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Mechanical Testing of Epoxy Adhesives for Naval Applications

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MECHANICAL TESTING OF EPOXY ADHESIVES FOR NAVAL APPLICATIONS

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With advances in composite technology and an understanding of composite application, requirements to develop new design approaches exist. With composite structures today, a basic understanding that both material architecture and joining process, affect the strength of the structure. These design requirements force old techniques of joining, such as bolting and riveting to be re-evaluated.

Advantages of adhesives over mechanical means of fastening include higher stiffnesses, more uniform load distribution, parts consolidation, no holes drilled in adherends (with resulting stress concentrations), and, generally, less labor.

Adhesives have proven to be a good solution for joining when composites are utilized, but this necessitates the next step in engineering, which is to quantify adhesive properties. By quantifying bulk properties for adhesives at varying conditions, application for adhesives is promoted.

The following study attempts to implement testing techniques for qualification of the use of adhesives in hybrid connections on naval hulls.

E-glass/vinyl ester composite specimens adhesively bonded to aluminum specimens were tested. The three varieties of specimens tested were: single lap tensile shear specimens, double lap tensile shear specimens, and single flexure specimens. These geometries where chosen because they closely resemble applications currently explored in the AHFID and MACH projects. Instrumentation was used to collect displacement and load data. Some samples where exposed to environmental conditions to determine the performance of the adhesive when exposed to moisture. Increased residual stresses due to moisture absorption are ignored in this study.

The data was then used to characterize the performance of the adhesive for varying bondline thickness and varying surface preparations. The results indicate that the grit blasted surface preparation technique had a marked effect on the strength of the bond. The bondline thickness markedly affected the ultimate load capacity of the joint. Modes of failures where characterized in an attempt to determine cause of failure.

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1. Introduction

Adhesively bonded connections comprise a significant class of joining methodologies, which can be used when attachment of composite to metal structure is required. Oftentimes an adhesive joint is the method of choice when compared to mechanically fastened alternatives such as bolting. Careful attention to detail must be paid in use of adhesives for structural connections, especially when dissimilar materials are to be attached. Not only is proper adhesive selection critical but also proper techniques in application of the adhesive must be carried out. There are many issues to consider when selecting an adhesive joint for a structural component. The focus of this thesis is to address some of the major concerns of using adhesive joints in underwater naval ship applications.

A ship is a heavily loaded dynamic structure and mitigation of structural failures is essential. Structural failures are typically caused by fatigue, corrosion enhanced fatigue, or abnormal overloading, and typically result in a requirement for routine maintenance or major overhaul, depending on the severity of the damage. More often than not, structural failures occur at connections and interfaces, and rarely occur in the bulk material sections. Standard testing of material coupons cannot represent these failure modes; therefore it is impossible to ascertain the durability of the ship and its connections from simple material test alone. One must perform a thorough investigation into the mechanics of the connections and interfaces of the vessel, because this is where failures typically initiate. Furthermore, loads acting upon ships over their lifetime are difficult to predict. A proper assessment of the structural safety of a ship is dependent upon the proper quantification of the loads and upon proper assessment of the integrity and durability of the connections and interfaces.

One of the primary goals of a ship designer is to minimize cost and weight. Significant savings in structural weight can be achieved by using composite materials. It has been shown that composites are structurally an optimum design solution in cases where minimal weight and high stiffness are required. However, robust connection methodologies and issues surrounding the manufacturing of the composite/metal interfaces have stood in the way of more widespread use of composite construction for underwater hulls and other structural components, especially in Naval vessels. One area where much research is needed is on adhesively bonded interfaces between composites and metals such as steel and aluminum.

The U.S. Navy currently has an objective to develop advanced hull-forms to enhance the future naval capabilities. One of the primary cost drivers in developing advanced hull-forms with conventional techniques is in the metal forming of complex shapes. Composite materials offer a solution due to their inherent ability to perform complex shaping at relatively little incremental cost compared to flat panels. Navy ships are large, complex structures with large amounts of material used in their hulls. For this reason, relatively inexpensive fiberglass reinforced polymer (GRP) composite systems using a vacuum assisted resin transfer molding (VARTM) process, are currently endorsed by the Navy. In order to be efficient, the structure of the hull-form must be lightweight and stiff to resist the loads and to maintain its shape. It also must be fatigue, impact and shock resistant.

Unfortunately there have been difficulties in the implementation of composite construction as a wide spread solution on the underwater hulls of Navy surface ships. To address some of these research needs, the University of Maine has recently been involved in two major research efforts focusing upon connections of composites to metal structures. The Advanced Hull form Inshore Demonstrator (AHFID) program is a program with a goal of installing an advanced drive system on the SES 200 ship. One of the proposed methods of attaching this advanced drive to the ship is by using composite struts. The Modular Advanced Composite Hullform (MACH) is another program with a goal of installing hybrid composite panels to underwater lifting bodies. In addressing the question of using adhesives for hybrid connectors, the University of Maine initiated an adhesive study in an effort to provide adhesive data for the (AHFID) program and the (MACH) programs.

1.1 Objectives

The long-term goal of this research effort is to develop and demonstrate adhesive bonded hybrid connection approaches and evaluation methodologies for adhesives to be used in a structural capacity on advanced hull-form structures. The immediate goal that will be met in this thesis is to implement robust techniques for evaluation of the use of adhesives in hybrid connections on naval ship hulls. This project will focus on adhesive joints between composites to metallic structures.

A large percentage of the adhesive bonding research to date has focused on ASTM standard testing of adhesives in order to support the aircraft industry where bondlines are typically less than 0.060". Adhesives in the marine industry represent a different set of criteria compared to the aerospace industry. By producing a large database of known adhesives, giving their properties specific to the marine environment, will help naval architects, designers, and ship engineers apply adhesive technology to the marine environment. This study is designed to populate a database with information regarding bondlines greater than 0.060" for the marine community.

The specific near term objectives of this study are as follows:

1. Provide baseline mechanical properties data that will guide adhesive selection for both the MACH and AHFID programs,
2. Quantify strength and stiffness of the adhesive for composite / metal connections,
3. Quantify the effect of the surface preparation,
4. Quantify the effect of bondline thickness,
5. Quantify the effect of the environmental conditions, and
6. Quantify the effect of various connection geometries.

Adhesives were tested in this study at a sub-component level under loads of shear and flexure. Geometry for the test included both single lap and double lap specimens.

1.2 Scope of Work

A scope of work outline was constructed to meet requirements set forth and stated in the objective section of this document. This work started with a literature review that is described in Section 1.3 of this document. This review provided details into current technology positions within the industry for adhesives. After completing the literature review a plan was outlined. This plan allowed for adhesive properties such as strength, surface preparation, bondline thickness, environmental conditions, and connection geometry to be studied. Section 2 of this document describes the geometry selected for testing the adhesives and the materials used. In order to understand and predict failure mechanisms of the adhesives during the testing, finite element analysis was also performed. This information is also presented in Section 2.

A procedure was written to construct adhesive coupons and to perform tests, in order to limit errors in test results. Section 2.5 of this document outlines procedure for testing. Results were collected electronically to allow accurate determination of specific adhesive properties. A summary of the test results are presented in Section 3 along with a comparisons of adhesive strength, stiffness, failure modes and environmental performance. Section 4 provides a summary, conclusion, and recommendations as to which adhesives are better suited for use in hybrid connections subjected to a marine environment.

1.3 Literature Review

The following review is intended to provide insight into earlier work in the area of the behavior of adhesive joints, and more specifically studies involving hybrid joints. Much of the literature dealing with joining of metals and composites with adhesives concentrates on investigating the bond strength for relatively thin bondlines. Particular areas of concentration for these investigations deal with such topics as: surface preparation, joint configuration, adhesive properties, environmental conditions, and test methods. These areas of investigation are of particular interest to this study.

Volkersen [1938] was considered one of the firsts to model single-lap adhesively bonded joints. Volkersen determined from his models that shear transfer of the axial stresses in the adherends resulted in what he termed as "shear lag". Goland and Reissner [1944] conducted further research with single-lap adhesive bonds. Their research provided insight into the effects of peel stresses on the strength of adhesively bonded joints and the consequences of bending deflections of the joint due to load path eccentricity. Guess and Gerstle [1977] made further steps in the development of analytical models in the 1970s when they compared different test methods both experimentally and analytically. Hart-Smith [1973] began modeling the behavior of the single lap joint based on Volkersen's methods. In 1975, Oplinger [1975] organized most publications on bonded joints.

1.3.1 Effects of Surface Preparations

Surface preparation should be considered one of the most critical steps when bonding with adhesives, especially with aluminum. Surface preparation must be tailored to the adherend and may differ for various metal or composites. Aluminum, for instance is in itself very resistant to corrosion since on exposure a thin film of oxide forms which protects the base metal from further corrosion. This thin oxide film is where the problem exists when bonding to aluminum. Surface treatments prior to the applications of coatings or adhesives is recommended in order to achieve maximum mechanical strength. According to Molitor, et al. [2000] bond strengths can be significantly improved by surface treating the adherends prior to bonding. Traditional methods of surface treatment such as grit blasting, mechanical abrasion, and acid etching have been used with good success. These surface treatments cause changes in surface tension, surface roughness, and surface chemistry, which in turn affect bond strength.

Because chemical surface treatment is expensive and toxic waste is generated, mechanical abrasion is a very good first alternative to consider. It is commonly observed that roughening surfaces prior to bonding enhances the strength of adhesive joints, and many manufacturers specify the use of some form of abrasion as a surface treatment method. This recommendation is based on the perception that the abrasive process removes loose contaminated layers and the roughened surface provides some degree of mechanical interlocking with the adhesive. It is sometimes argued Possart et al. [2002] that the increased roughness also forms a larger effective surface area for the bond. Kinloch [1987] supports the mechanical treatment techniques and emphasizes the necessity of degreasing the surface prior to bonding. Comyn [1997] also suggests that grit blasting along with degreasing or solvent cleaning will achieve good strength in dry conditions.

The reason that surface preparation of metals is so important is due to the oxidization build up that occurs with metals. This is especially important with metals such as aluminum and titanium. Lee [1991] states that aluminum and titanium quickly form coherent, adherent oxides, which make it difficult to achieve good adhesion. As stated by Grenestedt and Melograna [2002] "no treatment has been as widely adopted or shown to be superior to grit blasting"

Although mechanical abrasion is not as efficient as grit blasting, it is a technique that applies mechanical means to remove the oxides and impurities on the adherend's surface. As with grit blasting, mechanical abrasion has been demonstrated to provide a highly rough surface for bonding. Bishopp and Sim [1988] states that with mechanical abrasion there is the possibility that residual debris will be embedded into the adherend and that mechanical damage to the adherend could occur which could be detrimental to bonding. This consideration should be realized when applying mechanical abrasion processes for surface preparation of adherends. Studies have been done to quantify joint properties when mechanical abrasions surface preparation was utilized. Schultz et al. [1989] performed experiments using emery cloth to treat the surface of the adherends.

The acid etching process, although not as popular as grit blasting is an efficient technique for removing oxides and impurities on the surface of metals. This process of chemically treating the surface of metals was developed as a preparation for painting and spot-welding in the 1930's, but was soon adopted for treatment of adherends being bonded.

Today there are a range of acid etch processes that exist. Some of the more successful processes include phosphoric acid etching and chromic acid etching.

There are several patented systems employing the phosphate principle, which include the proper cleaning followed by chemical treatment. Crystalline phosphate treatment is one type of phosphate treatment. The crystalline phosphate solution consists of phosphoric acid and metal phosphates, which react with and deposit complex crystals on the metal surface. The crystalline process produces a somewhat porous surface, which is excellent as a paint base, giving improved adhesion, corrosion, and corrosion creep resistance. Another type of phosphate treatment is the amorphous type of treatment. The amorphous types are used in much the same way as the crystalline types. The major advantages of amorphous types of etching are that they are generally lower in cost. The amorphous chemical treatments are recommended for use both with and without the final chromic acid rinse when treating aluminum. Chromic acid etching became popular as a result of work by Eickner and Schowalter [1950]. Their work supported the US aircraft industry by reporting bond strength when surface treating with a dichromate solution. For best results, the chromic acid rinse is desirable since it has been proved that where the final rinse is neutral (clean water), the resistance to corrosion is much lower. In fact, under certain conditions, a cleaning cycle with a chromic acid rinse is preferable to using a cleaning-phosphate cycle without the final acid rinse. The final rinse in any system should never be alkaline. Preferably, it should be acidified with chromic or chromic-phosphoric acid.

With greater emphasis on environmental friendly chemicals, there is a push to find better ways to promote bonding to metals. The phosphoric and chromic treatments, although very effective, produce toxic residue. Silane treatment of metals is a relatively new chemical process that seems to be producing good results. These "silane" chemicals are hybrid organic-inorganic compounds that can be used as coupling agents across the organic-inorganic interface.

These silane coatings have been shown to be an effective replacement for phosphating (including final chromate rinse) pretreatments of metals. The performance of these silanes on metals has been shown to outperform the current phosphating pretreatments. Ooij and Sundararajan [2000] have performed research in this area specific to bonding 6061-T6 aluminum. Gupta [2002] has looked at bonding to steels. His results relative to environmental exposure are shown in Section 1.3.5 of this document.

Surface preparation is not a requirement just for metallic adherents. There is also a need to surface treat composites. This is especially important for secondary bonding to composites. Surfaces of composite materials have a high variability of texture, but they need to be prepared for bonding. Such techniques as sanding and grit blasting are harsh techniques that cause erosion. At present research is experimenting with the use of ion bombardment techniques to treat the surface of composites such as graphite/epoxy. It is anticipated that the ultimate failure load will increase when using ion bombardment compared to traditional methods of surface treatment.

1.3.2 Effect of Joint Configuration

Joint configuration, unlike surface preparation, is usually a product of design. According to Adams and Wake [1984] if adhesive properties are understood, "Adhesive bonding is attractive as it reduces the localized stresses encountered when using bolts." Tong [1997] states that when designing composite to metallic adhesive joints, the layered nature of composite adherends and relative weakness in the through-the-thickness direction, makes the failure mechanism more complex. It is safe to conclude that due to these uncertainties in joint strength many designers use higher safety margins to account for these uncertainties. Because this is usually the case, many books have been written to aid in joint selection. Bonanni et al. [2000] developed a process for joint selection in marine composites. Although the design requirements of the aircraft industry can be different from the design requirements of the marine industry, it is possible to extract valuable lessons about what to do and what not to do when bonding a composite metallic structure. Hart-Smith [1987] provides many recommendations for the design and analysis of adhesive joints in fibrous composite structures specific to the aircraft industry. These recommendations are good lessons learned if applied correctly, to the marine industry.

Besides conservative engineering and sharing of best practices in design, some investments have been made in the area of stress analysis computer codes for bonded joints. To mention a few, closed-form analytical solutions of adhesively bonded joints were obtained by Delale et al. [1980], Groth [1986], Liu [1976], Pahoja [1972] and Srinivas [1975]. Adams and Peppiatt [1974], Amijima et al. [1989], Roy and Reddy [1984], Sable and Sharifi [1991], Humpherys and Herakovich [1977], Barthelemy et al. [1984], and Barker and Hatt [1973] all performed finite element based analysis of bonded joints to compare to the close-form analytical solutions. Finite element analysis has been used successfully to investigate adhesive bonded joints. According to MIL-HDBK-17 [1997], there are serious pitfalls, which the analyst must be aware of to avoid problems. The biggest is mesh refinement specifically around ends of the overlap. According to Stroud et al. [2001] geometrically nonlinear analyses are essential for accurately predicting the response of the single lap shear join and its fracture failure mode. Rastogi et al. [1997] looked at the codes that existed for joint analysis used in the aerospace industry. Codes such as: JOINT, JTSDL / JTSTP, BOND3 / BOND4, BONJO I Series, MOSAIC, A4EI, AND PGLUE were designed by military entities. They explored the capabilities and limitations of codes in an effort to develop life prediction methodologies for composite joints.

1.3.3 Effects of Bondline Thickness

According to Bonanni et al. [2000], adhesive properties may not stay constant as bondline thickness is increased. Sometimes the adhesive strength degrades if the bondline thickness is too great. Thicker bondlines may create a more severe stress state. As stated by Bonanni et al. [2000] the ratio of adhesive shear modulus to bondline thickness controls the joint response. Increasing the thickness tends to reduce the peak stress, and spreads the load transfer over a longer distance. In addition, a thick bondline may exaggerate the peel stress distribution. Slight variation in joint design can also vary the peel stresses. According to MIL-HDBK-17-1E [1997] double overlap specimens reduce the peel stress when comparing to single lap shear specimens. Also reducing the bondline thickness reduces the peel stresses setup by joint geometry. To understand how an adhesive performs at thicknesses other than those recommended by the manufacturer, computer modeling and testing should be performed to verify stress distributions and adhesive properties.

1.3.4 Adhesive Selection

To achieve a good bond, you must first start with a good adhesive but adhesive selection includes many factors. Before an adhesive can be specified for an application, screening tests should be conducted in order to compare and evaluate the various adhesion parameters. This is especially true for structural adhesives where failures during actual use can have devastating consequences. Properties of adhesives can vary greatly; therefore appropriate selection is essential to a proper joint design. Many companies within the industry have produced charts, which help in the selection process. Figure 1 shows a chart that has been designed by Loctite to help select a bonding adhesive. The chart is intended to serve as a general guideline to help determine which adhesive categories are best suited for a specific application. The data presented represents typical properties for each adhesive category; however, individual product properties may differ. This chart should not be used to specify adhesives without specific testing.

PERFORMANCE CONSIDERATIONS	ADHESIVE CATEGORY							
	Acrylics	Cyanoacrylates	Epoxies	Hot Melts	Silicones	Urethanes	2-Part Acrylics	2-Step Acrylics
Benefits	Good impact resistance/ flexibility	Excellent adhesion to rubber or plastics	Wide range of formulations	Fast, large gap filling	Excellent temperature resistance	Excellent toughness/ flexibility	Good impact resistance/ flexibility	Good impact resistance/ flexibility
Limitations	Primer required	Low solvent resistance	Mixing required	Low heat resistance	Low strength	Sensitive to moisture	Mixing required	Primer required
Temperature Resistance								
Typical for the category (°F)	-65 to +300	-65 to +180	-65 to +180	-65 to +250	-65 to +400	-65 to +250	-65 to +250	-65 to +300
Highest Rated Product (°F)	400	250	275	330	600	300	250	400
Environmental Resistance								
Polar Solvents *(ex. H20, Ethylene Glycol, IPA, Acetone)*	Good	Poor[1]	Very good	Good	Good	Good	Good	Good
Non-Polar Solvents *(ex. Motor Oil, Toluene, Gasoline, ATF)*	Very good	Good	Excellent	Good	Poor	Good	Very good	Very good
Adhesion to Substrates								
Metals	Excellent	Very good	Excellent	Good	Good	Good	Excellent	Excellent
Plastics[2]	Fair	Excellent	Fair	Very good	Fair	Very good	Excellent	Fair
Glass	Excellent	Poor	Excellent	Good	Very good	Good	Good	Excellent
Rubber	Poor	Very good	Fair	Fair	Good	Good	Poor	Poor
Wood	Good	Good	Very Good	Excellent	Fair	Fair	Good	Good
Overlapping Shear Strength	High	High	High	Low	Low	Medium	High	High
Peel Strength	Medium	Low	Medium	Medium	Medium	Medium	High	Medium
Tensile Strength	High	High	High	Low	Low	Medium	High	High
Elongation/Flexibility	Medium	Low	Low	High	Very High	High	High	Medium
Hardness	Semi-Rigid	Rigid	Rigid	Semi-Soft	Soft	Soft	Semi-rigid	Semi-rigid
PROCESS CONSIDERATIONS								
Number of Components	2	1	2	1	1	2	2	2
Cure Temperature	Room Temp.	Room Temp.	Room Temp.	Room Temp.[3]	Room Temp.	Room Temp.	Room Temp.	Room Temp.
Fixture Time								
Average	10 minutes	60 seconds	35 minutes	70 seconds	25 minutes	25 minutes	20 minutes	5 minutes
Fastest	30 seconds	10 seconds	3-5 minutes	20 seconds	10 minutes	5 minutes	3-5 minutes	30 seconds
Full Cure Time	24 hours	24 hours	12 - 24 hours	1 hour (or when cooled)[4]	24 hours	24 hours	24 hours	24 hours
Gap Fill								
Ideal (in inches)	0.002 - 0.004	0.001 - 0.003	0.004 - 0.006	0.002 - 0.005	0.004 - 0.006	0.004 - 0.006	0.010 - 0.040	0.002 - 0.004
Maximum (in inches)	0.040	0.010	0.125	0.240	0.240	0.125	0.5	0.040
Dispensing/Mixing Equipment Required?	No	No	Yes	Yes	No	Yes	Yes	Yes
Light Cure Versions Available?	Yes	Yes	Yes	No	Yes	No	No	Yes

Figure 1 – Adhesive Selection Guide [Loctite]
(http://www.loctite.com/pdf/bondingguide.pdf)

1.3.5 Environmental Factors

As stated by Vodicka [1997], "There are many environmental factors, which can create changes in the properties of an adhesively bonded joint, which in turn can affect the ultimate mechanical performance." These factors need to be carefully identified and related to the type of service the material will see. Moisture absorption is one such factor, which is an obvious concern in the marine environment. With absorption of water, reductions in mechanical properties occur. Gupta [2002] quantified the effect of humidity (moisture) on interface fracture energy of a joint comprised of steel to E-glass epoxy as shown in Figure 2. He compared the durability of joints with and without silane surface preparation and found the use of silane to be beneficial when the long-term response is considered.

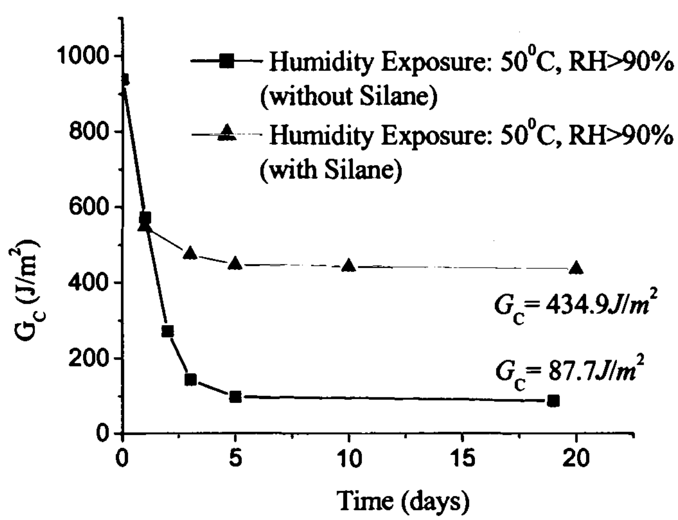


Figure 2– Surface Treating in a Humid Environment [Gupta 2002]

Moisture is also of concern in bonding to aluminum. Brewis et al. [1990] supported this research by showing that there exists a critical relative humidity for a given joint, and if the environment exceeds this relative humidity that joint strength declines. Comyn [1983] also supported this research by discussing the various mechanisms by which water enters the joint, and by which the joint can be weakened. He stated that the presence of moisture at the interface could cause swelling stresses, hydrolysis and cracking or crazing of the adhesive, plasticization of the adhesive, and hydration of the metal or metal oxide. In order to alleviate failure due to degradation by moisture, it is important to acquire an understanding of these mechanisms so that appropriate measures can be taken into account, so that a stable joint will result in the given environment.

Moisture related property degradation of adhesive joints should be accounted for during the joint design process and adhesive selection, in a manner consistent with its incorporation in the design of the overall structure. Stoud and Krishnamurthy [2001], in doing so used both probabilistic and deterministic methods can be used to account for uncertainties in design. Hayer[1998] showed the mechanics involved with moisture absorption. Hayer [1998] showed that for graphite-reinforced composite with moisture weight gains of as little as 3-4%, that principle internal stress could approach 60 MPa.

1.3.6 Testing Method and Standards

Currently there are many American Society of Testing and Material Standards, which have been written to analyze and experimentally verify adhesive properties. These ASTM Standards provide a basis for testing. Specific to epoxy adhesives, ASTM D6412/D 6412M provides direction as to the other standards that should be referenced when bonding to metallic and nonmetallic materials.

The most widely used adhesive-bond test specimen is the one-half inch single overlap tension test. [ASTM D 1002]. Figure 3 shows the dimensions of the specimen.

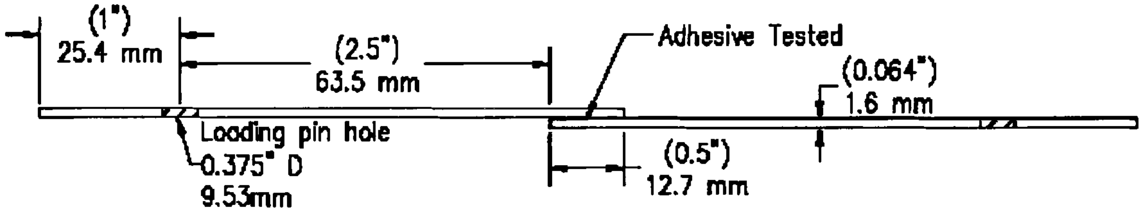


Figure 3 - ASTM D 1002 Test Specimen Profile [ASTM 1002]

The failure mode of the single overlap joint is rarely controlled by the shear strength of the adhesive but is largely the result of joint deflections and rotations and induced peel stresses. As you can see in Figure 4, testing following guidelines in ASTM D1002 causes rotations at the overlap. Because of this rotation, data from single overlap tension test specimen cannot be used to obtain adhesive shear design data but are often used for screening tests to compare several adhesive systems and the effects of the environment on the adhesive properties in the selection process of the adhesive.

(a) ASTM D 1002

Figure 4 – ASTM D 1002 Under Load [ASTM 1002]

From ASTM 1002, the average shear strength is given as:

$$\tau_m = P/bl$$

Where τ_m is the average shear strength, P is the applied load, and b & l are the joint width and length respectively. Liechti et al. [1987] stated that lap shear testing is the most widely used test to characterize relative strength properties of an adhesive. The reason that this joint configuration is used is because it is simple to construct. Liechti et al. [1987] emphasized that single lap strength testing should only be used for relative comparisons. Once the material has been evaluated with this initial test, subsequent testing methodology can be designed with respect to the proposed use. In this case the proposed test would require testing metal to composite bonds.

ASTM D 3165 is another standard, which provides insight into the testing of adhesives in shear by tension loading of single lap joint laminate assemblies. Figure 5 shows the geometry associated with this test.

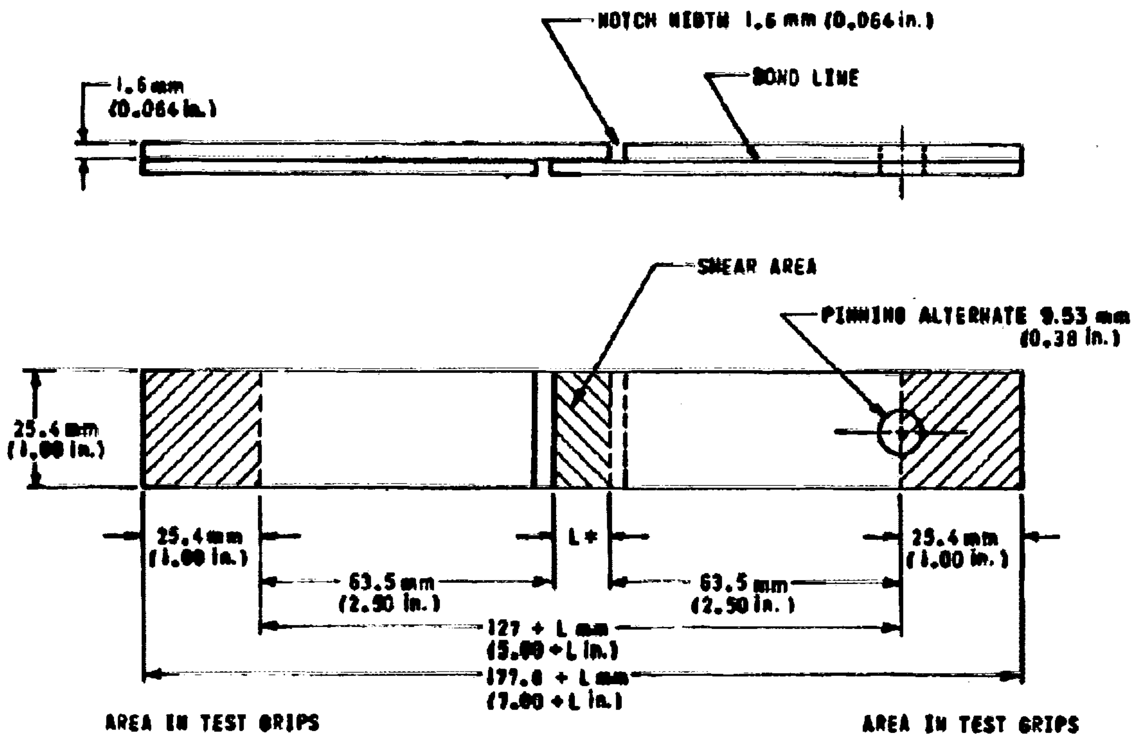


Figure 5 – ASTM D 3165 Test Specimen Profile [ASTM 3165]

Just like in ASTM D 1002 there are rotations induced at the overlap. This test also induces high peel stresses that can cause premature failure.

To limit rotations at the overlap, thick adherends need to be used. ASTM D 5656 supports these criteria. As shown in Figure 6 the geometry helps reduce the rotation at the joint. Figure 7 shows an ASTM D 5656 joint under a load. The rotation is not as severe as in ASTM D1002 or D3165 the other tests. ASTM D 5656 is a test method that covers preparation and testing of thick-adherend lap-shear samples for the determination of the stress-strain behavior of adhesives.

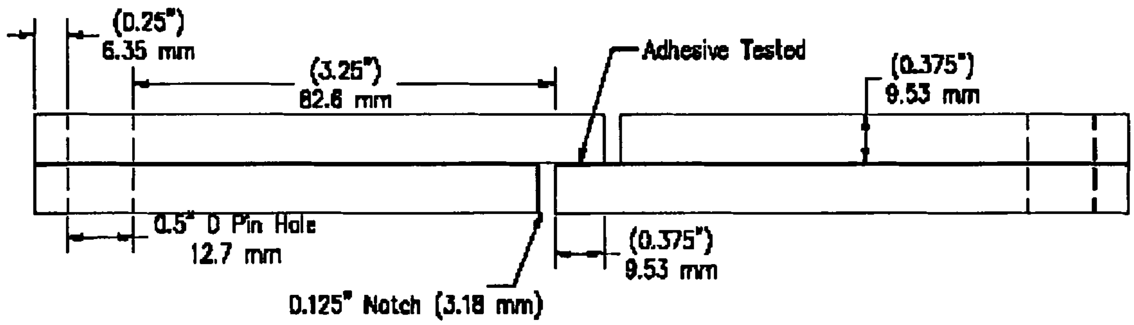


Figure 6 - ASTM D 5656 Test Specimen Profile [ASTM 5656]

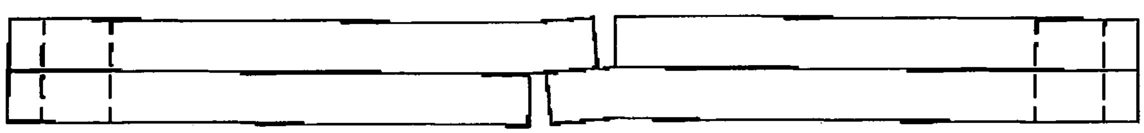


Figure 7 - Test Specimen Deformation - Loaded [ASTM D5656]

ASTM D 3528 is used for double lap shear adhesive joints by tension loading. In this specification the recommendations for aluminum to use is a 2024 T3 alloy. The thicknesses specified are 0.064" and 0.125" respectively. Although these tests utilize a particular type of aluminum, testing with actual materials should be performed to ensure correct application. Tests should also be tailored to ensure that the adhesive is tested in conditions, which will closely replicate actual conditions.

ASTM standards also provide some information as to surface treatments. Particularly, ASTM D 2651 gives an overall summary of most chemical surface treatments currently used. As stated in ASTM 2651, " Procedures for aluminum alloys are well standardized, possibly because more bonding has been done with these alloys. Preliminary tests should be conducted with the specific adhesive and the exact lot of metal to determine performance." Although chemical surface treatment is becoming popular, it is recommended by this ASTM that surfaces, which are scaled, corroded, or otherwise oxidized, should be abraded using a nonmetallic abrasive. This process will promote the chemical surface treatment. Care should be exercised in using the mechanical methods to prevent deep gouges or rough surfaces, which are not conducive to good bonding. ASTM D5229 and D1151 deal with moisture absorption properties and equilibrium conditioning. ASTM D5229 states, "worst case aircraft service water vapor environment is generally considered 85% relative humidity." For the marine environment this level of exposure is usually much higher, with the potential of full immersion in water. For accelerated conditioning it is possible to expose the samples to 95 - 98% relative humidity for a period of time. Elevated temperatures will also promote bond degradation due to moisture. It was noted that exposure to liquids immersion is not generally equivalent to exposure to an environment of 100% relative humidity. ASTM standards also help quantify the physical properties of adhesives.

ASTM D 1338-99 provides a procedure to determine the working life of a liquid or paste adhesive by consistency and bond strength. Working life is particularly important when utilizing adhesives in a shipyard environment. Insufficient working life can cause inadequate bonding during installation of bonded structures.

1.3.7 Failure Modes

Failure modes are determined by the quality of bond at each interface, specimen geometry, and loading. In order to gain a full understanding of the properties of the adhesive and the joint being investigated, the modes of failure must be characterized. In adhesives, there are three typical characterized modes of failure. These failure modes are: cohesive failure, adhesive failure, or substrate failure. These modes are defined as follows:

1. Cohesive failure is a failure of the adhesive itself.
2. Adhesive failure is a failure of the joint at the adhesive/adherend interface. This is typically caused by inadequate surface preparation, chemically and/or mechanically. Specimens that fail adhesively tend to have excessive peel stresses that lead to failure and often do not yield a strength value for the adhesive joint, but rather indicate unsuitable surface qualities of the adherend.
3. Substrate failure is a failure that occurs when the adherend fails instead of the adhesive. In metals, this occurs when the adherend yields. In composites, the laminate typically fails by way of inter-laminar failure, i.e., the matrix fails in between plies. A substrate failure indicates that the adhesive is stronger than the adherend in the joint being tested. This is a desirable situation in practical design, but not when determination of adhesive behavior is being studied.

Figure 8 provides a depiction of failure types experienced when bonding with adhesives. From this description Figure 9 through Figure 12 show the types of failures specific to bonding aluminum to composite. Figure 9 shows a typical adhesive failure of the adhesive with the aluminum adherend. From observation you can see that de-bond occurred such that practically all the adhesive did not stay bonded to the aluminum specimen. Figure 10 shows a similar phenomena but the de-bonding took place between the composite and the adhesive. Cohesive failure is shown in Figure 11. As you can see there was no adhesive failure between the adhesive and the adherends. Figure 12 shows the last failure mode experienced in this study, which was the failure of the composite adherend. This failure resulted in the de-lamination of the composite just below the surface.

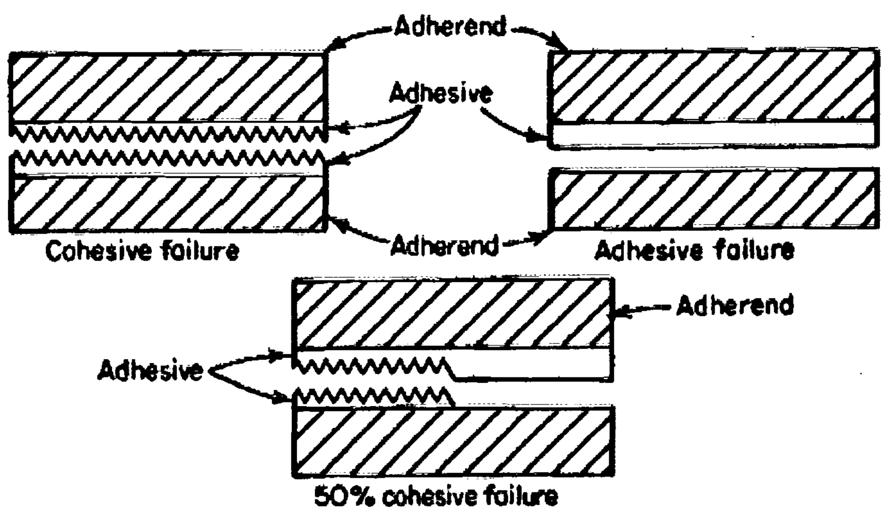


Figure 8 - Cohesive and Adhesive Failures of Bondline

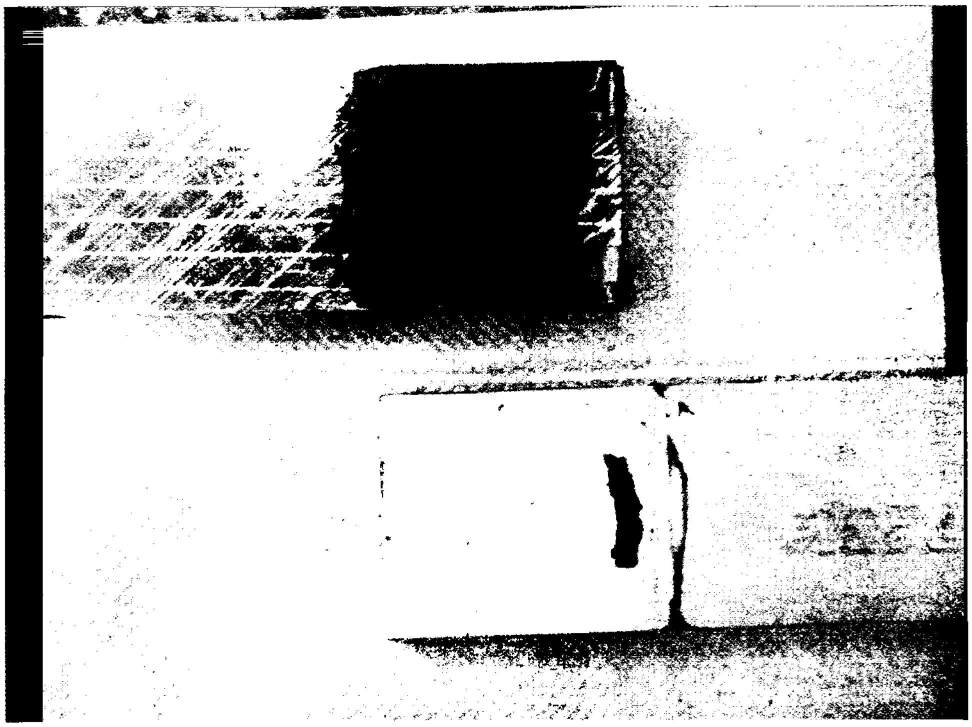


Figure 9 - Adhesive Failures with Aluminum

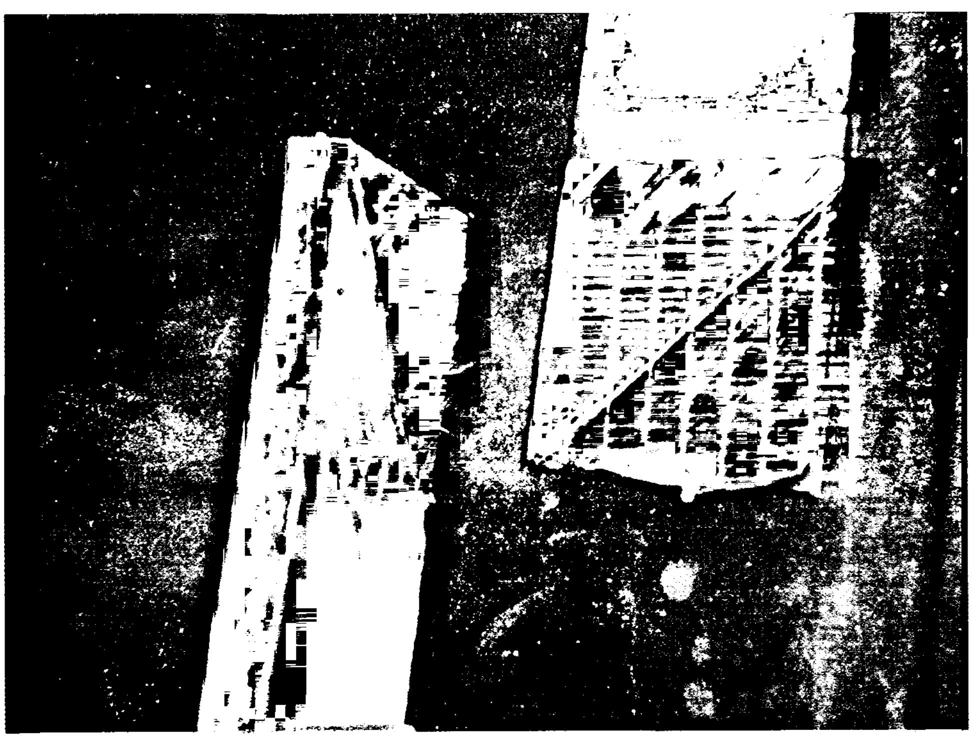


Figure 10 – Adhesive Failures with Composite

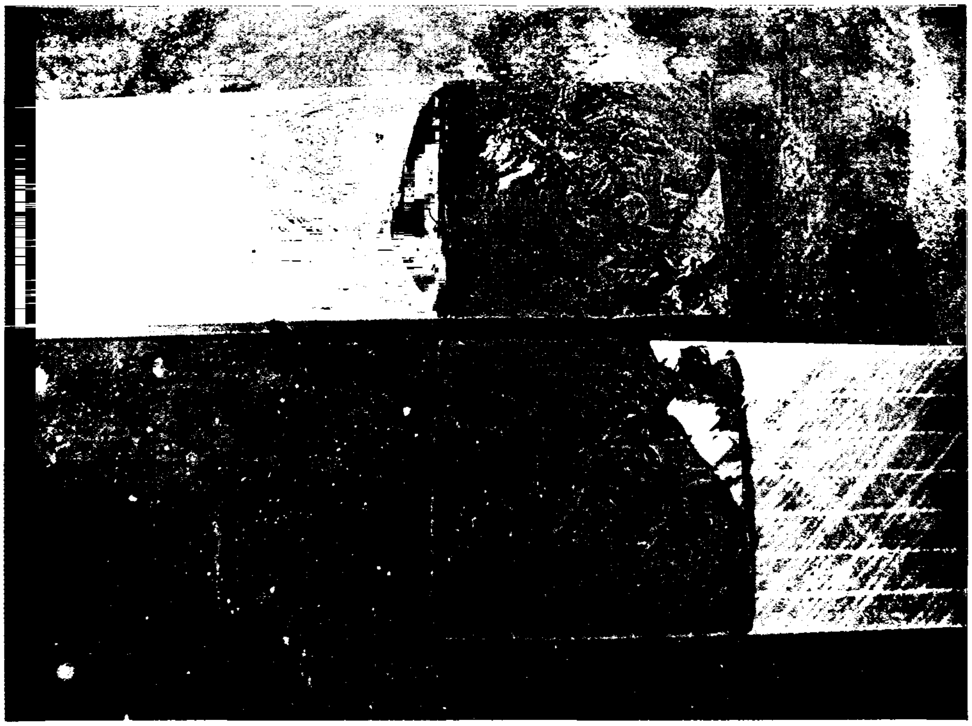


Figure 11 – Cohesive Failures in the Adhesive

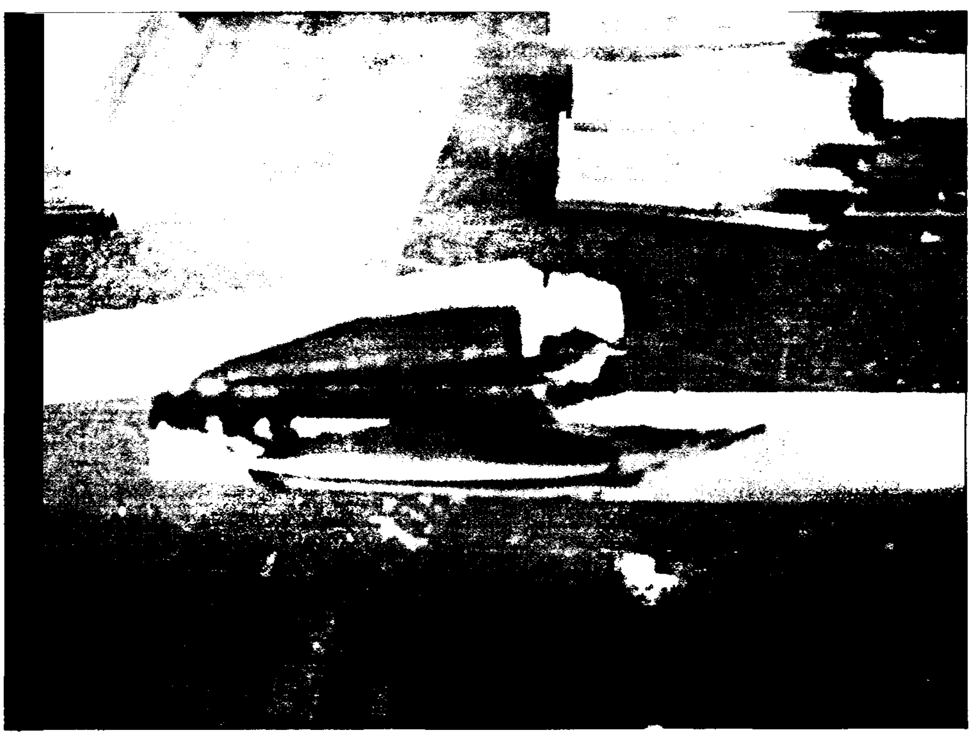


Figure 12 – Substrate Failure in the Composite

1.4 Use of Adhesives in the MACH Project

In 2000, the University of Maine teamed with Pacific Marine (PACMAR) of Honolulu, HI, and Applied Thermal Sciences of Sanford, Maine on the MACH program. These collaborators have undertaken a mission to develop fast efficient surface vessels that use additional underwater bodies attached to a more traditional hull-form. They are working in conjunction with the Navy labs at Carderock, MD (NSWC-CD) and Newport, RI (NUWC) and are funded through ONR. The end goal is to deploy ships where more payload and/or higher speeds can be achieved at little or no additional power consumption and with excellent sea keeping ability. Figure 13 shows one example vessel called the MIDFOIL where a hydrofoil and a parabolic lifting body shape are combined with a catamaran hull to achieve additional buoyancy and dynamic lift which greatly improves the performance and sea-keeping of the vessel. Relatively inexpensive pilot tests on the MIDFOIL and similar vessels have shown that this method has great advantage for fast military support craft and commercial vessels such as ferries. Recent efforts under MACH have shown, on non-optimized structures, that the addition of underwater lifting bodies can dramatically improve speed, reduce fuel consumption and increase payload. These efforts have also demonstrated that composite material can bring about high structural efficiency.

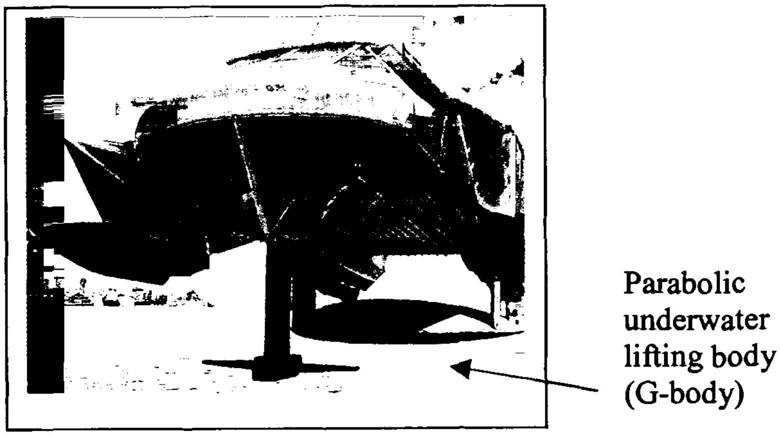


Figure 13 - MIDFOIL Craft with Parabolic Underwater Lifting Body

The MACH concept was developed as a blending of technologies as illustrated in Figure 14. It was based upon work conducted at the University of Maine in support of NASA's X-38 crew return vehicle. The highly complex outer shape of this spacecraft was attained by a system of high-temperature composite panels over a metallic frame. These construction techniques led the University of Maine and Pacific Marine to propose a panelized construction concept for advanced high-speed vessels.

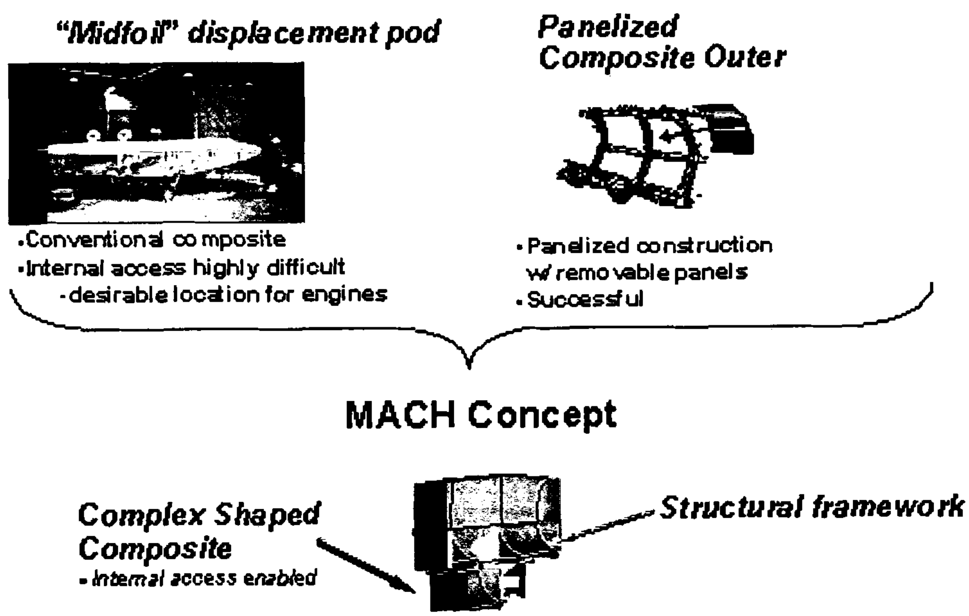


Figure 14 - The MACH Concept as Applied to HYSWAC

The central motivation of the MACH effort is a desire to break out of the restrictions of conventional hull construction techniques and conventional hull forms. Conventional hull construction techniques have limited the ability to build and maintain the complex shapes required for high speed military support vessels in a cost effective manner. The core of MACH effort is to develop hybrid systems consisting of a metallic supporting structure (i.e. framework or central metallic ship hulls section) and composite structural sections (i.e. complex curved panels or complex shaped bow/stern sections). The focus is research on hybrid structural systems where various components are joined together to take advantage of the beneficial properties of each. Therefore, development of hybrid connection technology is one of the primary goals of this effort. In general, the complex shapes required for advanced ship designs will drive the use of composites in construction. The complex shape composite ship sections can have many forms, from composite panels, which simply seal the hull, to complex sections containing transducers for structural monitoring and sonar applications. The emphasis of the proposed project is on the development of hybrid construction and joining systems.

As a case study, researchers are currently attempting to implement the MACH methodology on a newly developed underwater body designed by PACMAR called the HYSWAC. Current plans are that this underwater body will have in its design a place to apply modular composite panels as shown in Figure 15.

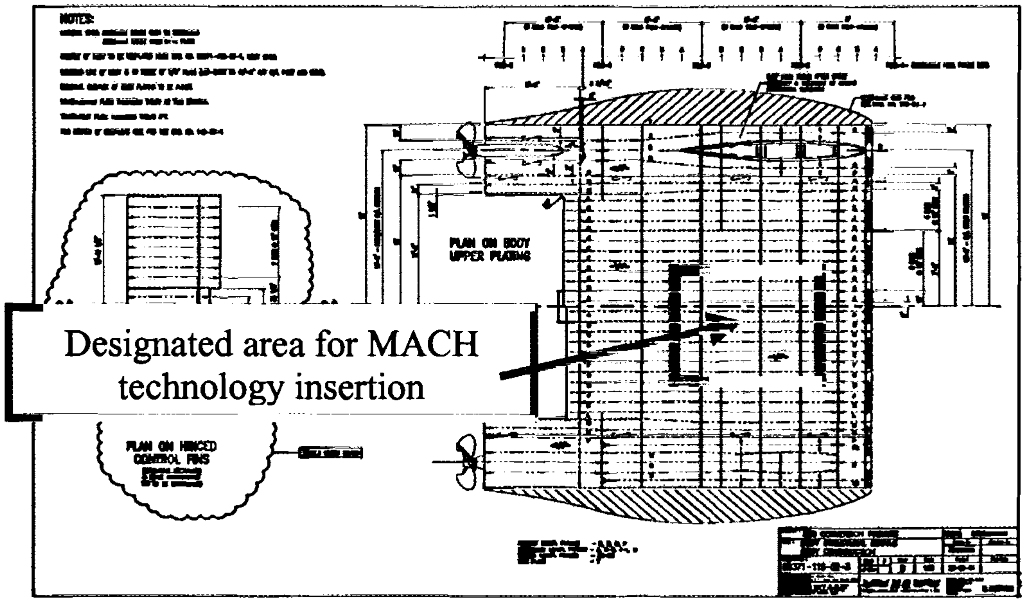


Figure 15 – Dedicated Area for MACH Panel

The base structure of the HYSWAC is aluminum and there are requirements for attaching the MACH panel to the aluminum structure that must be addressed. This leads to requirements for joining the panel to the larger structure. Currently methods of attaching the composite panel to the framework are being resolved.

Various connection concepts including adhesives, mechanical fasteners or a combination of both are being studied under the MACH program. Utilizing an adhesive as a primary or secondary method of joining the panel to the structure provides a means to join complex shapes yet maintain structural integrity.

1.4.1 Panel Joint Design

The MACH effort, having a goal to incorporate panelized composites into the design and construction of underwater ship bodies, directed the effort to analyze joint construction where composites interface with metal substructures. The University of Maine began this effort by constructing and testing several bolted and adhesive bonded joints, as a baseline for their research. To reduce the large stress concentrations that occur in the regions where the bolts penetrate the composite, use of adhesives was attempted. Figure 16 shows a baseline bolted / bonded joint that was constructed by the University of Maine. This subcomponent connection test article includes a ¾" thick E-glass/vinyl ester composite panel connected to a ¾" steel T-section. The composite was bolted on each flange using 6 - ¾" bolts. Influence of the adhesive on connection response is being studied.

As the MACH program advances in design, the effort will be to have a composite panel attach to a metallic substructure of an under water body, with the outer composite face, having a smooth profile.

Figure 16 – Adhesively Bonded and Bolted MACH Test Panel

1.4.2 Adhesive Study Recommendations for the MACH Program

In building a metallic substructure where compound curves are present, there becomes a potential problem with fit-up of a pre-made composite part to the metallic substructure. Because of this, there is a need for an adhesive, which performs well with bondline variations having gaps, which are much higher than those, encountered for aerospace applications and that exceed the bondline thickness for which most adhesives are tested. Therefore, testing is required for adhesives in this application. Furthermore these joints will be required to operate below the waterline and watertight integrity is of paramount importance. Therefore if adhesives are to be used as part of the MACH effort, understanding of the environmental response to water and appropriate temperature is essential.

1.5 AHFID Case Study

As another case study of where adhesives are needed on ship structures, the Advanced Hull Form Inshore Demonstrator (AHFID) program focuses upon the development of a rim drive propulsor (RDP) to be interfaced to the SES-200 ship at Pacific Marine and Supply Company (PACMAR) of Honolulu, HI. Figure 17 shows the RDP attached to the ship via a composite strut in a V-configuration. A subtask of the AHFID program undertaken by the University of Maine is to perform preliminary R&D for a composite strut, and the ship interface to the SES-200. The main structure of the SES-200 is aluminum, therefore a hybrid metal / composite connection is required at the ship to strut interface. The adhesive study presented is directly relevant to the composite strut subtask.

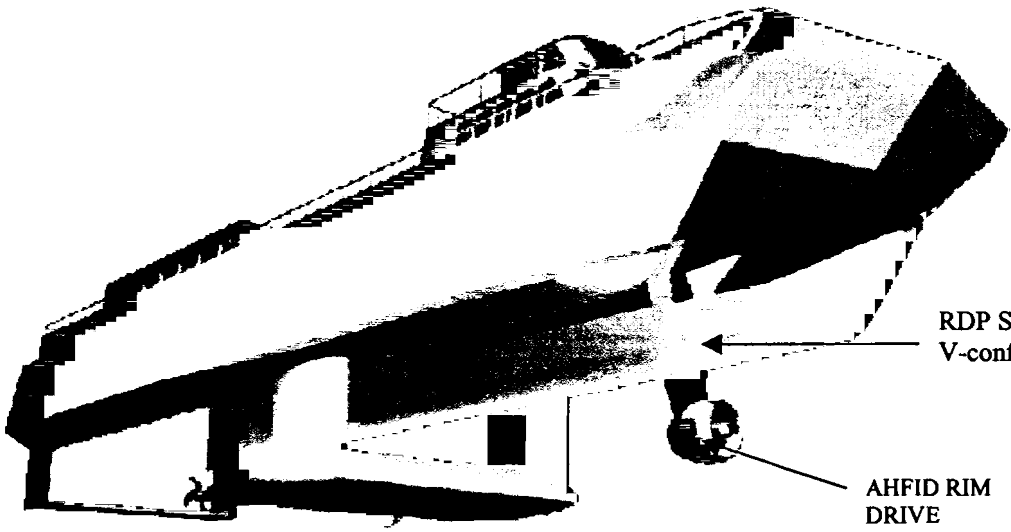


Figure 17 -SES 200 with AHFID Rim Drive

Composite strut technology for structures such as the RDP is not well proven. Therefore, prior to implementation of a composite strut for systems such as the RDP, full scale proof concept testing is imperative. This full scale test is planned for the University of Maine, Boardman Laboratory on a single cantilevered strut configuration, with the strut mounted vertically in the Boardman Hall reaction frame (Figure 18). The strut / ship interface consists of an aluminum boot, as designed by Electric Boat. Sprecace [2001] provides a preliminary analysis of the strut system subject to shiploads. The strut structure in the V-configuration will transfer loads acting primarily as a cantilever beam in the thrust direction, and as a beam/truss in the lateral direction. A primary consideration in the strut design is the connection between the composite strut, a metallic boot, and the ship.

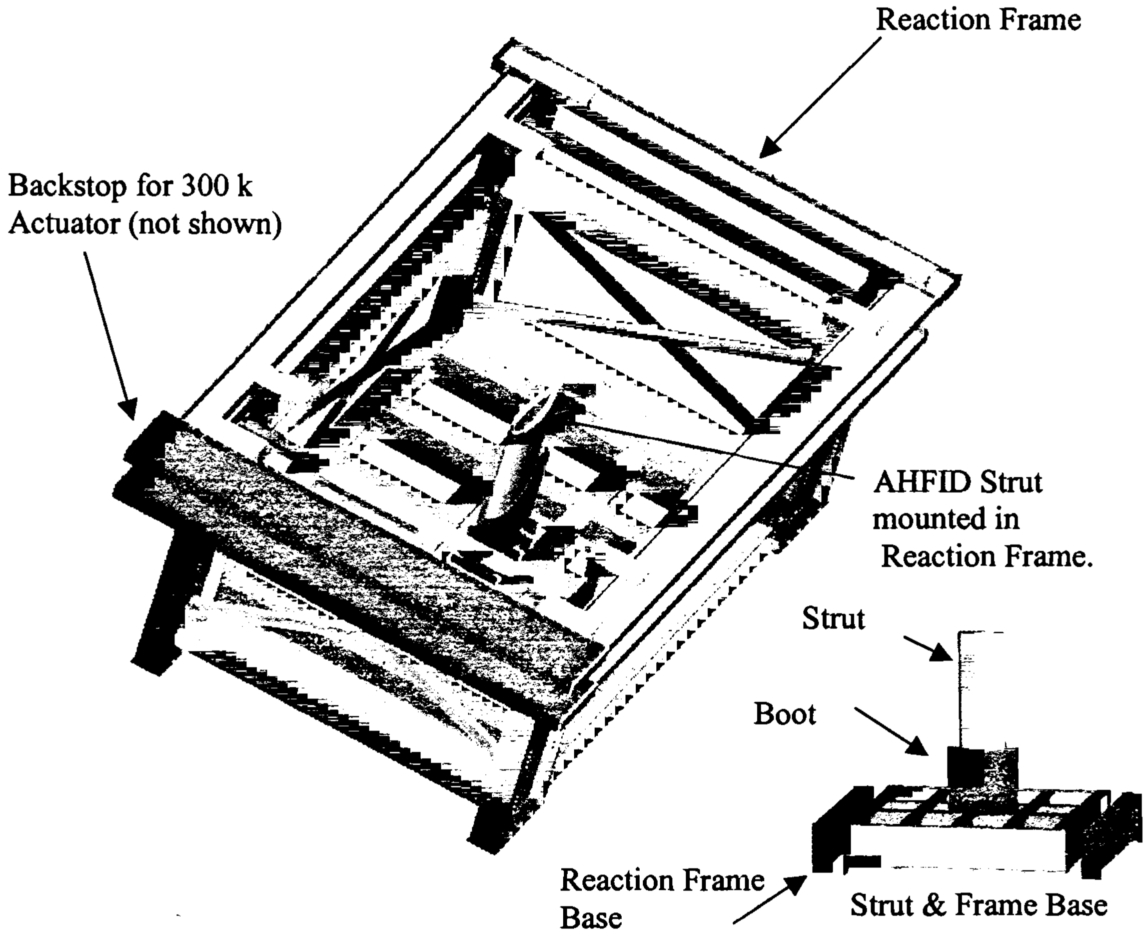


Figure 18 – View of AHFID Strut Mounted in Reaction Frame

1.5.1 Strut Design

The RDP attachment structure has, as a goal, the design of a strut to minimize the cross section for hydrodynamic effects, while permitting adequate space within the strut to house the power cables for the RDP. This necessitates a strut with cavities for clearance and a thick shell with adequate strength for transferring loads to the ship structure. Figure 19 shows the baseline strut cross-section.

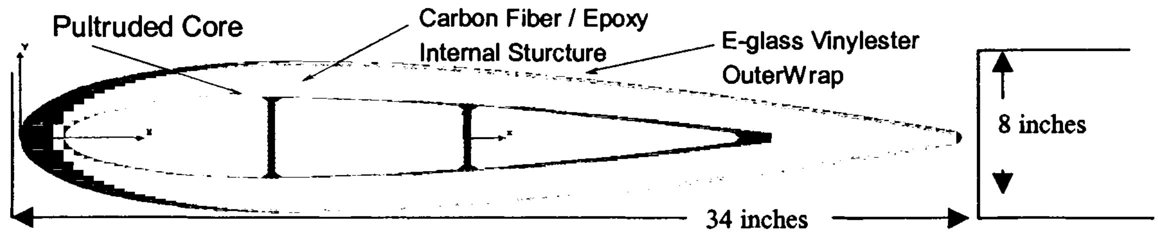


Figure 19 – Cross Section View of Strut

The majority of the composite strut volume, which constitutes the primary structural element, is carbon/epoxy. The layers of carbon fiber/epoxy were filament wound about the outer surface of a pultruded E-glass/epoxy core that is approximately .375" thick. The center core acts as a bulkhead creating the necessary internal cavities and as a mandrel for the filament wound carbon fiber structural material.

Since the goal of the strut design was to be as stiff as possible in longitudinal bending, the desired orientation would require unidirectional fibers to be placed along the length of the strut. However, the filament winding process was limited to a sequence of $[10^{\circ}/-10^{\circ}]_{NS}$. The last few passes during winding applied purely hoop (or $90^{\circ})_N$) piles for compaction. The carbon fiber layer was machined to a NACA 0024 profile, leaving a wall thickness of approximately 1.550" at the maximum strut thickness. The strut was subsequently wrapped with a filament wound E-glass vinyl ester wrap for surface protection. The lay-up sequence for the outer wrap was $[45^{\circ}/-45^{\circ}/90^{\circ}]_{NS}$ and the thickness was .300". It is this outer layer that will be adhesively bonded to the metallic boot interface. Figure 20 shows the strut prior to machining the carbon fiber wrap.

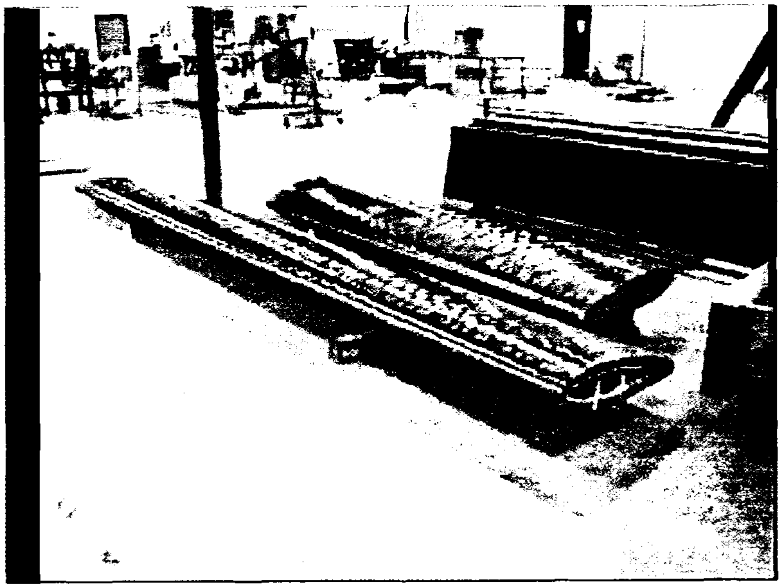


Figure 20 – Filament Wound Strut after CF Winding Prior to Machining

1.5.2 Boot Connection

The current ship/strut connection design concept relies on a metallic boot to be adhesively bonded to the strut. The assembly will be mechanically fastened to the ship's hull. Electric Boat [Sprecace, 2001] who supplied fabrication drawings for the boot performed the interface design. Figure 21 shows an exploded view of the metallic boot connector at the vertical bolted joint. Dimensions specified for fabrication are shown in Figure 22 and are given in US customary units (inches). The boot consists of two parts made of 6061 - T6 aluminum. The inner sections are made of four sheets of 1" thick aluminum, which has been roll, formed to the outer shape of the strut. The upper 36" of the strut/boot are where the boot will attach to the ship structure or in the case of the laboratory test, to the reaction frame. The lower 36 inches are for stiffness tapering. To increase surface area at the adhesive bond, machined grooves ½" wide and .050" deep, are cut into the plates on 2" spacing. The quarter sections are then welded to form the two half sections shown. The outer frame work which acts as a stiffener and provides for bolting at the horizontal joint are fabricated from 1" x 4" 6061 T6 aluminum flat bar.

