This is to certify that the

thesis entitled

A STUDY OF BOLTED SINGLE LAP JOINTS
BETWEEN COMPOSITES AND ALUMINUM

presented by

Scott Edwin Hodges

has been accepted towards fulfillment
of the requirements for

M.S. degree in Material Science Engineering

Gary Lee Cloud P.E.
Major professor

Date 1 December 2000

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A STUDY OF BOLTED SINGLE LAP JOINTS BETWEEN COMPOSITES AND ALUMINUM

By

Scott E. Hodges

A THESIS

Submitted to
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2000

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Abstract

A STUDY OF BOLTED SINGLE LAP JOINTS BETWEEN COMPOSITES AND ALUMINUM

By

Scott E. Hodges

This report studies the behavior of a bolted single lap joint using an aluminum and a PMC specimen. This type of joining system deserves increasing attention as PMCs make inroads into the ground vehicle community. Many of the applications will see larger impact loads than may be seen in aircraft uses, and they will require more mechanical fastening. In this report, the effects that bolt preload and washer size have on the strength and behavior of the joint are examined. Two different bolt preloads and two different washer sizes were tested. The two variables were combined to make four different test groups. The results showed that the strength of the joint is dependent on matching the bolt size to the preload. The smaller the washer size, the smaller the preload needed. In addition, washer size seems to have a significant impact on the amount of strain seen in the joint. Both the strength and the strain considerations need to be taken into account when designing these types of joints.

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Dedication

This thesis is dedicated to my Grandfather. His example has inspired me to achieve my education and occupation, which I now hold. In addition, his constant pestering has given me the will to finish this paper.

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Acknowledgements

This thesis owes much to the assistance of others. First, I would like to acknowledge the assistance of my employer, The US Army Tank-automotive and Armaments Command. My employer has provided the main financial support for my degree. They have also provided the materials and facilities for the research that made this paper possible. I am deeply indebted to the Army for their support without which this paper would not have been produced.

Second, I would like to thank my Team Leader, Mr. Donald T. Ostberg. Mr. Ostberg has allowed me the opportunity to work towards this degree. His flexibility in allowing me to attend classes and do research was also invaluable.

Third, Dr. Basavaraju B. Raju has also been of great value to this thesis. His knowledge of testing and composites proved highly useful.

Finally, my advisor, Dr. Gary Cloud who allowed me the opportunity to work with him on this project. Dr. Cloud was my instructor for several classes. His knowledge in the area of testing was also extremely valuable.

Many others provided assistance and encouragement in a number of ways. There are too many to name, but I would like to say, "Thank you", to all of you.

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Introduction

Background

Polymer Matrix Composites (PMCs) have advanced to become an integral part of vehicle design. It is well known that these materials have been, and continue to be, an increasingly major part of aircraft and other aerospace designs, as well as many marine applications. For a long time, their entrance into the land vehicle market has been hampered by their relatively high initial cost, their long manufacturing cycle times, and their inability to handle highly concentrated stresses.

These concerns have been an area of research for engineers and scientists for years. The areas of design, analysis, and manufacturing have all seen significant progress, especially over the last thirty years. Advances in these areas have allowed PMCs to make significant inroads into land vehicle components. The first inroads were in non-structural components. Probably one of the more notable areas in which composites have made significant contributions is in the area of body panels. Since the first Corvette rolled off the assembly line in the early 1950's, PMCs have been seen in an increasing number of automobiles.

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During the 1970s, the oil crisis caused the US government and car manufacturers to look at ways to improve fuel economy for cars. One obvious way to do this was to decrease the weight. One of the ways to decrease weight was to replace some heavy metallic components with lighter plastics and PMCs. This brought more research into other areas where heavy steel components could be replaced by lighter components.

As designers became more proficient in using these new materials, they also became more skilled in exploiting some of the advantages that PMCs have over their metallic counterparts; namely, their higher specific strength, directional strength, noise reduction, and non-corrosive nature. These materials are also excellent thermal and electrical insulators. All of these properties allowed automotive designers new options when designing their vehicles.

The last twenty years have seen great strides in computational capabilities by computers. These advances have allowed better analytical tools to be developed. The anisotropic properties of most PMC materials make them harder to analyze. Modern analytical tools, properly used, can make that task more manageable.

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All of these advances have allowed for the advancement of PMC usage in new ways. The Army has taken notice of these advances over the last fifteen years. Several components were developed to take advantage of these materials, most notably the hood of the High Mobility Multi-purpose Wheeled Vehicle (HMMWV).

The HMMWV, earlier in its design, was developing a weight problem. The vehicle was headed towards weighing too much to effectively accomplish its mission. Hence, the hood was targeted for weight reduction using Sheet Molding Compound (SMC), which is a type of PMC. This component, with subsequent modifications, has proved to be successful. Other successful material substitution programs have paved the way for larger-scale programs.

The first large-scale program was called the Composite Infantry Fighting Vehicle (CIFV). This program was initiated by the Army Research Laboratory (ARL) Materials Directorate located in Watertown, MA. This vehicle was, for the most part, a direct material substitution program using the Army's Bradley Fighting Vehicle. This means that very little, if any, design changes were made for the new material, and they directly replaced the major components of the Bradley Hull. This vehicle used an E-glass/Epoxy material

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material system, and was manufactured using hand lay-up. The vehicle was a success and passed all The Army's performance tests for the vehicle.

This success led The Army to initiate a full-fledged technology demonstrator using composites. The purpose of this program was to design a military vehicle from scratch, and then assess the advantages and disadvantages of the materials used for military applications. This vehicle was the Composite Armored Vehicle Advanced Technology Demonstrator (CAVATD). This vehicle entailed a very lengthy and involved concept stage. The concept stage involved evaluating two competing design philosophies, selecting the most advantageous one, doing a detailed design, and then fabricating a complete vehicle using the final design.

The final design used various PMC systems. It also used a variety of manufacturing processes in order to effectively analyze as many different materials and processes as possible. The system needed to use metallic materials as well. The need for metallic materials was essential in areas of the hull where the suspension system was mounted. This is due to the highly concentrated impact loads that are experienced in this area of the vehicle.

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This is a very realistic scenario for future vehicles. It is highly unlikely, especially in the near future, that the optimal vehicle will be all PMCs, or all metallic. It is likely that a combination of the two material types will be used. Each material system has advantages and disadvantages. It is now possible to better analyze the abilities of PMCs so that they can be implemented successfully in the future.

Description

It is inherent that PMC and metallic materials will be used together in a hybrid system. Hence, it will be, most likely, necessary to join these dissimilar materials together. This thesis looks at a bolted single lap joint using a metal, aluminum, and a PMC, Epoxy/S-glass. This is one of the material systems used on the CAVATD. Below is a rationale for the system that was implemented for this test.

This study was done in order to broaden the scope of understanding of joint behavior. Metal/PMC hybrid bolted single lap joints are not an area of study widely discussed in engineering journals. However, these joints represent a very viable method to join various types of hybrid material designs. Studying bolted single lap joints between two dissimil

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dissimilar materials allows us to broaden the scope of joint study and relate it to a contemporary engineering problem. Possibly, this type of research has been conducted by private firms and the results were not published. This research will provide published results, which are sorely needed.

The methodology used for selecting the design used was based on engineering design needs, and did not look to expand upon areas already examined in the past. Single lap joints represent one of the most common joint designs[1]. The single lap joint is simple and cost effective. It is more flexible and easier to assemble than other joints. A single lap design was chosen because it is the methodology of choice for most designers.

Bolted joints are a practical design choice in many applications. There have been many discussions comparing adhesive and mechanical joining methods[2]. When dealing with a system that entails extremely large loads, it is usually necessary to use some mechanical joining method[2]. Among mechanical joining methods, bolts offer an easy method for assembly and disassembly. Many times systems need to be disassembled, repaired, and reassembled. Bolted joints offer a simple, practical method for accomplishing this.

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Hence, the selected design was bolted to represent a realistic design for heavily loaded systems. It is important to note that many heavily loaded systems are both mechanically and adhesively joined in order to provide added strength. However, in order to study both joining systems (mechanical and mechanical/adhesive) it is best to control as many variables as possible. The adding of adhesives would add another variable that was unnecessary. Since these studies would most likely apply to mechanical/adhesive joints as well, the adhesive was deleted.

It is one of the objectives of this report to study as realistic a joint as possible. It was necessary to continue that simulation further. It is a logical conclusion that heavily loaded systems would, most likely, be thick. Hence, using the Army's CAVATD as a model, a system was selected that used .5" thick aluminum and composite panels. This selection was very important, especially for a single lap joint. Single lap joints, by their nature, are unsymmetrical. This lack of symmetry causes off-axis stresses, and these stresses are magnified as the joint thickens. Most PMCs in use are .25" or less. So, although they use a single lap joint, the off-axis stresses are minimized by their thinness. It was important to inco

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to incorporate this phenomenon in the study. Since heavily loaded structures will be thick, most likely, it is important to capture a true representation of what may occur.

The size of the hole and the bolt diameter were selected along similar lines. It was important to maintain a consistent, logical flow to the selection of the design. These parameters were also selected to represent a heavily loaded system and use The Army's CAVATD as model of such a system. However, a heavily loaded system may use a number of bolts in a variety of patterns. In order to isolate and study this design more accurately, the effect of only one bolt was selected for study. It may be important in the future to look at the effects of multiple bolt designs.

Many of the design constraints were limited by the available testing machine; these limitations are described in the body of the report. The overall length of our joint system had to be less than 12" in order to allow the crosshead enough room for system strain. The system used very expensive hydraulic grips for the experiments and it was important that the width of the specimens not exceed the size of the grips, which was 4". In addition, ASTM standard D5961 was used as an outline for our testing paramete

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parameters and results. The correlation of our test with the standard is done later in this report and will not be discussed at this time.

For testing, it was decided to look at the effect of two variables - bolt preload and washer size. Bolt preload is the amount of tension applied to the bolt while tightening the joint, the preload provides the clamping force to the joint. In order to keep this test manageable, only two bolt preloads and two washer sizes were selected for testing. It is hypothesized that bolt preloads may affect the joint, especially the composite portion. The material system, which will be described in detail later in the report, is a laminate. Laminate materials typically have excellent in-plane properties, but very poor out-of-plane properties. The bolt preload causes an out-of-plane compression load to be applied to the composite material. Since the out-of-plane direction is the material's weakest direction, and since the clamping load is near an area of fiber damage (the drilled hole), the load may cause additional damage. This additional damage may cause the strength of the joint to degrade. The area around the hole is analytically difficult for two main reasons. First, the drilled hole causes fiber damage that is difficult to account for[3]. Second, the hole is a stress concentration area.

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area. Having an area of damage undergo stress magnification, and subsequently adding more stress to the area, makes this a topic of concern. Further explanation of the test matrix will be done later in this report.

The washers should also have an impact on the strength of the joint. Washers allow the pressure applied from the bolt head to be transmitted through the washer first. If the washer is larger than the bolt head, it will create a larger surface area. This larger surface area causes the load to be distributed over a larger area, diminishing the impact on the composite material. This can allow for greater preloads, which can improve the strength of the joint, with less damage to the composite material, and also increasing the strength of the joint.

The basic premises of this thesis have been explained. The remainder of this report will include specimen manufacturing and preparation, testing setup and methodology, testing results, and conclusions and recommendations.

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Specimen Manufacture and Preparation

Manufacturing

Once the scope of the study was determined, it was necessary to have the specimens manufactured, machined, and built. The first thing that was needed was aluminum and composite material for specimens. The aluminum used was 6061 aluminum, ordered from Pierce Aluminum. The aluminum was ordered in 28″ X 28″ X.5″ sheets. Each of these sheets was cut into 4″ X 6″ specimens using an OMAX 2652 JetMachining Center.

The composite manufacturing was done at the US Army Tank-automotive and Armaments Command (USATACOM). TACOM was able to provide the facilities for the necessary manufacturing. The process chosen was Vacuum-Assisted Resin Transfer Molding (VARTM). VARTM was the best choice for this application. Hand lay-up was an alternative manufacturing process; however, this is not a process that will likely be chosen for most systems. Due to its intensive manual labor and high cycle time, it is too inefficient, except for aerospace and other specialized systems. Other composite manufacturing processes that may have been used required a large capital investment in either equipment or tooling. Processes such as Reaction Injection Molding (RIM), which has good cycle times, require

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require a RIM machine, a steel closed mold, and large presses. Outfitting for such an operation was too expensive for this project.

The required equipment for VARTM processing includes a flat one-sided mold, a vacuum pump, a pressure pot, plastic tubing, plastic sheets, and an infusion mesh. All of these components are relatively inexpensive and easily acquired. The one-sided mold that we used was a flat 3′ X 5′ X .5″ sheet of scrap aluminum. Since the sheets to be made were to be no larger than 28″ X 28″, and were to be flat panels, this was adequate for processing. The vacuum pump was chosen based on pump efficiency and cost. The pump prices tend to go up on an exponential scale as you come closer to complete vacuum. The pump selected was purchased at a local company, it was pre-assembled from a collection of parts of various manufacturers, thus making it difficult to identify by name or model type. The pump achieved close to 28″ Hg vacuum when it was sealed at the source. During our tests, we achieved 26″ Hg vacuum.

Since the vacuum pump pulls the resin towards it in order to infuse the mats, it was necessary to have a large trap installed after the mold outlet and before the pump. A pressure pot was used for this purpose. The remaining devices

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devices were used as molding accessories and they were purchased at various local manufacturers. Their uses will be explained as the process is explained.

The molding operation was set up inside a paint booth. The epoxy resin gives off volatile organic compounds (VOCs), which can be harmful in large amounts. The booth contains a fan that removes the VOCs from the area to make it safe for working. The aluminum plate mold was set up on a table with the vacuum pump and pressure pot on a stand next to the table. The setup was arranged in such a way as to provide working room around the equipment. A systematic procedure is given below to describe how the panels were fabricated.

The first step in fabrication was preparation of the glass fabric. The fabric used was an 18-oz. S-2 plain weave fabric. This fabric was stored on a roll that was mounted to a rack. The rack allowed the fabric to be easily rolled onto the working table. Once the fabric was rolled onto the table, a template was placed on top of the fabric for cutting. The template was a 28″ X 28″ rectangular piece of cardboard used to size and cut the fabric. The fabric was cut using a large scissors that was purchased from a local shop that sells fiberglass supplies.

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The scissors are typically used for such an operation, and cut the fabric cleanly and smoothly. The scissors were easily disassembled for cleaning. Every so often glass would clog the scissors, and they needed to be cleaned.

The lay-up used for this material was $[0/90, 45/-45]_S$. In order to achieve that layup, the fabric had to be cut two different ways. Half of the plies were cut using the template normal to the axis of the fabric warp, and the other half used the template at a 45-degree angle. Placing one ply on top of another gave the desired quasi-isotropic architecture.

It was important to determine the proper number of plies necessary to achieve the desired thickness. The plies were determined to be approximately .01" thick on average. With no vacuum, placing 50 plies down should achieve the desired thickness. However, two factors caused this to vary. First, the fabric was woven. The nature of the weave causes some plies to nest. If fibers do not nest, it results in less compaction of the laminates. The other factor was the vacuum; this caused compression of the fabric. Several plaques were made before a height of 54 plies was established. One of the disadvantages of an open mold is that an exact thickness can not be determined.

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Before the plies are put onto the mold, it is important to put mold release down. The mold release that was used for this process was a polyvinyl alcohol (PVA) release agent. The release agent must be applied carefully because tack tape must also be put down later. If the mold release runs too far out to the perimeter, where the tack tape goes, the tack tape will not adhere to the mold surface. This will cause vacuum leaks. For this system, two coats of mold release agent were put down on the mold surface where the plies were to be laid down. The mold release agent needed to dry for about a half-hour to an hour before the plies could be set in place.

Once the mold release agent dried, the first layer laid down was the infusion mesh. The infusion mesh is a critical part of the VARTM process. The mesh is a coarse screen material. The screen material can be made out of a variety of materials. The main concern is that the material should be inert to the resin/catalyst system, and the mold release agent. The tows in the setup were approximately 1/16″ thick and spaced approximately ¼″ apart. The purpose of the mesh is to provide a pathway for the resi

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the resin to soak into the preform. With the vacuum being applied to the preform, compression makes it difficult for the resin to flow directly into the preform. The mesh allows the resin to flow around the preform and soak through the material. The coarseness of the mesh is to hinder the vacuum bag from interfering with the mesh. The planar area of the mesh must be larger than that of the plies, especially on the sides used for inlet and outlet ports, as will be described later.

The plies can be placed on top of the bottom infusion mesh. It is important to lay the plies down carefully. The weave used in this process was moderately tight. This made the job easier. However, it is crucial that the plies be laid down in the proper direction and at the proper angle, as to achieve the correct properties. Because of fabric fray near the surface, and any imperfection in laying the fabric, 2″ around the perimeter was allowed for scrap. This is not typical for VARTM. VARTM parts can be molded as a net-shape preform. However, in order to ensure a good quality part, a trim section on the perimeter was added. Figure 1 shows the setup to this point.

Once all the plies were laid down correctly, they were covered with another layer of mold release fabric. This is

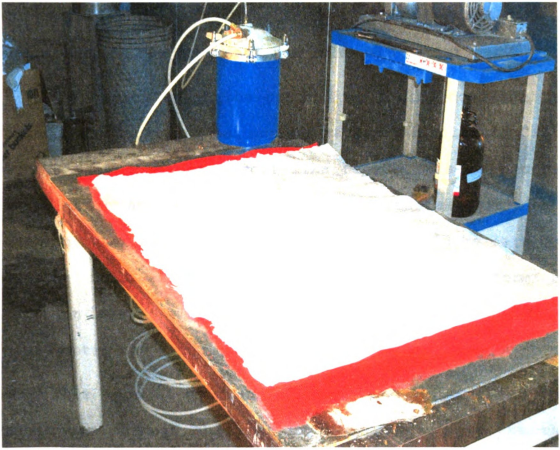

Figure 1. Mold setup showing the bottom infusion mesh and the plies

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a thin sheet used to separate the plies from the top infusion mesh and vacuum bag. The fabric makes it easier to disassemble the part when it is completed. The fabric also hinders any mesh imprints from being placed on the top of the part. The final ply is the top infusion mesh. The top infusion mesh should also be larger than the plies, especially on the ends near the inlet and outlet.

The next step in the process is to lay down the tack tape. The tack tape is a gummy material similar to Silly-Putty™ that comes on a roll like tape. This is a common material in any vacuum bag process. This material has a backing material on one side. The tape should be laid down on the mold around the perimeter of the preform and infusion mesh. The backing material should be left in place until the vacuum bag is ready to be put on.

This type of molding relies solely on vacuum to move the resin through the preform. It became apparent that there was a need to decrease the pressure gradient along the profile of the mold. Molders have found it best to insert "booster" ports. These "booster" ports have proven beneficial to transport the resin through the entire length of the part. They should be placed approximately 12" to 15" apart for the most efficient use. Since this mold is

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28″ long, it was established that one "booster" port should be added down the middle of the part, as well as the inlet port at one end and the outlet at the other end[7].

It was determined that line ports were the best method for transporting the resin through the preform. A line port injects resin along the face of the mold. The typical method for mold injection is point injection. Line injection offers a more homogeneous method for transporting the resin. This is achieved by using a plastic helical wire harness material. When this material is stretched, it allows for a line opening in which the resin can be transported through the mold. All three ports use this line injection method.

The helical coil provides a homogenous line vacuum pull as well, so the resin is not pulled to a point source. The three helical cords are wrapped in infusion mesh. The inlet and outlet cords use the "extra" mesh left at the ends, and the middle "booster" port is wrapped using an additional piece of mesh. The middle port mesh must provide a continuous mesh from the cord to the part, and provide some distance from the part and the cord. If the cord were allowed to lie directly on top of the part, it may leave an imprint on the top of the piece, which is undesirable. The ends of the inlet and outlet port are taped down with duct tape in order to keep them stretched out. The "booster" cord is taped to the end of its mesh; and is stretched out later.

The helical coil will work fine inside the molded area. However, outside the molded area something less porous is needed. 3/8" polyethylene tubing material was taped to the end of helical coil, for all three injection/vacuum ports. The tube connecting to the inlet and outlet port was adhered to the adhesive tape. Approximately 1" of the tube was placed inside the mold area. A small piece of the adhesive was placed over the tube to enclose the tube. This was done to both the inlet and outlet ports. The middle "booster" port was not adhesively mounted at this time, and is handled later in the process. Figure 2 shows the final setup before the mold is closed.

In order to enclose the top surface of the mold a vacuum bag material needs to be placed over the preform, infusion mesh, and the helical coils. The bagging material used was considered high quality (the exact material was not specified) and supplied by Rekien, a local composite fabrication equipment distributor. The material needs to

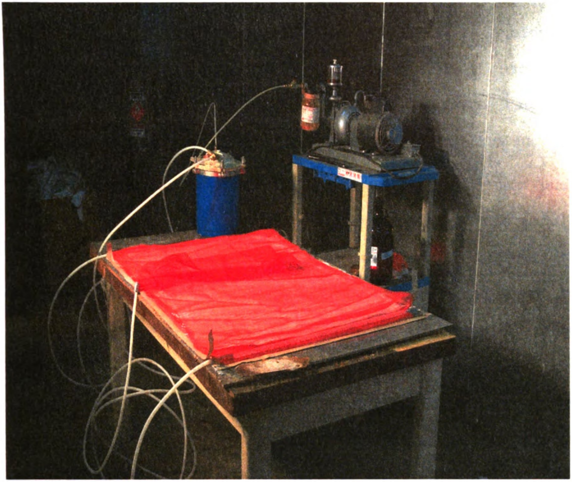

Figure 2. Setup of panel fabrication before the mold is bagged

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adhered to the tape smoothly, any creases or bumps along the adhesive line will damage the seal. A damaged seal will be a source of vacuum leak during the molding process. A pleat is made in the bag near the center on each side of the mold, normal to the middle port. This pleat needs to be approximately 3″ high. Additional adhesive tape is necessary to seal the pleats and the middle port tubing.

In order to complete the mold setup the vacuum pump needs to be used. The tubing for the outlet and the middle port should be connected to the pressure pot. Appropriate tubing connectors, reducers, and valves were used to accomplish this. The middle port should have a valve between the mold and any connection made to either the pressure pot or the outlet port, so it can independently be shut off when required. The inlet port should be temporarily sealed; a small piece of the adhesive tape used to cover the end will suffice. Running the vacuum serves two purposes; (1) it verifies the integrity of the vacuum seal throughout the system, (2), and it allows the middle port to be stretched and held in place. Once the vacuum is running it should be maintained at no more than 1″ of Hg below maximum pressure. The system should be examined for leaks. There are leak detectors available, or detection can be done manually by listening for them.

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Setting the middle port in place is the most difficult task of the process. The helical tube needs to be stretched from the outside of the bag. The vacuum holds the coil in place. However, to achieve this it may be necessary to adjust the vacuum pressure up and down to inch over the coil. This process can be laborious and must be done carefully as to not damage the seal of the rest of the bagging material. Once the middle port is properly secured, a final check is necessary to ensure the integrity of the seal. Figure 3 shows the Final Mold setup ready for molding.

Once the mold is properly setup, the resin can be mixed. The resin typically has a gel time. The gel time states how long the material remains in a liquid state before it begins to harden. This is the length of time between when the resin is mixed and when it has completely filled the mold. Hence, the mold setup is done first. The gel time needs to be established before any molding is to begin. This will accurately set a working time for the molder. The resin was selected in part because of its low viscosity and long gel time. Resins used in VARTM work best if they exhibit these properties. We chose to use the resin system used in the Army's CAVATD.

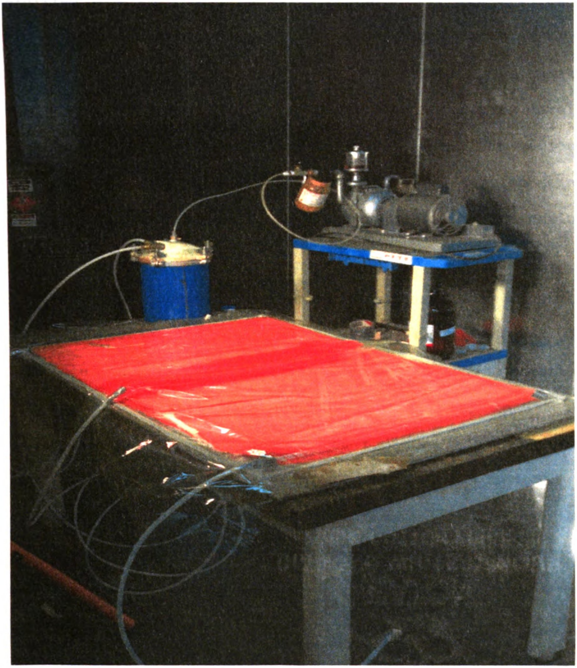

Figure 3. Final setup for panel fabrication

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This resin, named SC-4, was specifically made by Applied Poleramic for the VARTM process. It was also made to exhibit very good properties. The resin is a three-part epoxy resin system. The resin was mixed in a small container and the gel time was established at approximately 2-3 hours. This time was approximated due to the various amounts of resin mixed, and the method of manufacturing entails adding new resin to the system during processing which varies the gel time.

For the fabrication process, the resin was mixed in several five-gallon buckets. By mixing the batch in multiple buckets the contents could be added together moments before they were needed, reducing the amount of exothermic heat emanating from the buckets. It was found that larger amounts of resin mixed together produced a greater heat generation from the exothermic reaction of the resin and catalyst. This reduced gel time significantly. Hence, smaller batches were used and sequentially mixed as needed.

Once the resin was metered appropriately the first batch was mixed and prepared for use. Typically, the vacuum pump was left on during resin preparation. This time allowed the vacuum to pump air out of the system and

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compress the fabric. The plastic tubing from the inlet port was unsealed and quickly dropped in to the bucket of mixed resin. The resin then began to traverse the mold. As the resin in the bucket was used more was added.

Once the resin reached the middle port and it began to run up into the middle port helical coil the port was switched from a vacuum port to a resin inlet port. Another bucket was used for the middle port once it had been switched. The "booster" port served to boost the vacuum for the initial portion of the injection, and was switched to boost the resin flow to the next vacuum port.

Once the resin reached the other end of the mold, it continued along until the pressure pot was reached. The pressure pot contained a five-gallon bucket at the bottom, which collected the excess resin. When the bucket filled, the mold was sealed from the pressure pot, the pump was temporarily turned off, and the pressure pot was opened. The bucket was removed and emptied into the two inlet buckets. This allowed less resin to be used and did not cause an overflow in the pressure pot.

Since the resin needed to soak through the plies in order to completely wet the preform, more than one pass of the resin was required to completely penetrate the preform, especiall

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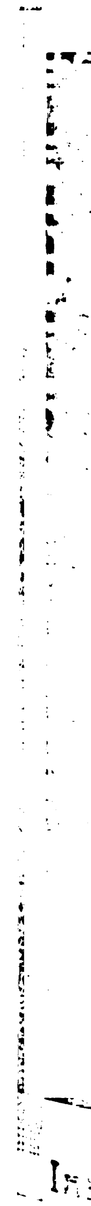
especially for the thicker preforms. To ensure maximum wetout the process was continued until the resin gelled. To gauge success in penetrating the preform, an ultrasonic analysis was performed on some of the finished parts. This showed very good penetration of the resin. The results are shown in Figure 4, with the darker areas representing more resin penetration.

Once the resin had gelled, the part needed to cure before it could be removed from the mold. The part was left overnight to cure. The mold was then torn apart and the part removed. The part was placed inside an oven for further curing and post curing. The part was placed in an unheated oven; the oven was then closed and heated to 250° F for 1.5 hours to cure the part. The temprature was then raised to 350° F one hour for a post cure cycle, then allowed to cool for several hours before removal. Once the part was cooled and removed from the oven, it was completed and ready for machining.

Machining

Once the composite panels had been fabricated, the aluminum panels and the composite panels were cut into specimens using the water-jet cutter specified. The panels were cut in accordance with the diagram shown in Figure 5.



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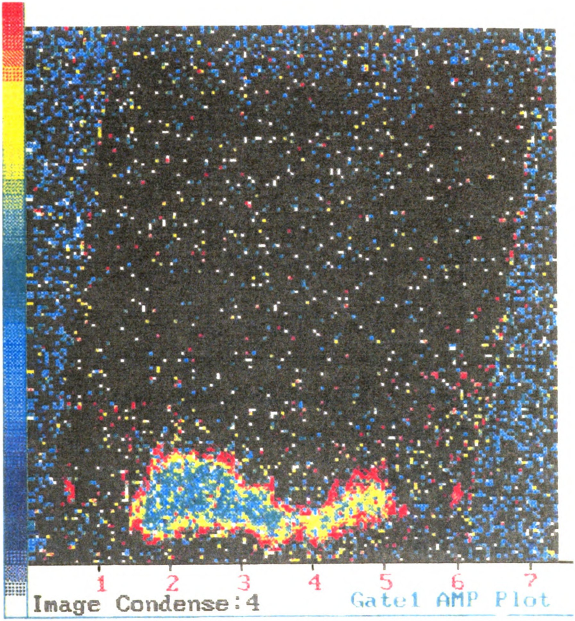
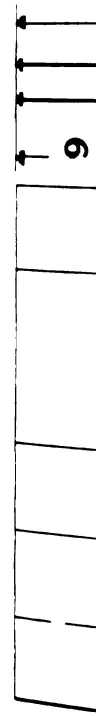


Figure 4. Results of composite panel ultrasonic inspection



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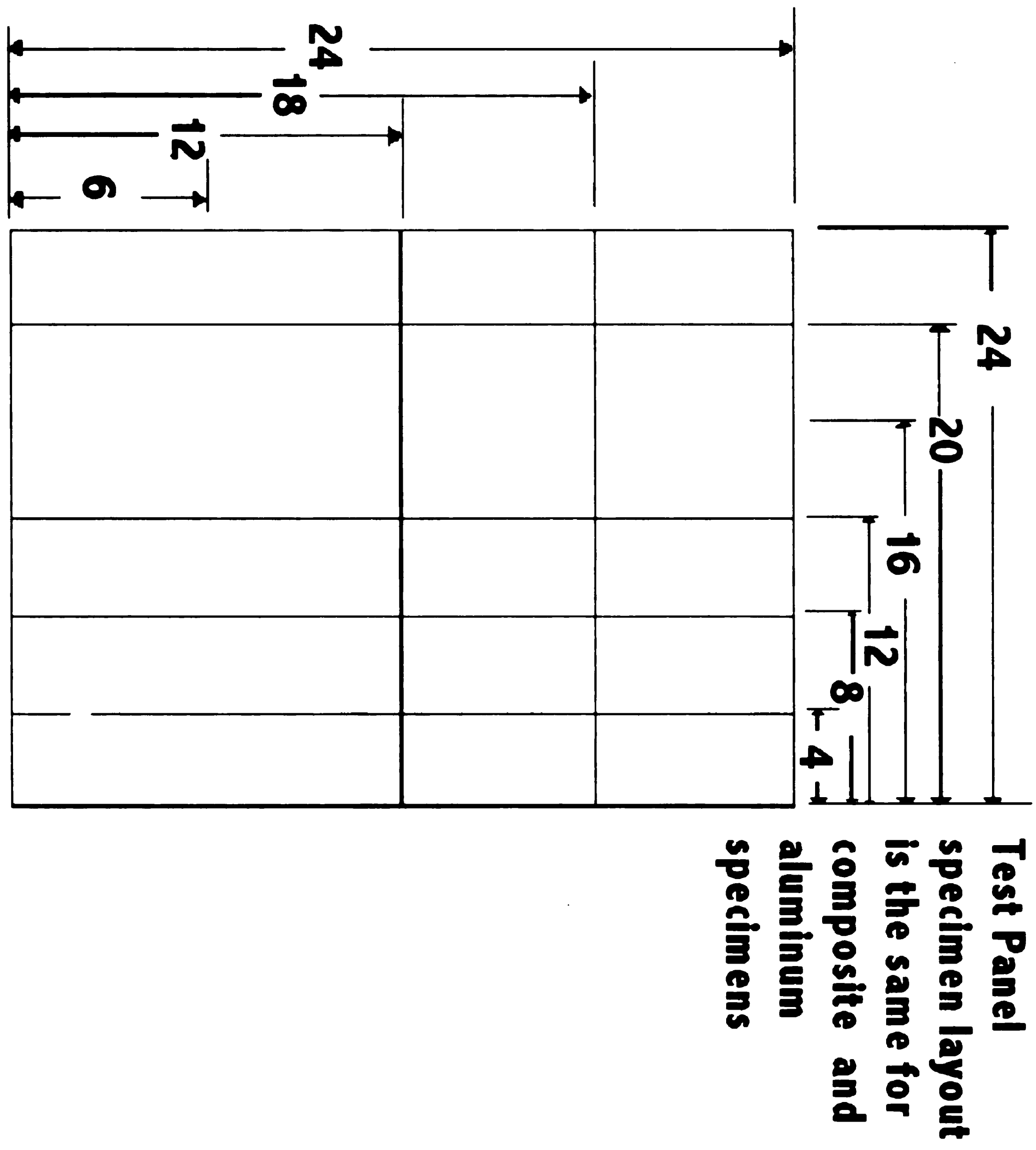

Figure 5. Diagram showing panel cutting pattern for specimens

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The tolerance of the water-jet cutter was such that the scrap size needed to be reduced. The thickness of the water-jet was not taken into consideration in the drawing. This consideration reduced the size of the scrap material specified by ¼" on each side of the panel.

