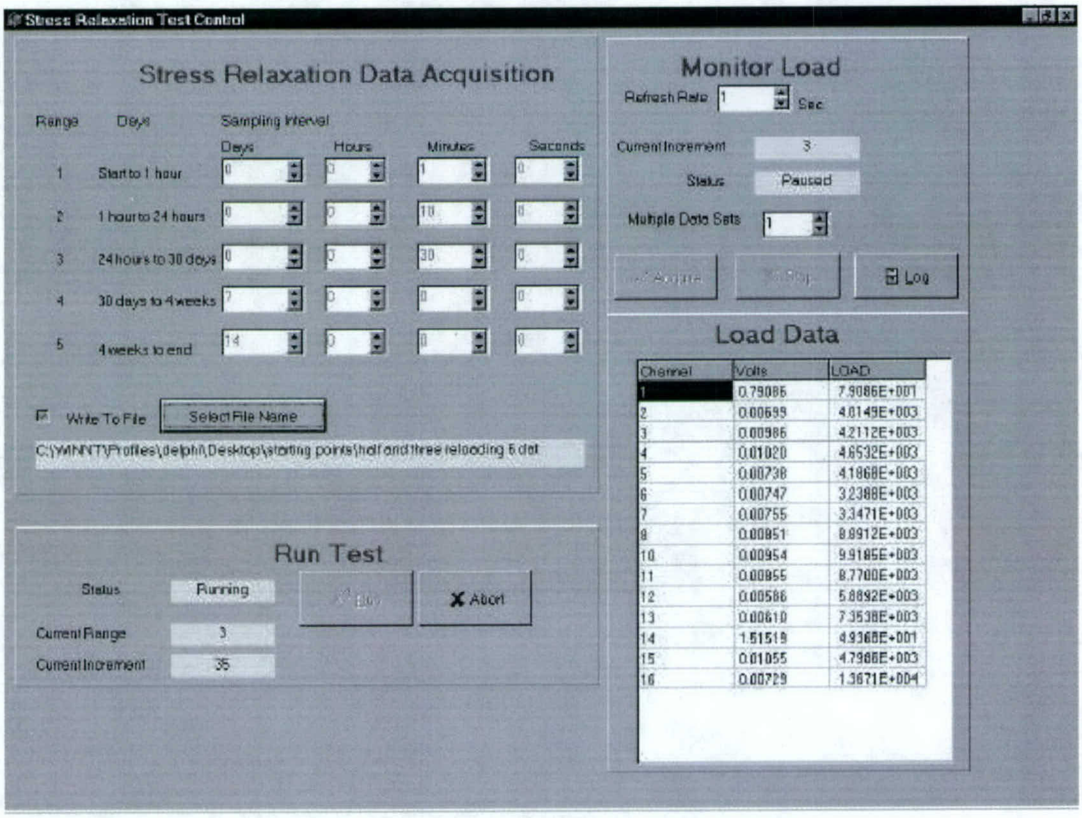


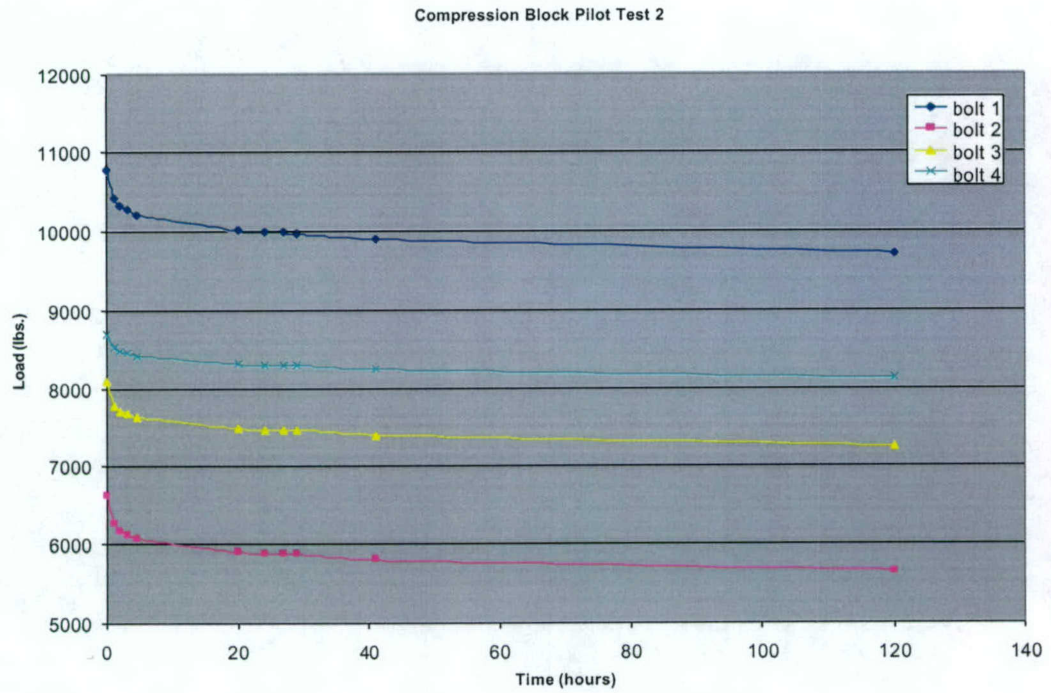

**Figure 2.17 - DaqFi-D5 Stress Relaxation Program**

On the right side of the screen, there is a place that displays both the output voltage for each channel, as well as the load on each channel. This is active when the program is taking data, but can also be activated in a manual mode. The refresh rate controls the data rate in manual mode. Below that is where the monitor can be turned on or off while the program is not in the run mode. The monitor allows the user to observe the load being applied to the sensors as the bolts are being tightened.

There is also a log button located on this screen. It allows the user to log a single data point, with a time stamp, during the setup phase, as the bolts are initially tightened or reloaded. Without this feature, some critical initial data would be lost, as the automated data acquisition system cannot be started until all bolts are tightened to the desired load. With this log button, one bolt can be tightened, a data point can be logged, and the initial load on every channel can be recorded. The data acquisition can then be initiated in the run mode when all bolts have been tightened to the desired load level.

**2.9 Pilot Test Results**

The first set of tests were relatively short-term tests that were performed to verify the testing methods. Figure 2.18 shows the results from one pilot test run using the compression block test fixture. These tests were run for approximately one week to determine any problems that might occur during testing. This group of tests was run prior to the DAQFI data acquisition program, and validated the need for an automated data taking system. It was run using an external power supply to supply the bridge excitation, and a voltmeter to record the data points. The four bolts are labeled 1 through 4, with bolt 1 being on the opposite side from bolt 3. The top graph in Figure 2.18 shows the bolt load for each sensor and portrays the relaxation experienced by each bolt during testing. The bottom graph shows the same data normalized with respect to each bolt's initial preload. It was desired that all bolts be loaded to the same value during the tests, and this test displayed the need for procedure modifications to ensure accurate preloading of the specimens.



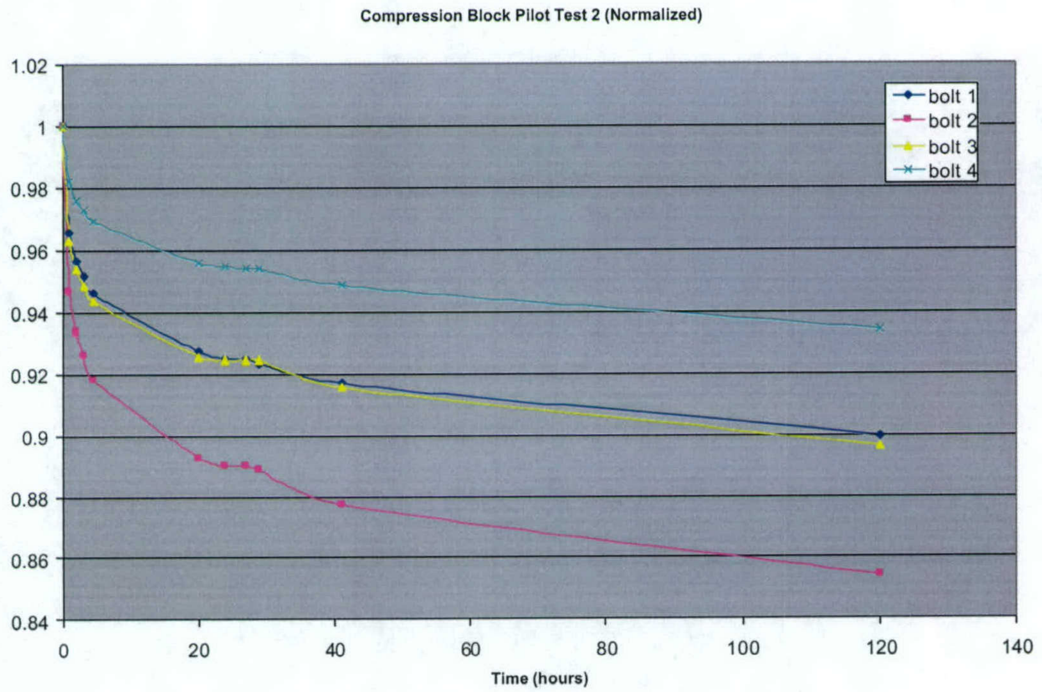




**Figure 2.18 – Compression Block Pilot Test Results**

Figures 2.19, 2.20, and 2.21 show results from the initial pilot tests for reloading of ½", ¾", and 1" thick single bolt hybrid connections, respectively. This series of tests were run for slightly over 1 month. These tests also showed the need for a few adjustments to the testing procedures and the DAQFI program. Once again, the need for a loading fixture to accurately apply the preload to the specimens was evident. The two other adjustments made, after this series of tests, were to the DAQFI program. The jaggedness in the curves is due to the inability, in part, to adjust the gain in the program. A selectable gain was added to the program to reduce fluctuation in the readings. The other feature that was added to the software at this stage in experimentation was the manual log button. This was done to insure that a data point was logged for each bolt exactly when initial preload was reached.