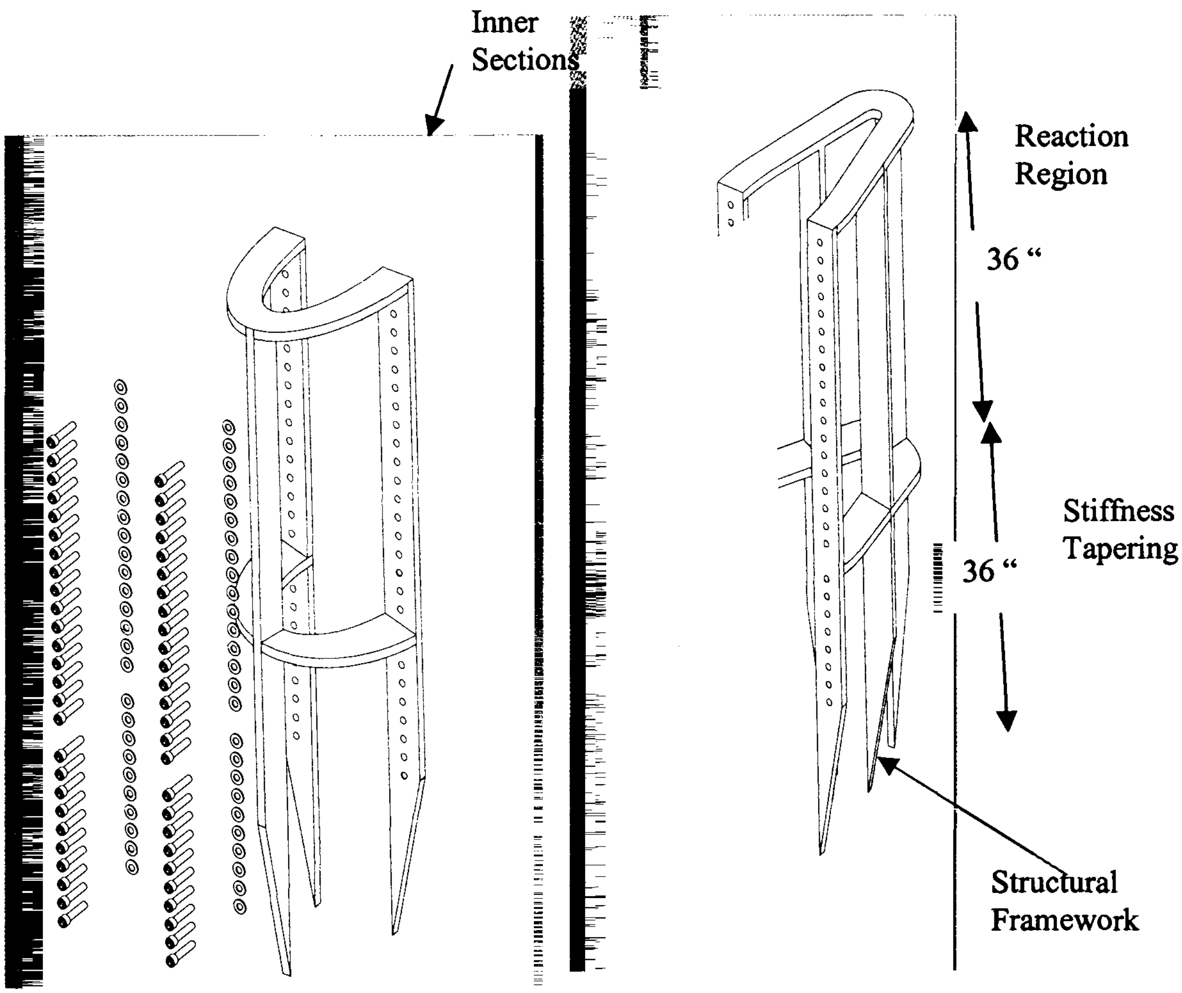
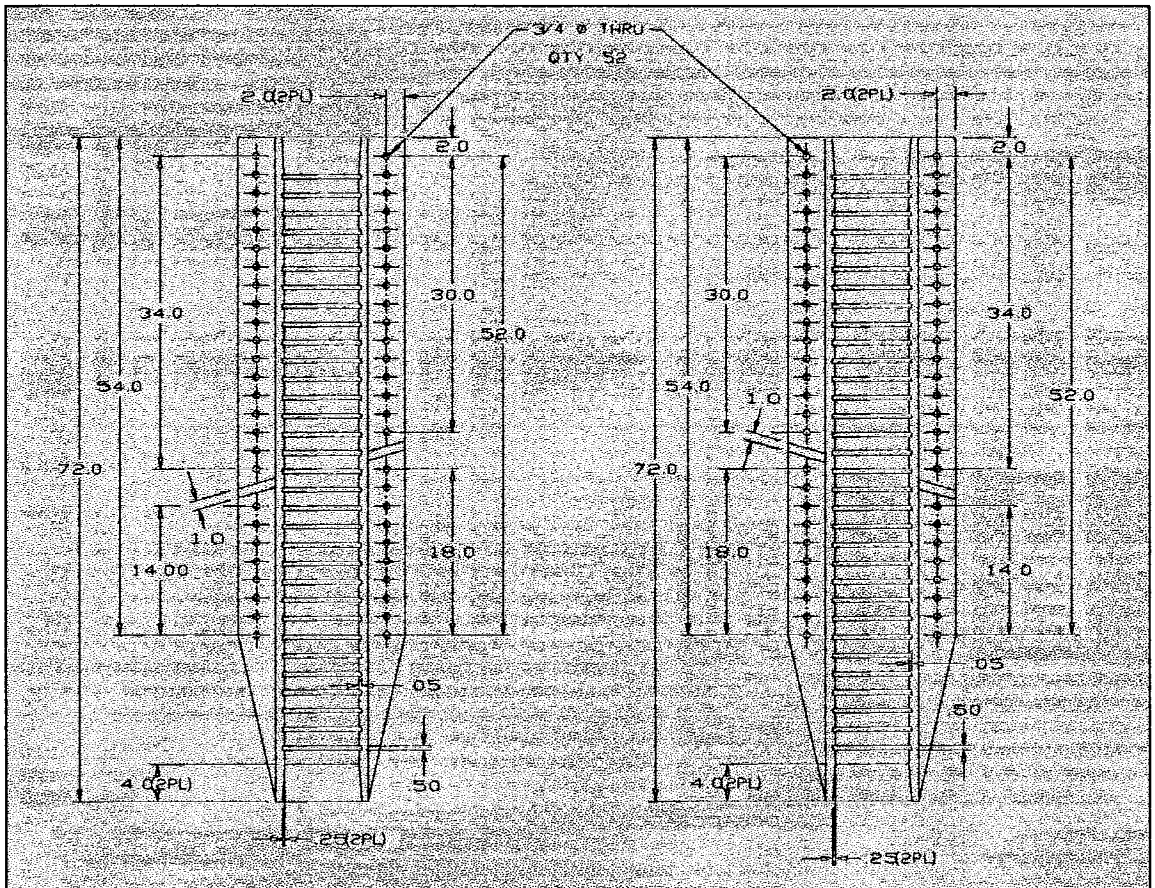


Figure 21 – Exploded View of Boot Fabrication Drawings as Supplied by Electric Boat [Sprecace 2001]



Note: All dimensions are given in inches.

Figure 22 – Boot Fabrication Dimensions

This fabrication process is labor intensive and the amount of welding required, causes distortion of the parts during manufacturing. This distortion leads to increased gaps and a subsequent relaxing of the adhesive joint tolerances is required if the boot is to be made cost-effectively. Figure 23 shows the boot during the fabrication process. At this stage the stiffeners are being cut to size and welded at the specified location.

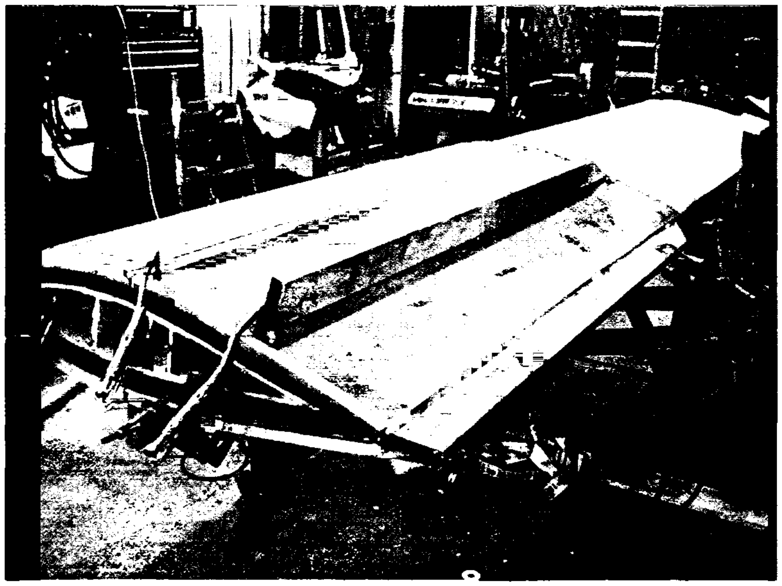


Figure 23 – Strut with GRP Over Wrap – During Boot Fabrication

1.5.3 Installation of Boot & Test Article

Installation of the AHFID boot into the reaction frame located in Boardman Hall required welding attachment points to the AHFID boot. These attachment points allow bolting of the upper boot to the reaction frame. Figure 24 shows the welding process during installation of the attachment points.

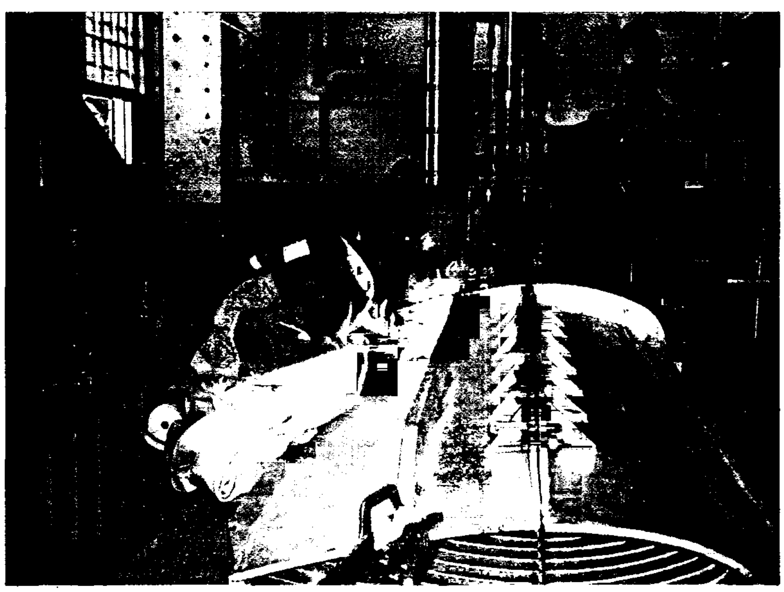


Figure 24 – Installation of AHFID Boot Interface Structure

1.5.4 Adhesive Study Recommendations for the AHFID Program

From inspection, bondline variations from touching to 0.375" gaps were realized at the adhesive joint due to the fabrication process for both the metallic boot and the AHFID composite strut. The larger gaps are located both fore and aft on the strut profile. These gaps are much higher than those realized in aerospace applications and exceed those for which most adhesives are tested. According to the manufacturer of the boot, having the bolted joint at the half cord requires the boot to be made in four sections with welding required both fore and aft. This leads to heat distortion causing deviation in profile and increasing the bondline thickness.

Figure 25 shows an end view of the boot assembly prior to bolting at the horizontal flange. This figure shows the gap between the strut and the boot at this location where the bondline was deemed to be the maximum. Stiffener plates were added to the bolting flanges because flexing of the bolting flange would occur during bolt up. With these gaps exceeding gaps analyzed by adhesive manufacturers, and it was advised that adhesive testing be performed to quantify adhesive bonding properties.

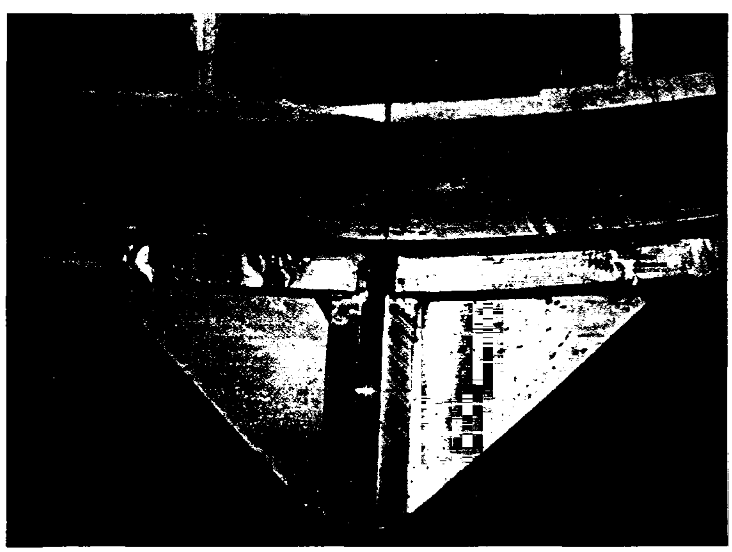


Figure 25 – Strut with Aluminum Boot Showing Bondline Thickness

1.6 Need for Adhesive Studies in Marine Applications

The marine industry has its own particular issues that must be addressed when considering use of structural adhesives. Because ships are relatively large structures, bondline thicknesses tend to become greater than those found in automotive or aircraft industries. With advanced hull forms, there are complex shapes that need to be considered and many issues with regard to connections that need to be resolved. These structures will be subjected to complex load in an environment that is mostly comprised of water. All these variables increase the complexity when designing a joint.

In order to build joints with high integrity, technology must provide shipyards with practical, inexpensive procedures for joint construction. Variables such as surface preparation need to be tailored so that they are relatively simple for shipyard personnel to implement. If such variables are perfected, the ability to produce a joint that is watertight will result.

2. Test Article Geometry and Test Description

Lap joints were tested using various adhesives, varying bondline thickness, surface preparation, and under room temperature and hot wet conditions, in order to quantify the adhesive properties associated with these parameters. Joint geometries studied were selected because they expose the adhesive being tested to a complex stress state. By testing the adhesives in a complex stress state, it provides a faster means to narrow the adhesive selection for various complex stress joint configurations. Subcomponent representations of these joints were tested in single lap tensile shear, double lap tensile shear, and flexure as described in the remainder of this section.

2.1 Single Lap Tensile Shear Test

Adhesive testing consisted of adhesively bonded hybrid joints made of aluminum and E-glass/vinyl ester adherends. Determination of test article geometry for the tensile single lap shear test is an important first step in the adhesive study. The geometric sizing should be such to avoid the adherends failing during the tests. It is undesirable to exceed the yield point of the metal or material limit of the composite adherends. To prevent this type of failure the permissible length of overlap in the specimen will vary with thickness and type of material, and on the general level of strength of the adhesive investigated. The maximum permissible length may be computed from the following relationship:

$$L = F_{ty} * t / \tau$$

L = length of overlap, in.,

t = thickness of material, in

F_{ty} = yield point of material (or stress at proportional limit), (psi.)

τ = 150 percent of the estimated average shear strength in adhesive bond, (psi.)

This calculation is discussed in detail in ASTM D 1002. To ensure that the material limit was not exceeded both the aluminum and the composite were analyzed for recommended overlap. Using yield strength of aluminum of 40,000 psi, a panel thickness of 0.375", and an adhesive shear strength of 4500 psi. It was determined that the maximum amount of overlap would be. 2.2" if the metal controls. Composite material strength of 51800 psi was used, with the same adhesive shear strength and panel thickness. This resulted in a maximum overlap of 2.849". For simplicity an overlap of 2" was used in these tests resulting in a 2" x 2" bond area.

To ensure proper grip area for the test specimens a length of nine inches long was selected. This would allow for 2 ½" at each end to be gripped by the test machine.

2.1.1 Single Lap Joint Geometry

The single lap joint consists of a 9" x 2" x 0.375" thick rectangular aluminum plate bonded to a 9" x 2" x 0.375" thick rectangular composite panel as shown in Figure 26. Bondline thickness is a parameter in this study and varies from 0.060" to 0.250".

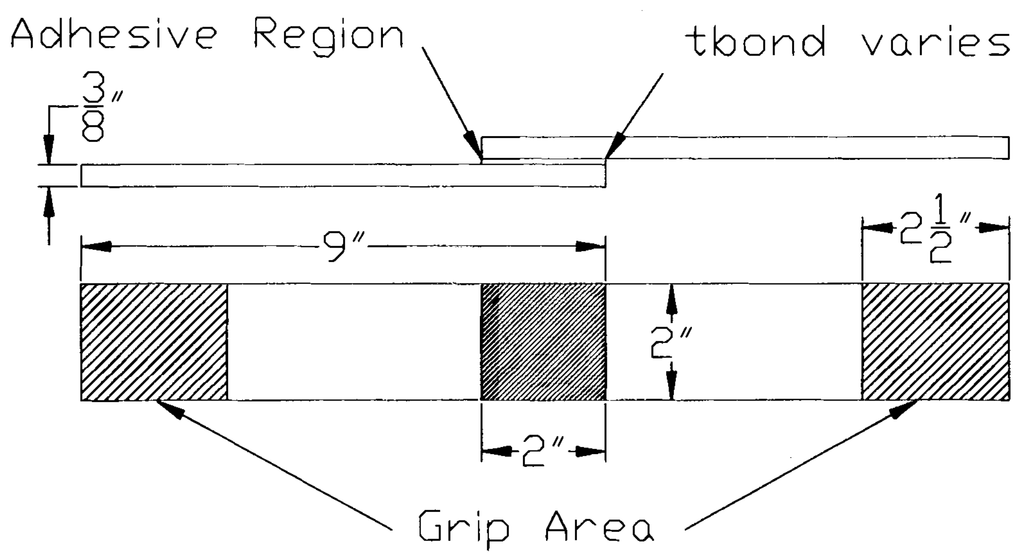


Figure 26 – Single Tensile Shear Lap Joint Geometry

2.1.2 Finite Element Analysis of Single-Lap Joint

A finite element analysis was performed to study the structural response of the single-lap shear test articles. The focus of this analysis was to investigate the deformation and combination of stresses that occurs during single lap shear tests. In doing so a linear quasi- isotropic model of the E-glass composite, 6061-T6 aluminum, and Loctite 9359.3 adhesive were constructed as a first cut estimate of the response. Furthermore fixtures were designed and instrumentation was placed based upon results of these models.

2.1.2.1 Description of Linear FEA Model

An isotropic, linear, two dimensional model was constructed for the single lap tensile shear specimen. This model consisted of 1794 nodes and 765 elements as shown in Figure 27. Two-dimensional plane stress elements where used for both the adhesive and the adherends. A unit thickness of 1 inch was used in the model. The model was divided into three groups, each specific to a material used in the model. Material properties as presented in Table 1, were acquired from various sources. For the E-glass adherend, properties were calculated using CompositePro ™ software. The software calculated the properties of the lay-up used ($[(+45/-45,0/90)_3]_S$) in the testing, given a 60% fiber volume content. The properties for the aluminum where found in a metals handbook and where checked against properties specified in the Algor ™ software, material database. Loctite supplied effective properties for the 9359.3 adhesive.

Table 1 – Material Properties Used in FEA Analysis

	Adhesive (Loctite 9359.3)	Composite	Aluminum
Tensile Modulus	330×10^3 psi	6.48×10^6 psi	9.9×10^6 psi
Shear Modulus	132×10^3 psi	5.94×10^5 psi	3.7×10^6 psi
Poisson Ratio	0.25	0.25	0.33

In the finite element model shown in Figure 27, the composite adherend is located on the right side and the aluminum adherend is located on the left. Meshing was performed using quad plane stress elements with a rectangular shape. At the location of the adhesive/adherend interface a total of 25 elements where used along the contact surface. The thickness of the adhesive was divided into increments of 0.010" resulting in 6, 10, and 25 elements thru the thickness for bondlines of 0.060", 0.100", and 0.250" respectively. Loading in the model was applied to the aluminum adherend. A force of 20 lbs was applied at each node along the edge where the tab is bonded to the aluminum adherend resulting in a total force of 1000 lbs over the unit thickness. Clamped boundary conditions where applied to the end of the composite adherend. No translations were allowed.

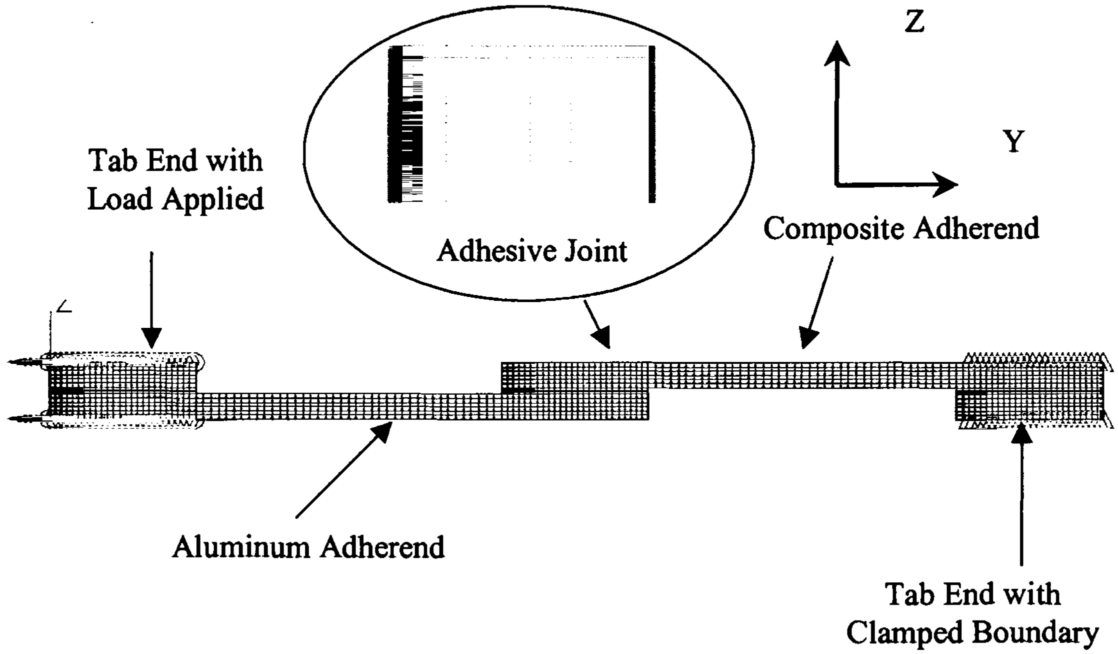


Figure 27 – FEA Model Layout

2.1.2.2 Deformation in Joint

Figure 28 shows the displaced shape of the specimen as predicted by the finite element analysis. It was observed that the out of plane deflection of the composite specimen is greater than the out of plane deflection of the aluminum adherend. This finite element model was analyzed, paying specific attention to instrumentation placement as shown in Figure 29. Instrumentation was placed at key locations, indicated by La, Lc, A and B in Figure 29. Values for in plane and out of plane movement and relative "y" displacement of A to B are given in Table 2 and correspond to instrumented locations used in the testing. These values are also used to determine the in plane stiffness and out of plane stiffness for each adhesive tested.

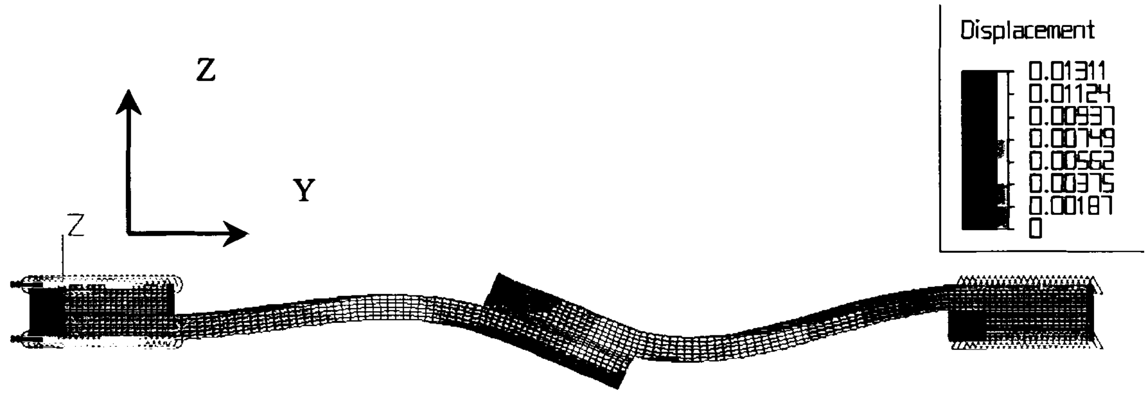


Figure 28 – FEA Analysis of Lap Joint Geometry

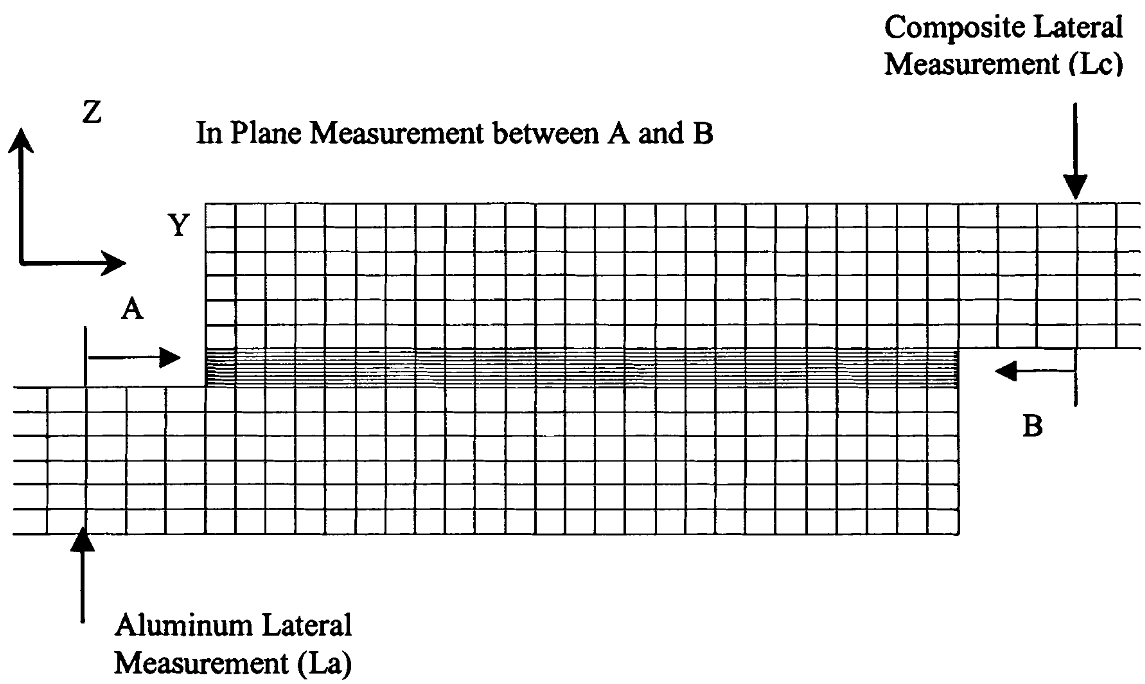


Figure 29 – Instrumentation / Fixture Locations

To understand the strain state, plots of maximum principle strain, in plane strain (ε_y), and out of plane strain (ε_z) are shown in Figures 30 through 32, respectively. These contour plots show that the major components of strain are concentrated in the adhesive located at the ends of the bonded joint.

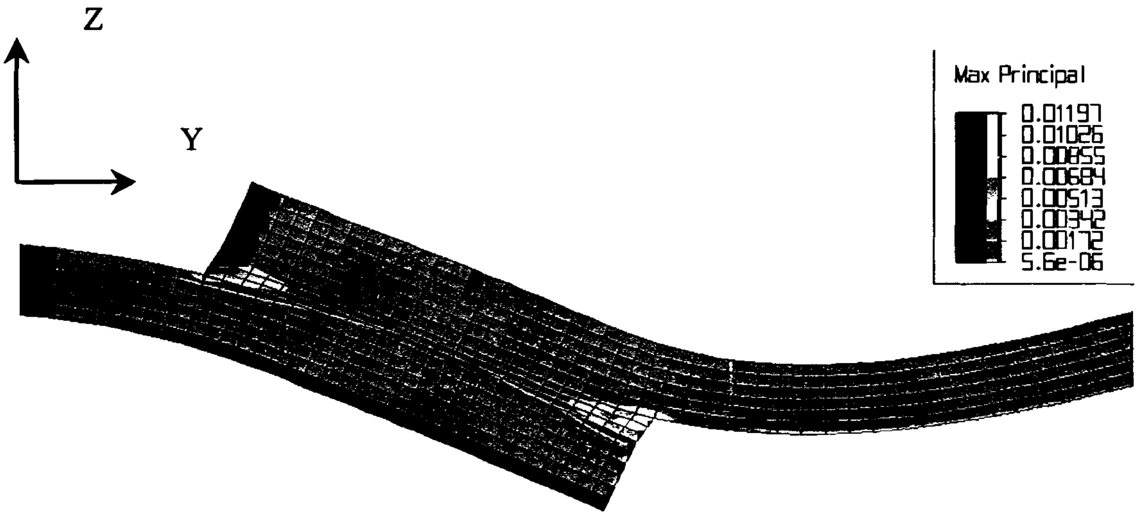


Figure 30 – Maximum Principle Strain of Single Lap Shear Bond

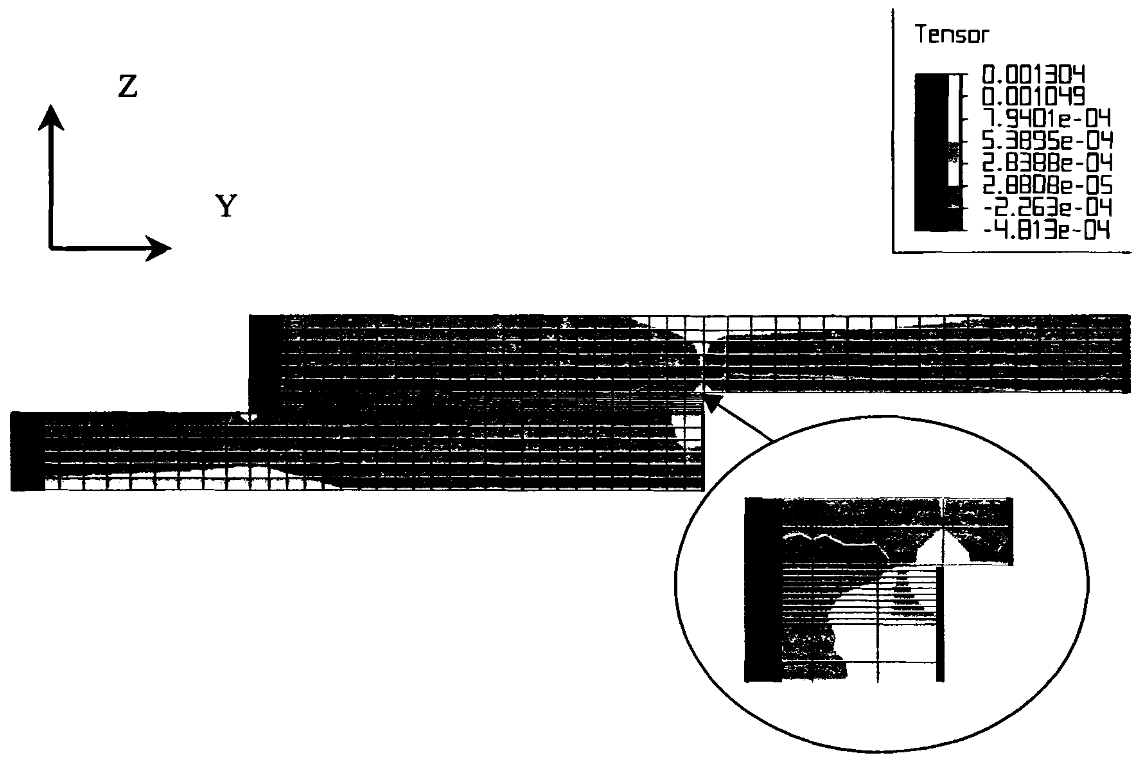


Figure 31 – Out of Plane Strain (ε_z)

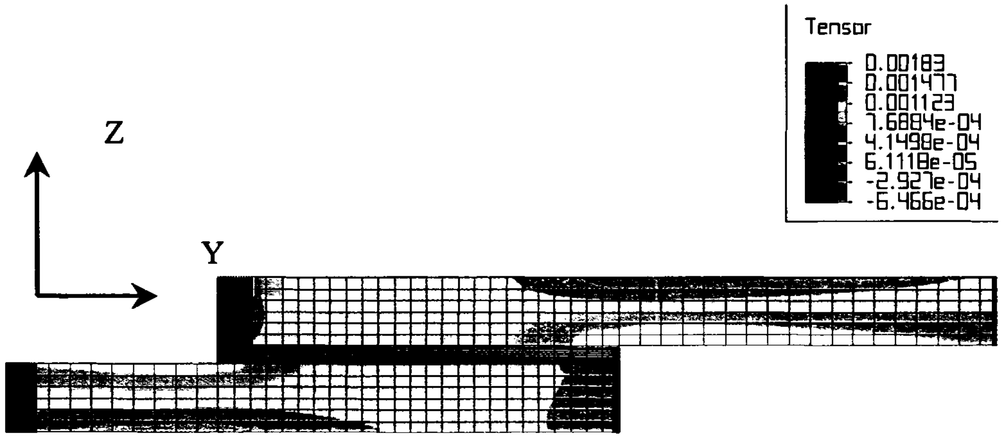


Figure 32 – In Plane Strain (ε_y)

2.1.2.3 Effect of Tensile Modulus

The tensile modulus for the adhesives in this test varied from adhesive to adhesive. In order to understand how this change in modulus affected adhesive performance, finite element models were run with the adhesive tensile modulus as a parameter, which changed by an order of magnitude smaller and an order of magnitude larger than the baseline Loctite modulus. With the change in modulus, it was noted that the stress changed by less than ¾ of one percent when measured at high stress areas. As shown in Table 2 the maximum strain was affected more than the maximum stress due to changes in the modulus. Also shown in Table 2 are the relative in plane movement across the joint, the out of plane movement of the aluminum and the composite, and the maximum displacement of the specimen.

Table 2 – Effects of Adhesive Tensile Modulus

Adhesive Tensile Modulus Comparison										
Tensile Modulus (psi)	Displacement (in)				Max Stress (psi)			Max Strain (in)		
	Max	La	Lc	Relative A-B	σ_{yy}	σ_{zz}	σ_{yz}	ϵ_{yy}	ϵ_{zz}	ϵ_{yz}
33,000	0.0146	0.00319	0.01206	0.00318	12014	3911	1280	0.0028	0.034	0.003
330,000	0.013	0.00324	0.01147	0.00276	11920	3879	1275	0.0018	0.007	0.004
3,300,000	0.0124	0.00313	0.01117	0.00255	11869	4557	1428	0.0018	0.001	0.005

2.1.2.4 Stresses in Joint

When looking at the stress, the desire was to determine the value of peel stress relative to the in plane stress. The peel stress is defined as the stress orthogonal to the adhesive interface, σ_{zz}. Figure 33 – 35 shows the transverse peel stress (σ_{zz}), the normal stress (σ_{yy}), and the shear stress (τ_{yz}), respectively. The value of shear stress is the stress induced from the racking of the adhesive along the joint. To understand how the stress is distributed across the joint and through the adhesive, values of the stresses were analyzed in the adhesive at the centerline of the adhesive, at the interface of the adhesive to the composite, and across the adhesive at the composite end of the joint. Figures 36-38 give a graphical representation of the stress distribution respectively across the joint. Computed in the finite element model as shown in Figure 36, Shigley [2001] also includes the theoretical shear stress as defined by Volkersen [1938]. The theoretical shear stress was calculated from the following:

$$\omega = ((G/h)((1/E_o t_o)+(2/E_i t_i)))^{1/2} \qquad \text{Eq. (1)}$$

$$\tau = (P\omega / (4b\sinh(\omega L/2)))\cosh(\omega x) + [(P\omega/(4b\sinh(\omega L/2)))(2E_o t_o - E_i t_i / 2E_o t_o - E_i t_i)]\sinh(\omega x) \qquad \text{Eq. (2)}$$

The variables used for these equations are: E_o and E_i are the tensile moduli of the two adherends respectively, t_o and t_i are the thicknesses of each adherend, P is the load applied to the specimen, L is the length of the bond, h is the thickness of the adhesive, G is the shear modulus of the adhesive, b is the width of the bond, and ω is a parameter defined by geometry and the ratio of material stiffness.

Analysis of Figures 33 – 38 indicates that failure will most likely initiate at the adhesive bond ends.

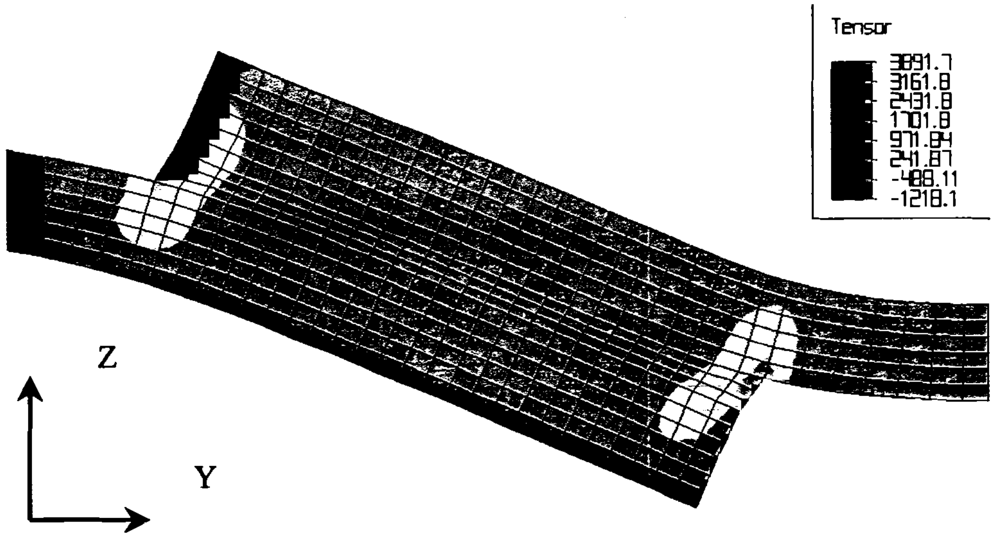


Figure 33 – Stress Tensor Component (σ_{zz})

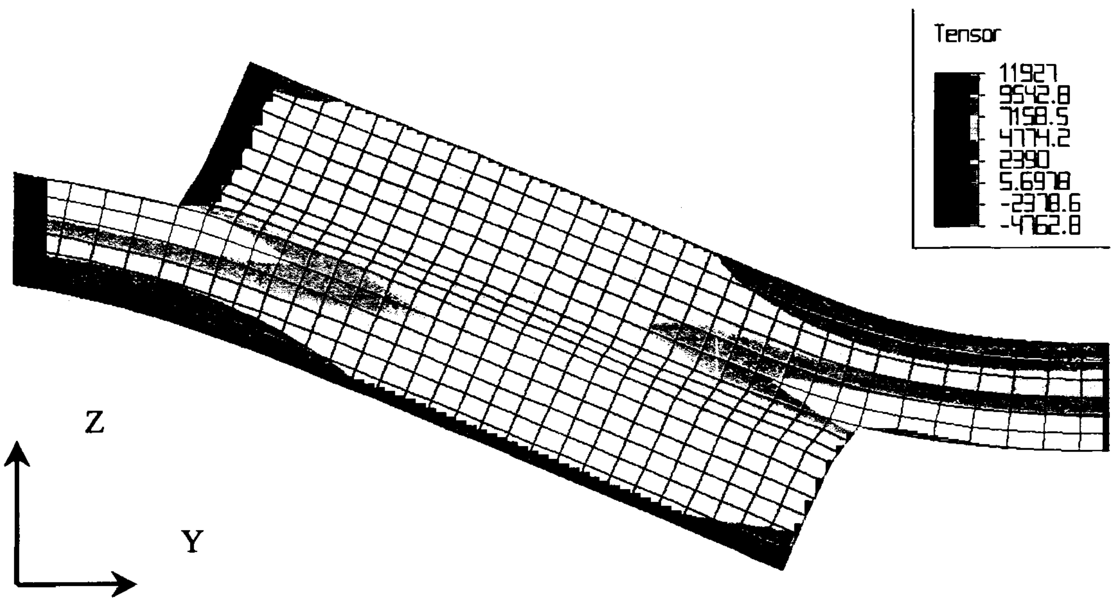


Figure 34 – Stress Tensor Component (σ_{yy})

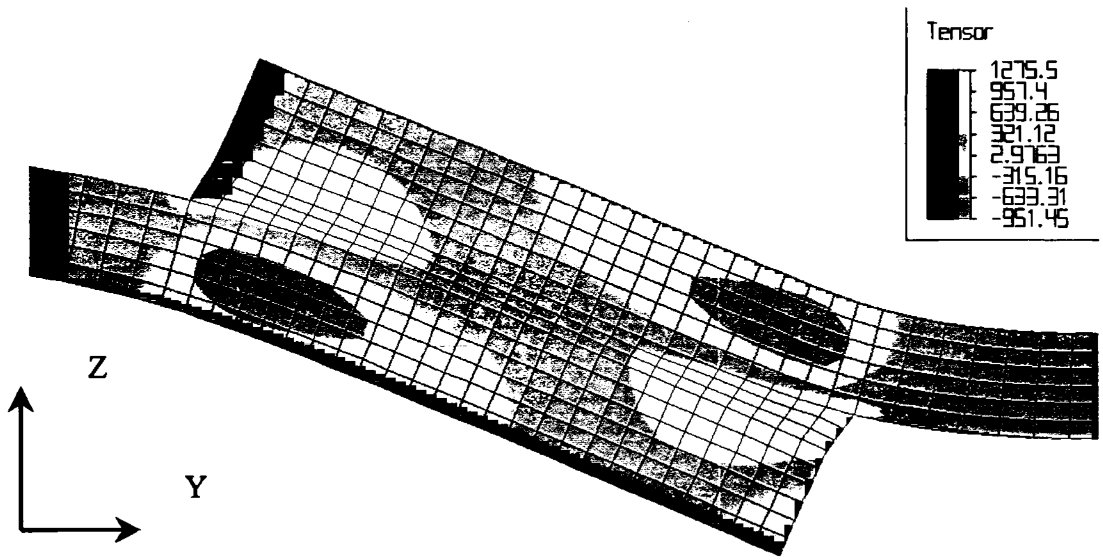


Figure 35 – Stress Tensor Component (τ_{yz})

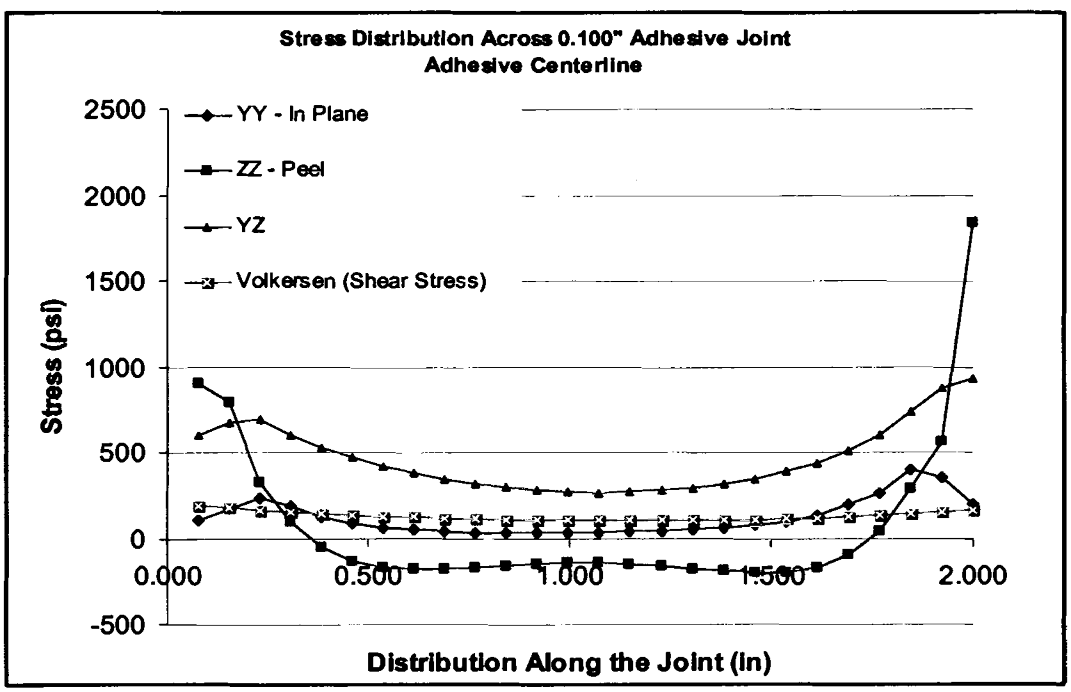


Figure 36 – Stress Distribution Along Joint (Adhesive Centerline)

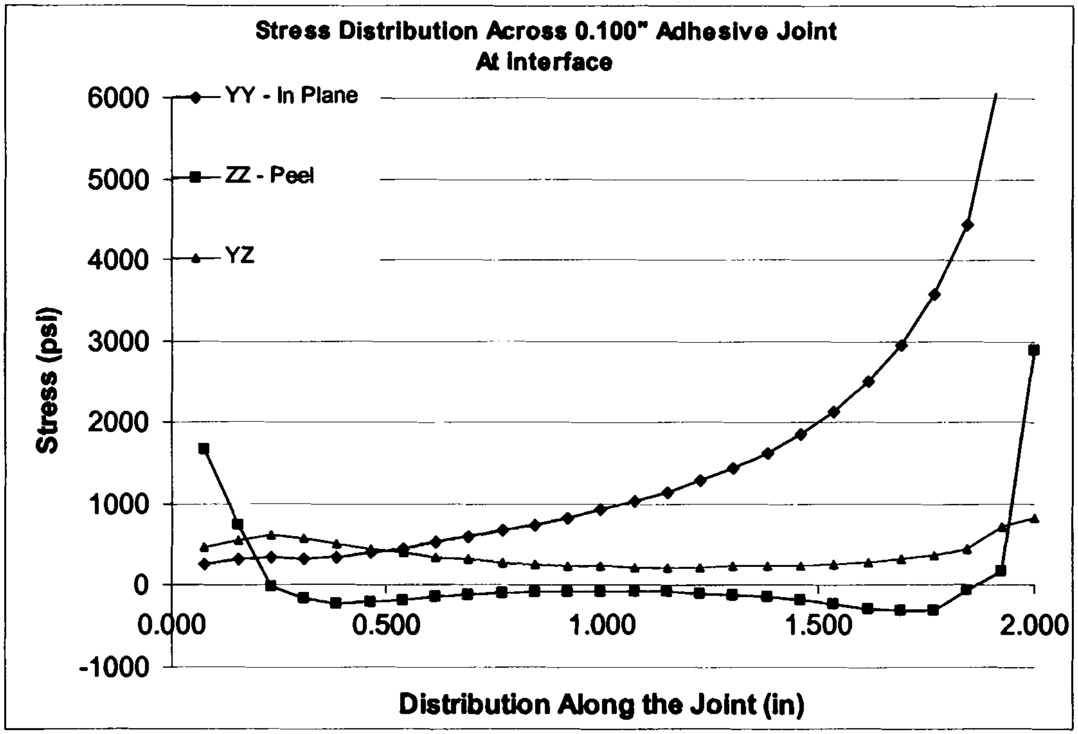


Figure 37 – Stress Distribution Along Adhesive to Composite Interface

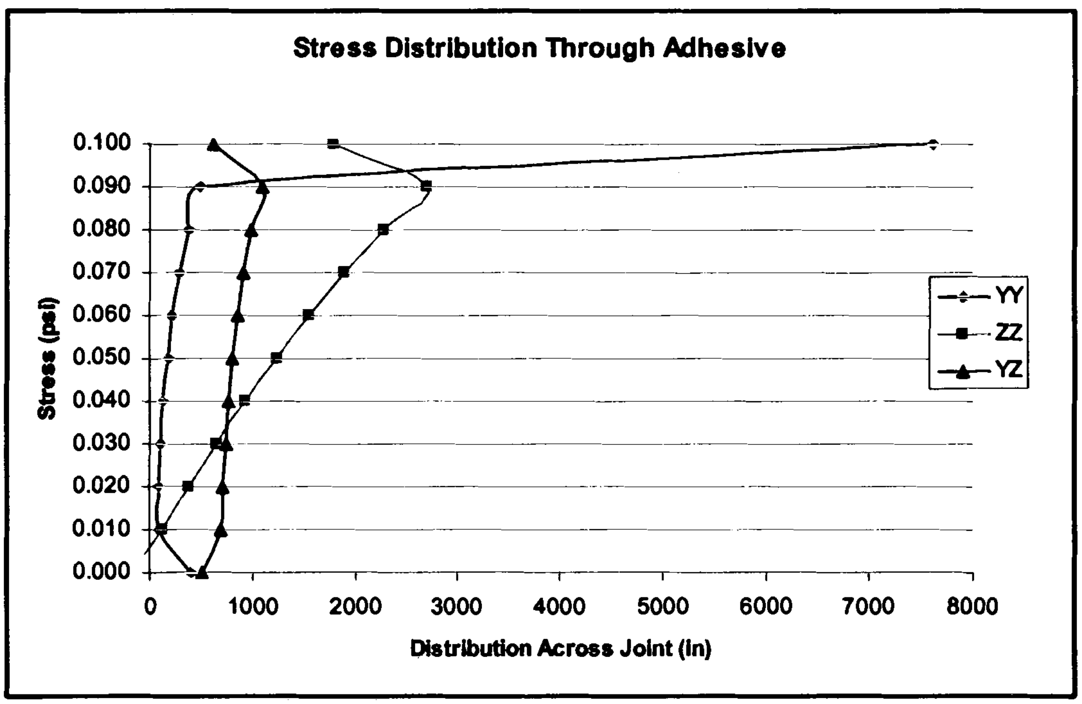


Figure 38 – Stress Distribution through Adhesive (Composite End)

2.1.2.5 Effects of Bondline Thickness

The relationship of stress, strain, and displacement, relative to bondline thickness was investigated by creating two additional models with a bondline of 0.060" and 0.250". Table 3 shows the values for peel stress, in plane stress, and shear stress for each bondline thickness. Peel stress is defined as the value of σ_{zz} along the baseline. These values are shown graphically in Figure 40. Values were tabulated for a point located one element away for the composite/adhesive interface as shown in Figure 39.

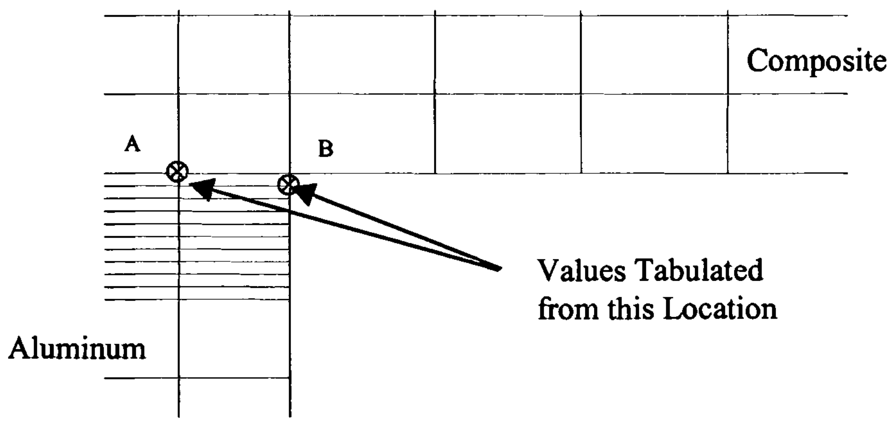


Figure 39 – Tabulation Point

Table 3 – Tabulated Values of Stress - Varying Bondline Thicknesses

STRESS	0.060" Point A	0.060" Point B	0.100" Point A	0.100" Point B	0.250" Point A	0.250" Point B
σ_{zz} – Peel (psi)	448	2426	415	2699	595	3472
σ_{yy} – In Plane (psi)	4697	461	5050	501	6242	632
τ_{yz} – Shear (psi)	677	1221	603	1097	544	1061

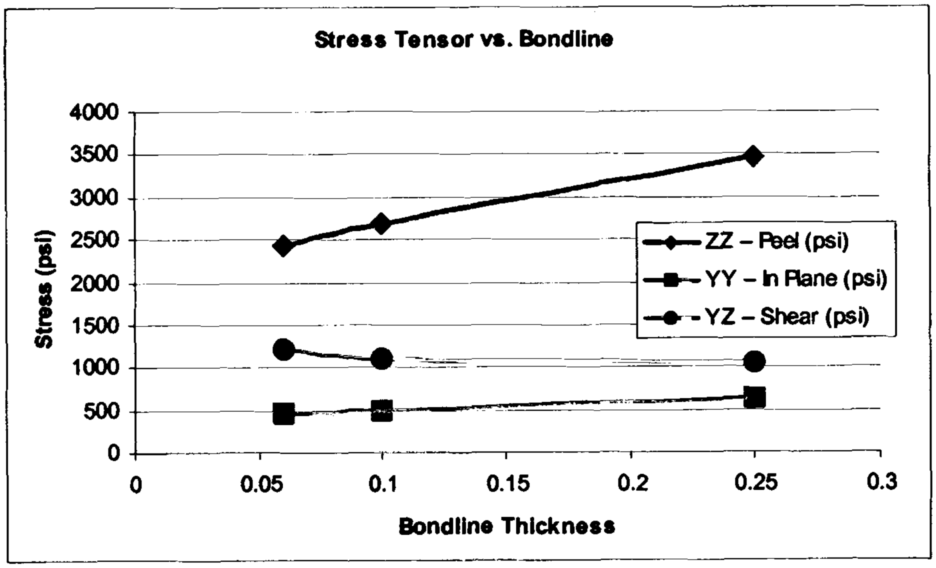


Figure 40 – Stress Tensor vs. Bondline Thickness (Composite to Adhesive Interface)

2.1.3 Double Lap Shear Joint Geometry

The double lap shear joint consist of a rectangular aluminum plate bonded to two rectangular composite panels. As shown in Figure , the dimensions for both the aluminum plate and the composite plate are the same as used in the single lap joint. Bondline thickness was not varied at this stage of testing. All bondlines will be 0.100". The inner gap between the outer adherends will vary. Smaller gaps will help minimize the peel stresses induced by the geometry. As the inner gap is changed the composite adherends will be cut to length to ensure a 2" bond area at the aluminum interface.

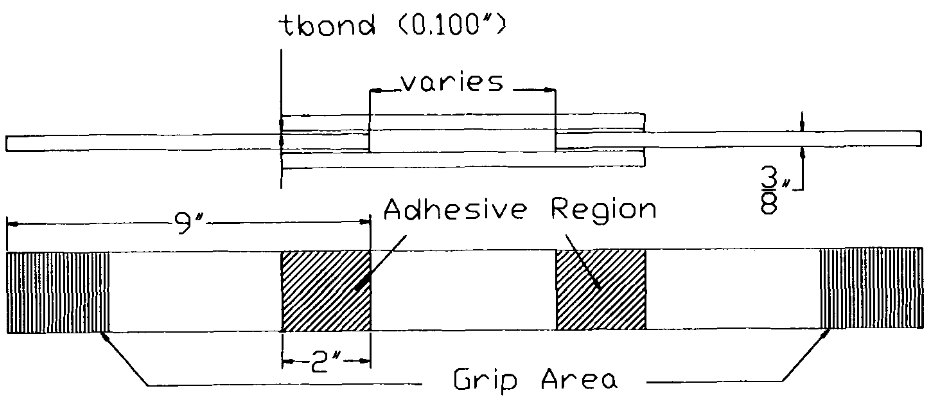


Figure 41 - Double Lap Shear Joint Geometry

To provide an understanding of this double lap tensile shear geometry, finite element analysis was performed. Just as in the case of the single lap tensile shear, an isotropic model of the E-glass composite, 6061-T6 aluminum, and Loctite 9359.3 adhesive were constructed. The same properties used in the single lap tensile shear model were used for the double lap tensile shear model. The model was constructed with the aluminum adherends located on the outer extents with two composite adherends bonded in parallel. Results of both cases were comparable. The geometry produced little effect on the stresses in the specimens. Just as in the single lap tensile shear tests; values were tabulated for stresses located at the adhesive to aluminum interface at the end of the bondline. See Table 4 for results.

Table 4 – FEA Results for Double Lap Tensile Shear Tests

	½" Gap	5" Gap
σ_{zz} – Peel (psi)	466	472
σ_{yy} – In Plane (psi)	2016	2018
τ_{yz} – Shear Stress (psi)	192	194
Von Mises (psi)	2119	2123

2.2 Flexure Test

2.2.1 Overview

The flexure test performed in this study allows determination of moment transfer capability through a hybrid adhesive bonded joint. Four-point bending tests were designed to study the response of the hybrid joint subjected to constant moment.

2.2.2 Flexure Joint Geometry

The flexure joints consisted of two rectangular aluminum plates bonded to a rectangular composite panel. As shown in Figure 42, coupons consist of a 2" x 6"x 0.375" thick composite specimen bonded to two 2" x 12" x 0.375" thick 6061 – T6 aluminum plate specimens. The composite plate is sized to ensure an overlap of 2" in the bonded region. Bondline thickness was chosen to be 0.100" for this study.

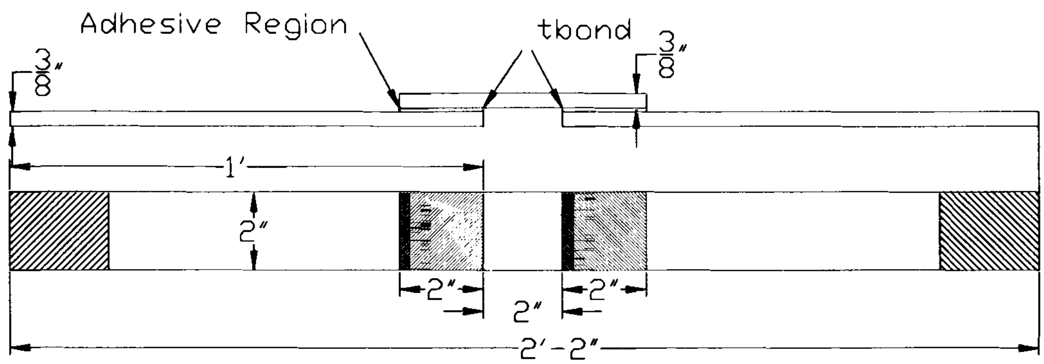


Figure 42 – Flexure Joint Geometry

2.3 Test Plan Methodology

A matrix of the testing that was accomplished during this effort is outlined in Table 5. The methodology used for selecting the adhesives for testing involved the following:

1. Perform a series of three tensile single lap shear tests on subcomponent joints using six adhesives in combination with three different surface preparations at a bondline thickness of 0.100"
2. Select the promising two adhesives and two surface preparations for further study.
3. Run a series of flexure tests at room temperature with the two adhesives and two surface preparations at a bondline thickness of 0.100"
4. Run a series of three tensile shear tests on the most promising two adhesives and two surface preparations with a bondline thickness at 0.250"
5. Run a series of three tensile shear tests on the most promising two adhesives and two surface preparations with bondline thickness at 0.060"
6. Run a series of "long" double lap tensile shear tests at room temperature.
7. Run a series of "short" double lap tensile shear tests at room temperature.

Table 5 - Test Matrix

			Test Condition					
			Tensile Shear					
	Adhesive	Bondline	RTD Prep 1	RTD Prep 2	RTD Prep 3	RTD Prep 4	HW Prep1	HW Prep2
Single Lap	A	.100	5	5	3	5	5	5
	E	.100	5	5	3	5	5	5
	B	.100	3	3	3			
	C	.100	3	3	3			
	D	.100	3	3	3			
	F	.100	3	3	3			
	A	.250	5					
	E	.250	5					
	A	.060	5	5				
	E	.060	5	5				

			Flexure	
	Adhesive	Bondline	RTD Prep 1	RTD Prep 2
Single Lap	A	.100	3	3
	E	.100	3	3

			Shear	
			RT	RT
	Adhesive	Bondline	Prep 1	Prep 2
Double Lap (Short)	A	.100	3	3
	E	.100"	3	3

			Shear	
			RT	RT
	Adhesive	Bondline	Prep 1	Prep 2
Double Lap (Long)	A	.100	3	3
	E	.100"	3	3

2.4 Materials and Material Testing

2.4.1 Metallic Components

The metallic components were fabricated of 6061 – T6 Aluminum. The properties of this alloy are as follows:

Table 6 – Aluminum 6061 T6 Properties [Gere and Timoshenko, 1997]

Physical Properties	**SI**	**US Customary**	**Comments**
Density	2.7 g/cc	0. 0975 lb/in^3	
Mechanical Properties			
Hardness, Brinell	95	95	500 kg load with 10 mm ball
Tensile Strength, Ultimate	310 MPa	45 ksi	
Tensile Strength, Yield	275 MPa	40 ksi	
Elongation @ break	12%	12%	
Poisson's Ratio	.33	.33	
Modulus of Elasticity	69 GPa	10008 ksi	
Shear Modulus	26 GPa	3771 ksi	
Shear Strength	205 MPa	29,733 psi	
Fatigue Strength	95 MPa	13,779 psi	500,000,000 Cycles

2.4.2 Metal Specimen Preparation and Conditioning

Durable adhesive bonds between metal-to-metal or metal-to-composite can be obtained reliably only through proper selection and careful control of the adhesive, the adherend materials and the preparation and conditioning steps in the bonding process. The preparation of the metallic substrates to obtain surfaces with appropriate characteristics is a critical step. Improper surface preparation can produce seemingly acceptable bonds that can degrade rapidly with time under effects of the environment.

The surface preparations used in this study are as follows:

1. Mechanical Surface Prep (Sanding/Cleaning)
2. Grit blasting (3-5 mil blast profile)
3. Acid Etch with Chromate Conversion

2.4.2.1 Surface Prep - Mechanical Prep - Sanding

Mechanical surface prep is performed in preparation for adhesive bonding to remove scale, rust, oxidation and old coatings, as well as to provide a surface profile necessary for good adhesion to the substrate. The metal specimens typically come with a mill surface finish at the adhesive region. One type of surface preparation is sanding to ensure that an adequate profile is achieved. Figure 43 shows aluminum specimens during sanding process. Cleanliness after sanding is important. Any remaining traces of spent abrasive or other debris must be blown, swept, or vacuumed from the surface prior to adhesive bonding. Figure 44 shows cleaning adherends surface.

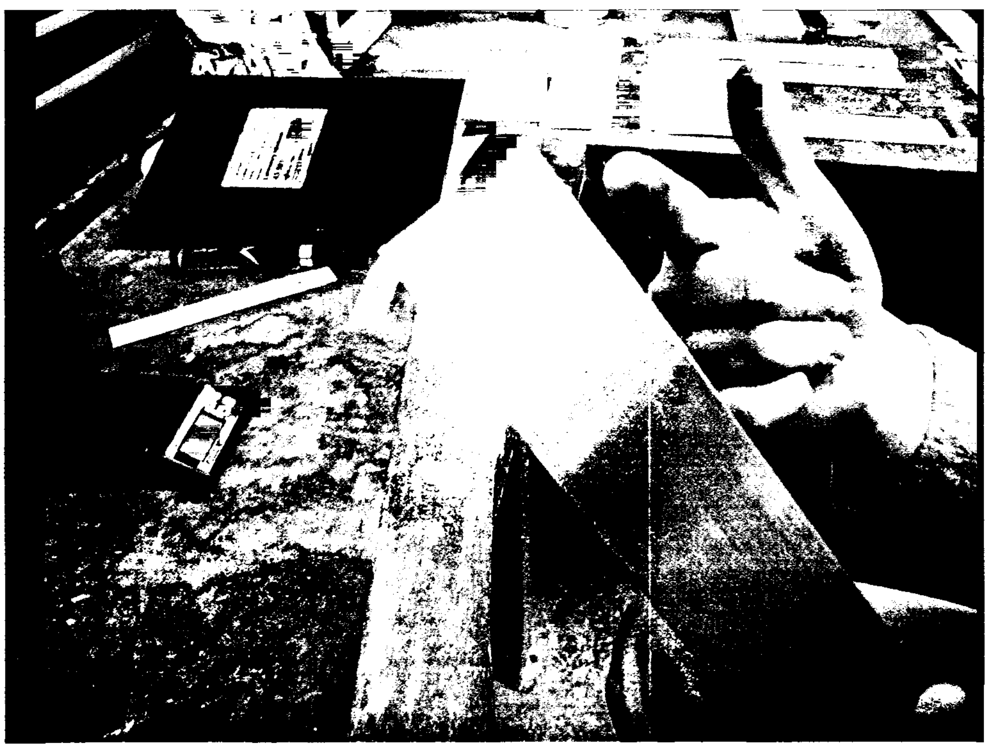


Figure 43 - Specimen Sanding

Figure 44 - Cleaning Specimens

After completion and inspection of the final profiling sanding, the substrate should be adhesively bonded as soon as possible. A maximum period of 4 hours is generally allowed between the completion of surface prep and adhesive bonding. The last step prior to applying adhesive should be to clean the surface with an acceptable non-oil base cleaner such as alcohol.