Once the specimens were made, the holes were drilled. Drilling the holes for the composites was the most difficult. The holes that were desired for this experiment needed to be drilled with no collateral fiber damage, no burning of the material, and no fraying from hole punch-through. One of the problem areas with drilling holes in composites is caused by the drill bit pulling on fibers and ripping them out of the material. These problems can be caused by a bit becoming too dull and snagging fibers. Burning can be caused by several factors including drill speed, feed speed, or soft bits. Hole "punch-through" is cased by delamination of the bottom layer of composite material, and leaves a rough surface near the hole on the bottom of the panel. These problems can usually be eliminated by using the proper bit, speed, and feed rate. In addition, a backing plate beneath the composite usually hinders punch-through. However, it was essential to have the holes drilled professionally to ensure that the holes were

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were not damaged before testing. The specimens were sent to Applied Composites for this work.

Standard drilling practices were used on the aluminum. The aluminum does not have the same damage problems that composites exhibit. The holes for the aluminum were drilled at TACOM using a Kings Mill LINCOLN (Model #: KM20PF) drill press at a speed of 325 RPM, and a feed rate of .01"/min.

At this time, the specimens were ready to be assembled for testing. This assembly is discussed in the following chapter, along with the standards and deviations from standard that were used for this testing.

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Testing Methodology

This chapter describes the outline and rationale for the tests performed, the controls and variables of the tests, equipment used, testing procedures, and data acquisition. There is a standard for the test that is used extensively, ASTM D5961 "Standard Testing Method for Bearing Response of Polymer Matrix Composite Laminates". This standard was written for a single lap joint between two composite materials. However, everything else in the standard allows for the tests being performed for this paper. Hence, the standard is complied with for these tests. A copy of this standard is provided in Appendix B.

PURPOSE AND RATIONALE

The purpose of this test is to discern the relative bearing strength of bolted single lap joints of composite-to-metal. Since documentation of testing in this area could not be found, these tests are considered initial. This beginning should lay a good foundation for future tests, which is the intent. It was decided to start with bolt preload. Preload recommendations have not been applied to this configuration and may have an impact on joint strength.

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Bolt preload is typically determined using the proof load of bolts. For SAE grade bolts these numbers are standard[5]. Bolt preload has been stated at both 90% and 75% of proof load by various sources[4]. The basic concept is to achieve as much clamping load as possible without yielding or fracturing the bolt. However, it is entirely possible that this clamping load will cause damage to a composite material. It is well known that composite laminates have excellent planar orthotropic properties. These planar properties exceed those of metals of the same weight[6]. However, the out-of-plane properties of these materials fall drastically. The clamping load is acting in this out-of-plane direction. This test will look at the possible effect of this load.

Bolt hole damage may weaken the surrounding area. There have been studies done on the effect of loads around a hole in composites[8]. However, none of these studies covers the complex loading scheme being applied by a bolted single lap joint. The studies primarily cover bearing and bending loads. The clamping load effects on the bearing load have not been widely studied for single lap joints. Single lap joints also add an unsymmetrical loading pattern. This unsymmetrical loading pattern is magnified by the thickness of the material. Most studies found used composi

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composites under ¼" thick, and were not bolted, which includes a hole in the specimen. Hence, the unsymmetrical loading effects are also not explored. In conclusion, this system includes many different loading patterns acting simultaneously. The effect of this complex loading pattern is not known.

This test looks at another factor as well, washer size. Washer size may help to alleviate some of the clamping load problems. Larger washers spread the load being applied by the bolt over a larger surface area. Washers were added to study their potential benefits to this problem.

This study looks at the combined effect of washers and preload on a composite joint. It is the hope that this effort will lead to more studies. This area is extremely lacking in public literature, and needs to be studied. By increasing the available data and knowledge in this area, engineers and scientists can increase their use of these materials with additional confidence of success.

TEST PROCEDURE

This test uses a flat, rectangular cross-section coupon composed of two like halves fastened together through one centerline hole located near one end of each half as shown

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in figure 6. A doubler plate is used to minimize the effects caused by an unsymmetrical load pattern in the specimen. The testing results are based on the applied load and the associated deformation. The results are plotted on a chart using bearing stress and bearing strain, as calculated later in this report. These specifications can not change.

There are several variations allowed in the test specification. To accurately describe this test procedure, these variations will be presented and what this test hopes to accomplish will be explained. This test uses a single-shear loading pattern. This loading pattern is one of the most widely used patterns in commercial products. The purpose of this report is to simulate such a pattern.

This study uses one hole for several reasons. First, to control extraneous variables for this initial test; an extra hole adds additional factors to the test. Since testing results in this area are severely limited, it was necessary not to add a second hole to this test. Second, the one hole design was more affordable: the drilling of holes in composites is very expensive, and the second hole would have doubled the cost of drilling. Third, the additional hole is beyond the test machine's size capacity.

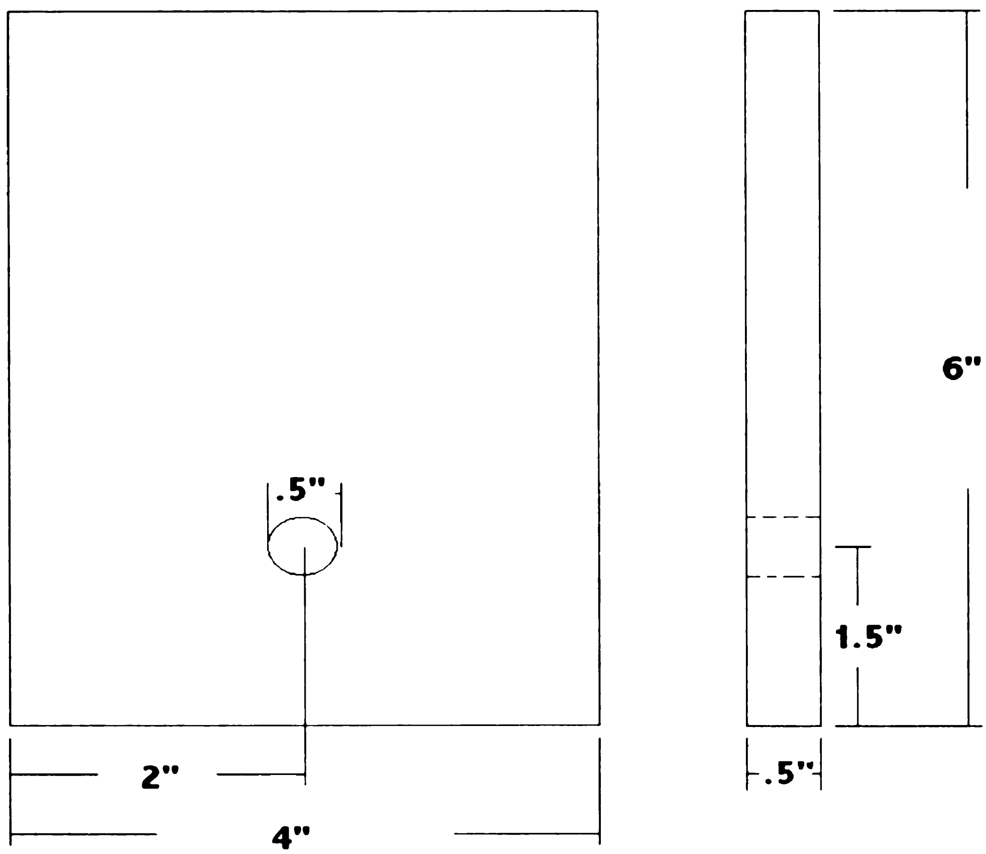

Figure 6. Diagram of a specimen half showing dimension used for data reporting

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An additional hole would have made the joint specimen too large.

ASTM D5961 also allows for grommets and countersunk holes. These additions may be beneficial and could be studied later. As stated above, this is an initial test and additional factors were not considered at this point.

As described above, this test uses an aluminum-to-composite lap joint. The composite is a quasi-isotropic material with a stacking pattern of $[0\backslash 90\backslash 45\backslash -45]_S$, and the aluminum is 6061 Al, as described earlier. The bolt and hole are both .5″ nominal size. The edge-to-hole distance ratio is three, the pitch-to-hole distance ratio is eight, and the diameter-to-thickness distance ratio is one.

TEST EQUIPMENT

A calibrated digital Vernier scale, capable of measuring to .001″, was used to perform all necessary dimensional measurements. The bolt was an SAE grade 9 .5″ bolt w/ nut threaded to UNC code. There were two types of washers used, SAE flat washer types 1# and 2#. The large washer had an outside diameter of 1.375″ nominal, and an inside diameter of .5625″ nominal. The small washer had an outside diameter of 1.0625″ nominal, and an inside diameter of .531″ nominal. The torque wrench used was properly

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calibrated by our own calibration group who keep our equipment updated, and met the standard for use.

A separate bearing strain indicator could not be used for this experiment. In order to properly integrate this equipment into the rest of the testing apparatus a piece of Instron equipment would need to be purchased. Instron did not have an indicator that met the needs of this test. For most strain indicators, the gage length was too long. Strain indicators for rubber materials have longer gage lengths, but lower resolution. A digital extensometer was available, but the cost was prohibitive. Hence, crosshead motion was chosen to measure bearing strain for this test. This was a concern for accuracy, especially due to any specimen slip, machine deformation, or crosshead deformation. Several specimens were done ahead of time to check for slippage. Visual inspection of the specimens showed little or no slippage, after initial settling in. The tensile loads applied during testing were well below the machine's capabilities. Since these loads were low, relative to the machine capabilities, it tended to minimize any machine or crosshead deformations.

The tests were performed using an Instron 1333 Tensile Test Machine. This apparatus has a loading capacity of 110 kips.

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kips. The machine was upgraded and calibrated, and it meets the standard specifications. The upgrades included a new digital controller unit for the machine, and a computer hook-up with new software used for data acquisition and report generation. The machine motion is controlled by hydraulics. The top crosshead can be moved up and down using hydraulic controls, and remains stationary during testing. The bottom accuator is responsible for motion during testing. It is this part of the machine that is under the direct influence of the hydraulics. The machine is computer controlled. It provides digital readouts for applied load and deformation.

Instron modular hydraulic grips (Model#: 2742-504) were used to hold the test specimens in the tensile machine. The grips were 300kN types with a maximum 10,000-psi maximum grip pressure. A universal joint was placed between the top grip and the machine. The joint allowed the grip to be rotated with three degrees of freedom. Allowing the grip to rotate prevented any prestress or bending to be applied to the specimen due to any grip-to-specimen misalignment.

SPECIMEN TEST PREPARATIONS

For this test, there were four variable sets. Test set A used a preload of 60% of proof load and small washe

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washers, test set B used a preload of 75% of proof load and small washers, test set C used a preload of 60% of proof load and large washers, and test set D used a preload of 75% of proof load and large washers, Figure 7 shows all four group and their varying specifications. Each test set used seven samples. This is in accordance with standard practices of having at least five specimens for a statistical sample size.

The specimens were prepared the same way for each specimen. Before each sample was tested, the specimens were measured (length, width, and thickness). Once the specimens were properly measured, they were assembled. First the bolt was lubricated with automotive and artillery grease MIL-G-10924F. Next, the washers were added, three large ones or four small ones. It was necessary to add multiple washers because the bolt had a 1-1/4″ shoulder length. The bolt was then inserted through the aluminum, then the composite. A second set of washers was then put on the other side; again, three large washers, or four small washers. The nut was then added.

The next step was to torque the bolt down. In order to determine how much torque to apply, a test was run using a strain gauged bolt. A setup was done using a strain

FOUR TEST GROUPS

TEST GROUP A • 60% PROOF LOAD USED FOR BOLT PRELOAD (75 FT.-LBS. OF TORQUE) • SAE 1# WASHERS USED (SMALL WASHERS)	**TEST GROUP B** • 75% OF PROOF LOAD USED FOR BOLT PRELOAD (100 FT.-LBS. OF TORQUE) • SAE 1# WASHERS USED (SMALL WASHERS)
TEST GROUP C • 60% PROOF LOAD USED FOR BOLT PRELOAD(75 FT.-LBS. OF TORQUE) • SAE 2# WASHERS USED (LARGE WASHERS)	**TEST GROUP D** • 75% PROOF LOAD USED FOR BOLT PRELOAD (100 FT.-LBS. OF TORQUE) • SAE 2# WASHERS USED (LARGE WASHERS)

Figure 7. Matrix showing the four test groups and their characteristics

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gauged bolt and a load indicator first. Torque was applied until the clamping load required was achieved on the load indicator, then the torque level that was applied to achieve that load was recorded. For the 60% specimens, the needed clamping load of 12,345 pounds was obtained with a torque of 75 ft.-lbs.; and for the 75% specimens, the needed clamping load of 15,431 pounds was obtained with a torque of 100 ft.-lbs.

The specimens were placed into the grips with the doubler plates. Since hydraulic grips were used, it was deemed unnecessary to attach the doubler plates directly to the specimen. The purpose of the doubler plates is to alleviate the eccentricity of the test.

Slipping of the specimen was a concern. Several sample specimens were run ahead of time to test for slipping. It was necessary to apply 35,000psi of clamping force to avoid specimen slipping during testing.

The specimen data needed to be entered into the software before starting the test. Hole diameter, specimen thickness, and gage length were entered for bearing stress and bearing strain calculations. The tests were run at a constant rate of .075 in./min. This rate was chosen in order to complete the test within 5 to 10 min., which is the ti

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the time limit recommended by ASTM 5961. The tests were run until the bearing stress had dropped to 70% of the ultimate bearing load. This was done according to ASTM D5961 test procedure, and ensures that the true ultimate bearing load has been reached.

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Test Data and Setup

There are a number of pieces of data acquired for this test. This data was collected before, during, and after the test. The purpose of this chapter is to offer an explanation as to what data were collected, when, and how it was measured. First, an explanation will be given about the data collected before the test. Second, a description of the data collected during the test, and, finally, the way that the data were normalized is given.

The initial data collected were primarily used to describe the specimen. Below are a description of each piece of data, how they were collected, and for what they were used.

Length - The length of each specimen, aluminum and composite, was measured using a Vernier scale. The scale measured each specimen to .001". This data was used for calculating the average length of each specimen. The data collected compares to the nominal length of each specimen, which is 6.000".

Width - The width of each specimen, aluminum and composite, was measured using a Vernier scale. The scale measured each specimen to .001". This data was used for calculating the average width of each specimen. The data collecte

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Thickness - The width of each specimen, aluminum and composite was measured using a Vernier scale. The scale measured each specimen to .001″. This data was used for calculating the average thickness of each specimen, and for calculating the bearing stress area. The data compares to the nominal thickness of each specimen, which was .500″, and was used in conjunction with the hole diameters to calculate the bearing stress area.

Hole Diameter - The diameter of both holes in each specimen, aluminum and composite, was measured using a Vernier scale. The scale measured each hole to .001″. These data were used for calculating the average hole diameter and calculating the bearing stress area. The data compares to the nominal hole diameter, which was .500″, and was used in conjunction with the thickness data to calculate bearing stress area.

Gage Length - The gage length of each test coupon was measured using a Vernier scale. The scale measured the length to .001″. The length measured to determine the gage length is shown in Fig 8. Ideally, the gage length would

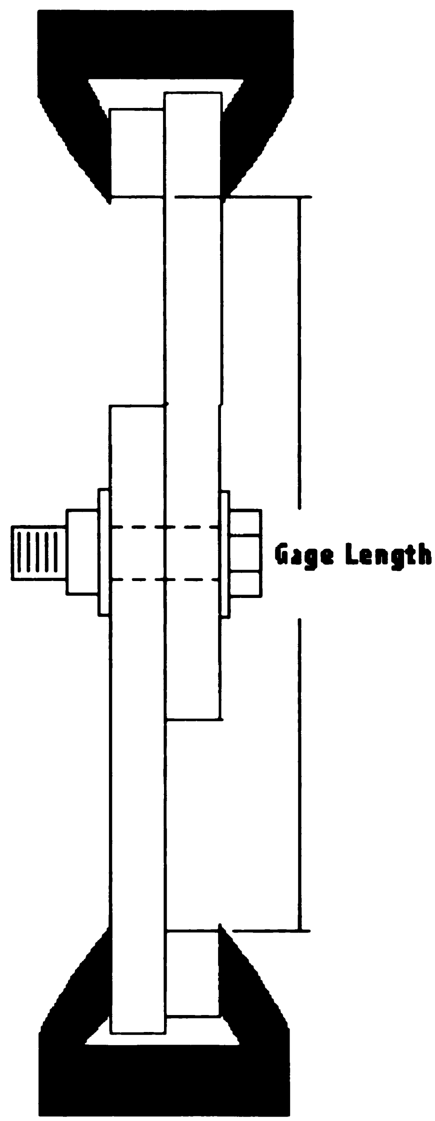

Figure 8. Drawing showing gage length measurement

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be closer to the hole, since this is the area of activity. This is explained in detail below.

Edge-to-Diameter ratio - The edge distance is from the center of the hole to the side of specimen closest to the hole, in line with the load direction. This distance was divided by the diameter of the hole. This ratio was calculated for composite and aluminum specimens. This data was used for normalizing the data set for comparison with other specimen sets of different dimensions.

Pitch-to-Diameter ratio - The pitch distance was the width of the specimen. The width was divided by the diameter. This data was used for normalizing the data, for comparison to other specimens of different dimensions.

Diameter-to-thickness ratio - The diameter was divided by the thickness. This data was also used for normalizing the data, so that they can be compared to other specimens of different dimensions.

Weight - The weight of each specimen, aluminum and composite was measured using a Mettler Toledo PG503-S DeltaRange® scale. This data is used to characterize the specimen, and to calculate density of each specimen.

Density - The density of each specimen was calculated using the weight and volume data collected. This data is used to

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used to characterize each specimen, and to compare test coupons with other similar data sets.

Bolt torque - The torque applied to each bolt was measured using an analog torque wrench. The torque was measured within five ft.-lbs. The standard requires that the torque be accurate within 10%. This exceeded the standard requirements.

The test machine used was computer controlled. The data acquisition was digitally acquired at a rate of 10 points per second. The data acquired from the machine were load, in units of pounds. and displacement, in units on inches. These data were transmitted to the computer software program. The software automatically calculates the necessary stresses and strains, as defined by the user. Below is the terminology and definitions of the calculations done.

Bearing Stress Area - The load acts upon this area. This area was standardized for simplicity and was calculated as diameter times thickness as shown in Figure 9. It was extremely difficult to calculate the exact load area on two circular boundaries. In addition, this data was unnecessary. If the bolt diameter and hole diameters are provided, an accurate comparison can be made between

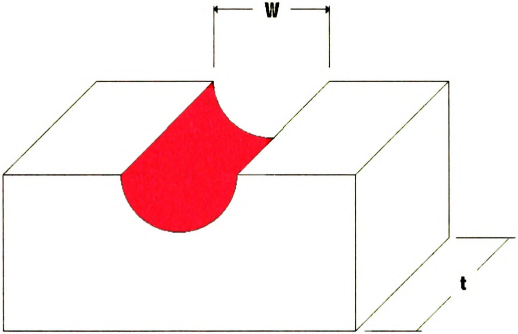

Figure 9. Diagram of bearing Stress area details

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like specimens. For this calculation the thickness of the aluminum and composite specimens used are added together. Since the specimens are clamped together tightly, it was assumed no gap exists. The two hole diameters were averaged together to give the diameter. This was necessary for the computer calculations. The computer accepted two dimensions for area calculations, one length and one width. Since these specimens were nominally ½ the coupon size, and the difference between the hole sizes are typically less than 1/16", the average was used for computer calculations. However, each piece of data was recorded so that other calculations can be done if necessary.

Bearing Stress - This value was calculated by the computer software as the software receives the load data from the testing machine. This number was calculated by dividing the load by the bearing stress area.

Bearing Strain - this value was calculated by the computer software using the displacement information supplied by the testing machine. The displacement information was divided by the gage length provided. This measurement did deviate from the standard definition of bearing strain based upon the hole diameter. However, it was not possible to acquire the necessary devices to measure

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measure the strain near the hole. The gage length and range required could only be met with a video strain gauge, which would have cost more than $5,000.

Ultimate Bearing Strength - This value was recorded by the computer at the end of the testing cycle. It merely recorded the highest value input during the test.

Ultimate Bearing Strain - This value was recorded by the computer. It was the value of the strain at the Ultimate Bearing stress point.

Bearing Chord Modulus - Bearing Chord Modulus is a value in joint design that is simillar to modulus of elasticity. It is the slope the linear elastic range of joint behavior. This value was calculated by the computer. The user input several points along the proportional section of the graph, and the computer made a best-fit line. The slope of the line generated was the value. This is a standard method of calculation.

Finally, after all samples were tested they were grouped and analyzed. Analysis was done using statistical methods. There were three statistical variables calculated for each group. These calculations and their use are documented below.

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Sample Mean (χ) - This is the average value of all specimens tested. This value is used to determine how much difference there might be in each group tested.

Standard Deviation (s_{n-1}) - The standard deviation tells how widely dispersed data points are. The equation for deriving this value can be found in appendix B

Sample Coefficient of Variation, % (CV) - This coefficient states the average amount of variance for each specimen from the mean. This value can assist in determining the repeatability of the mean value generated. The equation for this value can also be found in appendix B.

These factors were used to perform initial data analysis. The next chapter uses the above data to evaluate the tests and their results.

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Test Results and Discussion

The test results contained a large amount of data to help explain the behavior of the tested joints. This data was divided into several categories, which are described in detail. First, the raw data, which were the data collected before, during and after the test which describe the condition of the actual specimens. The calculated data normalizes the raw data results for a comparative analysis, and helps to determine any trends in data. The graphs show the behavior pattern of the specimen during testing, and help to illustrate certain trends in behavior of the specimen. Finally, numerous photographs help fully explain the description of specimen. By combining all of those data types, an accurate and useful description of the tests performed on the joints can be developed.

The raw data collected includes the physical dimensions taken, the ratios described in the previous chapter, that are used for specimen comparison, and other initial pre-test data necessary for specimen analysis. This data gives a clear description of each specimen used.

The physical measurements taken were used to characterize the specimen and to normalize the test data. Each specimen's overall dimensions are provided in Tables 1

	Aluminum					
	Height	**Width**	**Depth**	**Hole center (vertical)**	**Hole center (horizontal)**	**Hole Dia.**
A1	5.99	3.99	0.51	1.53	2.01	0.53
A2	5.94	3.99	0.51	1.48	1.99	0.53
A3	5.94	3.99	0.51	1.48	2.01	0.53
A4	5.95	3.99	0.51	1.48	2.01	0.53
A5	5.95	3.95	0.51	1.48	2.00	0.52
A6	5.99	4.00	0.52	1.53	2.02	0.53
A7	5.95	4.00	0.51	1.48	2.02	0.53
B1	5.99	3.95	0.51	1.42	2.03	0.53
B2	5.94	3.95	0.51	1.35	2.03	0.53
B3	5.94	4.00	0.51	1.36	1.99	0.53
B4	5.94	4.00	0.51	1.34	1.99	0.53
B5	5.95	3.95	0.51	1.38	1.93	0.54
B6	5.99	3.99	0.51	1.43	2.01	0.52
B7	5.94	3.95	0.51	1.36	2.00	0.53
C1	6.00	4.00	0.51	1.54	2.01	0.52
C2	5.95	3.99	0.51	1.47	2.00	0.49
C3	5.94	4.00	0.51	1.50	2.01	0.50
C4	5.99	3.99	0.51	1.55	2.02	0.50
C5	5.94	3.94	0.51	1.48	1.95	0.50
C6	5.94	3.95	0.52	1.47	2.02	0.50
C7	6.00	3.94	0.51	1.54	2.01	0.50
D1	5.94	3.95	0.51	1.47	2.01	0.53
D2	5.99	4.00	0.52	1.52	2.01	0.52
D3	5.99	4.00	0.51	1.52	2.01	0.53
D4	5.94	3.95	0.51	1.49	1.96	0.53
D5	5.99	4.00	0.51	1.52	2.01	0.52
D6	5.94	4.00	0.51	1.48	2.03	0.53
D7	5.99	3.95	0.51	1.55	1.98	0.54

Table 1. Initial measurements taken for the aluminum specimen

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and 2. The hole diameter data were also used directly in the test for bearing stress calculations.

The physical dimension ratios are also included, as specified in ASTM 5961. This standard outlined the ratios specified in Tables 3 and 4 as necessary for comparison. ASTM 5961 recommends an edge/diameter ratio of 3, a pitch/diameter ratio of 6, and a diameter/thickness ratio between 1.2 and 2. This test does not follow this recommendation, as this test has basic ratios of 3, 8, and 1 respectively. However, the ratios are recorded so that proper comparisons and evaluations can be made with future tests.

Additional physical data was collected and are included in table 5. The gage length data were used for strain calculations and were directly entered into the computer before each specimen test. The bolt torque data were provided as a record of torque used. The dial gage was not precise and the tolerance on the values recorded is +/- five Ft.-lbs. The mass and density information are not used in this report. However, since these test results are by no means conclusive, it is impossible to know what information may be needed for further studies. Hence, all data that were recorded is provided for use with future results.

	Composite					
	Height	Width	Depth	Hole center (vertical)	Hole center (horizontal)	Hole Dia.
A1	5.948	3.994	0.445	1.467	2.015	0.490
A2	5.991	3.993	0.551	1.487	1.991	0.491
A3	6.002	3.952	0.447	1.515	1.951	0.492
A4	5.998	3.992	0.446	1.501	2.009	0.495
A5	5.995	3.985	0.454	1.502	2.015	0.498
A6	5.947	3.951	0.444	1.496	2.008	0.490
A7	5.992	3.952	0.445	1.497	1.963	0.497
B1	5.943	3.948	0.450	1.491	2.011	0.498
B2	6.000	3.996	0.445	1.496	2.009	0.497
B3	5.997	3.945	0.558	1.487	1.997	0.499
B4	5.993	3.990	0.561	1.484	2.005	0.499
B5	6.002	3.940	0.548	1.491	2.022	0.497
B6	5.997	3.953	0.557	1.493	1.984	0.495
B7	5.996	3.950	0.567	1.488	1.981	0.499
C1	5.943	3.993	0.446	1.491	2.005	0.496
C2	5.951	3.952	0.595	1.534	2.018	0.495
C3	5.946	3.948	0.447	1.501	2.004	0.497
C4	5.945	3.948	0.549	1.530	2.007	0.494
C5	6.002	3.950	0.586	1.568	2.008	0.492
C6	5.956	3.993	0.597	1.525	2.002	0.498
C7	6.010	3.994	0.439	1.583	2.022	0.497
D1	5.947	3.998	0.480	1.463	2.019	0.500
D2	5.996	3.952	0.445	1.500	1.999	0.485
D3	6.002	3.947	0.444	1.503	2.003	0.497
D4	5.945	3.999	0.554	1.497	1.984	0.498
D5	6.002	3.992	0.441	1.477	2.011	0.498
D6	5.992	3.985	0.550	1.487	1.981	0.498
D7	5.987	3.996	0.451	1.498	2.008	0.498

Table 2. Initial measurements taken for the composite specimen

	Aluminum		
Specimen ID	Edge-Diameter Ratio	Pitch-Diameter Ratio	Diameter-Thickness Ratio
A1	2.889	7.536	0.968
A2	2.791	7.536	0.964
A3	2.786	7.506	0.966
A4	2.806	7.577	0.975
A5	2.839	7.563	0.985
A6	2.879	7.538	0.972
A7	2.776	7.497	0.964
B1	2.663	7.403	0.961
B2	2.536	7.391	0.961
B3	2.568	7.524	0.968
B4	2.524	7.517	0.966
B5	2.582	7.381	0.961
B6	2.725	7.618	0.981
B7	2.568	7.443	0.970
C1	2.944	7.655	0.979
C2	3.024	8.199	1.053
C3	3.015	8.010	1.028
C4	3.101	8.000	1.030
C5	2.985	7.936	1.034
C6	2.940	7.894	1.030
C7	3.081	7.872	1.026
D1	2.795	7.506	0.975
D2	2.909	7.639	0.985
D3	2.863	7.509	0.964
D4	2.809	7.443	0.966
D5	2.911	7.646	0.981
D6	2.802	7.552	0.970
D7	2.898	7.378	0.959

Table 3. Initial calculated ratio data for the aluminum specimen

	Composite		
Specimen ID	Edge-Diameter Ratio	Pitch-Diameter Ratio	Diameter-Thickness Ratio
A1	2.994	8.151	0.908
A2	3.027	8.132	1.122
A3	3.079	8.033	0.909
A4	3.031	8.065	0.901
A5	3.016	8.002	0.912
A6	3.053	8.063	0.906
A7	3.011	7.952	0.895
B1	2.994	7.928	0.904
B2	3.009	8.040	0.895
B3	2.979	7.906	1.118
B4	2.973	7.996	1.124
B5	2.999	7.928	1.103
B6	3.015	7.986	1.125
B7	2.981	7.916	1.136
C1	3.006	8.050	0.899
C2	3.098	7.984	1.202
C3	3.019	7.944	0.899
C4	3.097	7.992	1.111
C5	3.187	8.028	1.191
C6	3.062	8.018	1.199
C7	3.184	8.036	0.883
D1	2.926	7.996	0.960
D2	3.092	8.148	0.918
D3	3.023	7.942	0.893
D4	3.006	8.030	1.112
D5	2.966	8.016	0.886
D6	2.986	8.002	1.104
D7	3.008	8.024	0.906

Table 4. Initial calculated ratio data for the composite specimen

	Gage Length	Bolt Torque	Mass (g) (Comp.)	Mass (g) (Alum.)	Density (comp.)	Density (Alum.)
A1	5.250	75	308.100	532.500	0.002	0.052
A2	5.225	75	322.300	525.400	0.002	0.039
A3	5.240	75	305.200	526.300	0.002	0.051
A4	5.670	80	308.000	527.000	0.002	0.051
A5	5.479	75	309.200	520.700	0.002	0.050
A6	5.387	75	303.000	531.000	0.002	0.052
A7	5.638	75	306.100	528.000	0.002	0.052
B1	5.250	120	304.100	525.200	0.002	0.051
B2	5.460	120	310.000	520.000	0.002	0.050
B3	5.432	100	331.600	526.800	0.002	0.039
B4	5.420	100	328.000	527.300	0.002	0.038
B5	5.382	100	321.600	520.900	0.002	0.039
B6	5.320	100	321.400	531.100	0.002	0.040
B7	5.452	100	325.800	527.400	0.002	0.038
C1	5.255	75	307.300	530.800	0.002	0.052
C2	5.326	75	351.900	527.900	0.002	0.039
C3	5.300	75	300.200	523.600	0.002	0.054
C4	5.241	75	350.500	529.000	0.002	0.042
C5	5.065	75	353.000	521.100	0.002	0.038
C6	5.175	75	371.700	520.000	0.002	0.037
C7	5.158	75	308.900	525.300	0.002	0.054
D1	5.346	100	306.500	520.900	0.002	0.046
D2	5.335	100	304.600	527.000	0.002	0.052
D3	5.490	100	304.900	531.700	0.002	0.052
D4	5.249	100	334.900	518.800	0.002	0.038
D5	5.483	100	308.400	532.200	0.002	0.053
D6	5.448	100	329.100	526.500	0.002	0.039
D7	5.318	100	310.000	525.100	0.002	0.050

Table 5. Initial overall specimen physical data

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The bearing strain/bearing stress diagrams from the tests were produced as real-time graphic representations of the tests performed. These diagrams were recorded by the test machine computer. These diagrams document the stress and the strain changes throughout the specimen tests. These results graphically show the behavior of the specimen as can be seen in Figures 10-14 Contrasting each specimen group gives insight into possible behavior patterns for each data set. These results were used to derive possible conclusions for the test results, then verified with the normalized data provided.

The graph data show a significant change in behavior between the four groups. It can be seen by a cursory view of the graph profiles that, in general, the graphs for group A and B show a more brittle stress-strain profile than the graphs for group C and D. It appears that there is a significant increase in strain from groups A and B to groups C and D.

The normalized data are provided in Tables 6 and 7. The normalized data were used to confirm, or deny, the interpretations from the graphs. The data are normalized to minimize the physical dimension effects on the specimen load and deformation.