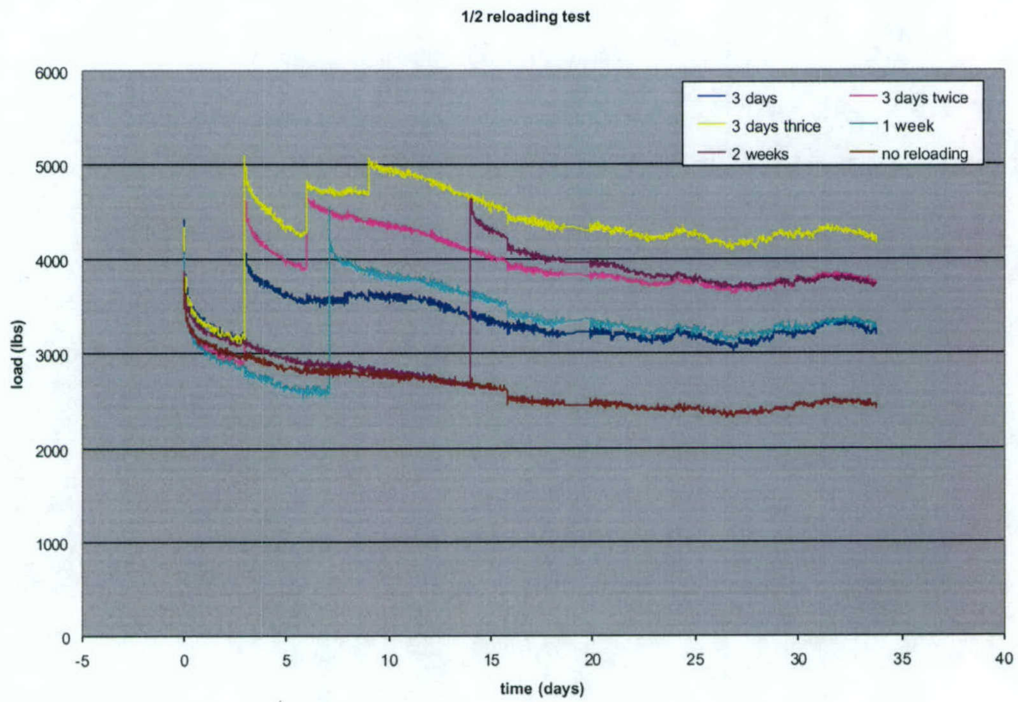



**Figure 2.19 – ½" Reloading Pilot Test**

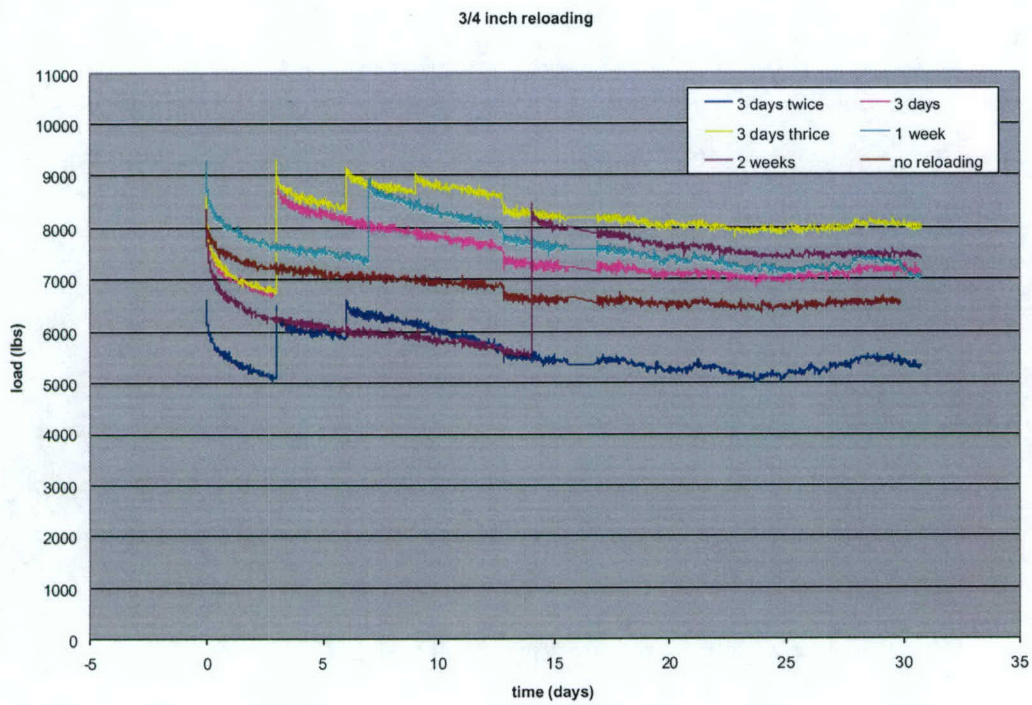



**Figure 2.20 – ¾" Reloading Pilot Test**

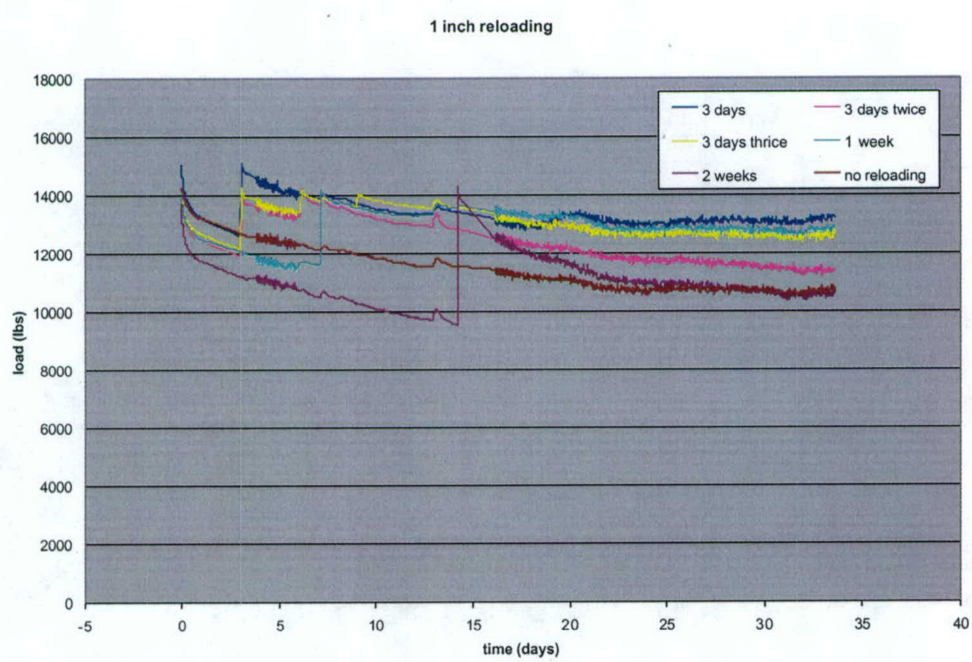



**Figure 2.21 – 1" Reloading Pilot Test**

# 3. TEST RESULTS

## 3.1. Compression Block Test Results

The results of the compression block test with nominal preloads of 10,000 and 5,000 pounds are shown in Figures 3.1 and 3.2, respectively. Table 3.1 summarizes the initial and final bolt loads recorded during the test period of 115 days. Due to the geometry of the fixture, it was difficult to load each bolt to the same preload. The actual initial preload ranged from 10,000 lbs. to 10,740 lbs. for series 1, and from 5,000 to 5,020 lbs for series 2. In series 1, all four bolts show a reduction in the initial preload that occurs at approximately the same rate. Each bolt lost on the average of 15.4% of its initial preload over the time period of 110 days.

Figure 3.2 shows a second compression block test loaded to a nominal initial preload of 5,000 pounds. Actual initial preloads ranged from 5,000 lbs. to 5,020 lbs. Final loads for each bolt decreased 14.5% on the average after a test period of 115 days. Bolts 1, 2, and 3 lost an average of 10.7% of their initial preloads, while bolt 4 lost 25.7% of its initial preload. It is unclear why bolt 4 lost a disproportionate amount of its preload. It is recommended that this series of tests be repeated.

**Table 3.1 – Initial and Final Bolt Loads for Compression Block Tests**

| Bolt | Series 1 | | | Series 2 | | |
|---|---|---|---|---|---|---|
| | Initial Load, lbs. | Final Load, lbs. | Loss, % | Initial Load, lbs. | Final Load, lbs. | Loss, % |
| No. 1 | 10,480 | 8,320 | -20.6 | 5,010 | 4,550 | -9.2 |
| No. 2 | 10,120 | 8,660 | -14.4 | 5,000 | 4470 | -10.6 |
| No. 3 | 10,740 | 9,510 | -11.5 | 5,000 | 4,380 | -12.4 |
| No. 4 | 10,000 | 8,490 | -15.1 | 5,020 | 3,730 | -25.7 |
| **Avg.** | **10,335** | **8,745** | **-15.4** | **5,008** | **4,283** | **-14.5** |

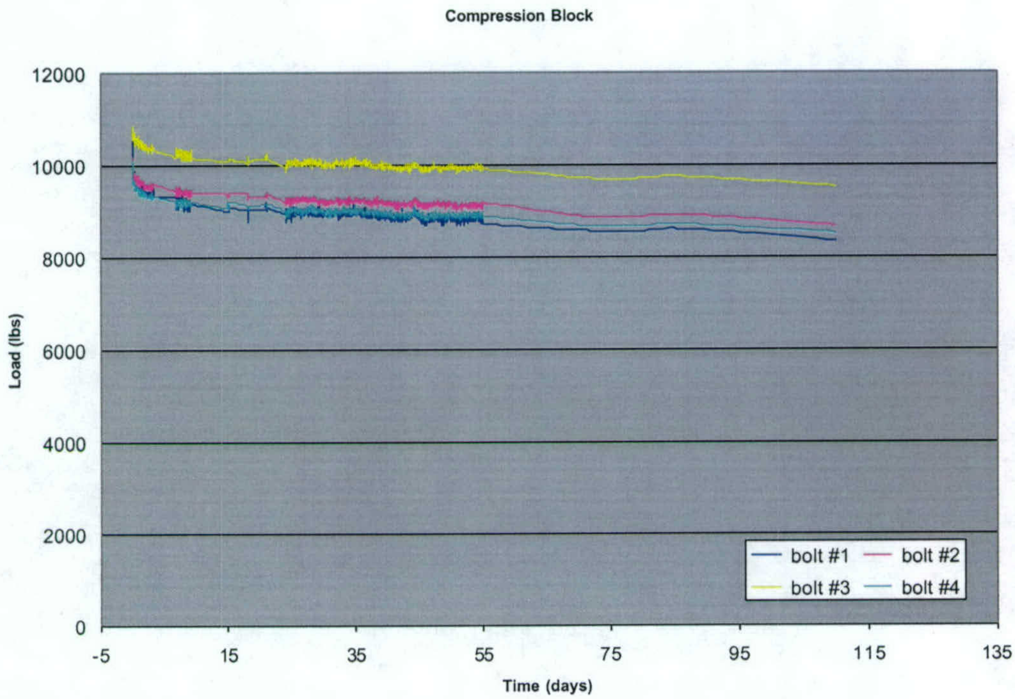



**Figure 3.1 – Series 1 - Compression Block Test Results with a Preload of 10,000**

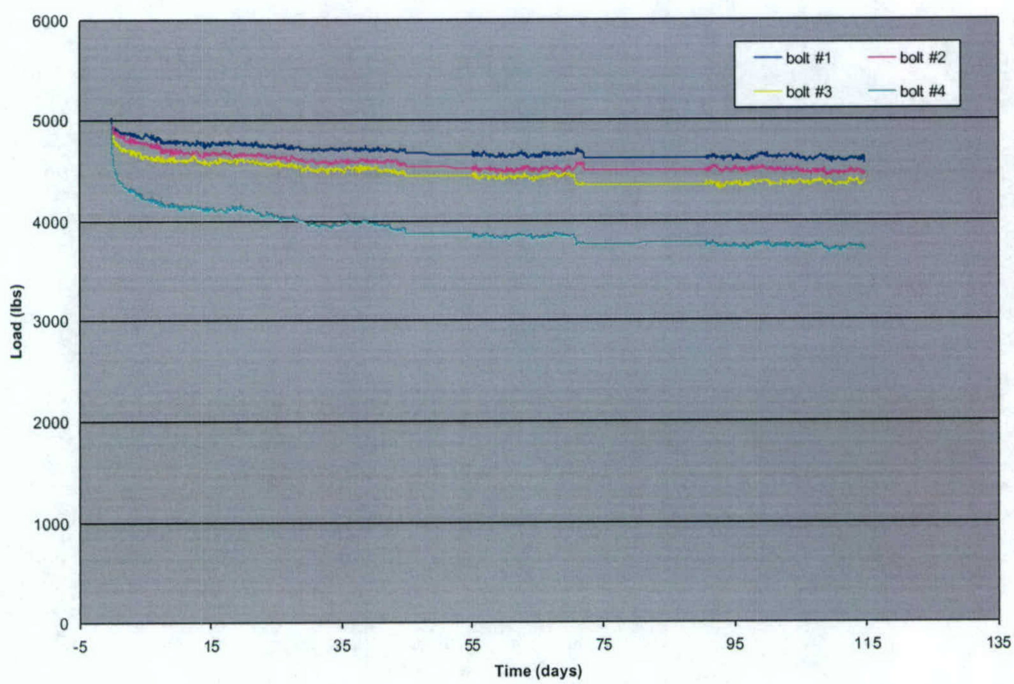



**Figure 3.2 – Series 2 - Compression Block Test Results with a Preload of 5,000**

### 3.2. Single Bolt, Reloading Hybrid Connection Test Results

The results from three groups of ½" thick single bolted reloading test specimens are presented in Figures 3.3, 3.4 and 3.5. All three of these test series were run for a time period of at least 90 days. The specimens shown in Figure 3.3 were preloaded to 2,500 lbs, while the specimens in Figures 3.4 and 3.5 were preloaded to 5,000 lbs, with a variance of ±1%. Temperature and humidity are displayed at the bottom of the graphs in Figures 3.4 and 3.5, with temperature in degrees Fahrenheit, and humidity in %RH, while temperature alone is displayed at the bottom of Figure 3.3.

Figures 3.3 and 3.4 show that the stress relaxation of the hybrid connection is temperature dependent, as expected. In general, it is observed that the more the bolt retains its preload the greater the temperature dependency. The specimens in Figure 3.3 underwent short-duration temperature shifts of between 5 °F and 20 °F, and these shifts are observed in the results. In Figure 3.4, there are two places on the graph where this temperature dependence is best shown. Ambient room temperature was approximately 80°F for this series of tests. At day 31, however, there was a temperature drop to about 75°F. Corresponding to this temperature drop, is a drop in the bolt load of each specimen. Between days 46 and 60, there is a prolonged temperature increase of roughly 5°F, from about 80°F to 85°F. This increase corresponds to an increase in the stress relaxation of the specimens, especially those reloaded multiple times. This is attributed to the higher coefficient of thermal expansion of the aluminum plate compared to the steel bolt, indicating that the test article will compress relative to the bolt thus increasing the bolt load. This is also evident on the graph in Figure 3.5, though to a lesser degree. The room temperature when running these tests was roughly 10°F lower than the previous two series of tests. Between days 40 and 45 of this group of tests, there was a temperature increase of about 5°F. During this time, the load in the connections increased slightly. This increase was more prominent in the connections that have been reloaded multiple times. The loads in the connections returned to what was expected after the temperature had returned to normal. In general, the reloaded connections seem to be sensitive to temperature fluctuations, particularly extended periods of temperature change, even relatively small changes. Accordingly, it is recommended to further study the effects of temperature and humidity independently.