2.4.2.2 Surface Prep - Grit Blasting

Abrasive blasting is a relatively simple method performed in preparation for adhesive bonding. It requires portable blasting equipment or a blasting cabinet. Figure 45 shows the grit blasting process, which was performed in an Eastwood blast cabinet in Crosby Laboratory at the University of Maine. A medium grade #BB1243, black boiler slag abrasive was used because of the following advantages: low moisture content, high degree of etch for permanent bonding of coatings, readily available, inert, fast cutting due to sharp angular edges, hardness, more economical, longer lasting and leaves minimum dust. This grade of grit is typically used for general-purpose repair and maintenance blasting.

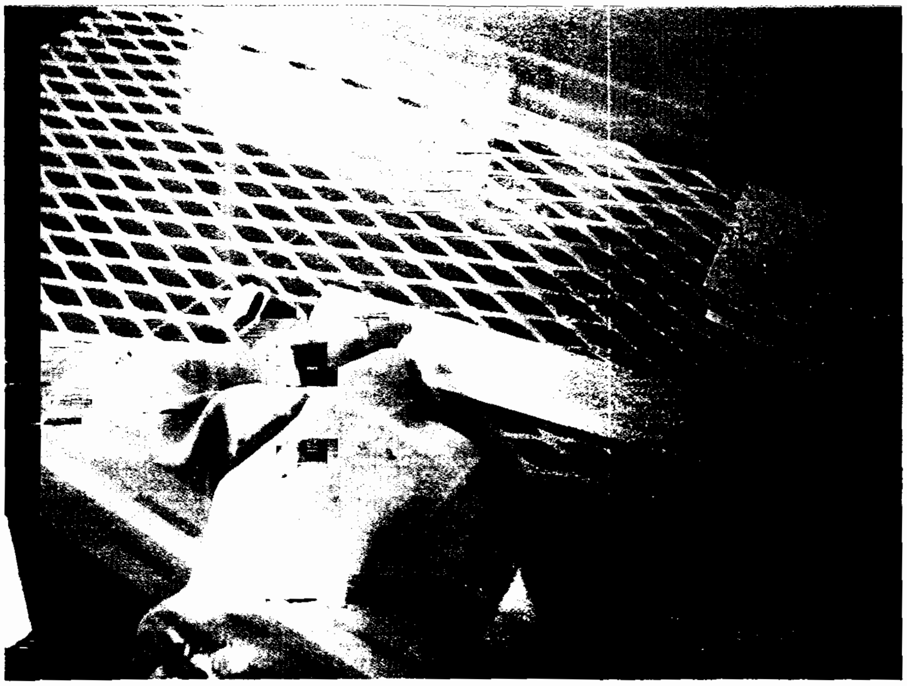


Figure 45 - Grit Blasting Process

Like mechanical sanding, abrasive blasting is conducted to remove scale, rust, oxidation and old coatings, as well as to provide a relative rough surface profile when compared to sanding. The grit blasting process should be performed to achieve a 3-5 mil surface profile.

Conventional abrasive blast cleaning is accomplished through high-velocity propulsion of a blast media in a stream of compressed air (90-100 psi) against the substrate. The particles' mass and high velocity combine to produce kinetic energy sufficient for blasting. Figure 46 shows a comparison of a grit blasted specimen and a machined specimen.

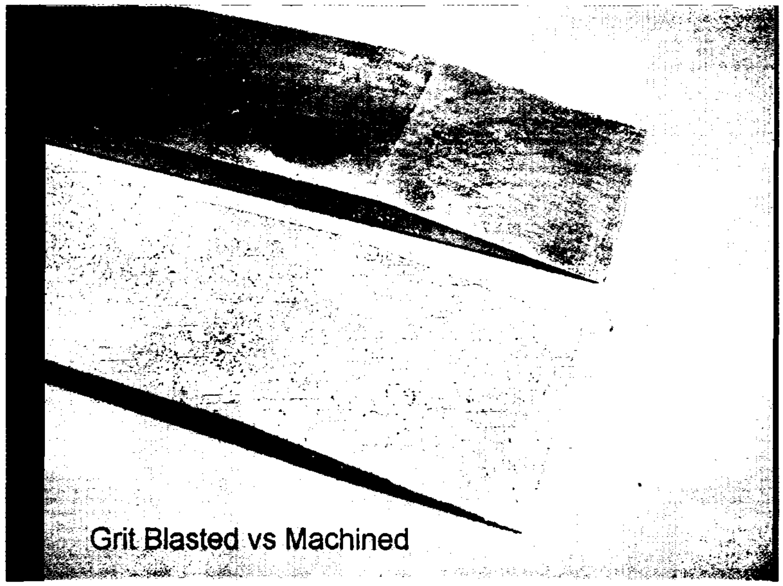


Figure 46 – Surface Profile Comparison

After completion and inspection of the final profiling, the substrate should be adhesively bonded as soon as possible. As with sanding a maximum period of 4 hours is generally allowed to elapse between the completion of blast cleaning and adhesive bonding. The last step prior to applying adhesive should be to clean the surface with an acceptable non-oil base cleaner such as alcohol.

2.4.2.3 Surface Prep - Acid Etch with Chromate Conversion

Acid etching is another process used to preparing aluminum for adhesive bonding. There are many concerns that need to be dealt with when using acid to etch a metallic surface, compared to the mechanical abrasion techniques. All safety procedures and recommendations should be followed when using chemicals. West Systems, who is a supplier of products used in boat manufacturing, recommends using a phosphoric acid etch process with chromate conversion when bonding to aluminum. Figure 47 shows the acid solution supplied by Gougeon Brothers, Inc. Gougeon Brothers, Inc. of Bay City, Michigan is the US distributor for West Systems products.

Figure 47 – Acid Etch Solution

The phosphoric acid is used to chemically remove the oxide layer from the aluminum. After the oxide layer is removed a chromate conversion coating is applied. This chromate conversion coating is a chemical treatment using a mixture of hexavalent chromium and water. This treatment converts the aluminum surface to a thin layer containing a complex mixture of chromium compounds. The coatings are usually applied by immersion although spraying, brushing, or swabbing methods may be used. The purpose of chromate conversion coating is to improve the corrosion resistance of the aluminum surface and can be used to increase the adhesion on aluminum parts. The chromate film is soft and gelantenous when first formed. It slowly age-hardens and therefore the bonded part should not be handled for a minimum of 25 hours. Exposure of the chromate film to temperatures in excess of 150 degrees F. may damage the film.

The process for etching the aluminum specimens is as follows:

- Clean aluminum coupons with alcohol making sure that all contamination is removed
- Protect areas that you don't want etched with masking tape and polyethylene sheeting
- Make sure to shake Part A of "West System – 860 Aluminum Etch Kit"
- Dilute with 2 or 3 parts water in a plastic or glass container.
- Use rubber gloves and eye shields for protection
- Apply the diluted Aluminum Cleaner freely to the surface with a brush or swab. On badly weathered surfaces use a wire brush or steel wool to aid cleaning. Allow the solution to remain on the surface for 1 to 3 minutes.
- Flush away the solution with clean water or mop up with damp rags.
- Reapply if rinse water beads up.
- Wipe with clean, dry rags and or allow to air dry. When dry, proceed with the chromate conversion coating.
- Dilute chromate conversion coating with an equal part water in a plastic or glass container.
- Apply the diluted conversion coating to the surface with a brush or swab.
- Allow the solution to remain on the surface for 2 to 5 minutes.
- Do NOT allow the surface to dry before rinsing.
- Flush away the solution with clean water.
- Allow the surface to air dry.

NOTE: Painting, Epoxy Coating, or Bonding should take place within twenty-five hours of treatment.

2.4.3 Composite Adherends

The composite specimens used in the tests were fabricated at the Crosby Laboratory, University of Maine. They consist of Dow Derakane 411 resin, which is a two- part epoxy vinyl ester resin, reinforced with E-glass cloth. Properties of Derakane 411 are listed in Table 7.

The lay-up used for the test specimens was quasi-isotropic $[(+45/-45,0/90)_3]_S$ E-glass fabric with a weight of 0.91-1.15 lb/in^{2}and a coupon thickness of 0.375". The properties of the E-glass are listed in Table 8 and where provided by BTI, the manufacturer of the E-glass fabric. The panels were fabricated with dimensions of 50" x 25". Adherend test article components were mapped before cutting, similar to that shown in Figure 48, and are labeled 1-46. Material test specimens were also cut as shown. Specimens were cut from each panel in accordance with the sizes specified in Figures 2.1, 2.2, and 2,3.

Table 7 -DERAKANE 411-350 Epoxy Vinyl ester Resin

Physical Properties	SI	US Customary	Comments
Viscosity	350 mPa.s		25°C/cps at 77°F
Specific Gravity	1.045	1.045	
Mechanical Properties			
Barcol Hardness	35	35	
Tensile Modulus	4.1 GPa	4.9×10^5 psi	
Tensile Strength, Yield	86 MPa	12,100 psi	
Elongation @ break	5/6 %	5/6 %	
Modulus of Elasticity	3.2 GPa	ksi	
Flexural Modulus	3.4 GPa	500 ksi.	
Flexural Strength	MPa	psi	
Flexural Modulus	MPa	psi	
Heat Distortion Temperature	105	220	(°C)F° at 1.82 MPa applied stress (at 264 psi applied stress)

See web site for more details: http://www.dow.com/derakane/specific/product/m411350.htm

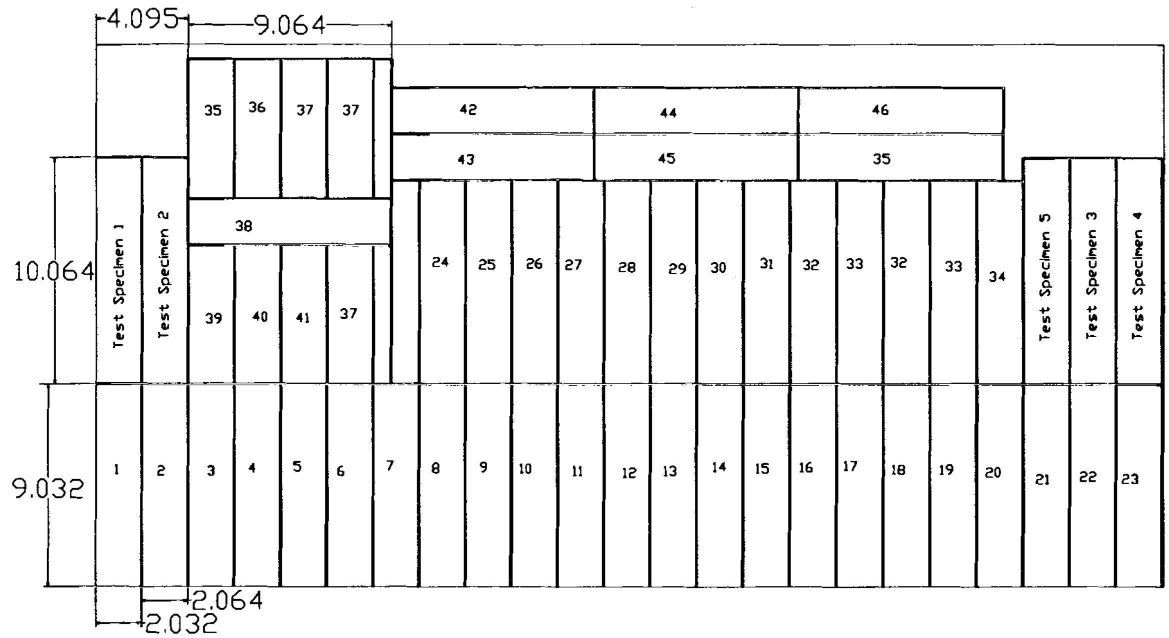


Figure 48 - Test Specimen Panel Cut Layout

Stiffness properties of the composite lay-up used in these tests are shown in Table 9. These values where calculated using CompositePro™ for Windows. CompositePro is software, which is produced by Peak Composite Innovation, LLC. In Littlton, Colorado. The assumption was made that the panel fabrication would produce a panel with a 60/40-fiber volume fraction.

Table 8 – E-Glass Properties Isotropic

Physical Properties	SI	US Customary
E1f	7.24×10^{10} Pa	10.5×10^{6} psi
G12f	3.03×10^{10} Pa	4.40×10^{6} psi
NU12f	2.00×10^{-1}	2.00×10^{-1}
=+S1f	1.86×10^{9} Pa	$.270 \times 10^{6}$ psi
=-S1f	-1.10×10^{9} Pa	$-.160 \times 10^{6}$ psi
DENSITY-f	2.55×10^{-2} kg/ m^2	9.40×10^{-2} lb/in^2
End Area	4.33×10^{-7} m^2	6.71×10^{-4} in^2

Table 9 – Laminate Properties Orthotropic

Physical Properties	SI	US Customary
E_x	2.355×10^{10} Pa	3.415×10^{6} psi
E_y	2.355×10^{10} Pa	3.415×10^{6} psi
E_z	1.314×10^{10} Pa	1.906×10^{6} psi
G_{xy}	9.184×10^{9} Pa	1.332×10^{6} psi
G_{xz}	4.556×10^{9} Pa	$.6608 \times 10^{6}$ psi
G_{yz}	4.557×10^{9} Pa	$.6609 \times 10^{6}$ psi
ν_{xy}	2.822×10^{-1}	2.822×10^{-1}
ν_{yx}	2.822×10^{-1}	2.822×10^{-1}
ν_{xz}	2.798×10^{-1}	2.798×10^{-1}
ν_{zx}	1.562×10^{-1}	1.562×10^{-1}
ν_{yz}	2.798×10^{-1}	2.798×10^{-1}
ν_{zy}	1.562×10^{-1}	1.562×10^{-1}
DEN	2.036×10^{4} kg/m^3	7.500×10^{-2} lb/in^3
Thick	9.144×10^{-3} m	3.600×10^{-1} in

2.4.4 Specimen Conditioning

Specimen conditioning pertains to temperature and moisture conditions at the time of testing. Conditioning will follow guidelines as referenced in ASTM D5229. A summary of test conditions is as follows:

a) RT – Room temperature of 73.4° +/- 3.6° F

b) ET – Elevated temperature 150° F +/- 3.6° F

c) D – Dry moisture conditions – conditioned at 50% RH and 73.4° +/- 3.6° F

d) W – Wet moisture conditions – conditioned at 98% RH and 150° F until specimen weight stabilizes.

The environmental chamber used for conditioning the specimens was a Tenney model T.H. Jr. which has chamber dimensions of 20"wide x 20"tall x 16" deep. To ensure that humidity and temperature were maintained as required, an Omega model RH-201°F temperature/humidity probe was used to monitor conditions inside the chamber. This probe was used because the calibration of the dials on this particular environmental chamber was not current.

2.4.5 Adhesives

Adhesives to be tested in accordance with this document were selected from various sources having association with both the MACH and the AHFID project. Table 10 presents a list of adhesives used in the study along with their costs.

Table 10 - Cost of Adhesives

Material	*Quarts*	*Gallons*	*5Gallons*
Belzona 1121	$225	$810	$3975
3M – Scotchweld 2216	$78***	$255	$1408**
Loctite 9430	$33	$135	$650
Loctite 9394/2	$53 *	N/A	$1053
Loctite 9359.3	$142	N/A	$4150
SIA E2119	N/A	N/A	$855

- 120 qt minimum
***** - When mixing doesn't produce 5 gallons.***
****** - Six-quart minimum***

Application of the adhesive is time dependent so it should be applied directly after mixing. Table 11 provides information on cure times as specified by the manufacturer and mixing information. Further details can be found on the following adhesives in Appendix B. Tensile shear strength and elongation are also reported for cases where manufacturer data was available.

Table 11– Adhesive Properties

Manufacturer	Product Name	Type of Tech.	Heat Req.	Mix Ratio (by Weight.)	Work Life	Full Cure	Tensile Shear Strength MPA	% Elong.
Belzona	1121	Silicon Steel Alloy	No	1.2:1	35 min @ 77 F	168 Hr	12.4	
3M	2216	Epoxy	No	7:5	90 min @ 73 F	24 Hr		
Loctite	9430	Epoxy	No	100:23	50 min @ 77 F	120 Hr	32.4	6
Loctite	9394/2	Epoxy	No	100:17	95 min @ 77 F	168 Hr		
Loctite	9359.3	Epoxy	No	100:44	40 min @ 77 F	168 Hr	31.0	7.7
SIA	E2119	Epoxy	No	100:85	25 min @ 73 F	72 Hr	18.27	

Properties of the adhesives are described as follows:

A. **Loctite (Hysol) 9359.3** is a two-component structural adhesive, which exhibits high peel and high tensile lap shear strength. A variety of substrates such as metals, thermoplastics and composites may be bonded with this product. Loctite 9359.3 was tested by Spencer composites and recommended for use in the AHFID project. This epoxy is a high-end epoxy, which is very expensive and relatively hard to work with.

B. **Loctite (Hysol) 9430** is a modified epoxy adhesive that attains structural properties after room temperature cure. This two-part adhesive is formulated to give very high peel strength coupled with excellent shear strength. The tough, flexible nature of this adhesive makes it useful for bonding dissimilar substrates and for assemblies requiring bondline thickness up to one-tenth inch. The Loctite Corporation as a substitute recommended the Loctite 9430, which would be less expensive than the 9359.3 yet provide similar properties.

C. **Loctite 9394/2** is a two-component structural adhesive. Loctite 9394/2 epoxy ranked high in an adhesive study conducted by Harrison and Crichfield [2002] detailed in a report "Adhesive and Sealants"

D. **Belzona 1121** is a two-component paste grade system based on a silicon steel alloy blended with high molecular weight reactive polymers and oligomers. Belzona 1121 was selected because of its ease of application, it's relatively easy to work with, and it's relatively low cost. For ease of application this material has an extended working life. Once cured, the repair is durable and fully machineable.

Another advantage is that the Belzona product is an odorless epoxy so it can be applied in any environment.

E. **SIA E2119** is a 1:1 two-component toughened epoxy adhesive that will achieve handling strength in less than 8 hours and full cure in 72 hours at room temperature. It can be gelled in 4 minutes at 180°F and post cured at room temperature or at elevated temperatures. Uses include bonding metal, plastic, FRP, and composite materials. E2119 is an excellent candidate where shock and impact resistance are needed..

F. **3M 2216** is a flexible, two-part, room temperature curing epoxies with high peel and sheer strength. 2216 meets MIL-A-82720 and is excellent for bonding many metals and woods, most plastics and rubbers, and masonry products.

2.5 Sub-component Test - Specimen Designation

Specimen designation will use a convention as follows: **CXX-P-B-TTM-S##.** This convention is summarized in Table 2-9. For example, C01-G-C-RTD-A02 would designate Adhesive "C" used in a lap joint configuration, having grit blasted adherends. The specimen was tested in tensile shear. Environmental conditions were room temperature dry. The bondline was set at 0.100". The specimen was number two in the series.

Table 12 – Summary of Sub-component Test Specimen Designations

C indicates type of Adhesive	**A** = Loctite 9359.3 **B** = Loctite 9430 **C** = Loctite 9394.2 **D** = Belzona 1121 XL Metal **E** = SIA 2119 **F** = 3M 2216 A/B Gray
XX indicates type of joint	**01** = Lap Joint **02** = Flexure Joint
P indicates type of Surface preparation	**G** = Grit Blasted **S** = Sanded **A** = Acid Etched
B indicates type of loading condition	**F** = Flexure test **C** = Tensile / Shear
TTM is Test temperature and moisture condition	**RT** = Room Temperature **ET** = Elevated Temperature (140° F) **D** = Dry **W** = Wet
T is the specimen bondline thickness	**A** = .100" **B** = .250" **C** = .060"
## is the specimen Number in the series	## = T01 through T___

2.6 Sub-component Testing

Destructive testing to failure was conducted on adhesively bonded subcomponents. This study included tensile lap shear and flexure tests conducted at room temperature and elevated temperatures. The test articles were fabricated in accordance with specifications in Section 2 and the test matrix in Table 5. The tests quantify the performance of the adhesive over various bondline gaps and under different surface conditions while being mechanically loaded to failure.

In total there were 156 tests including: 12 flexure tests at room temperature, 102 single lap tensile shear tests at room temperature, 24 double lap tensile shear tests at room temperature, and 20 tensile shear tests under hot wet conditions.

2.7 Sub-Component Testing Plan

2.7.1 General

This section describes the specimen preparation, test procedure, test setup, and instrumentation for sub-component tests. Test types include the following:

a) Tensile Lap Shear,
b) Flexure,

2.7.2 Sub-component Tensile Shear Test Plan

2.7.2.1 Sub-component Preparation of Tensile Lap Shear Specimen

Consistent preparation of adherends for adhesive joining is an extremely important step. After preparation of adherends with the desired surface preparations, the specimens are placed on a clean level-working surface. Next the shims for the desired bond gap are selected and staged for the adhesive bonding. Figure 49 shows the aluminum adherends staged for bonding with an aluminum shim and the correct gap shim installed.

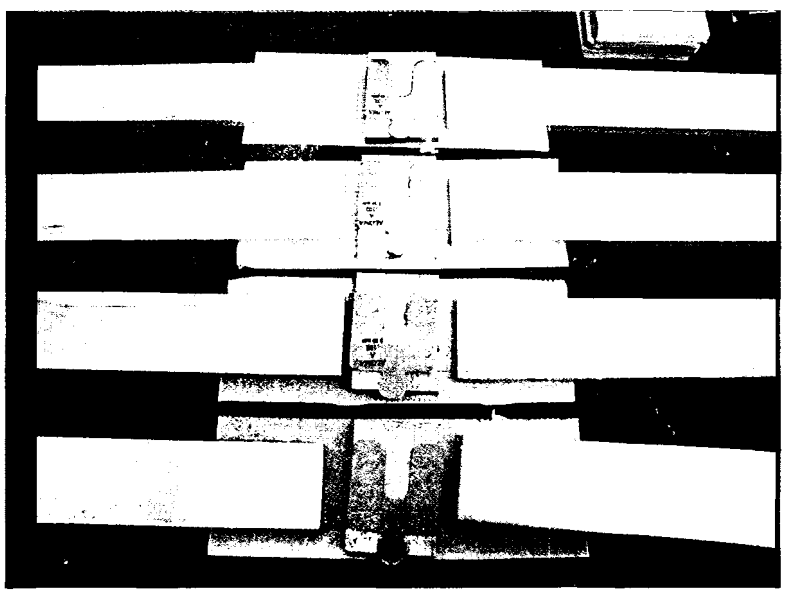


Figure 49 - Aluminum Adherends Staged for Bonding

The adhesives are mixed according to manufacturers recommendations. Shown in, Figure 50 is a mixing pallet that is placed on a scale and adhesive is added. Figure 51 shows adhesive being added to the pallet. After adding both parts, the adhesive is mixed until consistent. Next the two-part epoxy adhesive is mixed to a uniform consistency. The epoxy is applied on the composite coupon surface and the aluminum coupon surface to be bonded. Figure 52 shows the adhesive being applied to the aluminum adherends. The composite coupon is then placed flat on the shim surface. Bondline thickness is then set and the two parts are mated to ensure proper alignment and sufficient contact pressure for maximum bond area. Excessive epoxy is removed with a spatula. Bondlines are visually inspected for gaps in the epoxy. The specimens are cured at room temperature as per manufacturing recommendations. After the specimens have cured for the required time, they should be visually inspected prior to testing. They are then marked for identification as per Table 12.

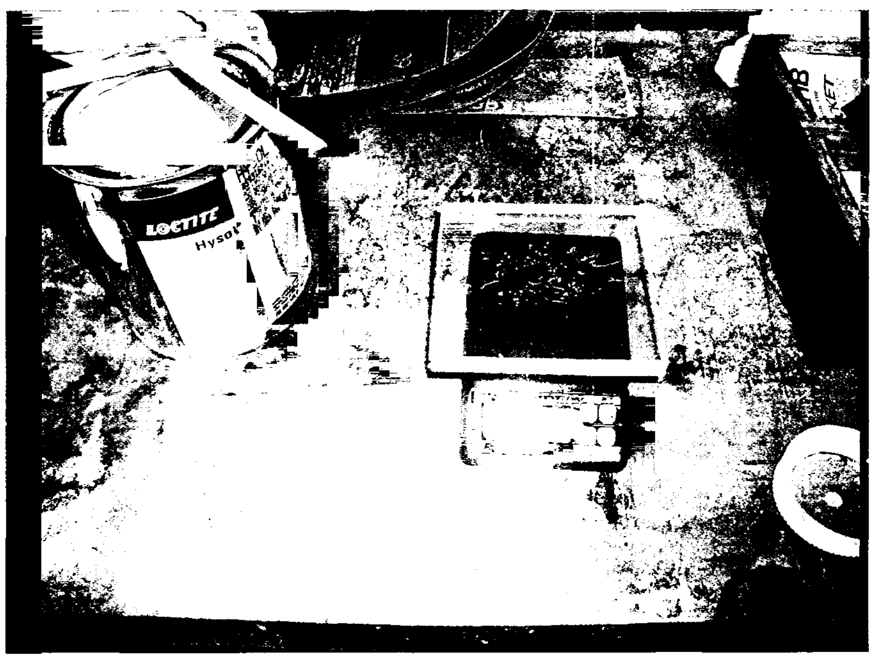


Figure 50 - Adhesive Mixing (By Weight)

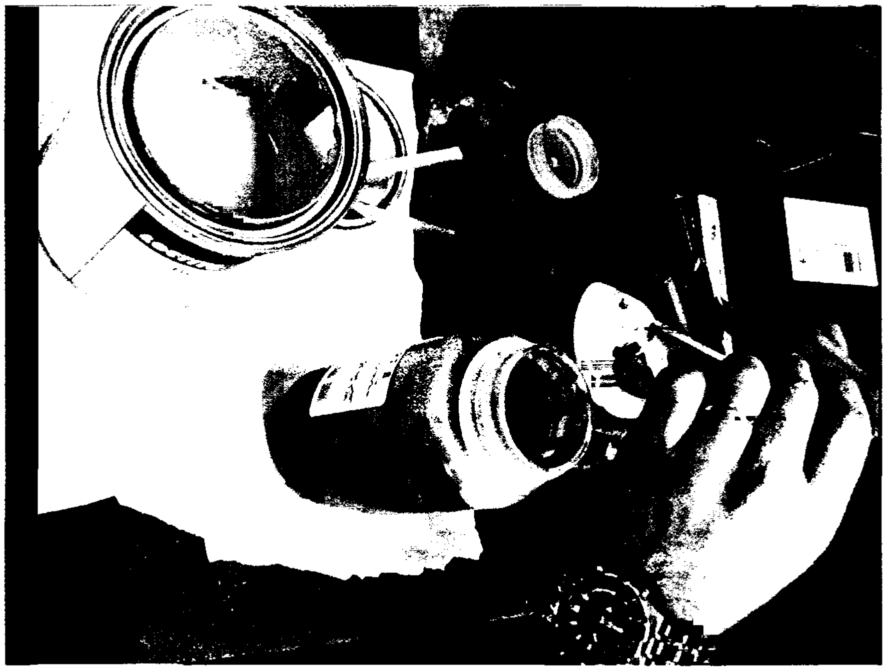


Figure 51 - Adhesive Mixing/Stirring (By Weight)

Figure 52 – Applying Epoxy to Aluminum Adherends

2.7.2.2 Sub-component Tensile Lap Shear Test Set-up

A photograph of the tensile lap shear test setup is shown in Figure 53. Prior to testing, shimming tabs are required to ensure load is applied parallel to the bondline. Tabs were applied to ensure a minimum of 2.5 inches of grip length. Once prepared the specimen is placed in the hydraulic grips of the MTS 810 testing machine so that the outer 2.5 inch of each end are in contact with the jaws and so that the long axis of the test specimen coincides with the direction of applied pull through the centerline of the grip assembly. Grip pressure was maintained at 3000 psi during the test. Upon commencing the test, load is applied due to a displacement rate of 0.025 in per minute displacement. The load is applied until failure and the failure load and failure mode are recorded.

2.7.2.3 Sub-component Tensile Shear Test Instrumentation Plan

A summary of the instrumentation for the tensile lap shear test is given in Table 13. The test specimens were instrumented to determine the relative movement along the joint versus applied load using the vertical LVDT and lateral movement vs. load. Test machine load and displacement between grips were measured using the MTS transducers with the signal recorded by the data acquisition system.

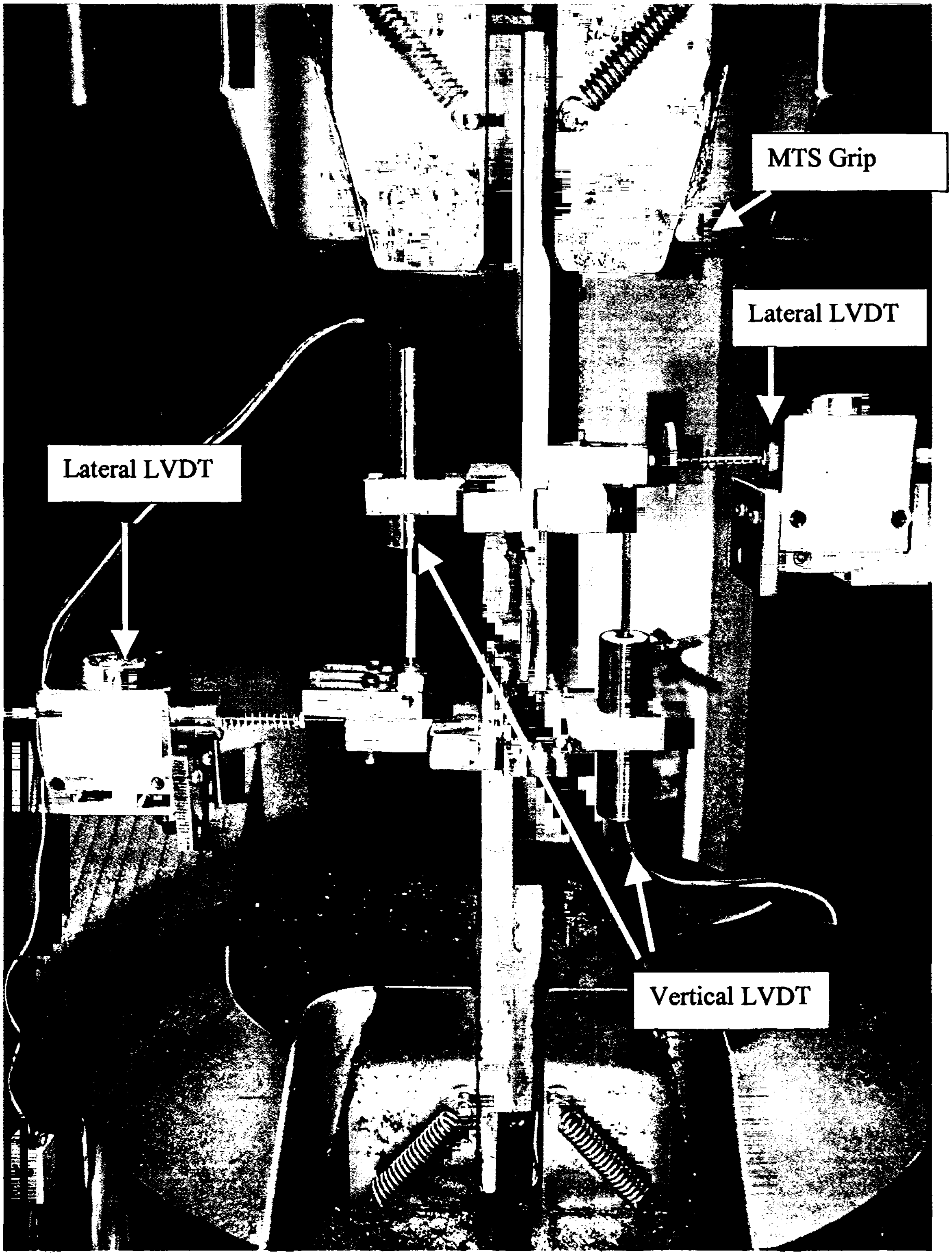


Figure 53 – Test Article in MTS Machine with Instrumentation

Table 13 – Tensile Shear Test Instrumentation Plan Summary

Designation	Variable	Remarks
L0	Load, lbs.	MTS Load Cell – 22 kip Capacity
D0	Displacement, in.	MTS Displacement Transducer–5" gage length
DA1	Displacement, in.	Displacement across adhesive joint
DA2	Displacement, in.	Displacement across adhesive joint
DL1	Displacement, in.	Displacement (Lateral – Aluminum)
DL2	Displacement, in.	Displacement (Lateral – Composite)

Data acquisition hardware consists of an IOTECH Daqbook 100 system capable of reading sixteen channels at a maximum throughput rate of 100KHz. Additional channels are available if deemed necessary by future test requirements. The data acquisition process is PC controlled. The data-taking rate was adjusted according to the specimen load rate. Sampling rate was chosen such that a minimum of 60 points was acquired during the linear portion of the load-deflection curve.

2.7.3 Sub-component Flexure Test Plan

2.7.3.1 Sub-component Flexure Test Set-up

This test was used to quantify the flexural resistance of the subcomponent under constant moment. To simplify the testing a single span beam specimen was used as shown in Figure 54. The end detail of the specimen was isolated on knife-edge pivots as shown in Figure 55. The size of the test article including connection is approximately 2" wide x 26" long. Load was applied across the member at two locations spaced 10" apart using a hinged load head.

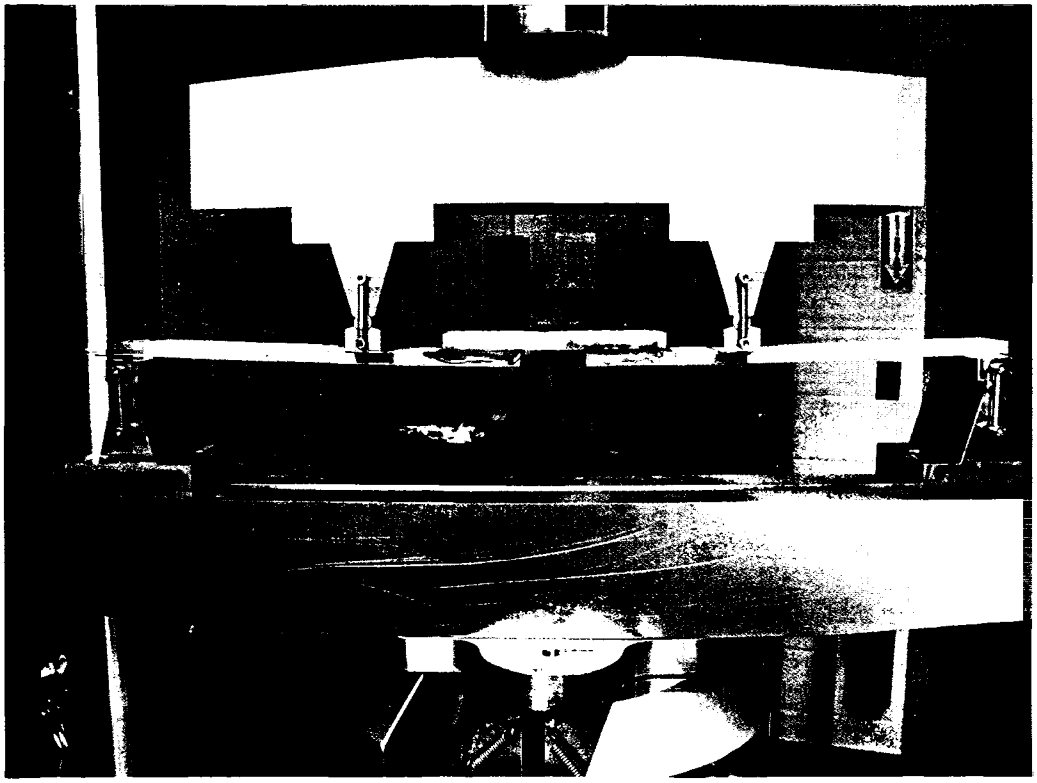


Figure 54 – Flexure Fixture

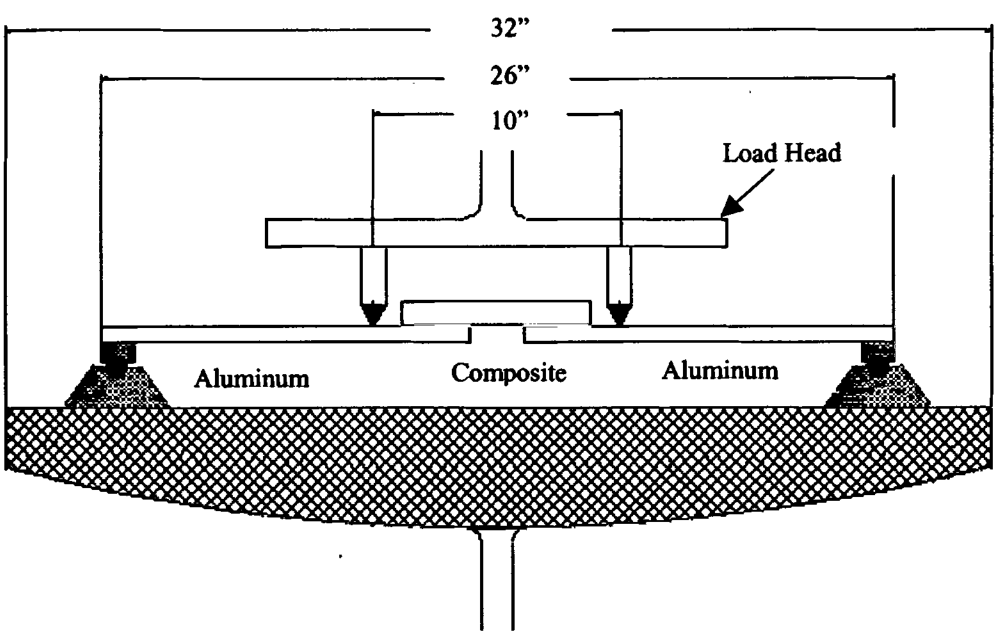


Figure 55 – Flexure Test Set-up.

2.7.3.2 Sub-component Flexure Test Procedure

The steps involved in the flexure test are summarized as follows:

a) Assemble the test article

b) Calibrate the LVDT and Load Channels.

c) Attach the load head to the MTS machine, Start-up the MTS, set the load range to 22,000 lbs., and zero the load cell.

d) Zero the position sensors.

e) Bring the load head in contact with the test article. Zero the MTS displacement.

f) Start up the data acquisition process. Data taking rate=1 sample per 2 seconds.

g) Run the test program in displacement control mode. Displacement rate = 0.025 inches per minute.

h) Observe, photograph and document damage as it occurs.

i) Test rate is such that failure occurs in 10-15 minutes.

j) Upon completion of the test record the peak load, displacement at peak load, and failure mode. Results were plotted and attached in Appendices.

2.7.3.3 Sub-component Flexure Test Instrumentation Plan

The test specimens were not instrumented for preliminary testing. Instrumentation for preliminary testing consisted of the MTS load cell and the MTS LVDT displacement transducer.

Table 14 – Instrumentation Plan Summary

Designation	Variable	Remarks
L0	Load, lbs.	MTS Load Cell
D0	Displacement, in.	MTS Displacement Transducer

The data acquisition process is PC controlled. The data-taking rate was adjusted to take data at a rate of one data point every 0.1-second. Loading rate was 0.025 in. per minute.

2.8 Sub-Component Test Data Reduction and Analysis Plan

As a minimum data reduction and analysis will include the following:

a) Plots of load versus: MTS displacement, DA1 displacement, DA2 displacement, and (DA1+DA2)/2 displacement. This will allow correlations between MTS displacement and the displacement along the adhesive joint to be understood. If direct correlation can be drawn: plots of load versus a representative displacement are all that was required.

b) Record the load at failure

c) Record the mode of this failure for each specimen.

Express all failure loads in pounds per square inch of shear area, calculated to the nearest psi.

3. Test Results

Presented and discussed in this section are the experimental results gathered from tests carried out during this study. In the literature review it was demonstrated that the adhesive resistance in a hybrid joint is tightly coupled to bondline thickness, environment, and surface preparation. Accordingly the focus of study will concentrate on summarizing the effects of bondline thickness, connection geometries, surface preparation, and environmental conditions on the strength and stiffness of the adhesives. In an effort to provide the reader a better understanding of each adhesive this section of the report will summarize the ultimate load, average nominal stress values, and failure modes recorded in all tests. Detail plots of load versus deflection can be found in the Appendix A and B.

3.1 Relative Strength and Stiffness of Adhesives

Single lap tensile shear screening tests were performed on six adhesives at a bondline thickness of 0.100" in an effort to determine the relative nominal shear strength for each adhesive. The nominal shear strength is defined as the applied load at failure divided by the bond area of 4 in^2. The average value for no less than three replicates is shown in Figure 56. This figure shows the average failure load of the adhesives relative to adhesive type and surface preparation. Regardless of surface preparation, the SIA and Loctite 9359.3 adhesives appear to be the strongest of the groups tested.

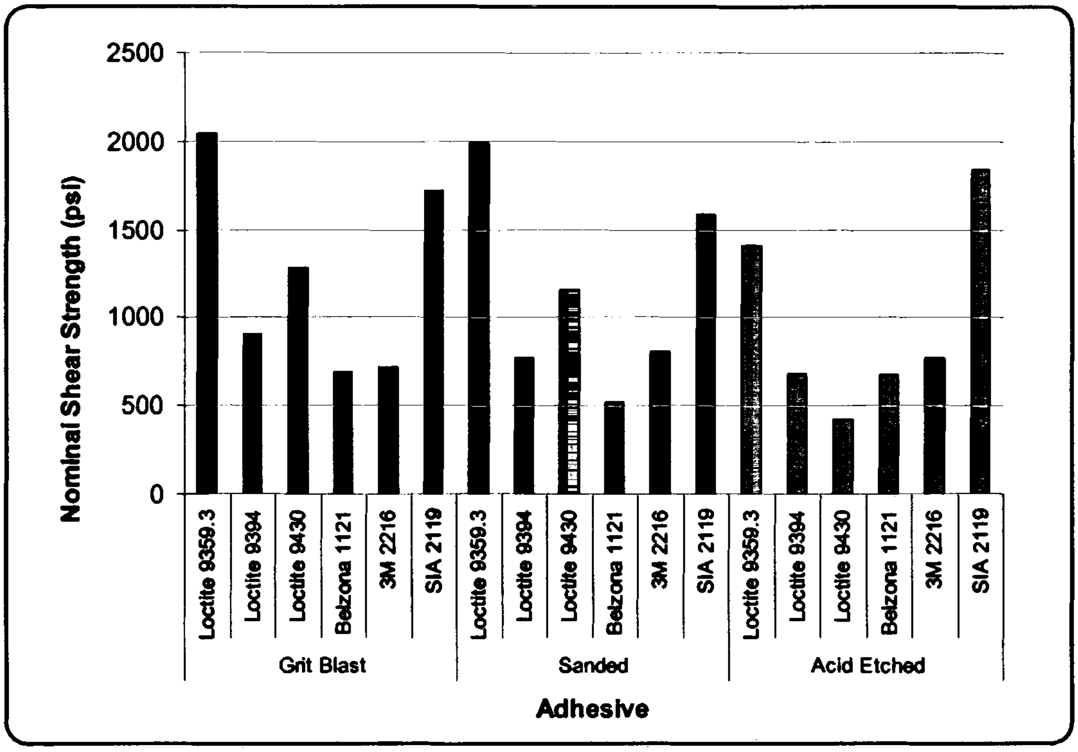


Figure 56 – Nominal Shear Strength of Adhesive (Room Temperature)

The baseline screening strength test results with the 0.100" bondline are summarized in Table 15. Failure load, nominal shear strength, stiffness, and failure mode are included for each adhesive and surface preparation. The nominal shear strength is a calculated value, which is derived by dividing the maximum load by the shear area of the joint, which was 2" x 2" or 4 square inches for all single lap shear tests

Modes of failure are listed in Table 15. Designation for the failure modes are: SFIC – Substrate Failure in Composite, CFIA – Cohesive Failure in Adhesive, AFWA – Adhesive Failure with Aluminum, AFWC – Adhesive Failure with Composite. All modes of failure were experienced in testing the initial six adhesives and a depiction of these modes was presented in Section 1.3.6.

The in plane stiffness of the adhesive was also computed and tabulated in Table 15 as the average movement of the in-plane LVDTs. The stiffness values were computed by analyzing the linear region of the load vs. deflection curve and data from the two vertical LVDTs. The Pearson product moment correlation coefficient "r" was used for analysis. This value is a dimensionless index that ranges from -1.0 to 1.0 inclusive, and reflects the extent of a linear relationship between data points in known y's and known x's. A positive coefficient indicates the values of the y variables vary in the same direction as the x variables (positive slope). A negative coefficient indicates a negative slope. Characterizations of Pearson's r has establish as 0.9 to 1 as having a very high correlation and 0.7 to 0.9 as having a high correlation. The r-squared value can be interpreted as the proportion of the variance in y attributable to the variance in x. The r-square value is sometimes called the confidence coefficient. To ensure that only the linear portion of the curve was analyzed a correlation coefficient of 0.95 or greater was used as a limiting value.

The lateral stiffness was also measured by a similar method for both the metal adherend and the composite adherend. These results had a high variability between test specimens. This variability is attributed partly to the lack of precise positioning of the lateral displacement transducers and to variability in material stiffness.

Table 15 – Adhesive Strength and Failure Data @ 0.100" Bondline

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Failure Mode	Stiffness (lbf/in)	Lateral Stiffness	
							Metal (lbf/in)	Composite (lbf/in)
SIA	Grit Blast	1	6923	1731	CFIA	74375	292502	378220
	Grit Blast	2	6438	1609	CFIA	98210	259603	449493
	Grit Blast	3	7293	1823	SFIC	105363	233396	995510
	Sanded	1	6075	1519	AFWA	125507	300548	385756
	Sanded	2	6806	1701	AFWA	144104	243291	1527127
	Sanded	3	6198	1550	AFWA	140982	301800	521595
	Acid Etch	1	7196	1799	SFIC	155487	362528	534472
	Acid Etch	2	7877	1969	SFIC	162131	333146	668167
	Acid Etch	3	7356	1839	AFWA	149144	444828	437005
	GB+AE	1	4313	1078	CFIA	143663	359962	406525
	GB+AE	2	5060	1265	CFIA	134626	219278	796092
	GB+AE	3	4680	1170	CFIA	123594	282289	548479
	GB+AE	4	5389	1347	CFIA	135622	480252	338236
	GB+AE	5	4892	1223	CFIA	131970	298219	417616

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Failure Mode	Stiffness (lbf/in)	Lateral Stiffness	
							Metal (lbf/in)	Composite (lbf/in)
Loctite 9359.3	Grit Blast	1	8337	2084	SFIC	155514	407692	560039
	Grit Blast	2	7792	1948	SFIC	157538	219818	5276390
	Grit Blast	3	8369	2092	SFIC	151308	208838	2316424
	Sanded	1	8363	2091	AFWA	147361	269396	1411939
	Sanded	2	8139	2035	SFIC	151568	305491	1423351
	Sanded	3	7385	1846	AFWA	175800	271846	3289332
	Acid Etch	1	7501	1875	AFWA	177010	416312	703653
	Acid Etch	2	4117	1029	AFWA	165786	363915	676578
	Acid Etch	3	5259	1315	AFWA	174807	328378	1022804
	GB+AE	1	6516	1629	AFWA	167296	572268	413464
	GB+AE	2	5024	1256	AFWA	166539	422614	676167
	GB+AE	3	7189	1797	AFWA	159989	384271	752682
	GB+AE	4	4879	1220	AFWA	168226	392845	538548
	GB+AE	5	2361	590	AFWA	168648	233054	1297917

Table 15 - Continued

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Failure Mode	Stiffness (lbf/in)	Lateral Stiffness	
							Metal (lbf/in)	Composite (lbf/in)
Loctite 9394	Grit Blast	1	3952	988	AFWA	173884	685794	359986
	Grit Blast	2	3668	917	AFWA	173969	362422	782961
	Grit Blast	3	3268	817	AFWA	164226	300929	656692
	Sanded	1	3282	820	AFWC	140457	288163	749263
	Sanded	2	2190	547	AFWC	150505	130397	175455
	Sanded	3	3746	937	AFWA	186053	497058	742712
	Acid Etch	1	2407	602	AFWA	179717	592999	699774
	Acid Etch	2	3083	771	AFWA	177553	636513	589052
	Acid Etch	3	2664	666	AFWA	180770	839414	523048

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Failure Mode	Stiffness (lbf/in)	Lateral Stiffness	
							Metal (lbf/in)	Composite (lbf/in)
Loctite 9430	Grit Blast	1	5319	1330	CFIA	151087	336275	668908
	Grit Blast	2	4191	1048	AFWA	179876	459549	447994
	Grit Blast	3	5860	1465	AFWA	140781	250287	786590
	Sanded	1	5739	1435	CFIA	171370	317461	978793
	Sanded	2	3887	972	CFIA	177046	332832	664751
	Sanded	3	4295	1074	CFIA	173149	256081	957730
	Acid Etch	1	1767	442	CFIA	8057	0	0
	Acid Etch	2	1490	372	CFIA	8121	0	0
	Acid Etch	3	1782	446	CFIA	9182	0	0

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Failure Mode	Stiffness (lbf/in)	Lateral Stiffness	
							Metal (lbf/in)	Composite (lbf/in)
3M	Grit Blast	1	3317	829	AFWC	142855	358309	498685
	Grit Blast	2	2091	523	AFWC	179852	467831	549988
	Grit Blast	3	3150	787	AFWC	167770	239247	594750
	Sanded	1	3638	909	CFIA	52710	77286	98988
	Sanded	2	3151	788	CFIA	54279	80814	105316
	Sanded	3	2912	728	CFIA	48636	73618	106118
	Acid Etch	1	2991	748	AFWA	41145	55898	67416
	Acid Etch	2	3017	754	AFWA	54050	71611	78366
	Acid Etch	3	3266	817	AFWA	43734	53139	56794

Table 15 - Continued

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Failure Mode	Stiffness (lbf/in)	Lateral Stiffness	
							Metal (lbf/in)	Composite (lbf/in)
Belzona	Grit Blast	1	2675	669	AFWC	122046	459905	594329
	Grit Blast	2	2709	677	AFWC	134174	8344139	592744
	Grit Blast	3	2866	716	AFWC	162528	402255	672352
	Sanded	1	1886	472	AFWA	181753	353606	1254134
	Sanded	2	2084	521	AFWA	193080	402435	509927
	Sanded	3	2219	555	AFWA	153909	502987	438759
	Acid Etch	1	1907	477	AFWA	190180	429145	702639
	Acid Etch	2	2856	714	AFWA	172667	371853	949126
	Acid Etch	3	3317	829	AFWA	195562	501630	627707

Table 16 presents a summary of the average strengths for each adhesive and surface preparation. Using strength at room temperature as the primary requirement, it was determined that the two most promising adhesives for further study are the Loctite 9359.3 and SIA E 2119. These adhesives achieved nominal average strength of over 1400 psi regardless of surface preparation used. The data above was also analyzed for stiffness. Representative load vs. deflection curves for the adhesives are shown in Figures 57-59.

Table 16 – Single Lap Shear Tensile Test Data @ 0.100" Bondline

Tensile Shear Test		
Adhesive	Surface Prep	Average Strength (psi)
Loctite 9359.3	Grit Blast	2042
	Sanded	1991
	Acid Etched	1406
	GB + AE	1298
Loctite 9394	Grit Blast	907
	Sanded	768
	Acid Etched	680
Loctite 9430	Grit Blast	1281
	Sanded	1160
	Acid Etched	420
Belzona 1121	Grit Blast	687
	Sanded	516
	Acid Etched	673
3M 2216	Grit Blast	713
	Sanded	808
	Acid Etched	773
SIA 2119	Grit Blast	1721
	Sanded	1590
	Acid Etched	1839
	GB+AE	1247

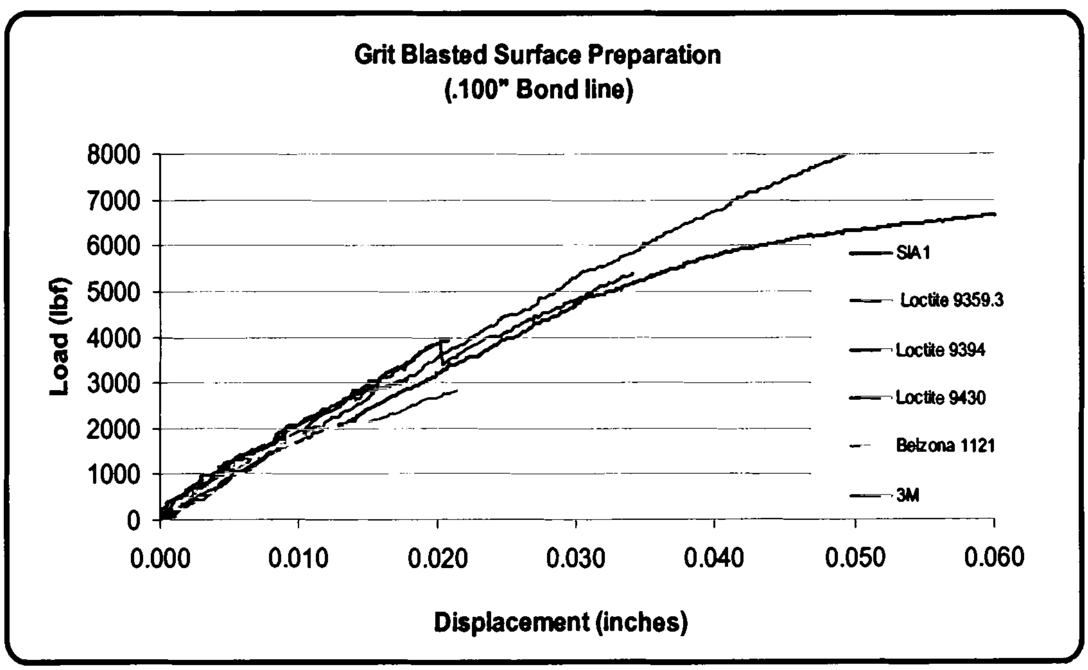


Figure 57 – Load vs. Deflection – Grit Blasted (Adhesives)

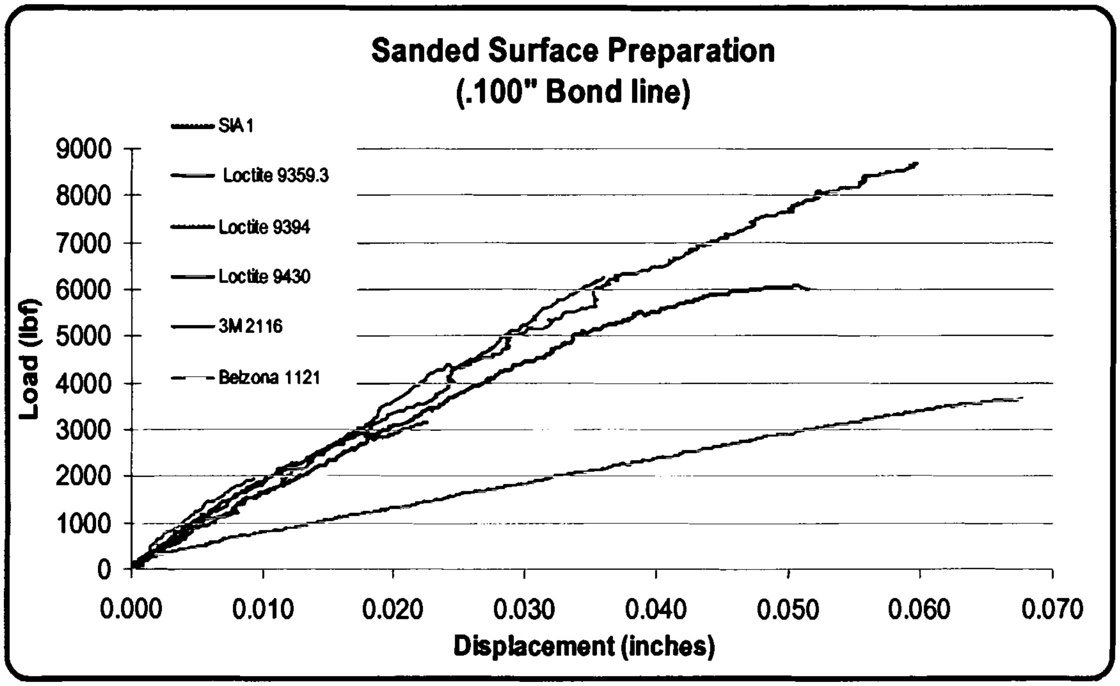


Figure 58 – Load vs. Deflection - Sanded (Adhesives)

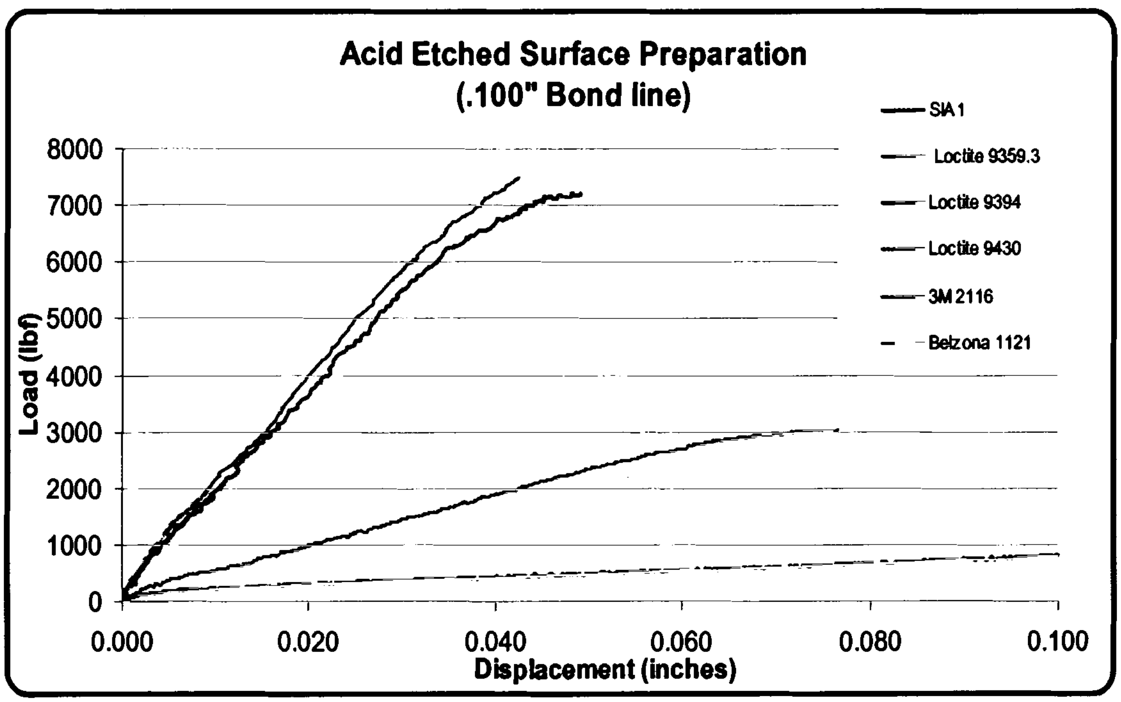


Figure 59 – Load vs. Deflection - Acid Etch (Adhesives)

3.2 Effects of Bondline Thickness

After initial screening test using 0.100" bondline thickness, the Loctite 9359.3 and the SIA E 2119 adhesives were studied at bondline thicknesses of 0.060", 0.100", and 0.250". A summary of each test including the average values for each specimen's maximum nominal shear strength, bondline thickness, and failure modes are given in Table 17 – Table 19. Designations for the failure modes are as before: SFIC – Substrate Failure in Composite, CFIA – Cohesive Failure in Adhesive, AFWA – Adhesive Failure with Aluminum, AFWC – Adhesive Failure with Composite. The Loctite 9359.3 adhesive achieved the largest nominal shear strength of 1909 psi, with the 0.100" bondline thickness and grit blasted surface preparation. This failure was controlled by the composite substrate and may not indicate the resistance of the Loctite adhesive. Further study revealed that this was not the case when the bondline thickness was reduced. At a bondline thickness of 0.060 and grit blasted surface preparation the SIA adhesive achieved 5% higher strength than the Loctite 9359.3. This was due to the premature failure of the composite substrate and may not be indicative of the adhesive capacity at this bondline thickness. Efforts to mitigate composite failure are recommended.