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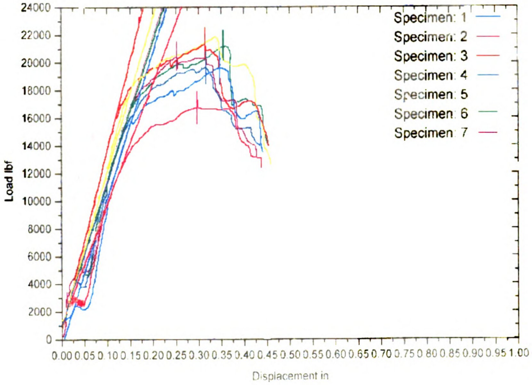
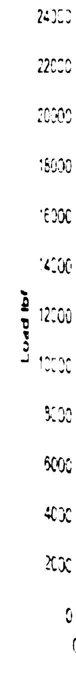


Figure 10. Bearing Stress/Bearing Strain results for all group A specimen



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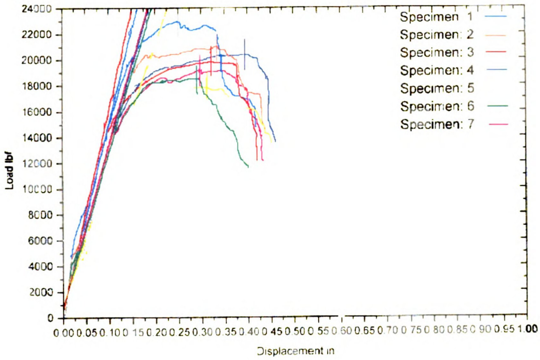

Figure 11. Bearing Stress/Bearing Strain results for all group B specimen

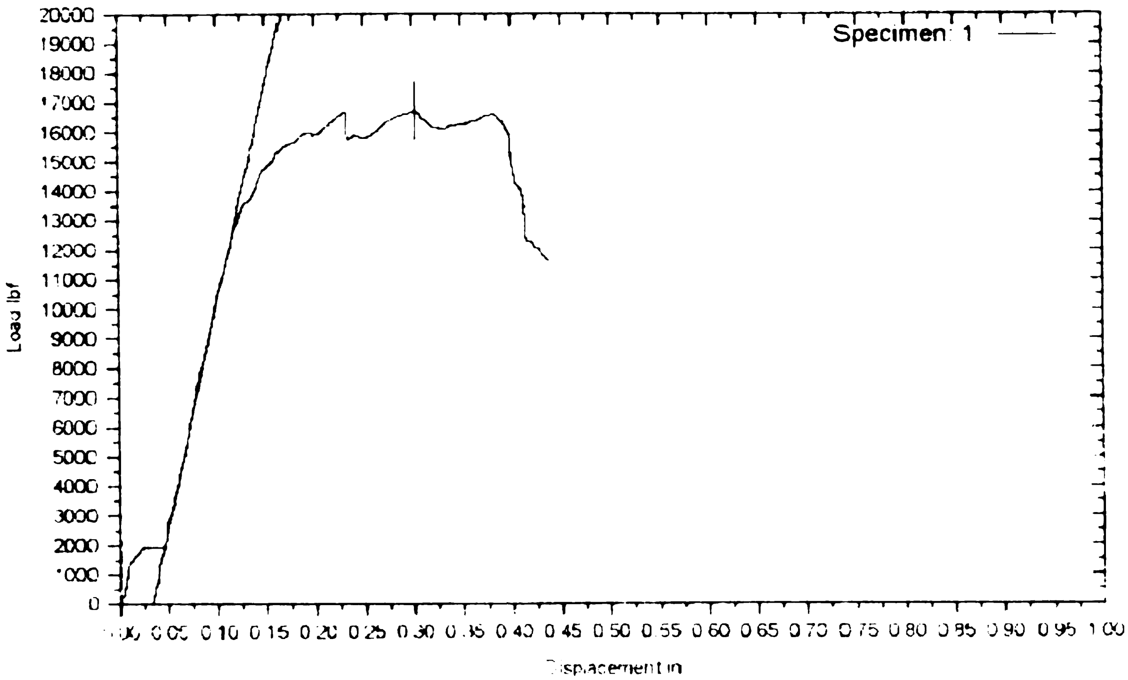

Figure 12. Bearing Stress/Bearing Strain results for specimen 1 of group C

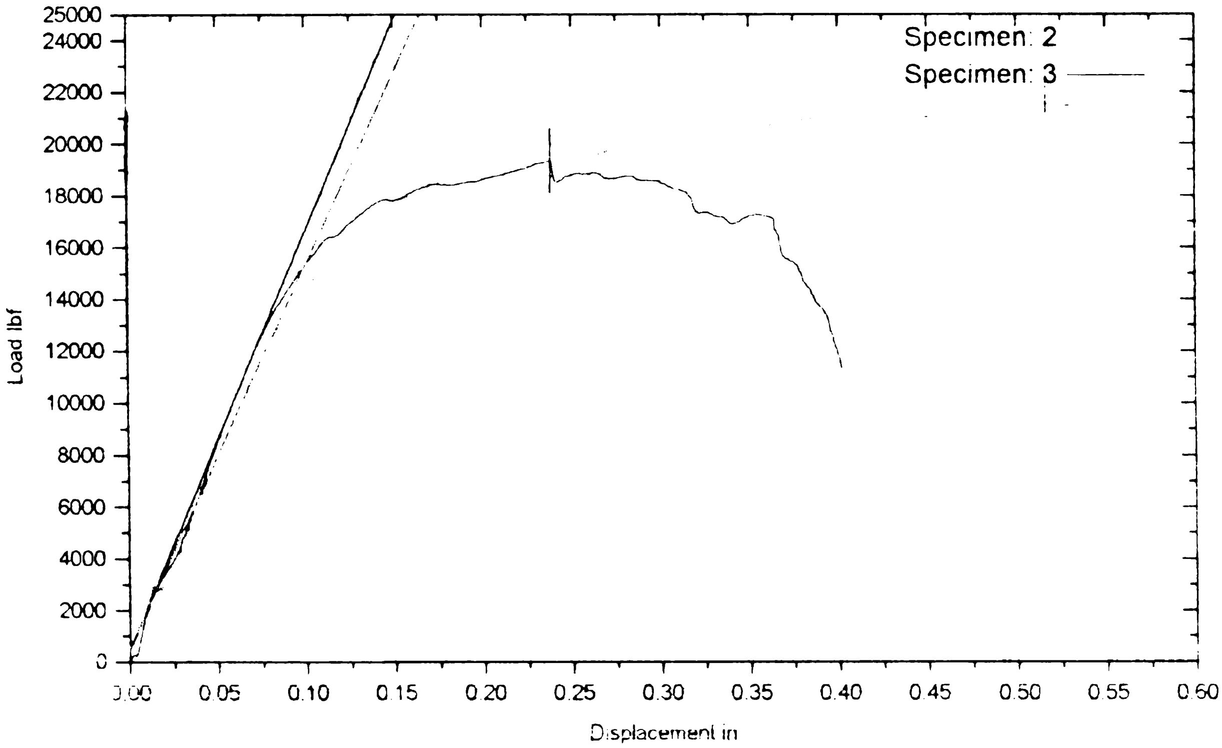

Figure 13. Bearing Stress/Bearing Strain results for specimens 2 and 3 of group C

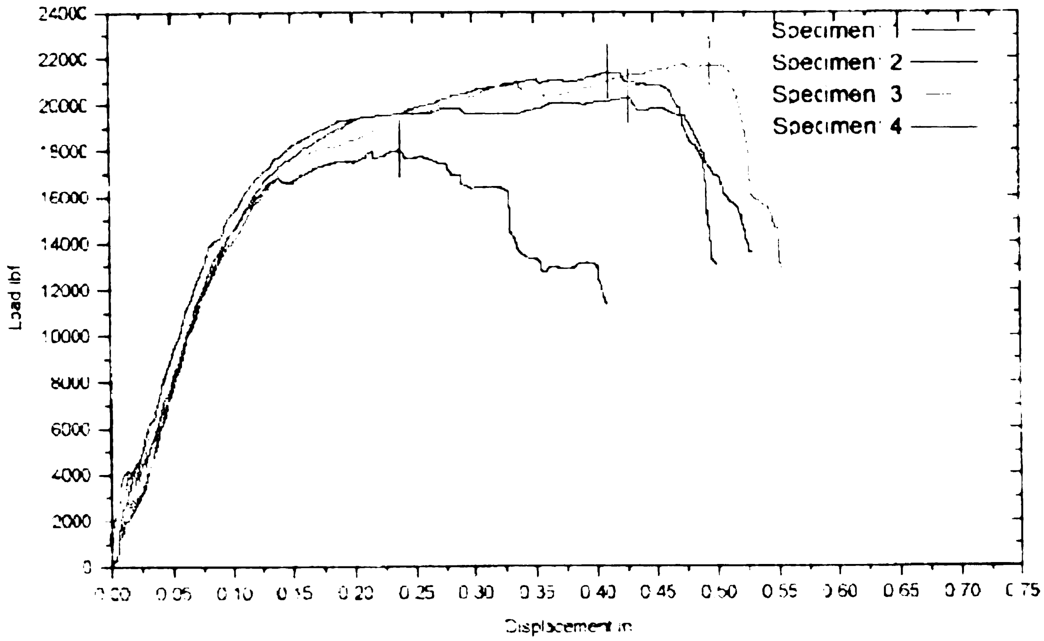

Figure 14. Bearing Stress/Bearing Strain results for specimens 4-6 of group C

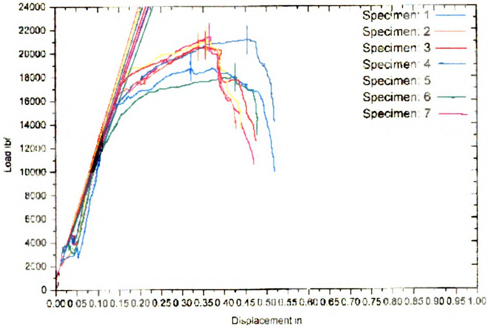

Figure 15. Bearing Stress/Bearing Strain results for all group D specimen

Specimen ID	Ultimate Bearing Stress	Ultimate Bearing Strain	Bearing Strain at Failure
A1	40,227	0.066	0.083
A2	30,939	0.057	0.084
A3	39,369	0.060	0.085
A4	40,084	0.056	0.076
A5	43,998	0.062	0.079
A6	43,342	0.066	0.082
A7	41,356	0.045	0.072
B1	47,744	0.048	0.079
B2	42,482	0.061	0.080
B3	37,061	0.059	0.077
B4	36,796	0.073	0.083
B5	32,589	0.058	0.084
B6	34,031	0.054	0.071
B7	34,740	0.055	0.079
C1		0.058	0.084
C2		0.097	0.105
C3		0.045	0.072
C4	40,629	0.079	0.099
C5	37,229	0.085	0.098
C6	39,049	0.096	0.105
C7	37,897	0.046	0.078
D1	36,784	0.060	0.095
D2	42,553	0.063	0.086
D3	42,081	0.065	0.077
D4	38,617	0.086	0.099
D5	43,211	0.065	0.080
D6	32,983	0.078	0.088
D7	43,026	0.069	0.081
Mean for Group A	39,902	0.059	0.080
Mean for Group B	37,920	0.058	0.080
Mean for Group C	38,701	0.072	0.092
Mean for Group D	39,893	0.069	0.087
Standard Deviation for Group A	4,311	0.007	0.005
Standard Deviation for Group B	5,369	0.008	0.004
Standard Deviation for Group C	1,489	0.022	0.013
Standard Deviation for Group D	3,910	0.009	0.008
Coefficient of Variance for Group A	10.803	12.347	5.916
Coefficient of Variance for Group B	14.160	13.287	5.377
Coefficient of Variance for Group C	3.848	31.034	14.663
Coefficent of Variance for Group D	9.802	13.379	9.357

Table 6. Specimen ultimate stress/strain and bearing failure results data

Specimen ID	Bearing Strain (Chord Modulus Range)	Bearing Stress (Chord Modulus Range)	Bearing Chord Modulus
A1	0.005	7,579	1,927,429
A2	0.002	2,444	1,707,934
A3	0.004	4,929	1,511,868
A4	0.002	4,026	1,847,792
A5	0.004	5,552	1,957,508
A6	0.003	4,224	1,916,347
A7	0.004	5,545	2,000,246
B1	0.002	2,939	1,285,191
B2	0.004	6,520	1,553,480
B3	0.002	2,441	1,649,866
B4	0.002	2,570	1,079,715
B5	0.002	2,473	1,315,498
B6	0.002	2,854	1,281,386
B7	0.002	2,257	1,625,150
C1		N/A	N/A
C2		N/A	N/A
C3		N/A	N/A
C4	0.003	3,308	1,687,017
C5	0.001	1,229	1,475,377
C6	0.002	3,715	1,608,038
C7	0.003	5,429	1,882,400
D1	0.003	5,039	1,862,638
D2	0.003	4,790	1,803,975
D3	0.002	3,615	1,874,932
D4	0.002	3,394	2,035,364
D5	0.002	3,753	2,032,984
D6	0.002	2,550	1,811,593
D7	0.002	2,986	1,699,378
Mean for Group A	0.003	4,899.734	1,838,446.036
Mean for Group B	0.002	3,150.485	1,398,612.250
Mean for Group C	0.002	3,420.075	1,663,207.969
Mean for Group D	0.002	3,732.422	1,874,409.393
Standard Deviation for Group A	0.001	1,595.278	172,296.089
Standard Deviation for Group B	0.001	1,504.593	213,557.823
Standard Deviation for Group C	0.001	1,725.785	170,231.537
Standard Deviation for Group D	0.000	904.628	122,972.958
Coefficient of Variance for Group A	33.072	32.558	9.372
Coefficient of Variance for Group B	33.072	47.757	15.269
Coefficient of Variance for Group C	42.552	50.460	10.235
Coefficent of Variance for Group D	21.348	24.237	6.561

Table 7. Bearing chord modulus and supporting data

Evidence shows that there is a very significant difference in bearing strain results. Figure 16 further emphasizes this difference as well. There is a profound difference between groups A and B, and groups C and D. This finding is confirmed with the data from Table 8.

The data presented in Table 8 are designed to elaborate on the bearing strain results. Since there is such a significant difference in bearing strain between groups A and B, and C and D, it appears that the washer size plays a critical role in these differences. There is a significant difference in the bearing strain at failure to washer outside diameter, between groups A and B, and Groups C and D. This difference is shown in figure 17. Hence, there is a strong possibility that larger washers may prove to be a much safer design.

To explore the data further for evidence of larger washers providing a safer design, the difference between the bearing strain at failure and the strain at ultimate bearing strength was calculated. It is apparent from Figure 18 that there is a significant differential in these two levels of strain. A larger difference can have some benefits; (1) it may provide more time before a catastrophic failure occurs, and (2) a larger amount of strain may be more noticeable and hence, expedite a

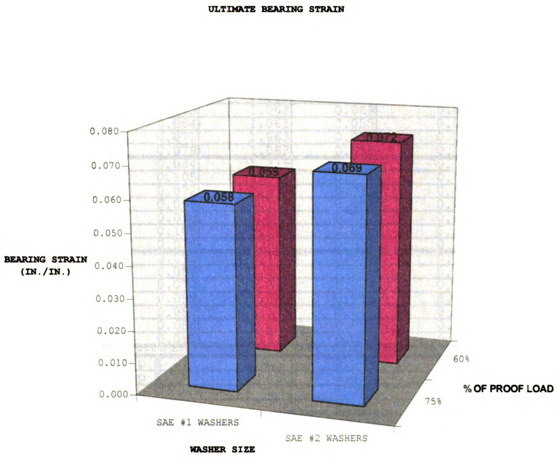

Figure 16. Ultimate bearing strain vs. washer size and bolt preload Chart

	ULTIMATE BEARING STRAIN	BEARING STRAIN AT FAILURE	WASHER O.D.	UBS TO WASHER OD RATIO	BS@FAILURE TO WASHER OD RATIO	BS@Failure - UBS
A1	0.066	0.083	1.063	0.062	0.078	0.017
A2	0.057	0.084	1.063	0.054	0.079	0.027
A3	0.060	0.085	1.063	0.056	0.080	0.025
A4	0.056	0.076	1.063	0.053	0.072	0.020
A5	0.062	0.079	1.063	0.058	0.074	0.017
A6	0.066	0.082	1.063	0.062	0.077	0.016
A7	0.045	0.072	1.063	0.042	0.068	0.027
B1	0.048	0.079	1.063	0.045	0.074	0.031
B2	0.061	0.080	1.063	0.057	0.075	0.019
B3	0.059	0.077	1.063	0.056	0.072	0.018
B4	0.073	0.083	1.063	0.069	0.078	0.010
B5	0.058	0.084	1.063	0.055	0.079	0.026
B6	0.054	0.071	1.063	0.051	0.067	0.017
B7	0.055	0.079	1.063	0.052	0.074	0.024
C1	0.058	0.084	1.375	0.042	0.061	0.026
C2	0.097	0.105	1.375	0.071	0.076	0.008
C3	0.045	0.072	1.375	0.033	0.052	0.027
C4	0.079	0.099	1.375	0.057	0.072	0.020
C5	0.085	0.098	1.375	0.062	0.071	0.013
C6	0.096	0.105	1.375	0.070	0.076	0.009
C7	0.046	0.078	1.375	0.033	0.057	0.032
D1	0.060	0.095	1.375	0.044	0.069	0.035
D2	0.063	0.086	1.375	0.046	0.063	0.023
D3	0.065	0.077	1.375	0.047	0.056	0.012
D4	0.086	0.099	1.375	0.063	0.072	0.013
D5	0.065	0.080	1.375	0.047	0.058	0.015
D6	0.078	0.088	1.375	0.057	0.064	0.010
D7	0.069	0.081	1.375	0.050	0.059	0.012

Mean for Group A	0.055	0.075	0.021
Mean for Group B	0.053	0.073	0.021
Mean for Group C	0.053	0.067	0.019
Mean for Group D	0.050	0.063	0.017
Standard Deviation for Group A	0.007	0.004	0.005
Standard Deviation for Group B	0.007	0.004	0.007
Standard Deviation for Group C	0.016	0.010	0.009
Standard Deviation for Group D	0.007	0.006	0.009
Coefficient of Var. for Group A	12.347	5.916	23.129
Coefficient of Var. for Group B	13.674	5.544	32.154
Coefficient of Var. for Group C	31.034	14.663	49.165
Coefficient of Var. for Group D	13.379	9.357	52.113

Table 8. Data showing correlation between bearing strain and washer O.D.

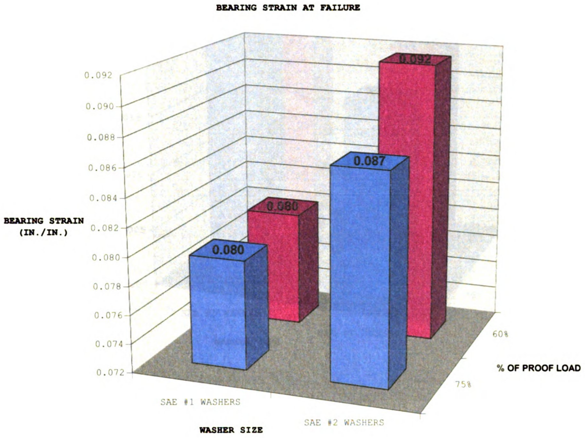

Figure 17. Bearing strain at failure vs. washer size and bolt preloand Chart

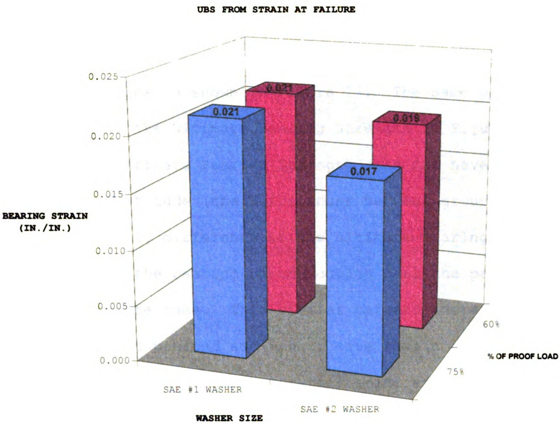

Figure 18. Bearing strain at failure minus ultimate bearing strain vs. washer size and bolt preload chart

needed repair. Testing on larger and smaller washers will provide information on the size most beneficial to safer designs.

The Bearing Chord Modulus showed significant differences between the four groups. A graphic display of these differences is shown in Figure 19. The same pattern can be seen in the Ultimate Bearing Strength in Figure 20. Although the Ultimate Bearing Strength does not have the statistical fortitude (the differences between groups are not statistically different for the ultimate bearing strength) that the bearing chord modulus has, the pattern appears to be the same. This similar pattern increases the possibility that preload and washer size have a significant and predictable effect on the overall joint strength.

Figures 21 thru 23 show the photographs of specimen A1. These photographs show the complete specimen, and the composite portion of each specimen after testing. These specimens show the damage and failure mode that was present in each specimen. These photographs show that each specimen failed in bearing. Photographs of all specimen are shown in the appendix. Damage that is more extensive is seen in groups C and D between the bearing strained area

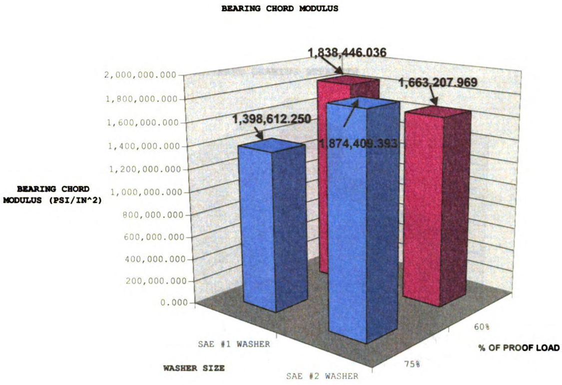

Figure 19. Bearing chord modulus vs washer size and bolt preload chart

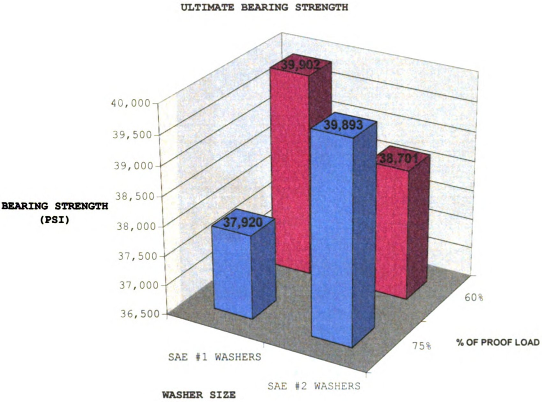

Figure 20. Ultimate bearing strength vs. washer size and bolt preload chart

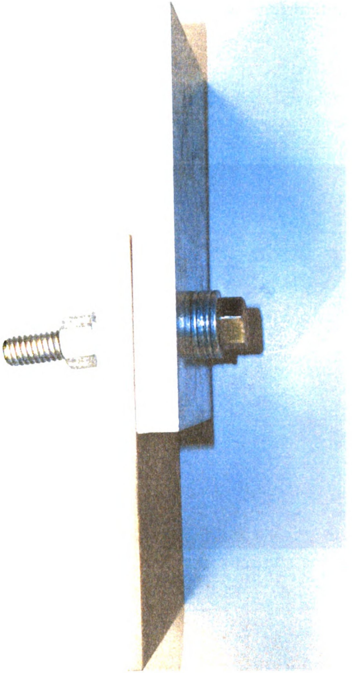

Figure 21. Specimen A1 - Side view

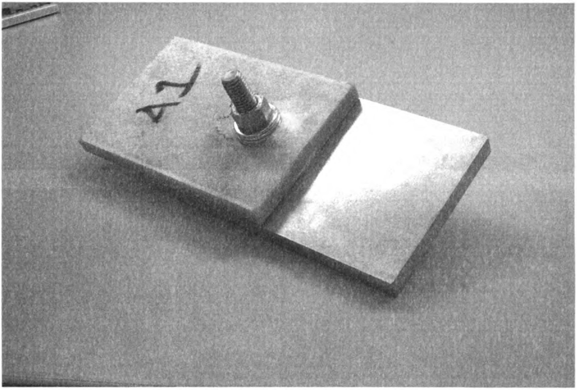

Figure 22. Specimen A1 - Top View

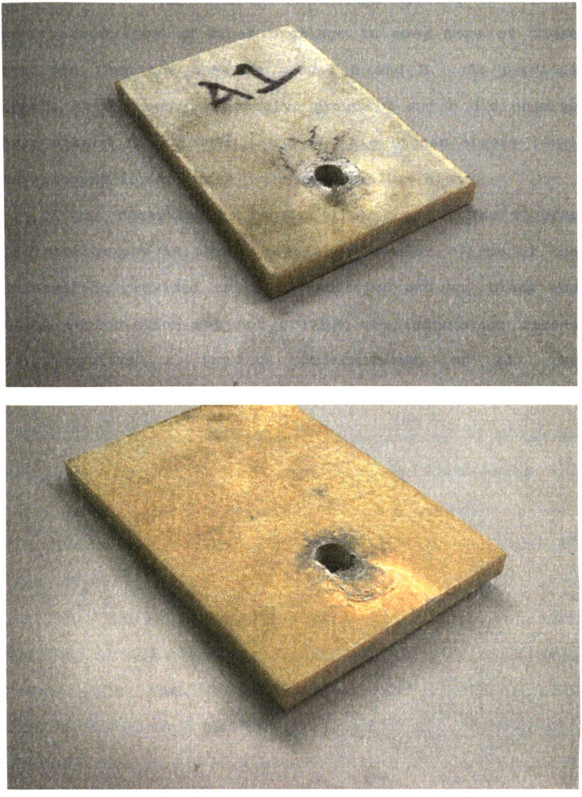

Figure 23. Specimen A1 - Composite portion front and back view

and the bottom of the specimen. There appears to be more pronounced lines of fiber breakage in many more of these specimen than the ones in groups A and B. As previous charts have shown, repeatedly, groups C and D did undergo more stress than groups A and B, this higher stress level may account for the more pronounced failure areas.

It is necessary to mention that most of the figures and photographs in this report are in color. Some of the information provided is color sensitive and any black and white reproduction may not provide the information needed to formulate a complete understanding of all the information provided in this paper.

Conclusions and Recommendations

Conclusions

The purpose of this paper is to show the effects of changing the bolt preload and the washer size on the tested joint system. The outcome was expected to show significant increases in strength for a decreased bolt preload, and a significant strength increase for the increased washer size. However, ultimate bearing strength is not the measure that was sought. A more crucial factor is the strength in the "working" or elastic range of the joint. Hence, the bearing chord modulus, which is very similar to the elastic modulus in a material, becomes the critical criteria. Below, is a review of the findings, a formation of potential conclusions that may be drawn from the results, and where further testing may be applicable.

The area of joint strength is the primary focus of this report. Two different strength variables were studied, Ultimate Bearing Strength and Bearing Chord Modulus. The Ultimate Bearing Strength differences between groups were shown insignificant, and the Bearing Chord Modulus difference between groups was shown significant. However, both groups show a very similar pattern, as can be seen through a comparison of Figures 17 and 18. This pattern shows a drop in strength, with the smaller washers, between the 60% preload and the 75% preload. This same pattern shows an increase in strength between the 60% and the 75% preload specimens using the larger washers. Due to the consistency of this information, it is reasonable to propose a potential relationship between washer size, preload strength, and joint strength.

In the original hypothesis, it was proposed that smaller washer size would degrade the strength of the joint. One reason for this behavior would be that the clamping load is distributed over a smaller surface in the joining materials. The amount of stress seen in the out-of-plane direction by the composite would be magnified, when a smaller washer is used.

Figure 24 shows a possible pattern that may be occurring. With the smaller washer, larger stresses are seen with less preload, causing strength degradation due to joint damage. The larger washer distributes the stress causing a lower load, at the same preload level, allowing for more clamping force to be applied before damage occurs. More testing is needed at lower and higher preload levels to determine that this is actually occurring. In addition, additional tests could determine what other factors might be contributing to this effect.

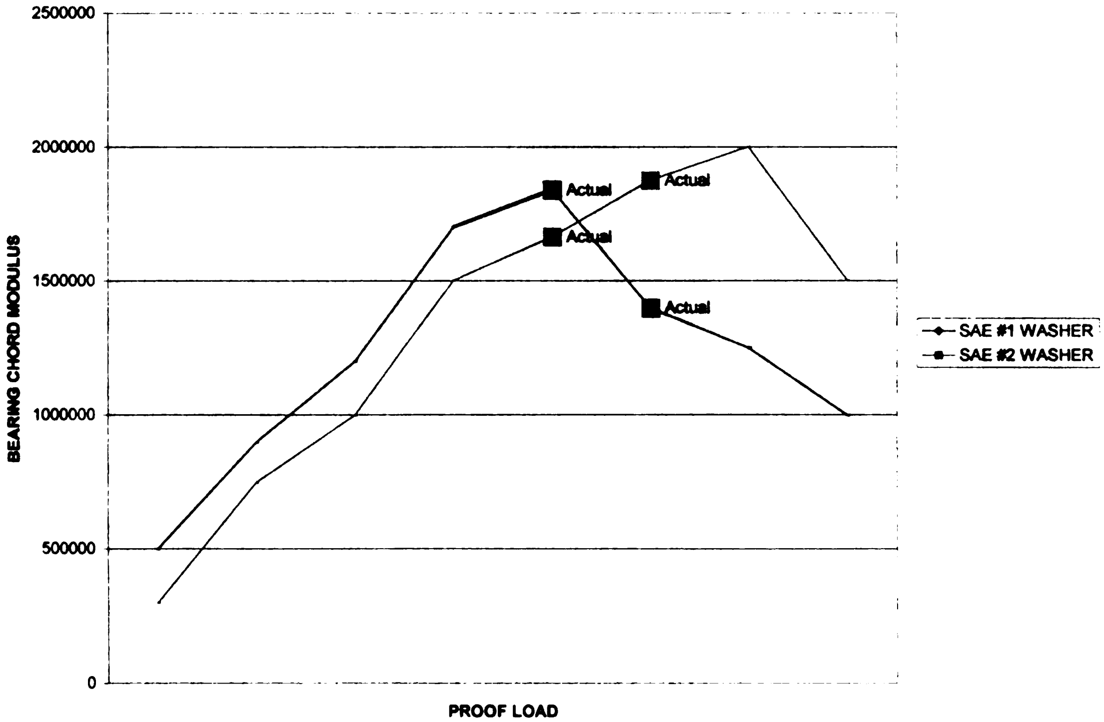

Figure 24. Potential projection of bearing chord modulus data

The data presented also showed that the bearing strains show some significant differences between the four groups. As shown in Table 6, the strain values are significantly higher for groups C and D. The higher strain values explain the more pronounced fractures seen for these specimen.

The results also seem to show a correlation between the larger washers and an increase in Ultimate Strain and Strain to Failure, as seen in Figures 14 and 15. This result was not anticipated, however, this effect could have a significant impact on design safety. The more strain accomodated by a joint until overload, or failure, the more time that is allowed for the impending failure to be noticed. This may decrease catastrophic failures in joints. However, although the larger washers appear to accommodate more strain, there seems to be less strain between ultimate bearing strain and strain at failure. The differences can be seen in the last column of data in Table 8. The difference is not statistically significant in this test. But, the results show enough consistency that they could warrant attention in the future since many of the photographs of specimens in groups C and D do show more advanced fracturing. This could be critical in designs that have a low design factor of safety.

Recommendations

The results of this test are very promising for increasing the efficiency of joining composite materials and metals. Of course, more research is needed to solidify and extend these findings. The author would like to offer several areas for further research.

First, a look should be taken at larger diameter bolts. Our tests had been designed for .5″ diameter bolts. We had the composite holes drilled by a company that specializes in this procedure. The bolts did undergo some deflection. However, it was evident that bolt deformation was not the primary mode of failure. Bearing Load was the primary failure mode. However, the bolt deformation did increase the Bearing Strain. The extent of this effect can not be determined through this series of tests.

The results tend to show that various washer sizes may have ideal preloads for use with composite joints. Tests would have to be run at a greater range of preload values for the same washers to determine what the ideal might be, and if there may be a discernable pattern. A pattern to the preload values may give assemblers a tolerance range for their preloads.

In addition, various washers sizes need to be examined. This will help to solidify the relationship between washer size and strain values. A more definitive model of how the washer size affects the rate of failure and the bearing stress/bearing strain curve would be useful.

It is also recommended that a finite element model be created for this problem. However, more testing would be needed to do this effectively. The interaction of unsymmetrical loading, friction, contact stresses, washers, and bolt deformation makes this problem extremely complex. It will be necessary to collect more data to create a reliable model.