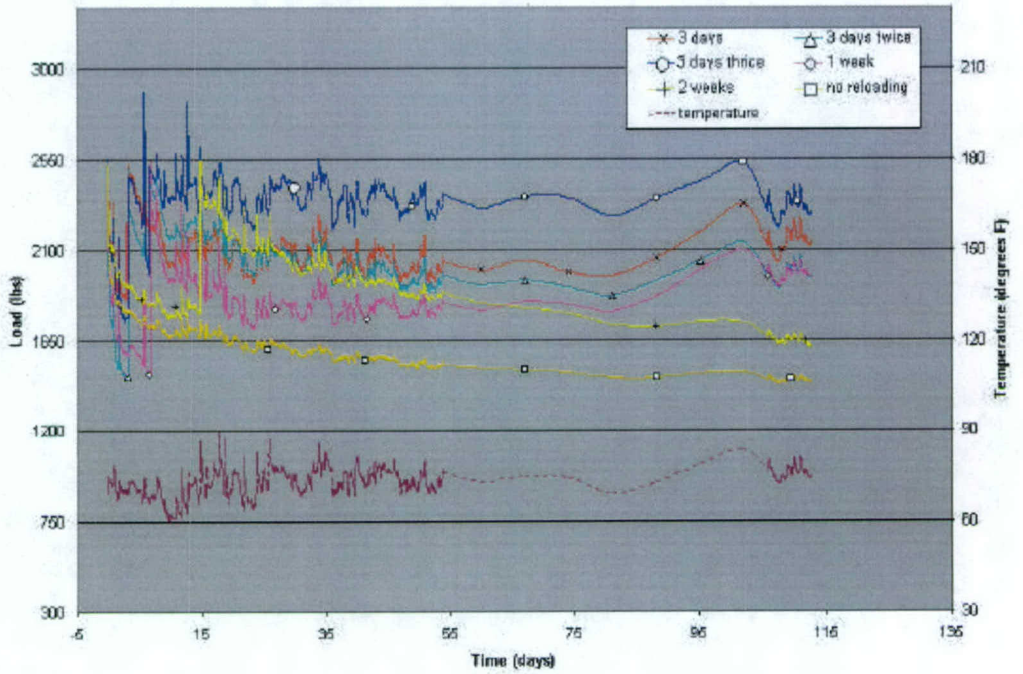



**Figure 3.3 - ½" Reloading Tests with a Preload of 2,500 lbs.**

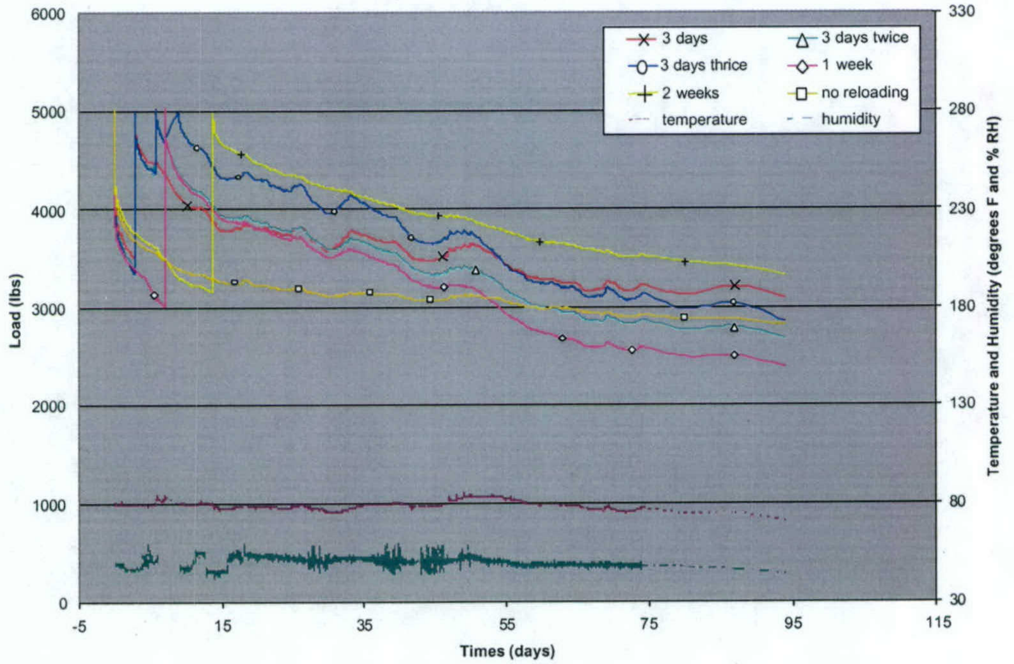



**Figure 3.4 – 1st ½" Reloading Test with a Preload of 5,000 lbs.**

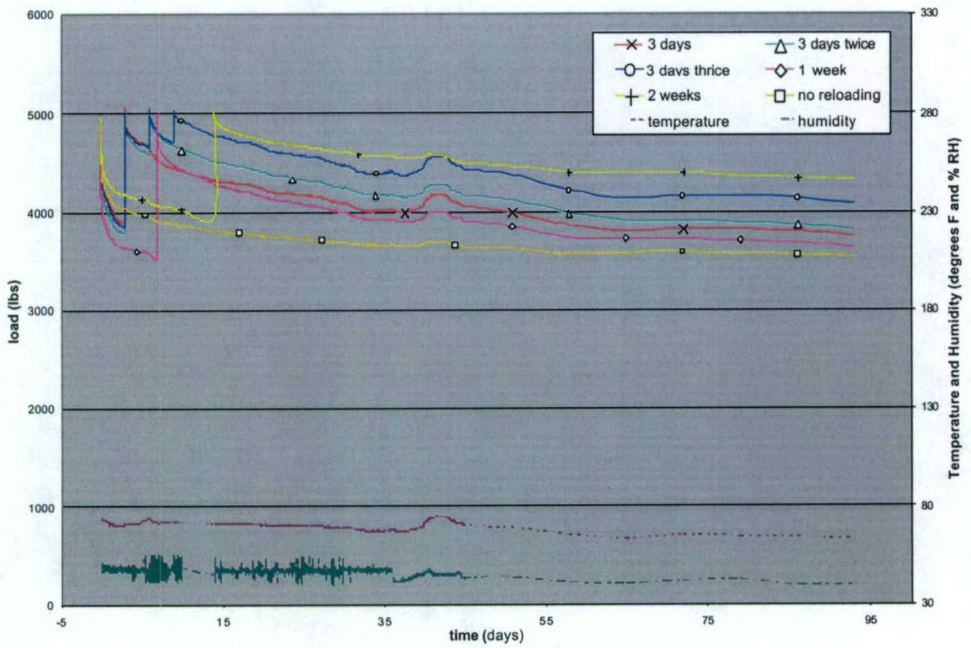



**Figure 3.5 – 2nd ½" Reloading Test with a Preload of 5,000 lbs.**

Tests performed using the ¾" diameter bolts are presented in Figures 3.6 and 3.7. Figure 3.6 shows results from 7/8" thick composite specimens bolted to ¾" thick aluminum plates with the ¾" bolts. A ¾" panel was not prepared to be tested at the time this trial was run, so the decision was made to use a 7/8" panel. Figure 3.7 shows the results from test run using ¾" thick composite samples. Both of these tests were run for a time period of just over 90 days. Each of the test specimens was loaded to 10,000 lbs, ±1%. In addition, reloading was done to 10,000 lbs, ±1%. Again, temperature (degrees Fahrenheit) and humidity (%RH) are plotted at the bottom of each graph.

These tests show the same temperature effects that the ½" thick tests show. The tests shown in Figure 3.6 were run at the same time as those in Figure 3.4, while the tests in Figure 3.7 were run concurrently with those in Figure 3.5. The graph in Figure 3.6 shows similar changes in stress relaxation over the same time periods as the graph in Figure 3.5. Figure 3.7 shows a similar load increase as the data in Figure 3.5, which corresponds to the temperature spike at day 40.

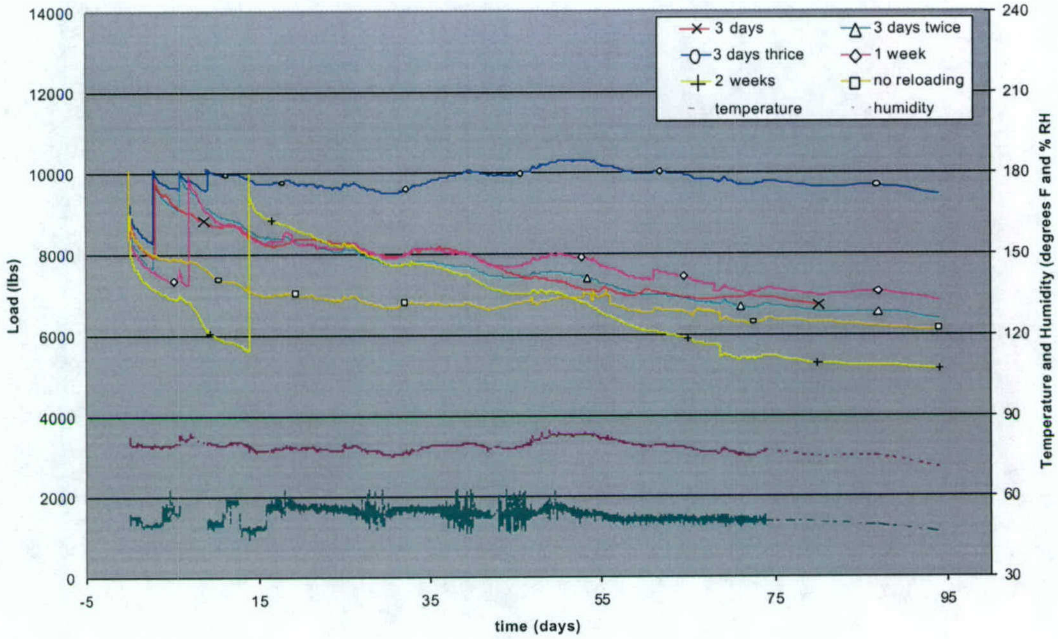



**Figure 3.6 - 7/8" Reloading Tests with a Preload of 10,000 lbs.**

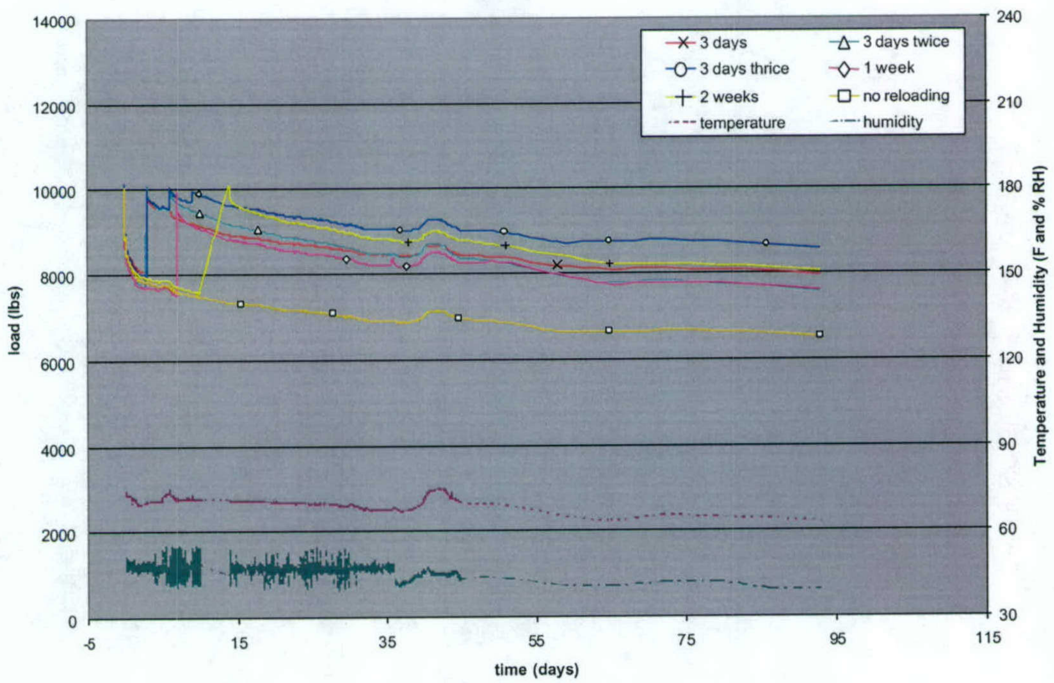



**Figure 3.7 – ¾" Reloading Tests with a Preload of 10,000 lbs.**

Figure 3.8 shows the results of reloading tests performed on 1-inch thick composite panels, using the 1" diameter bolts. Each bolt was loaded to 15,000 lbs, ±1% for this series, and reloading was performed to that same value. This series of tests was run during the same time period as the tests in Figures 3.5 and 3.7. It has the same temperature spike around day 40, and experiences brief load increases for all specimens corresponding to that temperature shift. The load levels return mostly to normal after the temperature has dropped back to its previous level. Figure 3.9 shows results of tests performed on 1-inch thick panels initially loaded to 7,500 lbs, ±1%. No temperature or humidity data were recorded for this group of tests.

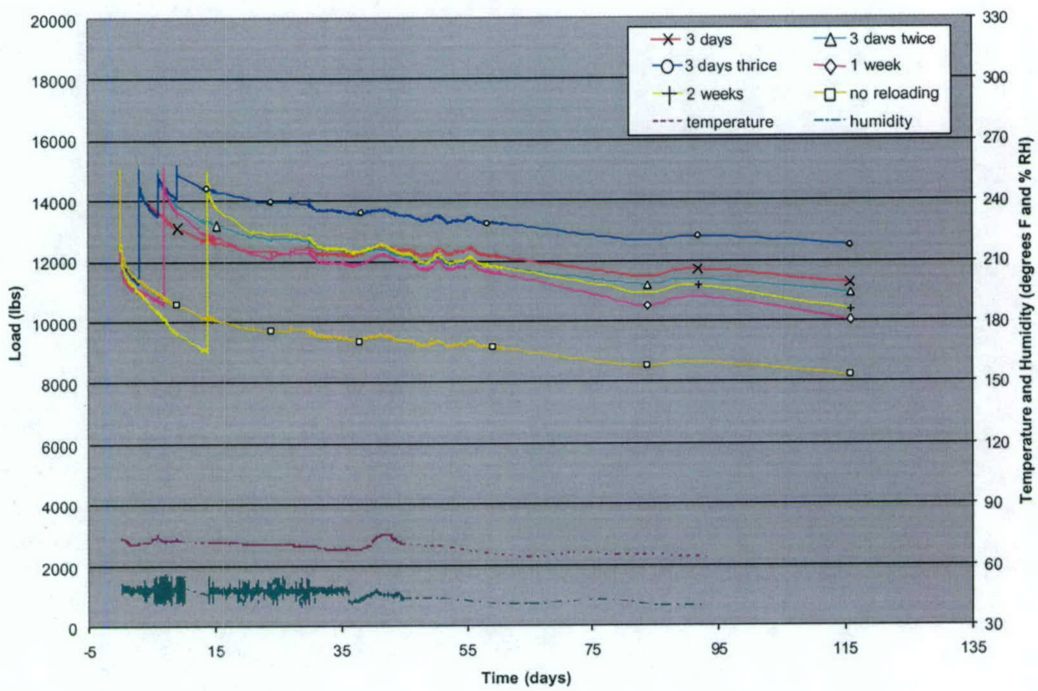



**Figure 3.8 – 1" Reloading Tests with a Preload of 15,000 lbs.**

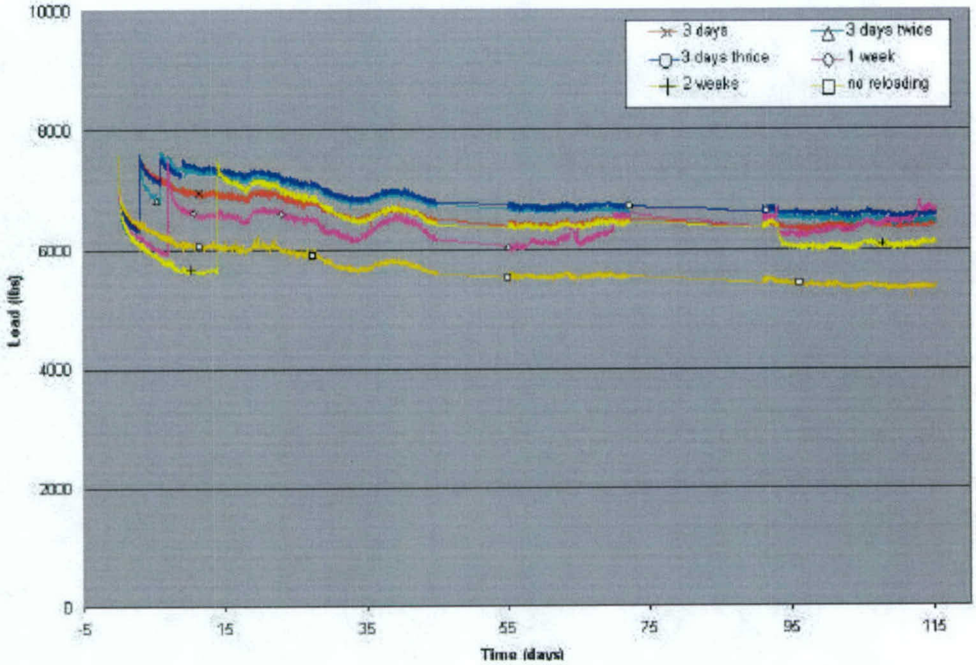



**Figure 3.9 – 1" Reloading Tests with a Preload of 7,500 lbs.**

### 3.3. Single Tapered Head vs. Non-Tapered Head Bolt Test Results

Figure 3.10 shows results from both tapered and non-tapered head bolts when loaded to 10,000 lbs, ± 1%. This group of four test specimens was run during the same time period. The tests were run in a room that had standard room temperatures and humidity. No temperature or humidity data were recorded for this group of tests, since there seems to be very little effect from small changes at ambient temperature when there is no reloading in the connection. There was no reloading done on this group of tests, since these tests were designed solely to study if using tapered head bolts changed the rate of stress relaxation when compared to non-tapered head bolts. Three tapered head bolts and one non-tapered head bolt were used for this group of tests. The results show no significant difference in stress relaxation rate between the connections with tapered head bolts and the connection with the non-tapered head bolt.