Table 17 – Tensile Shear Test Data (0.060") Room Temperature

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Stiffness (lbf/in)	Lateral Stiffness		Failure Mode
						Metal (lbf/in)	Composite (lbf/in)	
SIA .060" Bondline	Grit Blast	1	8741	2185	164553	297948	2972890	SFIC
	Grit Blast	2	8564	2141	168349	386380	806638	SFIC
	Grit Blast	3	8157	2039	167068	348509	692580	SFIC
	Grit Blast	4	7192	1798	163052	303504	1341328	SFIC
	Grit Blast	5	8318	2080	164748	376431	702570	SFIC
	Grit Blast	Ave	8487	2122	165554	342554	1303201	

Table 17 - Continued

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Stiffness (lbf/in)	Lateral Stiffness		Failure Mode
						Metal (lbf/in)	Composite (lbf/in)	
Loctite 9359.4 .060" Bondline	Grit Blast	1	8748	2187	162071	405825	1175097	SFIC
	Grit Blast	2	8036	2009	164810	467041	574504	SFIC
	Grit Blast	3	7658	1914	167558	797723	498242	SFIC
	Grit Blast	4	8367	2092	158331	300374	1021915	SFIC
	Grit Blast	5	7612	1903	147604	340973	938946	SFIC
	Grit Blast	Ave	8084	2021	160075.1	462387	841740.8	

Table 18 – Tensile Shear Test Data (0.100") Room Temperature

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Stiffness (lbf/in)	Lateral Stiffness		Failure Mode
						Metal (lbf/in)	Composite (lbf/in)	
SIA .100" Bondline	Grit Blast	1	6923	1731	74375	292502	378220	CFIA
	Grit Blast	2	6438	1609	98210	259603	449493	CFIA
	Grit Blast	3	7293	1823	105363	233396	995510	SFIC
	Grit Blast	4	7727	1932	159848	859633	325350	SFIC
	Grit Blast	5	7582	1896	162204	573089	382837	CFIA
	Grit Blast	Ave	7193	1798	120000.2	443644	506281.8	

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Stiffness (lbf/in)	Lateral Stiffness		Failure Mode
						Metal (lbf/in)	Composite (lbf/in)	
Loctite 9359.4 .100" Bondline	Grit Blast	1	8337	2084	155514	407692	560039	SFIC
	Grit Blast	2	7792	1948	157538	219818	5276390	SFIC
	Grit Blast	3	8369	2092	151308	208838	2316424	SFIC
	Grit Blast	4	6164	1541	173001	497548	852187	SFIC
	Grit Blast	5	7510	1878	161929	262121	5218532	SFIC
	Grit Blast	Ave	7634	1909	159858	319203	2844714	

Table 19 – Tensile Shear Test Data (0.250") Room Temperature

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Stiffness (lbf/in)	Lateral Stiffness Metal (lbf/in)	Lateral Stiffness Composite (lbf/in)	Failure Mode
SIA .250" Bondline	Grit Blast	1	6108	1527	111784	211613	356247	AFWA
	Grit Blast	2	5989	1497	101505	244512	324003	AFWA
	Grit Blast	3	5686	1421	96160	189230	462450	AFWA
	Grit Blast	4	5194	1299	98872	242986	265937	AFWA
	Grit Blast	5	3202	801	123652	258474	236323	CFIA
	Grit Blast	Ave	5928	1482	207110	229363	411240	

Adhesive	Aluminum Surface Preparation	Test #	Failure Load (lbf)	Nominal Shear Strength (psi)	Stiffness (lbf/in)	Lateral Stiffness Metal (lbf/in)	Lateral Stiffness Composite (lbf/in)	Failure Mode
Loctite 9359.4 .250" Bondline	Grit Blast	1	5341	1335	138678	235032	617857	AFWA
	Grit Blast	2	6003	1501	134267	248979	406120	AFWA
	Grit Blast	3	6707	1677	130473	231012	604935	SFIC
	Grit Blast	4	5710	1427	113663	154806	445176	SFIC
	Grit Blast	5	5996	1499	113450	243369	614612	SFIC
	Grit Blast	Ave	6017	1504	327906	238341	542971	

Figure 60 shows a graph of bondline thickness vs. nominal shear strength. It is noted that the database for this test is limited in that this graph has been derived from results of the three-bondline thicknesses studied. The response of the adhesives at different bondline thickness, shows that as the adhesive bond grows greater in thickness, the nominal shear strength of the joint is decreased. This is primarily due to the thicker bondline, which causes the eccentricity of the load path to increase. This, results in higher peel stresses at the edges of the overlap region as presented in Figure 36. The thicker bondline causes increased rotation at the joint resulting in more in plane and lateral elongation per unit load. This causes the graphs of load vs. displacement to decrease in slope as the bondline is increased and the stiffness of the system is reduced as portrayed in Figures 61 and 62. A change in failure mode is also observed. It was noted that the thinnest bondlines failed from substrate failure of the composite and will not indicate the actual adhesive strength. The thickest bondlines caused the failure mode to shift toward an adhesive failure at the aluminum adhesive interface. This was observed with both the Loctite and SIA adhesives. The Loctite adhesive did not fail cohesively in these tests where as the SIA adhesive failure mode was both cohesive and substrate at the bondline thickness of 0.100"

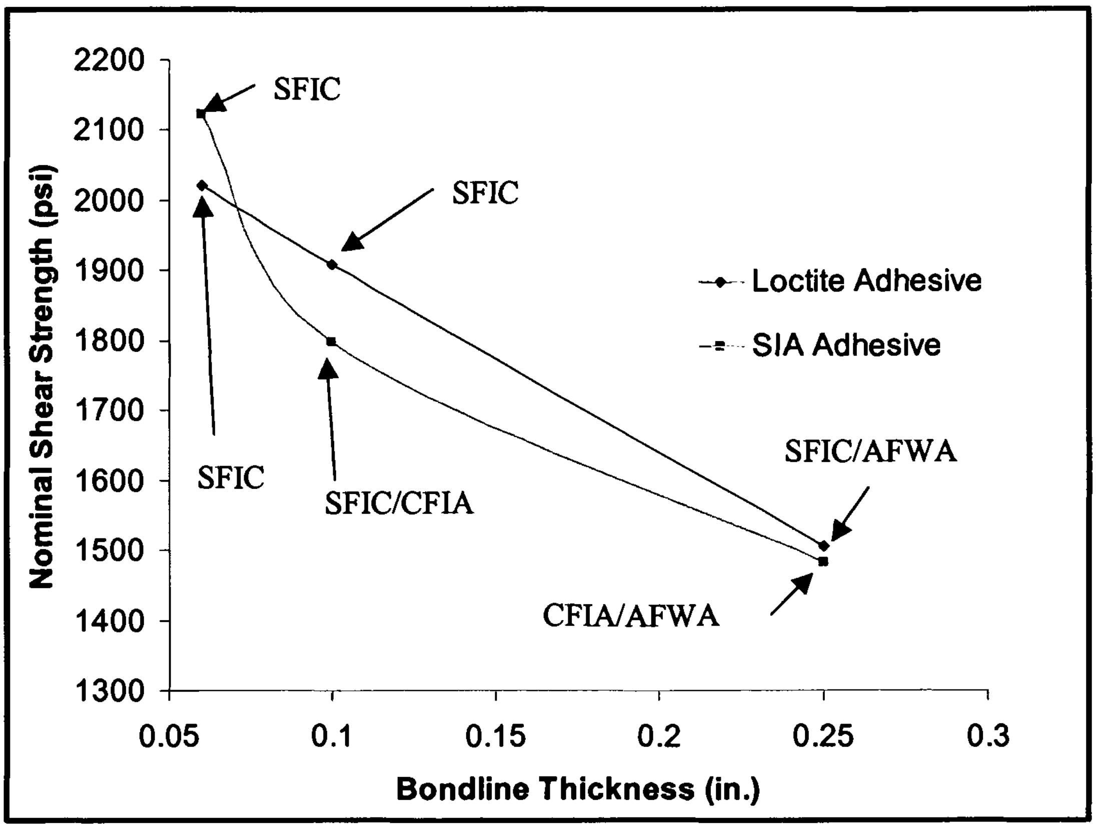


Figure 60 – Bondline Thickness vs. Apparent Shear Strength (Room Temperature)

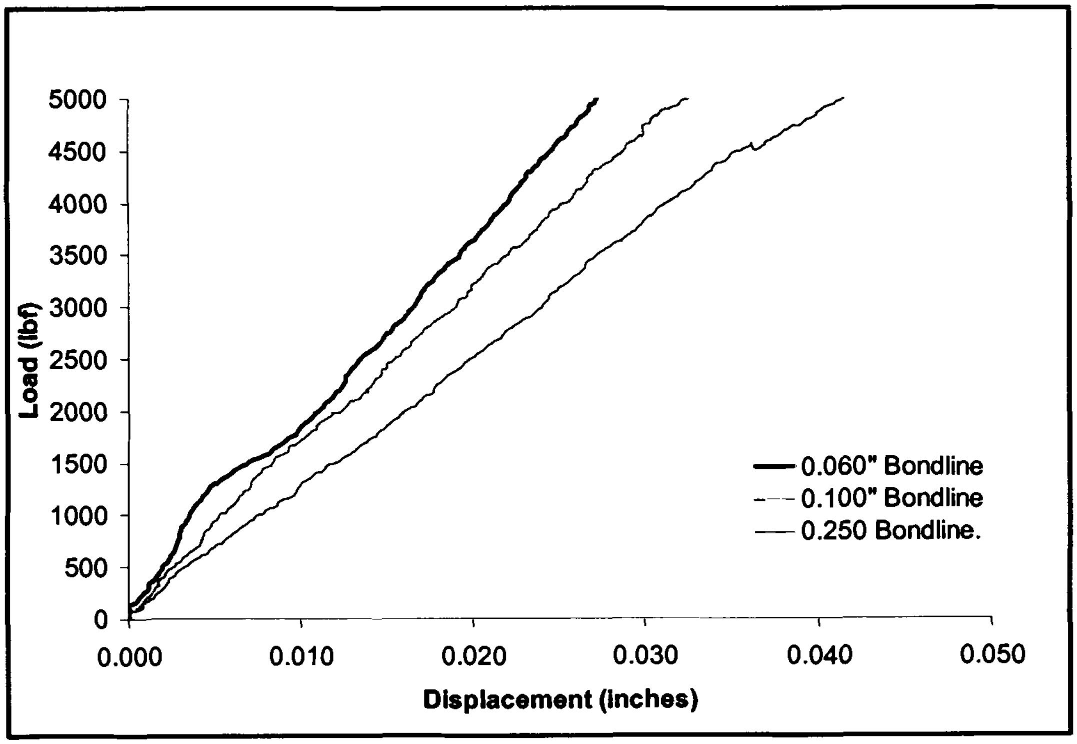


Figure 61 – Load vs. Displacement for Varying Bondlines (Loctite)

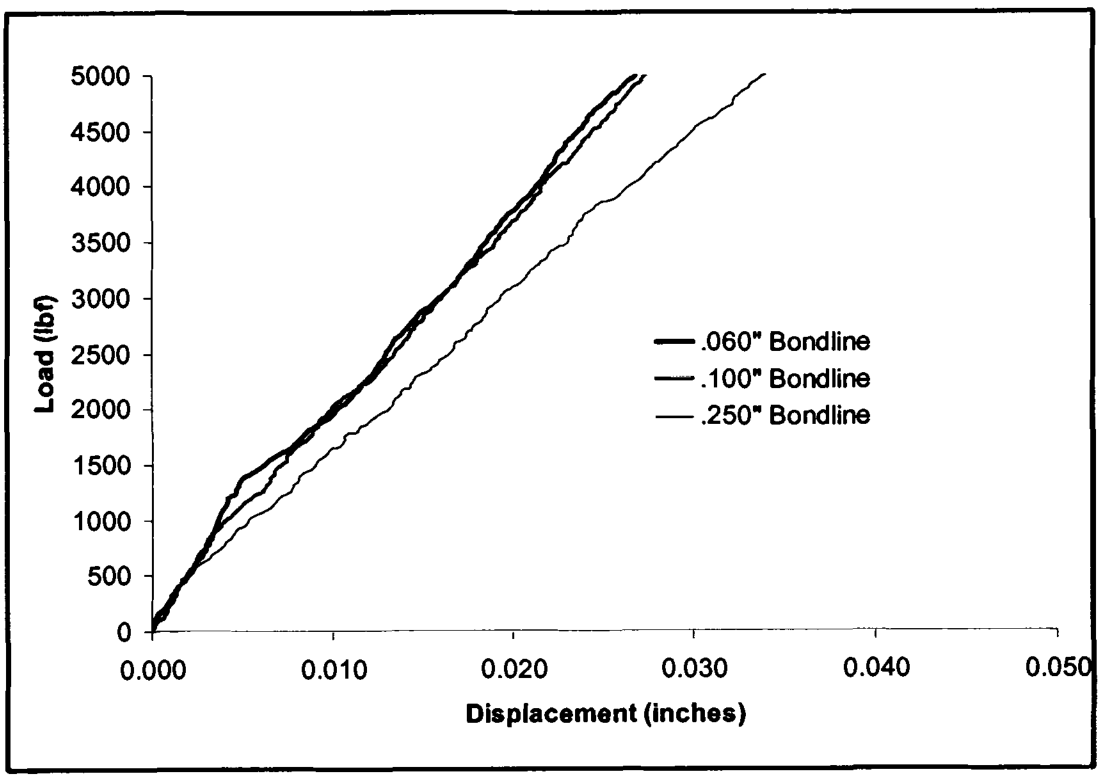


Figure 62 – Load vs. Displacement for Varying Bondlines (SIA)

3.3 Effects of Surface Preparation at Room Temperature

Adherend surface preparation plays a critical role in developing bonded joints. Inadequate surface roughening, bonding, and treatment can prevent adhesives from bonding properly to metal and/or composites, resulting in premature failures. Strong interaction between the adhesive and the substrate are necessary to achieve bonds, which will sustain the full capacity of the adhesive and adherends. Surface preparation techniques should be specified in design of adhesive joints to ensure that the joints fail cohesively. It is essential that testing be carried out to qualify the effects of surface preparation treatment.

Figure 63 shows a graphical representation of average nominal shear strength test results for the adhesives tested at room temperature with a bondline of 0.100". Varying surface preparations on some adhesives caused an effect on bond strength by as much as 67% (9430 adhesive – acid etch vs. grit blast). Comparing the bond strength of the Loctite 9359.3 and the SIA E 2119 it was interesting that the acid etch surface preparation did not affect the strength of the bond when using SIA, as it did when using the Loctite adhesive. Acid etching the surface of the aluminum adherend improved the strength of the bond when using the SIA adhesive. Further investigation of acid etching combined with grit blasting produced results that were reduced from the individual surface preparations. Investigation as to the cause is still ongoing.

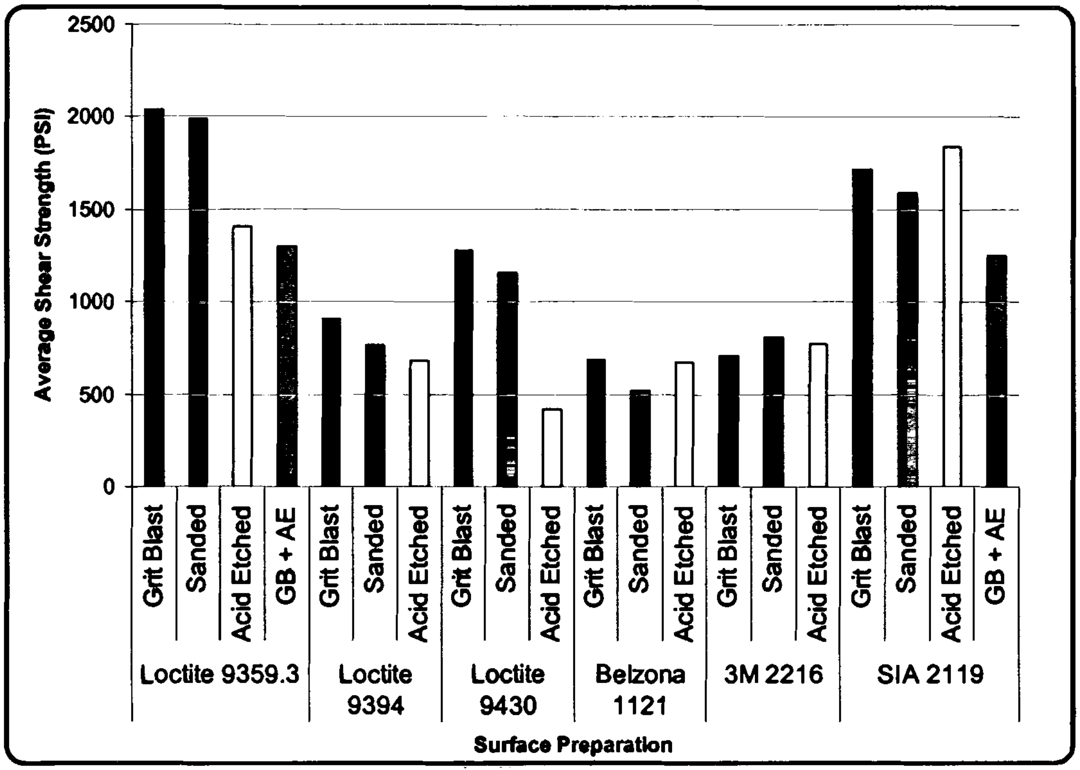


Figure 63 – Surface Preparation Strengths Relative to Adhesive

3.4 Quantify the Effects of the Environmental Conditions.

In Naval applications, joints are subjected to extreme moisture conditions. Because there was a concern with the adhesive bond degrading due to temperature and moisture effects, testing was performed on samples prepared with Loctite 9359.3 adhesive and SIA E 2119 adhesive. Samples were constructed with grit blasting surface preparation and with grit blasting and acid etching/chromate conversion surface preparations in this study. Environmental testing consisted of subjecting specimens to an environment of 150 deg F with a humidity level in excess of 98% relative humidity for a period of one month. After placing the specimens in the environmental chamber, they were monitored for moisture absorption every three days. By day 19, the Loctite adhesive showed signs of discoloration.

During removal of specimens from the environmental chamber to weight, it was noticed that the Loctite adhesive showed further signs of discoloration. Pockets of water were noticed collecting under the surface of the adhesive. This was especially noticeable in the adhesive, which attached the composite tab to the aluminum adherend.

During the one-month of conditioning, specimens were continually analyzed for their moisture absorption rate. The weight changes of the specimens were virtually asymptotic at the 23rd day as shown in Figure 64. Accordingly, testing after one month was performed.

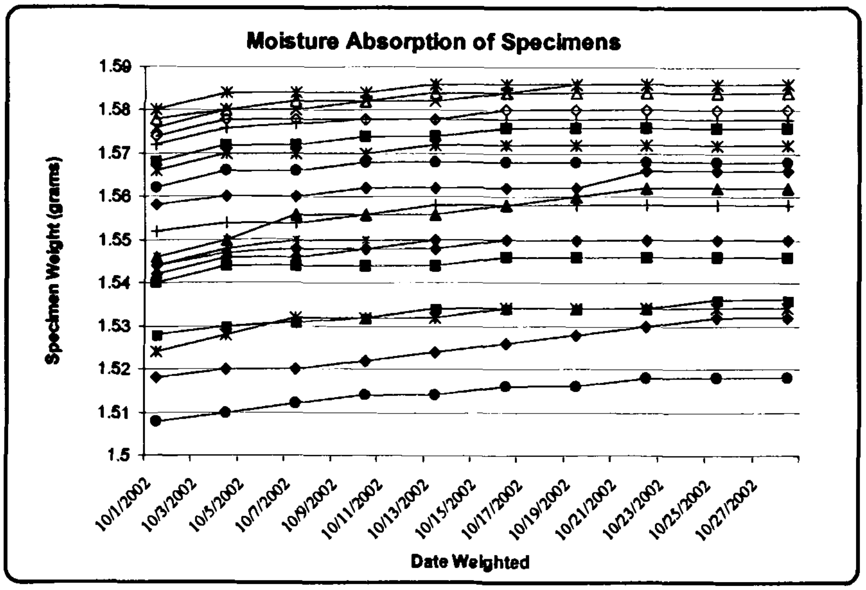


Figure 64 – Moisture Absorption of Specimens

During testing, the adhesive which bonds the tabs, showed signs of degradation when subjected to gripping in the MTS test machine. The compressive load of the grip caused the adhesive to be displaced between the tab material and the adherend. Grip slippage was monitored during the test but did not occur.

Although the Loctite adhesives showed signs of discoloration, results were compared to specimens that had not been subjected to environmental conditioning. Figure 65 and

Figure 66 show that the grit blasted plus acid etched specimens had results comparable to specimens that were grit blasted and tested at room temperature. The failure mode is observed to change from substrate failure at room temperature to adhesive failure after environmental conditioning.

Adhesive results before environmental conditioning were compared to results after environmental conditioning. Table 21 shows the comparison results. The grit blasted surface preparation degraded when exposed to environmental conditions for both adhesives. The Loctite degraded 22% and the SIA degraded by 14%. Results, which had chemical surface treatment, performed better when subjected to environmental conditions than specimens that had no chemical surface treatment. The Loctite adhesive that was grit blasted and chemical treated prior to environmental exposure had a 9% increase in failure load, than the specimen that was only grit blasted prior to environmental exposure. The SIA specimens show a 7% increase in failure load when comparing the specimen that where grit blasted, acid etched, and environmental conditioned to those that were just grit blasted and environmentally conditioned.

These results suggest that chemical treatments can help promote long-term bond integrity for conditions where environmental conditions are a factor.

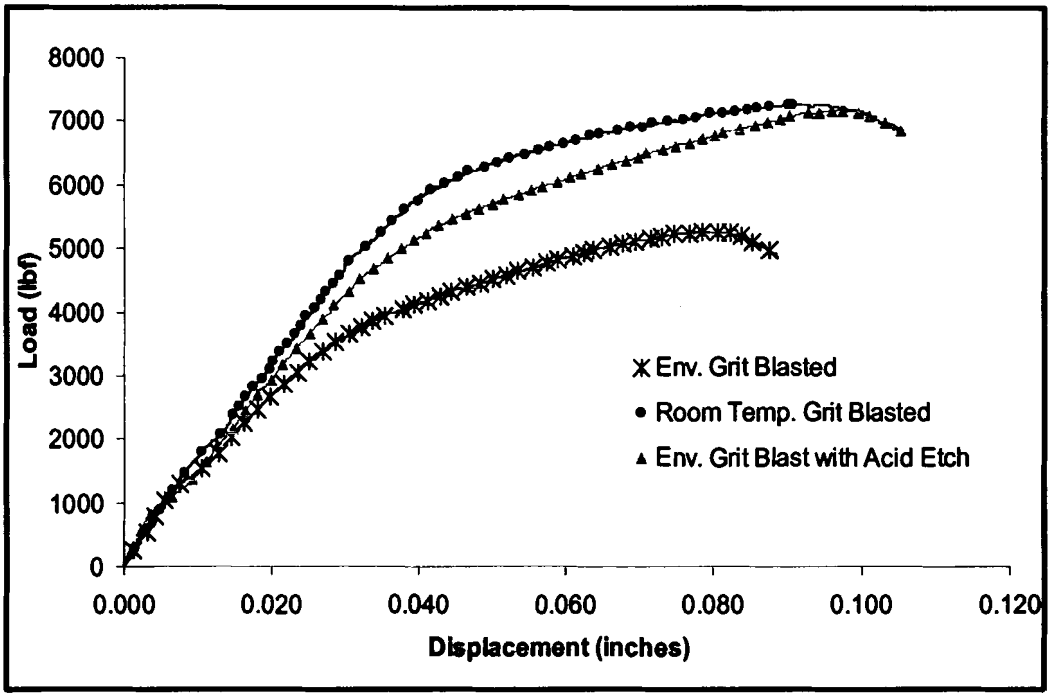


Figure 65– SIA Environmental Comparison of 0.100" Bondline Samples

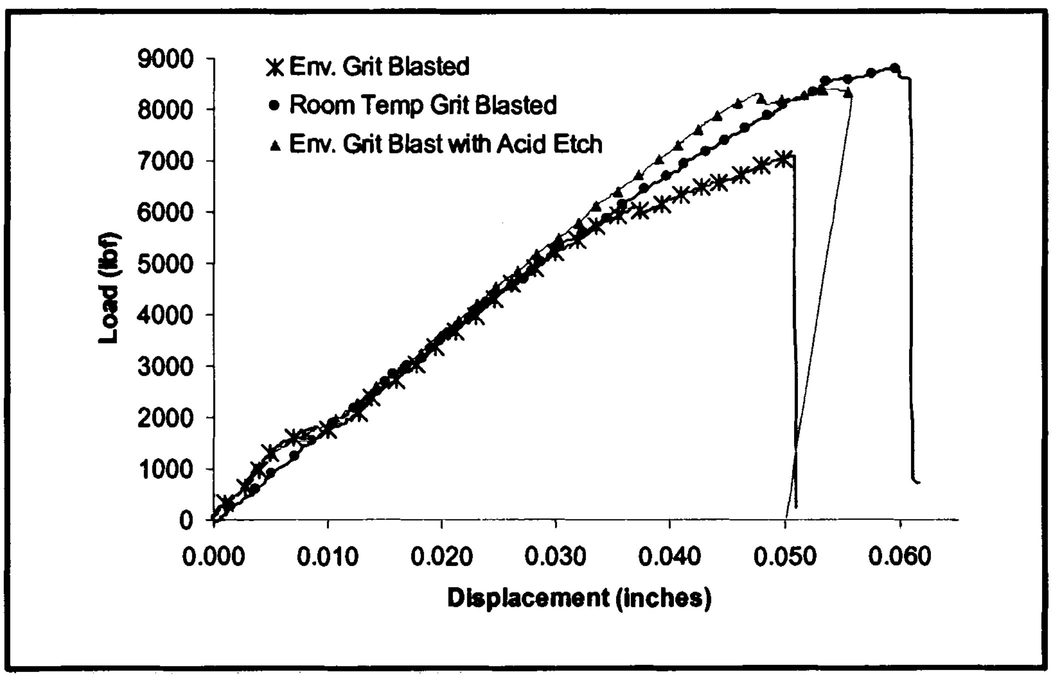


Figure 66 – Loctite 9359.3 Environmental Comparison of 0.100" Bondline Samples

Table 20 – Apparent Shear Strength – Environmentally Conditioned

Adhesive	Aluminum Surface Preparation	Test #	Failure Load	Nominal Stress	Failure Mode
Loctite 9359.4	Grit Blast	1	7105	1776	AFWA
		2	6113	1528	AFWC
		3	5600	1400	AFWA
		4	6794	1698	AFWA
		5	6175	1544	AFWA
		Ave	6357	1589	

Adhesive	Aluminum Surface Preparation	Test #	Failure Load	Nominal Stress	Failure Mode
Loctite 9359.4	Grit Blast and Acid Etch	1	5602	1400	SFIC
		2	8390	2098	AFWA
		3	7633	1908	SFIC
		4	7814	1954	AFWA
		5	5462	1366	SFIC
		Ave	6980	1745	

Adhesive	Aluminum Surface Preparation	Test #	Failure Load	Nominal Stress	Failure Mode
SIA	Grit Blast	1	5308	1327	AFWA
		2	5796	1449	AFWA
		3	6712	1678	AFWA
		4	6193	1548	SFIC
		5	5635	1409	AFWA
		Ave	5939	1485	

Adhesive	Aluminum Surface Preparation	Test #	Failure Load	Nominal Stress	Failure Mode
SIA	Grit Blast and Acid Etch	1	6554	1638	AFWA
		2	7024	1756	AFWA
		3	5541	1385	AFWA
		4	6278	1570	SFIC
		5	6703	1676	SFIC
		Ave	6373	1593	

Table 21 – Environmental vs. Room Temperature Comparison

Strength Change @ 0.100" Bondline			
Test Compared		% Difference	
		Loctite	SIA
Grit Blast - RT	GB + AE - RT	-36%	-27%
Grit Blast - RT	Grit Blast - HW	- 22%	- 14%
Grit Blast - RT	GB + AE HW	- 15%	- 7%
Grit Blast - HW	GB & AE HW	+ 9%	+ 7%

Average Failure Load @ 0.100" Bondline		
	Loctite	SIA
Grit Blast - Room Temp	8166	6885
Grit Blast + Acid Etch – RT	5194	4987
Grit Blast – HW	6357	5939
Grit Blast & Acid Etch – HW	6980	6373

3.5 Effects of Various Connection Geometries

With the concentration of this study focusing on single lap tensile shear testing, it was desired to test the adhesives in other hybrid joint configurations. Double lap shear tensile testing and flexure testing was chosen. The purpose of the double lap shear tensile test is to study the adhesive while preventing rotation of the joint. This prevention of rotation at the joint would limit the peel stresses induced in the joint. FEA analysis shows that the reduction of peel stresses could be as much as 50% for a single lap compared to a double lap joint. This reduction in peel stressed would allow a more accurate determination of adhesive shear strength. Initially specimens were fabricated with double lap joints such that the centerline adherends where spaced approximately 5 inches apart to resemble the single lap joints. This resulted in premature failure at a reduced load. Loads achieved where not much greater than those experienced by single lap shear testing with twice the shear area available. Table 22 shows the loads that were achieved prior to failure for the long double lap shear specimens. Figure 67 shows a double lap shear specimen that was fabricated with centerline adherends spaced approximately five inches apart.

Table 22 – Double Lap Shear Maximum Load

Adhesive	Specimen	Max Load	Failure Mode
Loctite	1	10276	AFWA
	2	6312	AFWA
	3	8647	SFIC
	Average	8412	
SIA	1	8434	SFIC
	2	8413	SFIC
	3	7998	SFIC
	Average	8282	

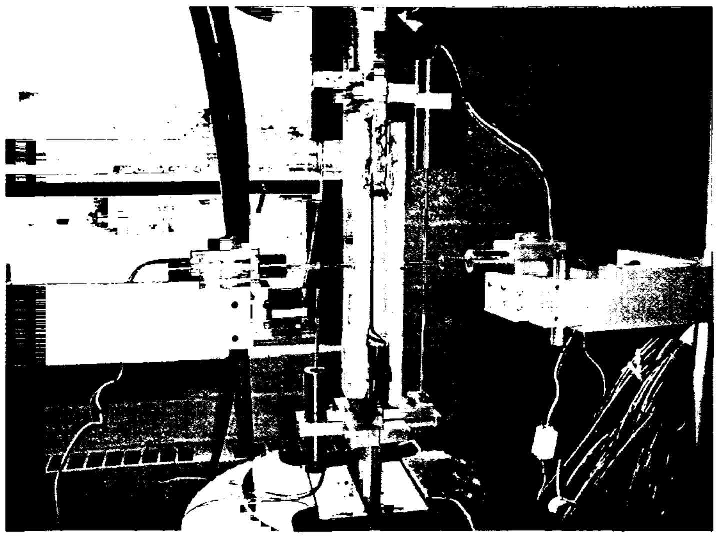


Figure 67 - Double Lap Shear Specimen During Testing

Even though FEA analysis showed little difference caused by changing the center adherend spacing, it was decided to reducing this spacing of the centerline adherends to approximately one half an inch. This reduction in spacing provided increased load transfer capability from the "long" double lap shear specimens. Figure 68 shows the testing of a double lap shear specimen that has a reduced gap between centerline adherends.

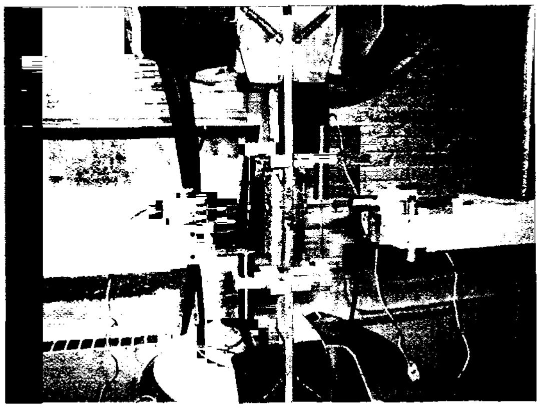


Figure 68 – Double Lap Shear Specimen with Reduced Gap

By reducing this gap between the centerline adherends, loads equivalent to, or greater than those experienced by the single lap shear where achieved. Table 23 shows the load achieved when testing the "short" double lap shear specimens.

Table 23 – "Short" Double Lap Shear Maximum Load

Adhesive	Specimen	Max Load	Failure Mode
Loctite	1	21577	SFIC
	2	14009	AFWA
	3	21267	AFWA
	Average	18951	
SIA	1	13016	CFIA
	2	13168	CFIA
	3	11071	SFIC
	Average	12418	

Moment transfer of a joint is also of importance in determining adhesive properties. Because moment capacity for adhesives needs to be established, four point flexure tests where implemented. These tests were preliminary test in order to understand the requirements associated with this type of test. Test results can be found in Table 24. It should be noted that the test fixtures used for this test were designed by University of Maine personnel and manufactured by Alexander's Welding and Machine. Figure 69 shows the flexure setup.

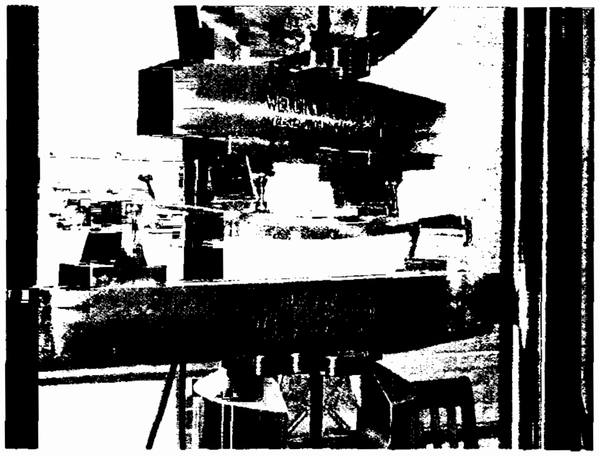


Figure 69 – Flexure Fixture

The results presented in Table 24 show that the Loctite 9359.3 adhesive with a sanded surface preparation achieved the highest load.

Table 24 - Maximum Load Achieve in Flexure Testing

Adhesive	Aluminum Surface Preparation	Sample	Max Load	Failure Mode
Loctite 9359.3	Grit Blasted	1	394	AFWC
		2	402	AFWC
		3	413	AFWC
		Ave	403	
	Sanded	1	422	AFWC
		2	452	AFWC
		3	416	AFWC
		Ave	430	
SIA E2119	Grit Blasted	1	349	CFIA
		2	224	CFIA
		3	288	CFIA
		Ave	287	
	Sanded	1	371	CFIA
		2	273	CFIA
		3	206	CFIA
		Ave	283	

4. Summary, Conclusions, and Recommendations

Summarized here in is an experimental study of adhesives for use in naval applications. This study was accomplished by performing single lap shear tests of six different adhesives and three different surface preparations, as screening tests to compare relative performance of the adhesives studied. Adhesives were of the epoxy type and included Loctite 9359.3, Loctite 9430, Loctite 9394, 3M 2116, SIA E 2119, and Belzona 1121. The surface preparations included: grit blasting, mechanical sanding, and acid etch with chromate conversion. Adherends consisted of Aluminum on one end and E-glass vinyl ester on the other. In addition, environmental testing was performed using Loctite 9359.3 and SIA E 2119 with surface treatments including grit blasted and grit blasted with acid etch. Some preliminary four point flexure tests and double lap shear tests were also accomplished. This study also included a linear finite element analysis of the single lap shear geometry as a first cut estimate of the stresses and deformations induced in the joint.

One of the goals of this effort is to provide baseline mechanical property data that will guide adhesive selection for both the MACH and AHFID programs. Both of these programs have as one of their objects the development of composites for naval application. Specifically, in the MACH program the goal is to develop a hybrid structural system that will employ connections where composites and metals are joined together. The focus of the AHFID program is to develop a rim drive propulsor that uses all electric drive technology. The information developed in this study will be used as part of a feasibility assessment of using a composite strut to attach the rim drive propulsor to an aluminum-hulled vessel. Techniques used in this study for specimen manufacturing were prescribed so as to be practical and economical for shipyard application.

Bondline thickness, surface preparation, and environmental conditions were varied in an effort to quantify the relative response on structural performance. In studying the relative response of the six different adhesives during the initial screening tests at room temperature a bondline of 0.100" was used. This phase 1 testing provided baseline data of the mechanical properties for each adhesive and for each surface preparation. From these initial tests, two adhesives (Loctite 9359.3 and SIA E 2119) were selected for further study due to their higher relative nominal shear strength. Three different bondline thicknesses (0.060", 0.100", 0.250"), two different surface preparations (grit blasted, grit blasted plus acid etching), and environmental exposure were studied for these two adhesive.

Several conclusions were made from the initial screening test results. First, the Loctite 9359.3 and the SIA E 2119 adhesive systems provided the greatest nominal shear strength regardless of surface preparation, for a 0.100" bondline. For the Loctite 9359.3 adhesive it appears that grit blasting results in higher nominal shear strength (2042 psi) than sanding or acid etching. For the SIA E 2119 the highest nominal shear strength was achieved using an acid etch surface treatment (1839 psi). Failure modes for the Loctite adhesive with a grit blasted surface preparation where substrate failures in the composite adherend. Indicating that improvement in composite architecture may results in higher joint strengths. Failure modes for the SIA adhesive with an acid etch surface preparation was also a composite failure. Two of the three specimens using the SIA adhesive and a grit blasted surface preparation failed cohesively.

It was verified that as the adhesive bondline increases the apparent shear strength decreases. A 26% and a 30% reduction in nominal shear strength were observed in the Loctite and the SIA adhesives respectively as the bondline increased from 0.060" to 0.250". The nominal shear strength of a given adhesive was found to be highly dependent on the combined shear, peel, and in plane stress state through the joint. As the bondline increases, the failure mode changes. At thinner bondlines the failure mode was predominately substrate failure in the composite for the Loctite and SIA adhesive where the composite adherends failed in the first ply due to delamination. The failure migrates from substrate failure toward adhesive failure as the bondline increases. Several specimens of the SIA adhesive were observed to fail cohesively at the intermediate bondline thickness. It was observed that the failure experienced with the Loctite 9359.3 adhesive was always very drastic in nature. This was due to the ductility of the adhesive once cured. The SIA adhesive produced failures that progressed slowly over a noticeable amount of time. This allowed the failure to be observed in more detail and makes detection of an in-service failure more likely.

The Loctite 9359.3 and SIA E 2119 adhesives combined with grit blasted and grit blasted plus acid etch were tested to evaluate the effect of environmental conditions on adhesive properties relative to joint characteristics. In an attempt to improve the results in a moisture environment, a surface treatment of grit blasting with subsequent acid etching and chromate conversion treatment where tested. Specimens where created with 0.100" bondline. After allowing the specimens to cure for a minimum of 120hrs, they were subjected to environmental conditions of 98-99 % relative humidity and 150 deg. F for one month. Moisture absorption as measured by the specimen's weight gain approached an asymptotic value at the one-month period. When grit blasting alone was used a decrease in strength of 22% and 14% were observed when comparing room temperature grit blasted to environmental conditioned grit blasted specimens with the Loctite 9359.3 and SIA E 2119 respectively. Under hot wet conditions, the grit blast plus acid etch surface treatment resulted in an increase in strength of 9% and 7% for the Loctite and SIA adhesives, respectively, when compared to grit blasting alone. There was a shift in failure mode to predominately adhesive failures under environmental conditions. Although there were still several failures observed in the composite substrate.

Due to the hybrid nature of the joint, consideration must be given to the effects of hygro-thermal response in different environments. The moisture in the environment causes absorption in the composite and adhesive that must be considered in the design of the joint. This study had a limited number of test articles. There is high variability in the nature of the response of the hybrid joints due to the materials used and the fabrication techniques. This study only touched on environmental effects relative to bond strength and bondline thickness. Control of temperature and humidity during specimen preparation and testing should be exercised in an effort to quantify their effects.

Relative to the data acquired from this testing, lessons have been learned thereby generating recommendations for further studies. These recommendations are as follows:

1. Improve composite quality used in tests to minimize substrate failure experienced.
2. Retest SIA E 2119 and Loctite 9359.3 using controlled temperature and humidity conditions during specimen fabrication and testing.
3. Expand database by including Loctite 9430 as a third adhesive system.

4. Expand study to include steel adherends.
5. Look for practical "novel" surface treatments, which can be applied in a shipyard environment.
6. Test adhesive systems under repetitive cyclic loading.
7. Expand flexure and double lap shear testing.
8. Perform tension testing on adhesive systems.

Implementing these recommendations will provide a better understanding of the adhesives tested so that this information might be used in composite ship hybrid joint design.

In an effort to support the AHFID and MACH program, it is the position of this author that the adhesive SIA E2119 be utilized for installing the AHFID strut into the manufactured boot fixture, which will be mounted in the University of Maine reaction frame located in Boardman Hall. Grit blasted with acid etch surface preparation should be performed. For the MACH program, testing should be performed on actual joint geometry at room temperature and at high moisture and elevated temperature for the SIA E 2119 and the Loctite 9430 adhesives. The Loctite 9430 should be considered due to its relative strength performance and low cost.

Acronyms

ASTM	American Society for Testing and Materials
BIW	Bath Iron Works
CTE	Coefficient of Thermal Expansion
FEM	Finite Element Model
FWT	Flat Wise Tension
HYSWAC	Hybrid Small Waterplane Area Craft
ICD	Interface Control Document
MPP	Manufacturing Process Plan
NDE	Non Destructive Evaluation
NAVSEA-CD	Carderock Division of the Naval Surface Warfare Center
PACMAR	Pacific Marine and Supply Company
PPT	Per Ply Thickness
STM	Standard Material Specification
STP	Standard Process Specification
TBD	To Be Determined
TBR	To Be Revised
UMaine	University of Maine

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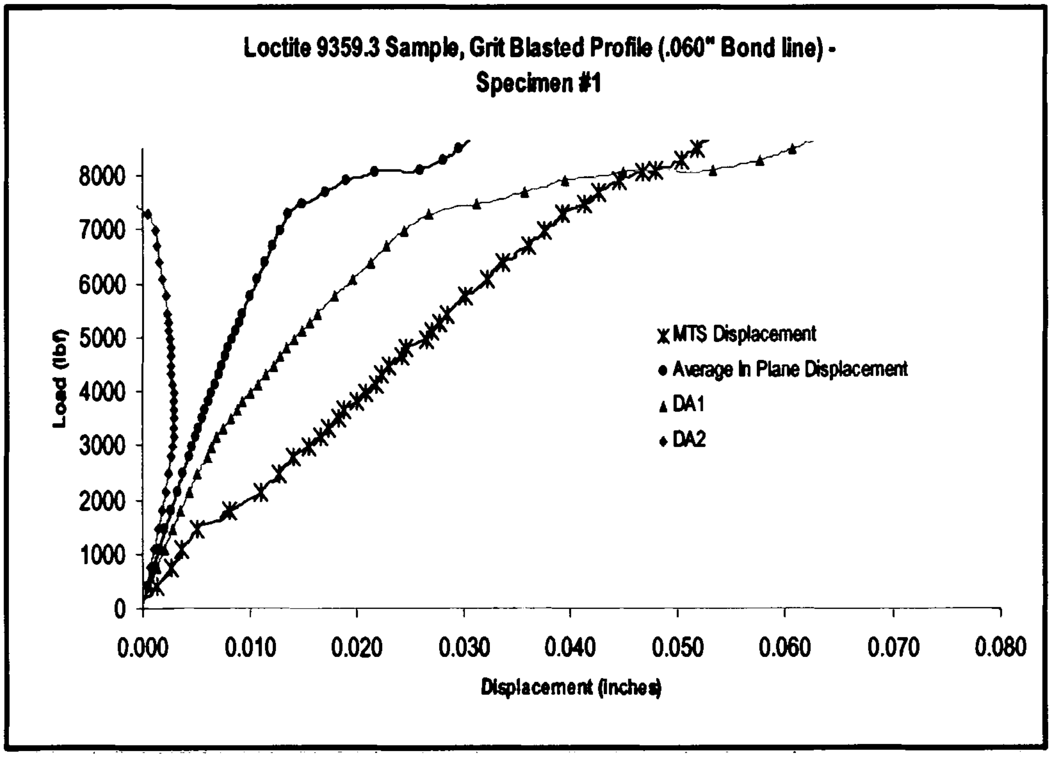
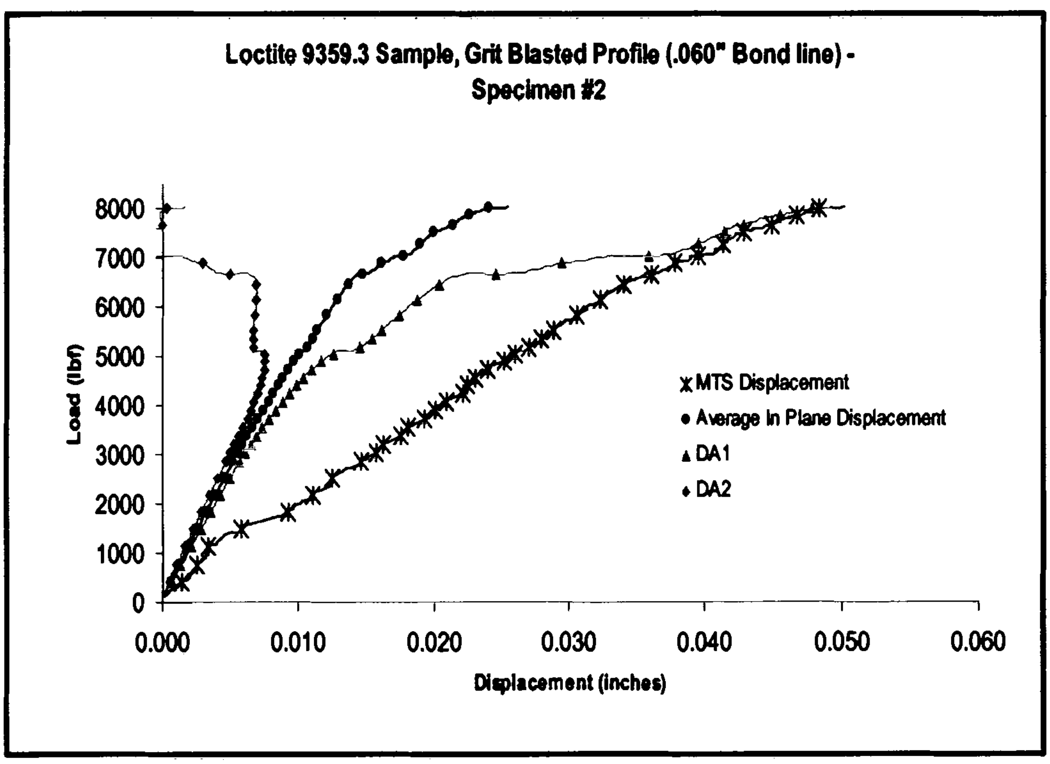
Appendicies

Appendix A

Mechanical Testing of Epoxy Adhesives Test Results

Figure A.1 - Lap Shear Testing Results





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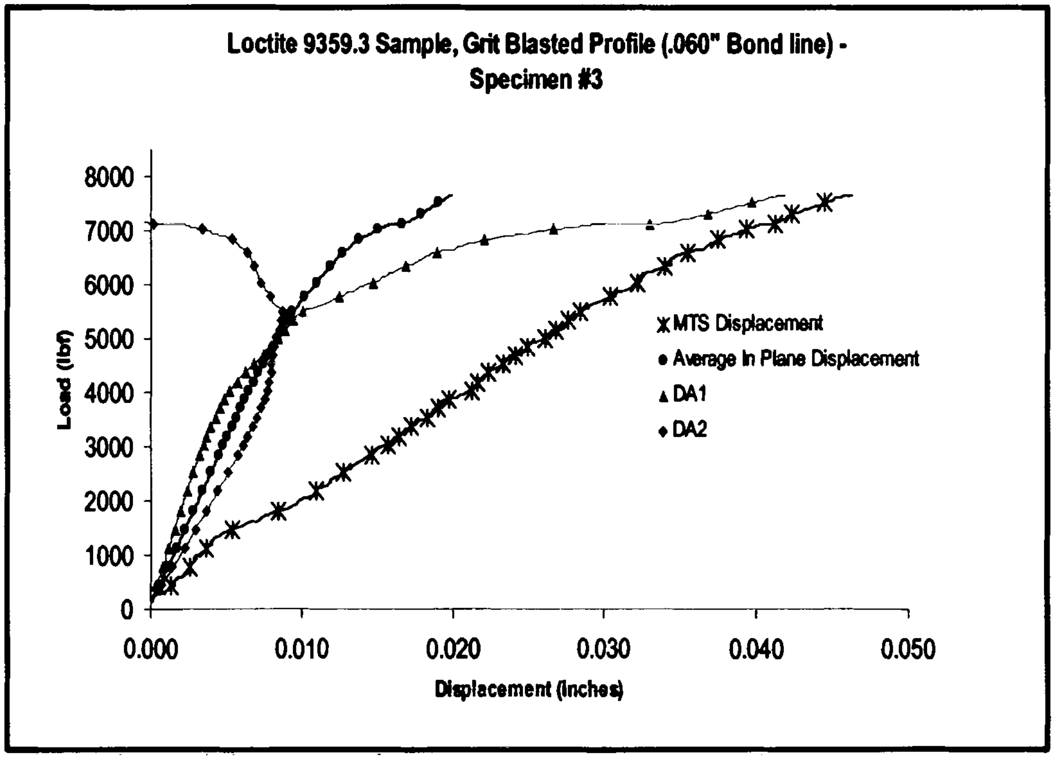

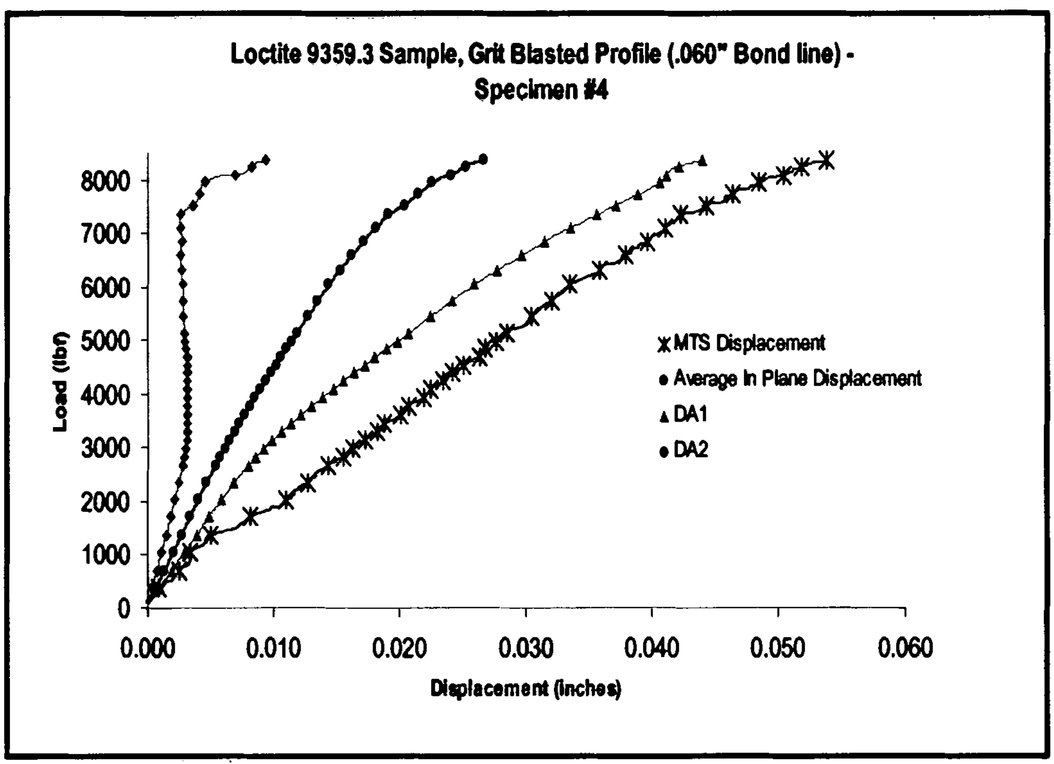

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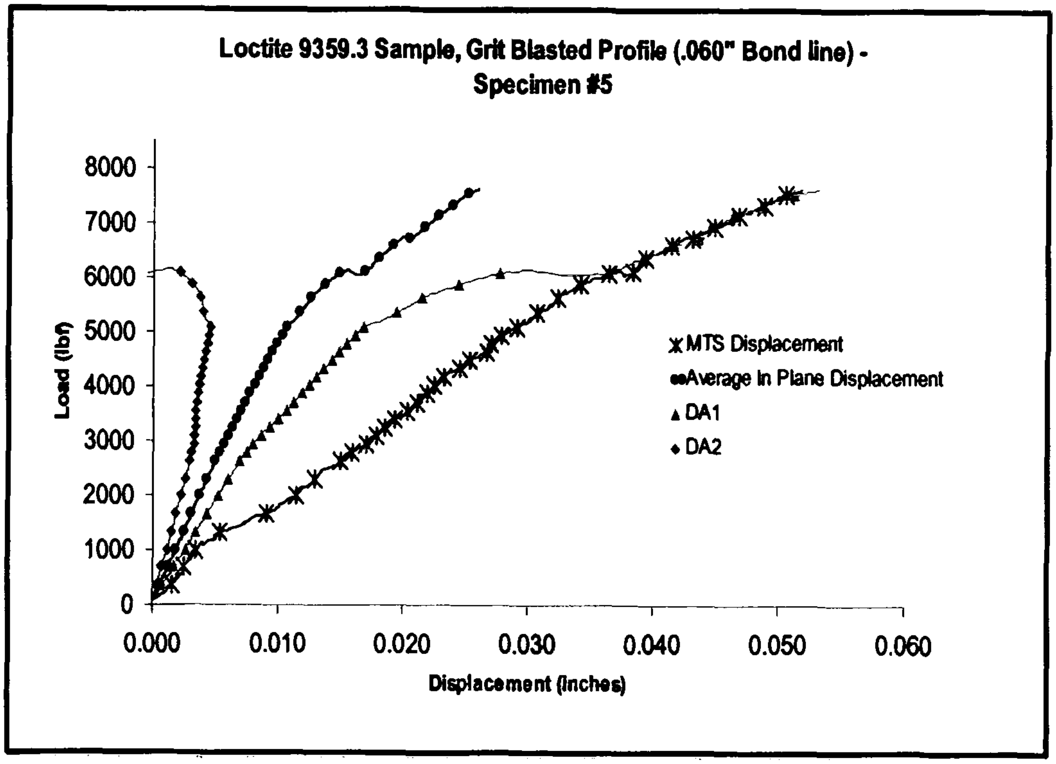

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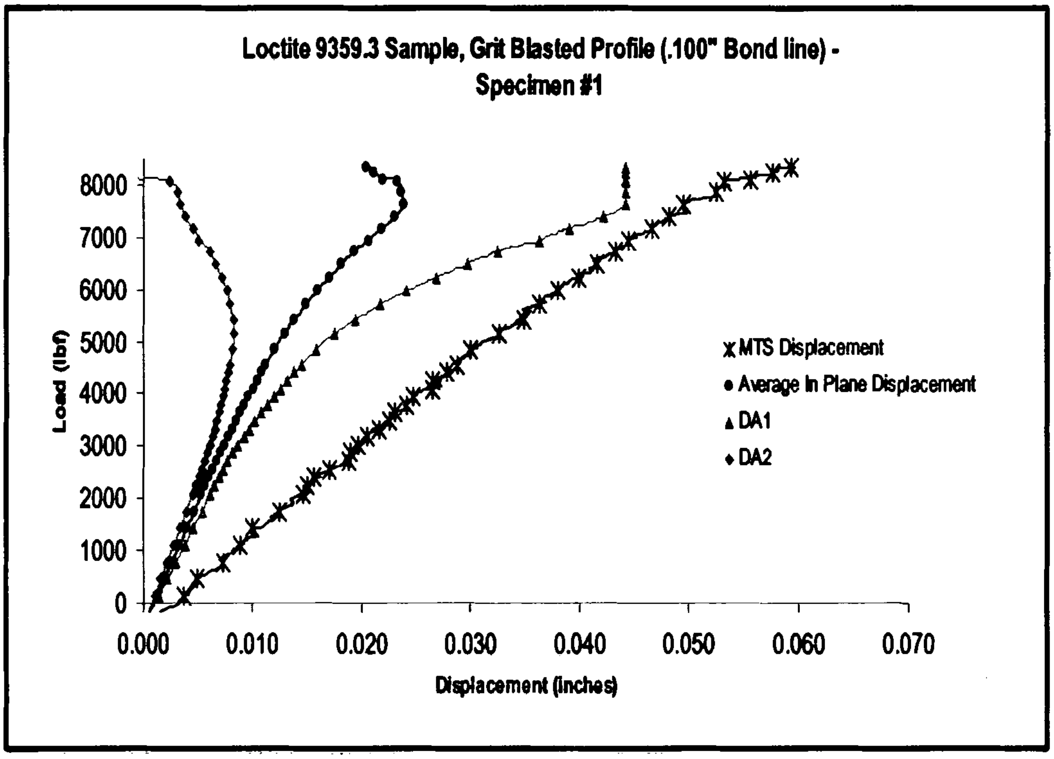

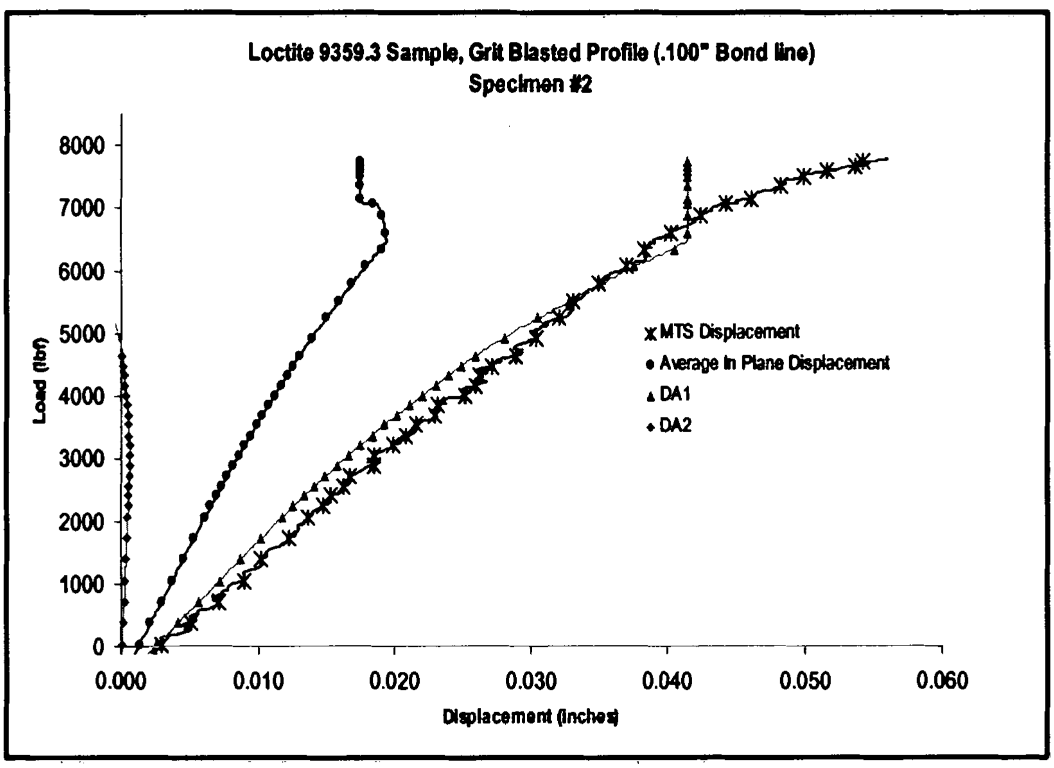

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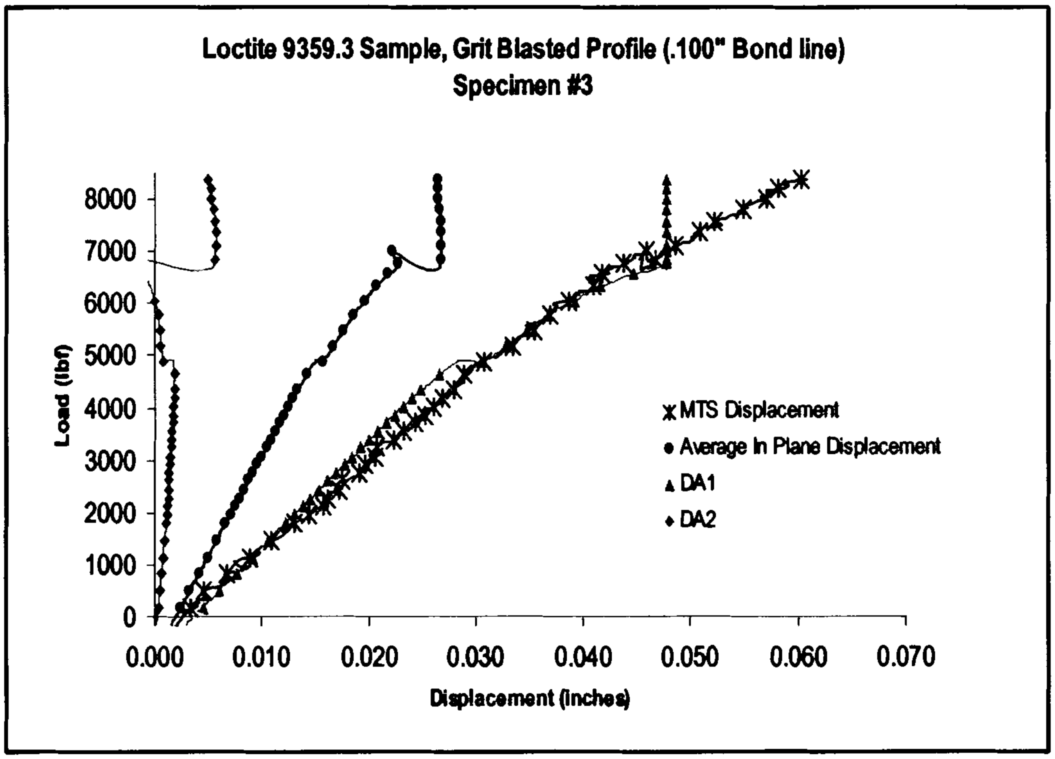

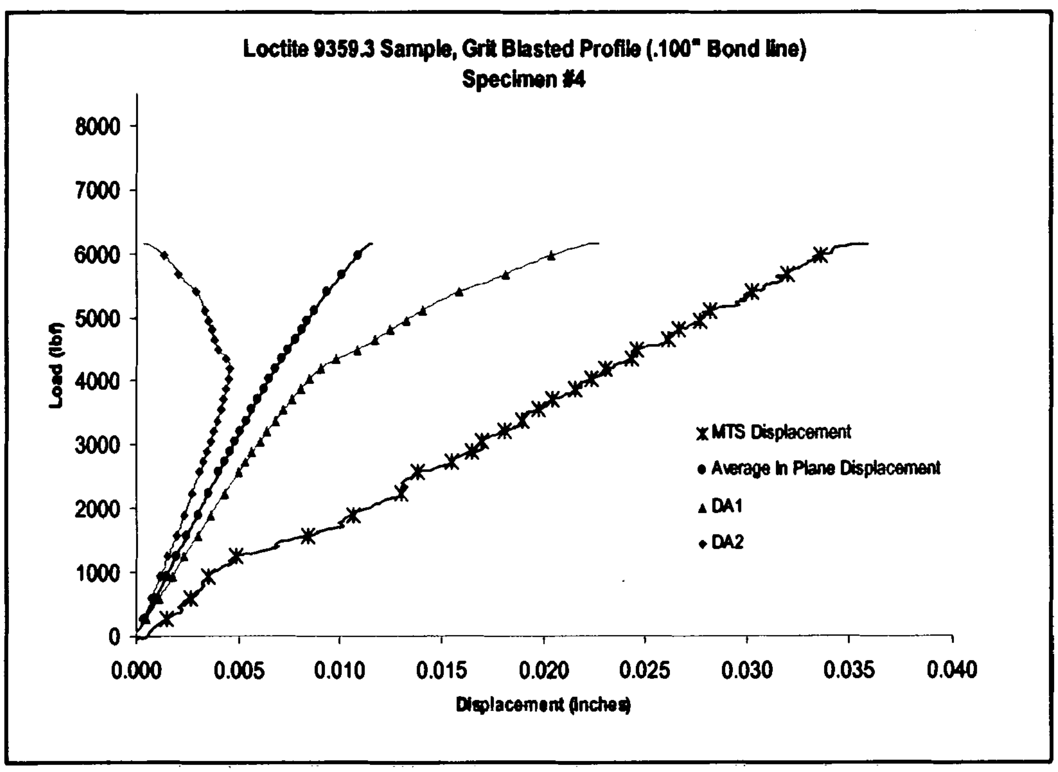

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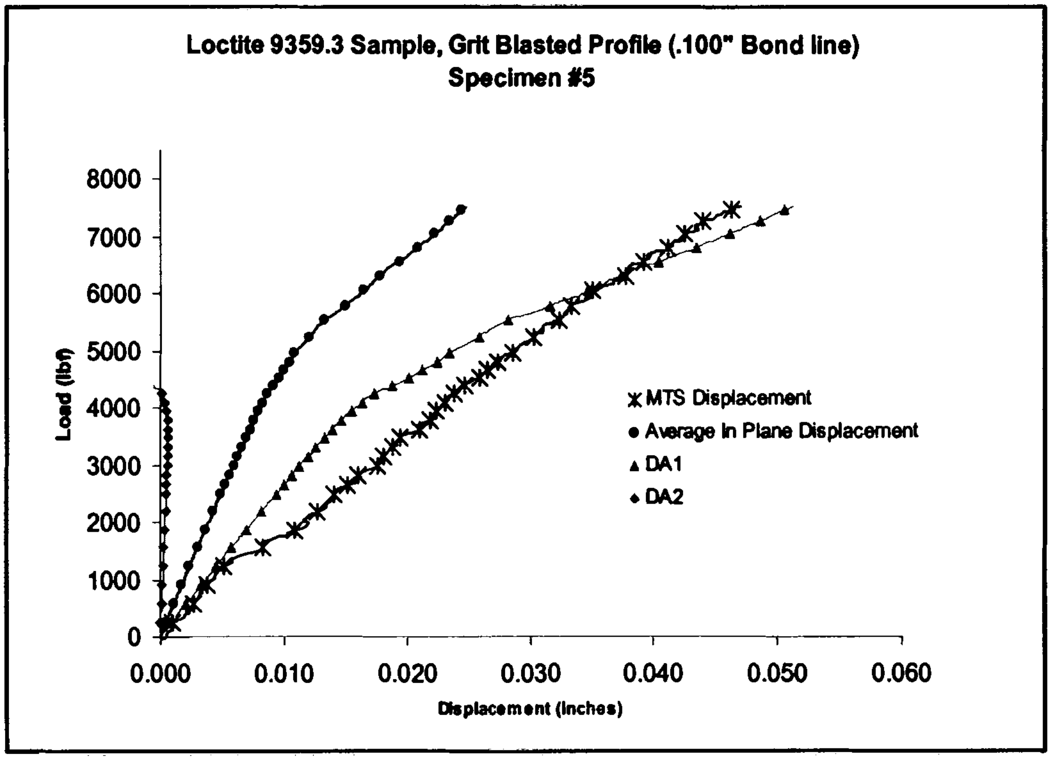

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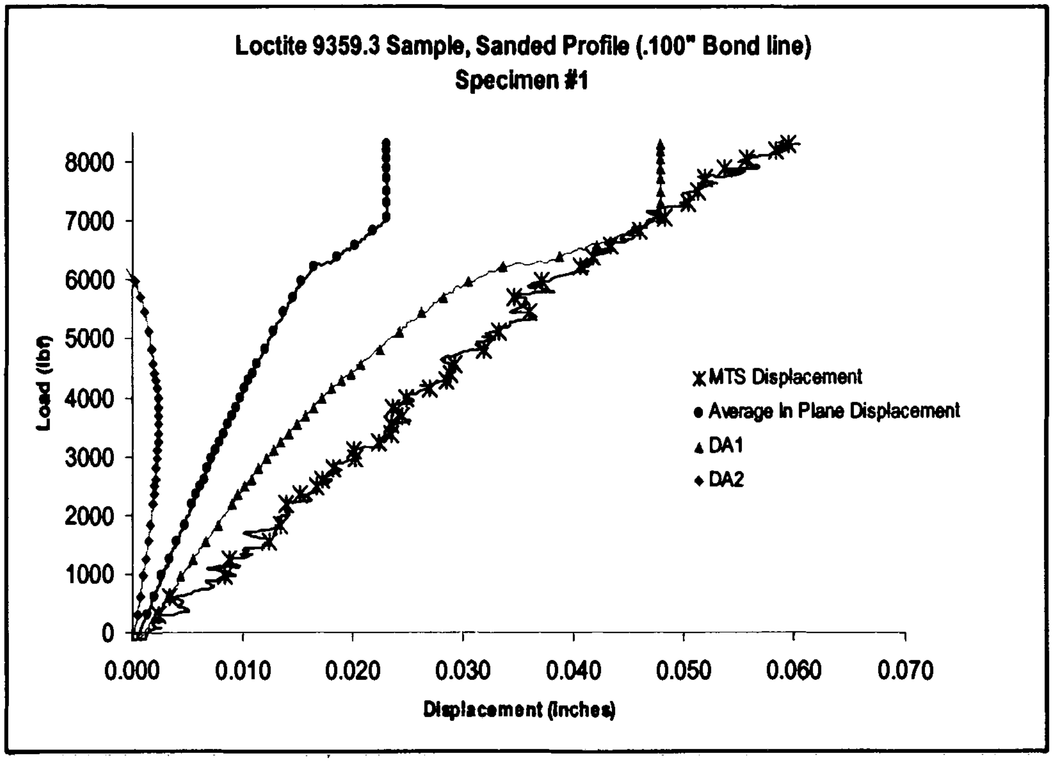