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APPENDICIES

APPENDIX A

SPECIMEN PHOTOGRAPHS

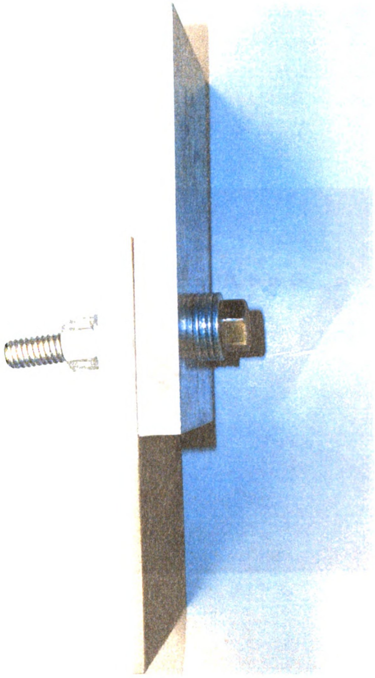


Figure 25. Specimen A1 - Side view

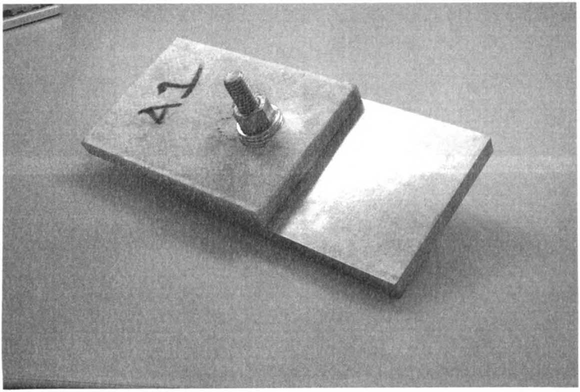


Figure 26. Specimen A1 - Top view

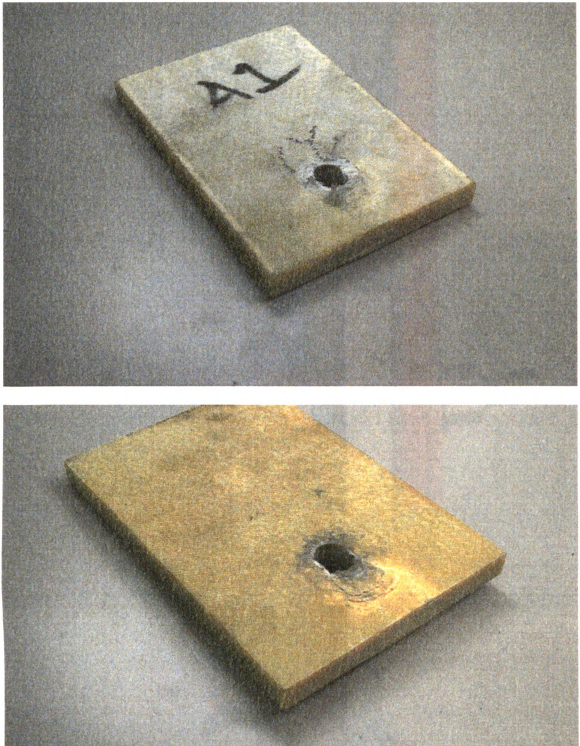


Figure 27. Specimen A1 - Composite front and rear views

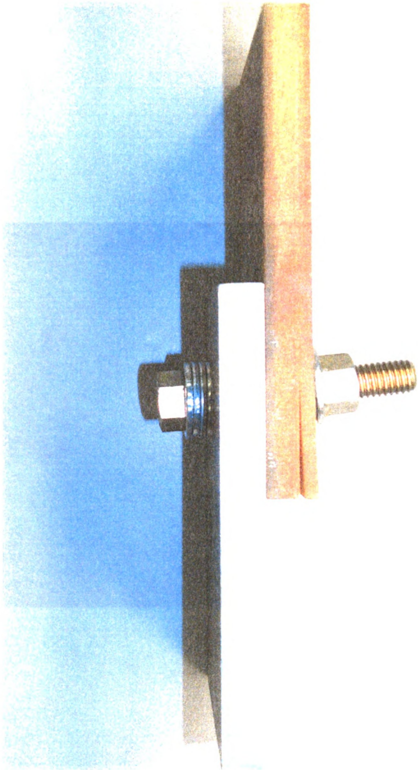


Figure 28. Specimen A2 - Side view

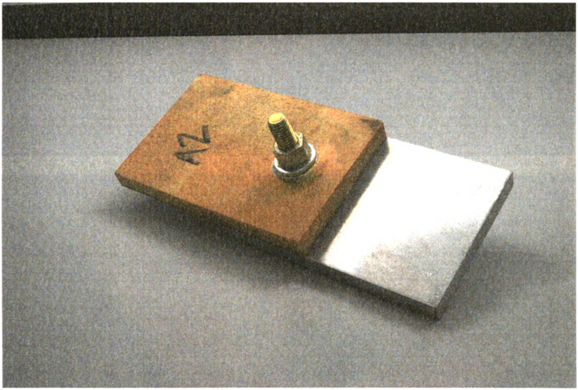


Figure 29. Specimen A2 - Top view

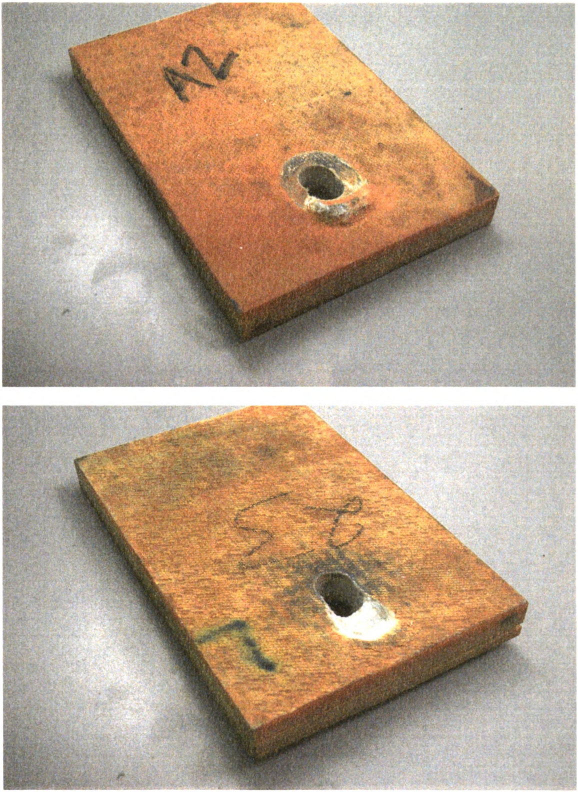


Figure 30. Specimen A2 - Composite front and rear views

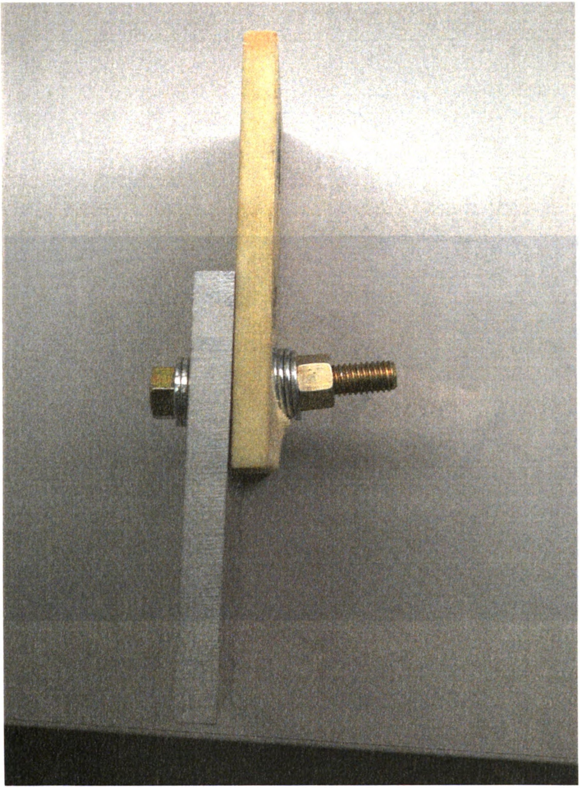


Figure 31. Specimen A3 - Side view

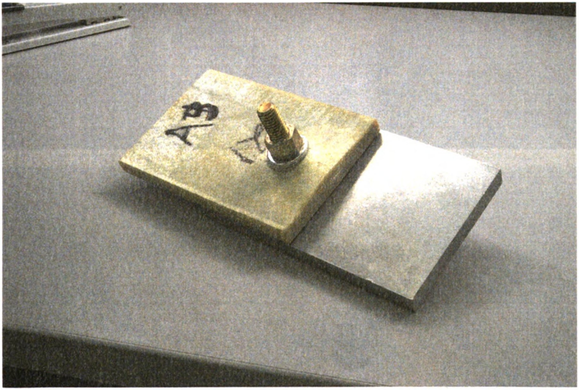


Figure 32. Specimen A3 - Top view

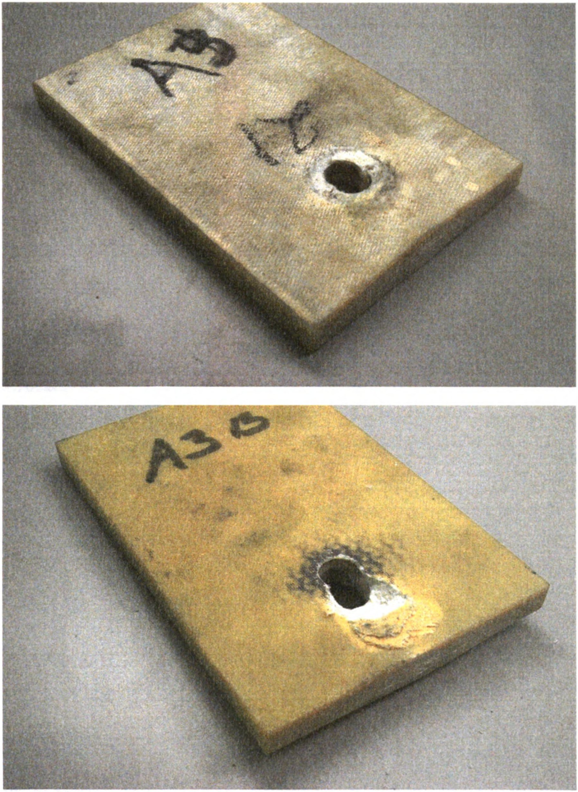


Figure 33. Specimen A3 - Composite front and rear view

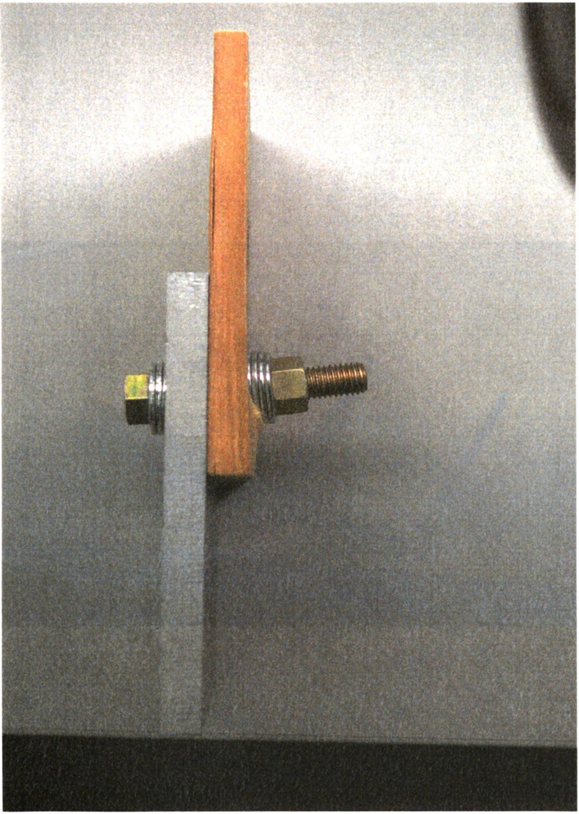


Figure 34. Specimen A4 - Side view

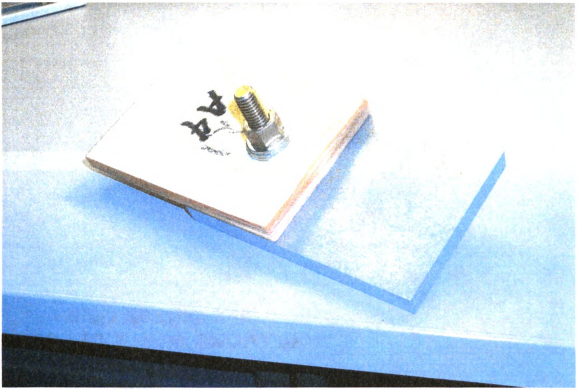


Figure 35. Specimen A4 - Top view

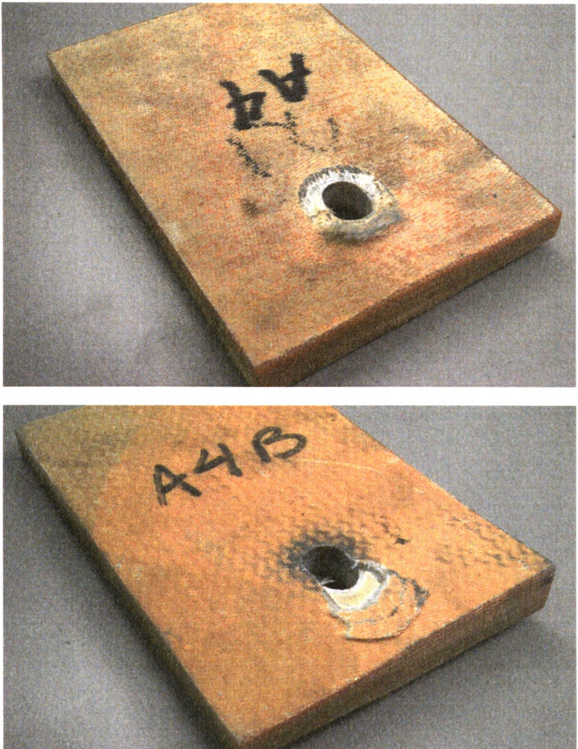


Figure 36. Specimen A4 - Composite front and rear view

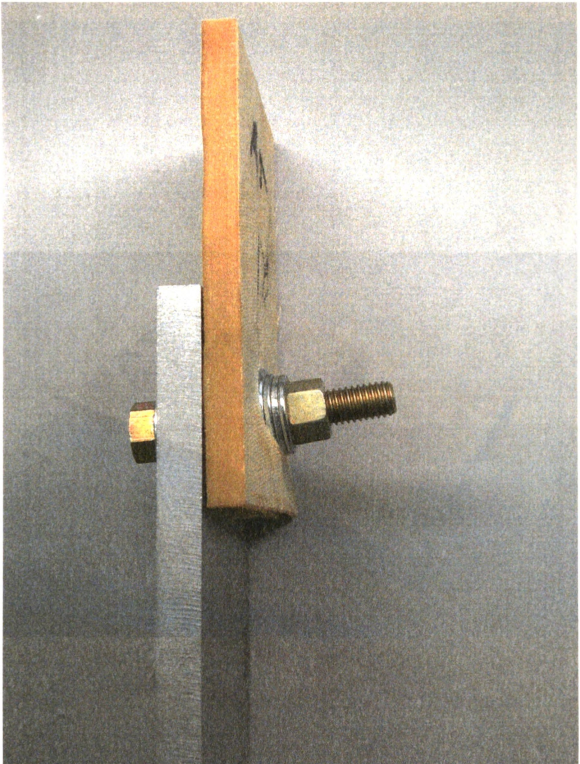


Figure 37. Specimen A5 - Side view

Figure 38. Specimen A5 - Top view

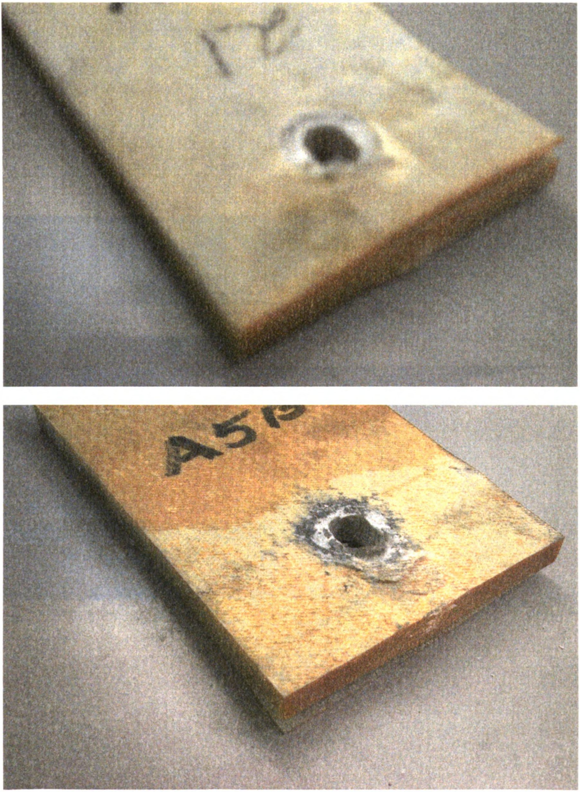


Figure 39. Specimen A5 - Composite front and rear views

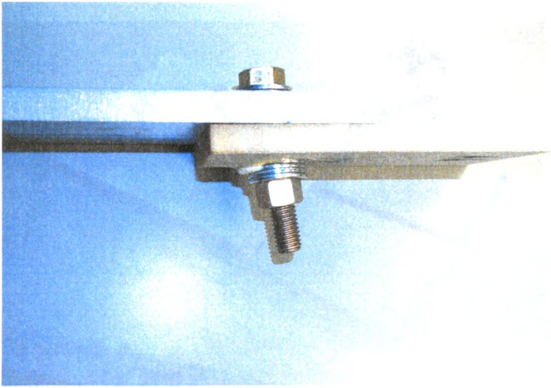


Figure 40. Specimen A6 - Side view

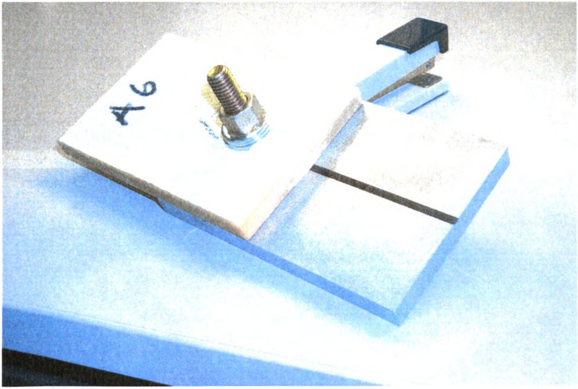


Figure 41. Specimen A6 - Top view

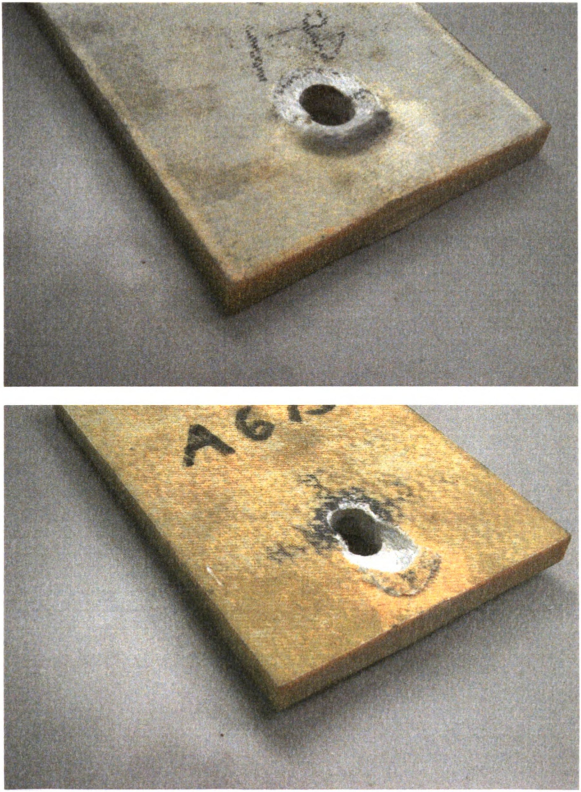


Figure 42. Specimen A6 - Composite front and rear views

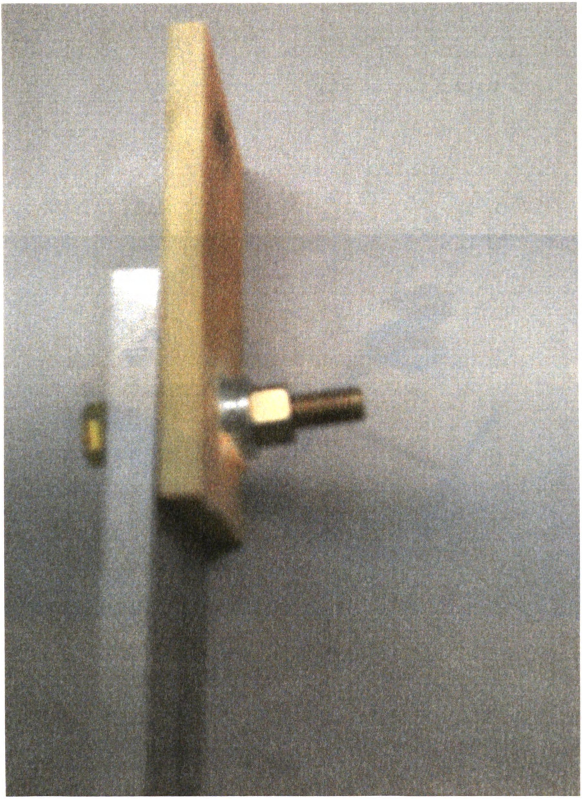


Figure 43. Specimen A7 - Side view

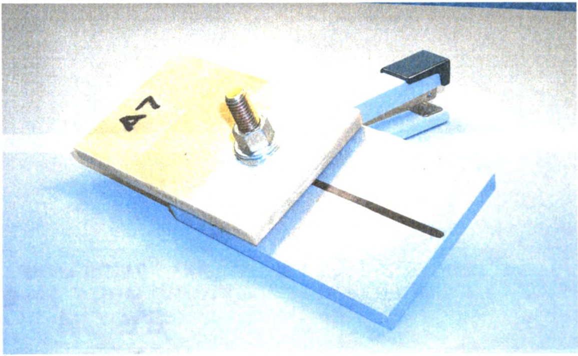


Figure 44. Specimen A7 - Top view

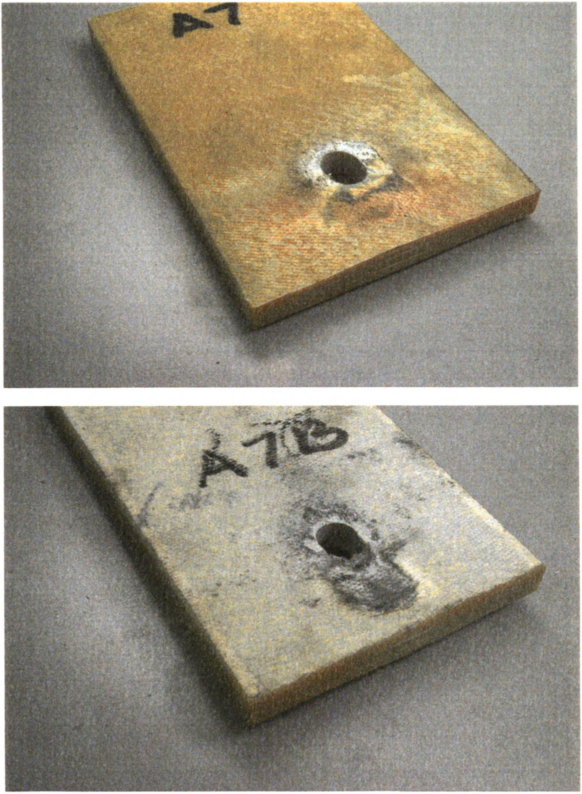


Figure 45. Specimen A7 - Composite front and rear view

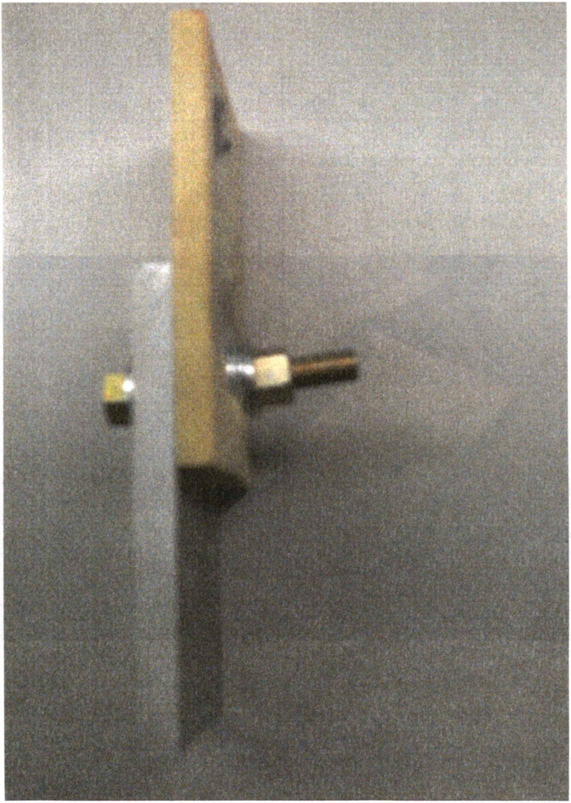


Figure 46. Specimen B1 - Side view

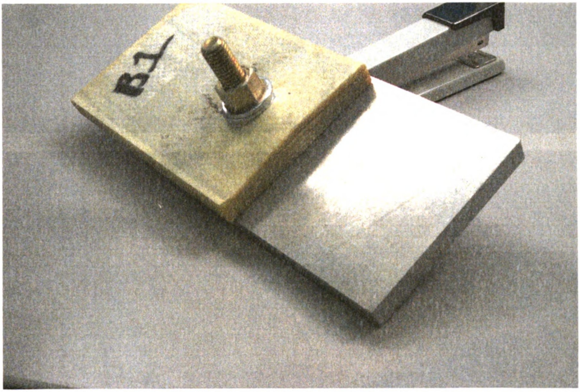


Figure 47. Specimen B1 - Top view

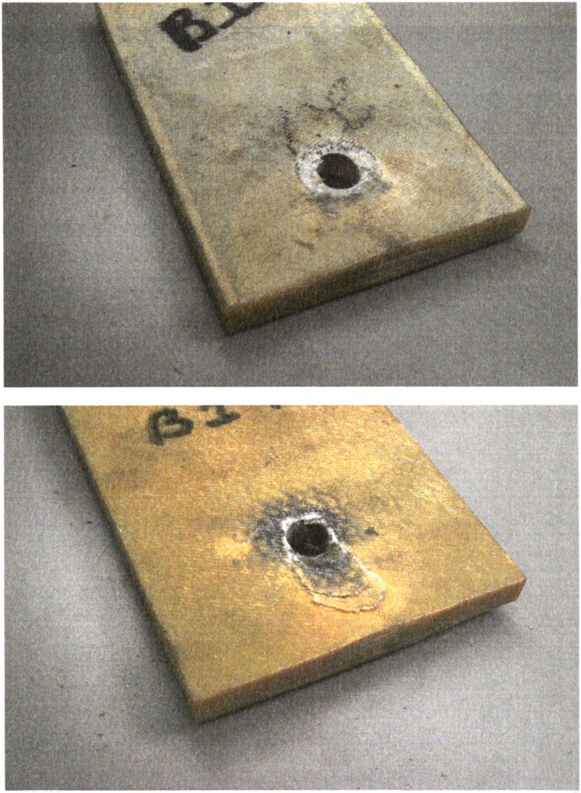


Figure 48. Specimen B1 - Composite front and rear view

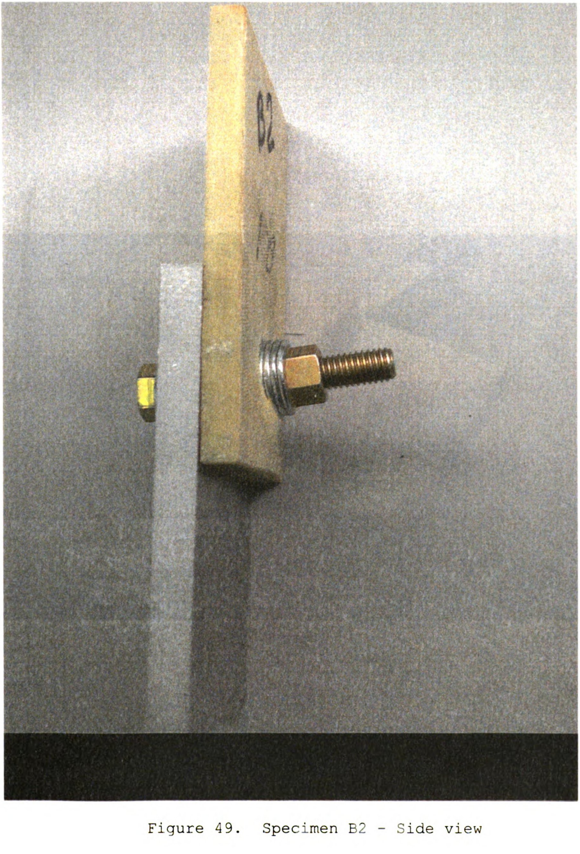


Figure 49. Specimen B2 - Side view

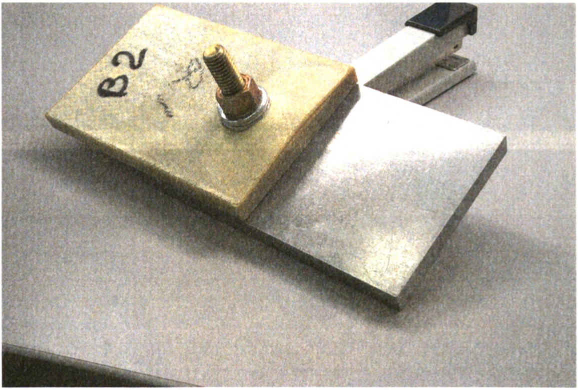


Figure 50. Specimen B2 - Top view

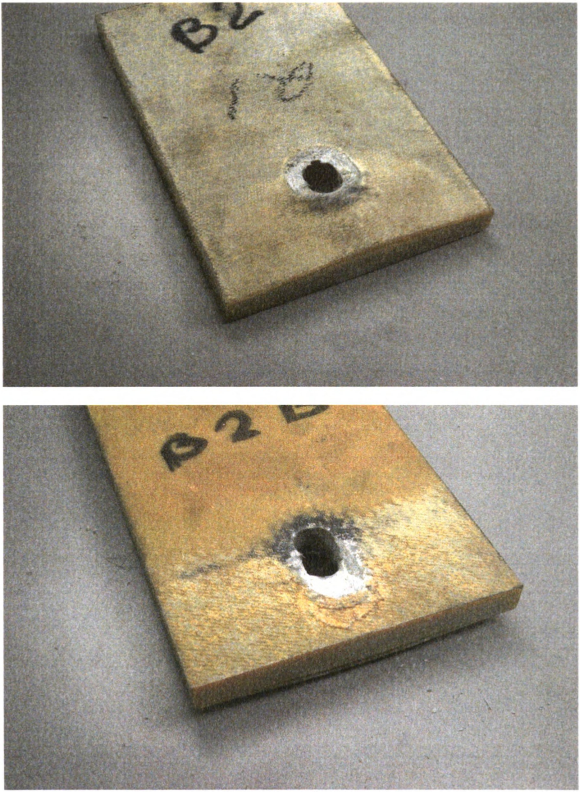


Figure 51. Specimen B2 - Composite front and rear views

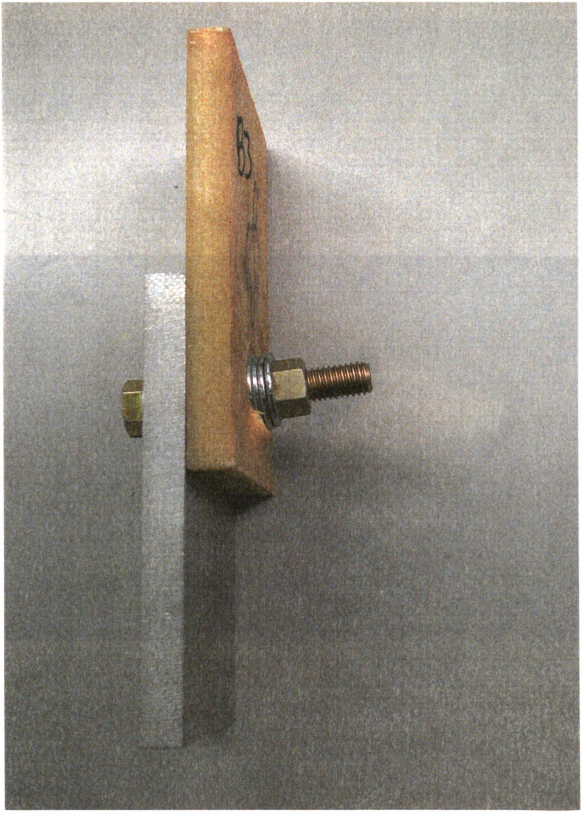


Figure 52. Specimen B3 - Side view

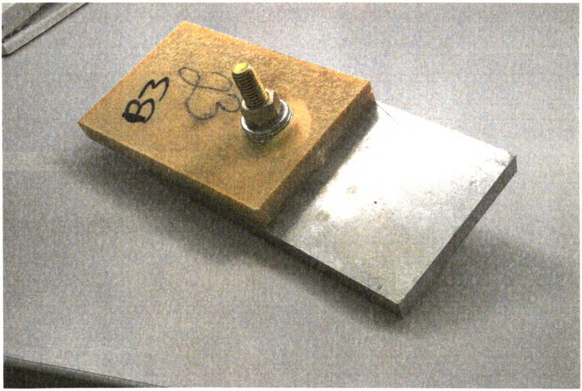


Figure 53. Specimen B3 - Top view

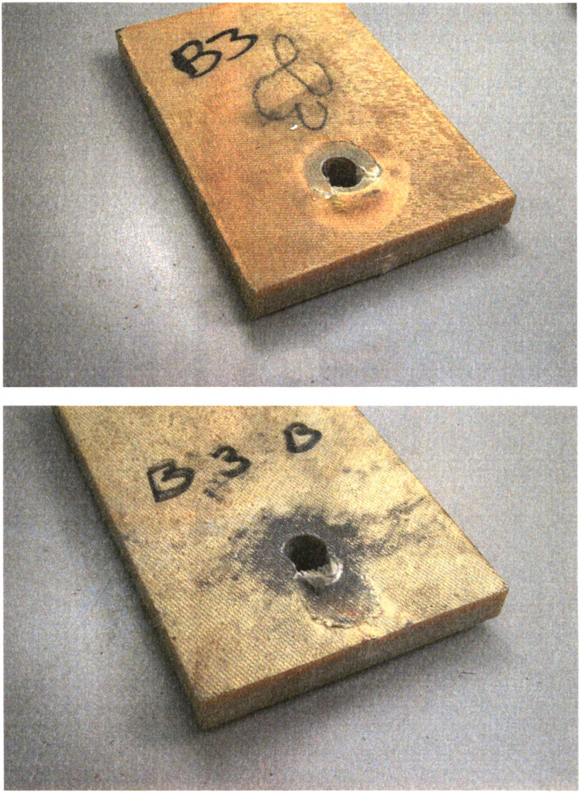


Figure 54. Specimen B3 - Composite front and rear view

Figure 55. Specimen B4 - Side view

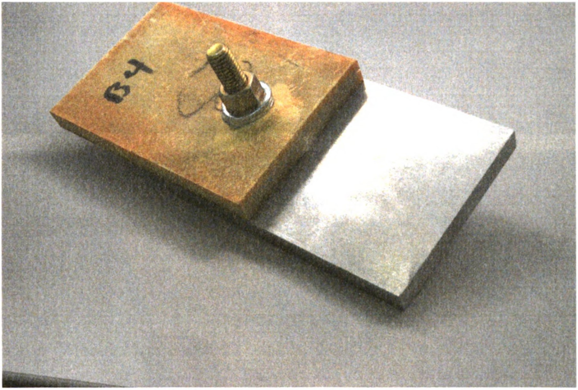


Figure 56. Specimen B4 - Top view

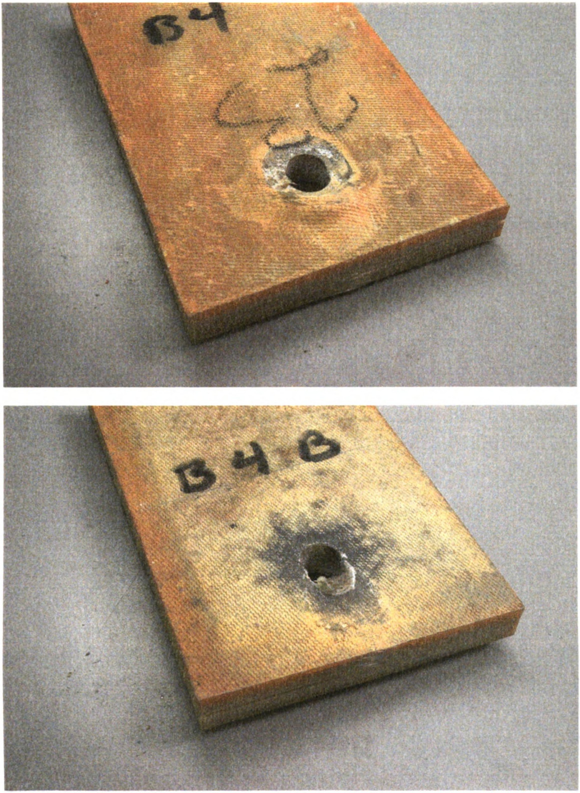


Figure 57. Specimen B4 - Composite front and rear views

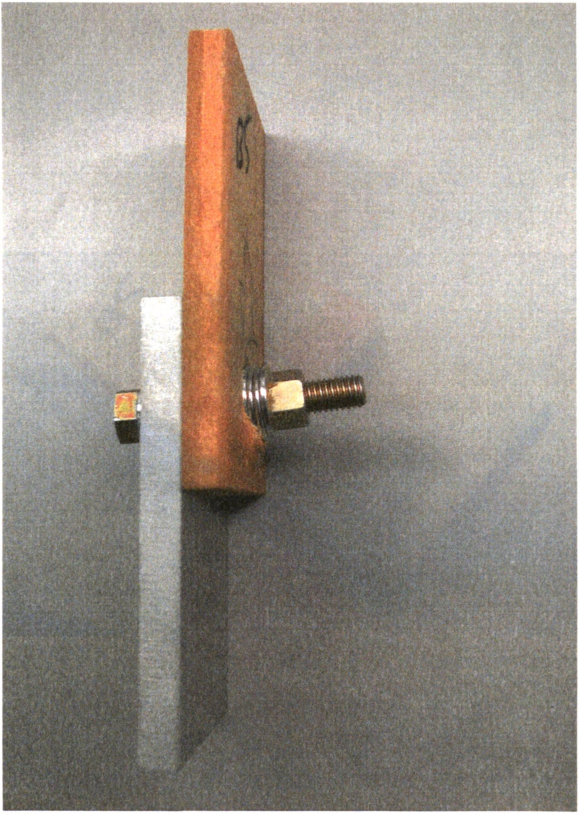


Figure 58. Specimen B5 - Side view

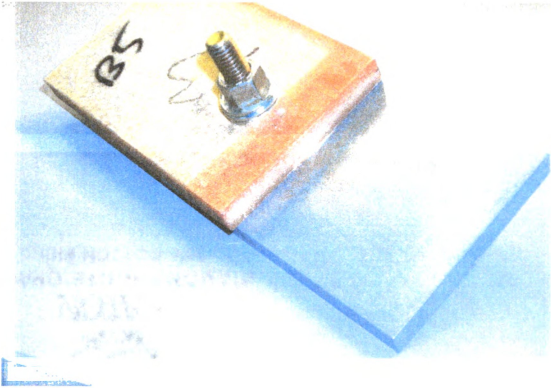


Figure 59. Specimen B5 - Top view

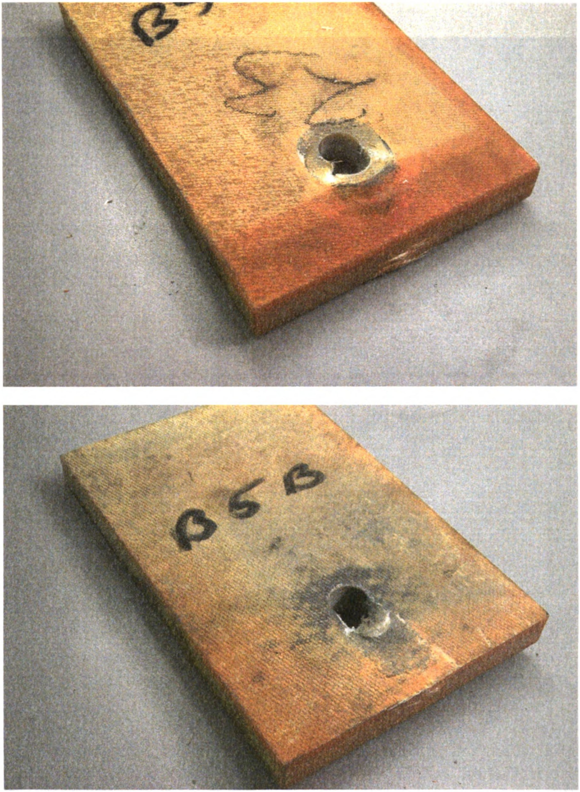


Figure 60. Specimen B5 - Composite front and rear views

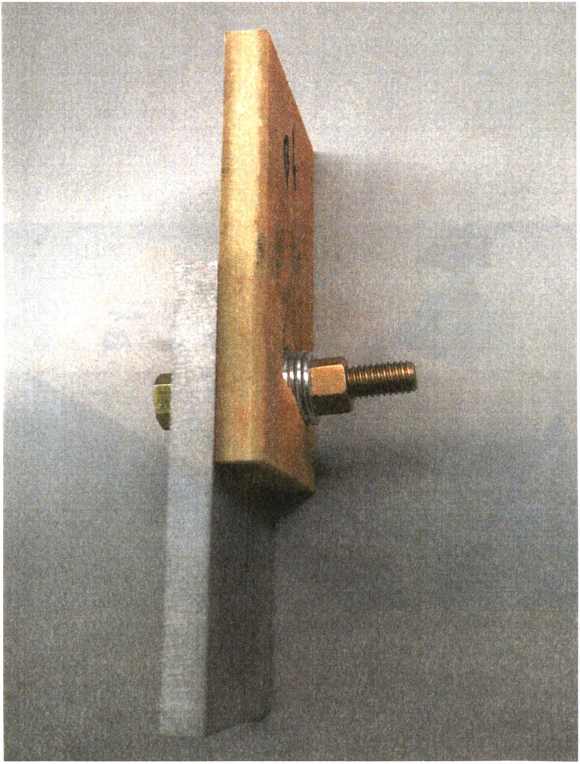


Figure 61. Specimen B6 - Side view

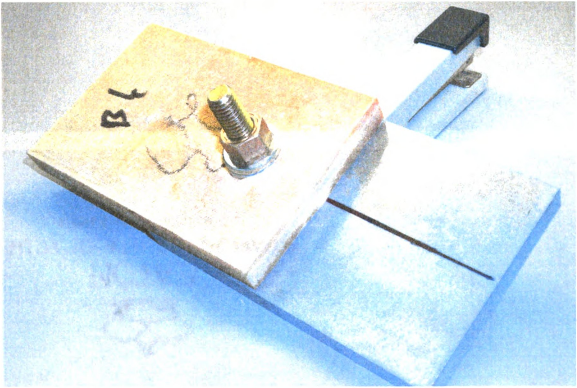


Figure 62. Specimen B6 - Top view

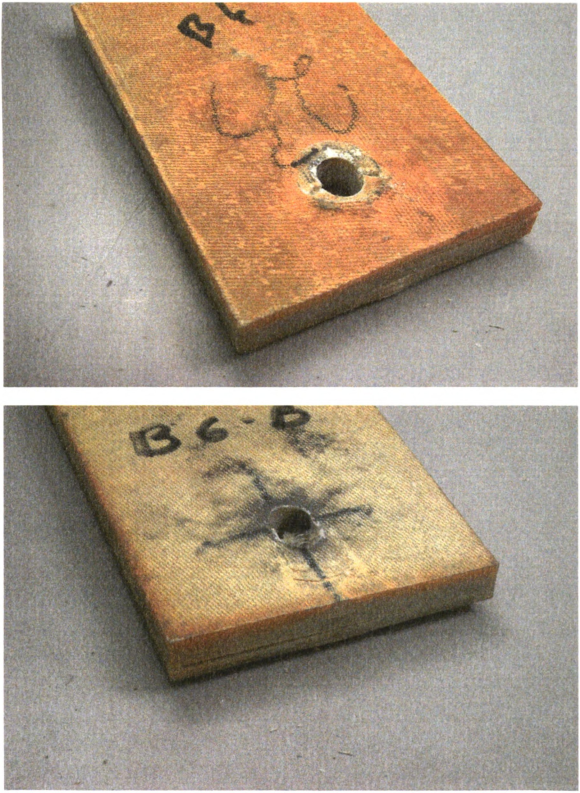


Figure 63. Specimen B6 - Composite front and rear views

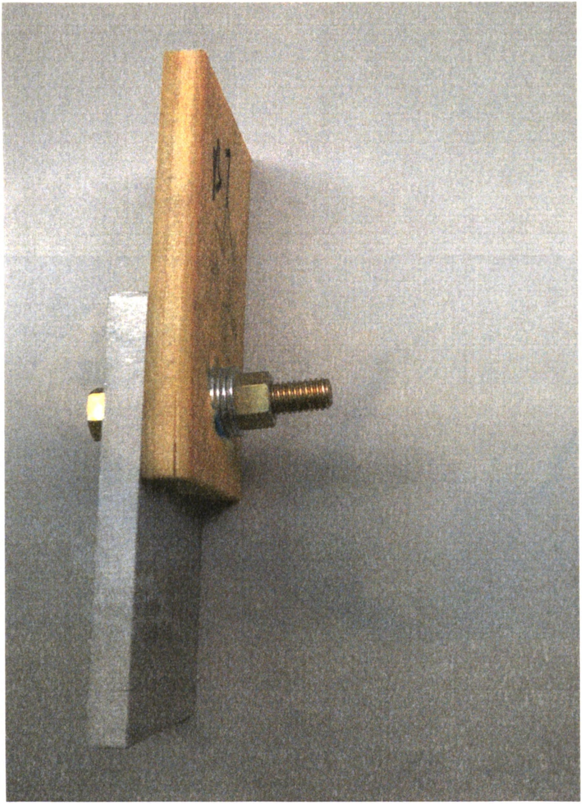


Figure 64. Specimen B7 - Side view

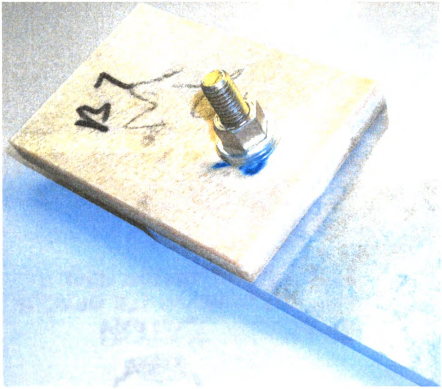


Figure 65. Specimen B7 - Top view

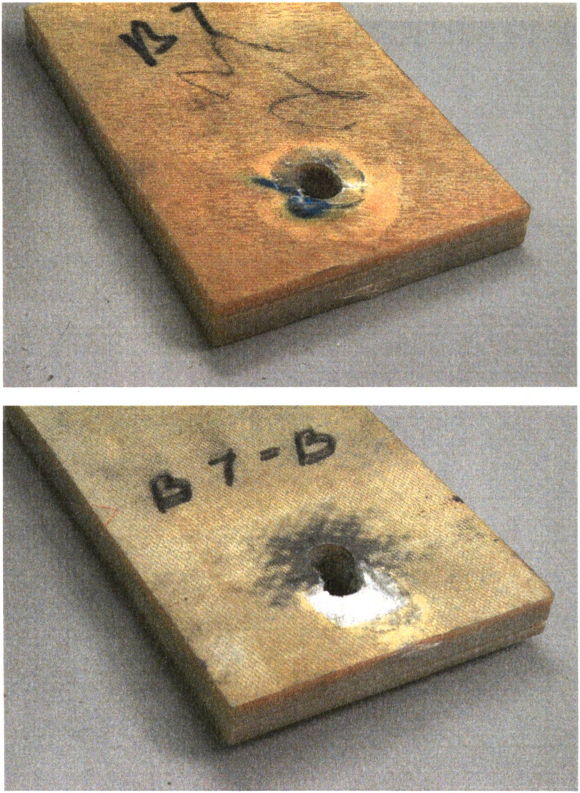


Figure 66. Specimen B7 - Composite front and rear view