The next group of tests, shown in Figure 3.11, shows results from tapered and non-tapered head bolts loaded to an initial preload of 5,000 lbs, ±1%. Again, no reloading was done on this series of tests. No humidity or temperature data were recorded, since the tests were running at ambient temperature. This group of tests used two tapered head bolts, and two non-tapered head bolts. Again, no significant difference is seen between the stress relaxation rate of the tapered head bolts and the stress relaxation rate of the non-tapered head bolts.

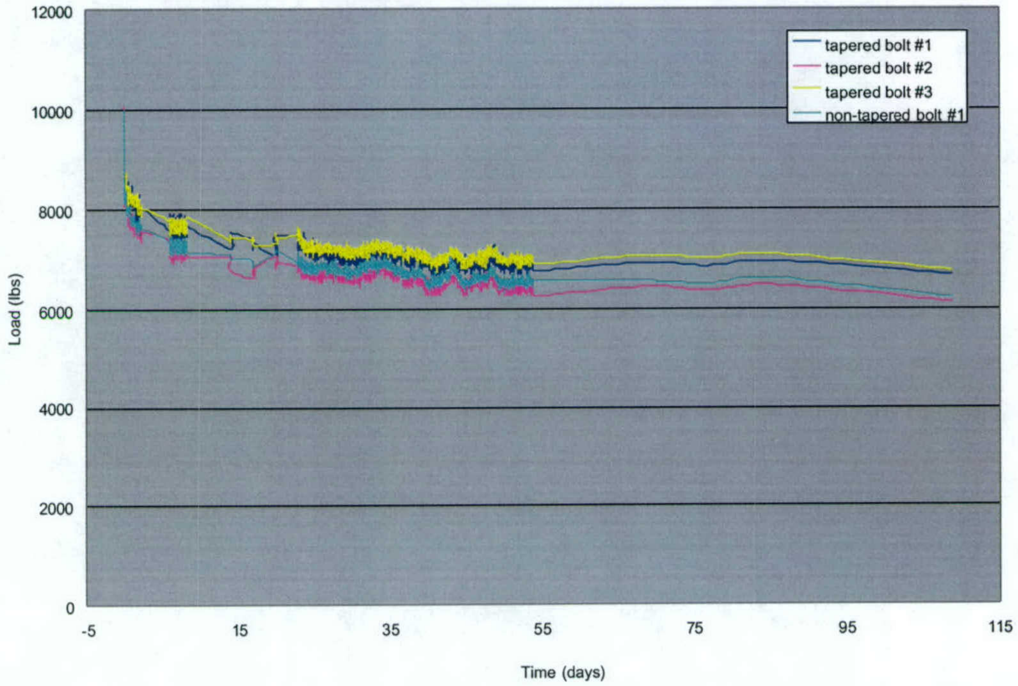



**Figure 3.10 – Tapered and Non-Tapered Head Bolt Test Results at 10,000 lbs.**

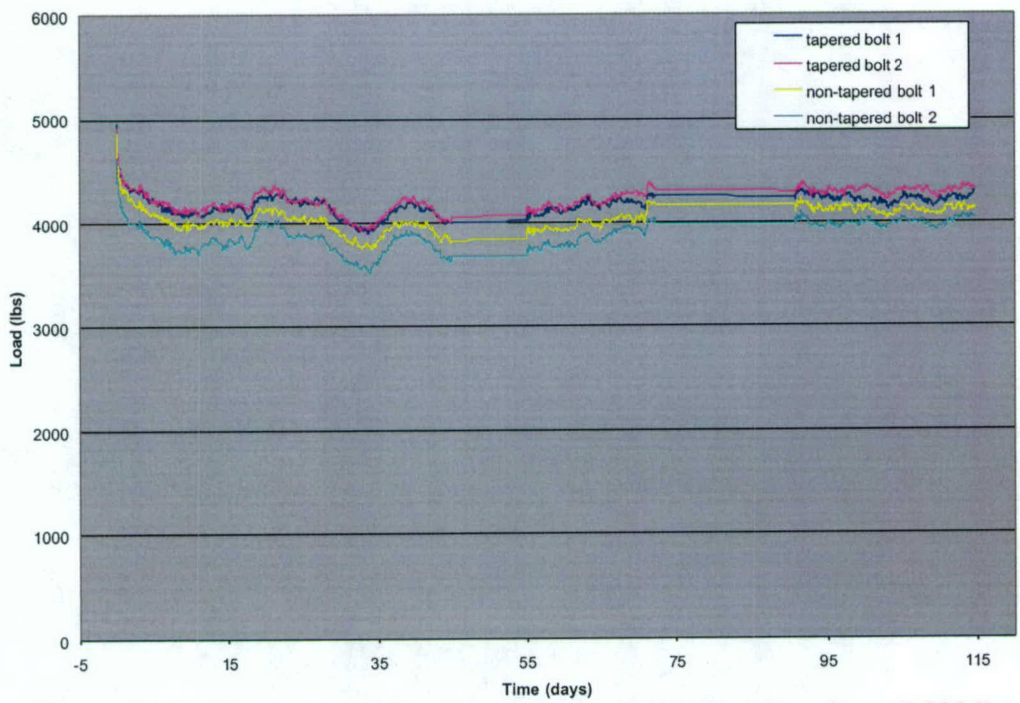



**Figure 3.11 – Tapered and Non-Tapered Head Bolt Test Results at 5,000 lbs.**

### 3.4. Pressure Distributions

Pressure distrib utions were measured for several of the single bolted tests using the Prescale pressure paper from FujiFilm. The pressure paper was used in both the reloading tests and the tapered head vs. non-tapered head bolts tests. Since the pressure paper used only indicates the maximum pressure distribution in the connection, reloading the connection to the same initial preload does very little to the pressure distribution indicated on the pressure film. For this reason, the pressure distributions in the reloading tests do not change significantly between tests done with different loading cycles. Figure 3.12 shows a chart legend which indicates the pressure corresponding to the colors in each pressure distribution in the photos that follow When analyzing the pressure distribution, there was not a clear separation between the different stress levels when one stress level changed to another. Thus the chart shows a gradual change in colors from one stress level to another.

Figures 3.13, 3.14, and 3.15, show pressure distributions from three of the control tests done with no reloading in the connections. Figure 3.13 is the pressure distribution between the composite and aluminum from one of the one-inch test specimens loaded with an initial preload of 15,000 lbs. Very little of the pressure applied to the connection by the bolt actually makes it to the center of the connection, as compared to the other thicknesses. This is likely due to the increase in thickness of the composite. Due to the greater thickness, the composite deflects less, and thus leaves less of a pressure distribution on the pressure paper. Figure 3.14 shows the pressure distribution from one of the ¾" thick test specimens loaded to 10,000 lbs. Being a thinner specimen, the pressure distribution shows better in this figure. It is applied over a larger area than that of the ½ inch thick specimens, but due to the stiffness of the composite panel, the magnitude at the center is not as great. Figure 3.15 shows the distribution from one of the ½" thick test specimens loaded initially to 5,000 lbs. This shows that the pressure in this size connection is more evenly distributed, though it is applied over a much smaller area. The pressure at the center is also at the limit of what the pressure paper can detect.

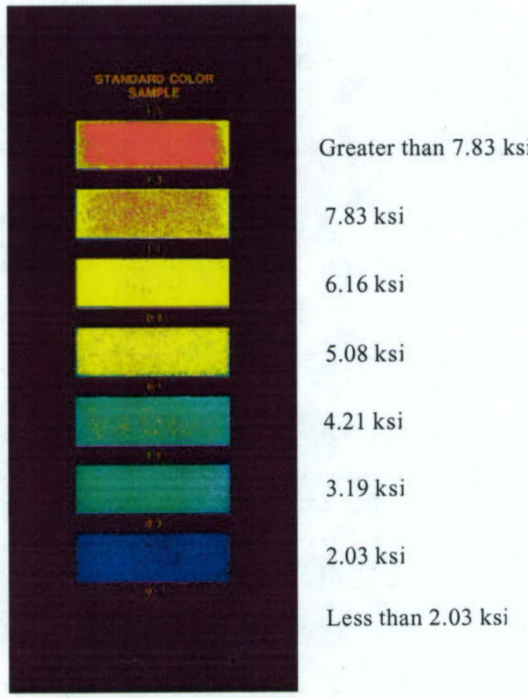



**Figure 3.12 – Pressure Distribution Color Chart**

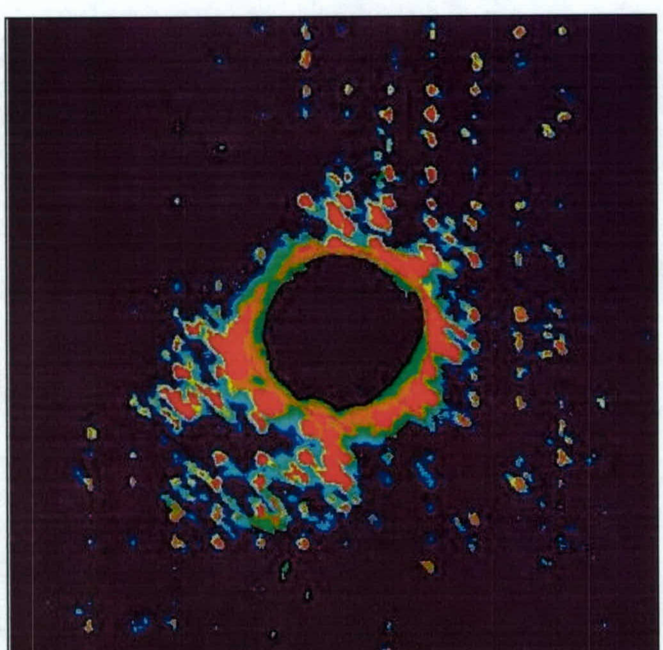


**Figure 3.13 – Pressure Distribution for 1" Thick Specimen Loaded to 15,000 lbs.**

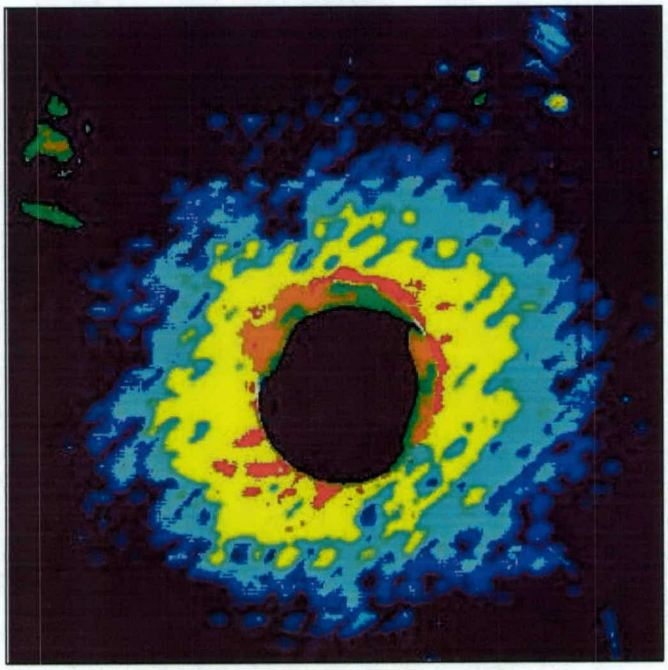


**Figure 3.14 – Pressure Distribution for ¾" Thick Specimen Loaded to 10,000**

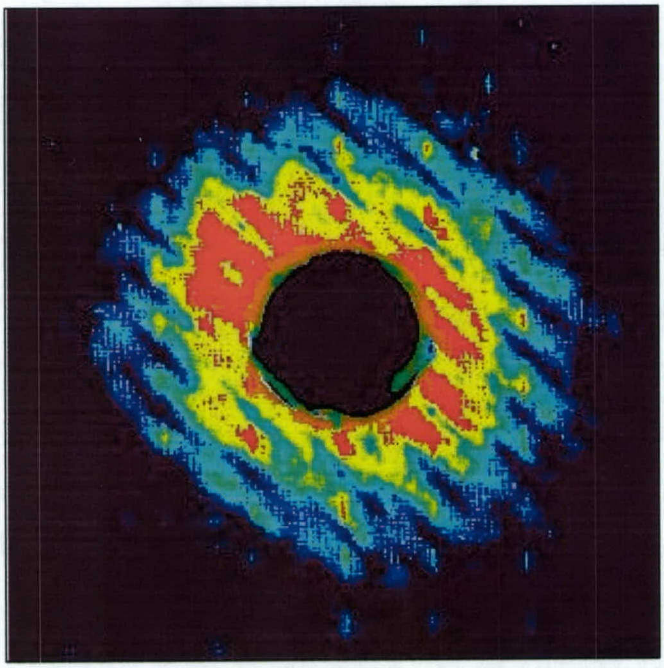


**Figure 3.15 – Pressure Distribution for ½" Thick Specimen Loaded to 5,000 lbs.**

Figures 3.16 and 3.17 show the pressure distribution of one of the tapered head bolt connections and one of the non-tapered bolt connections, respectively. Both test specimens were ¾" thick, and were loaded to 10,000 lbs. The pressures from these two tests are very similar to each other. Both are fairly evenly distributed over the central area of the connection. The only noticeable difference between the two is that the tapered head bolt seems to be applying the pressure more evenly over the connection than the non-tapered head bolt.