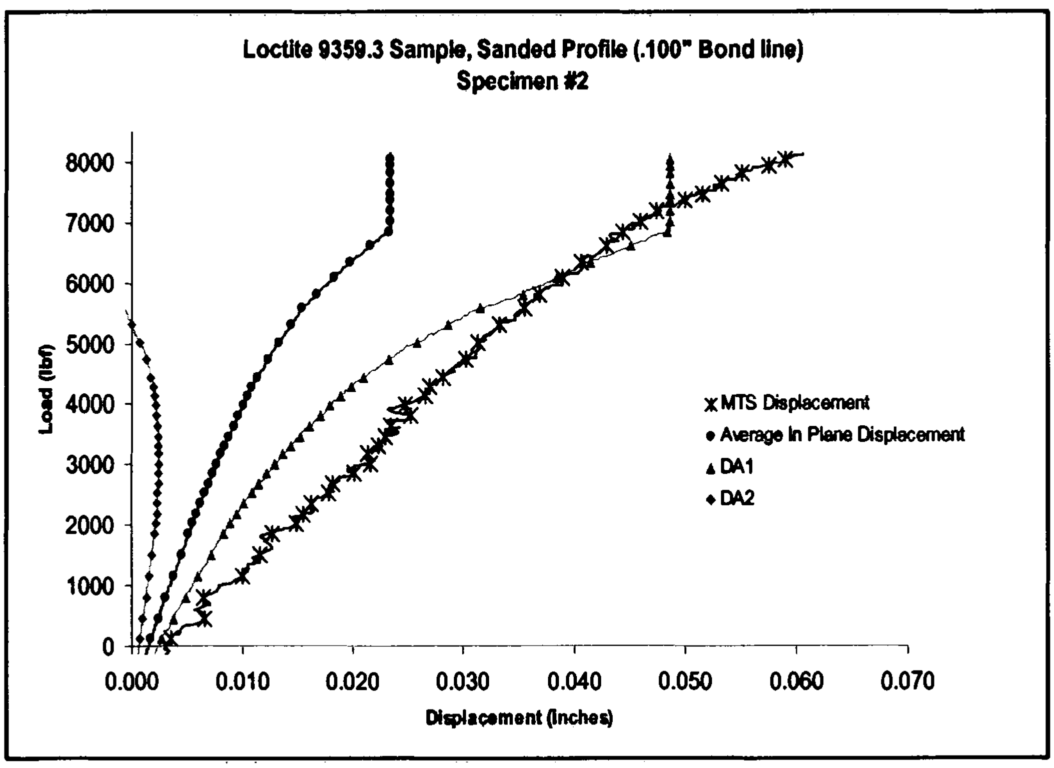

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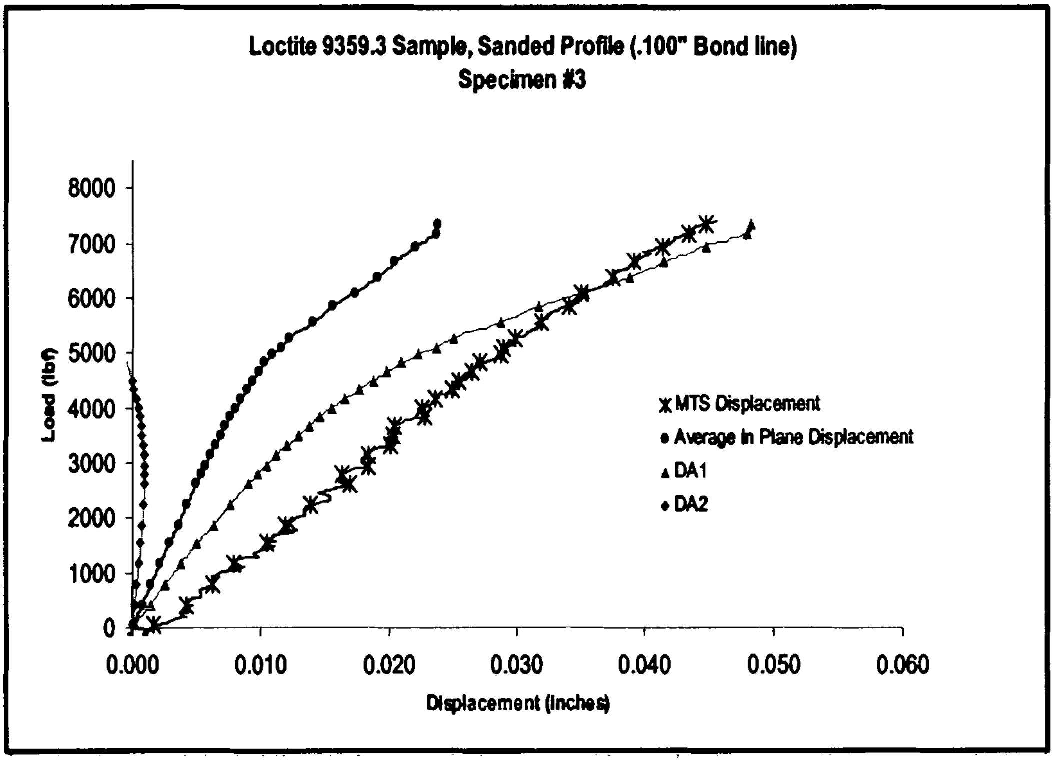

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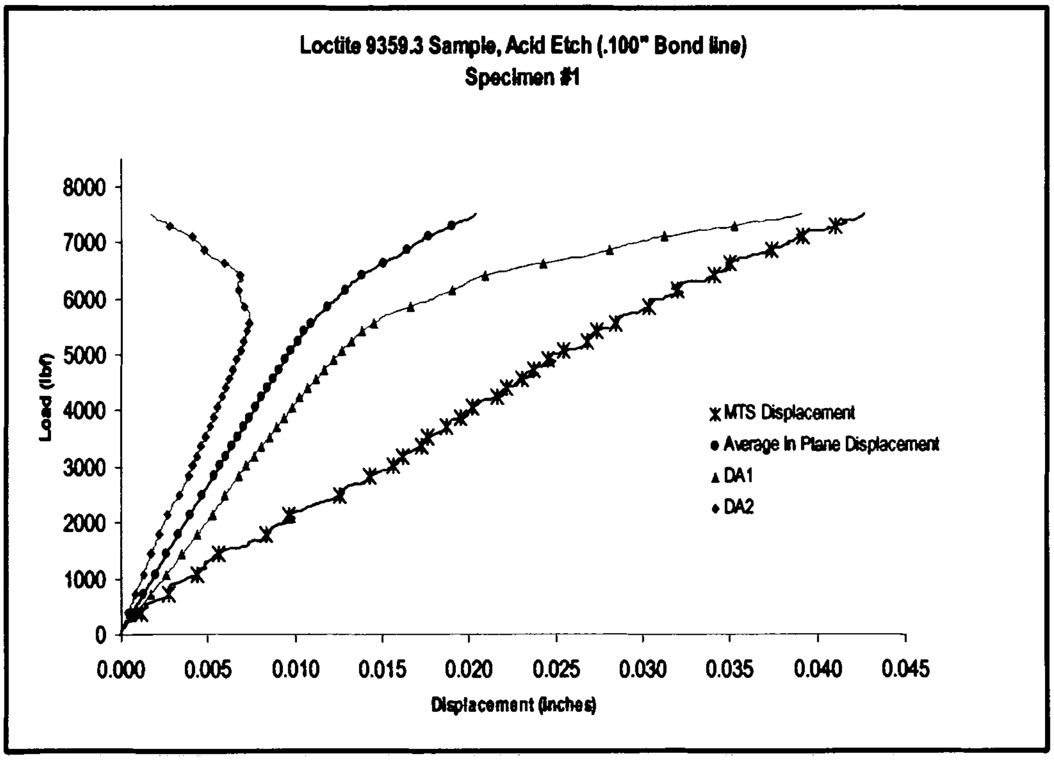

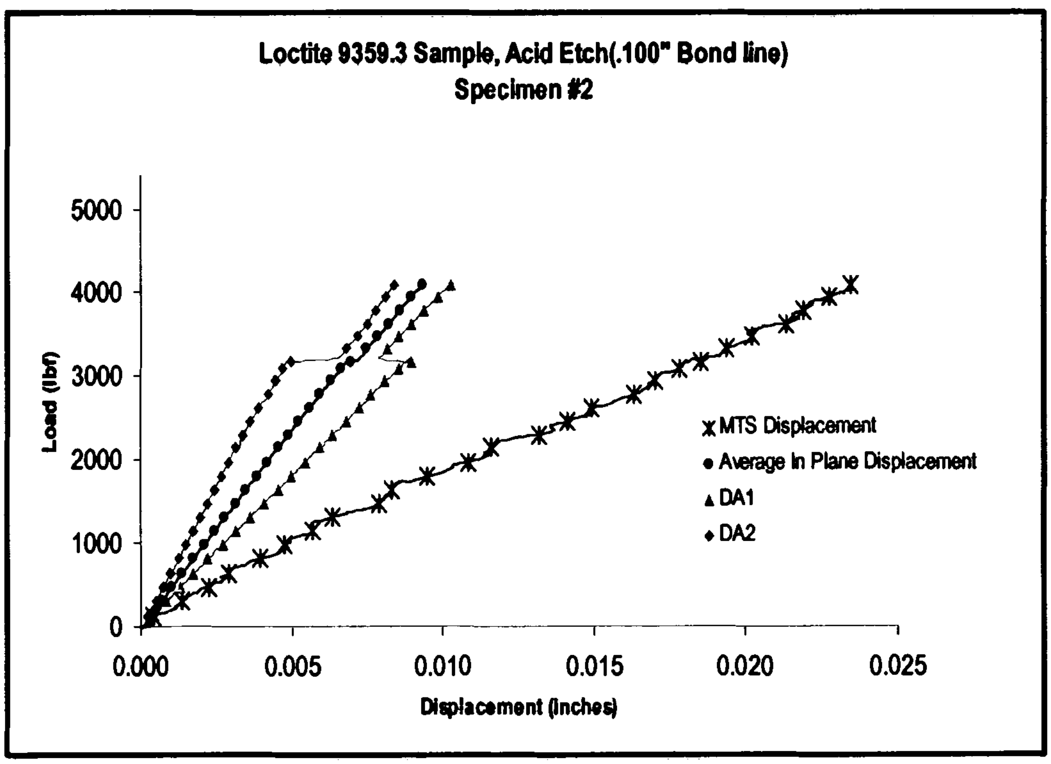

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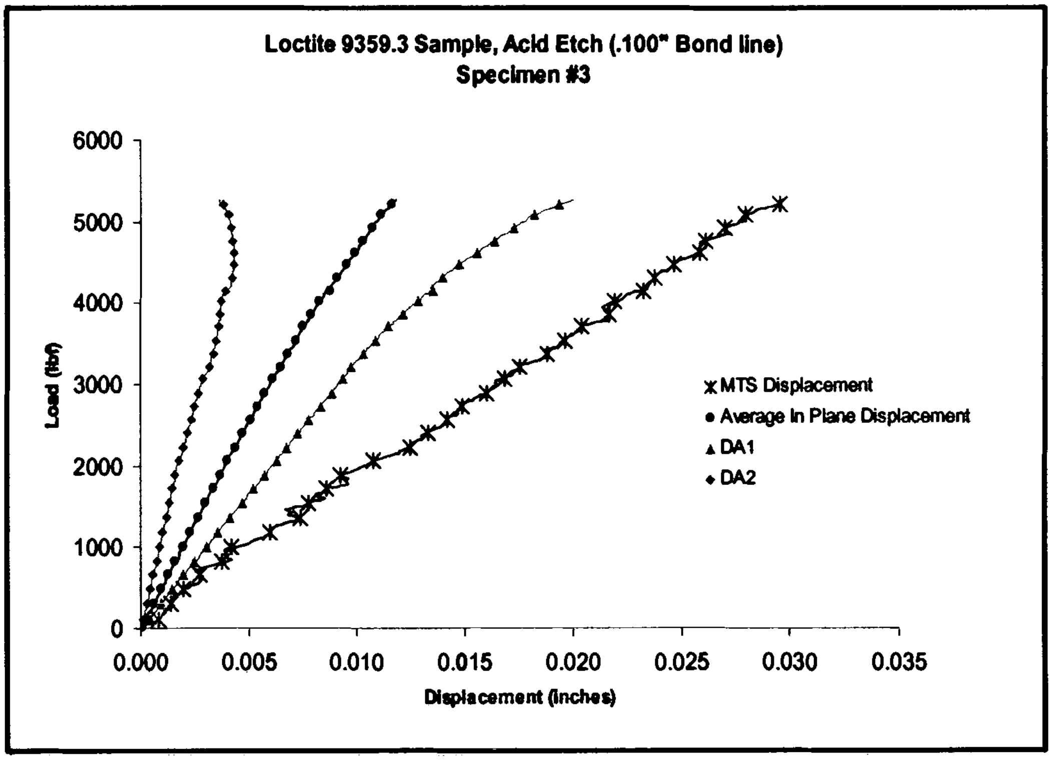

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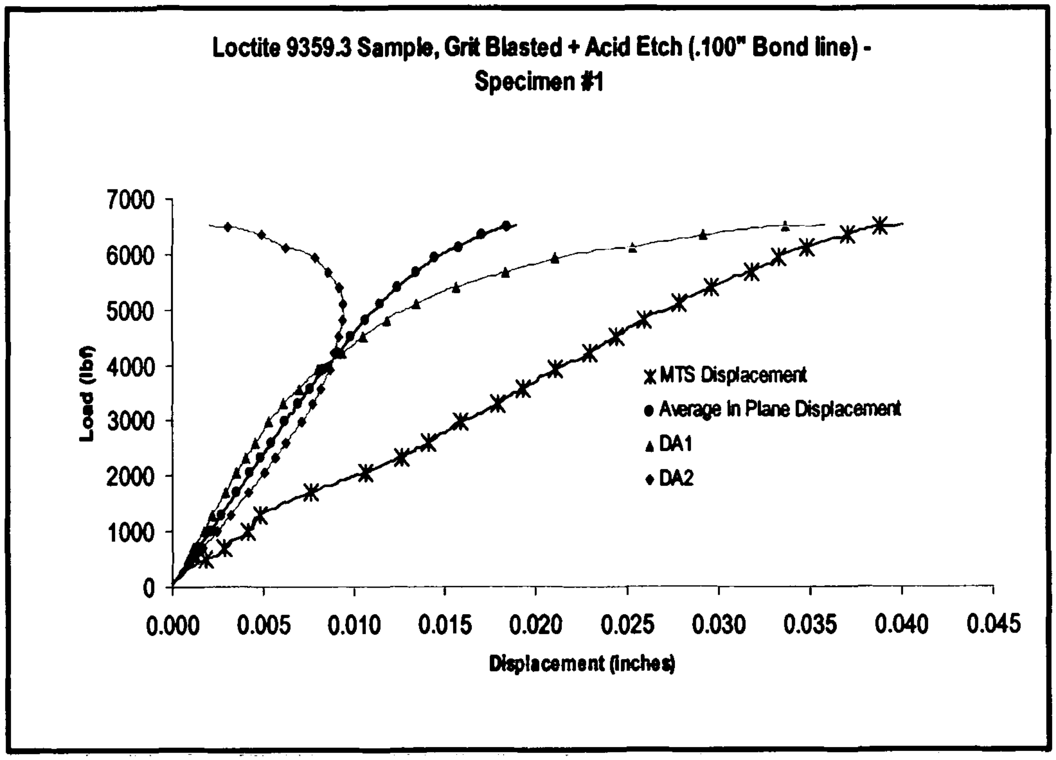

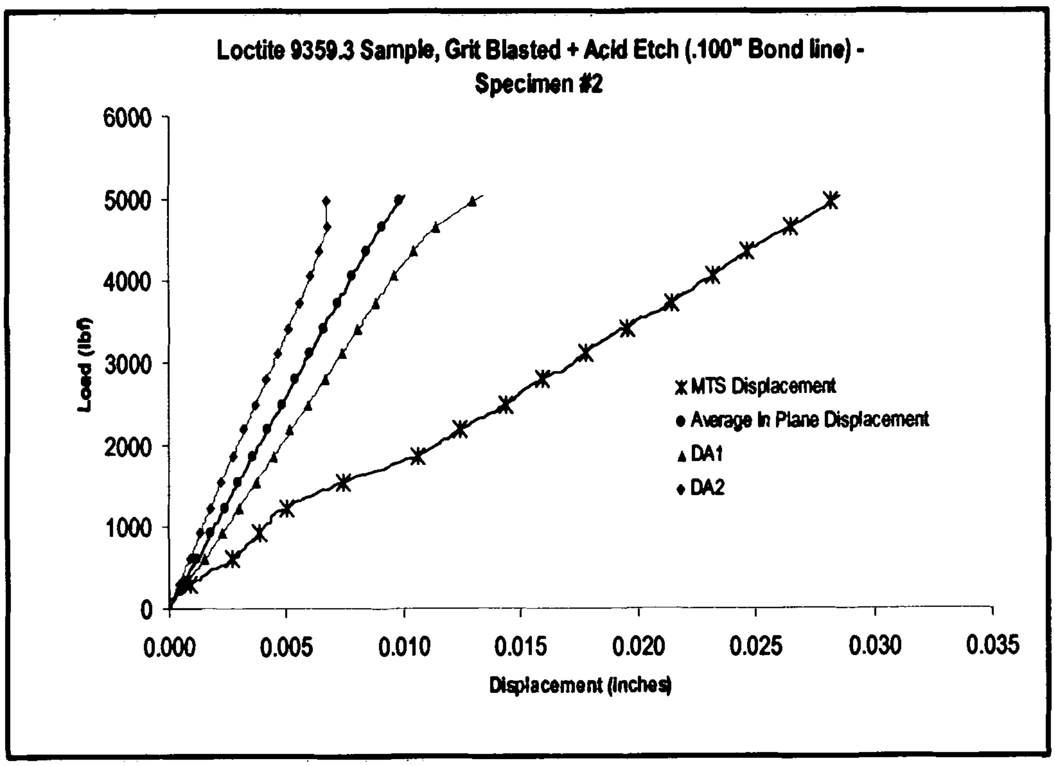

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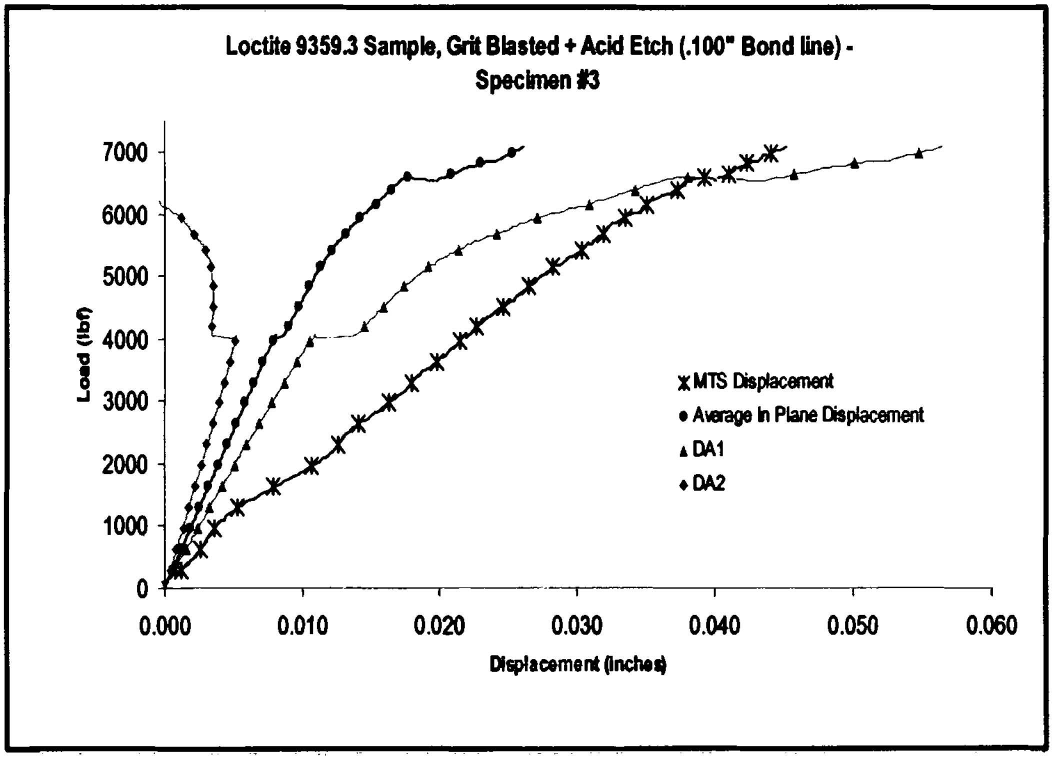

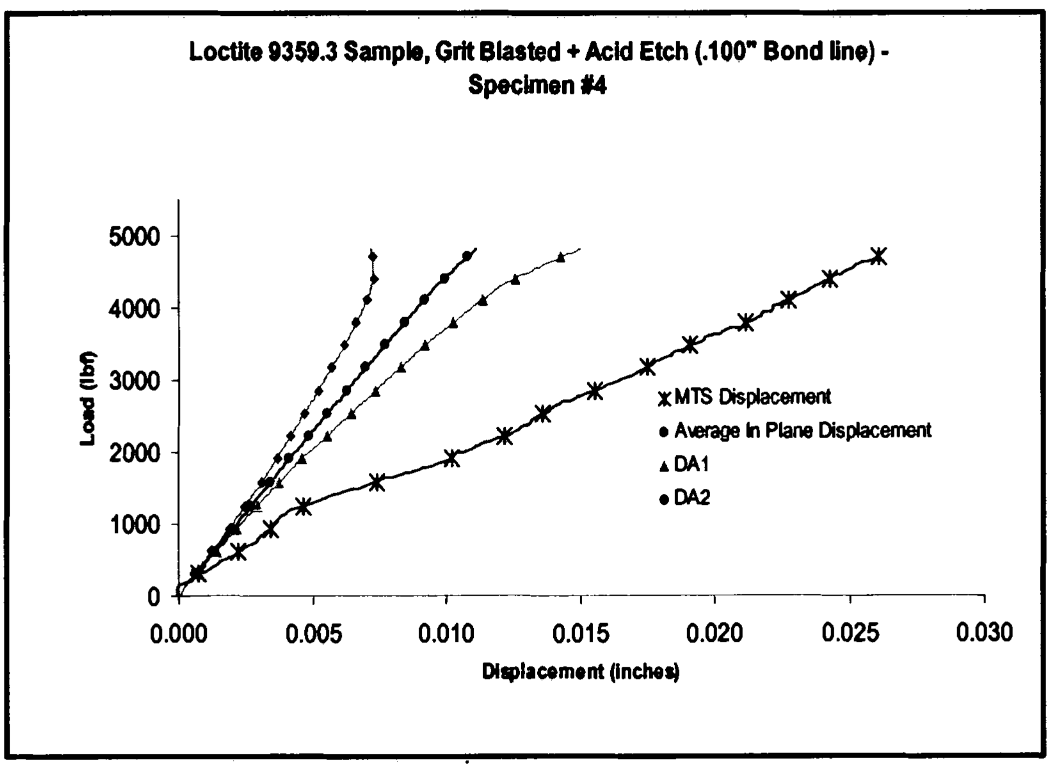

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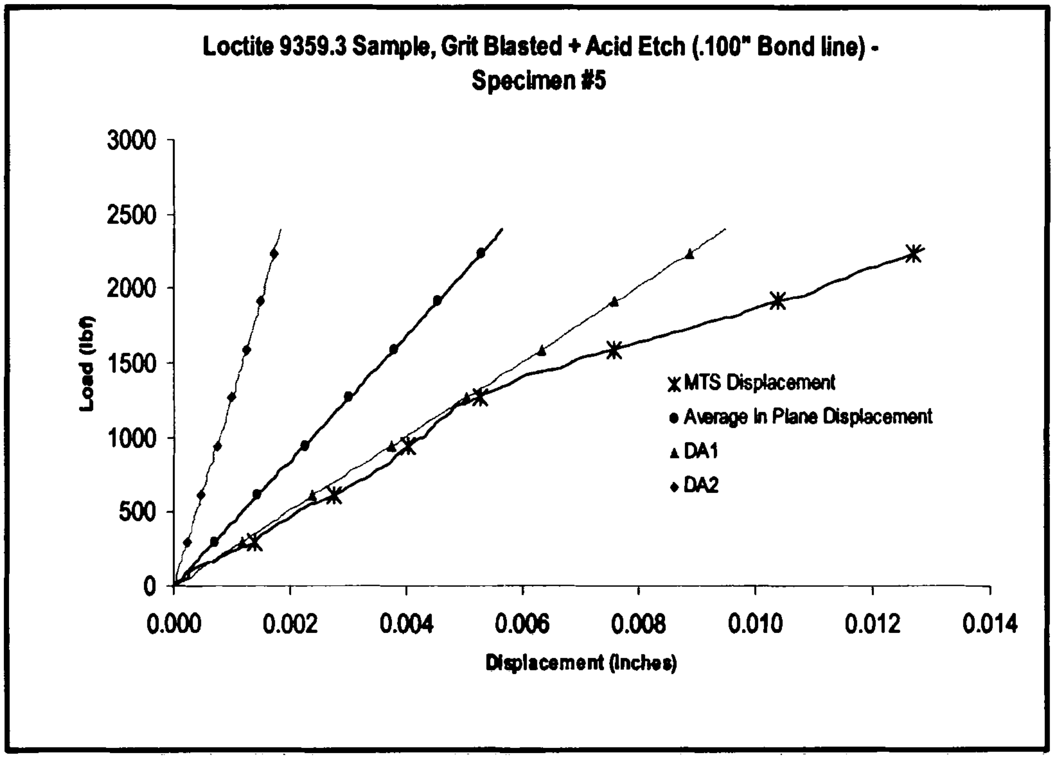

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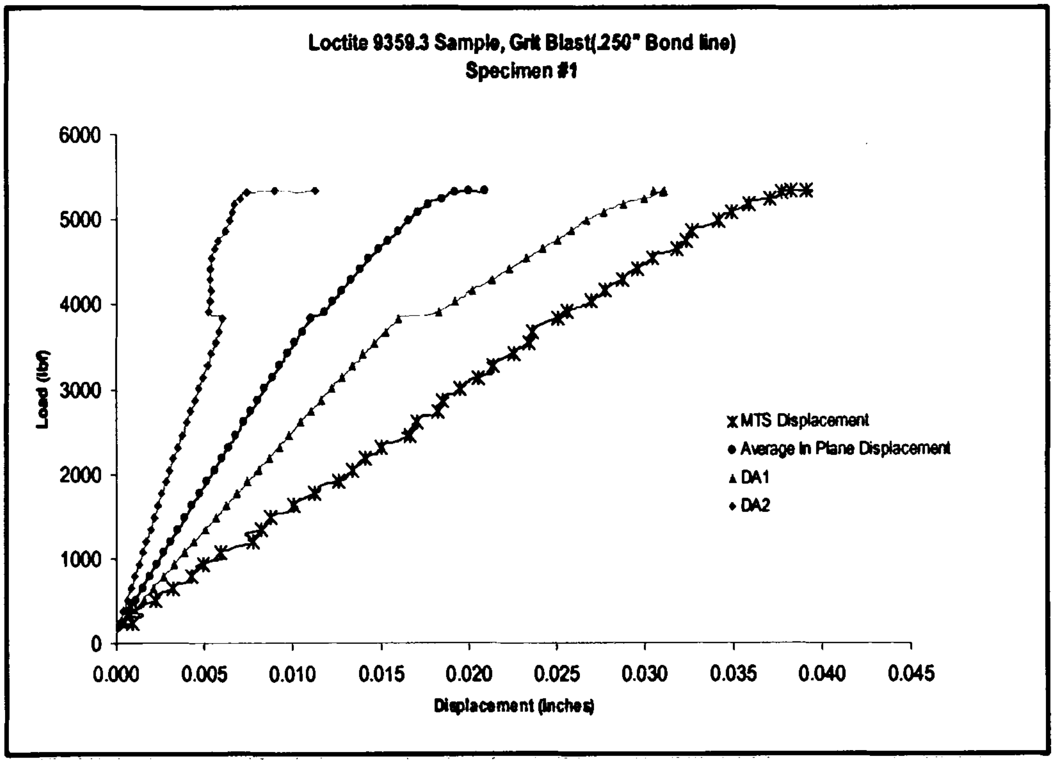

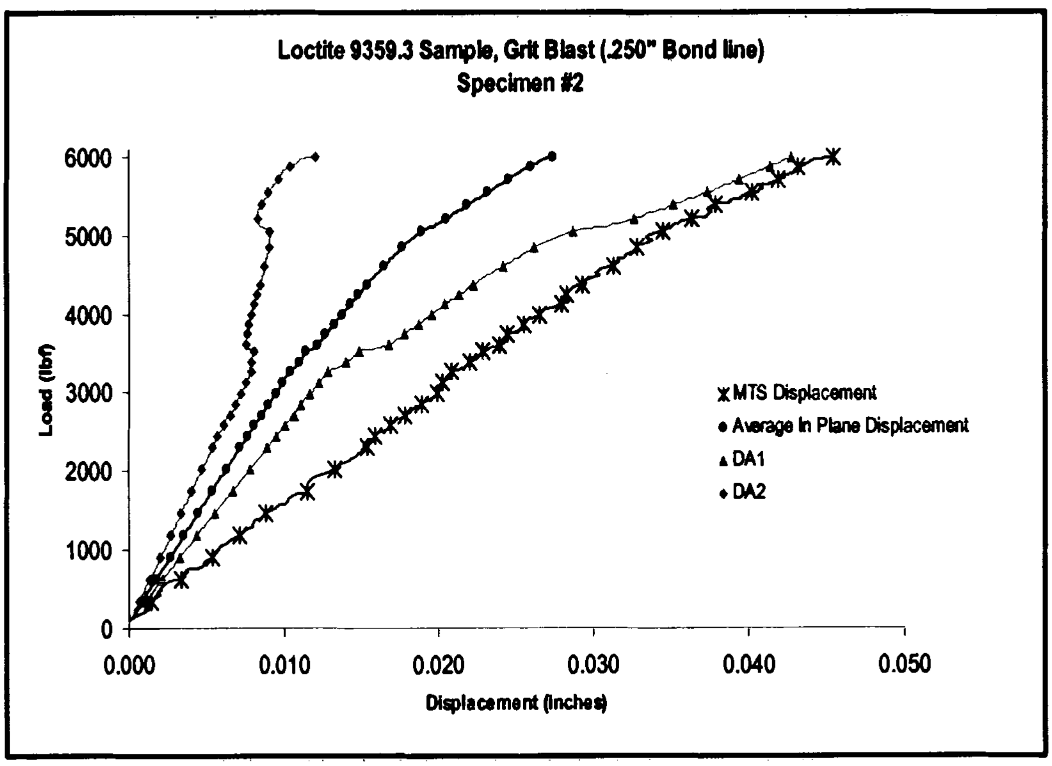

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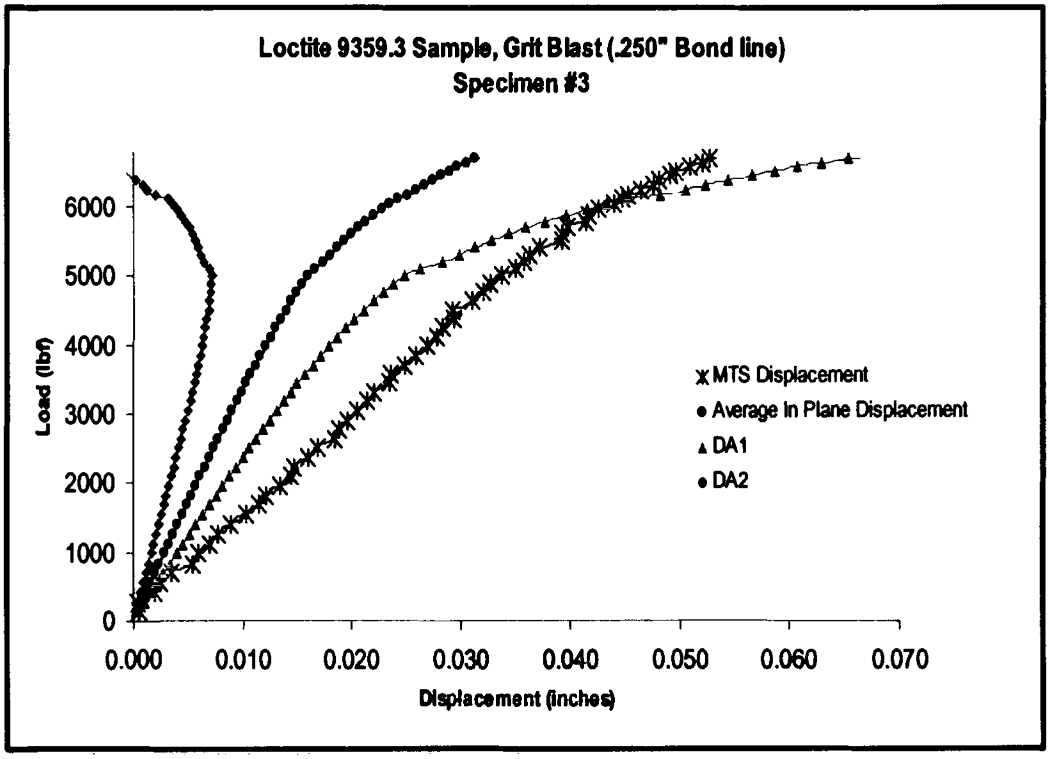

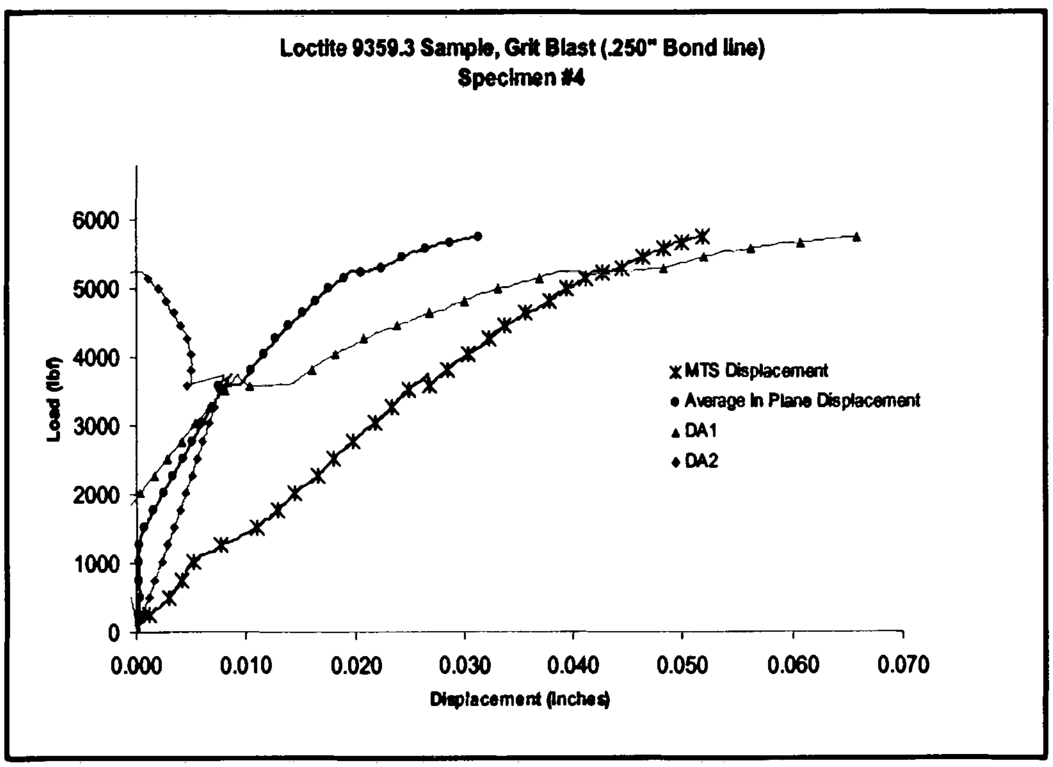

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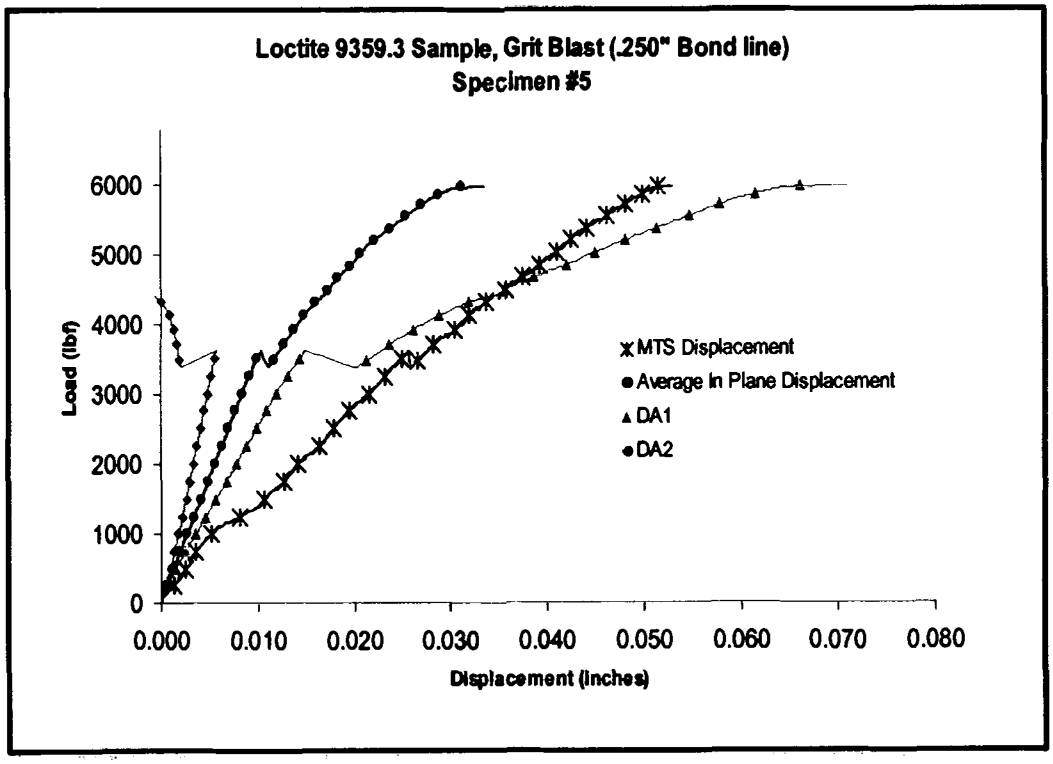

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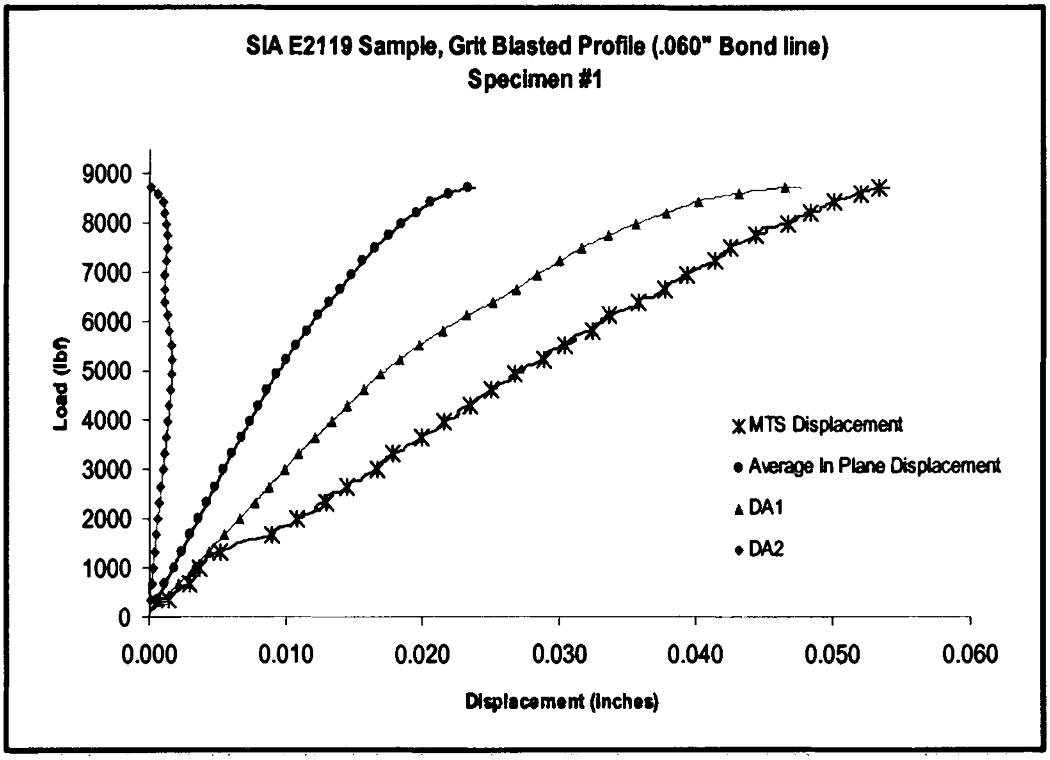

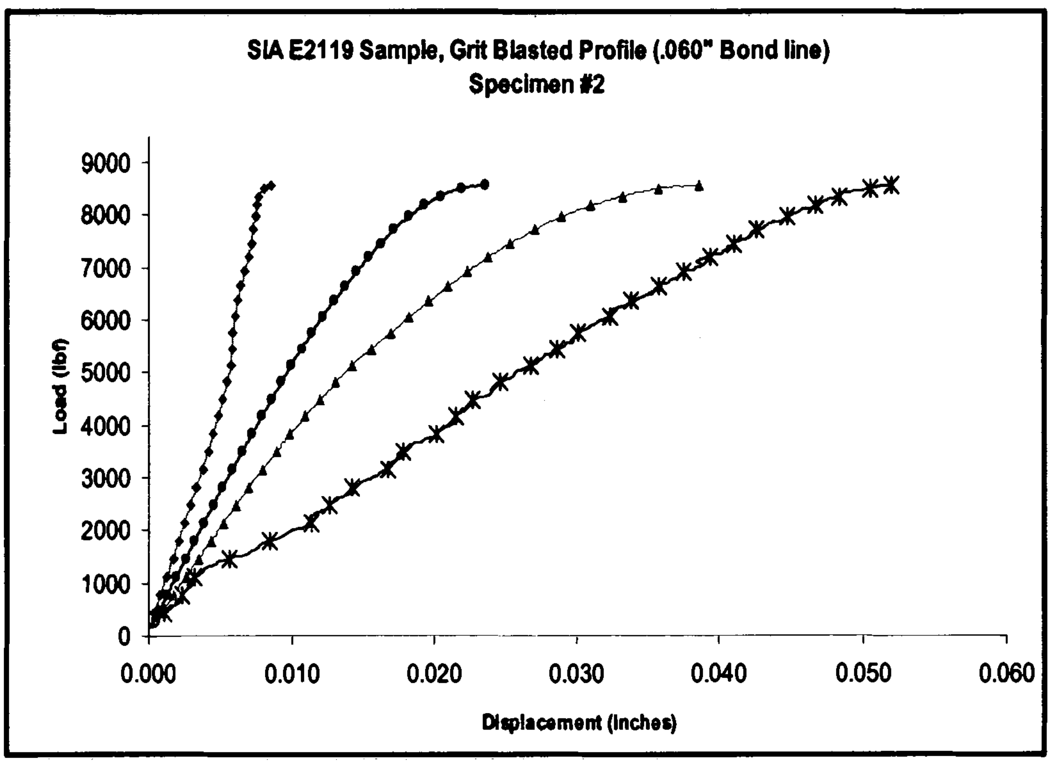

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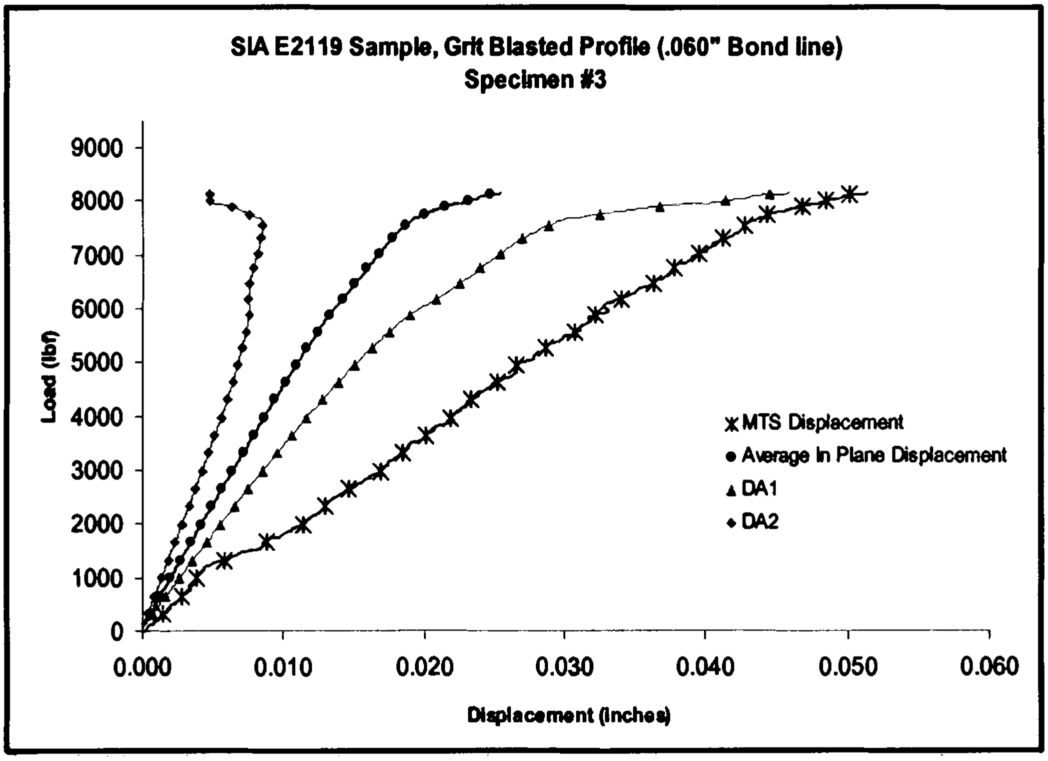

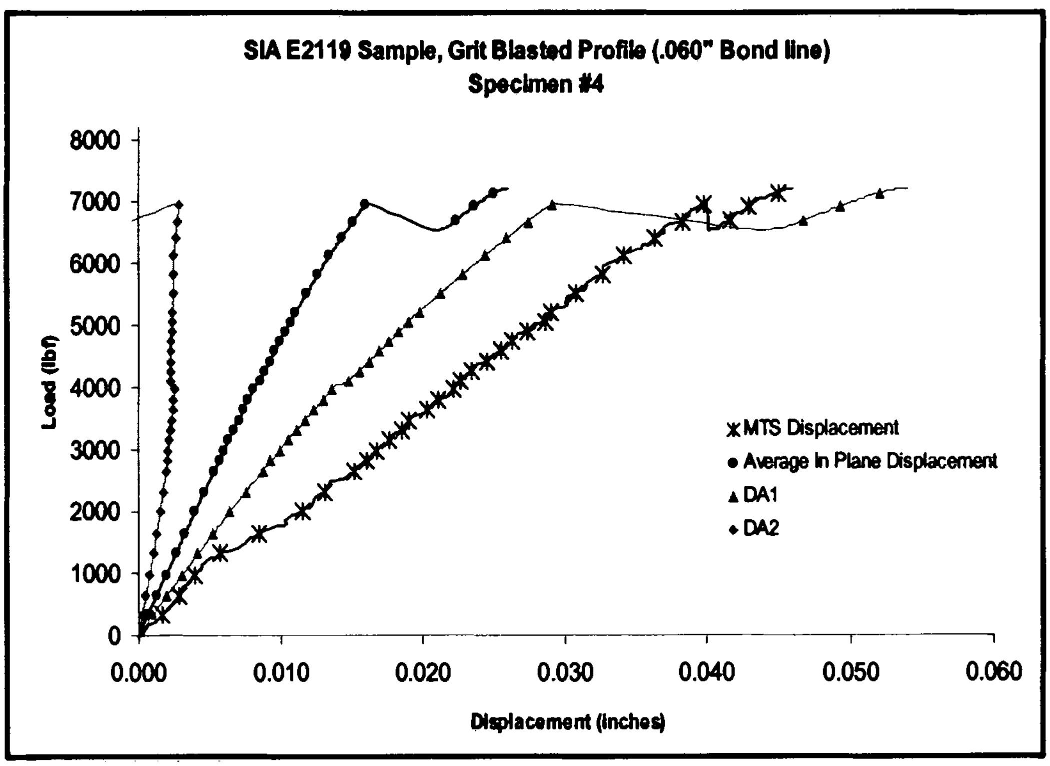

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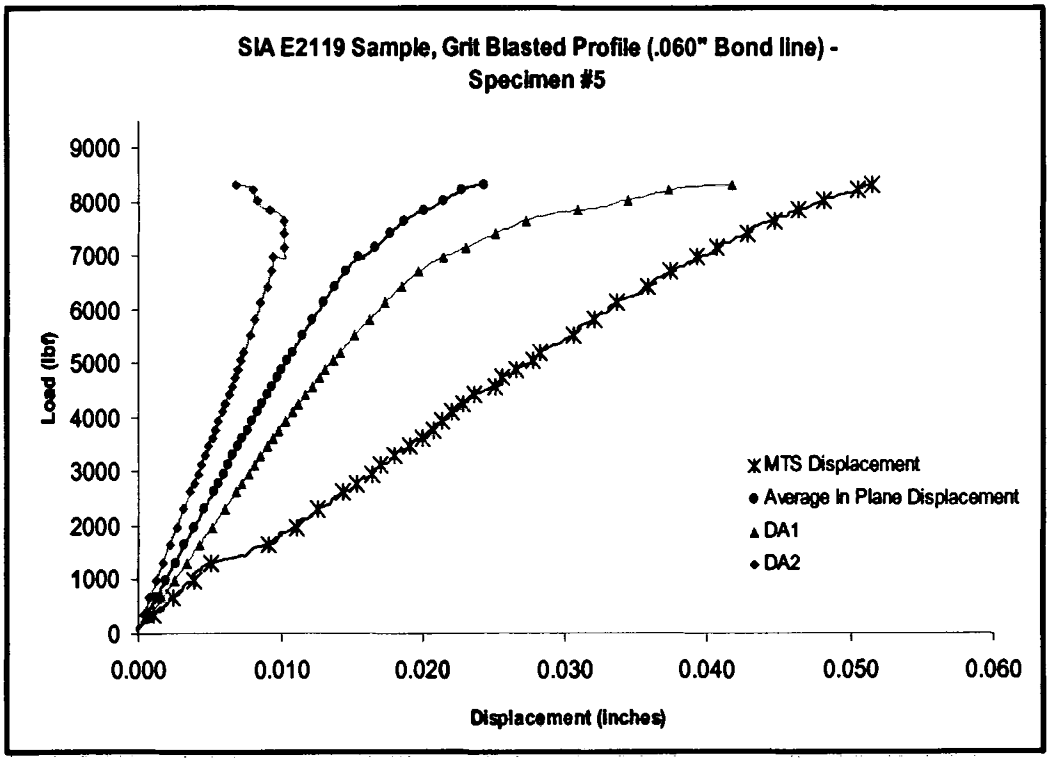

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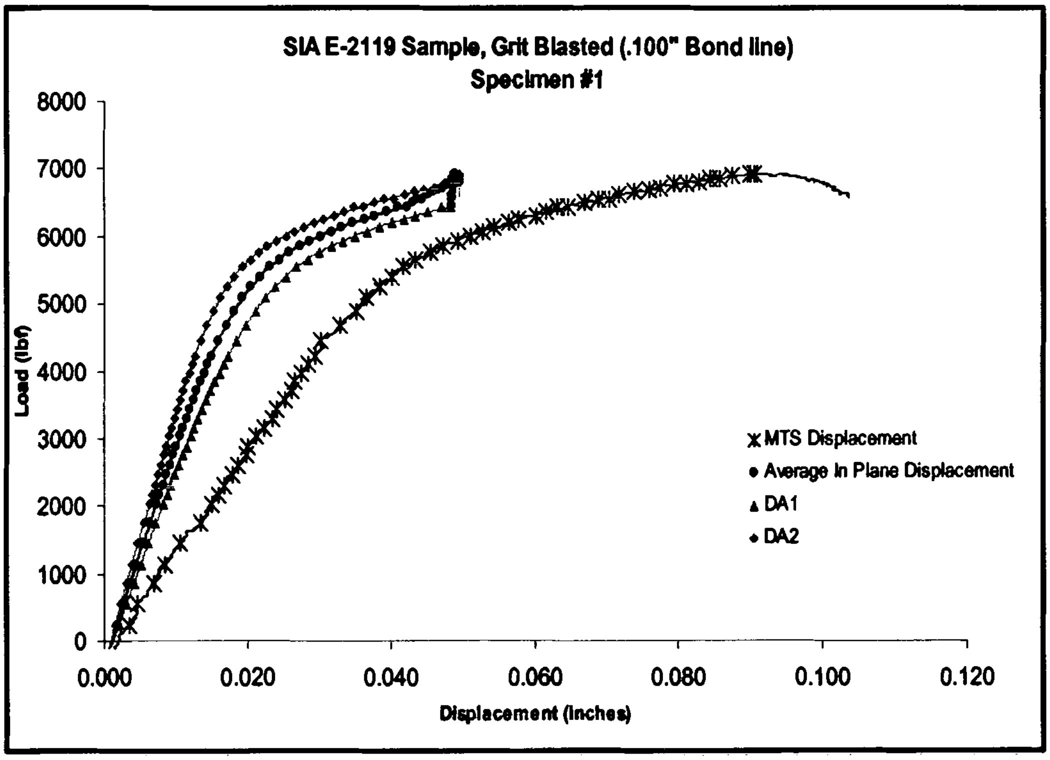

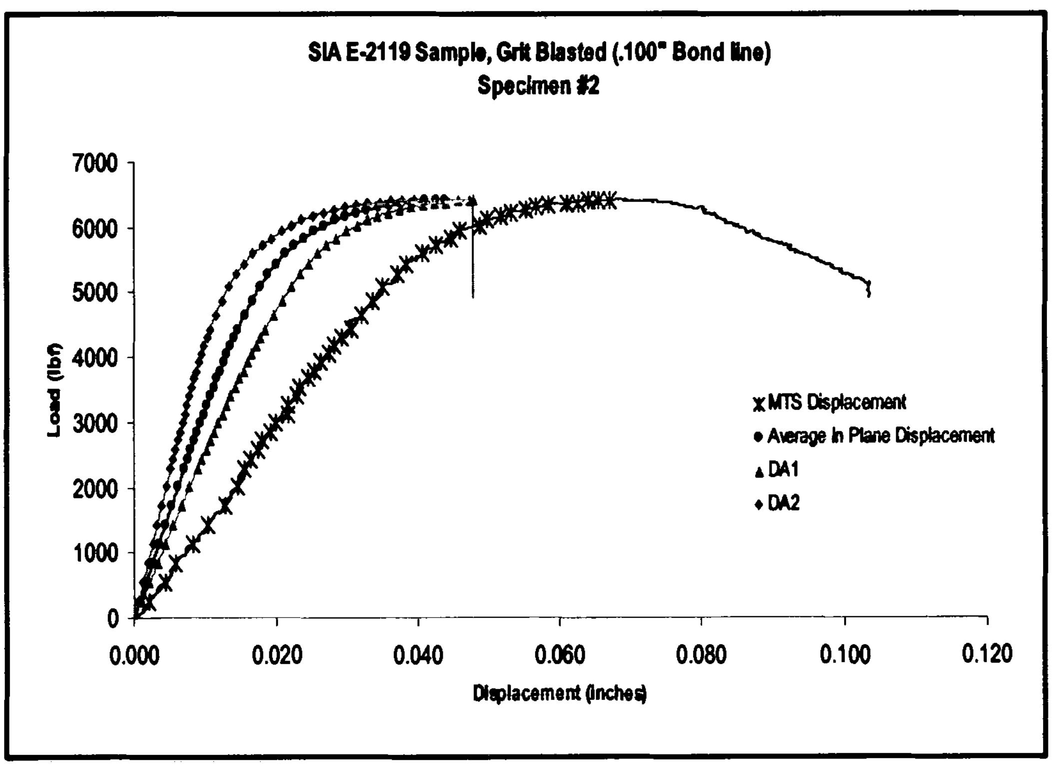

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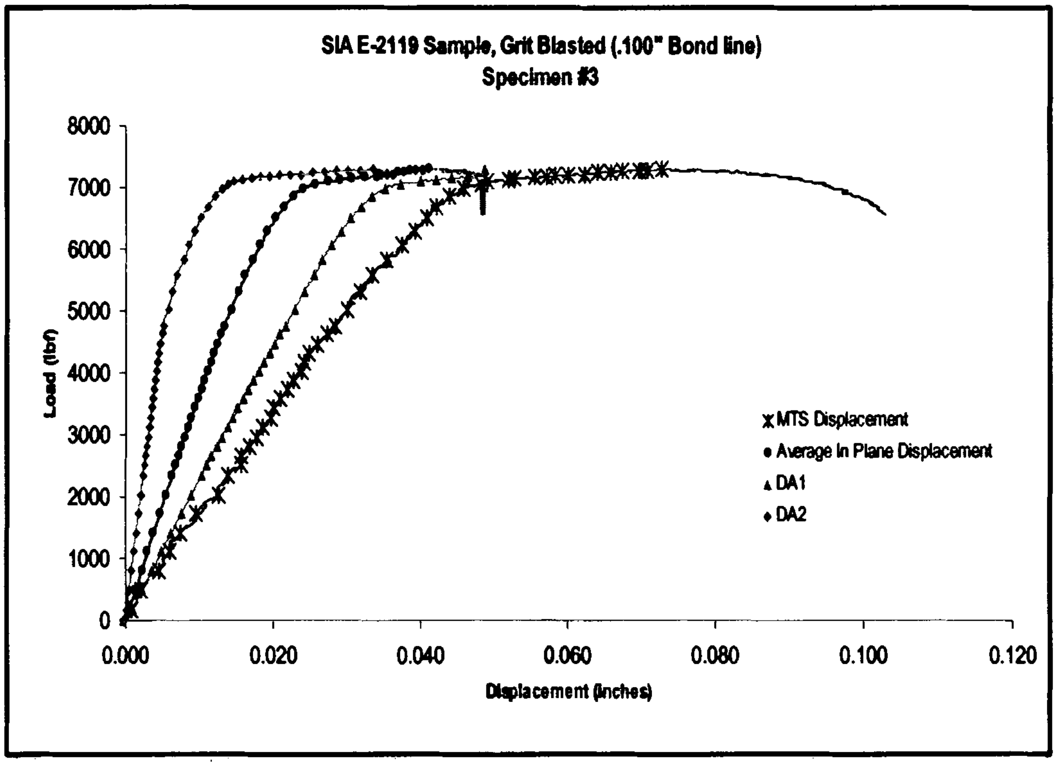

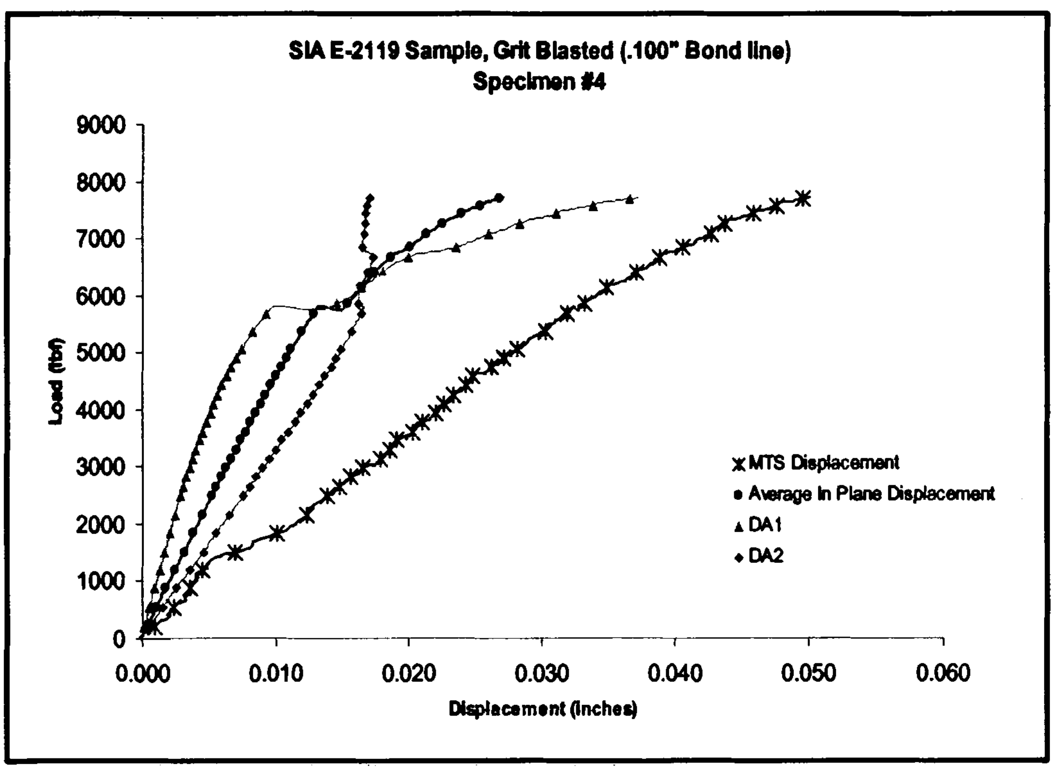

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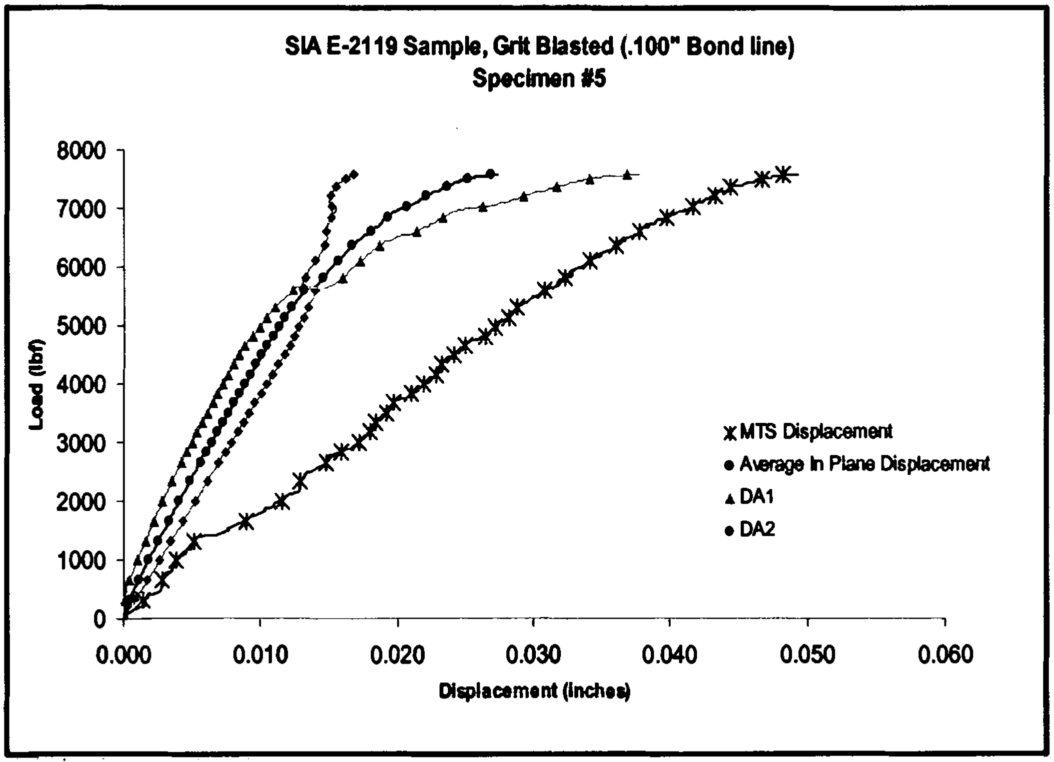

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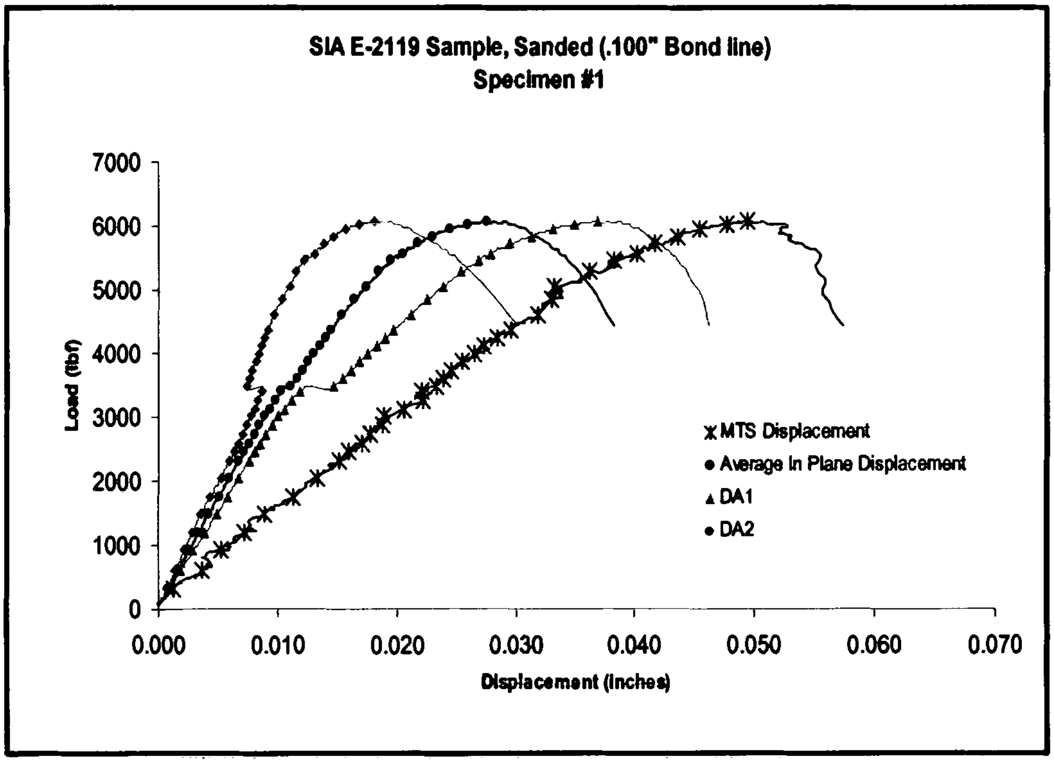