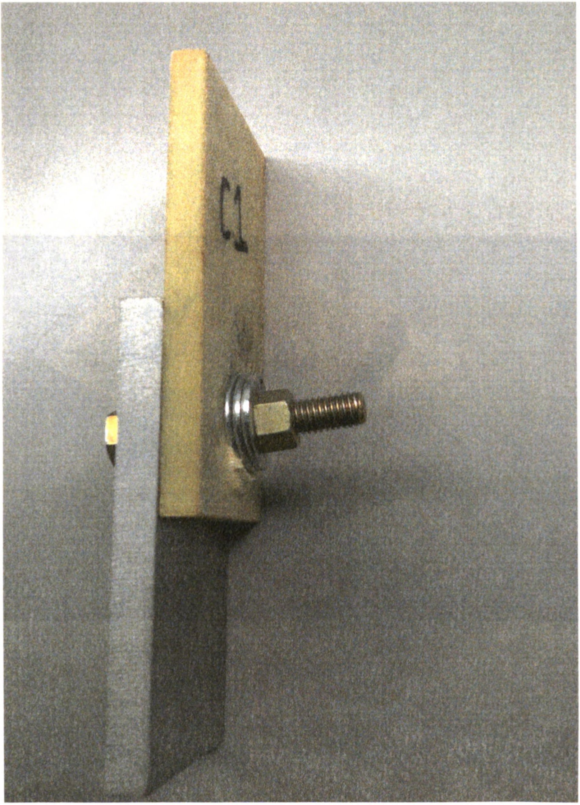


Figure 67. Specimen C1 - Side view

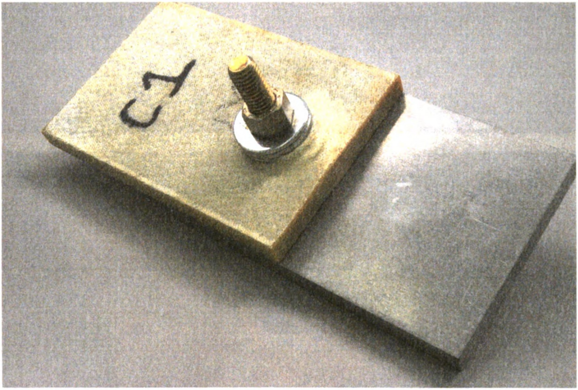


Figure 68. Specimen C1 - Top view

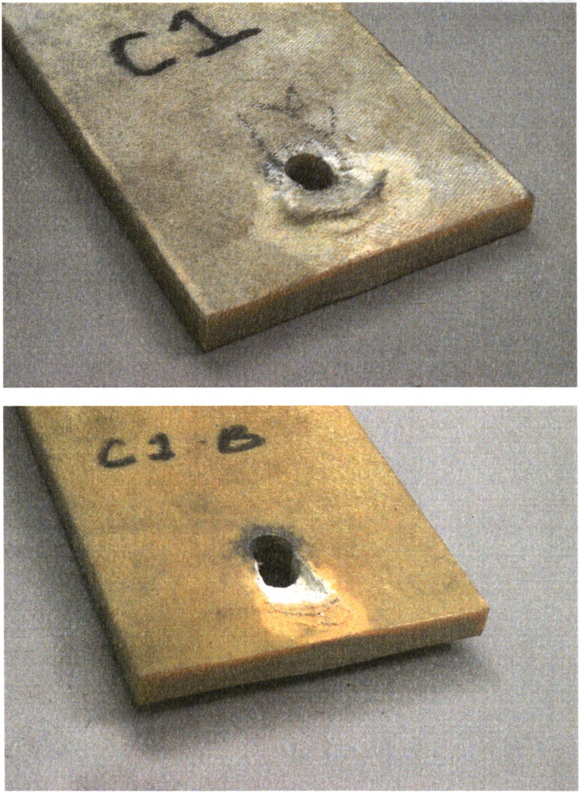


Figure 69. Specimen C1 - Composite front and rear views

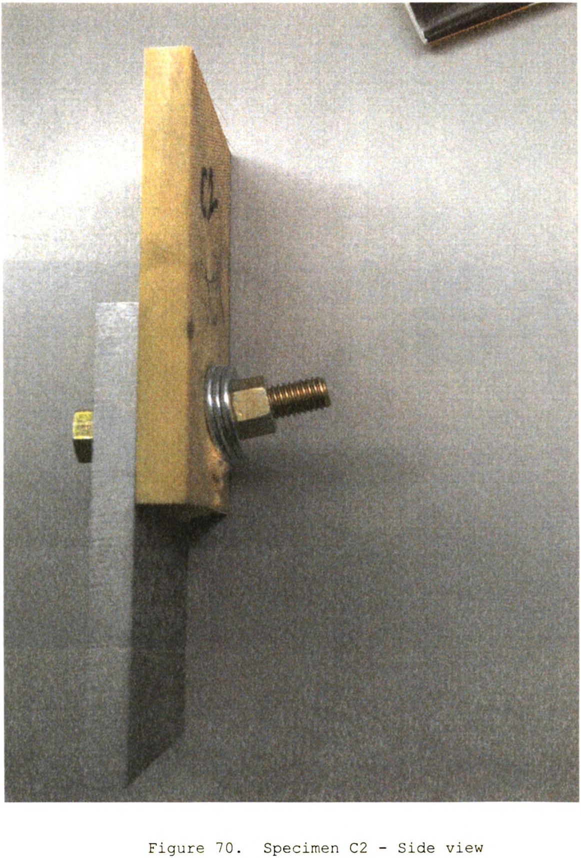


Figure 70. Specimen C2 - Side view

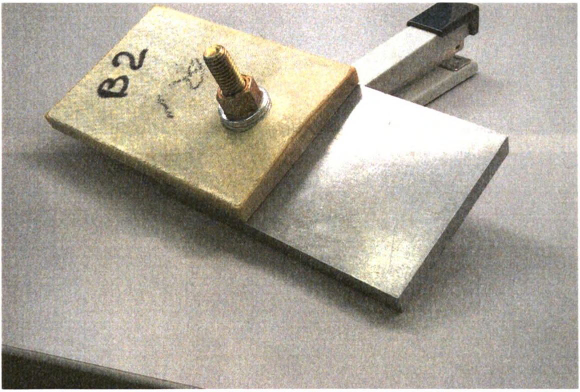


Figure 71. Specimen C2 - Top view

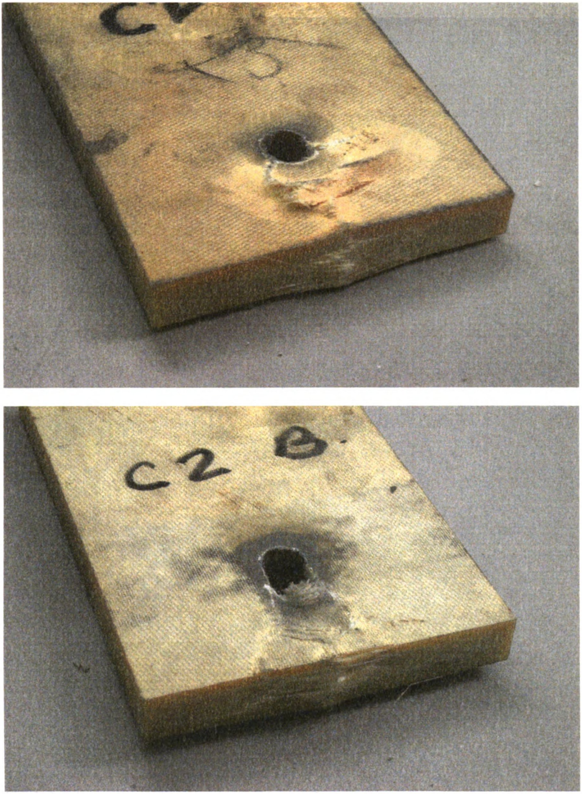


Figure 72. Specimen C2 - Composite front and rear views

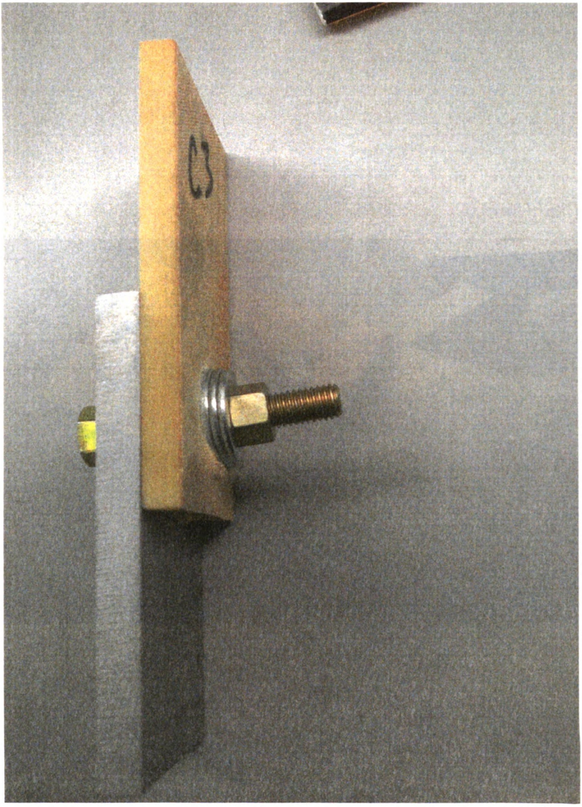


Figure 73. Specimen C3 - Side view

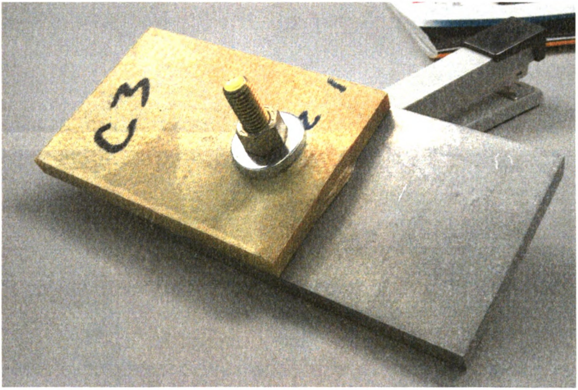


Figure 74. Specimen C3 - Top view

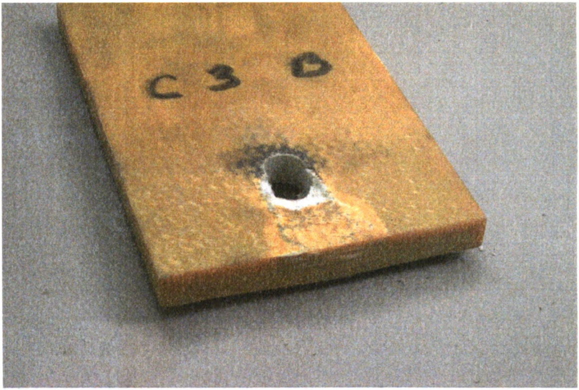


Figure 75. Specimen C3 - Composite front and rear view

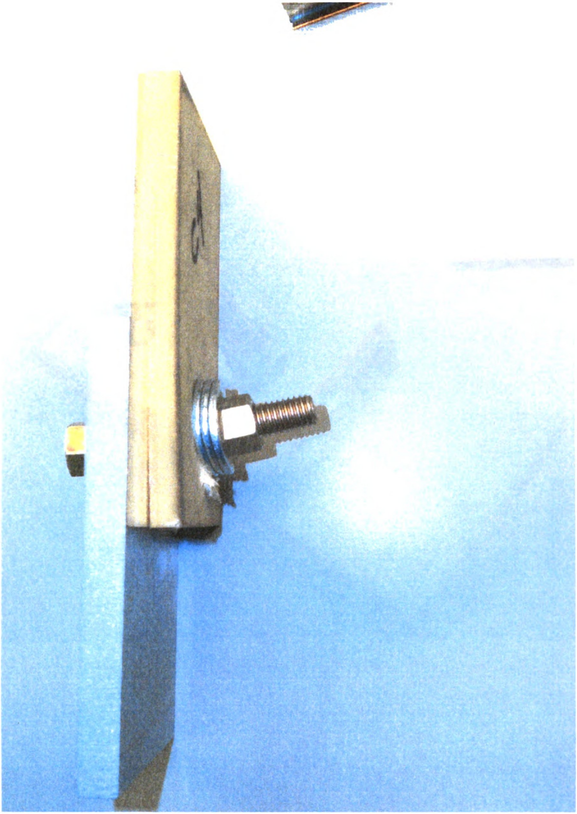


Figure 76. Specimen C4 - Side view

Figure 77. Specimen C4 - Top view

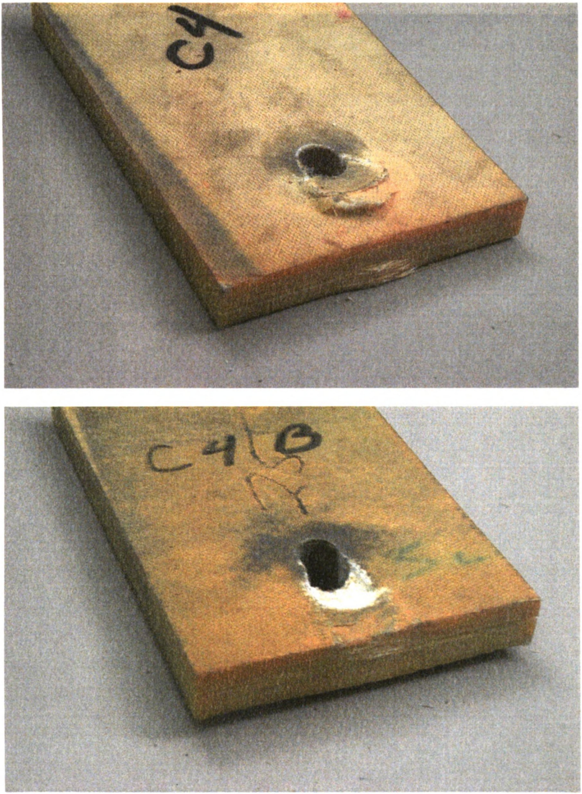


Figure 78. Specimen C4 - Composite front and rear views

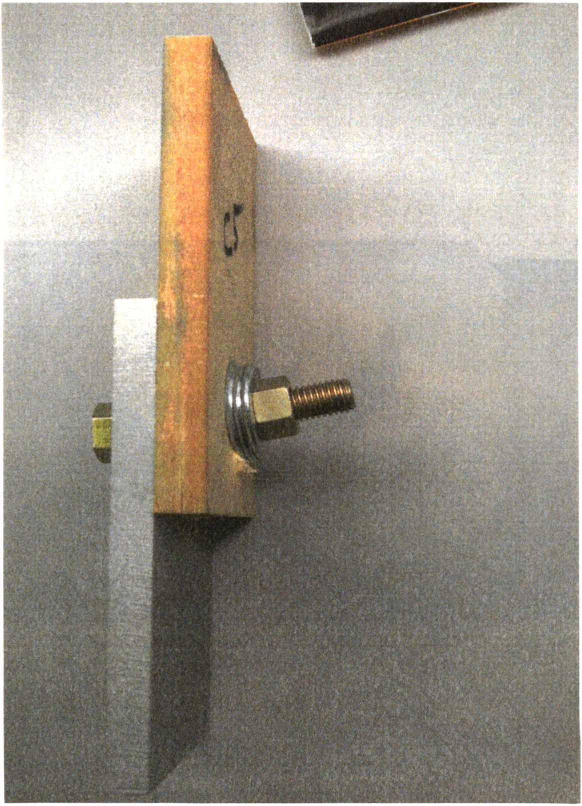


Figure 79. Specimen C5 - Side view

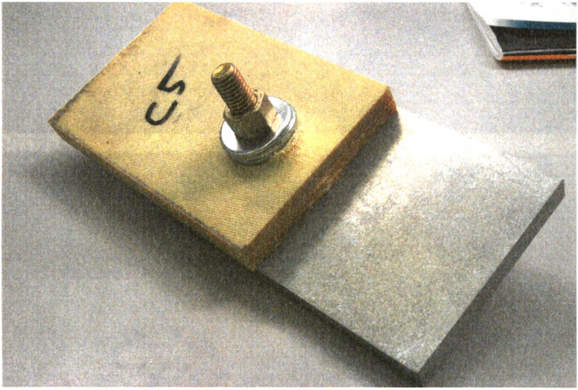


Figure 80. Specimen C5 - Top view

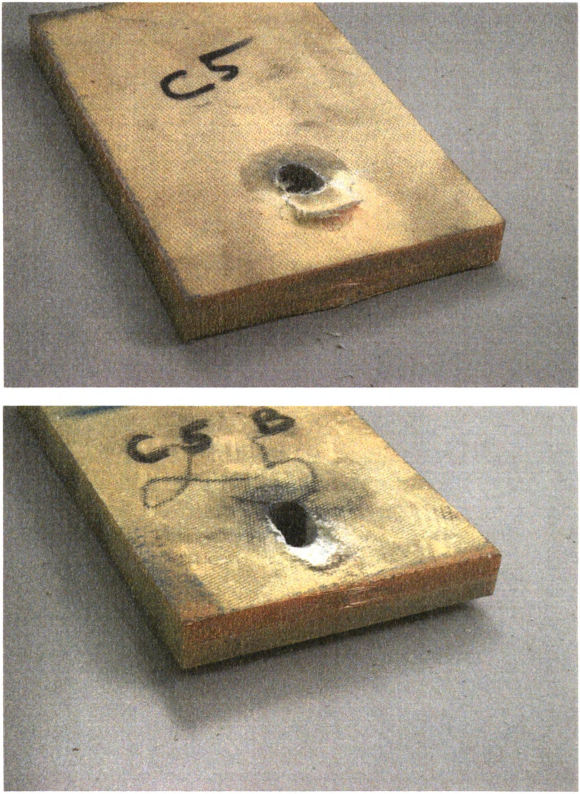


Figure 81. Specimen C5 - Composite front and rear views

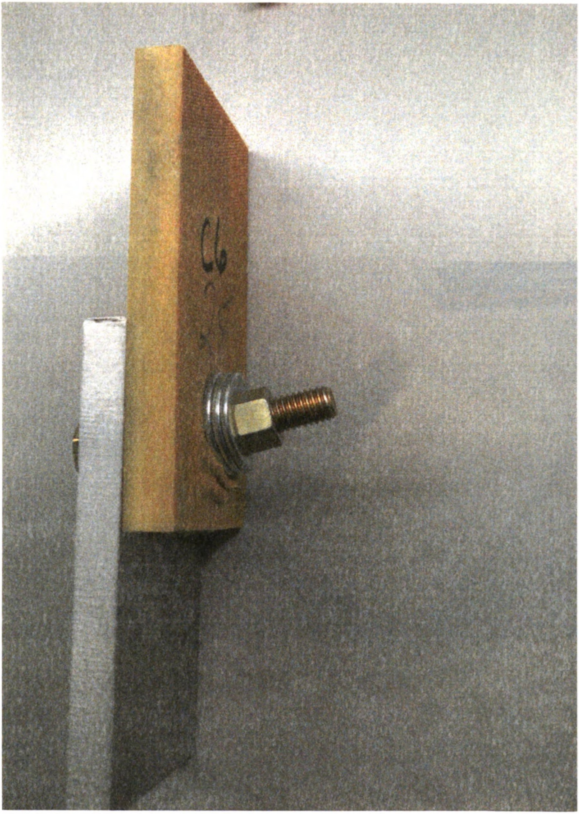


Figure 82. Specimen C6 - Side view

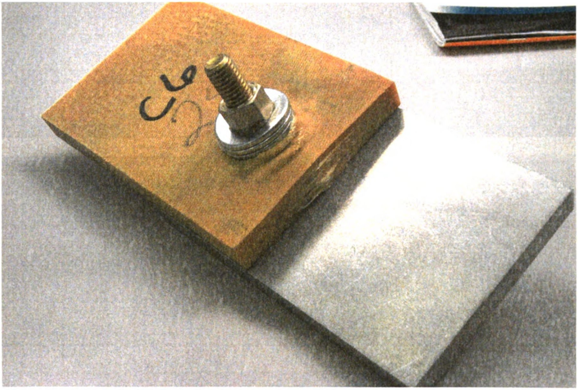


Figure 83. Specimen C6 - Top view

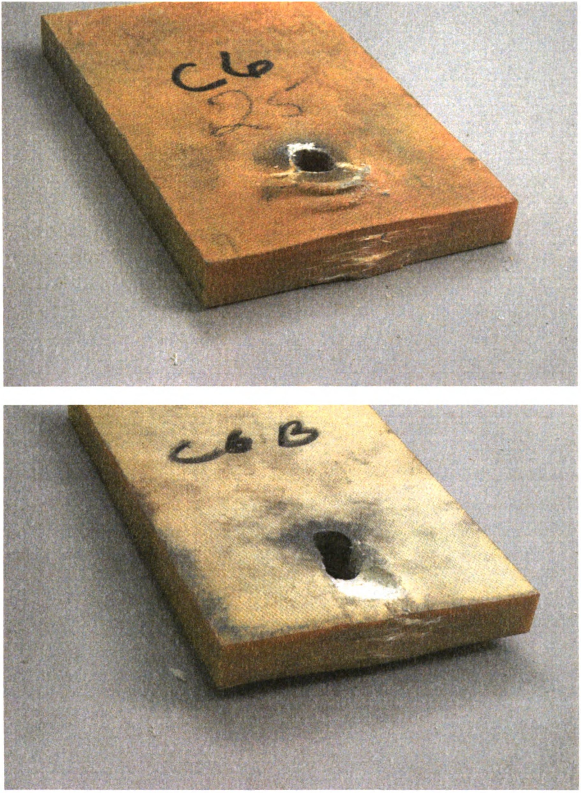


Figure 84. Specimen C6 - Composite front and rear views

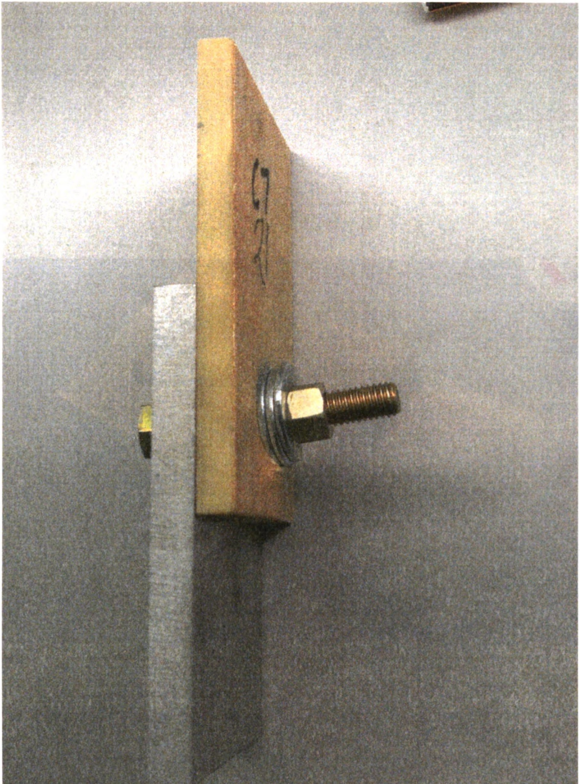


Figure 85. Specimen C7 - Side view

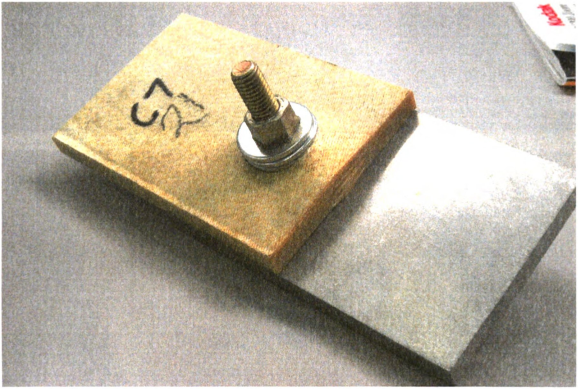
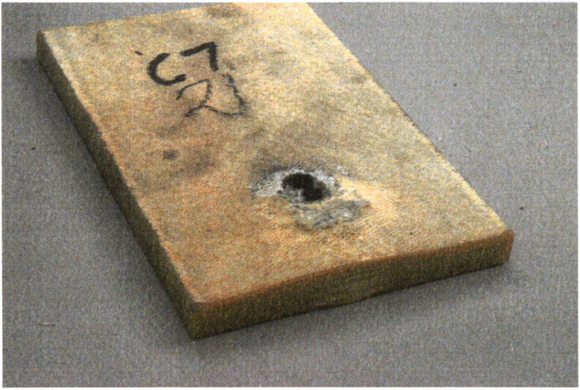


Figure 86. Specimen C7 - Top view



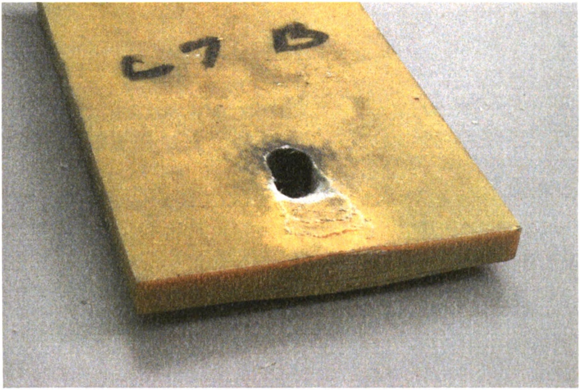


Figure 87. Specimen C7 - Composite front and rear views

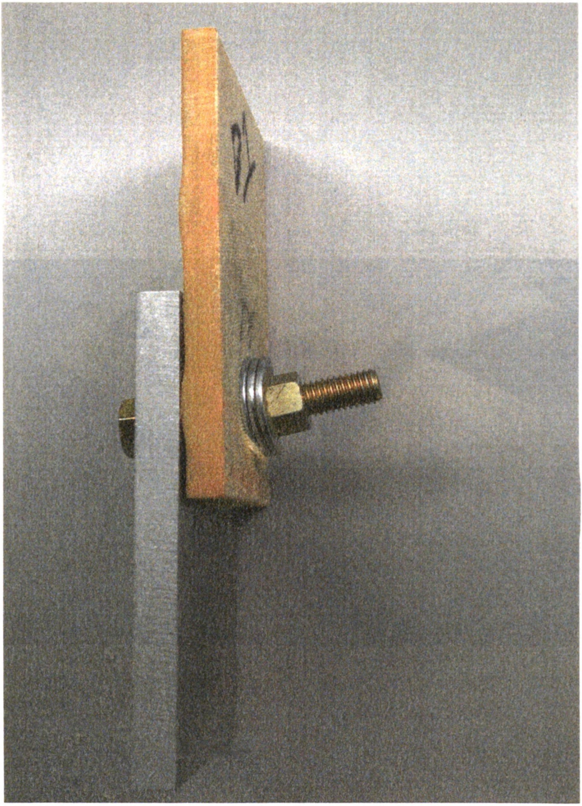


Figure 88. Specimen D1 - Side view

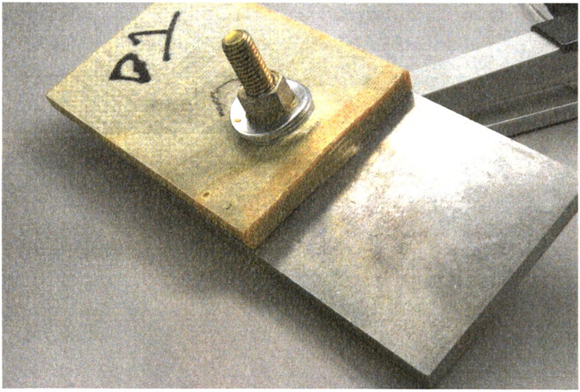


Figure 89. Specimen D1 - Top view

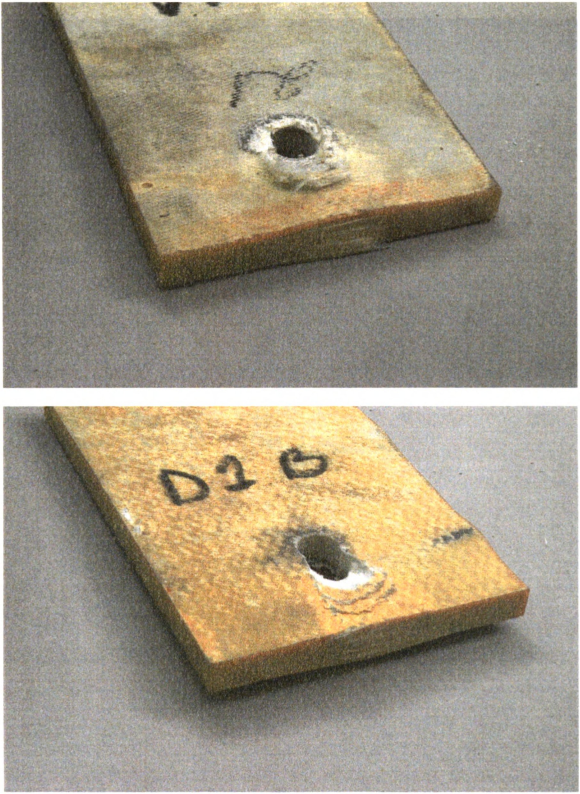


Figure 90. Specimen D1 - Composite front and rear views

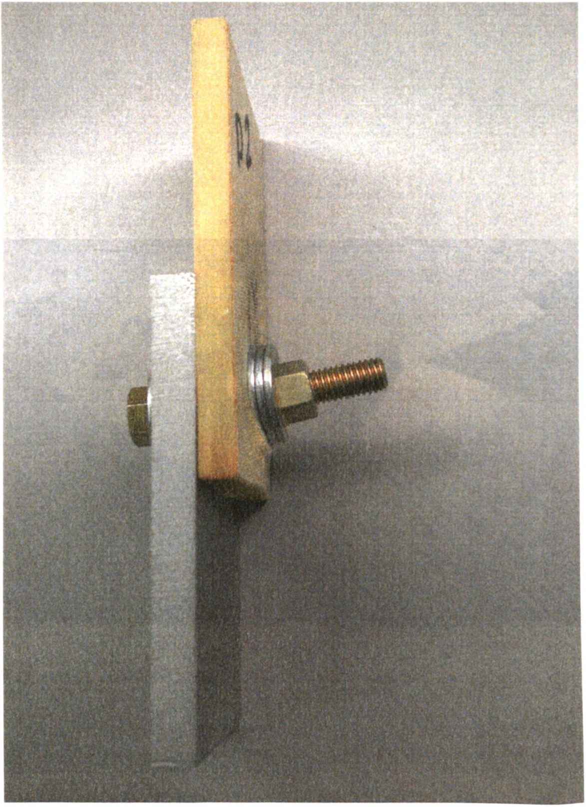


Figure 91. Specimen D2 - Side view

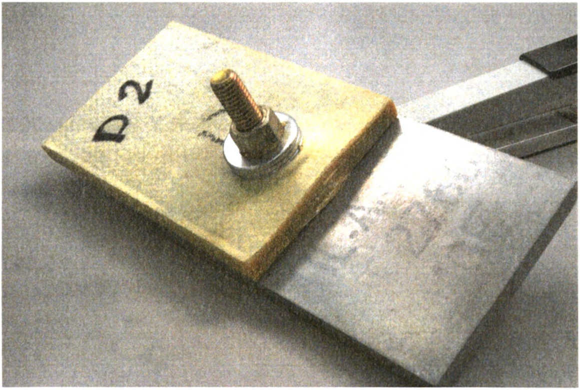


Figure 92. Specimen D2 - Top view

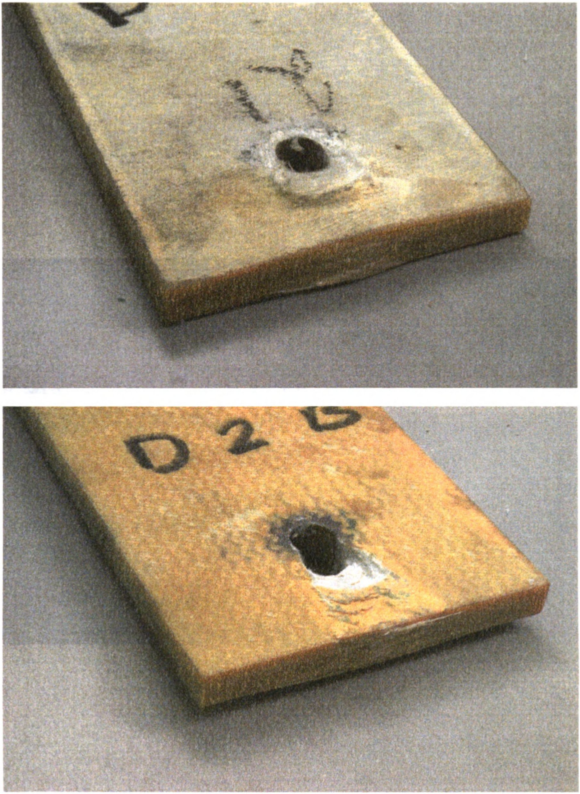


Figure 93. Specimen D2 - Composite front and rear views

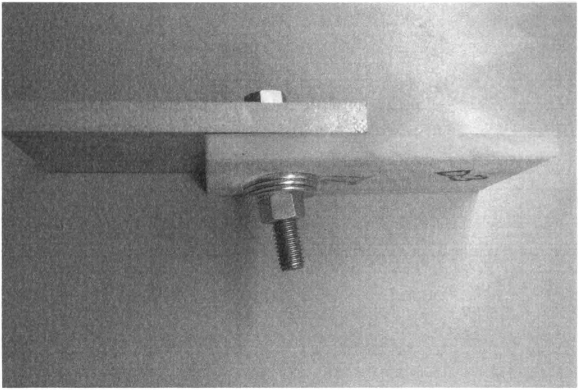


Figure 94. Specimen D3 - Side view

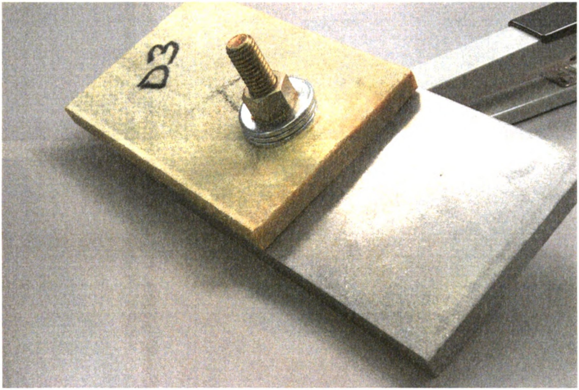


Figure 95. Specimen D3 - Top view

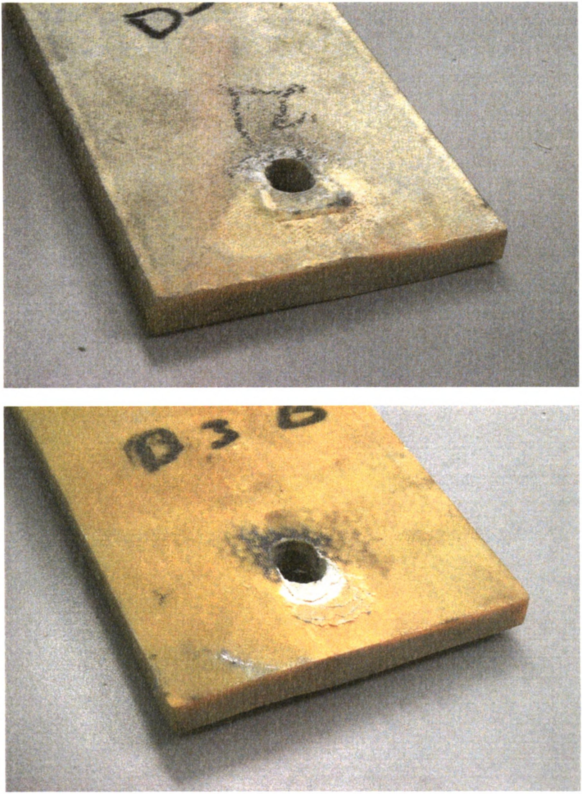


Figure 96. Specimen D3 - Composite front and rear views

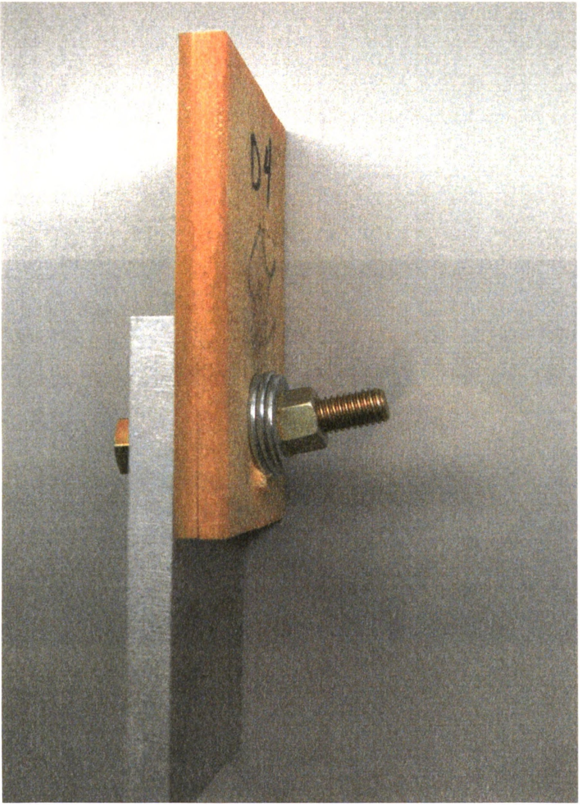


Figure 97. Specimen D4 - Side view

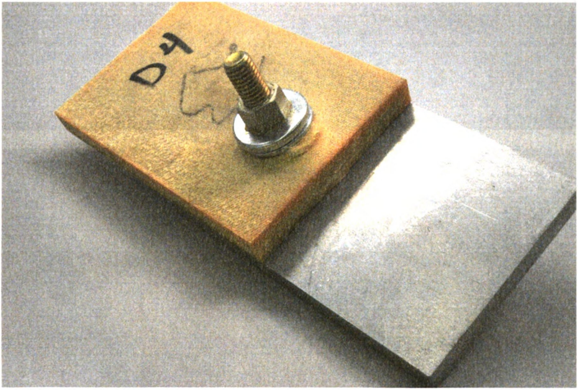


Figure 98. Specimen D4 - Top view

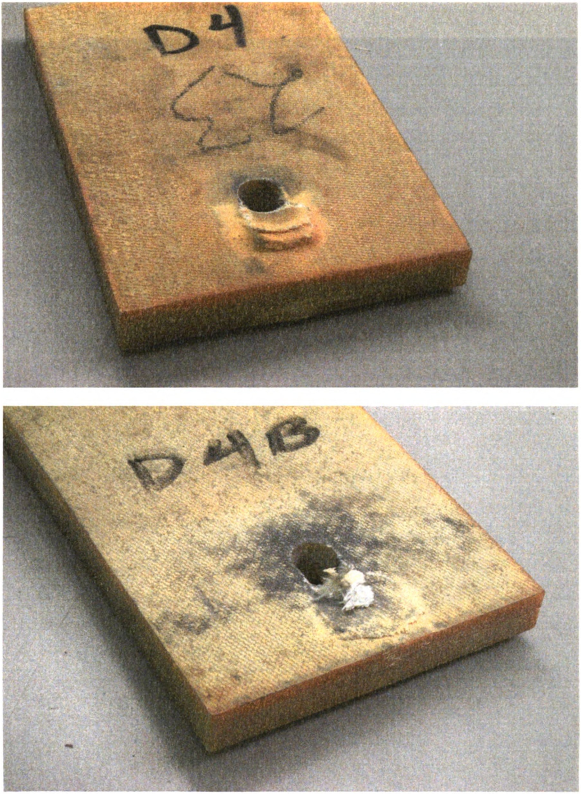


Figure 99. Specimen D4 - Composite front and rear views

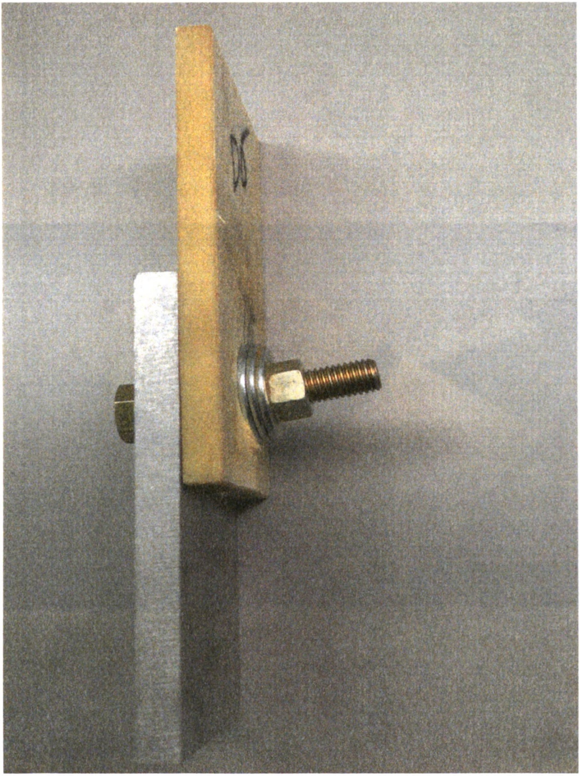


Figure 100. Specimen D5 - Side view

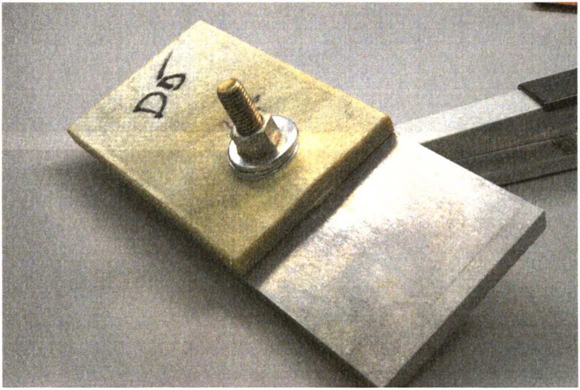


Figure 101. Specimen D5 - Top view

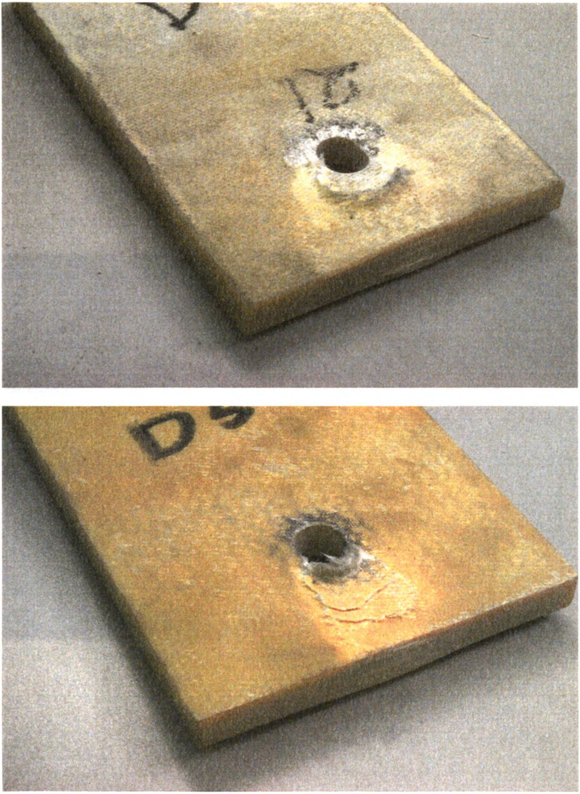


Figure 102. Specimen D5 - Composite front and rear views

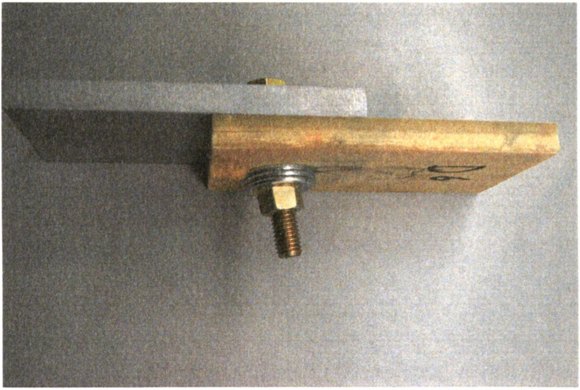


Figure 103. Specimen D6 - Side view

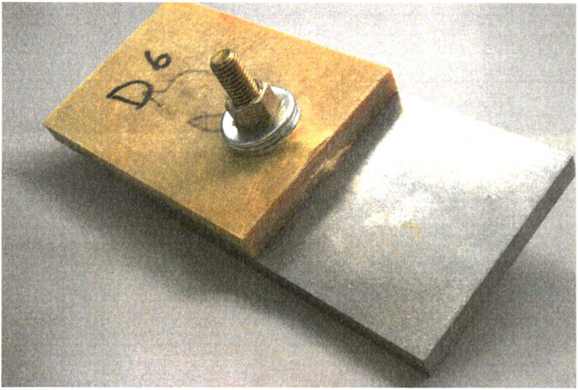


Figure 104. Specimen D6 - Top view

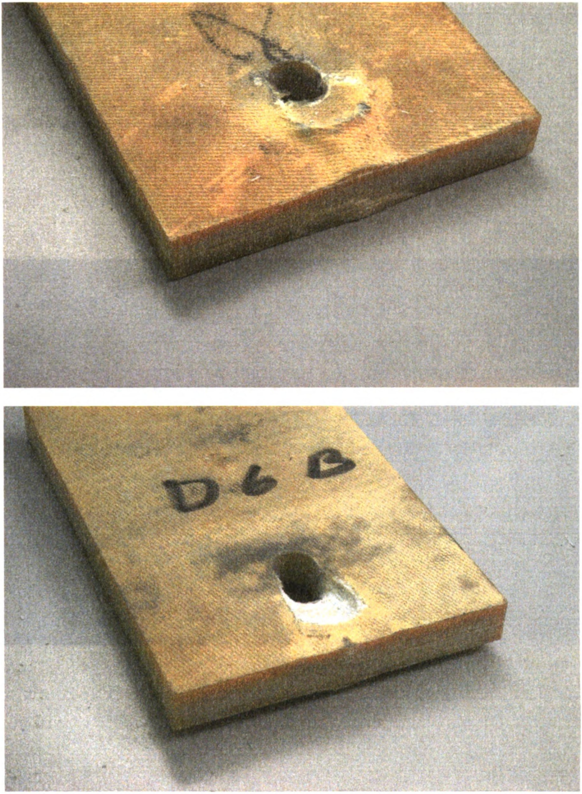


Figure 105. Specimen D6 - Composite front and rear views

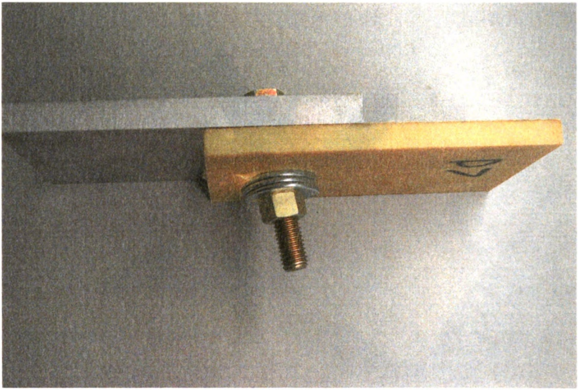


Figure 106. Specimen D7 - Side view

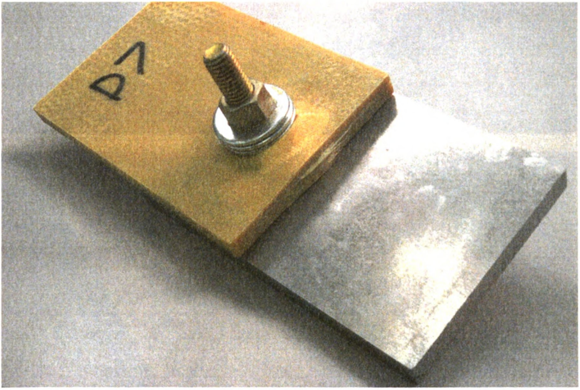


Figure 107. Specimen D7 - Top view

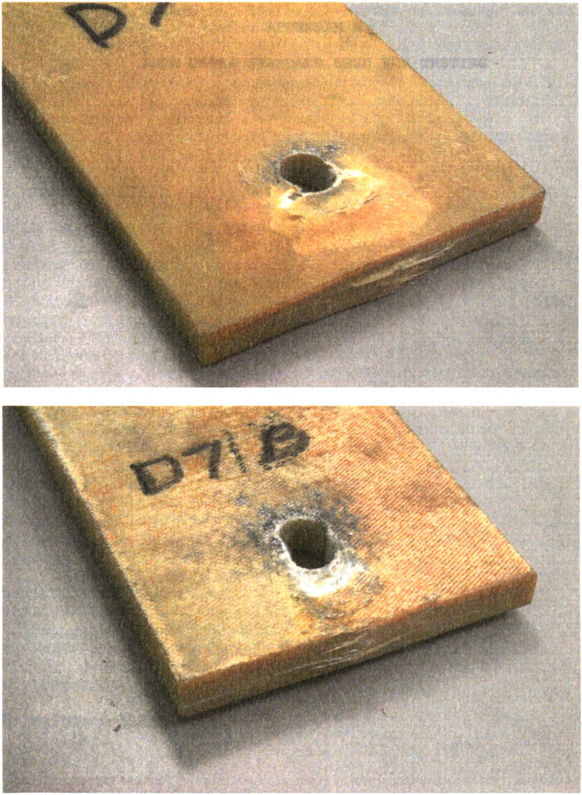


Figure 108. Specimen D7 - Composite front and rear views