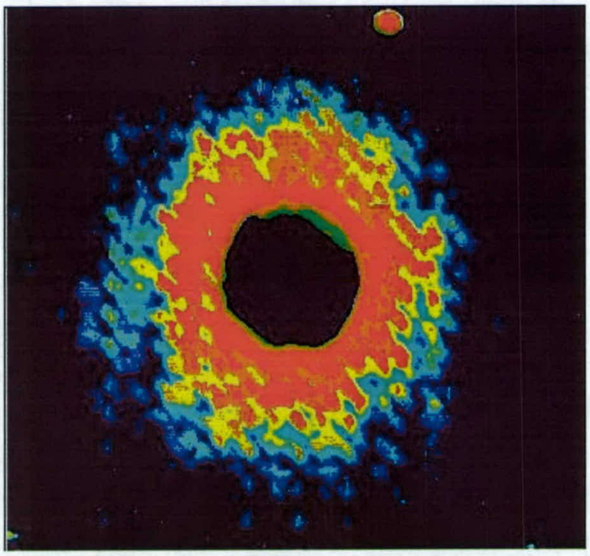


**Figure 3.16 – Pressure Distribution for Tapered Head Bolt Test Loaded to 10,000 lbs.**

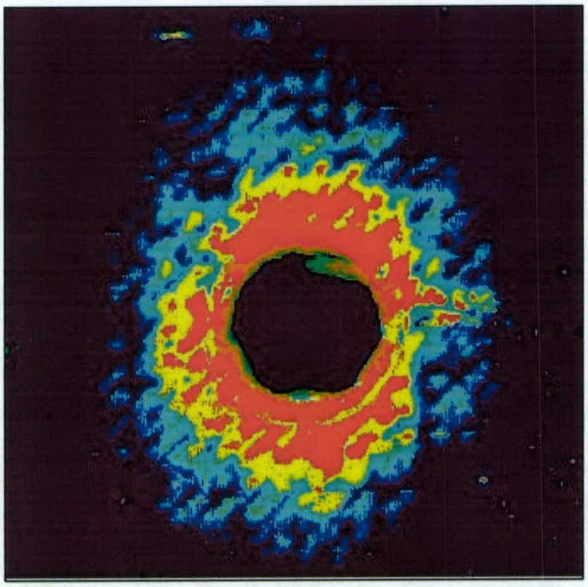


**Figure 3.17 – Pressure Distribution for Non-tapered Head Bolt Test Loaded to 10,000 lbs.**

### 3.5. Quantifying the Effects of Stress Relaxation on the E-Glass/Vinylester Composite

The general effects that stress relaxation has on the composite, in the transverse direction, can be seen in the results of the compression block tests, shown in section 3.1. Under relatively uniform loading, a great deal of the stress relaxation occurs over the first week after tightening the bolts. After a period of between 2 and 3 weeks, the load starts to level off, as there is relatively little difference in the bolt load between week 3 and the end of the 3-month time period.

The rate that the connection looses load over time most closely fits a power law curve, as follows:

$$P_t = \beta \cdot P_I \cdot t^{-\alpha} \tag{3.1}$$

In this equation, $P_t$ is the load at a given time, in pounds, $P_I$ is the initial preload, $\beta$ is a constant dependent on pressure distribution and reloading cycle, t is the time in days, and $\alpha$ is a constant which apparently depends on specimen thickness, initial preload, temperature, humidity and material properties of the composite. The expression stated as above can not resolved at time equal to zero, therefore an offset of 0.0069 days (10 minutes) was used to resolve this issue. The constant $\beta$ was used to account for the fact that curve fit is imperfect and to improve the prediction of the power law. The constant, $\beta$, is roughly 1 with a relatively uniform pressure distribution and no reloading. In that case $\beta * P_I$ is the initial preload. More testing needs to be done to determine what relationship $\alpha$ has to material properties, thickness, and preload.

Based on a power law fit to the curves, equations were developed for the load in each bolt in the compression block tests. These equations are shown in Tables 3.1 and 3.2 for two different load levels. Table 3.3 gives the values of $\beta$ for each bolt, as well as an average value, while Table 3.4 gives the values of $\alpha$. As seen in Table 3.3, the constant $\beta$ is on the average 0.95 in each bolt. In addition to the individual load equations for each bolt, a general equation is shown based on average values of $\beta$ and $\alpha$. These equations apply only to the cases where the specimen is ½" thick and the applied preload is either 10,000 or 5,000 pounds respectively. The equations developed fit the data very closely, with little error.

Tables 3.5 and 3.6 show estimates of the load in each bolt at different times, based on the power law equations from Tables 3.1 and 3.2. The actual data, at 1, 2, and 3 months, matches these estimates very closely. From these estimates, an average bolt-load in the composite joint at the given times was calculated, which is given at the bottom of the table. Extrapolating this data to a 10-year period is used for illustrative purposes only and is not intended as scientific or engineering data.

**Table 3.1 – Equations for Uniformly Compressed ½" Thick Specimen Loaded to 10,000 lbs.**

| bolt number | Equation |
|---|---|
| 1 | $P = 9544t^{-0.0201}$ |
| 2 | $P = 9629t^{-0.0133}$ |
| 3 | $P = 10439t^{-0.0121}$ |
| 4 | $P = 9434t^{-0.0147}$ |
| **average** | $P = 9761t^{-.0151}$ |

**Table 3.2 – Equations for Uniformly Compressed ½" Thick Specimen Loaded to 5,000 lbs.**

| bolt number | Equation |
|---|---|
| 1 | $P = 4890t^{-0.0117}$ |
| 2 | $P = 4845t^{-0.0158}$ |
| 3 | $P = 4758t^{-0.0168}$ |
| 4 | $P = 4453t^{-0.0353}$ |
| **average** | $P = 4737t^{-0.0199}$ |

**Table 3.3 - β Values for ½" Thick Compression Block Tests**

| 1/2 inch thick, 10000 lbs | | | 1/2 inch thick, 5000 lbs. | | |
|---|---|---|---|---|---|
| | **bolt #** | beta | | **bolt #** | beta |
| Test 1 | 1 | 0.91 | test 2 | 1 | 0.98 |
| | 2 | 0.95 | | 2 | 0.97 |
| | 3 | 0.97 | | 3 | 0.95 |
| | 4 | 0.94 | | 4 | 0.89 |
| | average | 0.95 | | average | 0.95 |

**Table 3.4 - $\alpha$ Values for ½" Thick Compression Block Tests**

| 5000 lbs. | |
|---|---|
| | |
| bolt number | Equation |
| 1 | 0.012 |
| 2 | 0.016 |
| 3 | 0.017 |
| 4 | 0.035 |
| average | 0.020 |

| 10000 lbs. | |
|---|---|
| | |
| bolt number | Equation |
| 1 | 0.020 |
| 2 | 0.013 |
| 3 | 0.012 |
| 4 | 0.015 |
| average | 0.015 |

**Table 3.5 – Extrapolated Load Predictions* for a Uniformly Loaded ½" Thick Composite Specimen Loaded to 10,000 lbs.**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| bolt # | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 1 | 8913 | 8790 | 8719 | 8598 | 8479 | 8209 | 8096 |
| 2 | 9203 | 9118 | 9069 | 8986 | 8904 | 8715 | 8635 |
| 3 | 10018 | 9934 | 9886 | 9803 | 9721 | 9534 | 9454 |
| 4 | 8973 | 8882 | 8830 | 8740 | 8652 | 8449 | 8364 |
| | | | | | | | |
| Averages | 9277 | 9181 | 9126 | 9032 | 8939 | 8727 | 8637 |

* Actual data period = 3 months

**Table 3.6 – Extrapolated Load Predictions* for a Uniformly Loaded ½" Thick Composite Specimen Loaded to 5,000 lbs.**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| bolt # | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 1 | 4699 | 4661 | 4639 | 4602 | 4565 | 4479 | 4443 |
| 2 | 4592 | 4542 | 4513 | 4464 | 4415 | 4304 | 4257 |
| 3 | 4494 | 4442 | 4412 | 4360 | 4310 | 4195 | 4146 |
| 4 | 3949 | 3854 | 3799 | 3707 | 3618 | 3418 | 3335 |
| | | | | | | | |
| Averages | 4434 | 4375 | 4341 | 4283 | 4227 | 4099 | 4046 |

* Actual data period = 3 months

### 3.6. Effects of Reloading on Stress Relaxation

In general, reloading the bolted hybrid connections decreases the rate of stress relaxation. Furthermore, there is a correlation between temperature shifts and the stress relaxation rate in specimens that have been reloaded. Based on the graphs in Section 3.2, the more a connection is reloaded, the greater effect temperature changes will have on the relaxation rate. As shown in those graphs, even small temperature changes of 5 to 10 degrees can cause a rapid increase in the stress relaxation rate, especially on the connections reloaded multiple times.

There also appears to be a correlation between the duration of a temperature shift and the increase in stress relaxation rate. Figure 3.3 shows the stress relaxation being effected by temperature shifts quite frequently during testing. Figures 3.4, and 3.6, show the stress relaxation rates increasing rapidly after an extended temperature change. In Figures 3.5, 3.7, and 3.8, there is not much change in stress relaxation rate, since the temperature shift occurs in a relatively short time period. Once the temperature returns to normal, the stress relaxation rate returns fairly close to what it was before the temperature change. There appears to be a trade off between reloading and extended temperature changes. Reloading helps to maintain the load in the connections, with varying success, depending on the number times the connection is reloaded, but reloaded specimens are much more sensitive to temperature changes that occur over extended time periods. It also seems that the more a specimen is reloaded, the more sensitive it is to those temperature changes.

Table 3.7 gives the power law equation for each test specimen from the tests shown in Figures 3.3 through 3.9. These are based on shifting the starting time of each curve to the last time that the connection was reloaded, since this is the curve the data will follow once all retorquing is complete. These equations apply only for the specific preloads used during those tests. The preloads for these tests were 2,500 and 5,000 pounds for the ½" thick specimens, 10,000 pounds for the ¾" thick specimens, and 7,500 and 15,000 pounds for the 1" thick specimens. These equations slightly overestimate the actual load curves, but in general are representative of the experimental data for the 3 month test period. The equation for the 7/8" thick specimen loaded to 10,000 pounds shows that there was a problem with that data acquisition channel during testing, since it is virtually a straight line.

**Table 3.7 – Equations for the Reloading Tests**

| | | Reloading Cycle | | | | | |
|---|---|---|---|---|---|---|---|
| thickness | Load (lbs) | 3 days | 3 days twice | 3 days thrice | 1 week | 2 weeks | no reloading |
| 1/2 inch | 2500 | $P = 2272t^{-0.0244}$ | $P = 2295t^{-0.0347}$ | $P = 2414t^{-0.0081}$ | $P = 2061t^{-0.0282}$ | $p = 2314t^{-0.0571}$ | $P = 1928t^{-0.055}$ |
| 1/2 inch | 5000 | $P = 4483t^{-0.0649}$ | $P = 4621t^{-0.0883}$ | $P = 4764t^{-0.0746}$ | $P = 4522t^{-0.0978}$ | $P = 4659t^{-0.0513}$ | $P = 3877t^{-0.0608}$ |
| 1/2 inch | 5000 | $P = 4656t^{-0.0345}$ | $P = 4703t^{-0.029}$ | $P = 4802t^{-0.0199}$ | $P = 4467t^{-0.0324}$ | $P = 4800t^{-0.0143}$ | $P = 4145t^{-0.0327}$ |
| 3/4 inch | 10000 | $P = 9507t^{-0.0271}$ | $P = 9569t^{-0.0288}$ | $P = 9686t^{-0.0153}$ | $P = 9172t^{-0.0259}$ | $P = 9500t^{-0.019}$ | $P = 8163t^{-0.0408}$ |
| 7/8 inch | 10000 | $P = 9217t^{-0.0473}$ | $P = 9444t^{-0.0642}$ | $P = 9866t^{0.00002}$ | $P = 9123t^{-0.0443}$ | $P = 9148t^{-0.0839}$ | $P = 8312t^{-0.0544}$ |
| 1 inch | 7500 | $P = 7272t^{-0.0272}$ | $P = 7502t^{-0.0282}$ | $P = 7420t^{-0.0235}$ | $P = 6773t^{-0.0166}$ | $P = 7207t^{-0.0322}$ | $P = 6711t^{-0.045}$ |
| 1 inch | 15000 | $P = 13709t^{-0.0288}$ | $P = 14035t^{-0.0375}$ | $P = 14478t^{-0.0188}$ | $P = 13551t^{-0.0344}$ | $P = 13458t^{-0.0282}$ | $P = 11786t^{-0.0584}$ |

Table 3.8 shows values of $\beta$ for each test shown in Figures 3.3 through 3.9, while Table 3.9 shows the values of $\alpha$ for these same tests. The value of $\beta$ seems to be dependent on both the number of times the connection is reloaded and the reloading cycle. It does not seem to be based on specimen thickness, since it does not seem to change much between the different thicknesses of each of the reloading tests. The constant $\alpha$ seems to be based on more than just the reloading cycle and preload. Temperature and humidity variations are shown to have a large effect on the constant $\alpha$ therefore it is recommended that future testing to determine $\alpha$ be done under very strict temperature and humidity control. Also the effect of temperature and humidity on $\alpha$ should be determined.

**Table 3.8 – Values of the Constant $\beta$ for the Reloading Tests**

| | | Reloading Cycle | | | | | |
|---|---|---|---|---|---|---|---|
| thickness | Load (lbs) | 3 days | 3 days twice | 3 days thrice | 1 week | 2 weeks | no reloading |
| 1/2 inch | 2500 | 0.91 | 0.92 | 0.97 | 0.82 | 0.93 | 0.77 |
| 1/2 inch | 5000 | 0.93 | 0.94 | 0.96 | 0.89 | 0.96 | 0.83 |
| 1/2 inch | 5000 | 0.90 | 0.92 | 0.95 | 0.90 | 0.93 | 0.78 |
| 3/4 inch | 10000 | 0.95 | 0.96 | 0.97 | 0.92 | 0.95 | 0.82 |
| 7/8 inch | 10000 | 0.92 | 0.94 | 0.99 | 0.91 | 0.91 | 0.83 |
| 1 inch | 7500 | 0.97 | 1.00 | 0.99 | 0.90 | 0.96 | 0.89 |
| 1 inch | 15000 | 0.92 | 0.94 | 0.97 | 0.90 | 0.90 | 0.79 |
| | | | | | | | |
| Averages | | 0.93 | 0.95 | 0.97 | 0.91 | 0.94 | 0.82 |

**Table 3.9 – Values of the Constant $\alpha$ for the Reloading Tests**

| | | Reloading Cycle | | | | | |
|---|---|---|---|---|---|---|---|
| thickness | Load (lbs) | 3 days | 3 days twice | 3 days thrice | 1 week | 2 weeks | no reloading |
| 1/2 inch | 2500 | 0.024 | 0.035 | 0.008 | 0.028 | 0.057 | 0.055 |
| 1/2 inch | 5000 | 0.065 | 0.088 | 0.075 | 0.099 | 0.051 | 0.061 |
| 1/2 inch | 5000 | 0.035 | 0.029 | 0.020 | 0.032 | 0.014 | 0.033 |
| 3/4 inch | 10000 | 0.027 | 0.029 | 0.015 | 0.026 | 0.019 | 0.041 |
| 7/8 inch | 10000 | 0.047 | 0.064 | 0.000 | 0.044 | 0.084 | 0.054 |
| 1 inch | 7500 | 0.027 | 0.028 | 0.024 | 0.017 | 0.032 | 0.045 |
| 1 inch | 15000 | 0.029 | 0.038 | 0.019 | 0.034 | 0.028 | 0.058 |

Based on these equa tions, predictions can be made for the loads at different times. Tables 3.10 through 3.16 show load predictions for the tests shown in Figures 3.3 through 3.9, respectively. Again, predictions overestimate the actual load in the connection after 3 months, by 2 – 8 %, depending on the reloading cycle.