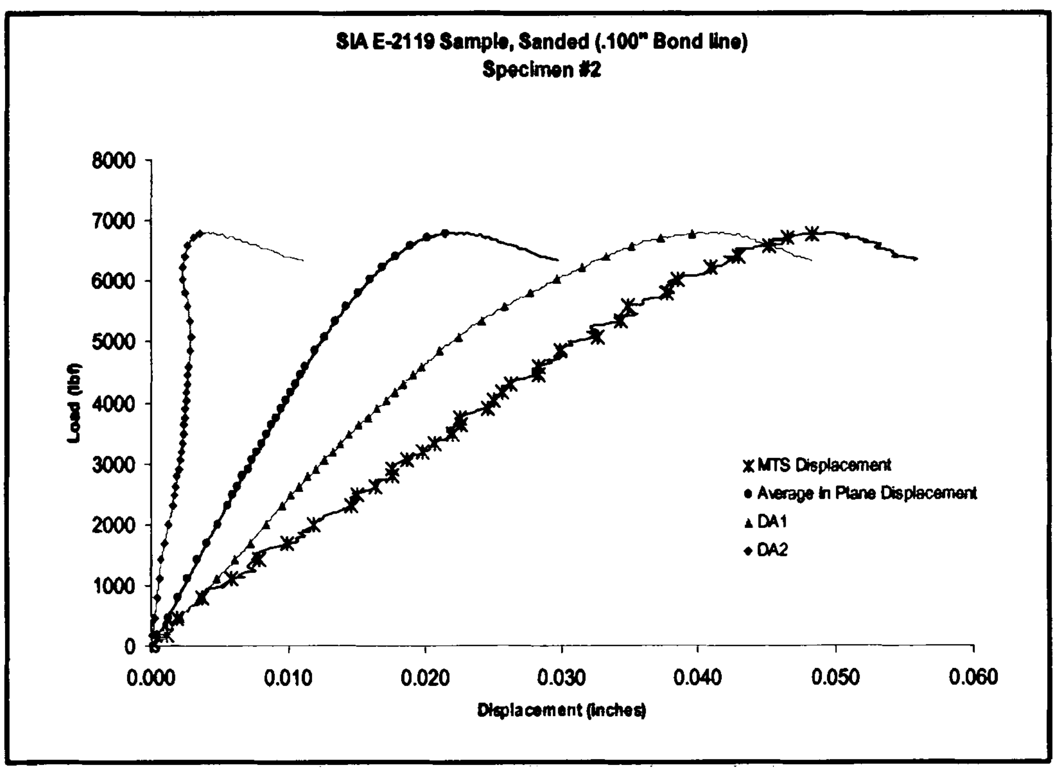

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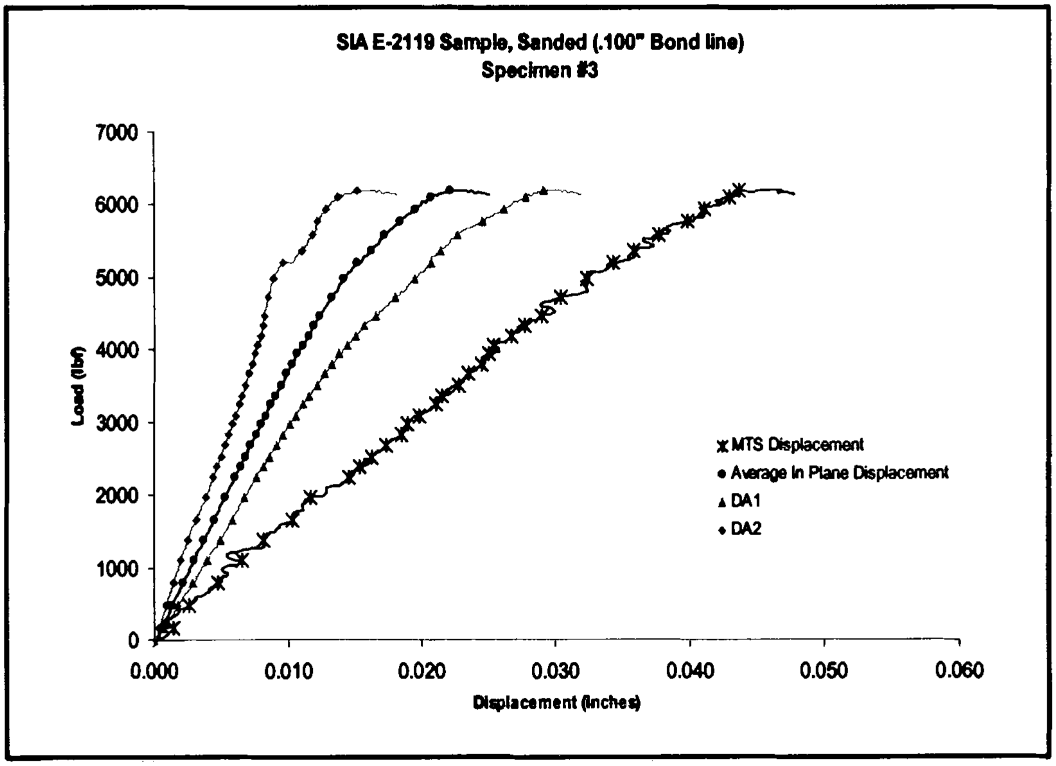

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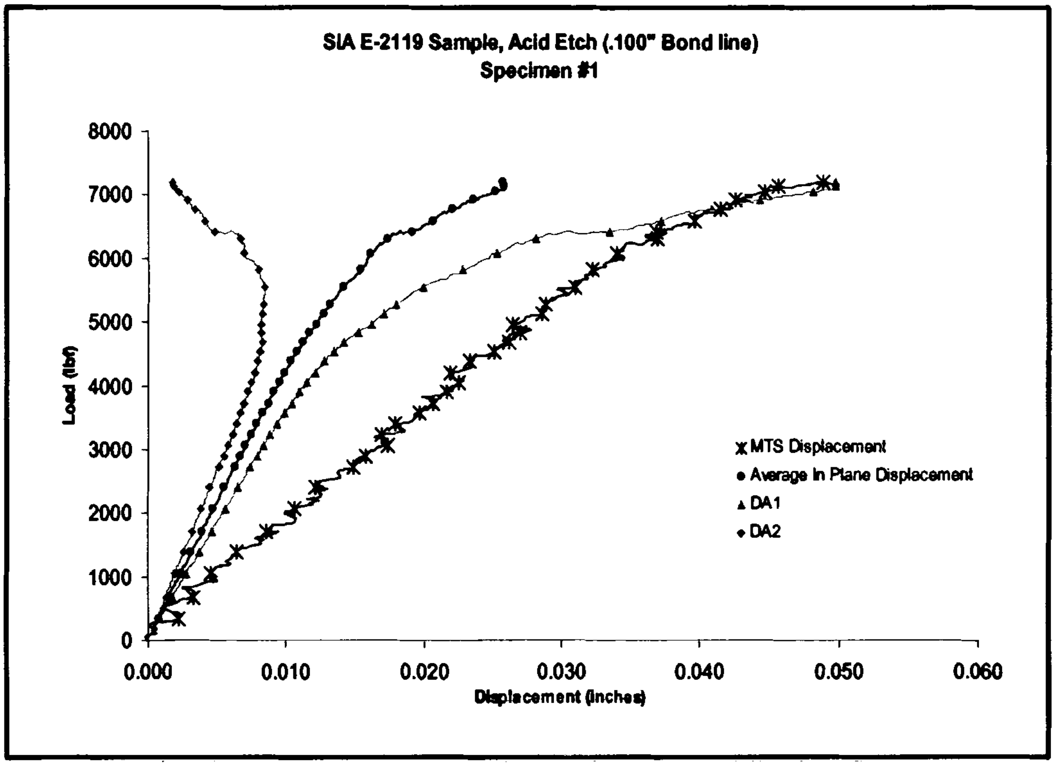

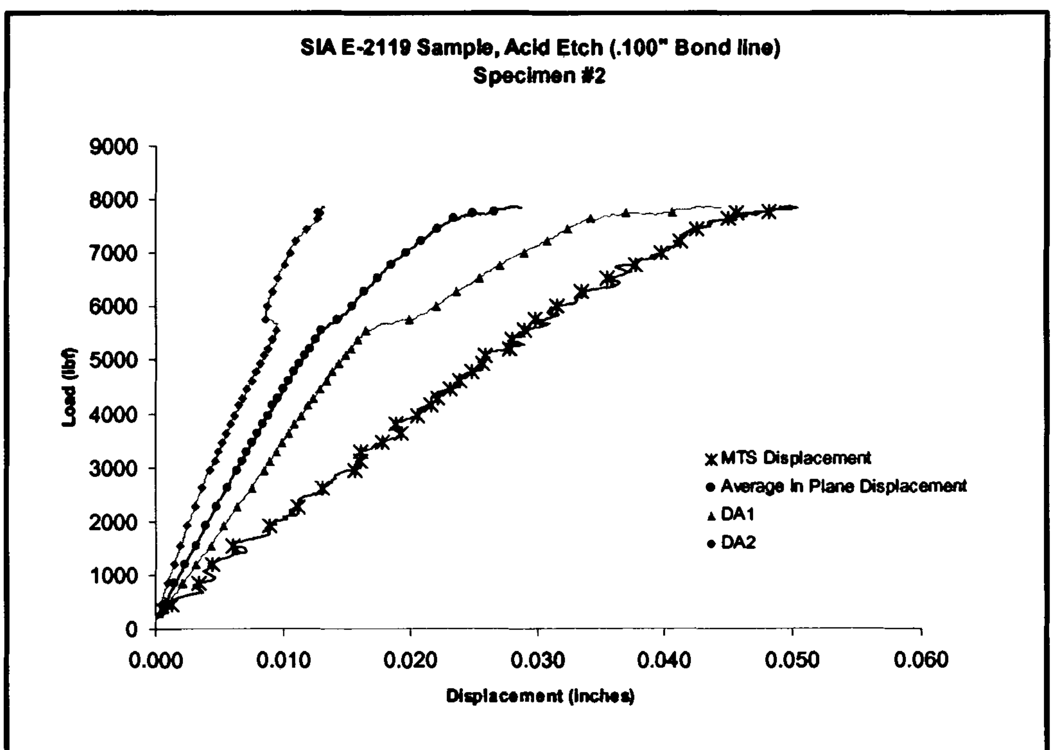

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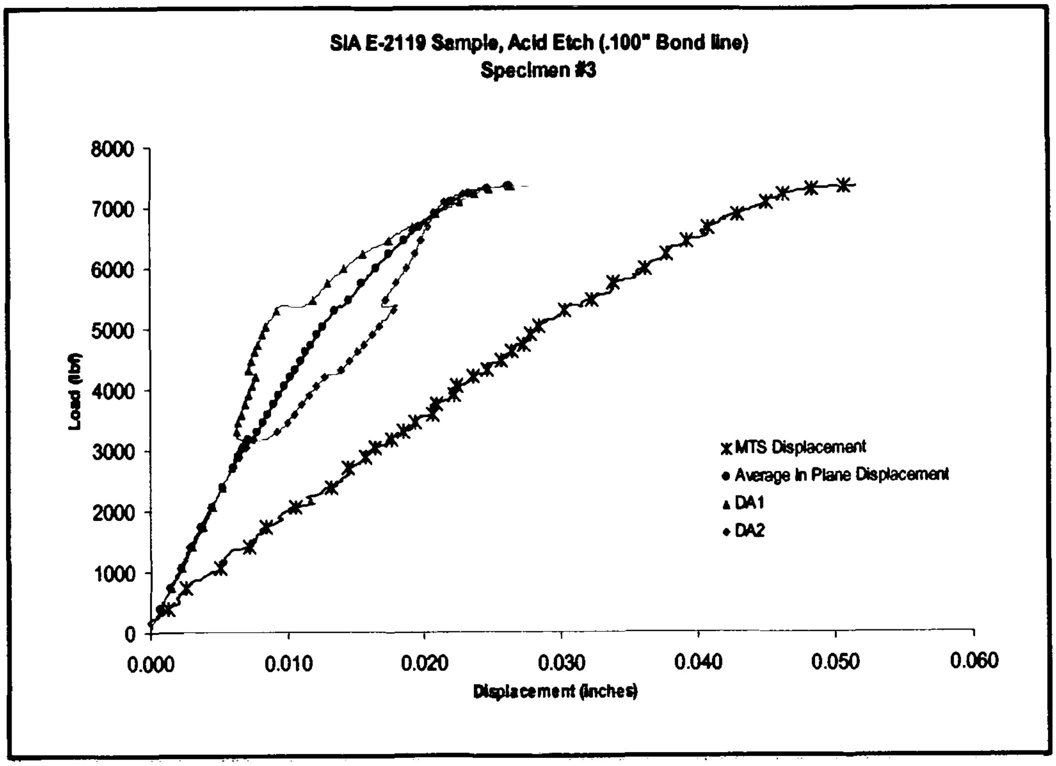

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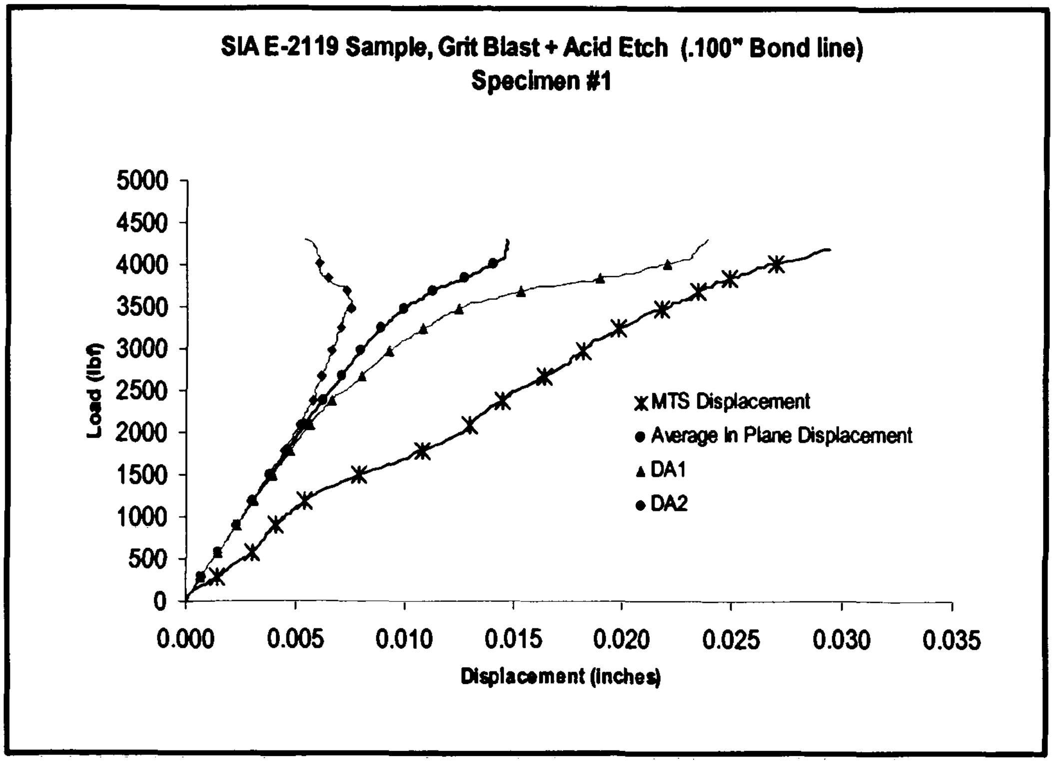

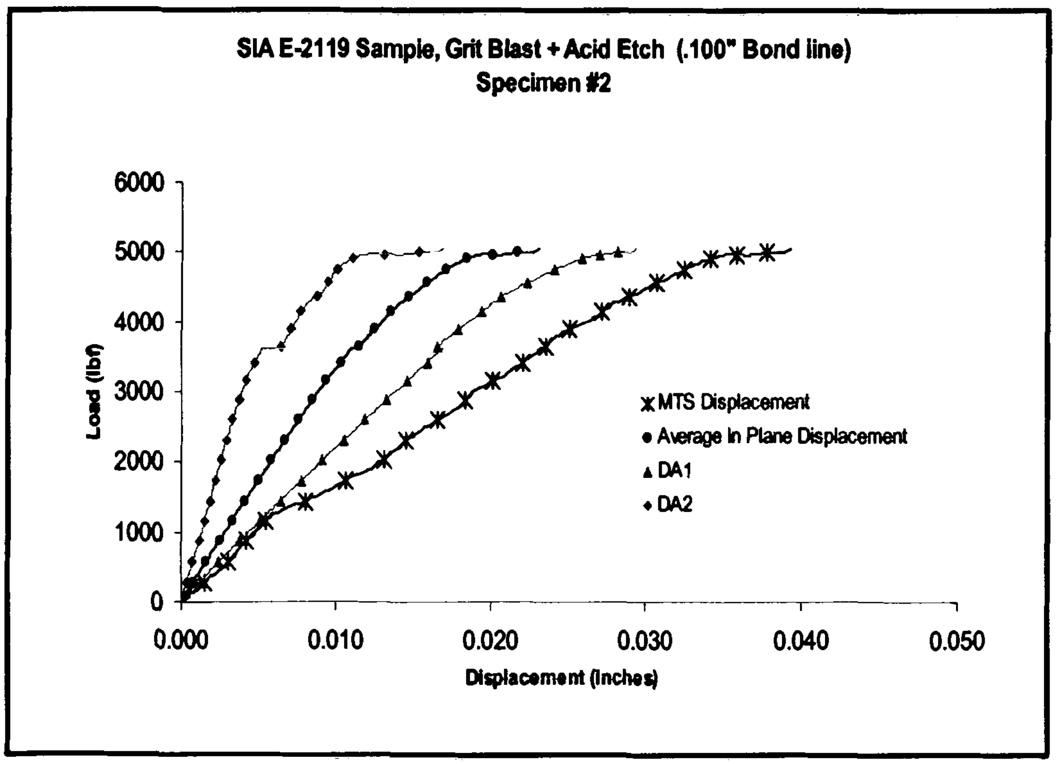

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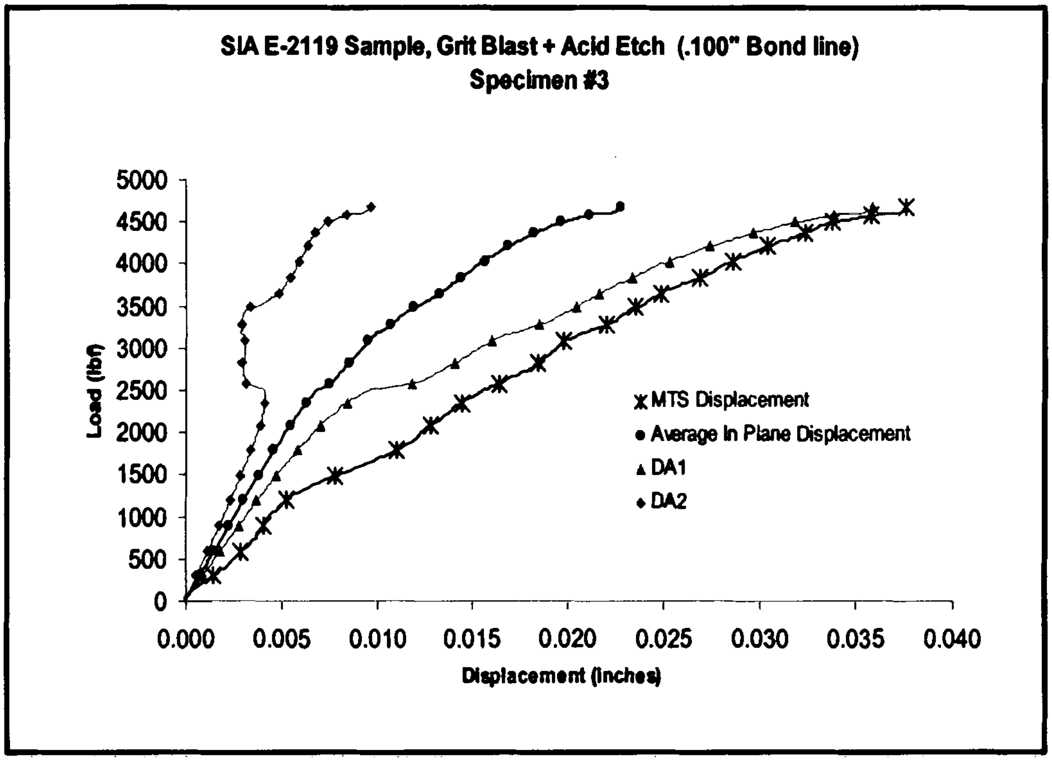

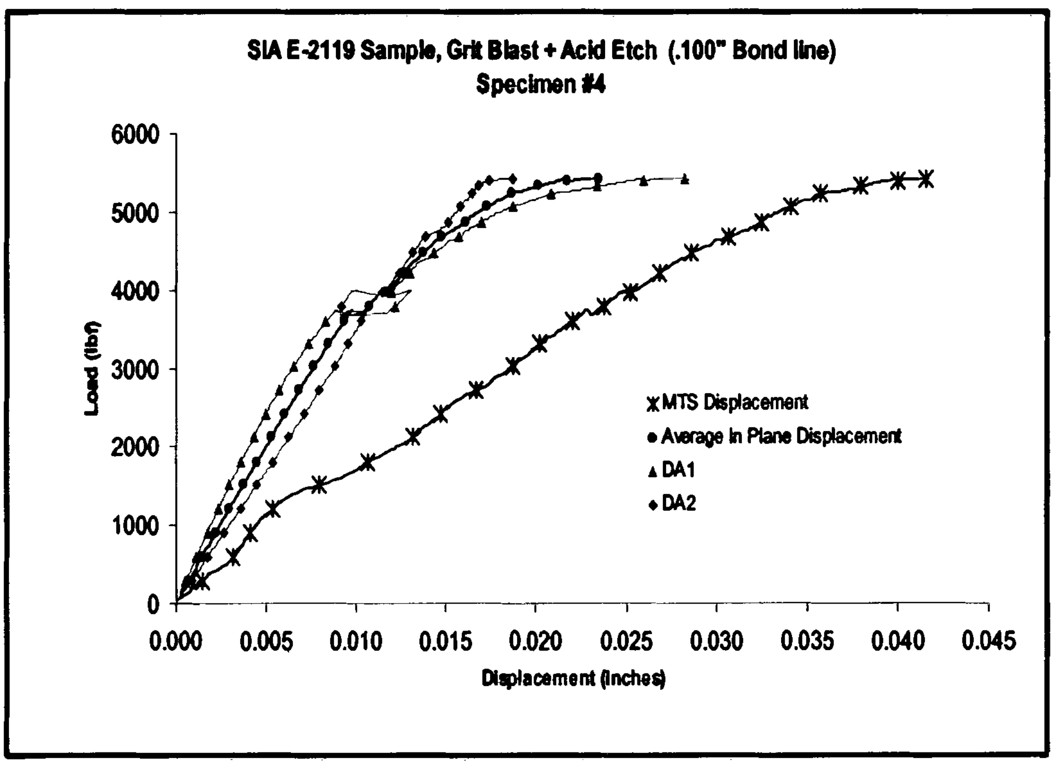

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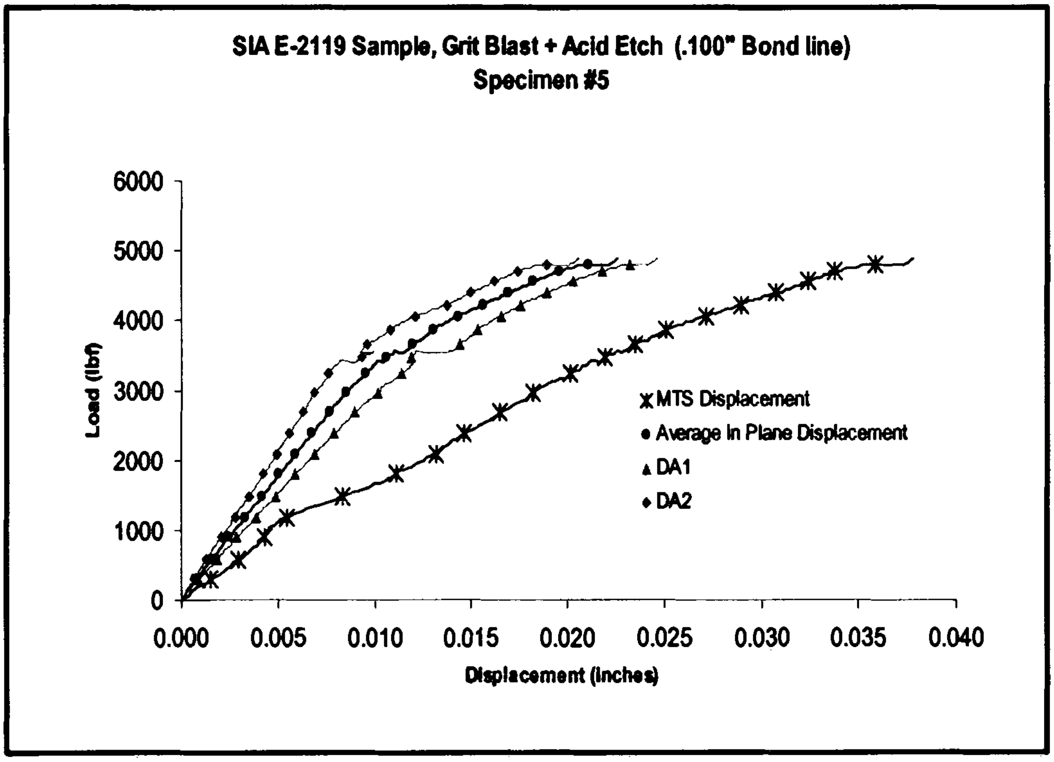

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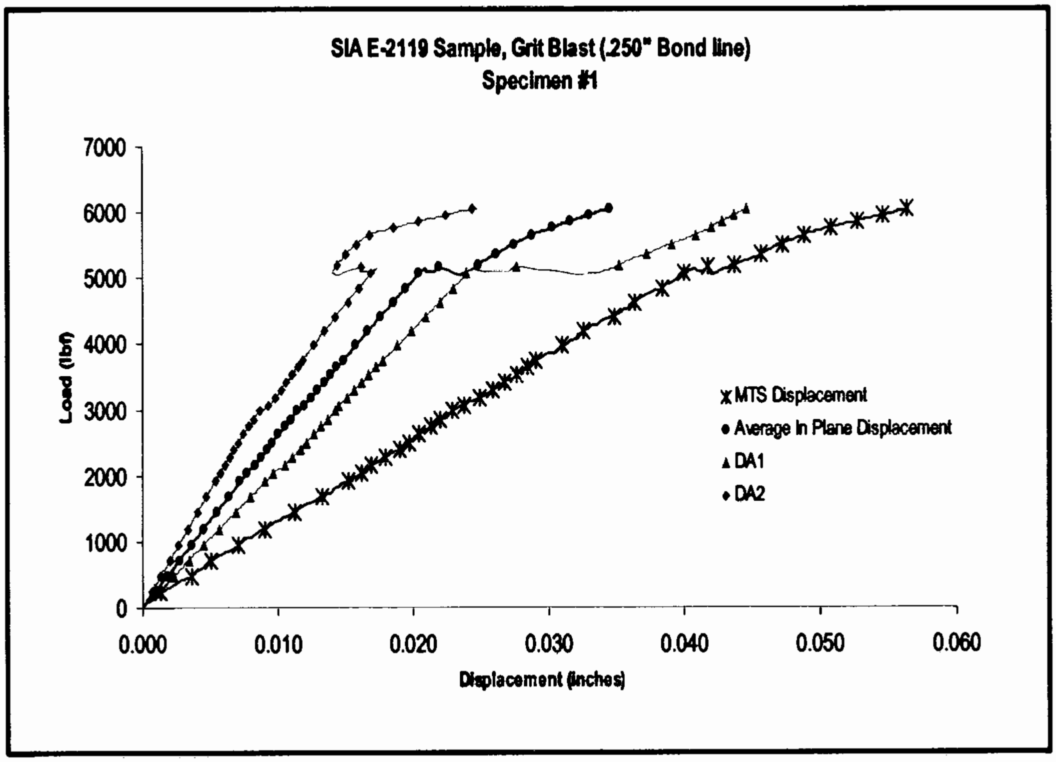

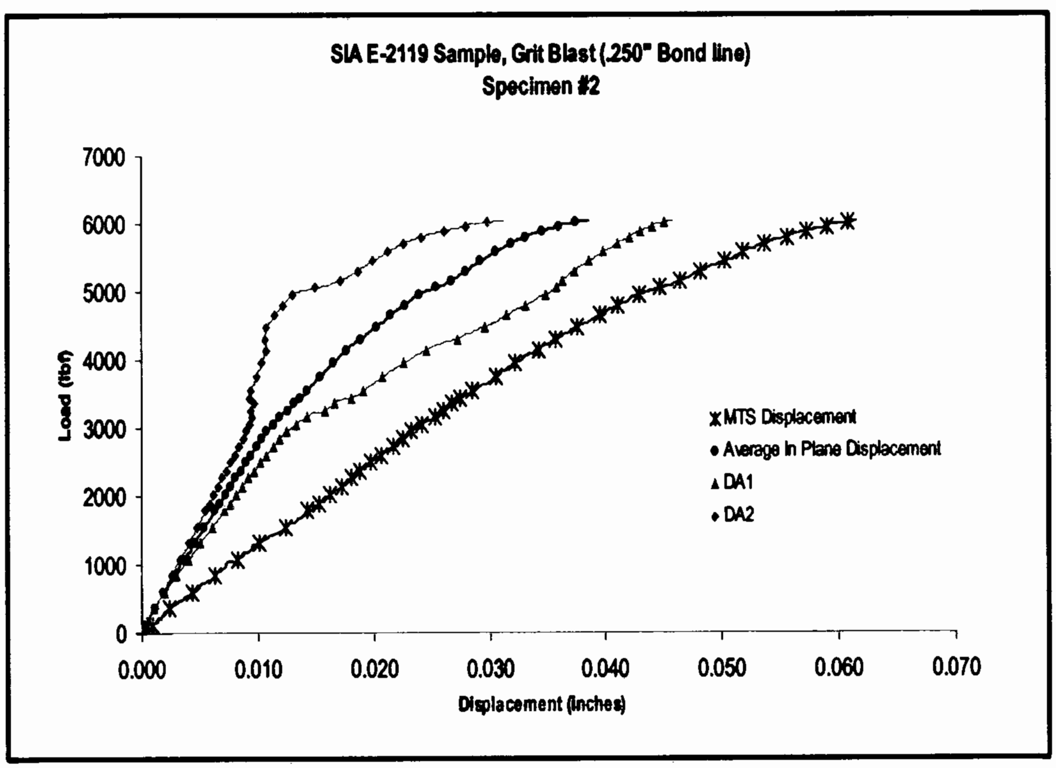

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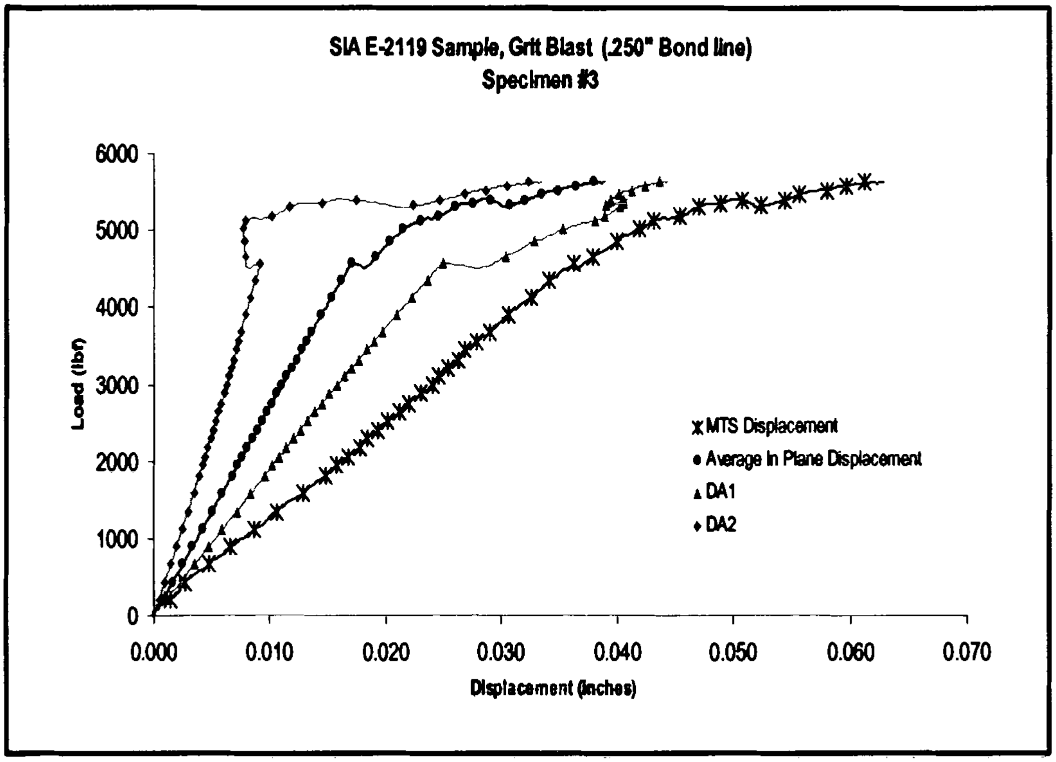

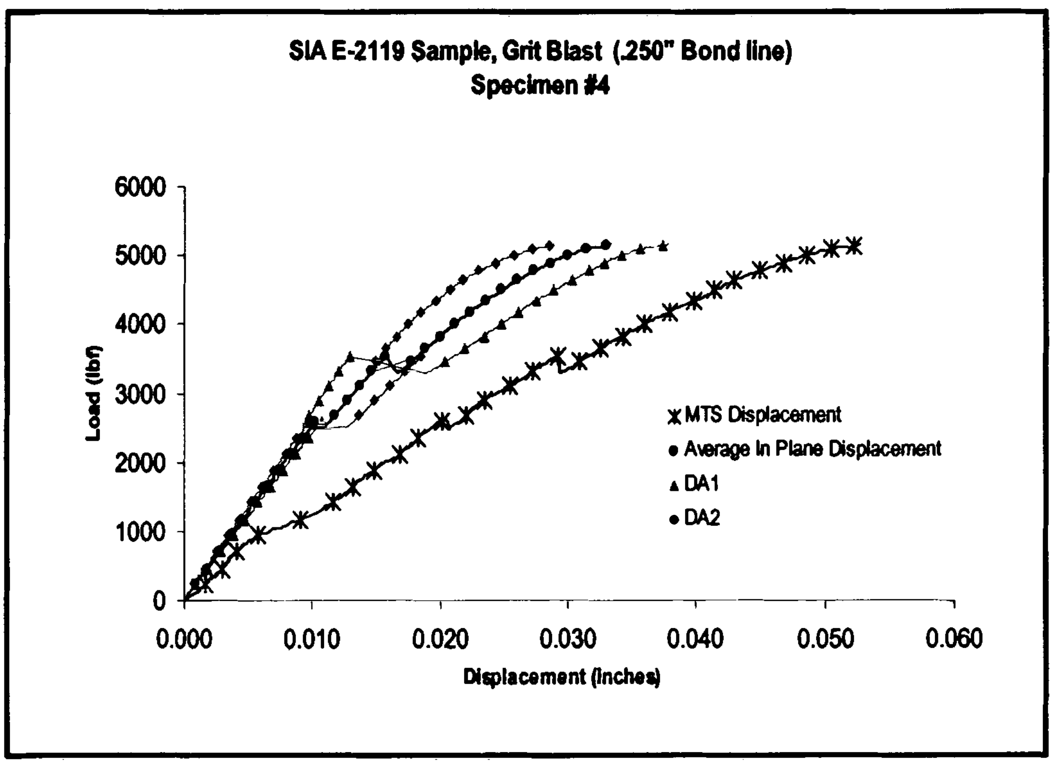

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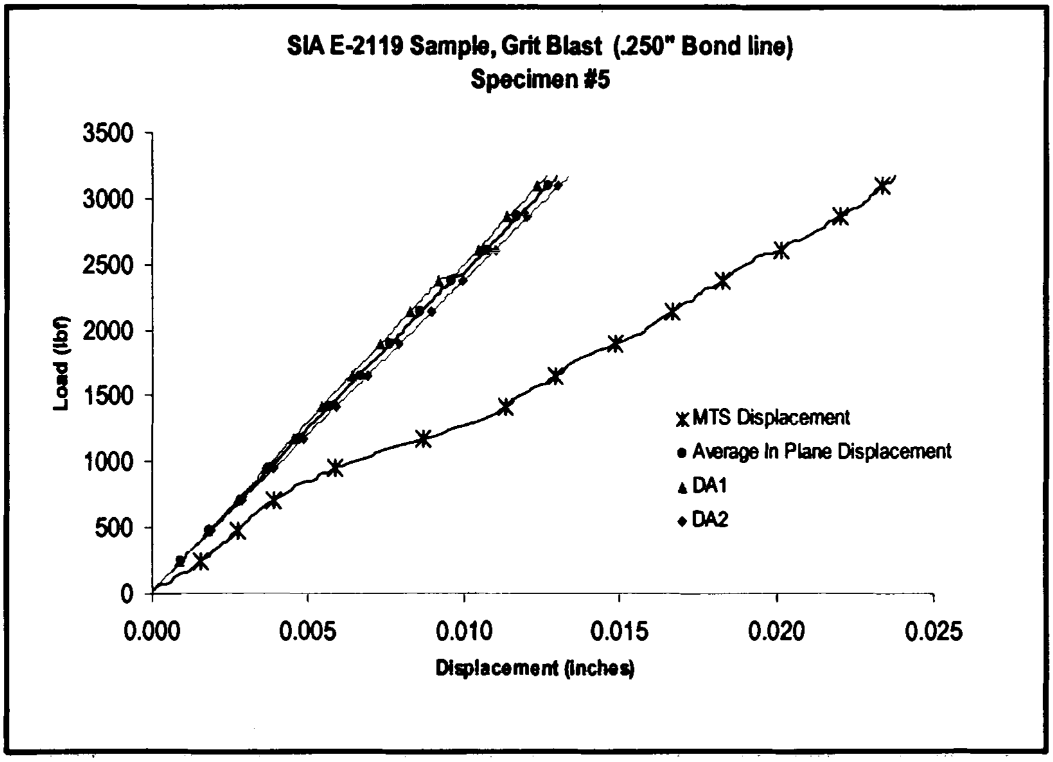

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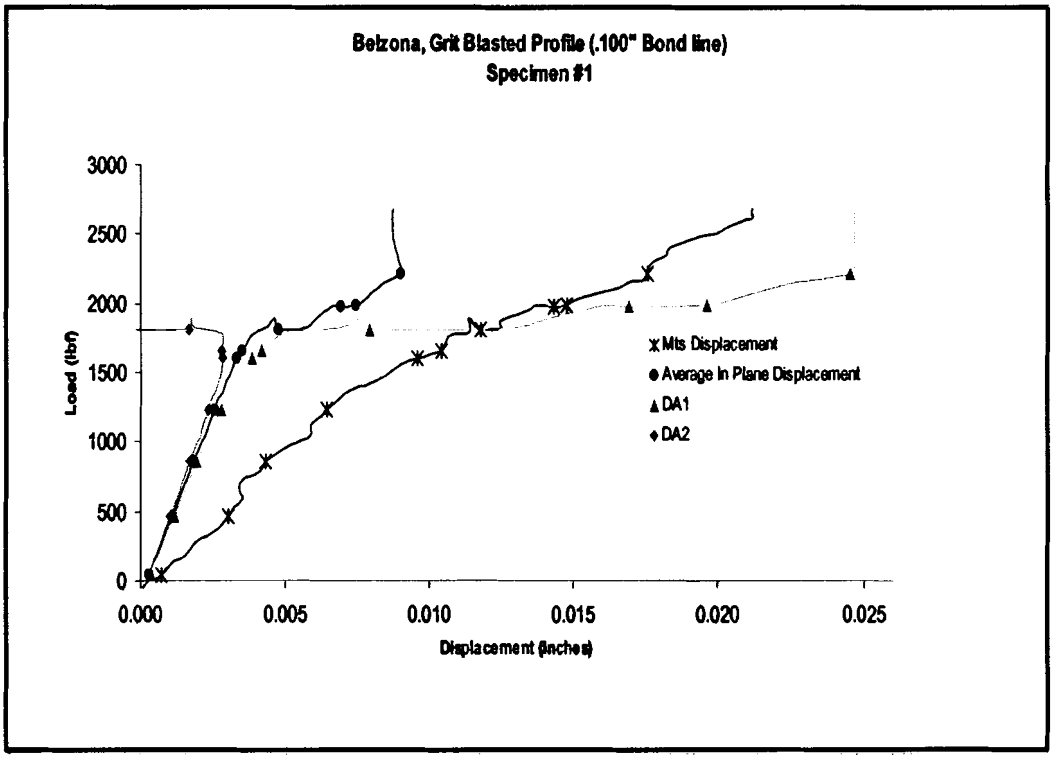

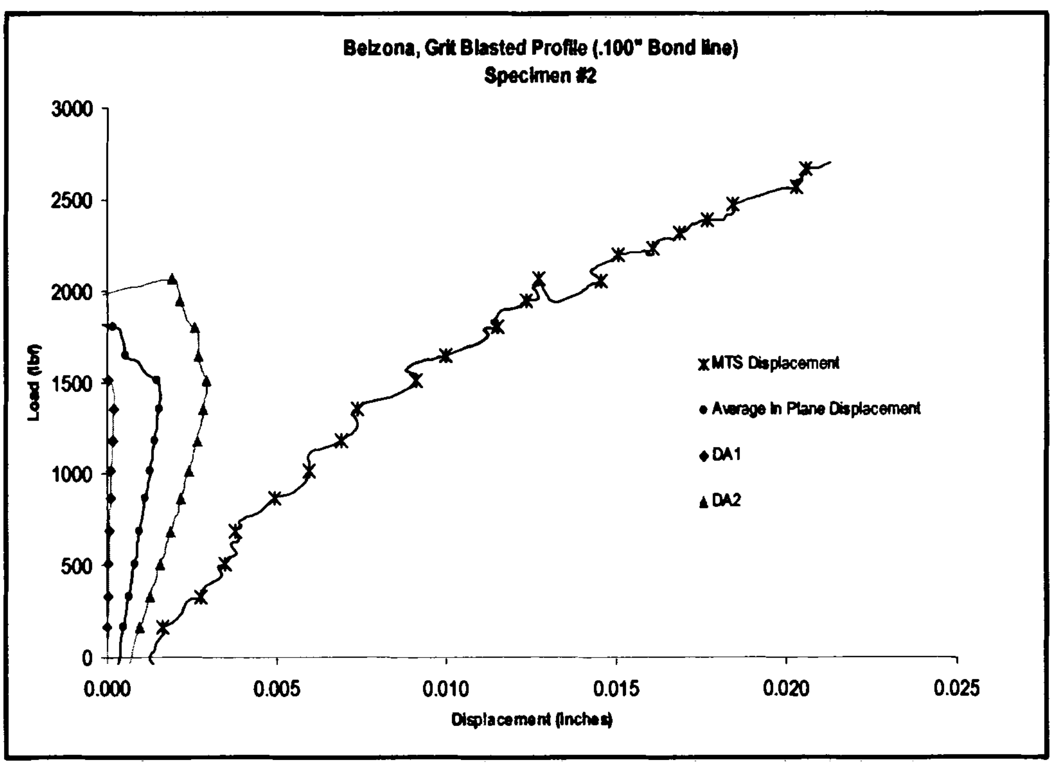

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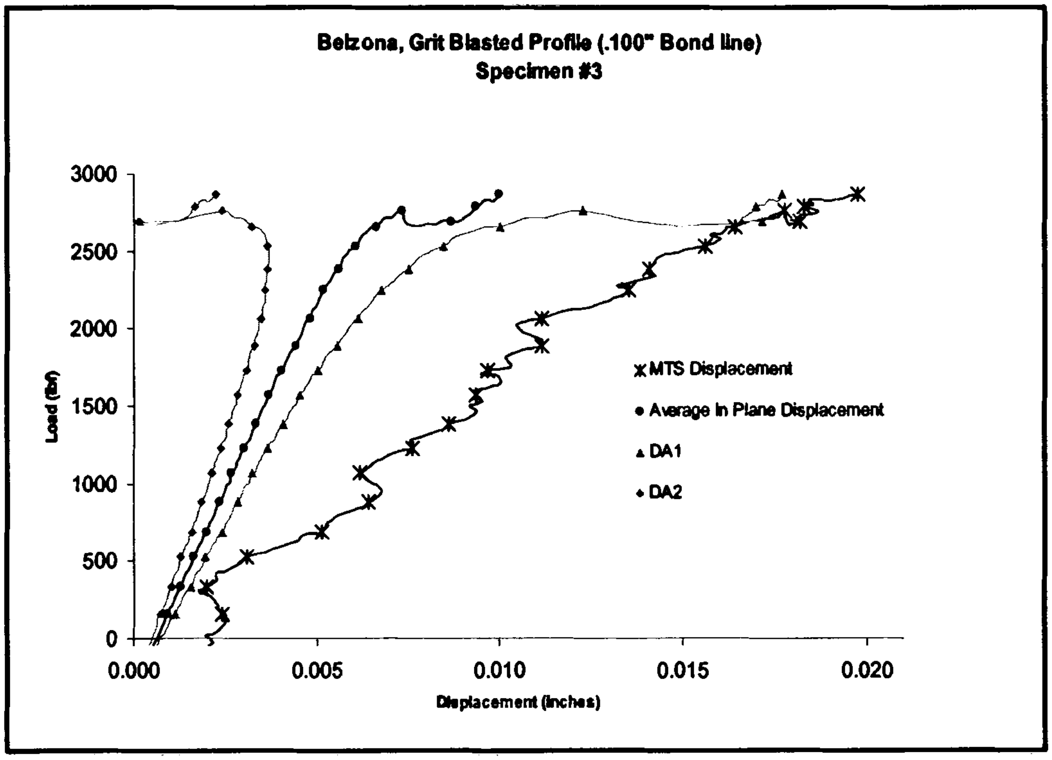

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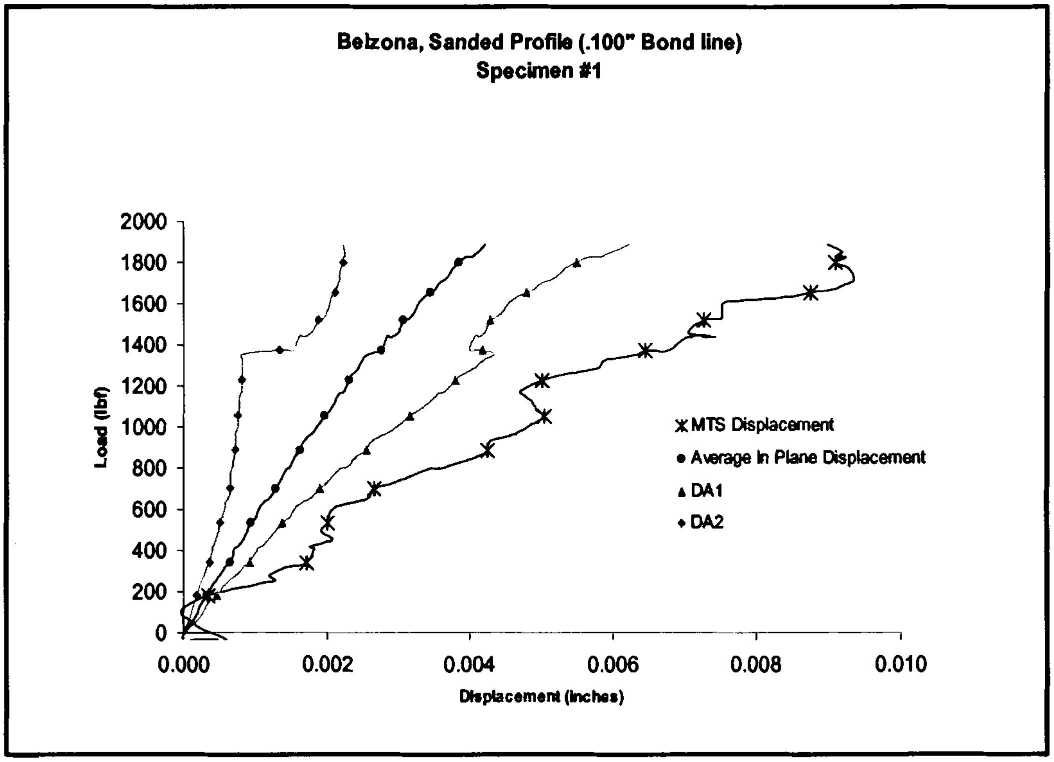

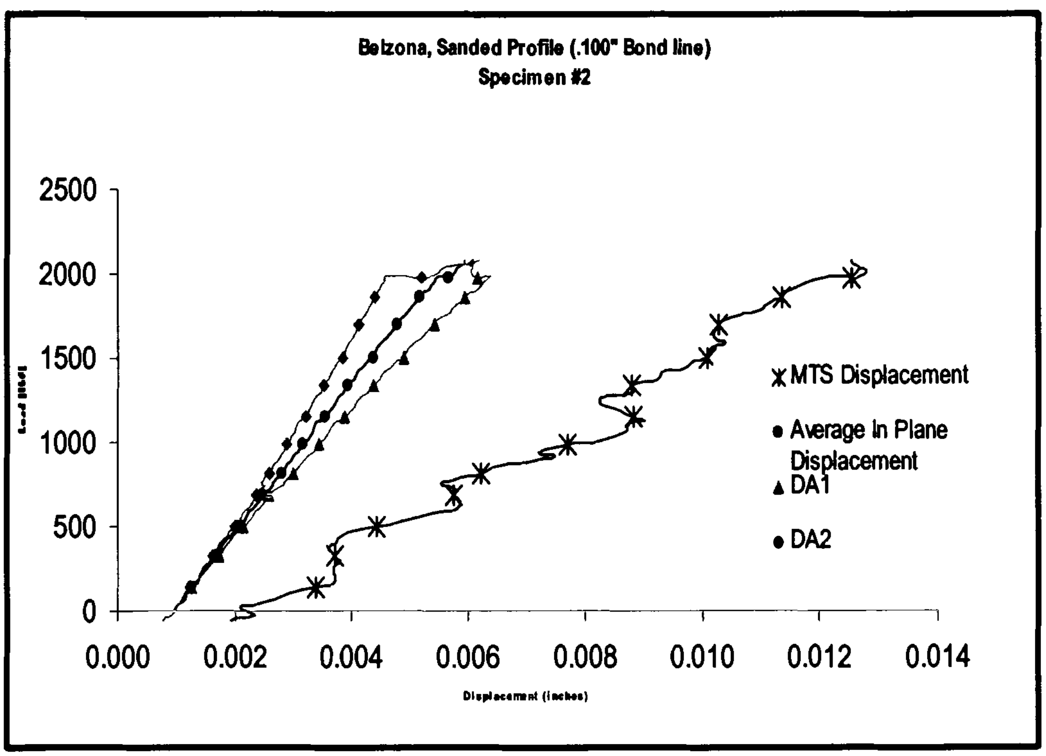

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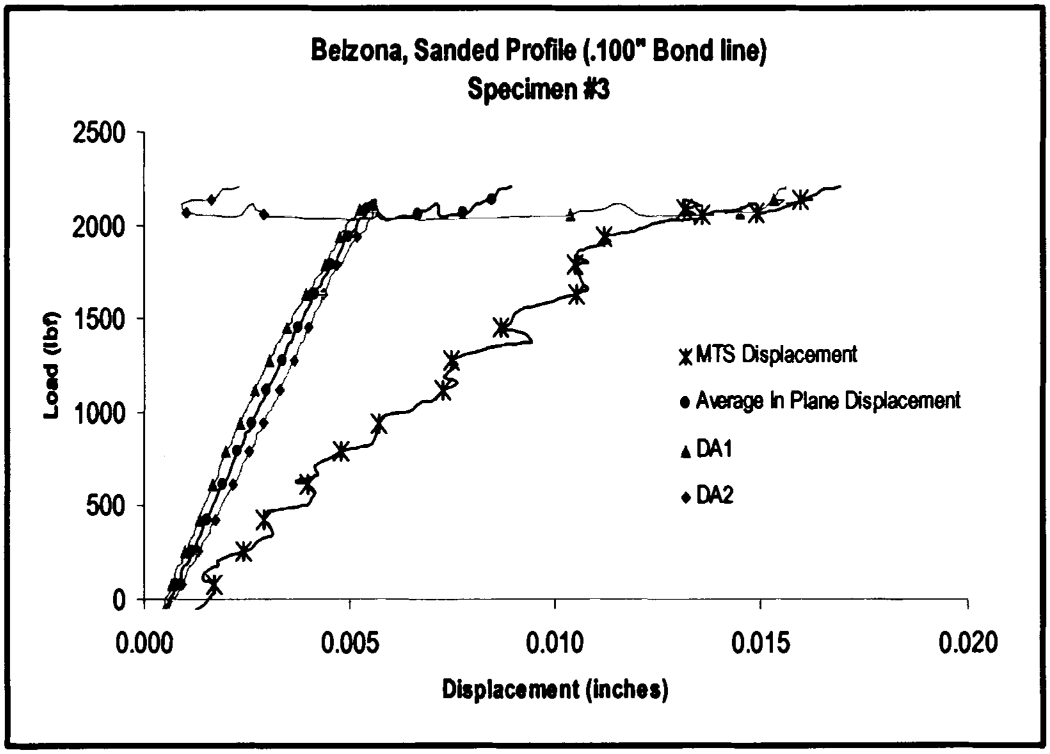

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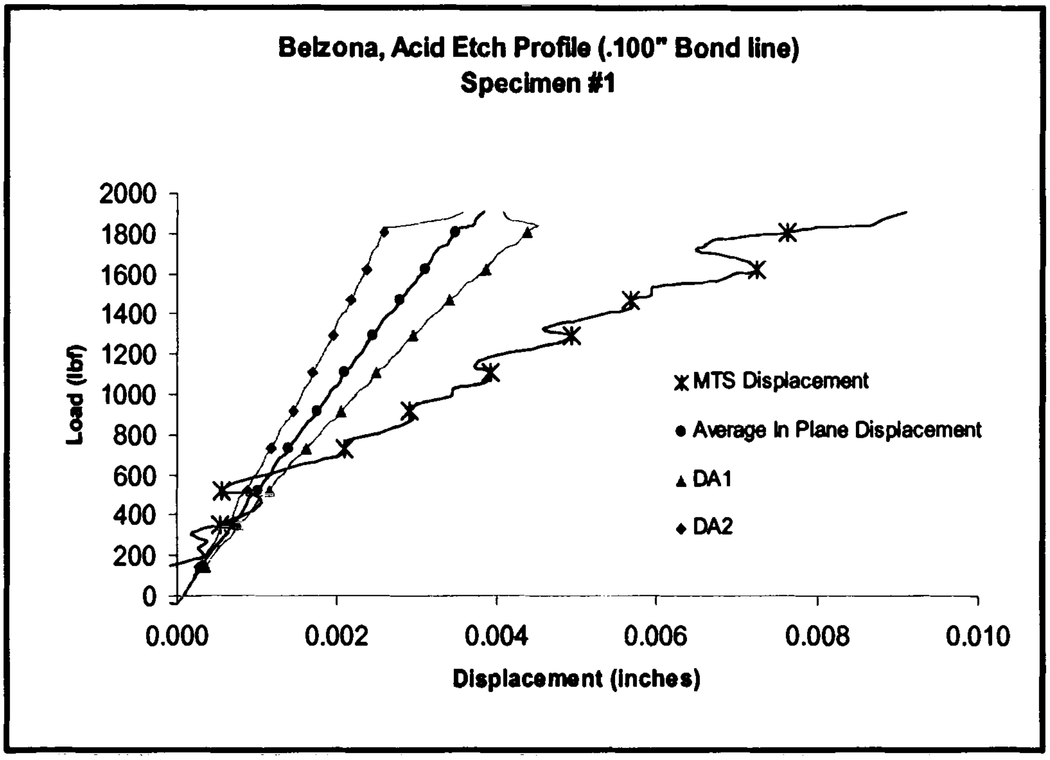

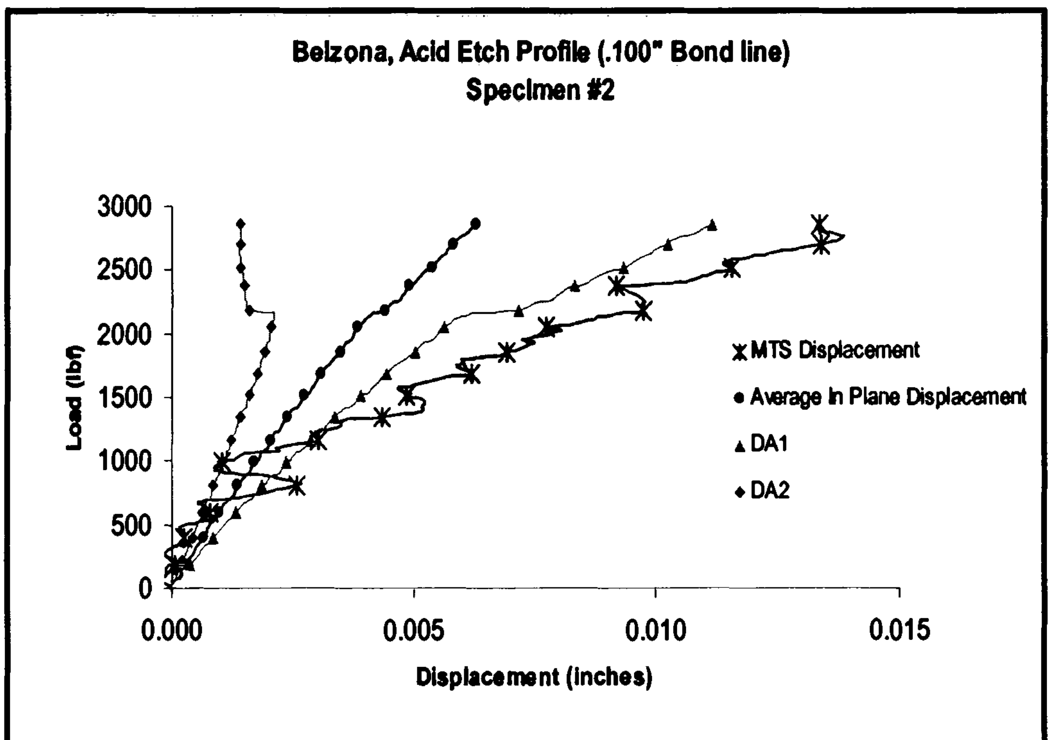

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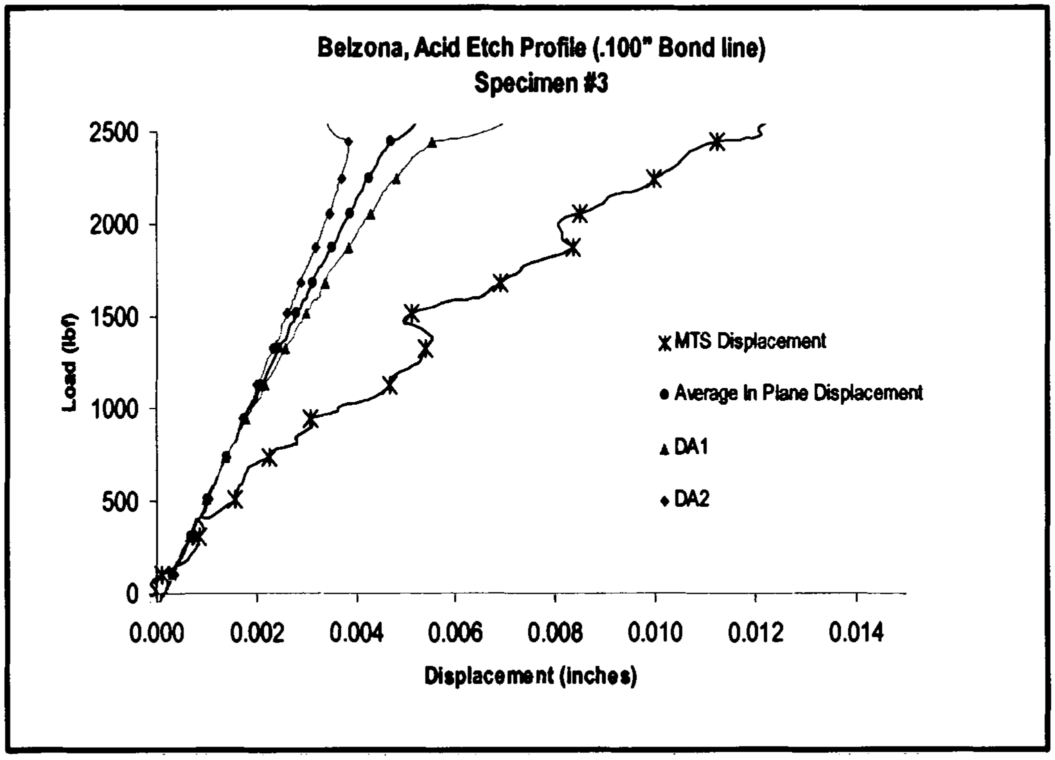

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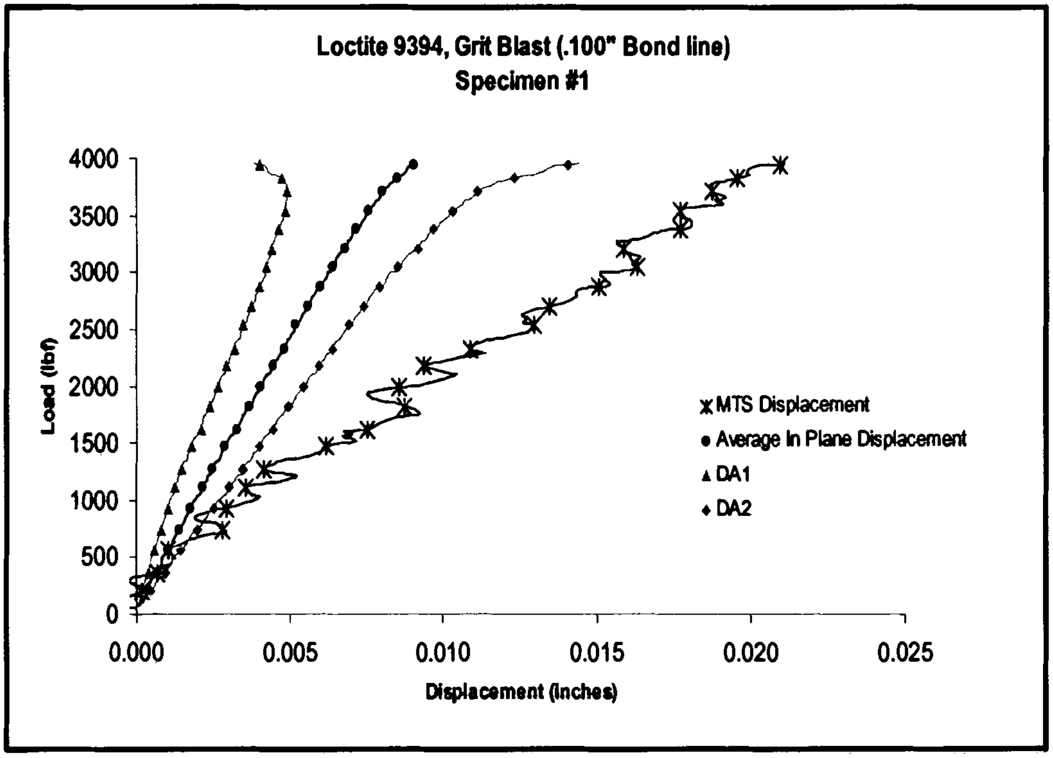