APPENDIX B

ASTM D5961 STANDARD USED FOR TESTING

Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates [1]

This standard is issued under the fixed designation D 5961/D 5961M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method determines the bearing response of polymer matrix composite laminates by either double shear (Procedure A) or single shear (Procedure B) tensile loading of a coupon. Standard specimen configurations using fixed values of test parameters are described for each procedure. However, when fully documented in the test report, a number of test parameters may be optionally varied. The material form is limited to high-modulus continuous-fiber or discontinuous-fiber reinforced composites for which the elastic properties are balanced and symmetric with respect to the test direction.

1.2 This test method is consistent with the recommendations of MIL-HDBK-17, which describes the desirable attributes of a bearing response test method.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.4 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the text the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

2. Referenced Documents

2.1 *ASTM Standards:*

D 792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement [2]

D 883 Terminology Relating to Plastics [2]

D 953 Test Method for Bearing Strength of Plastics [2]

D 2584 Test Method for Ignition Loss of Cured Reinforced Resins [3]

D 2734 Test Methods for Void Content of Reinforced Plastics [3]
D 3171 Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion [4]
D 3878 Terminology of High-Modulus Reinforcing Fibers and Their Composites [4]
D 5229/D 5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials [4]
D 5687/D 5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation[4]
E 4 Practices for Force Verification of Testing Machines [5]
E 6 Terminology Relating to Methods of Mechanical Testing [5]
E 83 Practice for Verification and Classification of Extensometers [5]
E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process [6]
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods [6]
E 238 Test Method for Pin-Type Bearing Test of Metallic Materials [5]
E 456 Terminology Relating to Quality and Statistics [6]
E 1309 Guide for the Identification of Composite Materials in Computerized Material Property Databases [4]
E 1434 Guide for Development of Standard Data Records for Computerization of Mechanical Test Data for High-Modulus Fiber-Reinforced Composite Materials[4]
E 1471 Guide for the Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Data-bases [4]

2.2 *Other Document:*
MIL-HDBK-17, *Polymer Matrix Composites*, Vol 1, Section 7[7]

3. Terminology

3.1 *Definitions*—Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology D 883 defines terms relating to plastics. Terminology E 6 defines terms relating to mechanical testing. Terminology E 456 and Practice E 177 define terms relating to statistics. In the event of a conflict between terms, Terminology D 3878 shall have precedence over the other documents.

3.2 *Definitions of Terms Specific to This Standard*:

NOTE 1 – If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [*M*] for mass, [*L*] for length, [*T*] for time, [Θ] for thermodynamic temperature, and [*nd*] for nondimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

3.2.1 *bearing area,* $[L^2]$, *n* – the area of that portion of a bearing coupon used to normalize applied loading into an effective bearing stress; equal to the diameter of the loaded hole multiplied by the thickness of the coupon.