**Table 3.10 – Extrapolated Load Predictions* for ½" Thick Specimens, Fig. 3.3**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| loading cycle | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 2091 | 2056 | 2035 | 2001 | 1968 | 1892 | 1860 |
| 3 days twice | 2039 | 1991 | 1963 | 1916 | 1871 | 1769 | 1727 |
| 3 days thrice | 2348 | 2335 | 2327 | 2314 | 2301 | 2272 | 2259 |
| 1 week | 1873 | 1836 | 1816 | 1780 | 1746 | 1668 | 1636 |
| 2 weeks | 1905 | 1831 | 1789 | 1720 | 1653 | 1508 | 1450 |
| no reloading | 1599 | 1539 | 1505 | 1449 | 1395 | 1277 | 1229 |

* Actual data period = 3 months

**Table 3.11 – Extrapolated Load Predictions* for ½" Thick Specimens, Fig. 3.4**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| loading cycle | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 3595 | 3437 | 3348 | 3201 | 3060 | 2756 | 2635 |
| 3 days twice | 3422 | 3219 | 3106 | 2921 | 2748 | 2384 | 2242 |
| 3 days thrice | 3696 | 3510 | 3405 | 3234 | 3071 | 2723 | 2586 |
| 1 week | 3242 | 3030 | 2912 | 2721 | 2543 | 2173 | 2030 |
| 2 weeks | 3913 | 3776 | 3698 | 3569 | 3445 | 3172 | 3061 |
| no reloading | 3152 | 3022 | 2949 | 2827 | 2710 | 2458 | 2356 |

* Actual data period = 3 months

**Table 3.12 – Extrapolated Load Predictions* for ½" Thick Specimens, Fig. 3.5**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| **loading cycle** | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 4140 | 4042 | 3986 | 3892 | 3800 | 3595 | 3510 |
| 3 days twice | 4261 | 4176 | 4127 | 4045 | 3965 | 3784 | 3709 |
| 3 days thrice | 4488 | 4427 | 4391 | 4331 | 4271 | 4137 | 4080 |
| 1 week | 4001 | 3912 | 3861 | 3775 | 3691 | 3504 | 3426 |
| 2 weeks | 4572 | 4527 | 4501 | 4456 | 4412 | 4312 | 4270 |
| no reloading | 3708 | 3625 | 3577 | 3497 | 3419 | 3244 | 3171 |

* Actual data period = 3 months

**Table 3.13 – Extrapolated Load Predictions* for 7/8" Thick Specimens, Fig. 3.6**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| **loading cycle** | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 7848 | 7594 | 7450 | 7210 | 6977 | 6466 | 6257 |
| 3 days twice | 7592 | 7261 | 7075 | 6767 | 6472 | 5837 | 5583 |
| 3 days thrice | 9867 | 9867 | 9867 | 9867 | 9867 | 9867 | 9868 |
| 1 week | 7847 | 7610 | 7474 | 7248 | 7029 | 6546 | 6348 |
| 2 weeks | 6877 | 6489 | 6272 | 5917 | 5583 | 4878 | 4602 |
| no reloading | 6908 | 6652 | 6507 | 6266 | 6034 | 5528 | 5324 |

* Actual data period = 3 months

**Table 3.14 – Extrapolated Load Predictions* for ¾" Thick Specimens, Fig. 3.7**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| **loading cycle** | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 8670 | 8509 | 8416 | 8259 | 8106 | 7760 | 7615 |
| 3 days twice | 8676 | 8505 | 8406 | 8240 | 8077 | 7711 | 7559 |
| 3 days thrice | 9195 | 9098 | 9041 | 8946 | 8852 | 8636 | 8545 |
| 1 week | 8399 | 8249 | 8163 | 8018 | 7875 | 7554 | 7419 |
| 2 weeks | 8905 | 8789 | 8721 | 8607 | 8495 | 8239 | 8131 |
| no reloading | 7106 | 6907 | 6794 | 6605 | 6420 | 6012 | 5845 |

* Actual data period = 3 months

**Table 3.15 – Extrapolated Load Predictions* for 1" Thick Specimens, Fig. 3.8**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| **loading cycle** | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 6630 | 6506 | 6434 | 6314 | 6196 | 5931 | 5820 |
| 3 days twice | 6816 | 6684 | 6608 | 6480 | 6355 | 6073 | 5955 |
| 3 days thrice | 6850 | 6739 | 6675 | 6567 | 6461 | 6221 | 6121 |
| 1 week | 6401 | 6328 | 6285 | 6213 | 6142 | 5980 | 5912 |
| 2 weeks | 6459 | 6316 | 6235 | 6097 | 5962 | 5661 | 5536 |
| no reloading | 5759 | 5582 | 5481 | 5313 | 5150 | 4790 | 4643 |

* Actual data period = 3 months

**Table 3.16 – Extrapolated Load Predictions* for 1" Thick Specimens, Fig. 3.9**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| **loading cycle** | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| 3 days | 12430 | 12184 | 12043 | 11805 | 11571 | 11047 | 10829 |
| 3 days twice | 12354 | 12037 | 11856 | 11552 | 11255 | 10596 | 10324 |
| 3 days thrice | 13581 | 13405 | 13304 | 13131 | 12961 | 12575 | 12412 |
| 1 week | 12055 | 11771 | 11608 | 11334 | 11067 | 10471 | 10224 |
| 2 weeks | 12227 | 11990 | 11854 | 11625 | 11400 | 10894 | 10683 |
| no reloading | 9663 | 9279 | 9062 | 8703 | 8358 | 7608 | 7306 |

* Actual data period = 3 months

### 3.7. Effects of Tapered vs. Non-Tapered Bolts

Based upon the results, there seems to be little difference in stress relaxation when using tapered head bolts as opposed to non-tapered head bolts. There seems to be a slight difference in the pressure distributions of the tapered and non-tapered head bolts, but there seems to be little to no effect on the rate of stress relaxation. The data on the graphs in Figures 3.10 and 3.11 are virtually on top of one another. Tapered head bolts appear to be better at producing an even pressure distribution, but beyond that, there seems to be no advantage to using tapered bolts over non-tapered ones.

These tests also closely follow a power law fit to the curves, as shown in equation 3.1. Based upon this, equations were generated that best fit each curve. Tables 3.17 and 3.18 show the equations for each of the bolted connections shown in Figures 3.10, and 3.11, as well as an equation which uses an average value of the constants $\beta$ and $\alpha$. The Equations from Table 3.18 closely resemble the equation for the reloading tests done on the ¾" thick specimen with no reloading in the connection and a preload of 10,000 lbs.. This is as expected since no reloading was done to any of the tapered vs. non-tapered test connections, and all connections were loaded to 10,000 lbs. preload.

**Table 3.17 – Equations for ¾" Tapered and Non-Tapered Head Bolt Tests When Loaded to 5,000 lbs.**

| bolt number | Equation |
|---|---|
| tapered bolt 1 | $P = 4309t^{-0.0098}$ |
| tapered bolt 2 | $P = 4315t^{-0.0067}$ |
| non-tapered bolt 1 | $P = 4183t^{-0.0103}$ |
| non-tapered bolt 2 | $P = 3944t^{-0.0057}$ |
| **avergage tapered** | $P = 4312t^{-0.0083}$ |
| **average non** | $P = 4064t^{-0.008}$ |

**Table 3.18 – Equations for ¾" Tapered and Non-Tapered Head Bolt Tests When Loaded to 10,000 lbs.**

| bolt number | Equation |
|---|---|
| tapered bolt 1 | $P = 8138t^{-0.0407}$ |
| tapered bolt 2 | $P = 7693t^{-0.042}$ |
| tapered bolt 3 | $P = 8194t^{-0.0388}$ |
| non-tapered bolt 1 | $P = 7806t^{-0.0415}$ |
| **avergage tapered** | $P = 8008t^{-0.0345}$ |

Values for the constant β are shown in Table 3.19, while the constant, α, is shown in Table 3.20. The values of α and β for the case where the initial preload was 10,000 lbs are very close to those of the ¾" thick specimen with no reloading and an initial preload of 10,000 lbs shown in Tables 3.8 and 3.9.

Future predictions were made with these tests, based on the equations for each connection. These predictions closely match the actual loads in each bolt for the corresponding 1-month, 2-month, and 3-month time periods. Tables 3.21 and 3.22 show the predictions, as well as an average prediction, of load for both the tapered and non-tapered head bolted specimens based on the average predictions of the load in each of the connections. The results from Table 3.22 closely match the predictions made for the ¾" thick non-reloading test loaded to 10,000 lbs., shown in Table 3.14.

**Table 3.19 – Values of $\beta$ for ¾" Tapered vs. Non-Tapered Bolt Tests**

| | load (lbs) | beta |
|---|---|---|
| Tapered Bolts | 5000 | 0.86 |
| | 5000 | 0.88 |
| | 10000 | 0.81 |
| | 10000 | 0.76 |
| | 10000 | 0.83 |
| | average | 0.83 |
| Non-Tapered Bolts | 5000 | 0.84 |
| | 5000 | 0.81 |
| | 10000 | 0.78 |
| | average | 0.81 |

**Table 3.20 – Values of $\alpha$ for ¾" Tapered vs. Non-Tapered Head Bolt Tests**

| 5000 lbs | |
|---|---|
| | |
| **bolt number** | **alpha** |
| tapered bolt 1 | 0.0098 |
| tapered bolt 2 | 0.0067 |
| non-tapered bolt 1 | 0.0103 |
| non-tapered bolt 2 | 0.0057 |
| **avergage tapered** | 0.0083 |
| **average non** | 0.0080 |

| 10000 lbs. | |
|---|---|
| | |
| **bolt number** | **alpha** |
| tapered bolt 1 | 0.0407 |
| tapered bolt 2 | 0.0420 |
| tapered bolt 3 | 0.0388 |
| non-tapered bolt 1 | 0.0415 |
| **avergage tapered** | 0.0345 |

**Table 3.21 – Extrapolated Load Predictions* for ¾" Tapered and Non-Tapered Head Bolt Tests Loaded to 5,000 lbs.**

| Estimates of Load over time | | | | | | | |
|---|---|---|---|---|---|---|---|
| bolt number | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| tapered bolt 1 | 4168 | 4140 | 4123 | 4095 | 4068 | 4004 | 3977 |
| tapered bolt 2 | 4218 | 4198 | 4187 | 4167 | 4148 | 4104 | 4085 |
| non-tapered bolt 1 | 4039 | 4010 | 3994 | 3965 | 3937 | 3872 | 3845 |
| non-tapered bolt 2 | 3868 | 3853 | 3844 | 3829 | 3814 | 3779 | 3764 |
| | | | | | | | |
| average tapered | 4193 | 4169 | 4155 | 4131 | 4108 | 4054 | 4031 |
| | | | | | | | |
| average non-tapered | 3954 | 3932 | 3919 | 3897 | 3875 | 3826 | 3804 |

* Actual data period = 3 months

**Table 3.22 - Extrapolated Load Predictions* for ¾" Tapered and Non-Tapered Head Bolt Tests Loaded to 10,000 lbs.**

| | Load Estimates using Power Law Equations (lbs) | | | | | | |
|---|---|---|---|---|---|---|---|
| **bolt number** | 1month | 2 months | 3 months | 6 months | 1 year | 5 years | 10 years |
| tapered bolt 1 | 7086 | 6889 | 6776 | 6588 | 6405 | 5999 | 5832 |
| tapered bolt 2 | 6669 | 6477 | 6368 | 6185 | 6008 | 5615 | 5454 |
| tapered bolt 3 | 7181 | 6990 | 6881 | 6699 | 6521 | 6126 | 5964 |
| non-tapered bolt 1 | 6779 | 6587 | 6477 | 6293 | 6115 | 5719 | 5557 |
| | | | | | | | |
| **averages of tapered** | 6979 | 6786 | 6675 | 6491 | 6311 | 5913 | 5750 |

* Actual data period = 3 months

### 3.8. Environmental Tests Results

A preliminary set of environmental tests is presented in this section including several tests performed at 150°F and 90-95% RH. The purpose of this study was to initiate the environmental testing and to check-out the equipment and procedures. A more comprehensive set of testing is planned for the future. In planning future environmental testing it is important to separate the thermal expansion effect from the creep, moisture and stress relaxation effect. Thus, late in the project, the testing was revised to the current proposed study given in the test matrix in Table 2.1 and the procedure given in Section 2.5. It was felt that these conditions would best simulate both underwater applications and dry dock conditions.

The results after a five-day period of the first series of environmental tests are presented in Figure 3.18. Each bolt in this series of tests was initially loaded to 10,000 lbs. Specimen C1 will be held at 70°F and 50% RH. Specimen C2 was preconditioned at 150°F and 90%RH for 2-3 months and is currently submerged in water at 70°F. Specimen C3 was preconditioned at 150°F and 90% RH for 2-3 months, and is now being held at 70°F and 50%RH. Specimen C4 was loaded and held at 70°F and 50% RH for one week, and will then be submerged in water at 70°F. Specimen C5 was submerged in water at 70°F after loading, and will be cycled in and out of water at a one-month interval.

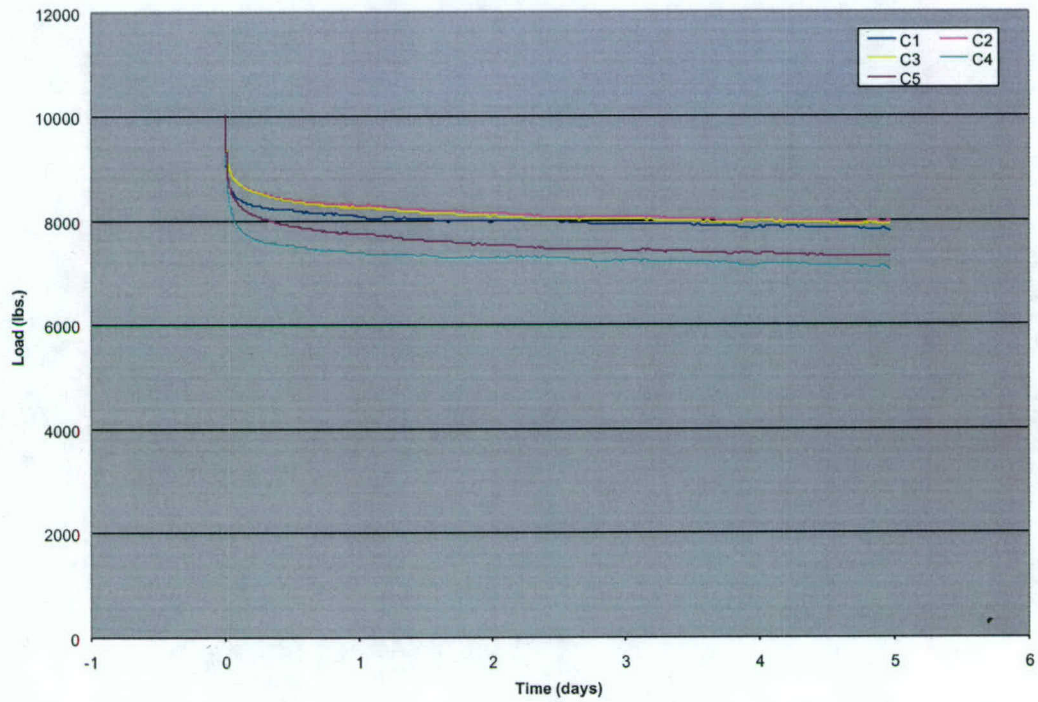



**Figure 3.18 - Initial 5 Day Environmental Test Results Loaded to 10,000 lbs.**

## 4. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Stress relaxation in hybrid composite/metal bolted connections was studied experimentally during this effort. In so doing, EGlass/vinyl ester plates of varying thickness were bolted to aluminum plates with instrumented steel bolts to determine the primary stress relaxation response. Specific test plans were developed to study stress relaxation under relatively uniform loading, the effect of retorquing the bolts, and the effect of tapered head versus protruding head bolts. A pilot study on the effect of the environment was also undertaken to develop parameters and procedures for future study.