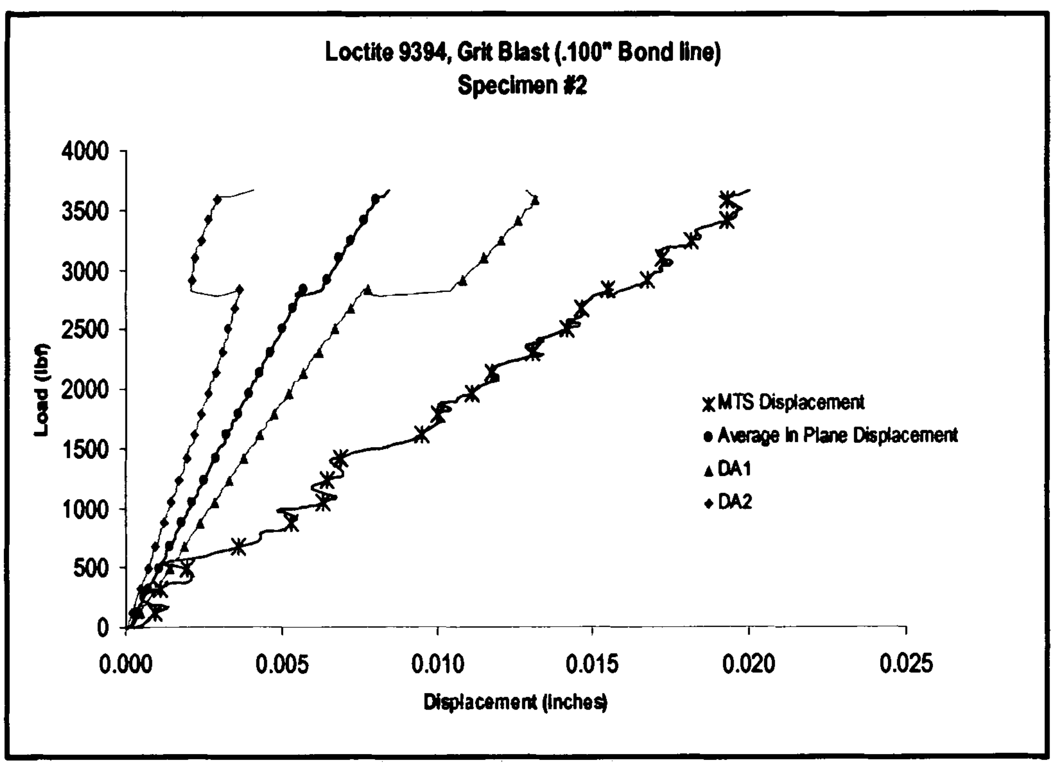

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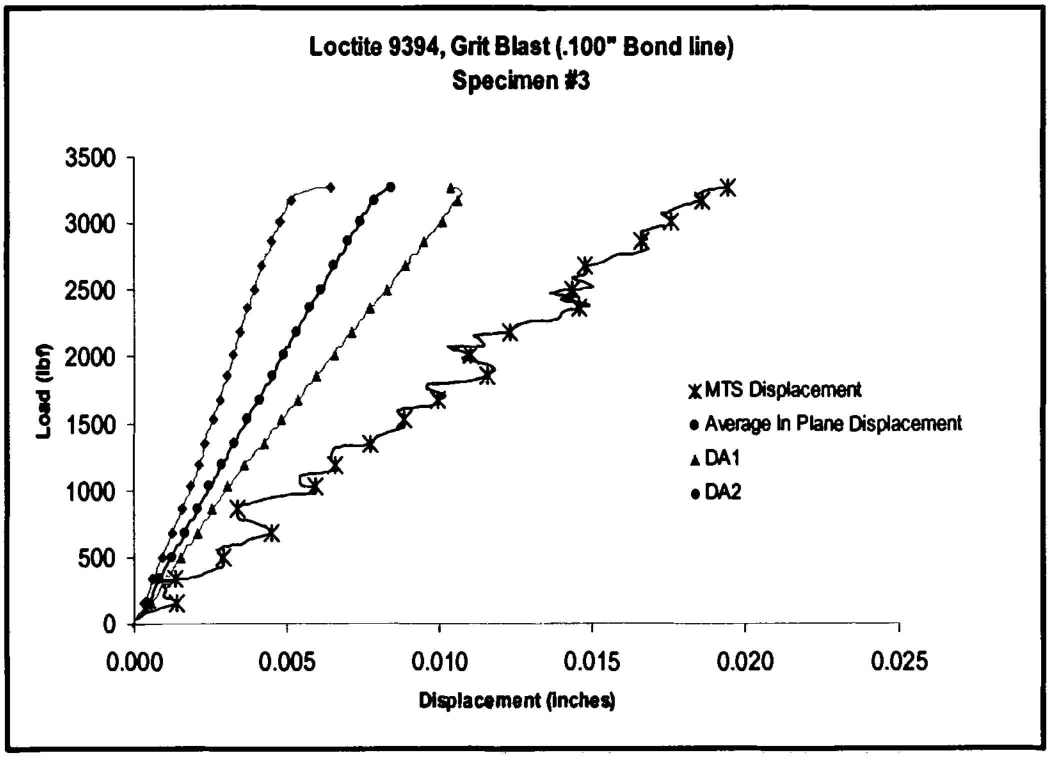

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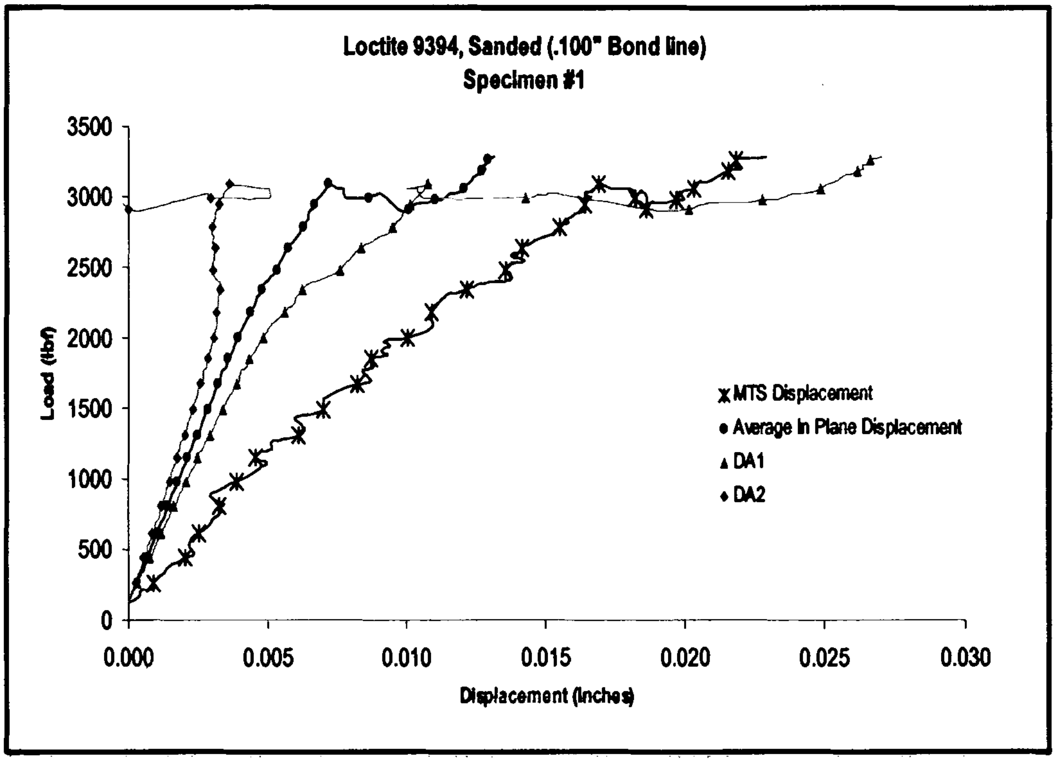

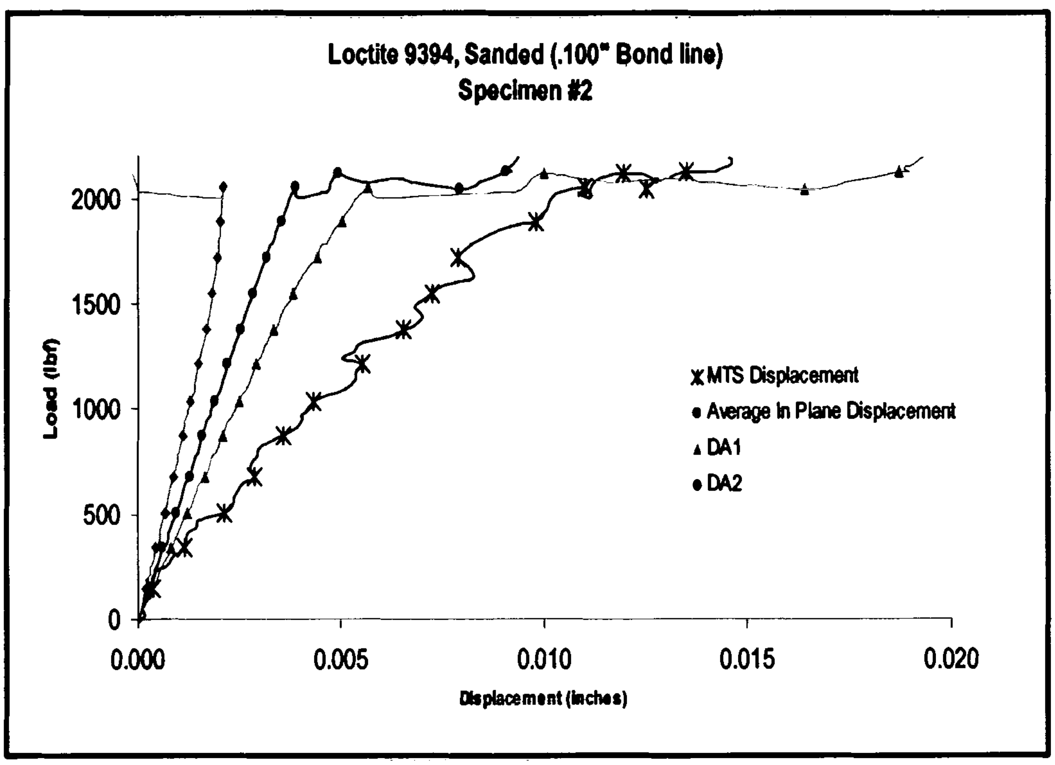

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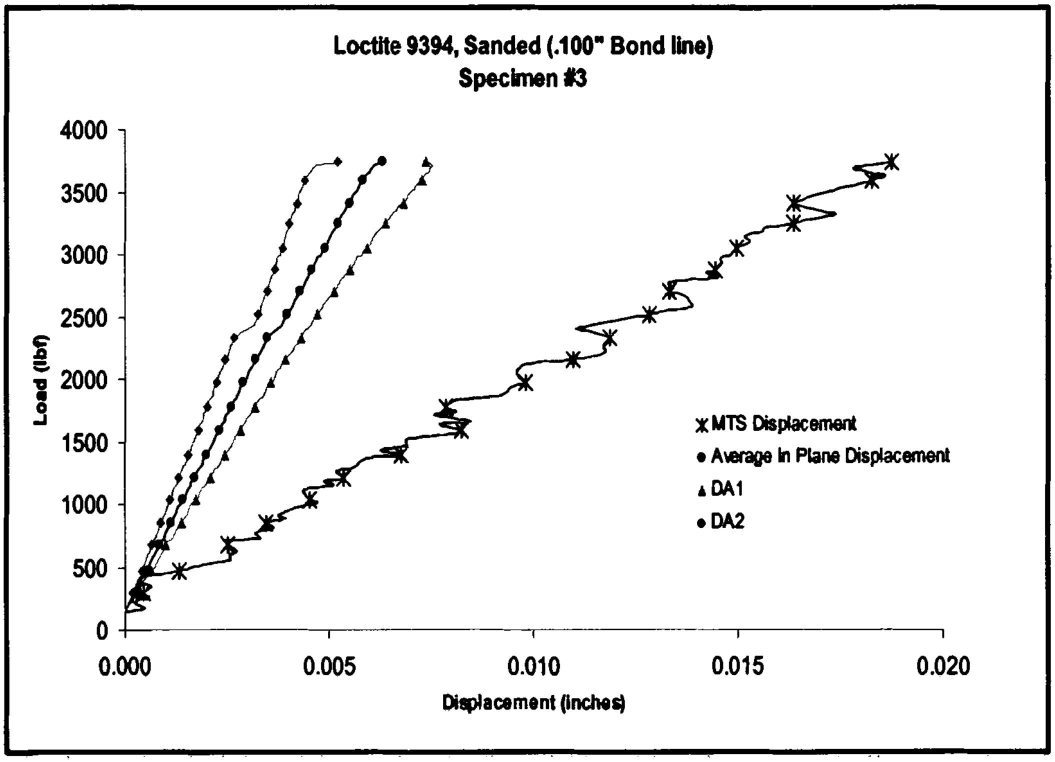

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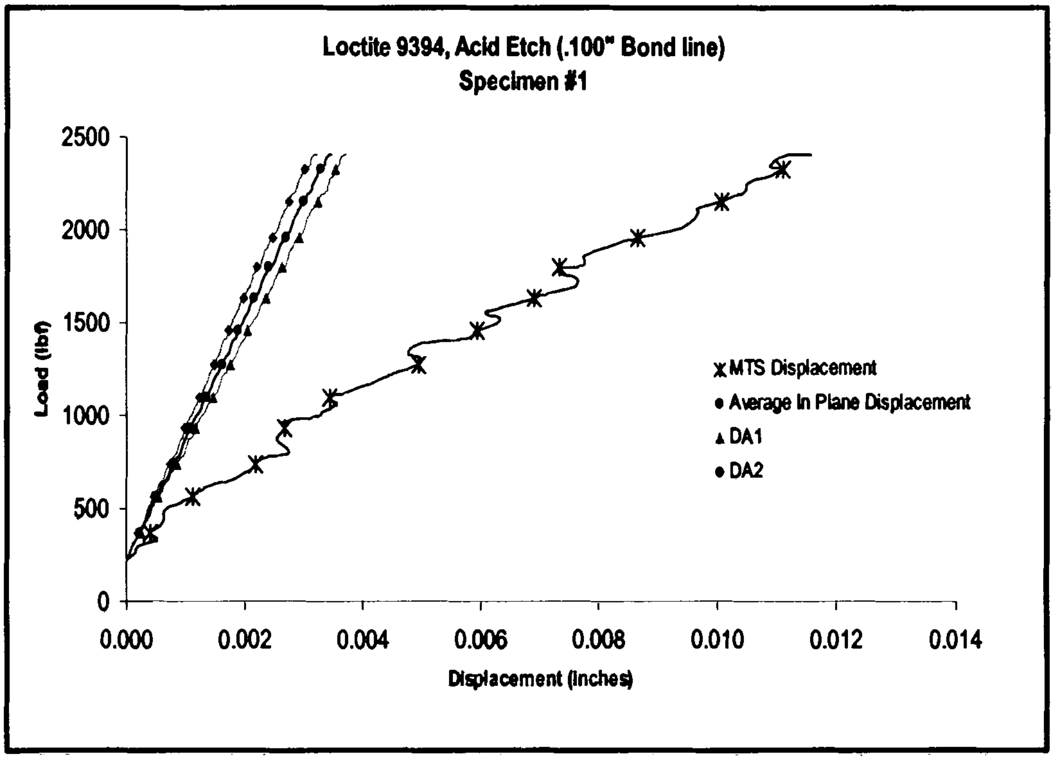

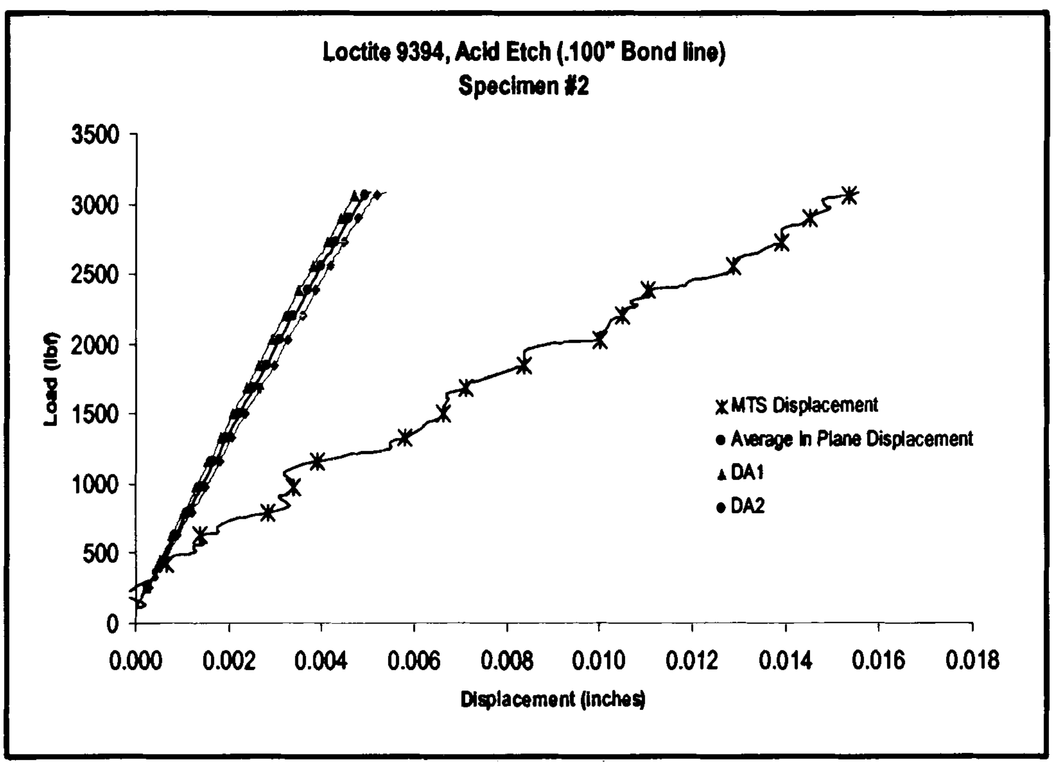

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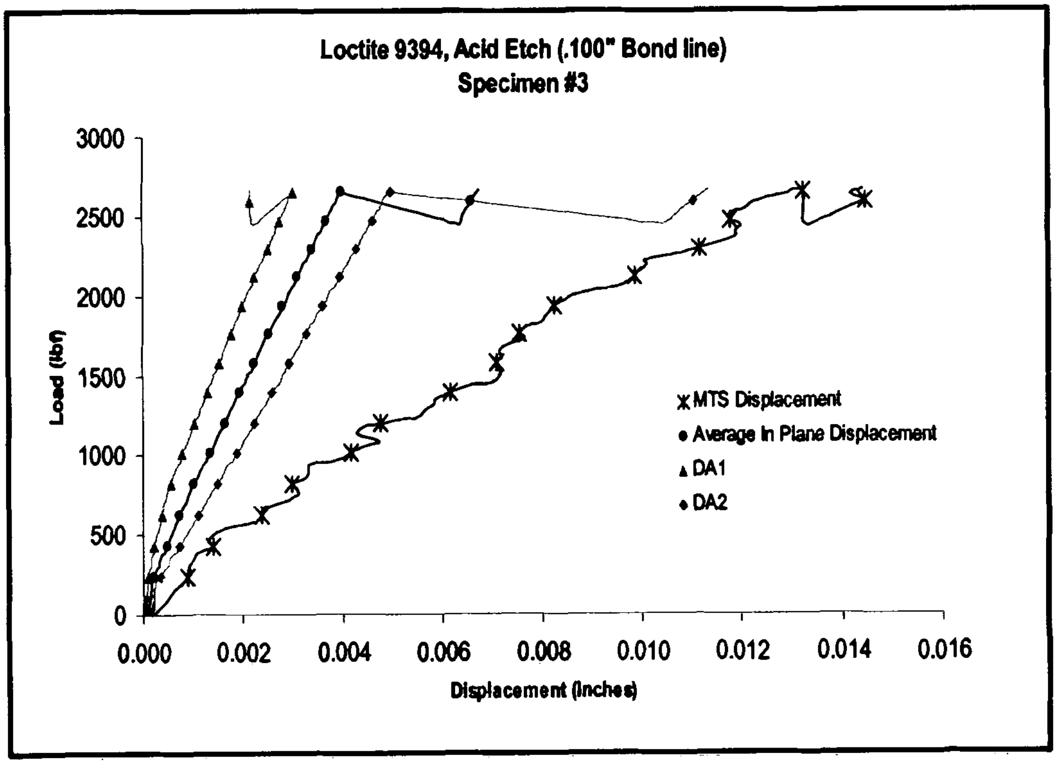

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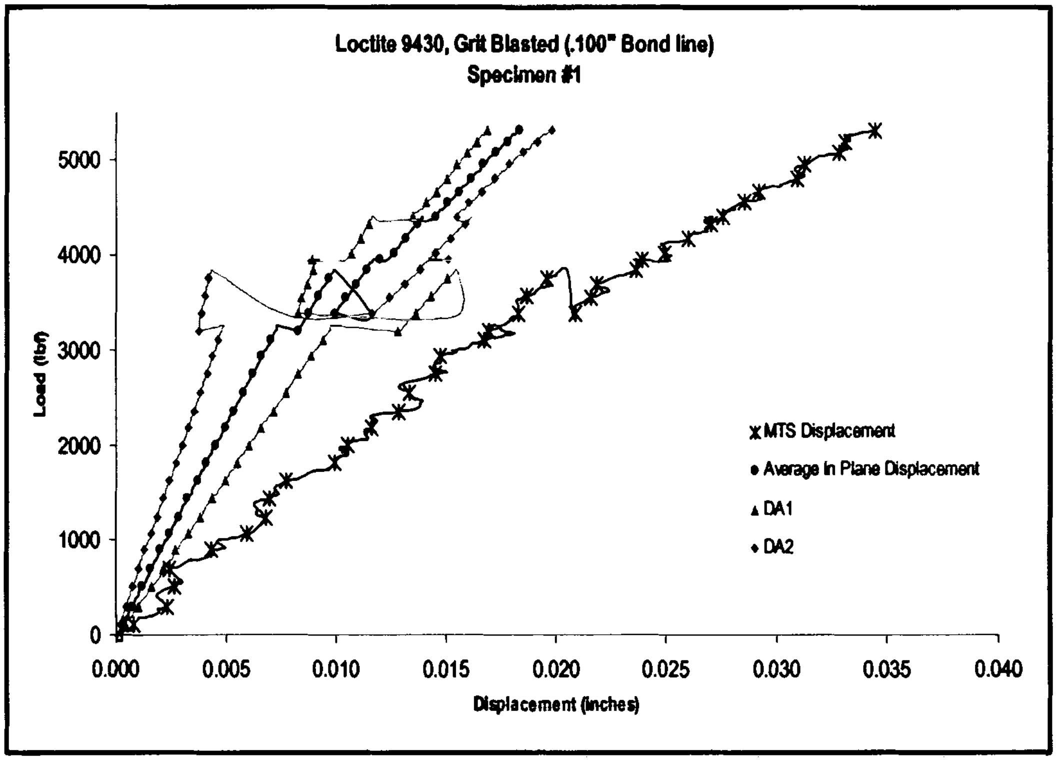

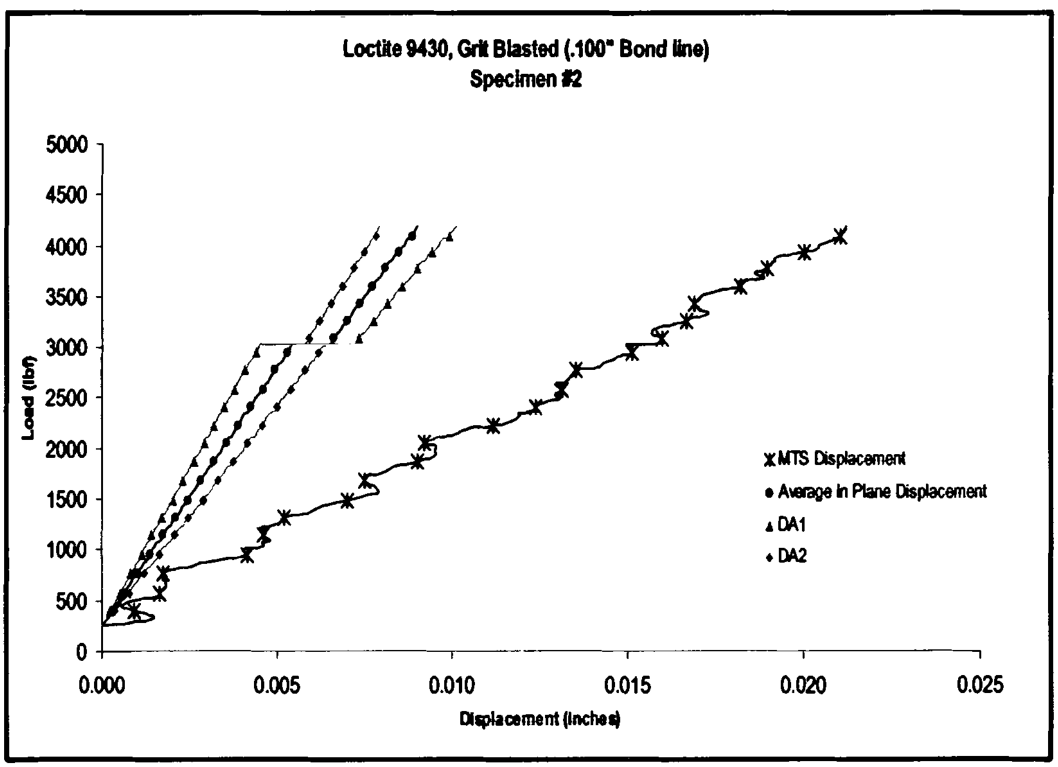

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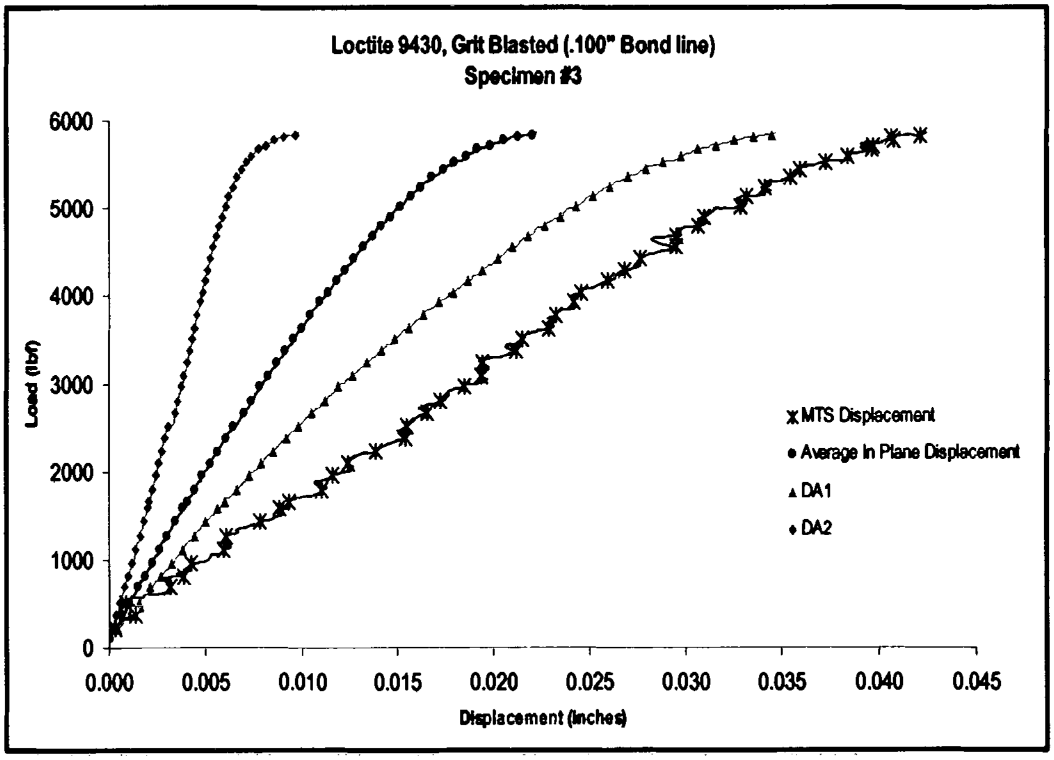

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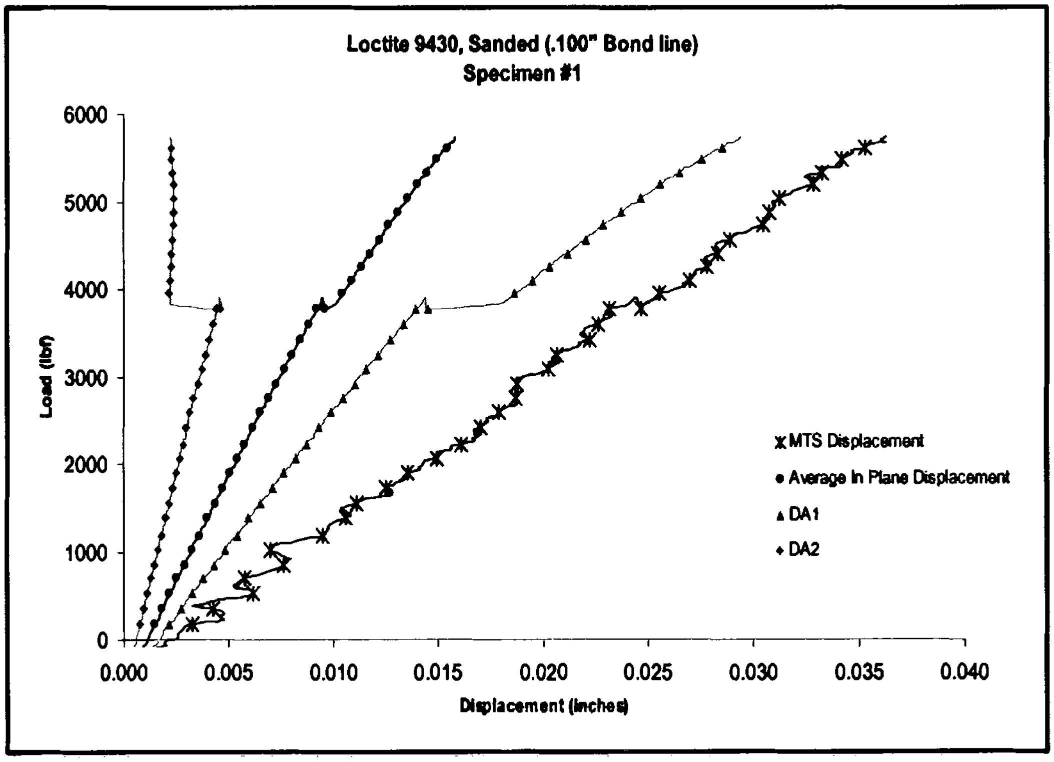

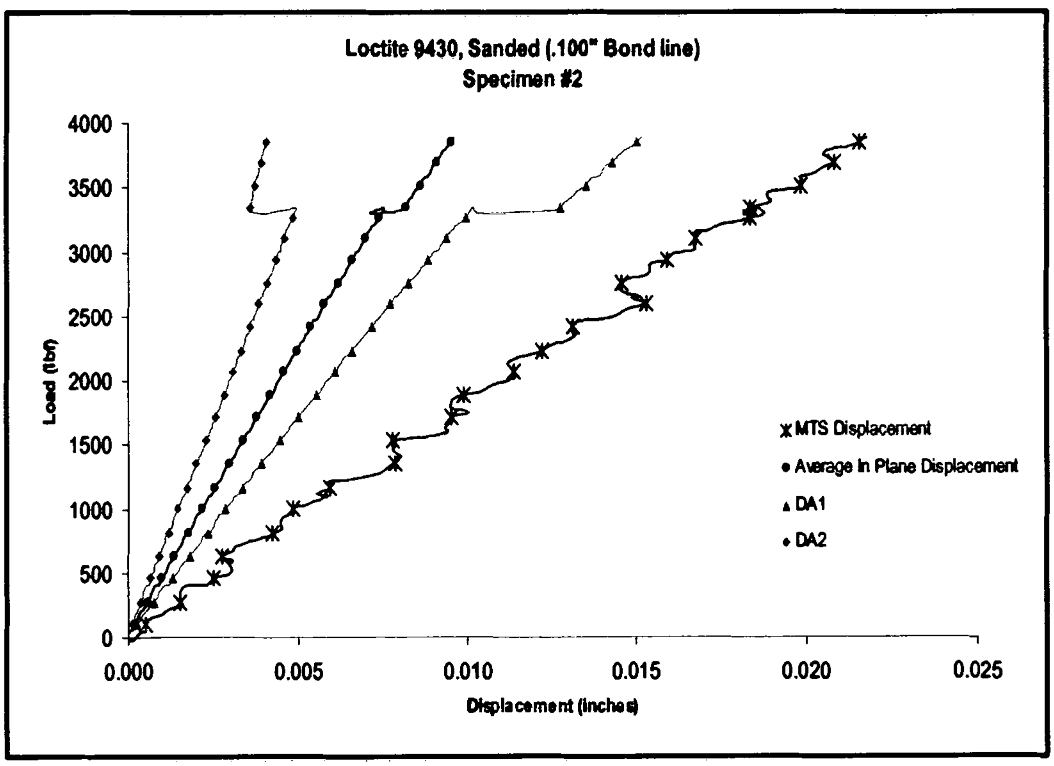

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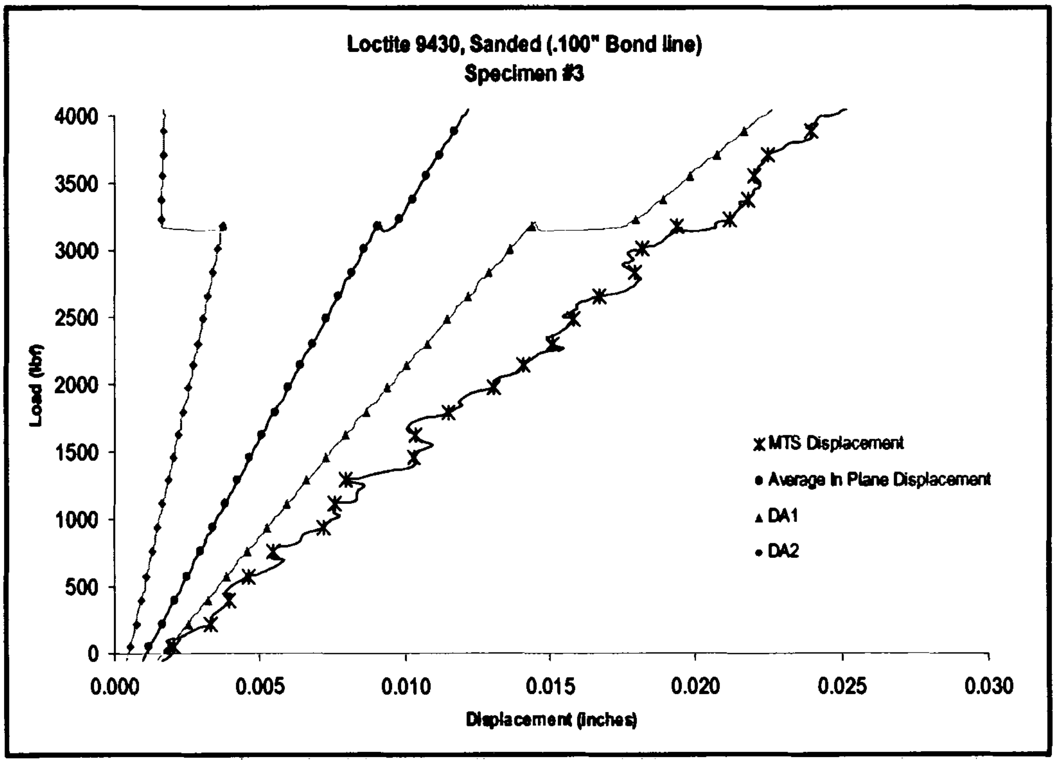

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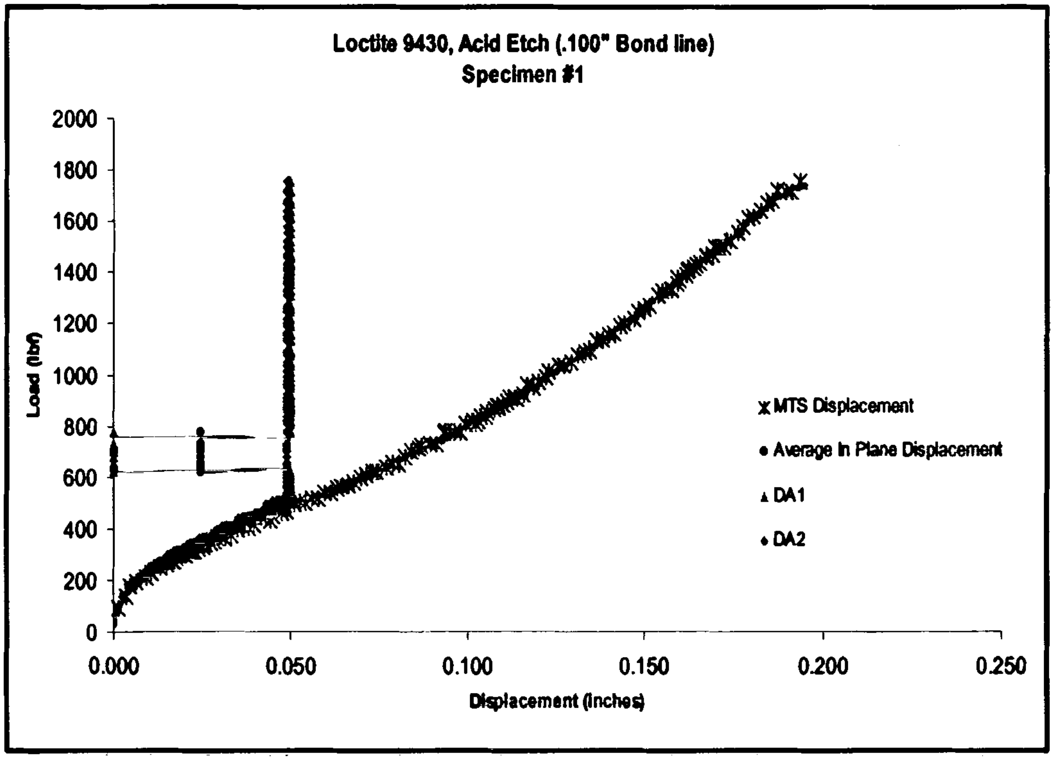

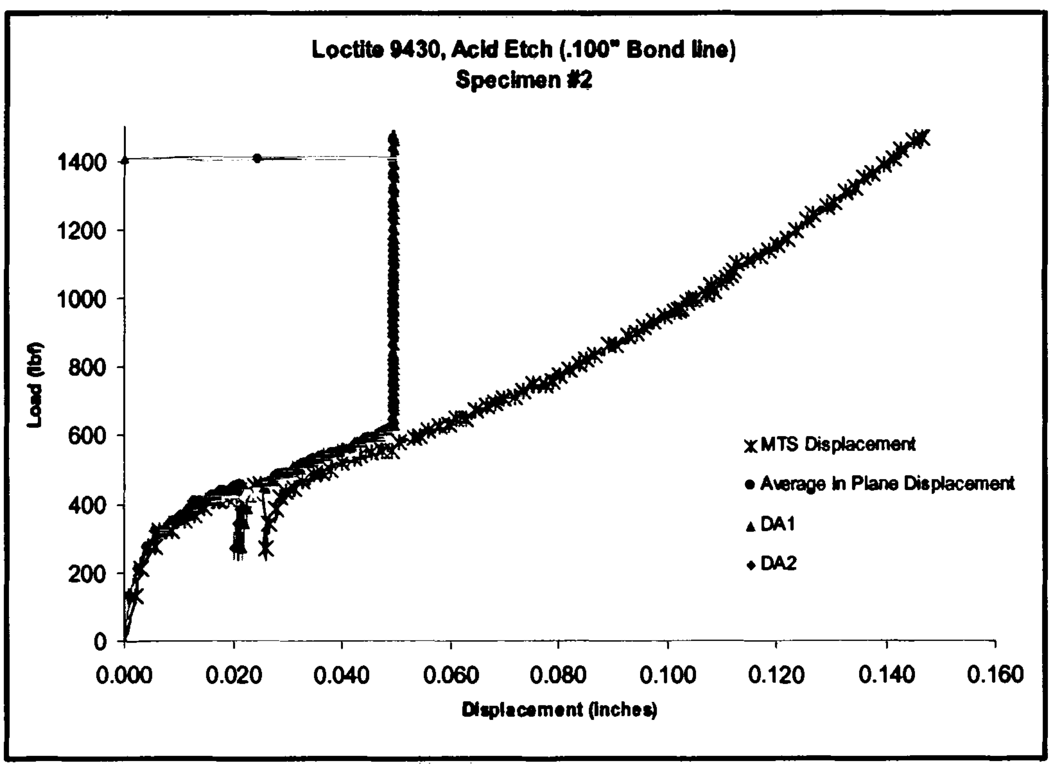

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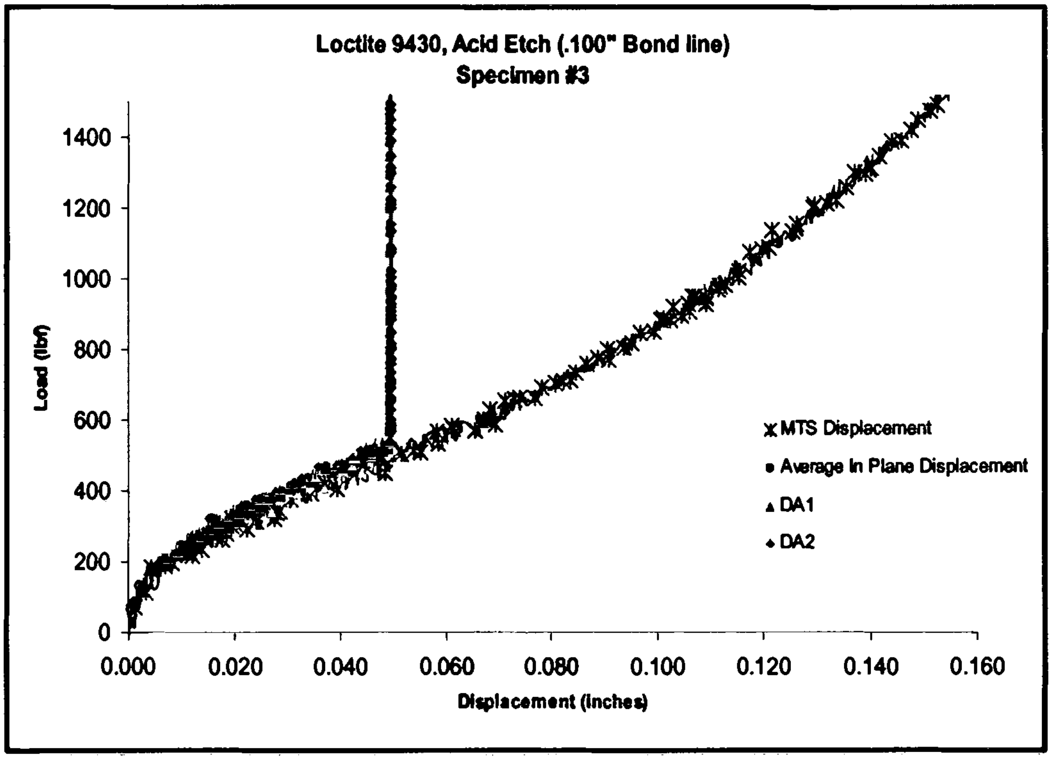

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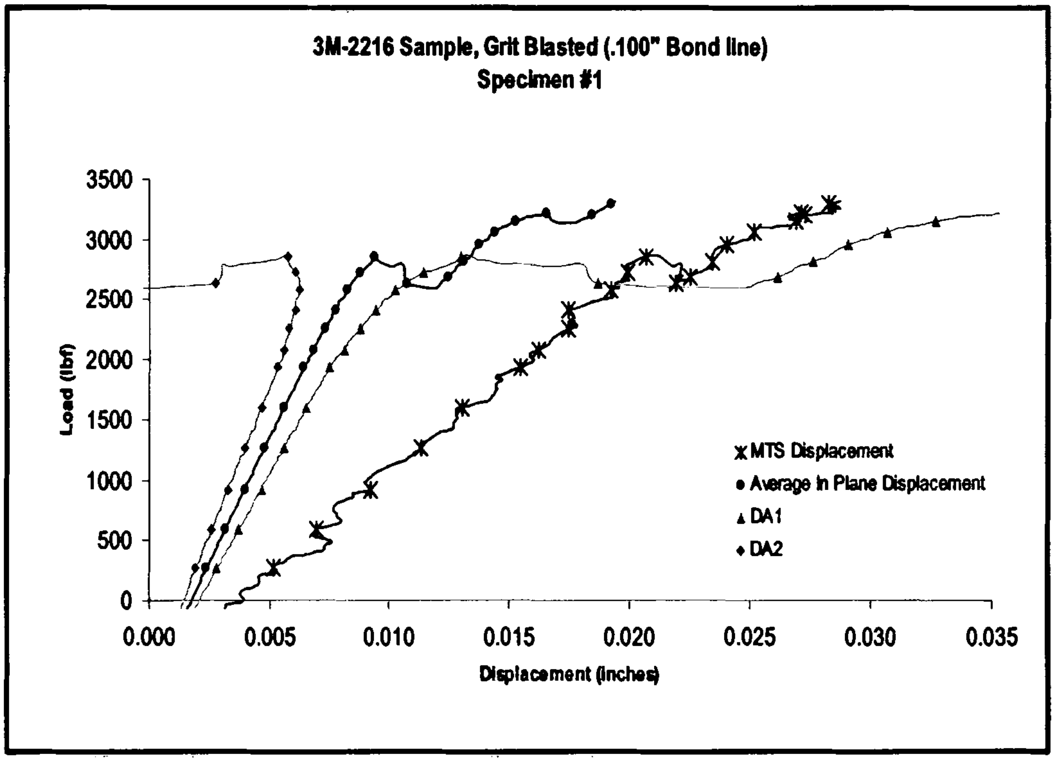

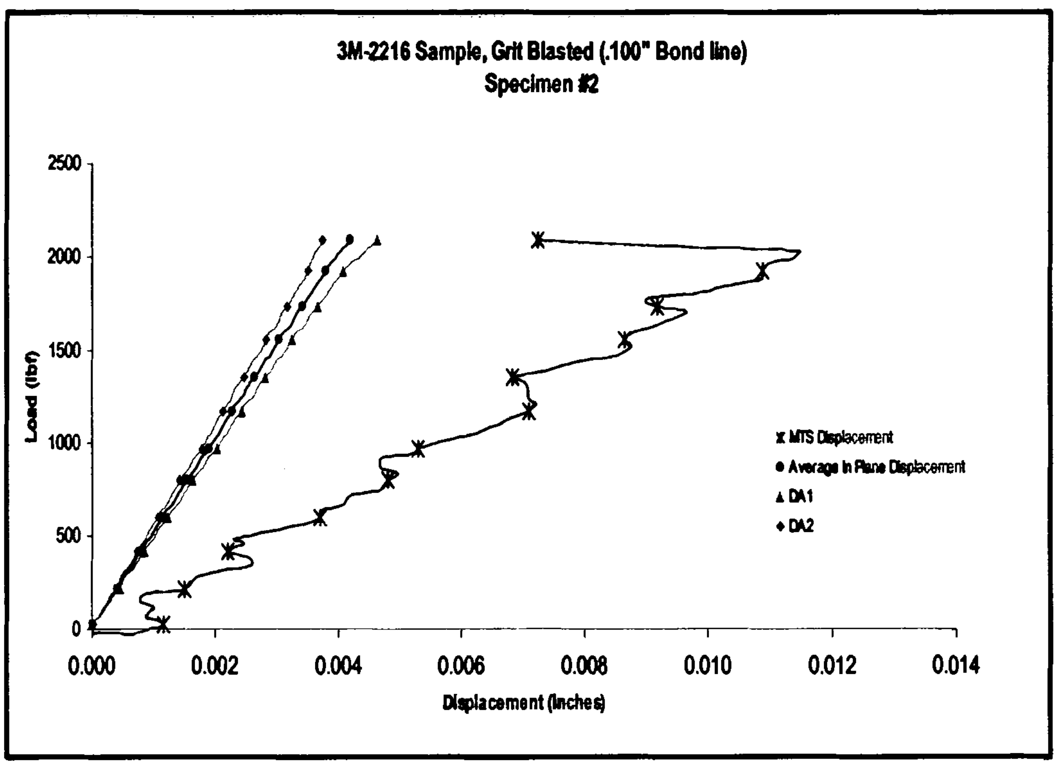

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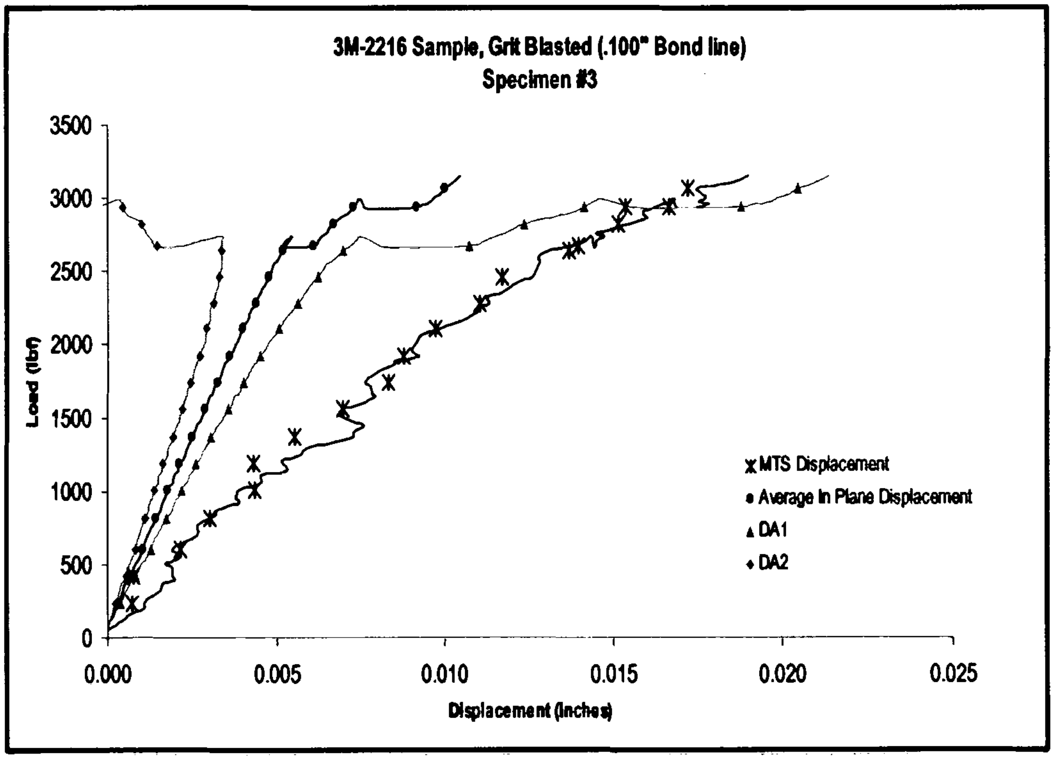

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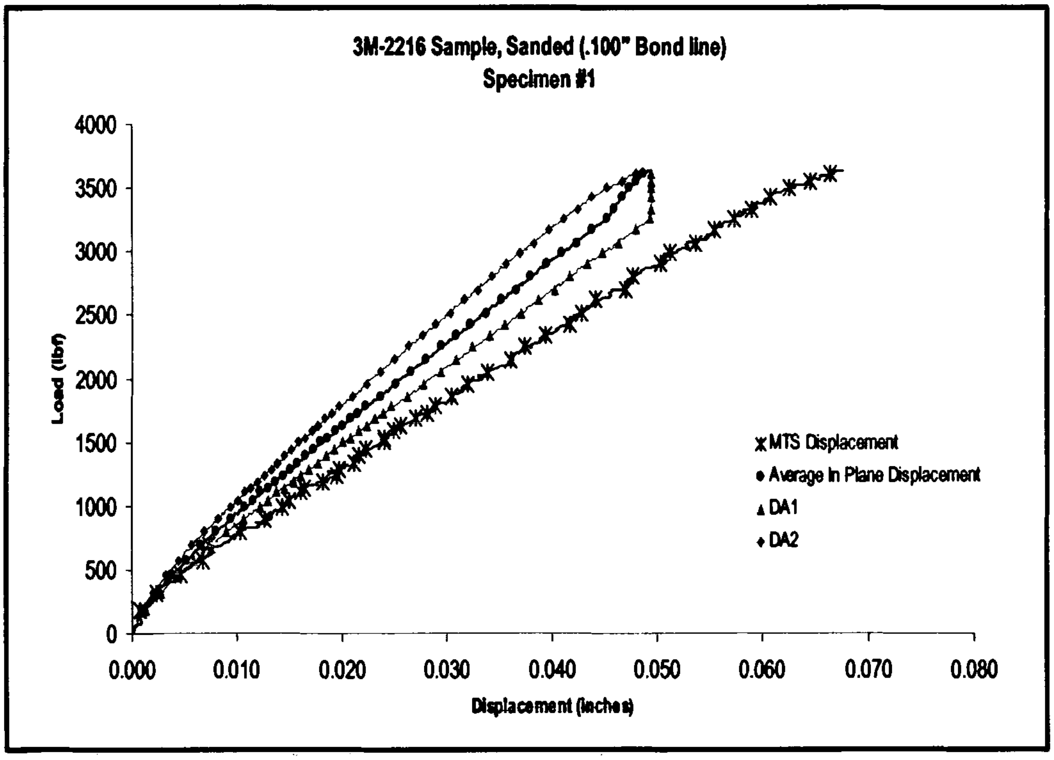

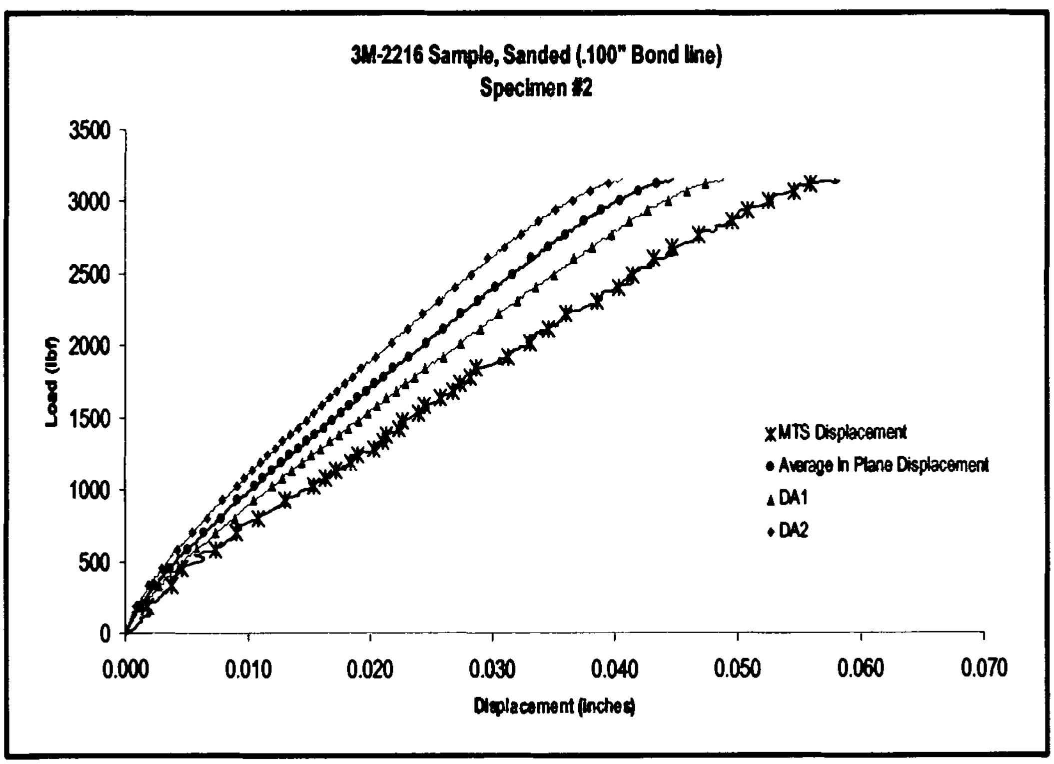

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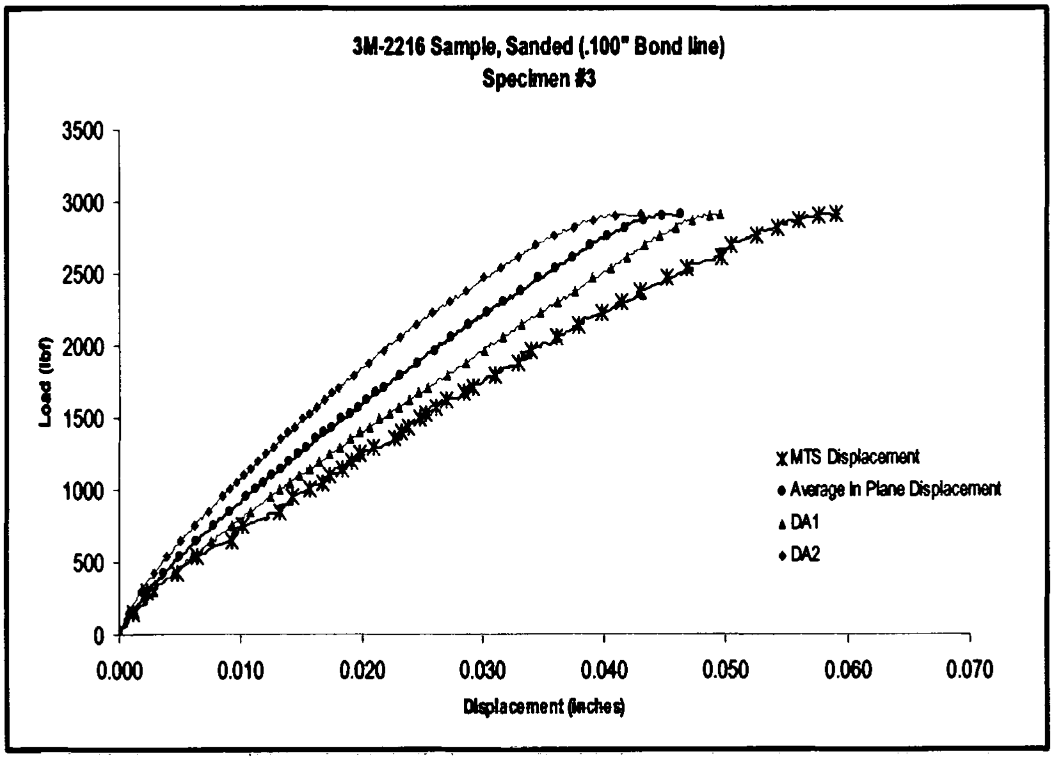

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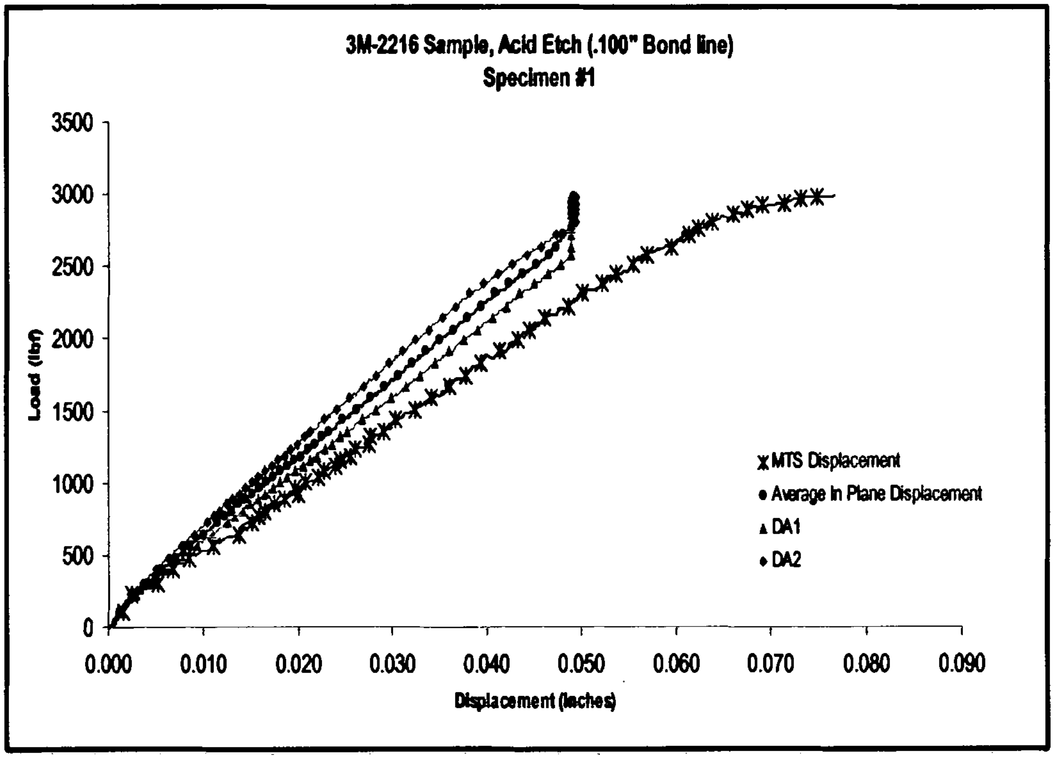

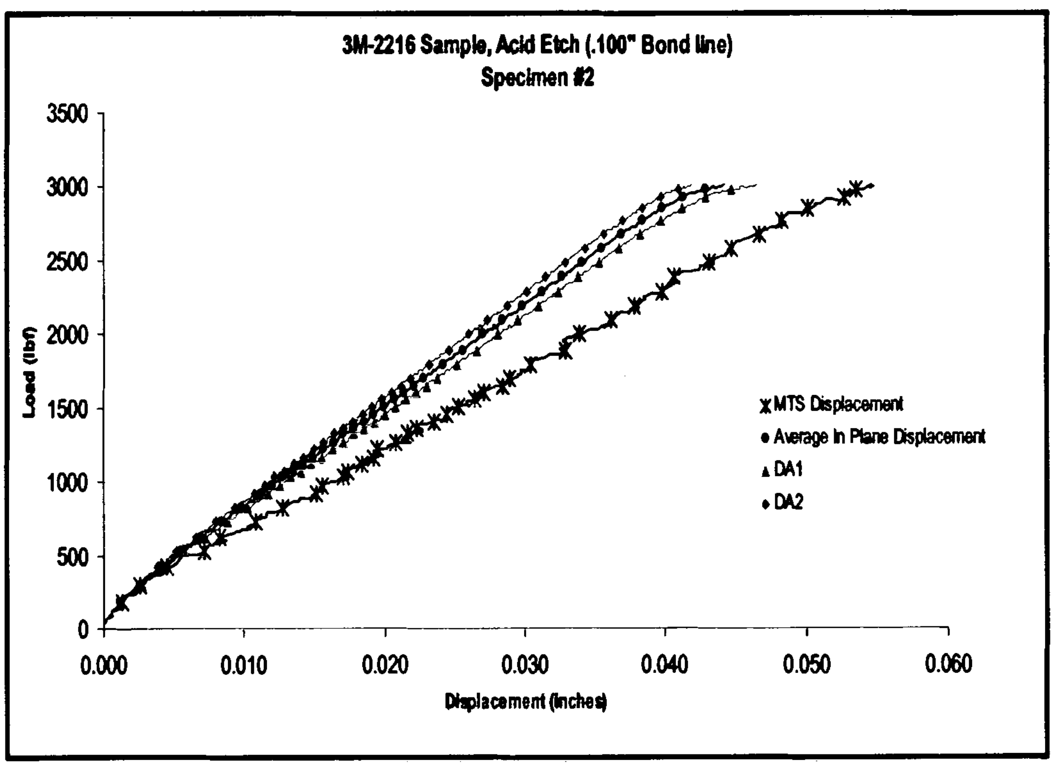

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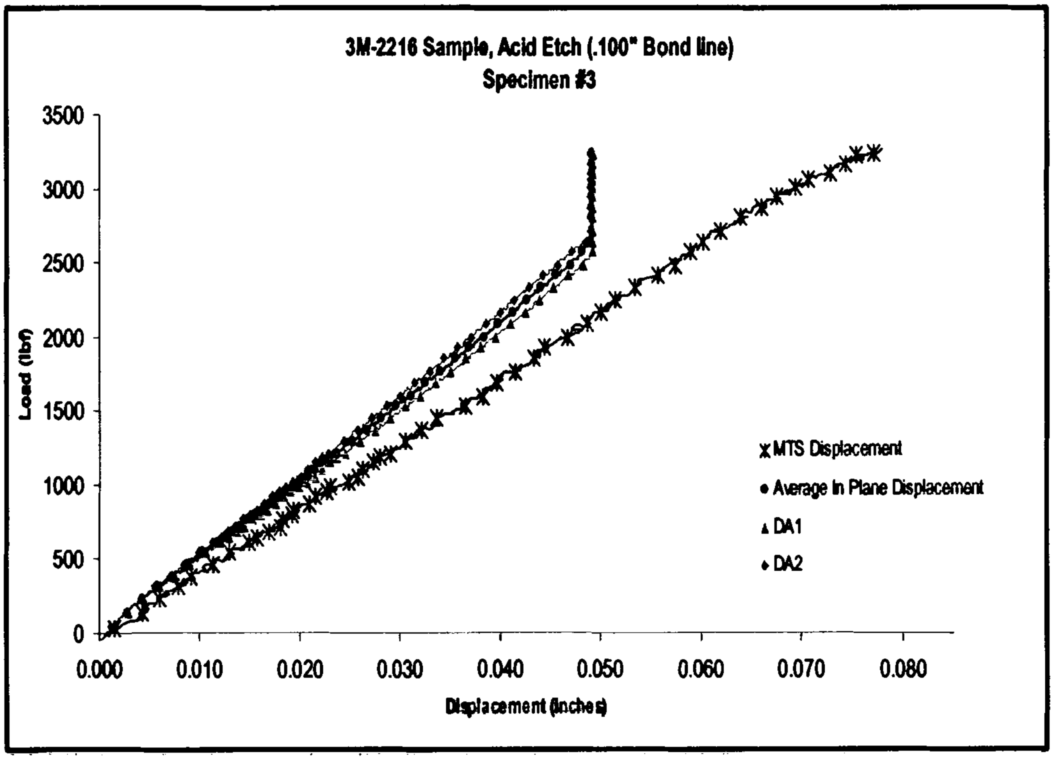
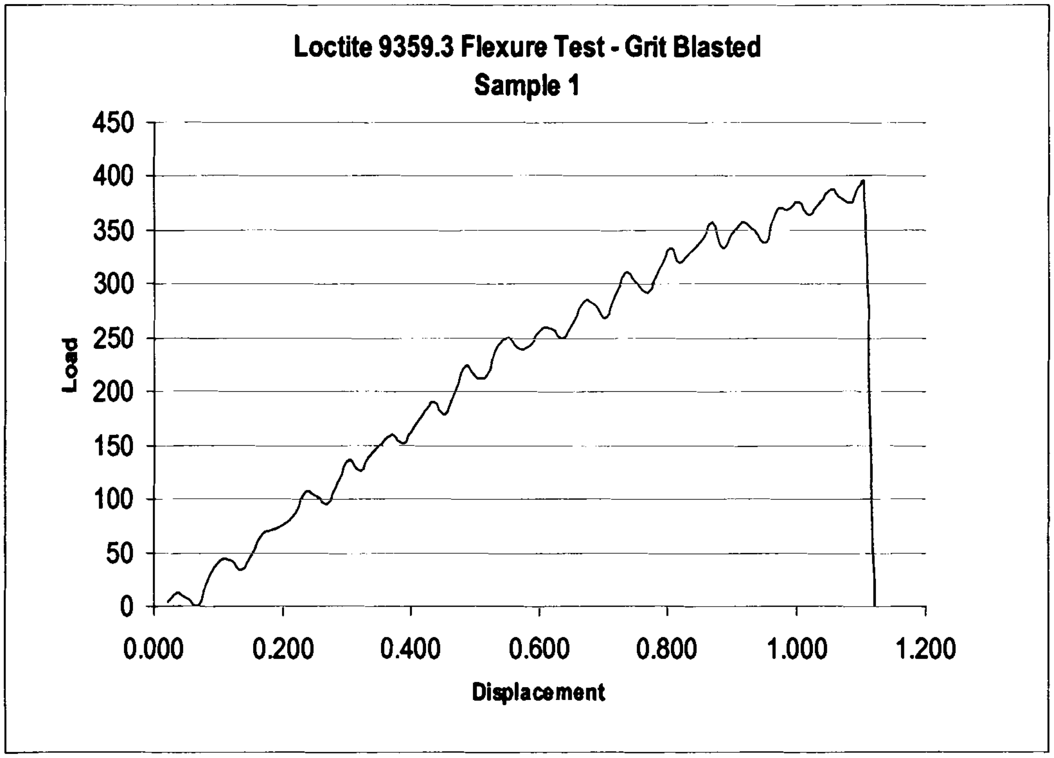
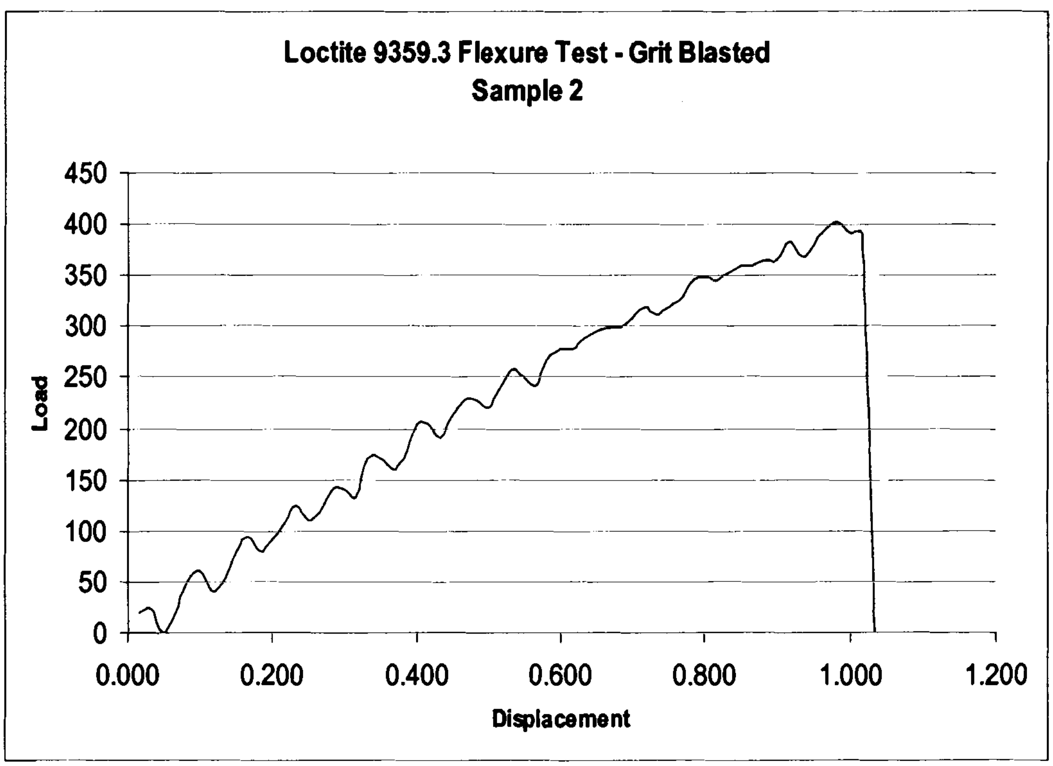