3.2.2 *bearing load, P* $[MLT^{-2}]$, *n* – the total load carried by a bearing coupon.

3.2.3 *bearing strain,* ε^{br} [*nd*], *n* – the normalized hole de-formation in a bearing coupon, equal to the deformation of the bearing hole in the direction of the bearing load, divided by the diameter of the hole.

3.2.4 *bearing strength,* F_x^{br} $[ML^{-1}T^{-2}]$, *n* – the value of bearing stress occurring at a significant event on the bearing stress/bearing strain curve.

3.2.4.1 *Discussion*—Two types of bearing strengths are commonly identified, and noted by an additional superscript: offset strength and ultimate strength.

3.2.5 *bearing stress,* σ^{br} $[ML^{-1}T^{-2}]$, *and n* – the bearing load divided by the bearing area.

3.2.6 *diameter to thickness ratio, D/h* [*nd*], *n – in a bearing coupon*, the ratio of the hole diameter to the coupon thickness.

3.2.6.1 *Discussion*—The diameter to thickness ratio may be either a nominal value determined from nominal dimensions or an actual value determined from measured dimensions.

3.2.7 *edge distance ratio, e/D* [*nd*], *n – in a bearing coupon*, the ratio of the distance between the center of the hole and the coupon end to the hole diameter.

3.2.7.1 *Discussion* – The edge distance ratio may be either a nominal value determined from nominal dimensions or an actual value determined from measured dimensions.

3.2.8 *nominal value, n* — a value, existing in name only, assigned to a measurable quantity for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the quantity.

3.2.9 *offset bearing strength,* F_x^{bro} $[ML^{-1}T^{-2}]$*, n* — the value of bearing stress, in the direction specified by the subscript, at the point where a bearing chord stiffness line, offset along the bearing strain axis by a specified bearing strain value, intersects the bearing stress/bearing strain curve.

3.2.9.1 *Discussion* — Unless otherwise specified, an offset bearing strain of 2 % is to be used in this test method.

3.2.10 *orthotropic material, n* — a material with a property of interest that, at a given point, possesses three mutually perpendicular planes of symmetry defining the principal material coordinate system for that property.

3.2.10.1 *Discussion* — As viewed from the principal material coordinate system of an orthotropic elastic material, extensional stresses are totally uncoupled from shear strains and the shear moduli are totally independent of the other elastic constants (unlike a metal, which is isotropic and that has a shear modulus that is dependent upon Young's modulus and Poisson's ratio). An orthotropic material has 9 independent elastic constants. The general concept of orthotropy also applies to material properties other than elastic, such as thermal, electromagnetic, or optical, although the number of independent constants and the type of mathematical transformation may differ, depending upon the order of the tensor of the property. The behavior of an orthotropic material as viewed from the principal material coordinate system is called *specially orthotropic*. However, if the material behavior is evaluated from another coordinate system coupling terms may appear in the stress/strain relation. While the material itself remains specially orthotropic, from this other coordinate system the material behavior is then called *generally orthotropic*.

3.2.11 *pitch distance ratio, w/D* [nd], *n — in a bearing coupon*, the ratio of specimen width to hole diameter.

3.2.11.1 *Discussion* — The pitch distance ratio may be either a nominal value determined from nominal dimensions or an actual value, determined as the ratio of the actual distance between the center of the hole and the nearest side-edge to the actual hole diameter.

3.2.12 *ply orientation, θ, n* — the angle between the reference axis and the ply principal axis, expressed in degrees, with a range of $-90° < \theta <= 90°$. The ply orientation is expressed as a positive quantity when taken from the reference direction to the ply principal axis, following a right-handed Cartesian coordinate system.

3.2.12.1 *Discussion* — The reference direction is usually related to a direction of load application or a major geometric feature of a component.

3.2.13 *ply principal axis, n* — the coordinate axis in the plane of a lamina that is used as the reference direction for that lamina.

3.2.13.1 *Discussion* — The ply principal axis will, in general, be different for each ply of a laminate. The angle made by this axis relative to the reference axis is the ply orientation. The convention is to align the ply principal axis with a material feature that is the direction of maximum stiffness (such as the fiber direction for unidirectional tape or the warp direction for fabric-reinforced material). Conventions for other laminated material forms have not yet been established.

3.2.14 *principal material coordinate system, n* — a coordinate system with axes that are normal to the planes of symmetry inherent to a material.

3.2.14.1 *Discussion* — Common usage, at least for Cartesian axes (123, *xyz*, etc.), generally assigns the coordinate system axes to the normal directions of planes of symmetry in order that the highest property value in a normal direction (for elastic properties, the axis of greatest stiffness would be 1 or *x*, and the lowest (if applicable) would be 3 or *z*). Anisotropic materials do not have a principal material coordinate system due to the total lack of symmetry, while, for isotropic materials, any coordinate system is a principal material coordinate system. In laminated composites the principal material coordinate system has meaning only with respect to an individual orthotropic lamina. The related term for laminated composites is reference coordinate system.

3.2.15 *quasi-isotropic laminate, n* — a balanced and symmetric laminate for which a constitutive property of interest, at a given point, displays isotropic behavior in the plane of the laminate. Common quasi-isotropic laminates are $[0/\pm60]_s$ and $[0/\pm45/90]_s$.

3.2.15.1 *Discussion* — Usually a quasi-isotropic laminate refers to elastic properties, for which case, the laminate contains equal numbers of identical plies at k orientations such that the angles between the plies are $180i/k$, ($i = 0, 1, \ldots, k - 1$); $k >= 3$. Other material properties may follow different rules. For example, thermal conductivity becomes quasi-isotropic for $k >= 2$, while strength properties generally are not capable of true quasi-isotropy, only approximating this behavior.

3.2.16 *reference coordinate system, n* — a coordinate system for laminated composites used to define ply orientations. One of the reference coordinate system axes (normally the Cartesian *x*-axis) is designated the reference axis, assigned a position, and the ply principal axis of each ply in the laminate is referenced relative to the reference axis to define the ply orientation for that ply.

3.2.17 *specially orthotropic, adj* — a description of an orthotropic material as viewed in its principal material coordinate system. In laminated composites a specially orthotropic laminate is a balanced and symmetric laminate of the [0:i/90:j] *ns* family as viewed from the reference coordinate system, such that the membrane-bending coupling terms of the stress/strain relation are zero.

3.2.18 *tracer yarn, n* — a small filament-count tow of a fiber type that has a color that contrasts with the surrounding material form, used for directional identification in composite material fabrication.

3.2.18.1 *Discussion*—Aramid tracer yarns are commonly used in carbon fiber composites and carbon tracer yarns are commonly used in aramid or glass fiber composites.

3.2.19 *ultimate bearing strength,* F_x^{bru} $[ML^{-1}\ T^{-2}]$, *n* — the value of bearing stress, in the direction specified by the subscript, at the maximum load capability of a bearing coupon.

3.3 *Symbols:*

3.3.1 *A* — minimum cross-sectional area of a coupon.

3.3.2 *CV* — coefficient of variation statistic of a sample population for a given property (in percent).

3.3.3 *d* — fastener or pin diameter.

3.3.4 *D* — coupon hole diameter.

3.3.5 *e* — distance, parallel to load, from hole center to end of coupon; the edge distance.

3.3.6 E_x^{br} — bearing chord stiffness in the test direction specified by the subscript.

3.3.7 *f* — distance, parallel to load, from hole edge to end of coupon.

3.3.8 F_x^{bru} — ultimate bearing strength in the test direction specified by the subscript.

3.3.9 F_x^{bro} (e%)—offset bearing strength (at e % bearing strain offset) in the test direction specified by the subscript.

3.3.10 *g* — distance, perpendicular to load, from hole edge to shortest edge of coupon.

3.3.11 *h* — coupon thickness.

3.3.12 *k* — calculation factor used in bearing equations to distinguish single-fastener tests from double-fastener tests.

3.3.13 *K* — calculation factor used in bearing equations to distinguish single-shear tests from double-shear tests in a single bearing strain equation.

3.3.14 L_g — extensometer gage length.

3.3.15 *n* — number of coupons per sample population.

3.3.16 *P* — load carried by test coupon.

3.3.17 P^f —load carried by test coupon at failure.

3.3.18 P^{max} —maximum load carried by test coupon prior to failure.

3.3.19 s_{n-1} — standard deviation statistic of a sample population for a given property.
3.3.20 w — coupon width.
3.3.21 x_i — test result for an individual coupon from the sample population for a given property.
3.3.22 $\bar{x}$ — mean or average (estimate of mean) of a sample population for a given property.
3.3.23 δ — extensional displacement.
3.3.24 ε — general symbol for strain, whether normal strain or shear strain.
3.3.25 ε^{br} — bearing strain.
3.3.26 σ^{br} — bearing stress.

4. Summary of Test Method

4.1 *Procedure A, Double Shear*:

4.1.1 A flat, constant rectangular cross-section coupon with a centerline hole located near the end of the coupon, as shown in the coupon drawings of Figs. 1 and 2, is loaded at the hole in bearing. The bearing load is normally applied through a close-tolerance, lightly torqued fastener (or pin)[8] that is reacted in double shear by a fixture similar to that shown in Figs. 3 and 4. The bearing load is created by pulling the assembly in tension in a testing machine.

4.1.2 Both the applied load and the associated deformation of the hole are monitored. The hole deformation is normalized by the hole diameter to create an effective bearing strain. Likewise, the applied load is normalized by the projected hole area to create an effective bearing stress. The coupon is loaded until a load maximum has clearly been reached, whereupon the test is terminated so as to prevent masking of the true failure mode by large-scale hole distortion, in order to provide a more representative failure mode assessment. Bearing stress versus bearing strain for the entire loading regime is plotted, and failure mode noted. The ultimate bearing strength of the material is determined from the maximum load carried prior to test termination.

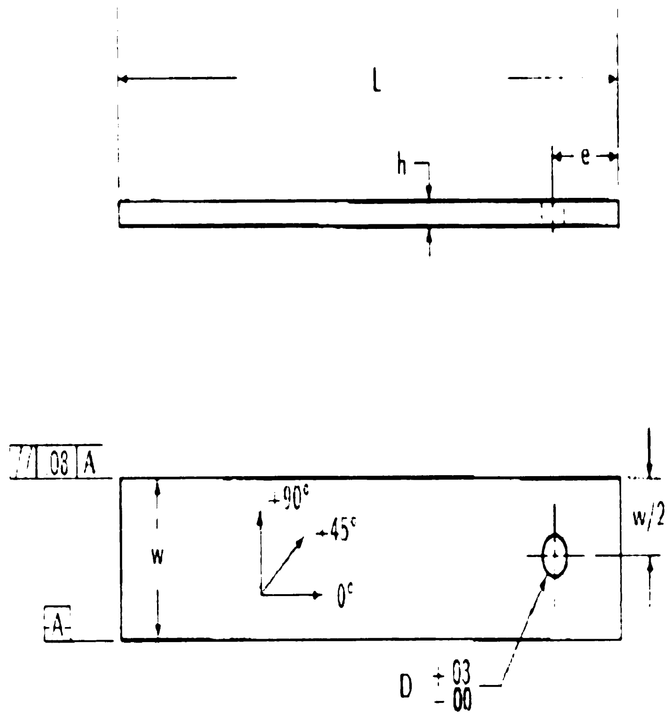
4.1.3 The standard test configuration for this procedure does not allow any variation of the major test parameters. However, the following variations in configuration are allowed, but can

DRAWING NOTES:

1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING:
2. ALL DIMENSIONS IN MILLIMETRES WITH DECIMAL TOLERANCES AS FOLLOWS

NO DECIMAL	.X	.XX
±3	±1	±.3

3. ALL ANGLES HAVE TOLERANCE OF ± .5°.
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO -A- IS RECOMMENDED TO BE WITHIN ± .5°. (See Section 6.1.)
5. FINISH ON MACHINED EDGES NOT TO EXCEED 1.6 √ (SYMBOLOGY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROMETRES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL, LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO -A-, OVERALL LENGTH, HOLE DIAMETER, AND COUPON THICKNESS.



Parameter	Standard Dimension, mm
fastener or pin diameter, d	6 +0.00/−0.03
hole diameter, D	6 +0.03/−0.00
thickness range, h	3-5
length, L	135
width, w	36 ±1
edge distance, e	18 ±1
countersink	none

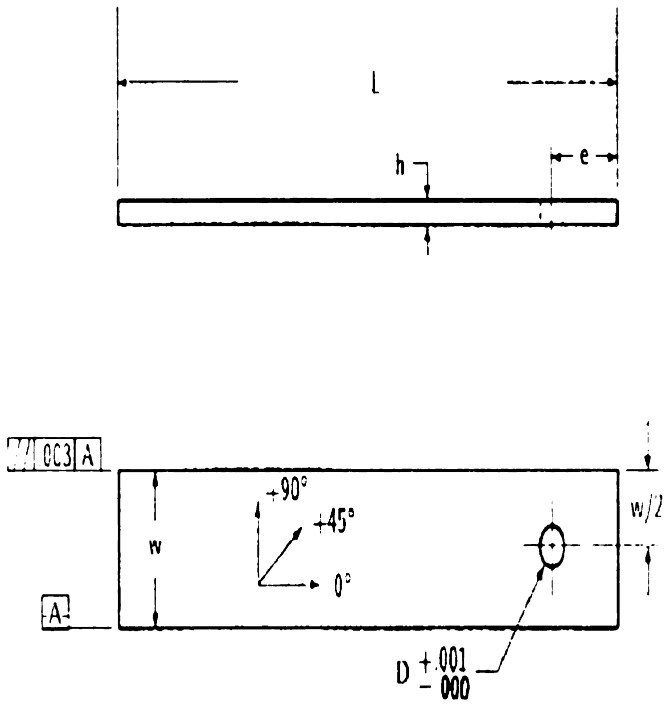
FIG. 1 Double-Shear Test Specimen Drawing (SI)

DRAWING NOTES:

1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING
2. ALL DIMENSIONS IN INCHES WITH DECIMAL TOLERANCES AS FOLLOWS:

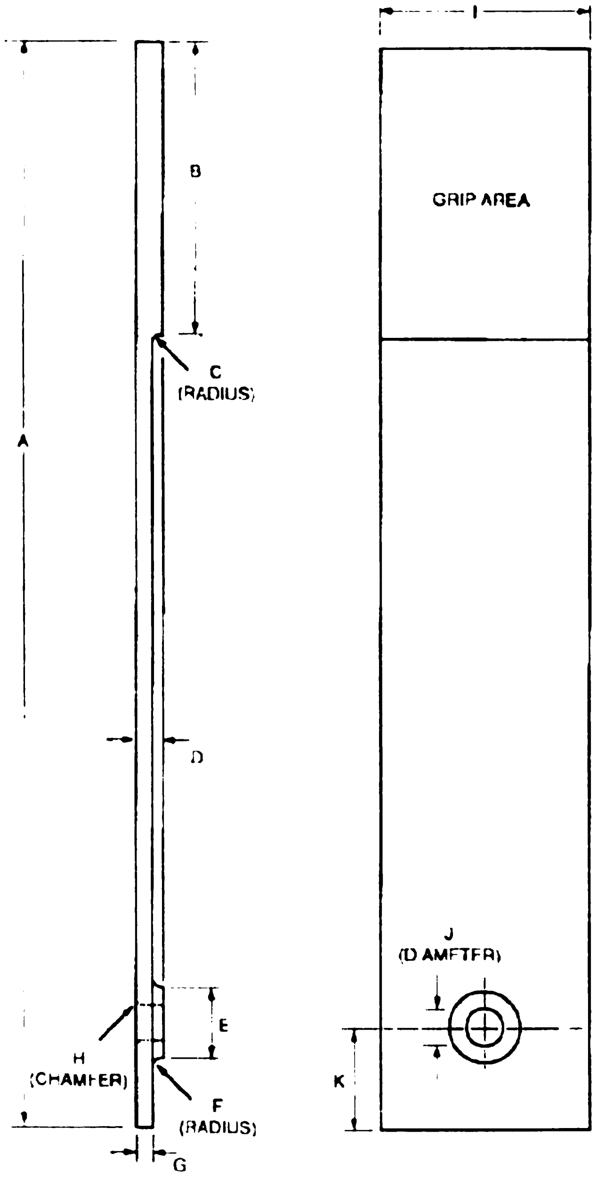
.X	.XX	.XXX
± .1	± .03	± .01

3. ALL ANGLES HAVE TOLERANCE OF ± .5°.
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO -A- IS RECOMMENDED TO BE WITHIN ± .5°. (See Section 6.1.)
5. FINISH ON MACHINED EDGES NOT TO EXCEED 64√ (SYMBOLOGY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROINCHES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL, LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO -A-, OVERALL LENGTH, HOLE DIAMETER, AND COUPON THICKNESS.



Parameter	Standard Dimension, in
fastener or pin diameter, d	0.250 +0.000/ −0.001
hole diameter, D	0.250 +0.001/−0.000
thickness range, h	0.125-0.208
length, L	5.5
width, w	1.5 ±0.03
edge distance, e	0.75 ±0.03
countersink	none

FIG. 2 Double-Shear Test Specimen Drawing (inch-pound)



Recommended Material 17-4PH Stainless Steel, 1 GPa [145 ksi] yield											
	A	B	C	D	E	F	G	H	I	J	K
mm	200	50	2	5	13	2	3	[illegible]	36	6	20
inch	7.75	2.00	0.06	0.20	0.50	0.06	0.12	0.04	1.50	0.25	0.75

FIG. 3 Fixture Loading Plate for Procedure A (2 Req'd)

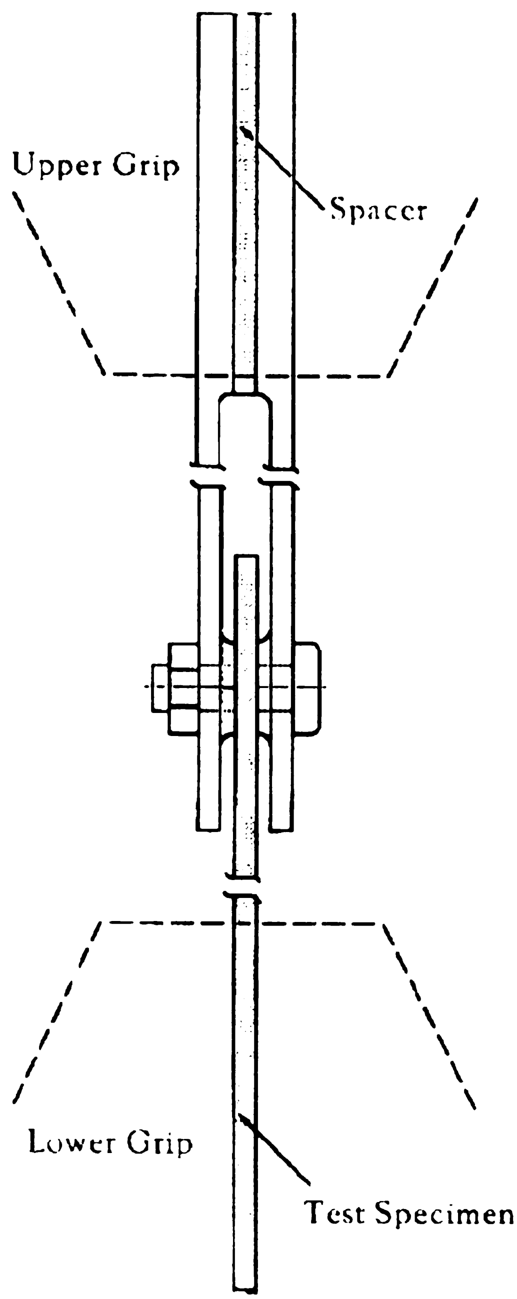


FIG. 4 Fixture Assembly for Procedure A

be considered as being in accordance with this test method only as long as the values of all variant test parameters are prominently documented with the results.

Parameter	Standard	Variation
Loading condition:	double-shear	none
Mating material:	steel fixture	none
Number of holes:	1	none
Countersink:	none	none
Fit:	tight	any, if documented
Fastener torque:	2.2-3.4 N·m [20-30 lbf-in.]	any, if documented
Laminate:	quasi-isotropic	any, if documented
Fastener diameter:	6 mm [0.250 in.]	any, if documented
Edge distance ratio:	3	any, if documented
Pitch distance ratio:	6	any, if documented
D/h ratio:	1.2-2	any, if documented

4.2 *Procedure B, Single Shear*:

4.2.1 The flat, constant rectangular cross-section coupon is composed of two like halves fastened together through one or two centerline holes located near one end of each half, as shown in the coupon drawings of Figs. 5 and 6. The ends of the coupon are gripped in the jaws of a test machine and loaded in tension. The eccentricity in applied load that would otherwise result is minimized by a doubler bonded to each grip end of the coupon, resulting in a load line-of-action along the interface between the coupon halves, through the centerline of the hole(s).

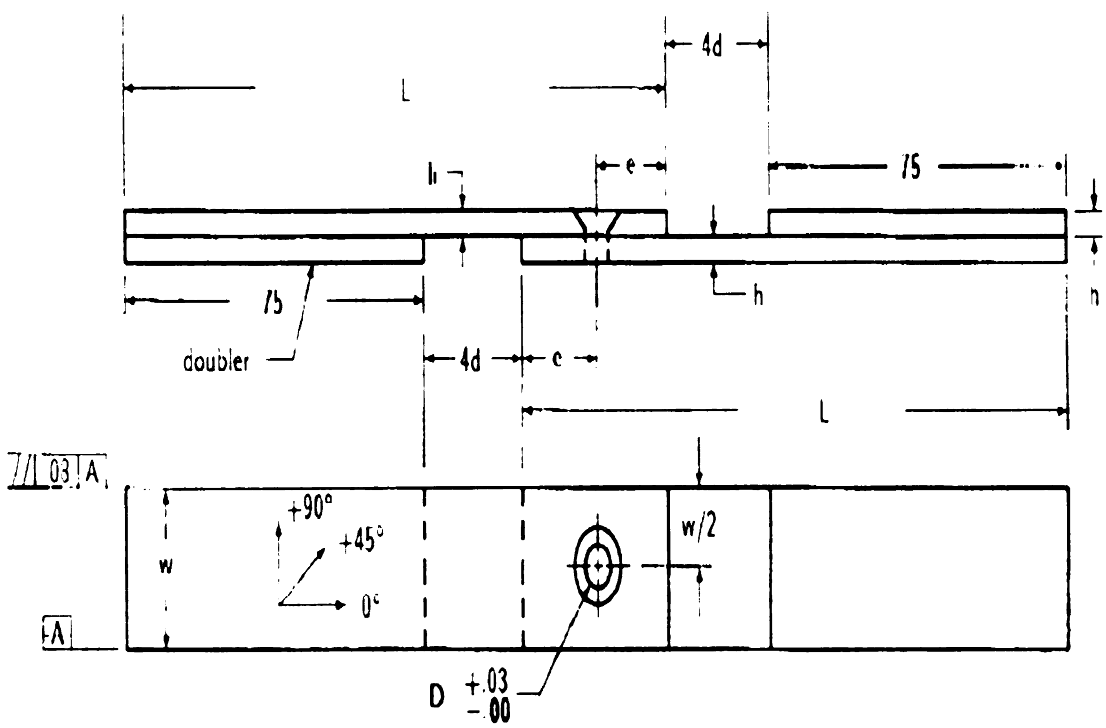
4.2.2 Both the applied load and the associated deformation of the hole(s) are monitored. The deformation of the hole(s) is normalized by the hole diameter (a factor of two used to adjust for hole deformation occurring in the two halves) to result in an effective bearing strain. Likewise, the applied load is normalized by the projected hole area to yield an effective bearing stress. The coupon is loaded until a load maximum has clearly been reached, whereupon the test is terminated so as to prevent masking of the true failure mode by large-scale hole distortion, in order to provide a more representative failure mode assessment. Bearing stress versus bearing strain for the entire loading regime is plotted, and failure mode noted. The ultimate bearing strength of the material is determined from the maximum load

DRAWING NOTES:

1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING.
2. ALL DIMENSIONS IN MILLIMETRES WITH DECIMAL TOLERANCES AS FOLLOWS:

NO DECIMAL	.X	.XX
± 3	± 1	± .3

3. ALL ANGLES HAVE TOLERANCE OF ± .5°
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO $\boxed{-A-}$ WITHIN ± .5°
5. FINISH ON MACHINED EDGES NOT TO EXCEED 1.6√ (SYMBOLOGY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROMETRES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL, LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO $\boxed{-A-}$, OVERALL LENGTH, HOLE DIAMETER, COUNTERSINK DETAILS, COUPON THICKNESS, DOUBLER MATERIAL, DOUBLER ADHESIVE.



Parameter	Standard Dimension, mm
fastener diameter, d	6 +0.00/−0.03
hole diameter, D	6 +0.03/−0.00
thickness range, h	3-5
length, L	135
width, w	36 ±1
edge distance, e	18 ±1
countersink	none (optional)

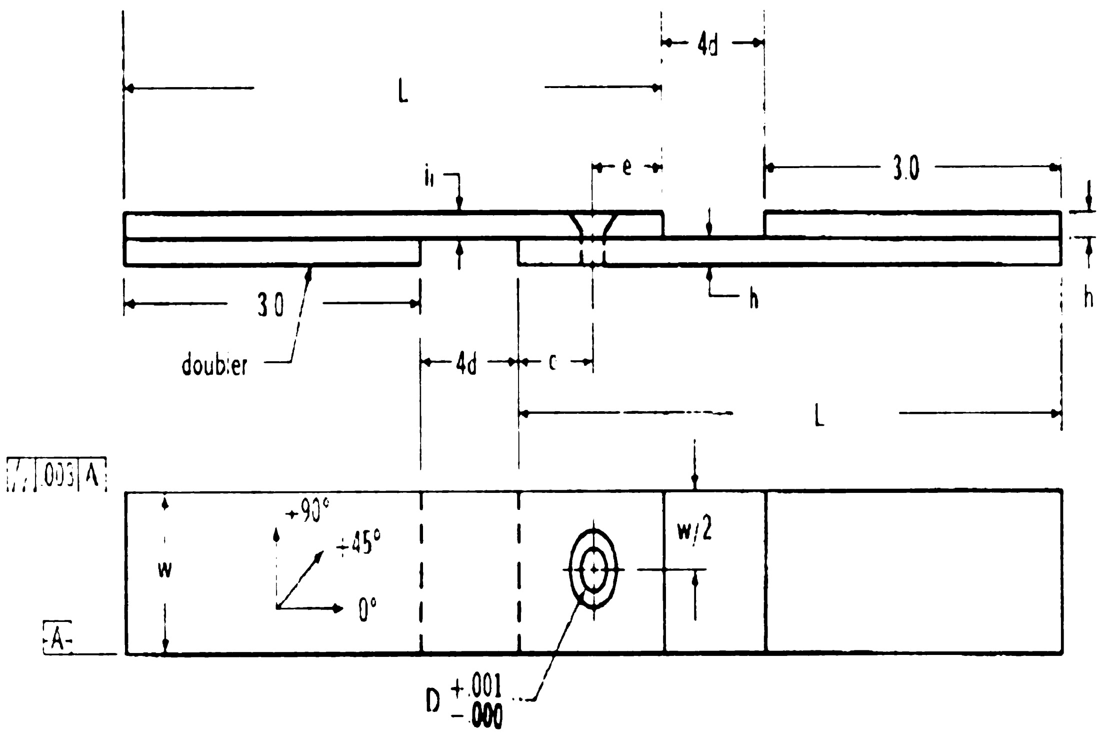
FIG. 5 Single-Shear, Single-Fastener Test Specimen Drawing (SI) (See Fig. 7 for details of double-fastener version.)

DRAWING NOTES:

1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING.
2. ALL DIMENSIONS IN INCHES WITH DECIMAL TOLERANCES AS FOLLOWS:

X	.XX	.XXX
± .1	± .03	± .01

3. ALL ANGLES HAVE TOLERANCE OF ± .5°
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO -A- WITHIN ± .5°
5. FINISH ON MACHINED EDGES NOT TO EXCEED 64√ (SYMBOLOGY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROINCHES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO -A-, OVERALL LENGTH, HOLE DIAMETER, COUNTERSINK DETAILS, COUPON THICKNESS, DOUBLER MATERIAL, DOUBLER ADHESIVE.



Parameter	Standard Dimension, in
fastener diameter, d	0.250 +0.000/−0.001
hole diameter, D	0.250 +0.001/−0.000
thickness range, h	0.125-0.208
length, L	5.5
width, w	1.5 ±0.03
edge distance, e	0.75 ±0.03
countersink	none (optional)

FIG. 6 Single-Shear Test Specimen Drawing (inch-pound) (See Fig. 7 for details of double-fastener version.)

carried prior to test termination.

4.2.3 The standard test configuration for this procedure does not allow any variation of the major test parameters. However, the following variations in configuration are allowed, but can be considered as being in accordance with this test method only as long as the values of all variant test parameters are prominently documented with the results.

Parameter	Standard	Variation
Loading condition:	single-shear	none
Number of holes:	1	1 or 2
Countersunk holes:	no	yes, if documented
Grommets:	no	yes, if documented
Mating material:	same laminate	any, if documented
Fit:	tight	any, if documented
Fastener torque:	2.2-3.4 N·m [20-30 lbf-in.]	any, if documented
Laminate:	quasi-isotropic	any, if documented
Fastener diameter:	6 mm [0.250 in.]	any, if documented
Edge distance ratio:	3	any, if documented
Pitch distance ratio:	6	any, if documented
D/h ratio:	1.2-2	any, if documented

5. Significance and Use

5.1 This test method is designed to produce bearing response data for material specifications, research and development, quality assurance, and structural design and analysis. The standard configuration for each procedure is very specific and is intended primarily for development of quantitative double- and single-shear bearing response data for material comparison and specification. Procedure A, the double-shear configuration, with a single fastener, is articularly recommended for basic material evaluation and comparison. Procedure B, the single-shear, single- or double-fastener configuration is more useful in evaluation of specific joint configurations. The variants of either procedure provide flexibility in the conduct of the test, allowing adaptation of the test setup to a specific application. However, the flexibility of test parameters allowed by the variants makes meaningful comparison between data sets difficult if the data sets were not tested using identical test parameters.

5.2 General factors that influence the mechanical response of composite laminates and should therefore be reported include the following: material, methods of material preparation and lay-up, specimen stacking sequence, specimen preparation, specimen conditioning, environment of testing, specimen alignment and gripping, speed of testing, time at temperature, void content, and volume percent reinforcement.

5.3 Specific factors that influence the bearing response of composite laminates and should therefore be reported include not only the loading method either Procedure A or B) but the following: (for both procedures) edge distance ratio, pitch distance ratio, diameter to thickness ratio, fastener torque, fastener or pin material, fastener or pin clearance; and (for Procedure B only) countersink angle and depth of countersink, type of grommet (if used), type of ating material, and number of fasteners. Properties, in the test direction, which may be obtained from this test method include the following:

5.3.1 Ultimate bearing strength,

5.3.2 Bearing chord stiffness,

5.3.3 Offset bearing strength, and

5.3.4 Bearing stress/bearing strain curve.

6. Interferences

6.1 *Material and Specimen Preparation* — Bearing response is sensitive to poor material fabrication practices (including lack of control of fiber alignment, damage induced by improper coupon machining (especially critical is hole preparation), and torqued fastener installation. Fiber alignment relative to the specimen coordinate axis should be maintained as carefully as possible, although there is currently no standard procedure to ensure or determine this alignment. A practice that has been found satisfactory for many materials is the addition of small amounts of tracer yarn to the prepreg parallel to the 0° direction, added either as part of the prepreg production or as part of panel fabrication. See Guide D 5687/D 5687M for further information on recommended specimen preparation practices.

6.2 *Restraining Surfaces* — The degree to which out-of-plane hole deformation is possible, due to lack of restraint by the fixture or the fastener, has been shown to affect test results in some material types.

6.3 *Cleanliness* — The degree of cleanliness of the mating surfaces has been found to produce significant variations in test results in some material types.

6.4 *Eccentricity (Procedure B only)* — A loading eccentricity is created in single-shear tests by the offset, in one plane, of the line of action of load between each half of the coupon. This eccentricity creates a moment that, particularly in clearance hole tests, rotates the fastener, resulting in an uneven contact stress distribution through the thickness of the coupon. The effect of this eccentricity upon test results is strongly dependent upon the degree of clearance in the hole, the size of the fastener head, the mating area, the coefficient of friction between the coupon and the mating material, the thickness and stiffness of the coupon, and the thickness and stiffness of the mating material.

6.5 *Other* – Test Methods E 238 and D 953 contain further discussions of other variables affecting bearing-type testing.

7. Apparatus

7.1 *Micrometers*—The micrometer(s) shall use a 4 to 5-mm [0.16 to 0.20-in.] nominal diameter ball-interface on irregular surfaces such as the bag-side of a laminate, and a flat anvil interface on machined edges or very smooth tooled surfaces. The accuracy of the instrument(s) shall be suitable for reading to within 1 % of the sample width and thickness. For typical specimen geometries, an instrument with an accuracy of 62.5 µm [60.0001 in.] is desirable for thickness measurement, while an instrument with an accuracy of 625 µm [60.001 in.] is desirable for width measurement.

7.2 *Loading Fastener or Pin*—The fastener (or pin) type shall be specified as an initial test parameter and reported. The assembly torque (if applicable) shall be specified as an initial test parameter and reported. The fastener or pin shall be visually inspected after each test, and replaced, if damage to the fastener or pin is evident.