Reloading the bolted hybrid connections in general allows the connection to retain more of its initial preload. It is projected that after a one-year period connections reloaded multiple times will retain more of their initial preload than connections not reloaded or reloaded a single time only. The predicted bolt load for connections loaded thrice after 3-days ranged from 13% to 65% greater than in connections not retorqued. This conclusion is based upon limited duration testing at ambient conditions. It is recommended that further tests are conducted under temperature and humidity controlled conditions and that the test period be extended. There appears to be a trade-off between reloading and temperature effects, however. It seems that the specimens reloaded multiple times are more sensitive to changes in temperature, even minor changes. Therefore, stress history appears to influence the thermal expansion properties. In particular, temperature shifts that occur for extended time periods seem to have a greater effect on the rate of stress relaxation. The rate of the stress relaxation increases in the reloaded specimens, while having little effect on the specimens that were not reloaded for cases where the temperature increases by 5 to 10 degrees F, and remains elevated for an extended period (about 2 weeks), and then drops to its previous value. In the case of the ½" bolts loaded to 2,500 lbs, a temperature shift of 20° F was observed. This caused the load in the bolts to increase dramatically and to exceed the initial preload in some cases. In summary, the material parameters need to be determined under constant environmental conditions and the influence of temperature on the stress relaxation and stress cycling needs to be studied.

The bolt load with respect to time, for the hybrid connection, was analyzed in the form of simple power law expression given previously as Equation 3.1 as follows

$$P_t = \beta \cdot P_I \cdot t^{-\alpha} \tag{3.1}$$

In this expression, $P_t$ is the load at time t, $P_I$ is the initial preload in pounds, $t$ is the time in days and $\alpha$ and $\beta$ are constants that depend on constituent materials, geometry and test conditions. Constants $\alpha$ and $\beta$ were determined using a least square power law fit of the relaxation data with the time offset by 0.007 days (10 minutes) to account for the fact that Equation 3.1 can not be resolved with time equal to zero. Allowing the constant $\beta$ to be other than unity aids in the prediction of the response at increased time values while compromising the prediction accuracy at small time values.

The constant, $\beta$, was found to be dependent primarily on the pressure distribution in the connection. When the composite is compressed relatively uniformly, such as in the compression block tests, this constant is roughly equal to 0.95, which indicates that a good first estimate for $\beta P_I$, under a uniform loading, is the prelaod value. In the single bolt connections, $\beta$ is smaller due to the non-uniform stress distribution, but tends to increase if the connection is reloaded. With no reloading, the average value of $\beta$ was 0.82, ranging from 0.77 to 0.89. Retorquing after 3-days, 3-days twice, and 3-days thrice caused the average value of $\beta$ to gradually increase to 0.93, 0.95 and 0.97, respectively. Waiting longer to perform a single retorquing is also apparently beneficial in that $\beta$ increased from 0.94 to 0.97 when the wait period was extended from 1 to 2 weeks. Accordingly, retorquing plays a significant role in determining this constant.

Quantifying the effects of $\alpha$ is a bit more complex. The constant $\alpha$ is dependent on factors such as initial preload level, specimen thickness, material properties, humidity and temperature. In the compression block tests, $\alpha$ averaged 0.020 and 0.015 at preload levels of 5,000 and 10,000 lbs respectively. Single bolt retorquing tests showed no trend in quantification of $\alpha$. In some cases $\alpha$ increased then decreased when 3-day, 3-day twice and 3-day thrice reloadings were compared. In the case of the ¾" bolts loaded to 10,000 lbs, the 3-day thrice loading showed a nearly zero value of $\alpha$. This was due to an increase in bolt load caused by thermal fluctuations. Observation of the load versus time plot for this case shows the load to be holding fairly constant and actually increases above the preload level during a time when the temperature relative to the initial state increases. More testing needs to be done to determine the dependence of $\alpha$ on thickness, temperature variations, and initial preload. This should include tests at the same initial preload on different specimen thicknesses, and tests at different preloads using the same specimen thickness under controlled environmental conditions.

It is recommended that an effort be made to replace the current power law model with one that can more accurately predict the response at small time values. Other curve fitting laws should also be evaluated which account for effects of initial stress level, stress level change with time, temperature and humidity.

The tapered vs. non-tapered head bolt tests show very little difference in response between these two bolt geometries. The average calculated value of the constant $\beta$ for the tapered bolt connections is 0.83, vs. 0.81 for the non-tapered bolt connections. The individual calculations for $\beta$ vary from 0.76 to 0.81 in the tapered case and 0.78 to 0.84 in the non-tapered case, demonstrating that there are some variations in quantifying $\beta$ in these cases. There also seems to be minor differences in the pressure distributions at the center of the tapered bolt connections vs. those of the non-tapered head bolt connections. More testing should be done using the two connections.

Environmental testing of the connections was commenced, on a pilot study basis, to establish the required equipment and techniques to perform this study. The importance of a controlled environment in establishing material parameters was demonstrated in the previous discussion. In the pilot testing performed thus far, some damage occurred to the gauged bolts due to moisture intrusion. Care must be taken when using instrumented bolts in wet environmental conditions.

It is recommended that the use of bolts for hybrid composite/metal connections be done with caution. Especially in the case of friction type joints where a minimum amount of bolt load must be maintained. A designer must consider the decrease in bolt load due to stress relaxation effects when choosing the working bolt load. Consideration must be made with respect to the amount of preload loss or the possibility for preload gain. This study was a first attempt to quantify such effects in hybrid EGlass composite/metal hybrid connections. Further studies are required. As stated, current results seem promising that reloading the connections helps to maintain the initial preload, however, the temperature effects seem to cause an increase in the stress relaxation rate when multiple retorquing occurs. More testing should be conducted to isolate the effects of temperature and moisture on the stress relaxation response.

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## Appendix A. Material Properties of the E-Glass/Vinylester Composite

Tension (ASTM 3094) and compression (ASTM 3410) tests were performed on ½" thick specimens cut from the E-Glass/Vinylester composite used the stress relaxation studies. Table A.1 gives the material properties found from this testing. Fiber volume (burn-off) tests were performed on the specific panels used in the stress relaxation tests. The fiber volumes are listed in Table A.2 for each panel. Panels 21 and 22 were used in the pilot tests. In addition, panel 21 was also used in the compression block tests shown in Figures 3.1 and 3.2, as well as the reloading tests shown in Figures 3.4 and 3.5, while panel 22 was also used for the tapered vs. non-tapered head bolt tests shown in Figure 3.10. Panel 54 was used in the reloading tests shown in Figure 3.3, while panel 45 is being used for the environmental tests. Panel 24 was used for the reloading tests shown in Figure 3.6, while panel 34 was used for the reloading tests shown in Figure 3.7, and the tapered vs. non-tapered tests shown in Figure 3.11. Finally, panel 36 was used for the reloading tests shown in Figure 3.8, while panel 44 was used for the tests shown in Figure 3.9.

**Table A.1 – Tensile and Compressive Properties of the E-Glass/Vinylester Composite**

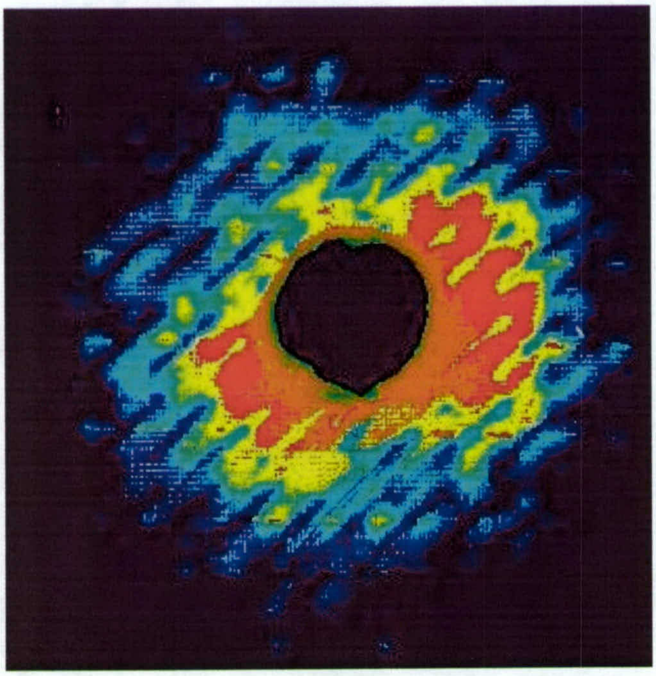
| | |
|---|---|
| Tensile Strength | 39,000 psi |
| Tensile Modulus | 2.0 Msi |
| Compressive Strength | 40,250 psi |
| Compressive Modulus | 2.7 Msi |

**Table A.2 – Fiber Volume Percents in Each Panel Used During Testing**

| Panel # | panel thickness | Fiber Volume (%) |
|---|---|---|
| 21 | 1/2" | 51.4 |
| 54 | | not yet tested |
| | | |
| 22 | 3/4" | 53 |
| 34 | | 50 |
| 45 | | 51 |
| 24 | 7/8" | 46.9 |
| | | |
| 36 | 1" | 52.1 |
| 44 | | 47.6 |

## Appendix B. Additional Pressure Distribution Scans

Additional pressure distributions were scanned and are included in this appendix. Figure B.1 shows two additional pressure distributions from the ½" thick reloading specimens loaded to 5,000 lbs. The pressure distributions shown in Figure B.2 are from two ¾" thick reloading test specimens loaded to 10,000 lbs. Finally, Figure B.3 show two additional pressure distributions from the tapered head bolt test specimens loaded to 10,000 lbs.



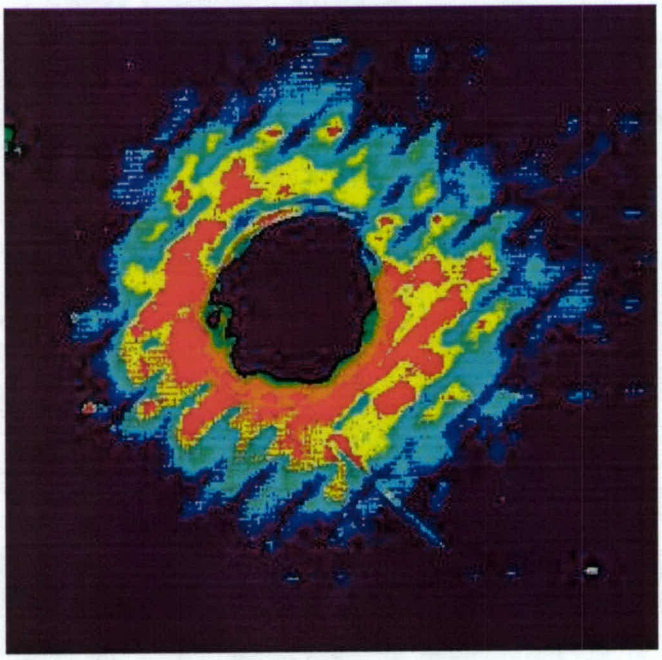


**Figure B.1 – Two Additional Pressure Distributions from ½" Thick Specimens**

**Loaded to 5,000 lbs.**

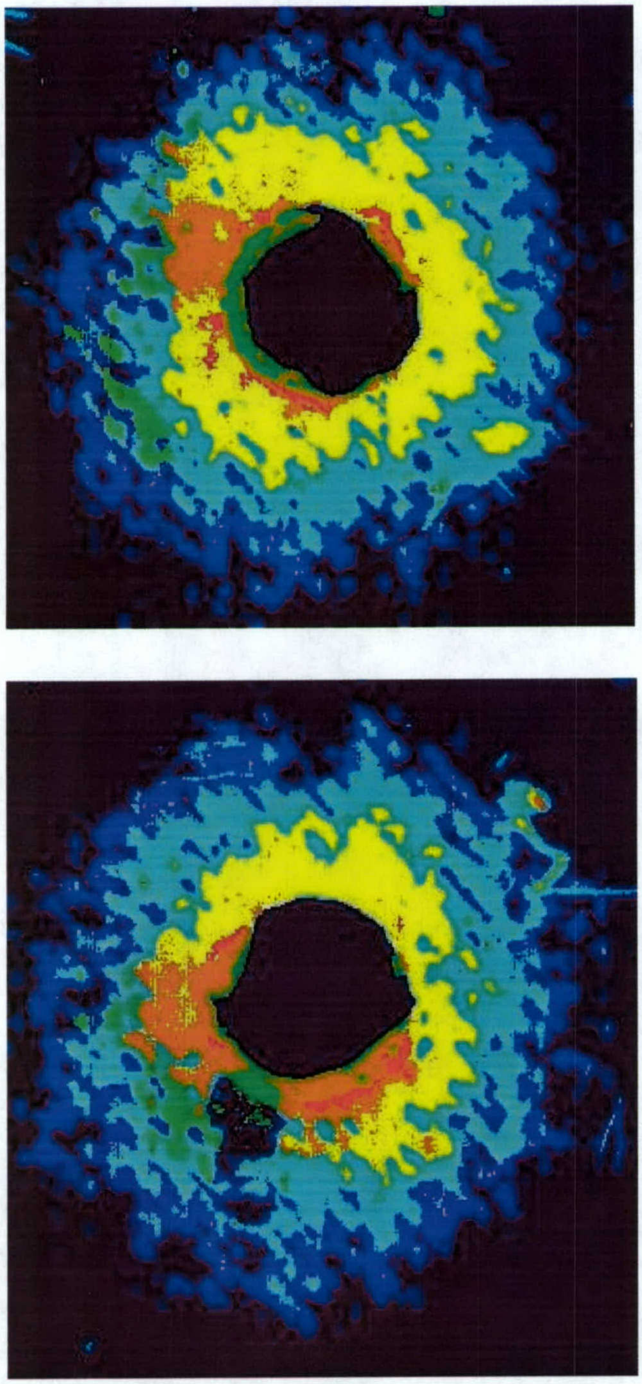
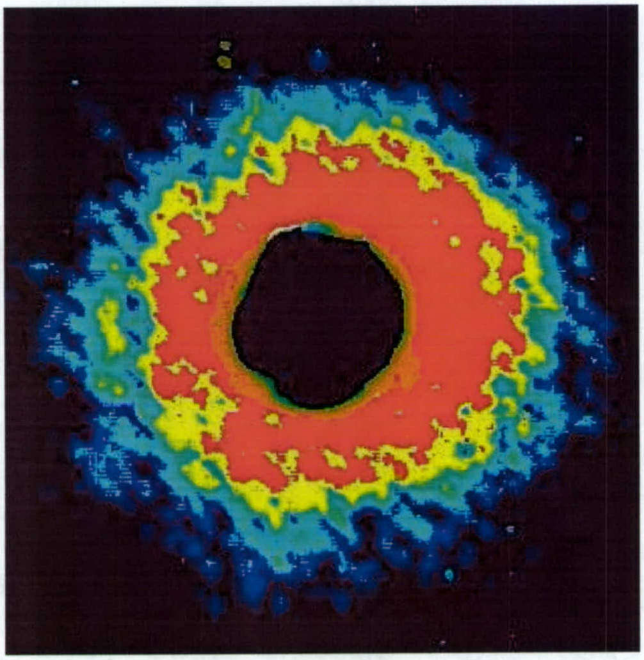


**Figure B.2 – Two Additional Pressure Distributions from ¾" Thick Specimens**

**Loaded to 10,000 lbs.**



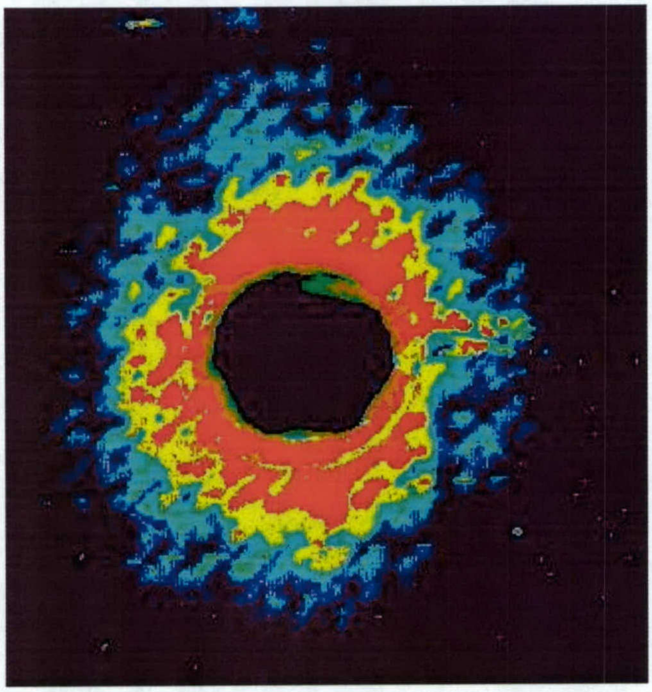


**Figure B.3 – Two Additional Pressure Distributions from Tapered Head Bolt Tests Loaded to 10,000 lbs.**

## Appendix C. Single Bolt Aluminum Tests

During testing, a few aluminum specimens were tested with no composite to examine whether there was any relaxation occurring in the bolt sensor. Figures C.1, C.2, and C.3 show the three bolted aluminum tests that have been run. Two bolt sizes were used, ½" and 1". For the ½" diameter bolt, a ½" by 5" by 5" specimen was used, while for the 1" diameter bolt, a 1" by 10" by 10" specimen was used. Figures C.1 and C.2 used the same bolt and the same piece of aluminum during two separate time periods. These show no relaxation in the sensors, but they do show possible drift in the sensors.

Using a statically indeterminent model based on thermal expansion for the tests in Figures C.1 and C.3, load changes based on a few of the temperature changes were calculated. These are shown in Table C.1, along with actual load changes. The actual changes from Figure C.3 vary slightly from theoretical most likely due to the simplified model used and drift in the sensor. A variation of a couple hundred pounds isn't uncommon when the 1" bolts are loaded to 15,000 lbs.

The first load change in Figure C.1 actually matches closely to the theoretical value. The second load change doesn't compare as well, however. The load goes up by about 400 pounds, but does not drop when the temperature does. This could very well indicate a sensor issue with that specific load bolt that carried over into the test shown in Figure C.2. No calculations were done on the test shown in Figure C.2, since it is apparent based on previous calculations that the load increase is not due to thermal expansion of the system. It is most likely due to a problem that occurred with that sensor. A sample calculation is shown on page 108.

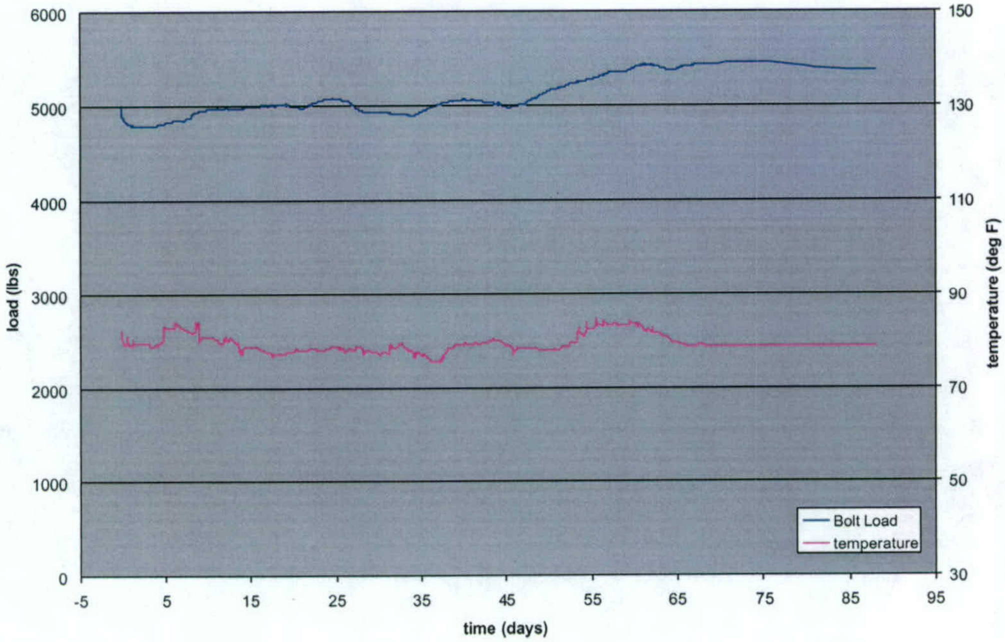



**Figure C.1 - ½" Bolted Aluminum Specimen Test 1**

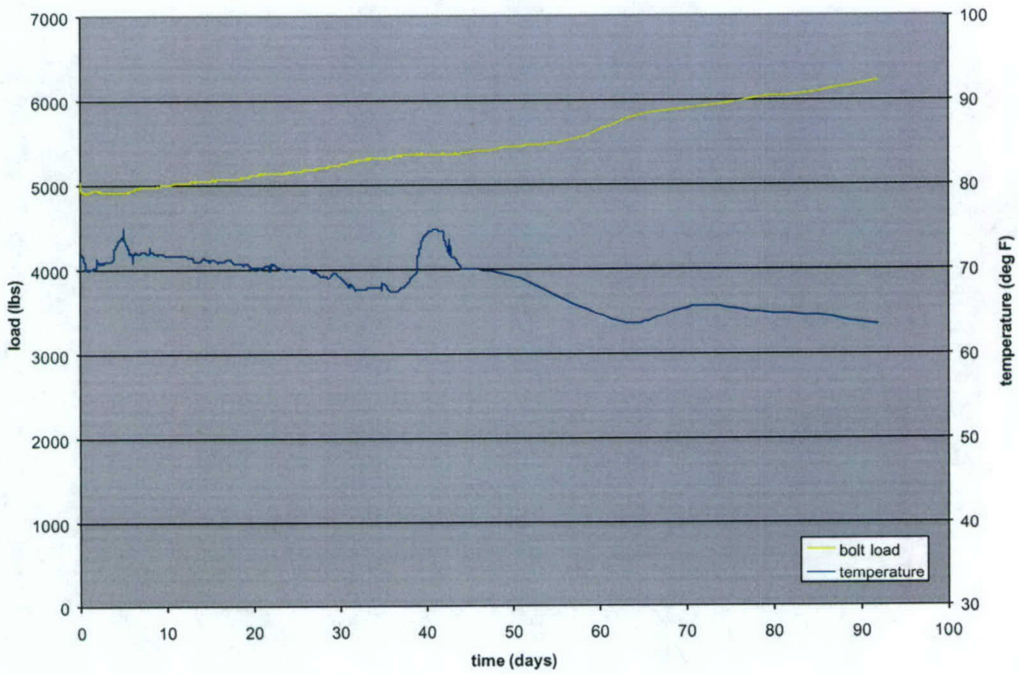



**Figure C.2 – ½" Bolted Aluminum Specimen Test 2**

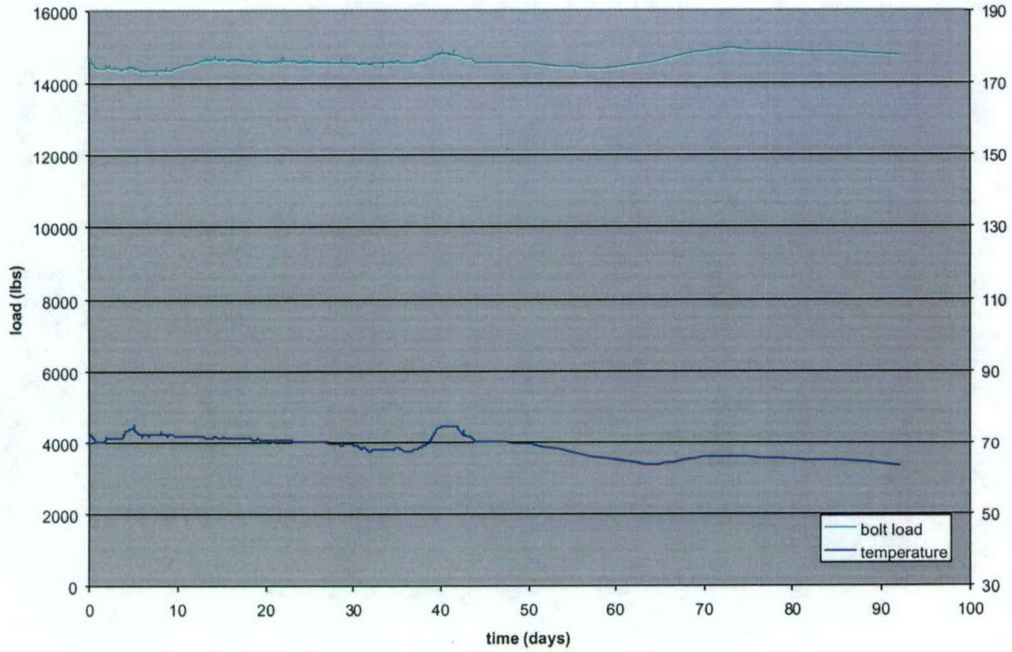



**Figure C.3 –1" Bolted Aluminum Specimen Test**

**Table C.1 – Theoretical vs. Experimental Load Changes Due to Thermal Expansion**

| Aluminum Test Specimen | Time Period Of Temperature Change | Temperature Change (deg F) | Theoretical Load Change (lbs) | Experimental Load Change |
|---|---|---|---|---|
| Figure C.1 | day 38 to 44 | 4 | 102 | 130 |
| | day 51 to 58 | 5.3 | 135 | 410 |
| Figure C.3 | day 37 to 41 | 6.7 | 683 | 300 |
| | day 60 to 70 | 2 | 204 | 500 |

Statically Indeterminate System

Known Values:

$E_{bolt} := 30 \cdot 10^{6}$ $\quad E_{aluminum} := 10 \cdot 10^{6}$

$\alpha_{bolt} := 6.5 \cdot 10^{-6}$ $\quad \alpha_{aluminum} := 12.8 \cdot 10^{-6}$

$D_{bolt} := .5$ $\quad ID_{washer} := .5$ $\quad OD_{washer} := 1.375$ $\quad delT := 5.\!:$

Cross-sectional Areas:

$A_{aluminum} := \frac{\pi}{4} \cdot \left(1.375^{2} - .5^{2}\right)$ $\quad A_{bolt} := \frac{\pi}{4} \cdot \left(.5^{2}\right)$

$A_{aluminum} = 1.289$ $\quad A_{bolt} = 0.196$

Load Increase or Decrease Due to Temperature:

$$F_{washer} = F_{bolt} = F$$

$$F \cdot \left(\frac{1}{A_{bolt} \cdot E_{bolt}} + \frac{1}{A_{aluminum} \cdot E_{aluminum}}\right) = \left(\alpha_{aluminum} - \alpha_{bolt}\right) \cdot delT$$

$$F := \frac{\left(\alpha_{aluminum} - \alpha_{bolt}\right) \cdot delT}{\left(\frac{1}{A_{bolt} \cdot E_{bolt}} + \frac{1}{A_{aluminum} \cdot E_{aluminum}}\right)}$$

$$F = 134.979$$

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**14. ABSTRACT**

An experimental investigation of the influence of stress relaxation on watertight integrity of hybrid composite-to-metal bolted connections is presented. This study focuses on the effects of bolt reloading, use of tapered-head bolts versus protruding-head bolts, and briefly addresses environmental effects. All tests were conducted for a time period of at least three months, in order to estimate primary and secondary stress relaxation effects. The reloading tests show that some of the preload in the connections can be maintained with periodic retightening of the bolts. In a limited amount of testing it was observed that temperature shifts caused more rapid stress relaxation rates. Little difference in relaxation was observed when comparing tapered-head bolts with protruding-head bolts, given that roughly equal stress relaxation rates were observed. Further research on this area is required.

**15. SUBJECT TERMS**

Composites; Hybrid Structures; Bolted Connections; Stress Relaxation; Structural Monitoring

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