7.3 *Fixture*:

7.3.1 *Procedure A* – The load shall be applied to the specimen by means of a double-shear clevis similar to that shown in Figs. 3 and 4, using the loading fastener or pin. For torqued tests the clevis shall allow a torqued fastener to apply a transverse compressive load to the coupon around the periphery of the hole. The fixture shall allow a bearing strain indicator to monitor the hole deformation relative to the fixture, over the length from the centerline of the fastener or pin to the end of the specimen.

7.3.2 *Procedure B*—The load shall be applied to the specimen by means of a mating single-shear attachment (normally identical to the specimen) using the fastener or pin. The mating material, thickness, edge distance, length, and hole clearance shall be specified as part of the test parameters. The line of action of the load shall be adjusted by specimen doublers to be coincident and parallel to the interface between the test specimen and the joint mate. If the mating attachment is permanently deformed by the test it shall be replaced after each test, as required. The fixture will allow a bearing strain indicator to measure the required hole deformation relative to the fixture.

7.4 *Testing Machine* — The testing machine shall be in conformance with Practices E 4, and shall satisfy the following requirements:

7.4.1 *Testing Machine Heads* — The testing machine shall have both an essentially stationary head and a movable head.

7.4.2 *Drive Mechanism* — The testing machine drive mechanism shall be capable of imparting to the movable head a controlled velocity with respect to the stationary head. The velocity of the movable head shall be capable of being regulated as specified in 11.4.

7.4.3 *Load Indicator*—The testing machine load-sensing device shall be capable of indicating the total load being carried by the test specimen. This device shall be essentially free from inertia-lag at the specified rate of testing and shall indicate the load with an accuracy over the load range(s) of interest of within 61 % of the indicated value.

7.4.4 *Grips*—Each head of the testing machine shall be capable of holding one end of the test assembly so that the direction of load applied to the specimen is coincident with the longitudinal axis of the specimen. Wedge grips shall apply sufficient lateral pressure to prevent slippage between the grip face and the coupon.

7.5 *Bearing Strain Indicator*—Bearing strain data shall be determined by a bearing strain indicator able to measure longitudinal hole deformation simultaneously on opposite edges of the specimen (the average of which corrects for joint rotation). The transducers of the bearing strain indicator may provide either individual signals to be externally averaged or an electronically averaged signal. The indicator may consist of two matched strain-gage extensometers or displacement transducers such as LVDTs or DCDTs. Attachment of the bearing strain indicator to the coupon shall not cause damage to the specimen surface. Transducers shall satisfy, at a minimum, Practice E 83, Class B-2 requirements for the bearing strain/ displacement range of interest, and shall be calibrated over that range in accordance with Practice E 83. The transducers shall be essentially free of inertia lag at the specified speed of testing.

7.5.1 *Torque Wrench*—A torque wrench used to tighten a joint fastener shall be capable of determining the applied torque to within 610 % of the desired value.

7.6 *Conditioning Chamber*—When conditioning materials at non-laboratory environments, a temperature-/vapor-level controlled environmental conditioning chamber is required that shall be capable of maintaining the required temperature to within 63°C [65°F] and the required relative vapor level to within 63 %. Chamber conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals.

7.7 *Environmental Test Chamber*—An environmental test chamber is required for test environments other than ambient testing laboratory conditions. This chamber shall be capable of maintaining the gage section of the test specimen at the required test environment during the mechanical test.

8. Sampling and Test Specimens

8.1 *Sampling* – Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens, as in the case of a designed experiment. For statistically significant data the procedures outlined in Practice E 122 should be consulted. The method of sampling shall be reported.

NOTE 2—If specimens are to undergo environmental conditioning to equilibrium, and are of such type or geometry that the weight change of the material cannot be properly measured by weighing the specimen itself (such as a tabbed mechanical coupon), then use a traveler coupon of the same nominal thickness and appropriate size (but without tabs) to determine when equilibrium has been reached for the specimens being conditioned.

8.2 *Geometry*:

8.2.1 *Stacking Sequence* — The standard laminate shall have a balanced and symmetric stacking sequence of [45/0/þ45/90]$_{ns}$, where *n* is selected to keep the laminate thickness as close as possible to 4 mm [0.160 in.], with a permissible range from 3 to 5 mm [0.125 to 0.208 in.], inclusive. Laminates containing satin-type weaves shall have symmetric warp surfaces, unless otherwise specified and noted in the report.

8.2.2 *Configuration*:

8.2.2.1 *Procedure A* — The geometry of the coupon for Procedure A is shown in Figs. 1 and 2.

8.2.2.2 *Procedure B* — The geometry of the coupon for Procedure B is shown in Figs. 5 and 6. Note that the countersink(s) shown in the drawings is optional. For a double-fastener configuration, extend the length of each coupon half by the required distance and place a second bearing hole in line with the first, as shown in the schematic of Fig. 7. If the double-fastener coupon is using countersunk fasteners, one countersink should be located on each side of the coupon, as shown.

8.2.3 *Doubler Material* — The most consistently used doubler material has been continuous E-glass fiber-reinforced polymer matrix materials (woven or unwoven) in a [0/90]$_{ns}$ laminate configuration. The doubler material is commonly applied at 45° to the loading direction to provide a soft interface. Other configurations that have reportedly been successfully used have incorporated steel doublers, or doublers made of the same material as is being tested.

8.2.4 *Adhesive* — Any high-elongation (tough) adhesive system that meets the environmental requirements may be used when bonding doublers to the material under test. A uniform bondline of minimum thickness is desirable to reduce undesirable stresses in the assembly.

8.3 *Specimen Preparation* — Guide D 5687/D 5687M provides recommended specimen preparation practices and should be followed where practical.

8.3.1 *Panel Fabrication* — Control of fiber alignment is critical. Improper fiber alignment will reduce the measured properties. Erratic fiber alignment will also increase the

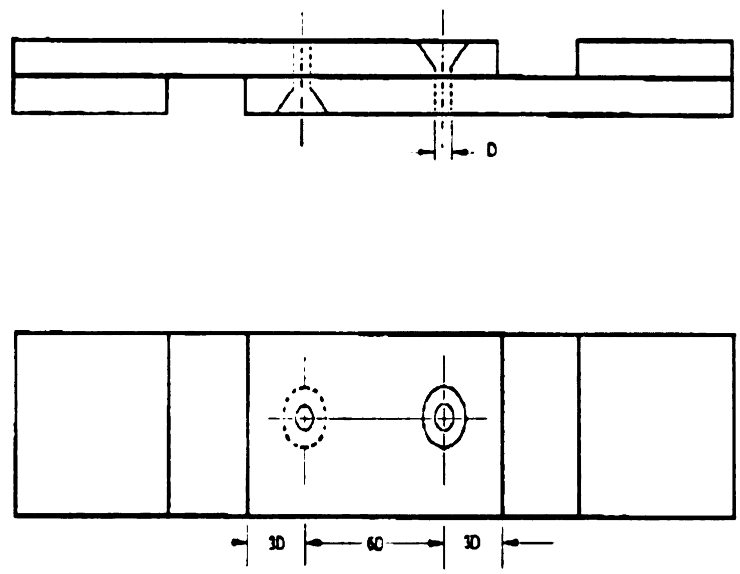


FIG. 7 Single-Shear, Double-Fastener Test Coupon Schematic

coefficient of variation. Report the panel fabrication method.

8.3.2 *Machining Methods* – Specimen preparation is extremely important for this specimen. Take precautions when cutting specimens from plates to avoid notches, undercuts, rough or uneven surfaces, or delaminations due to inappropriate machining methods. Obtain final dimensions by water lubricated precision sawing, milling, or grinding. The use of diamond tooling has been found to be extremely effective for many material systems. Edges should be flat and parallel within the specified tolerances. Holes should be drilled under-sized and reamed to final dimensions. Special care shall be taken to ensure that creation of the specimen hole does not delaminate or otherwise damage the material surrounding the hole. Record and report the specimen cutting and hole preparation methods.

8.3.3 *Labeling* – Label the coupons so that they will be distinct from each other and traceable back to the raw material, and in a manner that will both be unaffected by the test and not influence the test.

9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. Conditioning

10.1 *Standard Conditioning Procedure*—Unless a different environment is specified as part of the experiment, condition the test specimens in accordance with Procedure C of Test Method D 5229/D 5229M, and store and test at standard laboratory atmosphere (23 ± 3°C [73 ± 5°F] and 50 ± 10 % relative humidity).

11. Procedure

11.1 *Parameters to Be Specified Prior to Test*:

11.1.1 The bearing coupon sampling method, coupon type and geometry, fastener type and material, fastener torque, cleaning process, and conditioning travelers (if required).

11.1.2 The bearing properties, offset bearing strain value and data reporting format desired.

NOTE 3—Unless otherwise specified, an offset bearing strain of 2% shall be used.

NOTE 4—Determine specific material property, accuracy, and data reporting requirements prior to test for proper selection of instrumentation and data recording equipment. Estimate operating bearing stress and bearing strain levels to aid in transducer selection, calibration of equipment, and determination of equipment settings.

11.1.3 The environmental conditioning test parameters.

11.1.4 If performed, the sampling method, coupon geometry, and test parameters used to determine density and reinforcement volume.

11.2 *General Instructions*:

11.2.1 Report any deviations from this test method, whether intentional or inadvertent.

11.2.2 If specific gravity, density, reinforcement volume, or void volume are to be reported, then obtain these samples from the same panels being bearing tested. Specific gravity and density may be evaluated by means of Test Methods D 792. Volume percent of the constituents may be evaluated by one of the matrix digestion procedures of Test Method D

3171, or, for certain reinforcement materials such as glass and ceramics, by the matrix burn-off technique of Test Method D 2584. The void content equations of Test Methods D 2734 are applicable to both Test Method D 2584 and the matrix digestion procedures.

11.2.3 Condition the specimens as required. Store the specimens in the conditioned environment until test time, if the test environment is different than the conditioning environment.

11.2.4 Following final specimen machining and any conditioning, but before bearing testing, measure the specimen width, *w*, and the specimen thickness, *h*, in the vicinity of the hole. Measure the hole diameter, *D*, distance from hole edge to closest coupon side, *f*, and distance from hole edge to coupon end, *g*. Measure the fastener or pin diameter at the bearing contact location. The accuracy of all measurements shall be within 1% of the dimension. Record the dimensions to three significant figures in units of millimetres [inches].

11.2.5 *Cleaning* — Clean the specimen hole, surrounding clamping area, and fastener or pin shank. If the fastener threads are required to be lubricated, apply the lubricant to the nut threads instead of the fastener threads and take extreme care not to accidentally transfer any of the lubricant to the fastener shank, the specimen hole, or to the clamping area during assembly and torquing. Record and report cleaning method.

11.2.6 *Specimen Assembly*—Assemble test specimen to mating attachment or to double-shear fixture, as appropriate for the procedure, with fastener or pin.

11.3 *Fastener Torquing* — If using a torqued fastener, tighten the fastener to the required value using a calibrated torque wrench. Record and report the actual torque value.

NOTE 5—Take care not to work the joint after torquing. Joint rotation after torching and before and during insertion into the testing machine may relax the initial torque. Final torquing of the fastener may be necessary after the specimen is inserted into the test machine.

11.4 *Speed of Testing* — Set the speed of testing so as to produce failure within 1 to 10 min. If the ultimate bearing strain of the material cannot be reasonably estimated, initial trials should be conducted using standard speeds until the ultimate bearing strain of the material and the compliance of the system are known, and speed of testing can be adjusted. The suggested standard speeds are:

11.4.1 *Bearing Strain - Controlled Tests* — A standard bearing-strain rate of 0.01 min^{-1} .

11.4.2 *Constant Head - Speed Tests* — A standard head displacement rate of 2 mm/min [0.05 in./min].

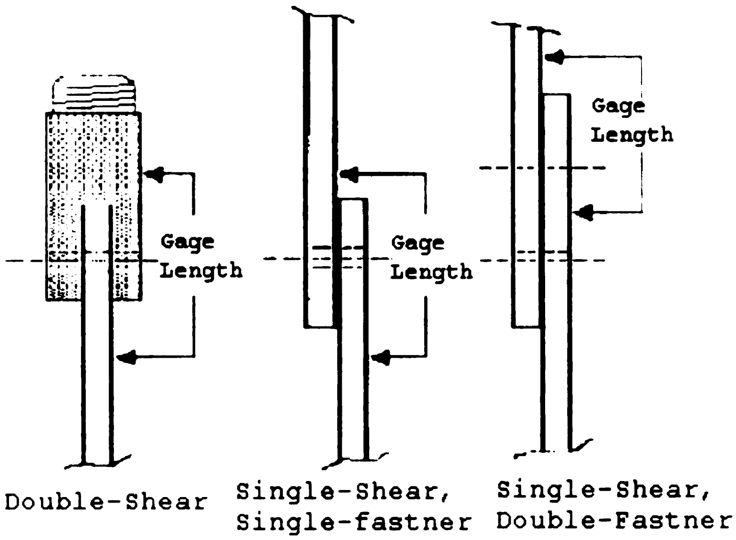
11.5 *Test Environment* — If possible, test the specimen under the same fluid exposure level used for conditioning. However, cases such as elevated temperature testing of a moist specimen place unrealistic requirements on the capabilities of common testing machine environmental chambers. In such cases the mechanical test environment may need to be modified, for example, by testing at elevated temperature with no fluid exposure control, but with a specified limit on time to failure from withdrawal from the conditioning chamber. Record any modifications to the test environment.

11.6 *Insert Specimen* — Insert specimen into the test machine, attaching loading interfaces or tightening grips as required.

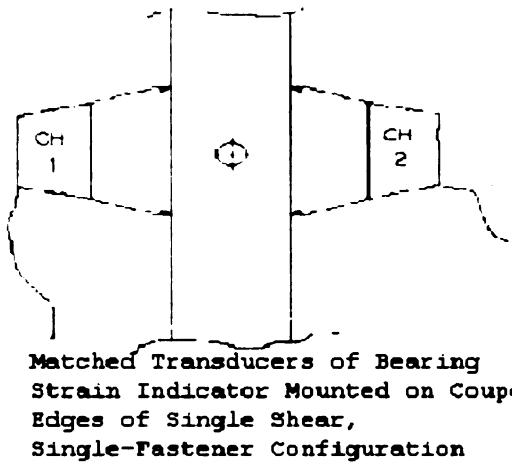
11.7 *Complete Bearing Strain Indicator Installation* — Attach the bearing strain indicator to the edges of the specimen as shown in Fig. 8 to provide the average displacement across the loaded hole(s) at the edge of the specimen. Attach the recording instrumentation to the indicator. Remove any remaining pre-load and zero the indicator. For Procedure B double-fastener specimens, one end of the indicator shall be on the edge of the specimen between the two fasteners and the other end on the edge of the mating coupon.

11.8 *Loading* — Apply the load to the specimen at the specified rate while recording data. The coupon is loaded until a load maximum is reached and load has dropped off about 30% from the maximum. Unless coupon rupture is specifically desired, the test is terminated so as to prevent masking of the true failure mode by large-scale hole distortion, in order to provide a more representative failure mode assessment.

11.9 *Data Recording* — Record load versus bearing strain (or hole displacement) continuously, or at



a)



b)

FIG. 8 Transducer Gage Length and Location

frequent regular intervals. If a transition region or initial ply failures are noted, record the load, bearing strain, and mode of damage at such points. If the specimen is to be failed, record the maximum load, the failure load, and the bearing strain (or hole displacement) at, or as near as possible to, the moment of rupture.

NOTE 6 – Other valuable data that can be useful in understanding testing anomalies and gripping or specimen slipping problems includes load versus head displacement data and load versus time data.

NOTE 7 – A difference in the bearing stress/bearing strain or load/bearing strain slope between bearing strain readings on the opposite sides of the specimen indicates joint rotation in the specimen.

11.10 *Failure Mode* – Record the mode and location of failure of the specimen. Choose, if possible, a standard description using the three-part failure mode code shown in Fig. 9. A multimode failure can be described by including each of the appropriate failure-type codes between the parens of the M failure-type code. For example, a typical failure for a $[45/0/\text{þ}45/90]_{ns}$ laminate having elements of both local bearing and cleavage might have a failure mode code of M(BC)1I.

NOTE 8 – The final physical condition of the test coupon following testing depends upon whether or not the test was stopped soon after reaching maximum load. If the test is not so stopped, the test machine will continue to deform the coupon and disguise the primary failure mode by producing secondary failures, making determination of the primary failure mode difficult. In some cases it may be necessary to examine the bearing stress/bearing strain curve to determine the primary failure mode; in other cases the failure mode may not be determinable.

12. Calculation

NOTE 9–Presentation and calculation of results by this test method is based on normalizing total joint load and overall joint displacement to the response at a single hole. In the case of a double-shear test there is no adjustment necessary in either load or displacement. However, for a single-shear test (assuming like coupon halves, and whether for one fastener or two), the total joint displacement is approximately twice the elongation of a given hole. For a double-fastener test, the hole load is one half the total load. This is the source of the k load factor and the K displacement factor used in the following equations.

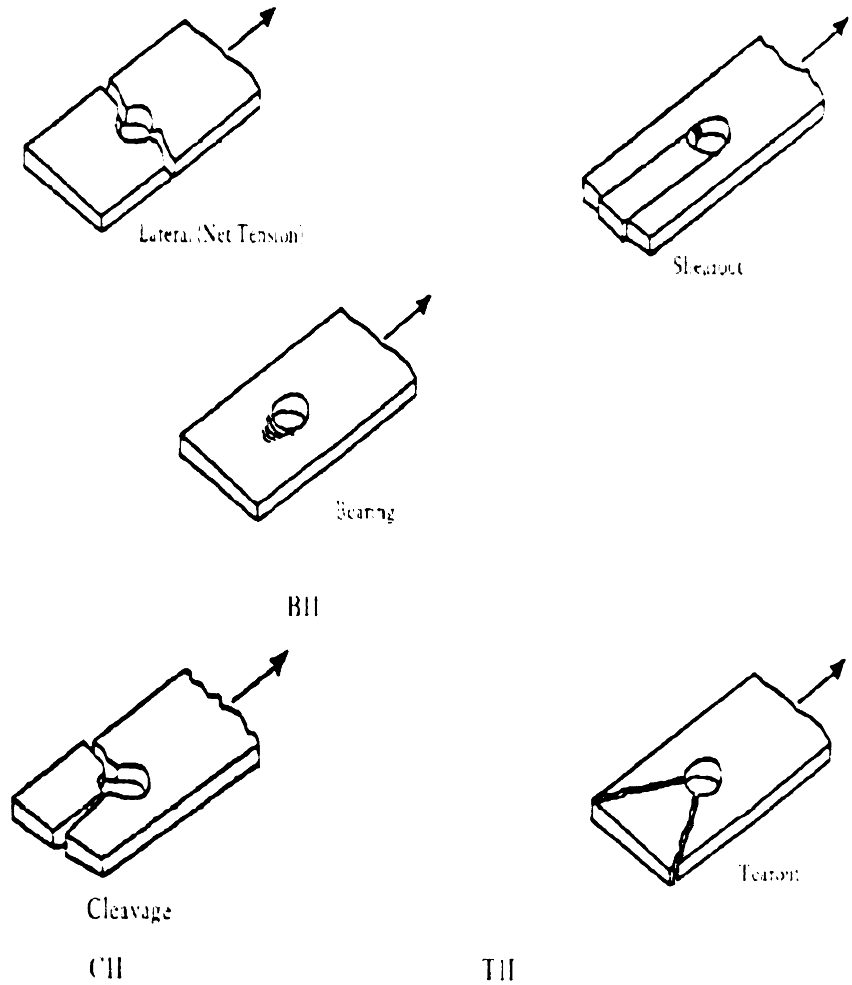
12.1 *Pitch Distance Ratio* – Calculate the actual specimen pitch distance ratio using measured values with Eq 1, and report the result to three significant digits.

$$w/D = 2 * \frac{f + D/2}{D} \qquad (1)$$

where:
w/D = actual pitch distance ratio,
f = shortest distance from hole edge to coupon side, mm [in.], and

D = hole diameter, mm [in.].

12.2 *Edge Distance Ratio* — Calculate the actual specimen edge distance ratio using measured values



First Part

Failure Type	Code
Bearing	B
Cleavage	C
Fastener or pin	F
Lateral (net tension)	L
Multi-mode	M(xyz)
Shearout	S
Tearout	T
Other	O

Second Part

Failure Area	Code
First Hole	1
Second Hole	2
Both Holes	B
Fastener or pin	F
Unknown	U

Third Part

Failure Location	Code
Bolt Head Side	B
Nut Side	N
Inapplicable	I
Unknown	U

FIG. 9 Bearing Test Failure Codes With Illustrations of Common Modes

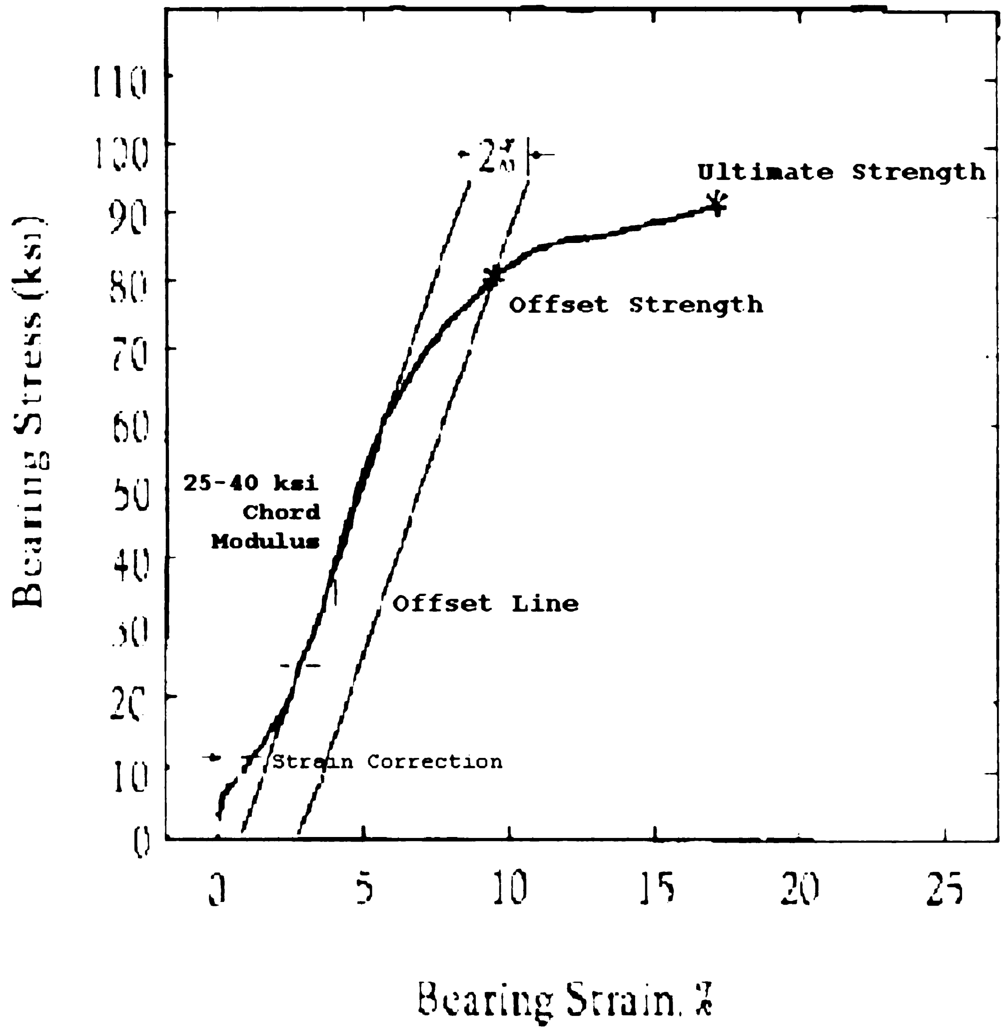


FIG. 10 Example of Bearing Stress/Bearing Strain Curve

with Eq 2, and report the result to three significant digits.

$$e/D = \frac{g + D/2}{D} \qquad (2)$$

where:

e/D = actual edge distance ratio, and

g = distance from hole edge to coupon end, mm [in.].

12.3 *Bearing Stress/Strength*—Determine the bearing stress at each required data point with Eq 3. Calculate the ultimate bearing strength using Eq 4. Report the results to three significant digits.

$$\sigma_i^{br} = P_i/(k*D*h) \qquad (3)$$

$$F^{bru} = P^{\max}/(k*D*h) \qquad (4)$$

where:
F^{bru} = ultimate bearing strength, MPa [psi],
P^{max} = maximum load prior to failure, N [lbf],
σ_i^{br} = bearing stress at *i*-th data point, MPa [psi],
P_i = load at *i*-th data point, N [lbf],
h = coupon thickness, mm [in .], and
k = load per hole factor: 1.0 for single-fastener or pin tests and 2.0 for double-fastener tests.

12.4 *Bearing Strain*—Determine the average bearing strain for each displacement value recorded using Eq 5 and report the results to three significant digits.

$$\varepsilon_i^{br} = \frac{(\delta_1 + \delta_2)/2}{K*D} \qquad (5)$$

where:
ε_i^{br} = bearing strain, microstrain,
δ_{1_i} = extensometer-1 displacement at *i*-th data point, mm [in.],
δ_{2_i} = extensometer-2 displacement at *i*-th data point, mm [in.], and
K = 1.0 for double-shear tests, 2.0 for single-shear tests.

NOTE 10 — The *K* factors for single-shear tests may not be appropriate if the mating coupon-half is significantly different in bearing stiffness.

12.5 *Bearing Chord Stiffness* — Calculate the chord stiffness between two specific bearing stress or bearing strain points in the essentially linear portion of the bearing stress/bearing strain curve. Report the result to three significant digits. Report whether bearing stress points or bearing strain points were used, as well as the value of the two end points.

$$E^{br} = \frac{\Delta\sigma^{br}}{\Delta\varepsilon^{br}} \quad (6)$$

where:

E^{br} = bearing chord stiffness, MPa [psi],

$\Delta\sigma^{br}$ = change in bearing stress over chord stiffness range, MPa [psi], and

$\Delta\varepsilon^{br}$ = change in bearing strain over chord stiffness range, mm/mm [in./in.].

NOTE 11—The initial portion of the bearing stress/bearing strain curve will usually have substantial variations in the bearing stress/bearing strain response due to combinations of joint straightening, overcoming of joint friction, and joint translation due to hole tolerance. The chord stiffness points should be determined after this behavior has dissipated. Because of these variations it is often most practical to use bearing stress end points to determine the chord stiffness.

12.6 *Determination of Effective Origin* — Intersect the chord stiffness line with the bearing strain axis to define an effective origin for use in determining offset bearing strength and ultimate bearing strain.

12.7 *Ultimate Bearing Strain* — After correcting the bearing stress/bearing strain data for the new effective origin, record the bearing strain at maximum load, to three significant digits, as the ultimate bearing strain.

12.8 *Offset Bearing Strength* — After correcting the bearing stress/bearing strain data for the new effective origin, translate the chord stiffness line along the bearing strain axis from the origin by the specified offset amount of bearing strain. Determine the intersection of this line with the bearing stress/bearing strain curve. Assess if an offset bearing strength is appropriate for this coupon from the discussion on initial peak bearing strength in 12.9. If an offset bearing strength is appropriate, report, to three significant digits, the bearing stress value at this point as the offset bearing strength F_x^{bro} (e %), where e is the value of the offset bearing strain expressed in percent. (See Note 3.)

12.9 *Initial Peak Bearing Strength* — Some bearing test configurations will show an initial peak bearing stress followed by a sharp drop in bearing stress and subsequent hole deformation such that the offset bearing strength will be lower than the initial peak bearing stress. If after further hole deformation the coupon resumes loading to bearing stress levels higher than the initial peak, report the initial peak bearing stress as an initial peak bearing strength, in addition to the offset and ultimate bearing strengths. However, if the initial peak bearing stress is the ultimate bearing strength of the coupon, do not report either an initial peak bearing strength or an offset chord bearing strength.

12.10 *Statistics* – For each series of tests calculate the average value, standard deviation, and coefficient of variation (in percent) for each property determined:

$$\bar{x} = (\sum_{i=1}^{n} x_i)/n \tag{7}$$

$$s_{n-1} = \sqrt{(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2)/(n-1)} \tag{8}$$

$$CV = 100 * s_{n-1}/\bar{x} \tag{9}$$

Where:
$\bar{x}$ = sample mean (average),
s_{n-1} = sample standard deviation,
CV = sample coefficient of variation, %,
n = number of specimens, and
x_i = measured or derived property.

13. Report

13.1 Report the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

NOTE 12 – Guides E 1309, E 1434, and E 1471 contain data reporting recommendations for composite materials and composite material mechanical tests. While these guides do not yet cover bearing response testing, they remain a valuable resource that should be consulted. A revision to the guides that adds the necessary additional fields is underway.

13.1.1 The test method and revision level or date of issue.
13.1.2 The procedure used and whether the coupon configuration was standard or variant.
13.1.3 The date(s) and location(s) of the test.
13.1.4 The name(s) of the test operator(s).
13.1.5 Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.
13.1.6 Identification of the material tested including: material specification, material type, material designation, manufacturer, manufacturer's lot or batch number, source (if not from manufacturer), date of certification, expiration of certification, filament diameter, tow or yarn filament count and twist, sizing, form or weave, fiber areal weight, matrix type, prepreg matrix content, and prepreg volatiles content.
13.1.7 Description of the fabrication steps used to prepare the laminate including: fabrication start date, fabrication end date, process specification, cure cycle, consolidation method, and a description of the equipment used.
13.1.8 Ply orientation stacking sequence of the laminate.
13.1.9 If requested, report density, volume percent reinforcement, and void content test methods, specimen sampling method and geometries, test parameters, and test results.
13.1.10 Average ply thickness of the material.
13.1.11 Results of any nondestructive evaluation tests.
13.1.12 Method of preparing the test specimen, including specimen labeling scheme and method, specimen geometry, sampling method, coupon cutting method, identification of tab geometry, tab material, and tab adhesive used.
13.1.13 Fastener or pin type and material, fastener or pin diameter, fastener torque, hole clearance, countersink angle and depth, grommet, mating material, and number of fasteners.
13.1.14 Fastener or pin and coupon cleaning method.
13.1.15 Calibration dates and methods for all measurement and test equipment.

13.1.16 Type of test machine, grips, jaws, grip pressure, alignment results, and data acquisition sampling rate and equipment type.
13.1.17 Dimensions of each test specimen.
13.1.18 Actual values of coupon hole diameter, coupon edge distance ratio, coupon pitch distance ratio, and coupon diameter to thickness ratio.
13.1.19 Conditioning parameters and results, use of travelers and traveler geometry, and the procedure used if other than that specified in the test method.
13.1.20 Relative humidity and temperature of the testing laboratory.
13.1.21 Environment of the test machine environmental chamber (if used) and soak time at environment.
13.1.22 Number of specimens tested.
13.1.23 Speed of testing.
13.1.24 Bearing strain indicator placement on the specimen, and transducer type for each transducer used.
13.1.25 Bearing stress/bearing strain curves and tabulated data of bearing stress versus bearing strain for each specimen.
13.1.26 Individual ultimate bearing strengths and average value, standard deviation, and coefficient of variation (in percent) for the population. Note if the failure load was less than the maximum load prior to failure.
13.1.27 Individual bearing strains at failure and the average value, standard deviation, and coefficient of variation (in percent) for the population.
13.1.28 Bearing stress or bearing strain range used for bearing chord stiffness determination.
13.1.29 If another definition of bearing stiffness is used in addition to chord stiffness, describe the method used, the resulting correlation coefficient (if applicable), and the bearing stress or bearing strain range used for the evaluation.
13.1.30 Individual values of bearing stiffness and the average value, standard deviation, and coefficient of variation (in percent) for the population.
13.1.31 If offset bearing strength is determined, the method of linear fit (if used), the bearing

stress or bearing strain ranges over which the linear fit or chord lines were determined, and the offset bearing strain value.

13.1.32 Individual values of offset bearing strength (if applicable), and the average value, standard deviation, and coefficient of variation (in percent) for the population.

13.1.33 If initial peak bearing strength is determined, the individual values of initial peak bearing strength and the average value, standard deviation, and coefficient of variation (in percent) for the population.

13.1.34 Failure mode and location of failure for each specimen.

14. Precision and Bias

14.1 *Precision* — The data required for the development of a precision statement is not available for this test method. Committee D-30 is currently planning a round-robin test series for this test method in order to determine precision.

14.2 *Bias* — Bias cannot be determined for this test method as no acceptable reference standard exists.

15. Keywords

15.1 bearing properties; bearing strength; composite materials

Document References

1 - This test method is under the jurisdiction of ASTM Committee D-30 on High Modulus Fibers and Their Composites and is the direct responsibility of Subcommittee D30.05 on Structural Test Methods. Current edition approved May 10, 1996. Published July 1996.

2 - *Annual Book of ASTM Standards*, Vol 08.01.

3 - *Annual Book of ASTM Standards*, Vol 08.02.
4 - *Annual Book of ASTM Standards*, Vol 15.03.
5 - *Annual Book of ASTM Standards*, Vol 03.01.
6 - *Annual Book of ASTM Standards*, Vol 14.02.
7 - Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.
8 - Variations in hole clearance and fastener torque are allowed if recorded.