Figure A.2 – Flexure Test Results





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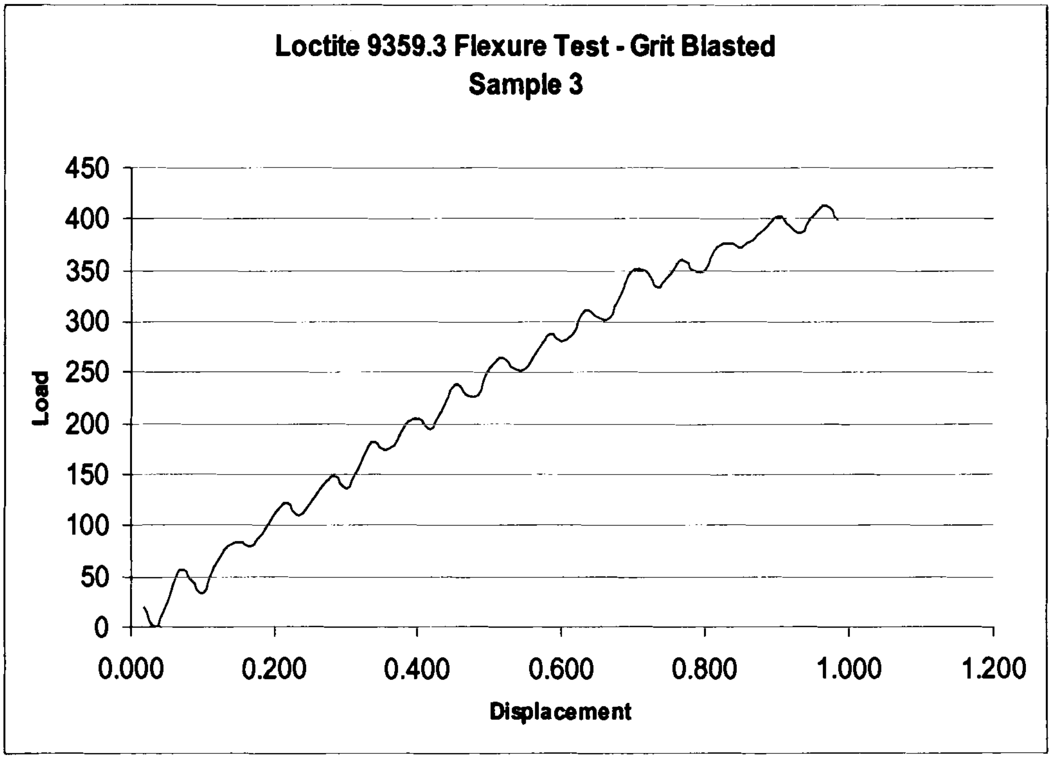

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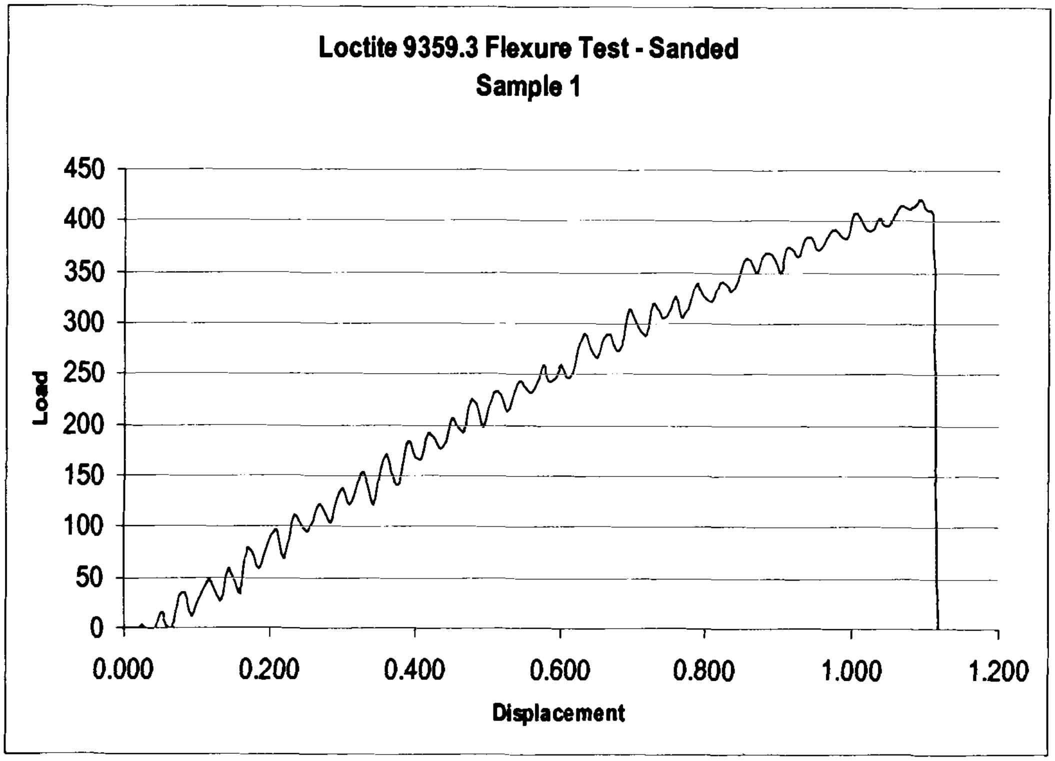

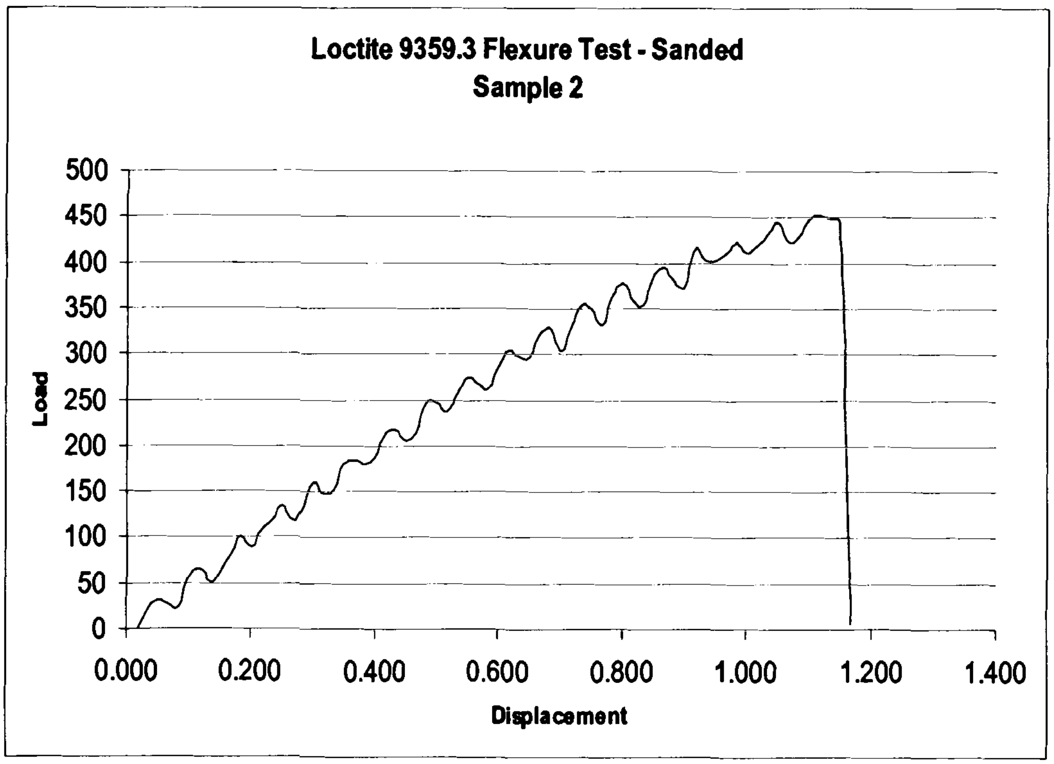

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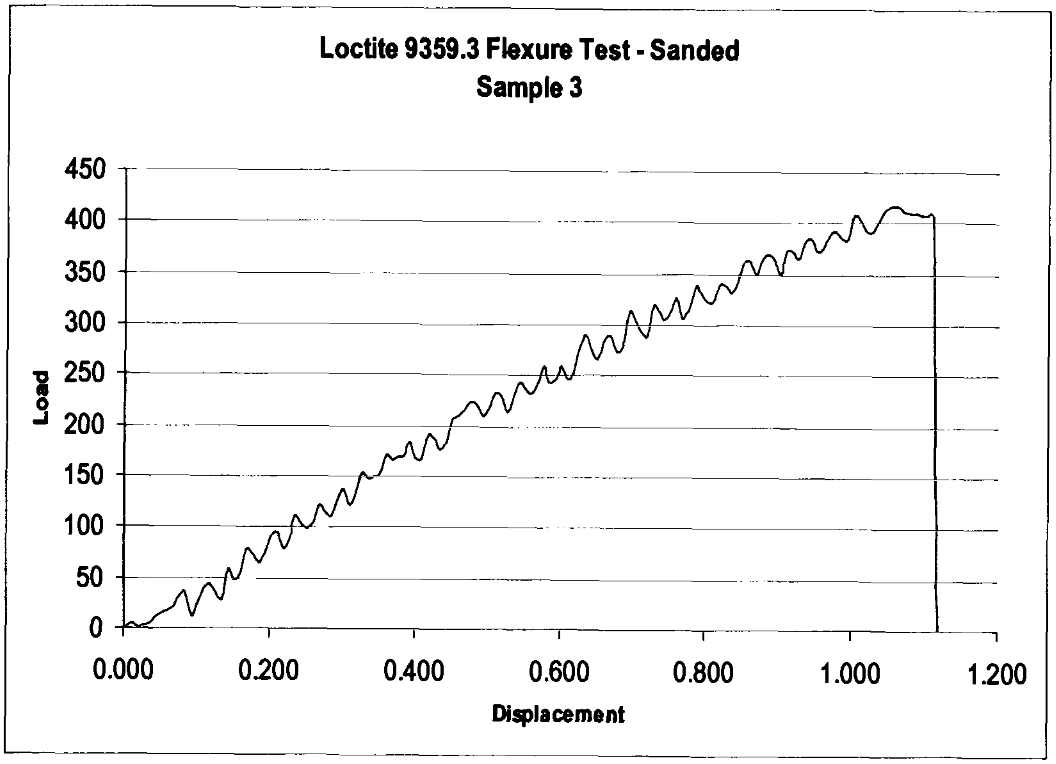

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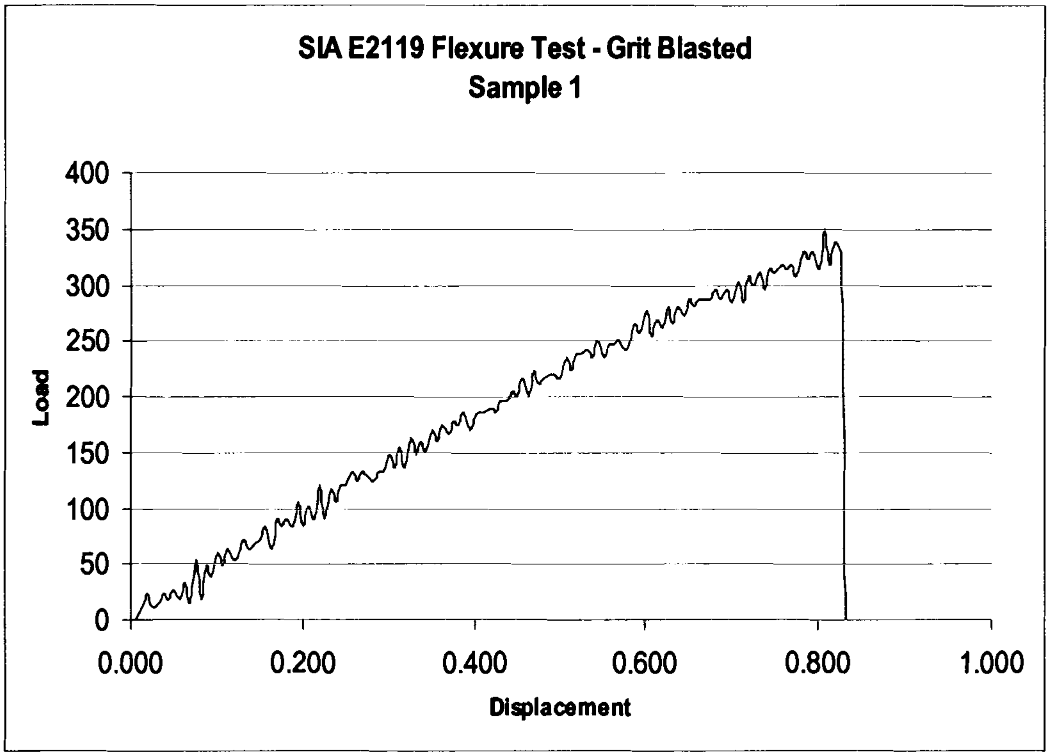

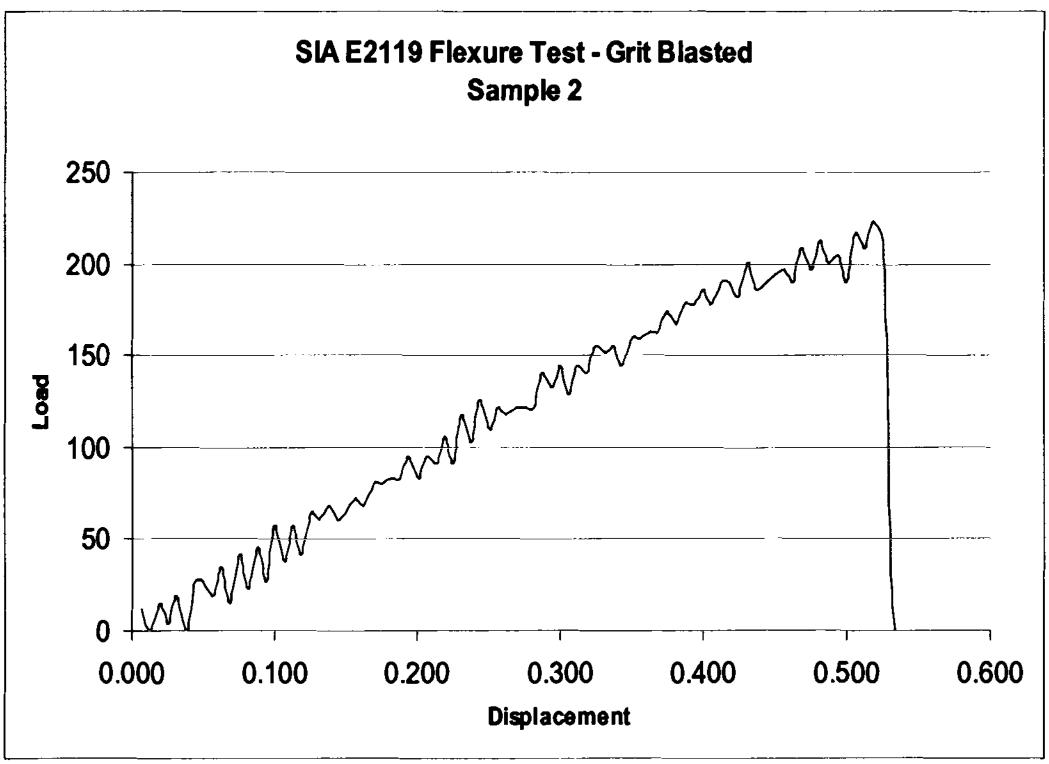

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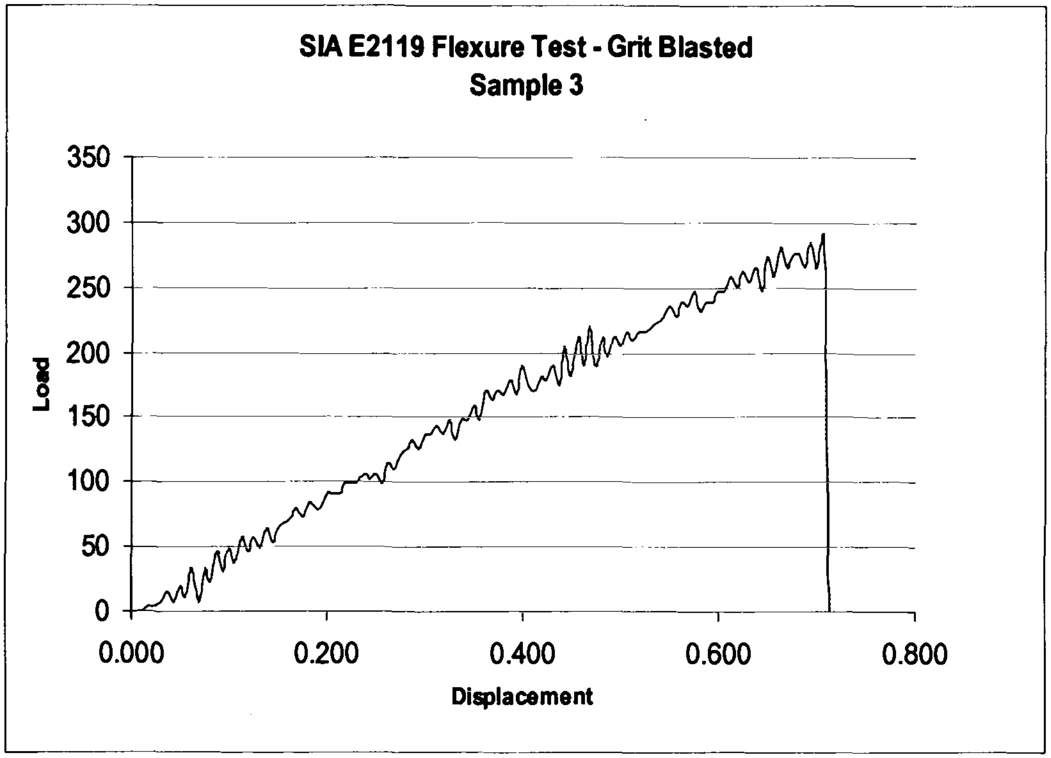

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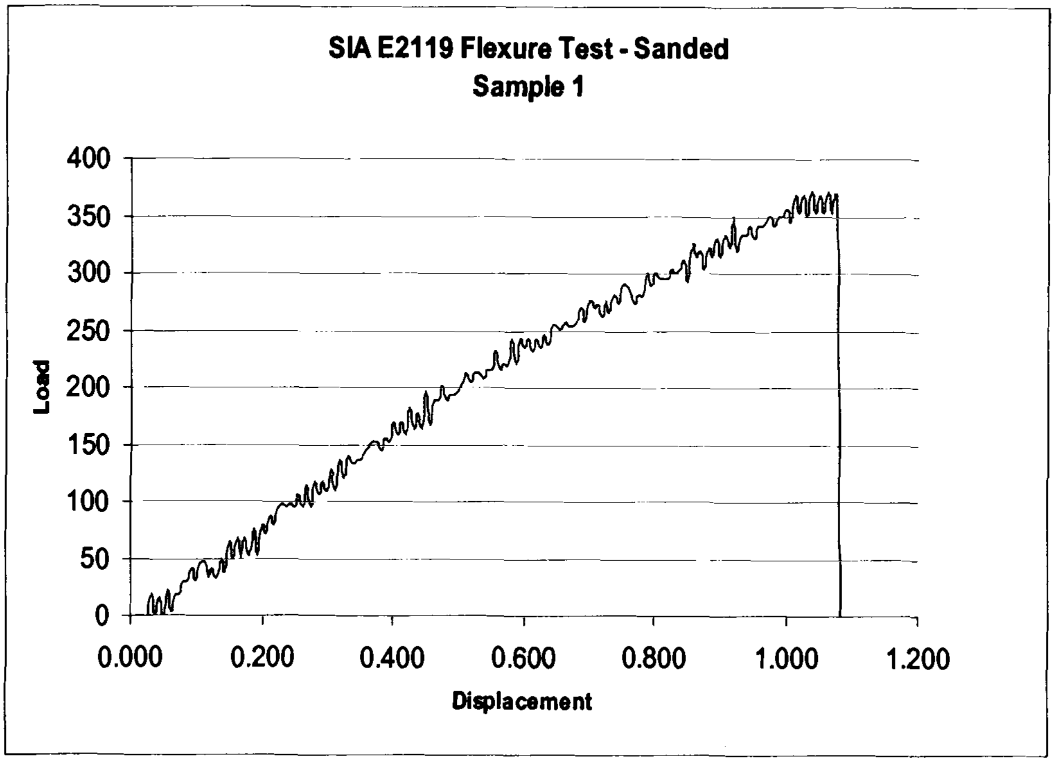

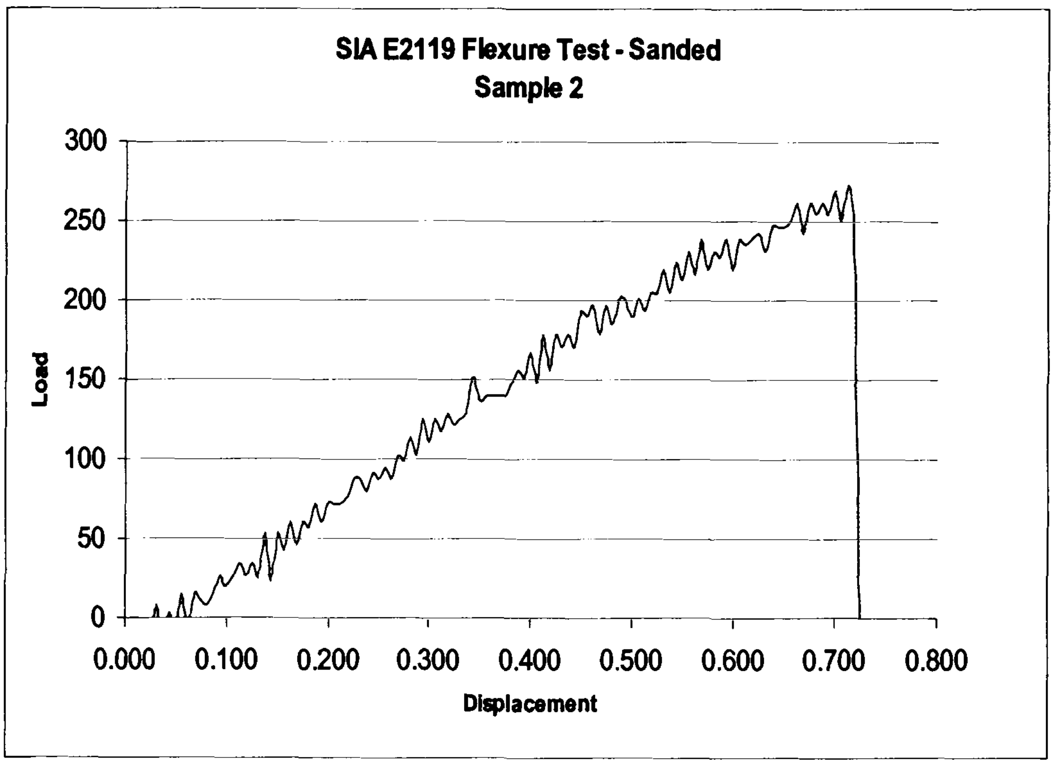

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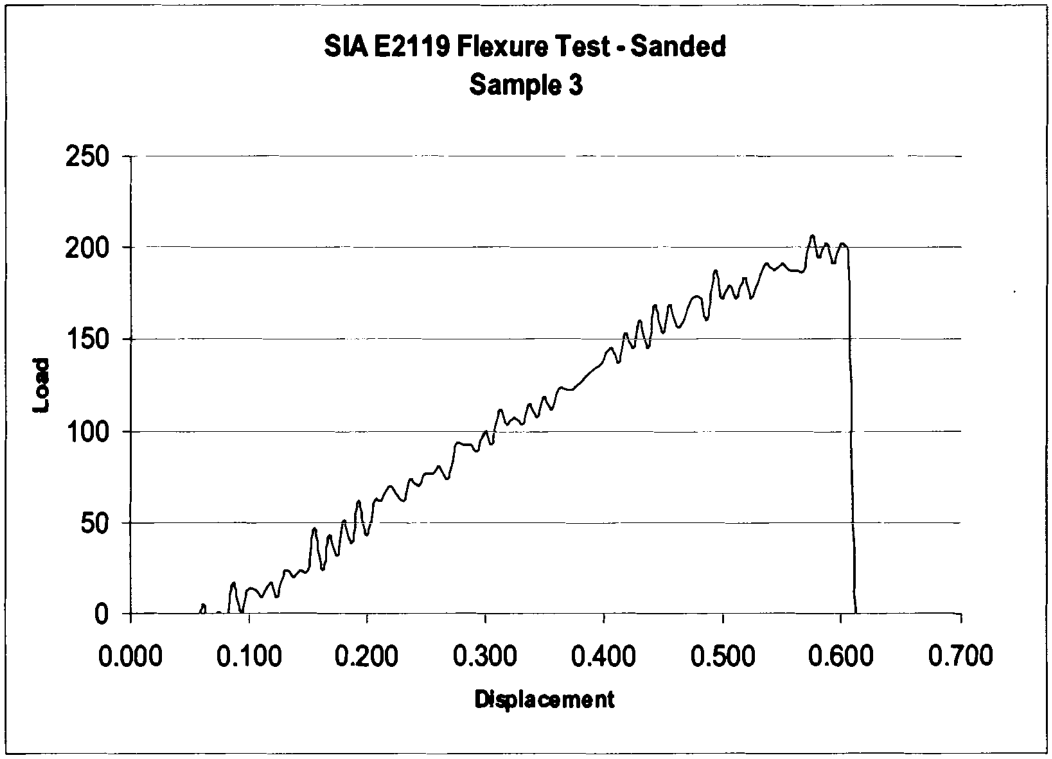
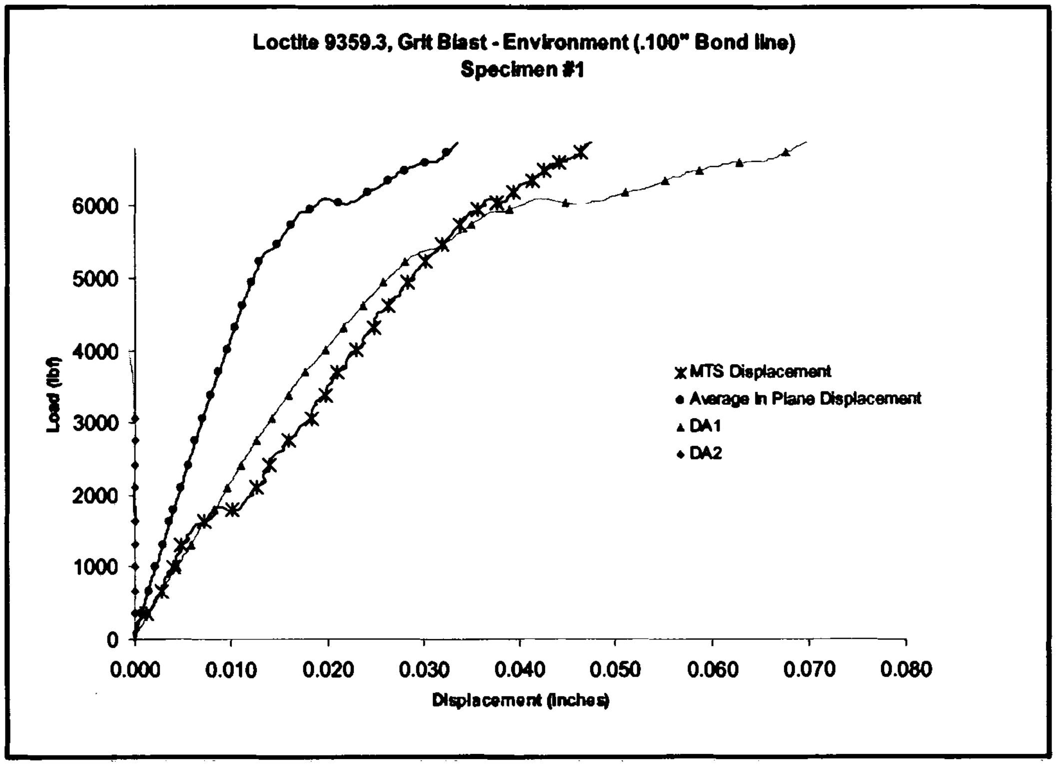
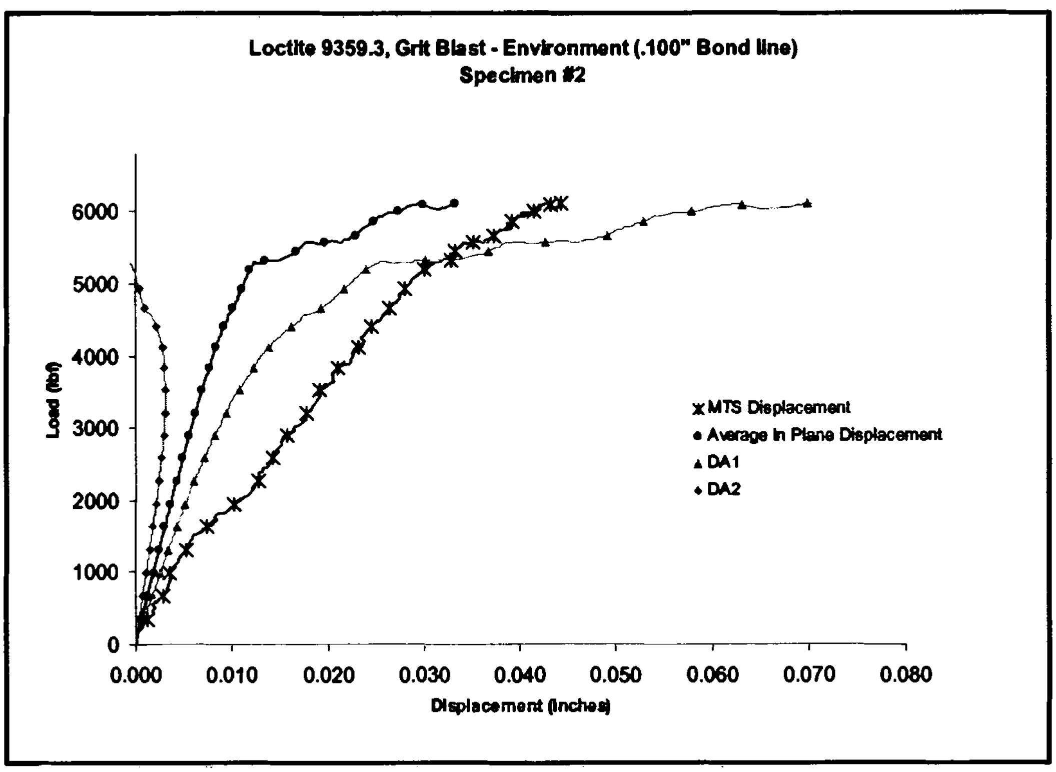


Figure A.3 – Environmental Test Results





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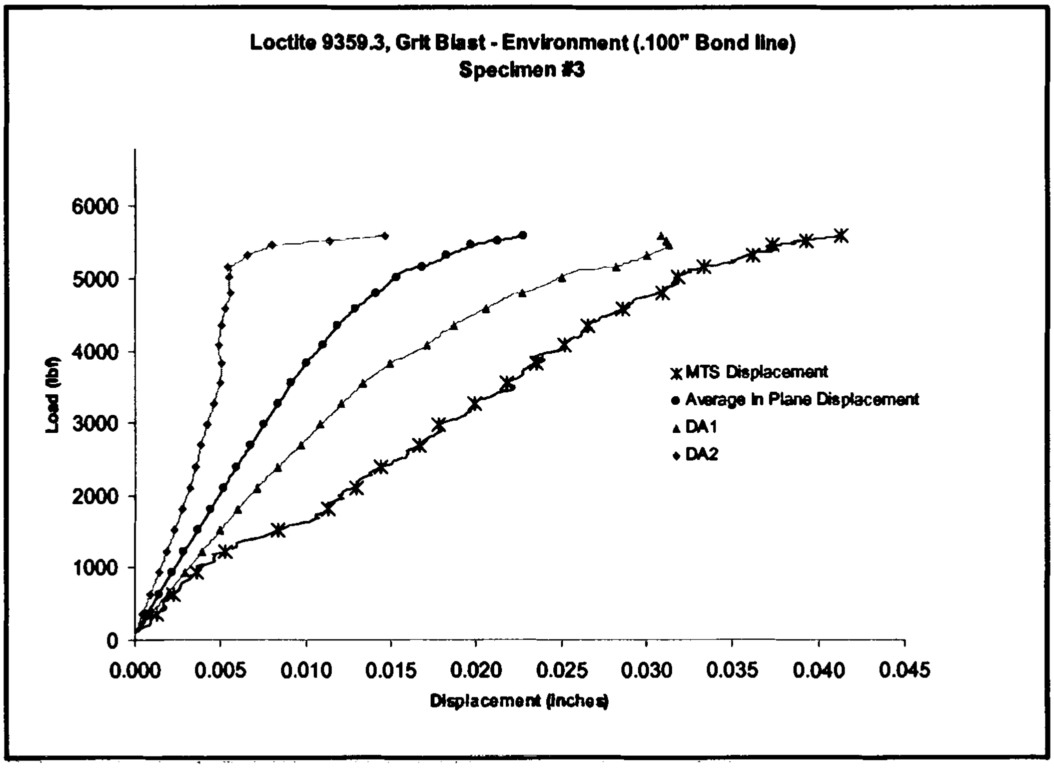

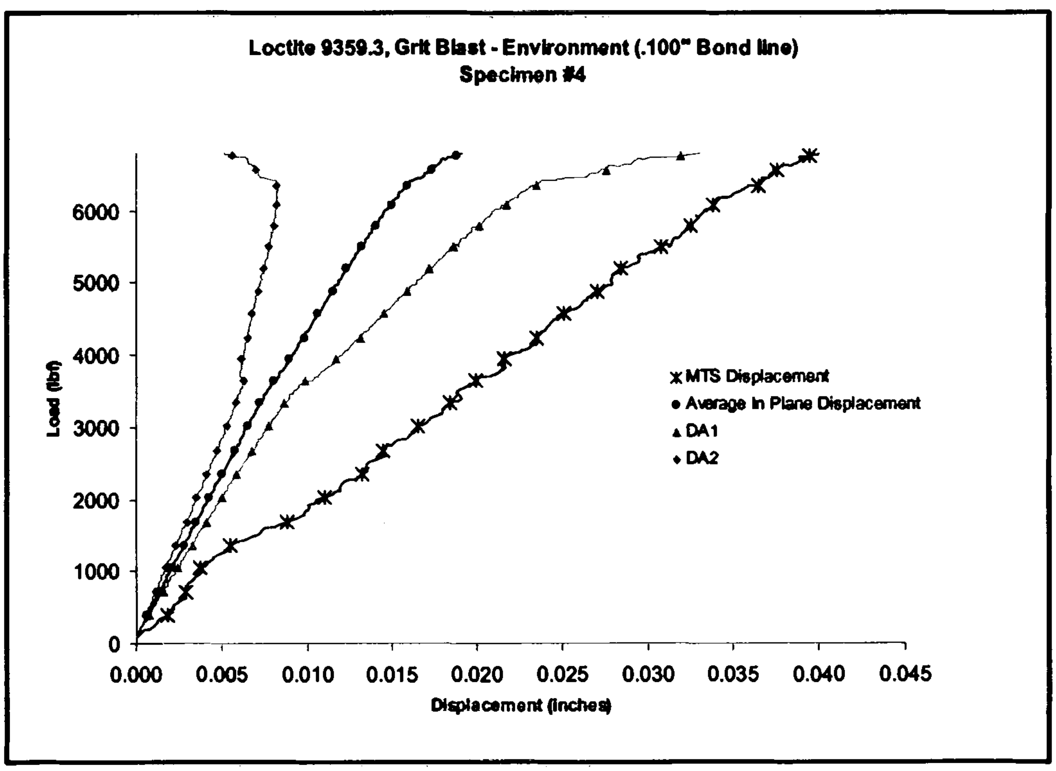

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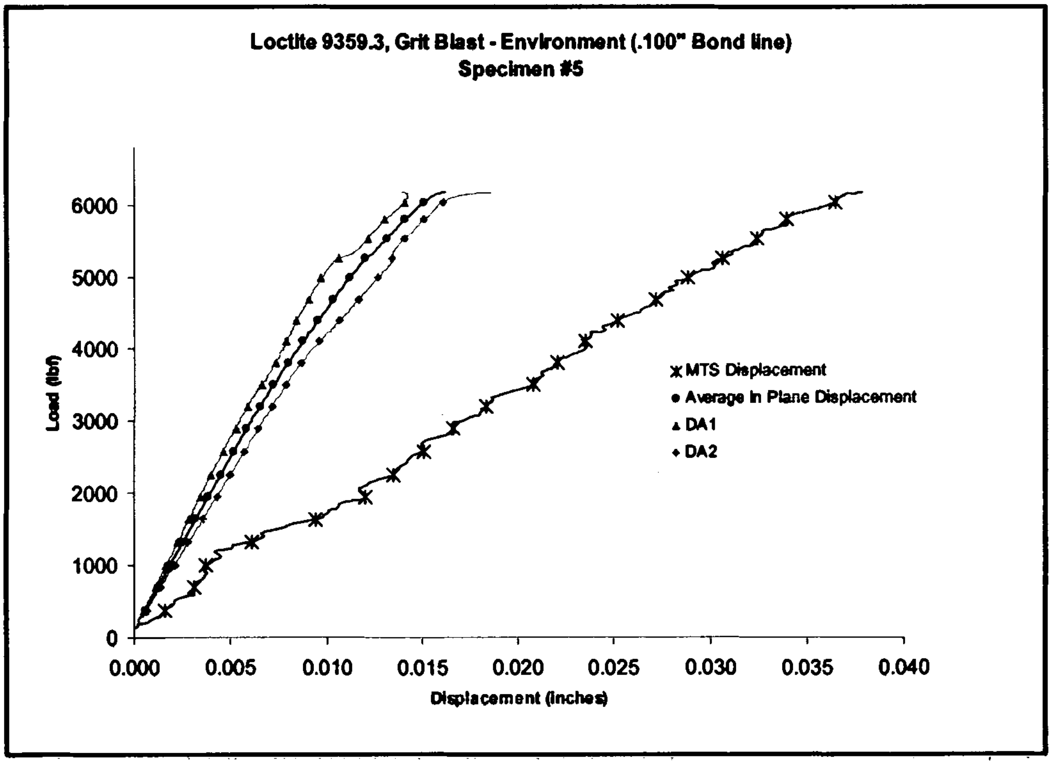

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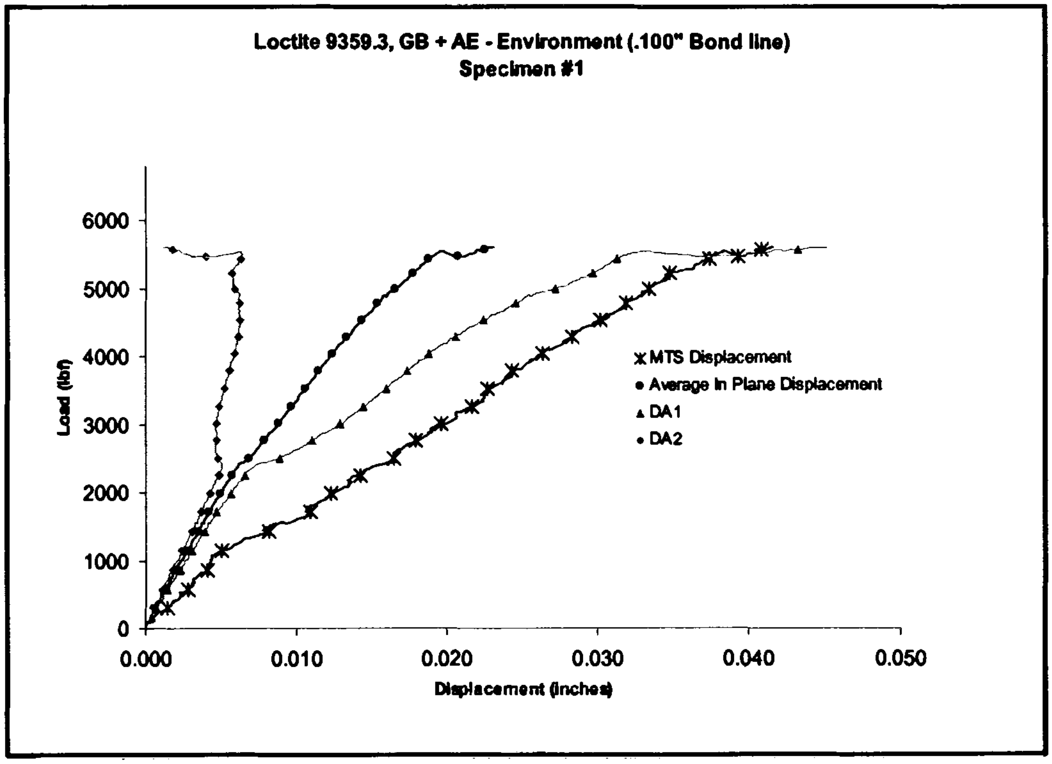

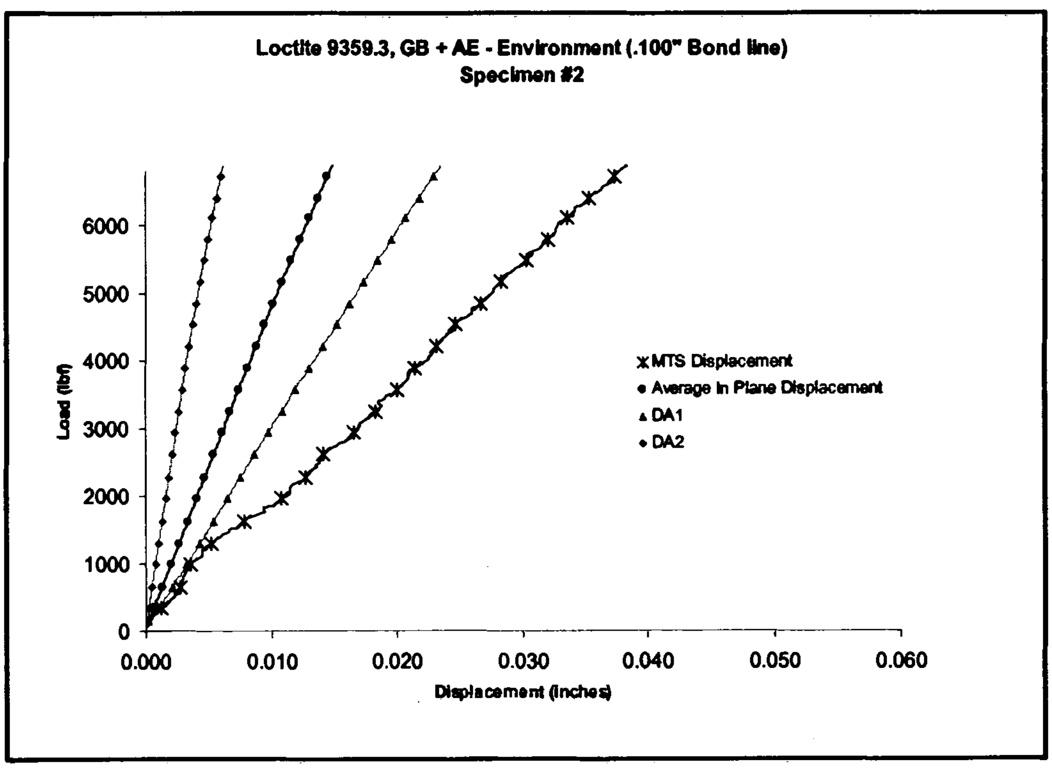

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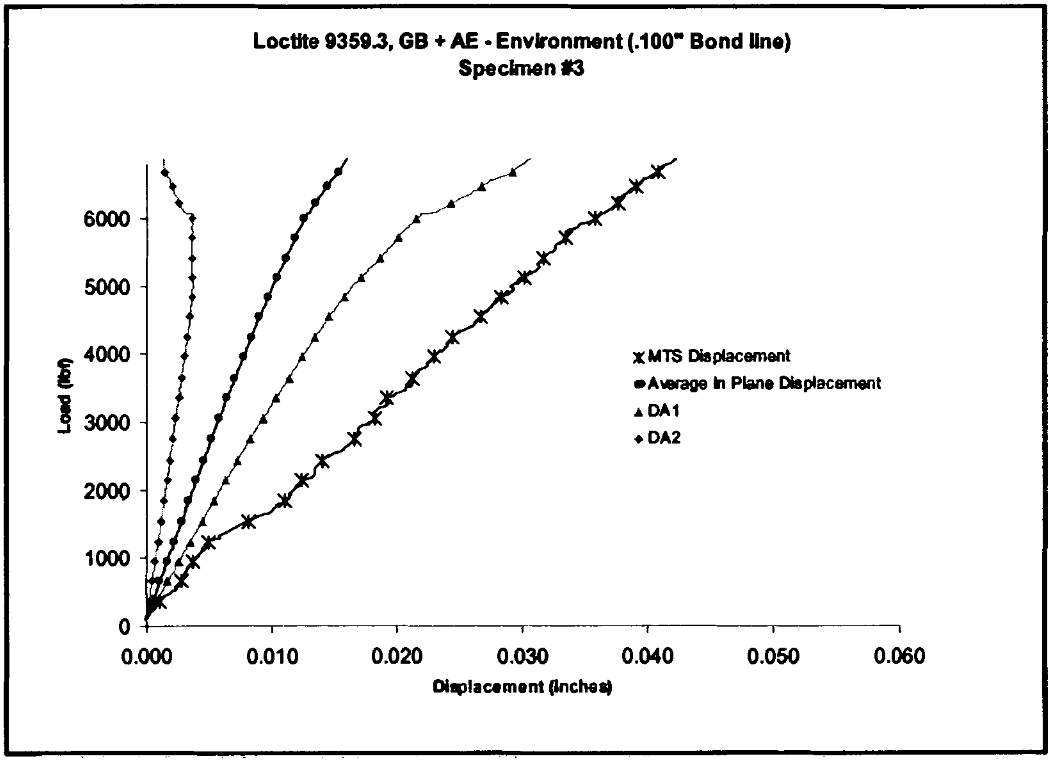

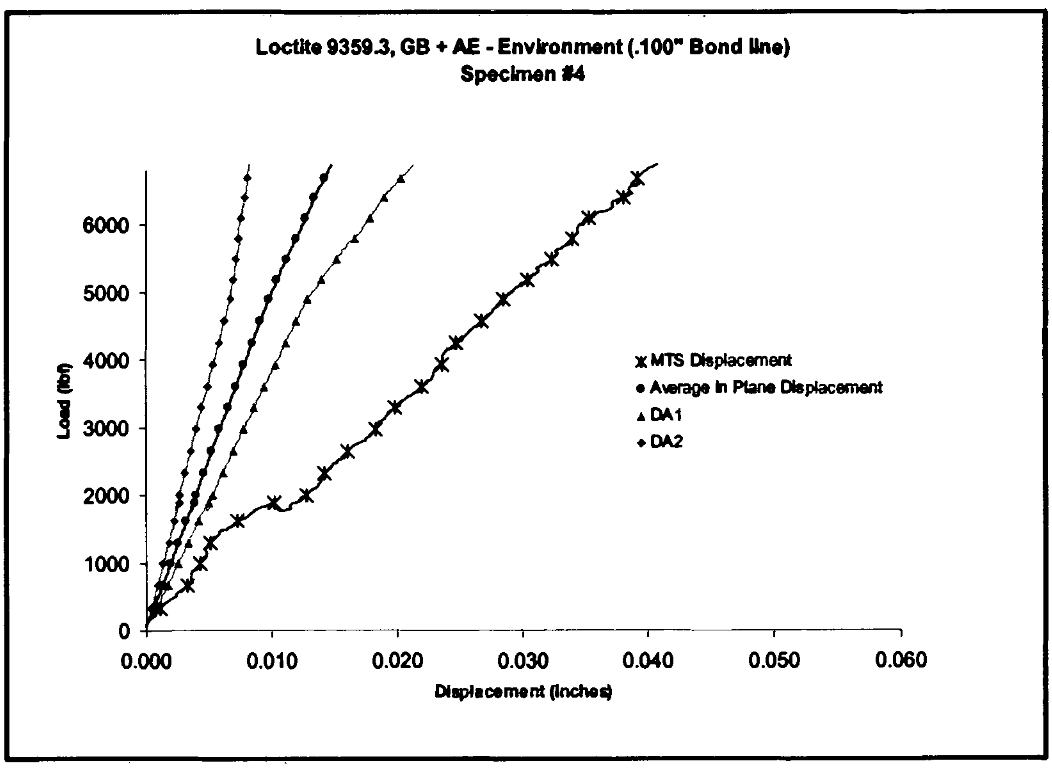

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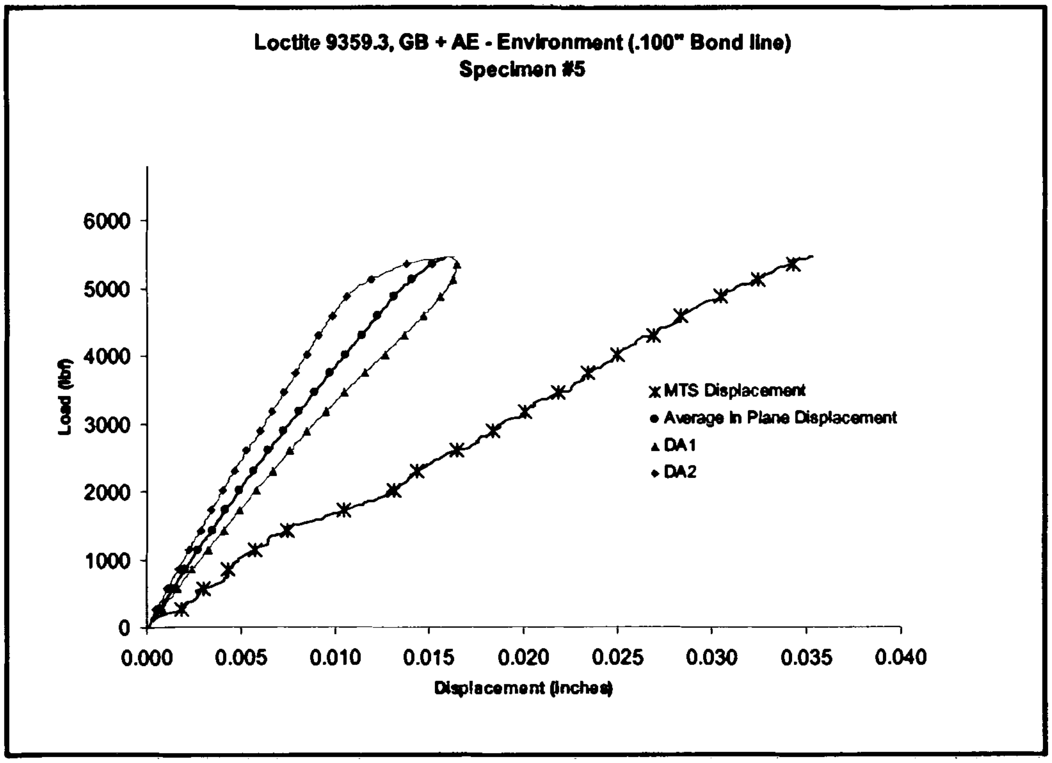

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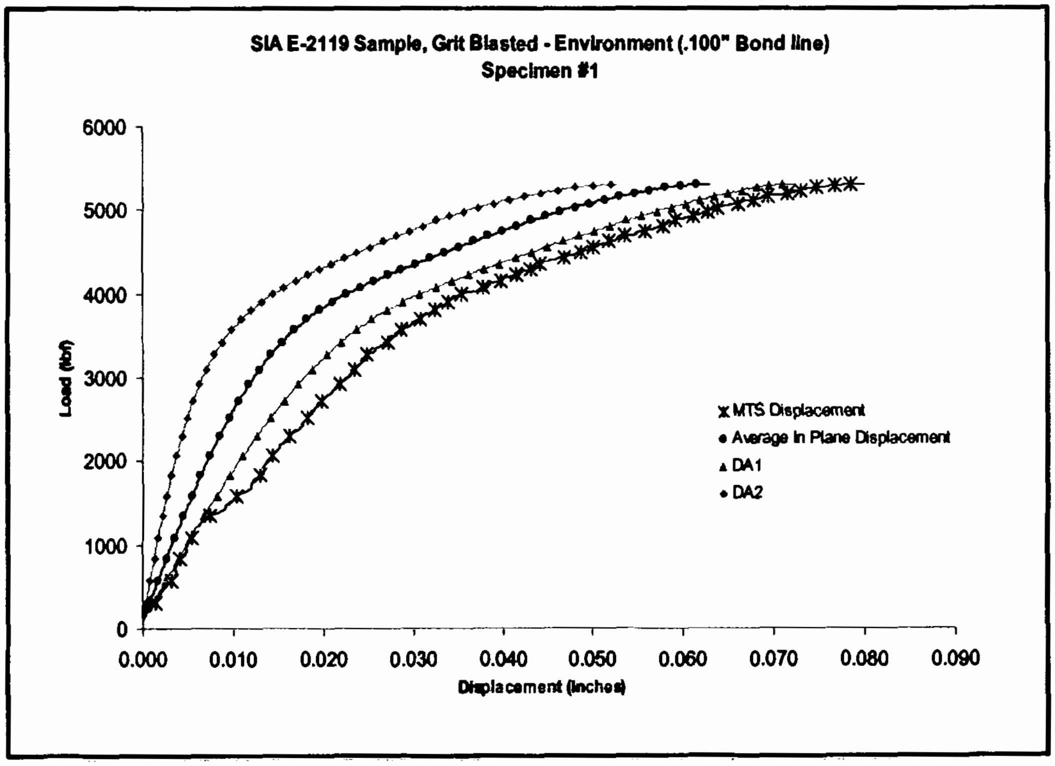

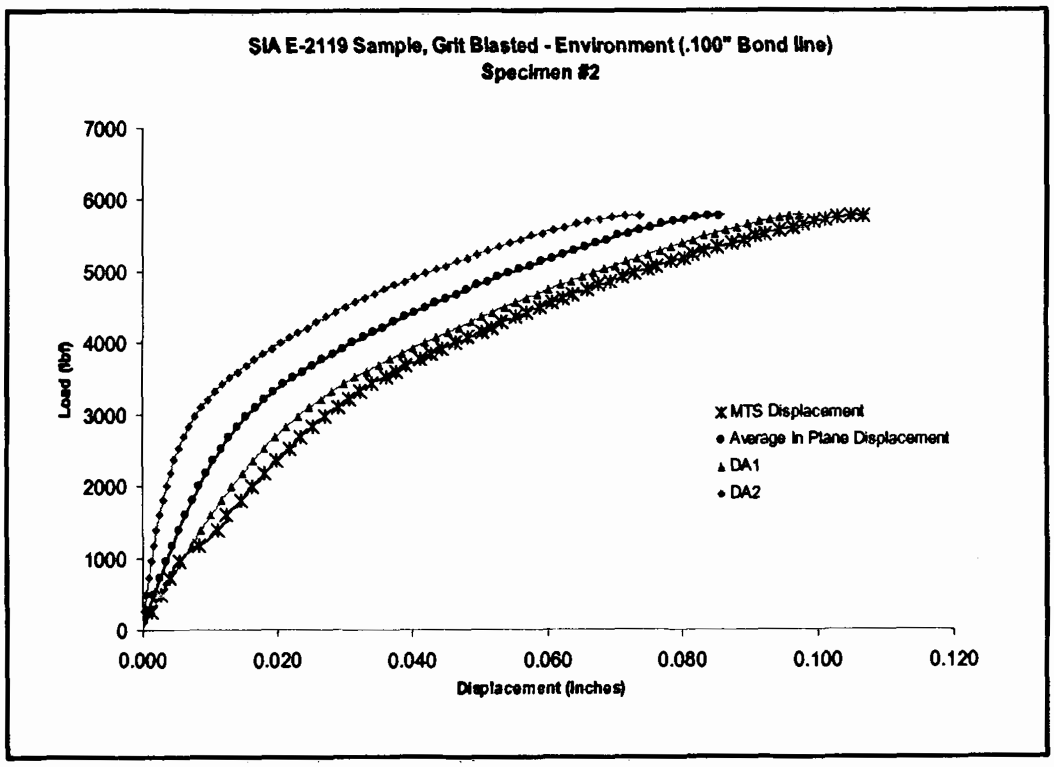

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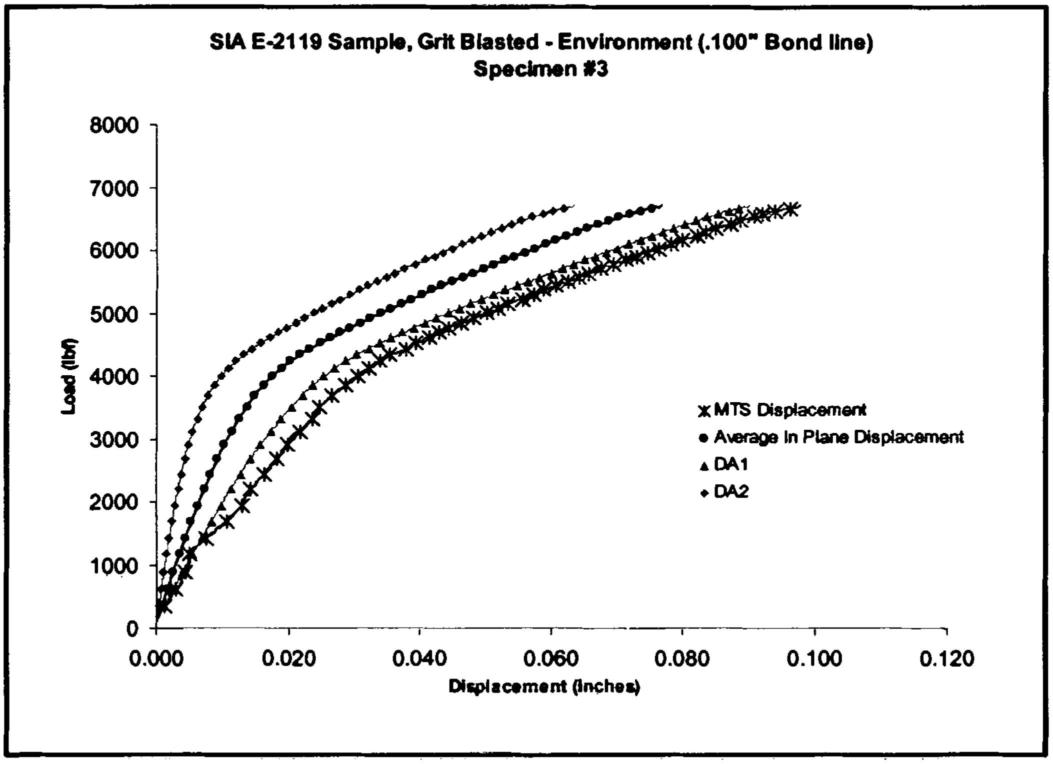


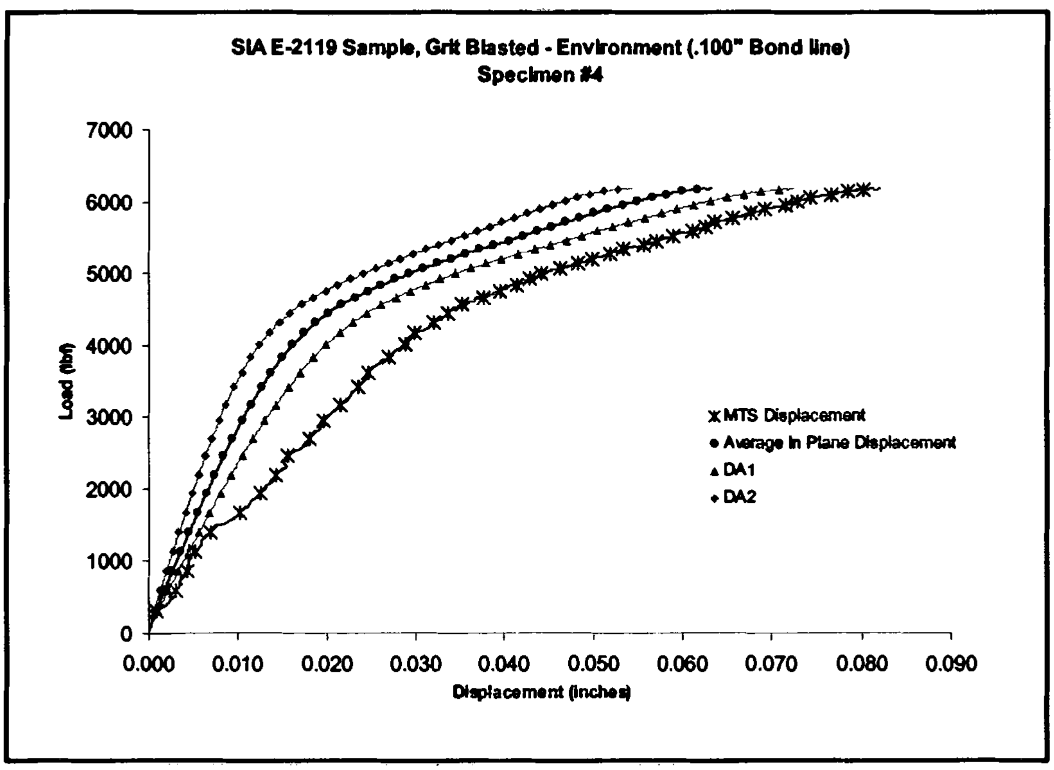


Figure A.3 – Continued

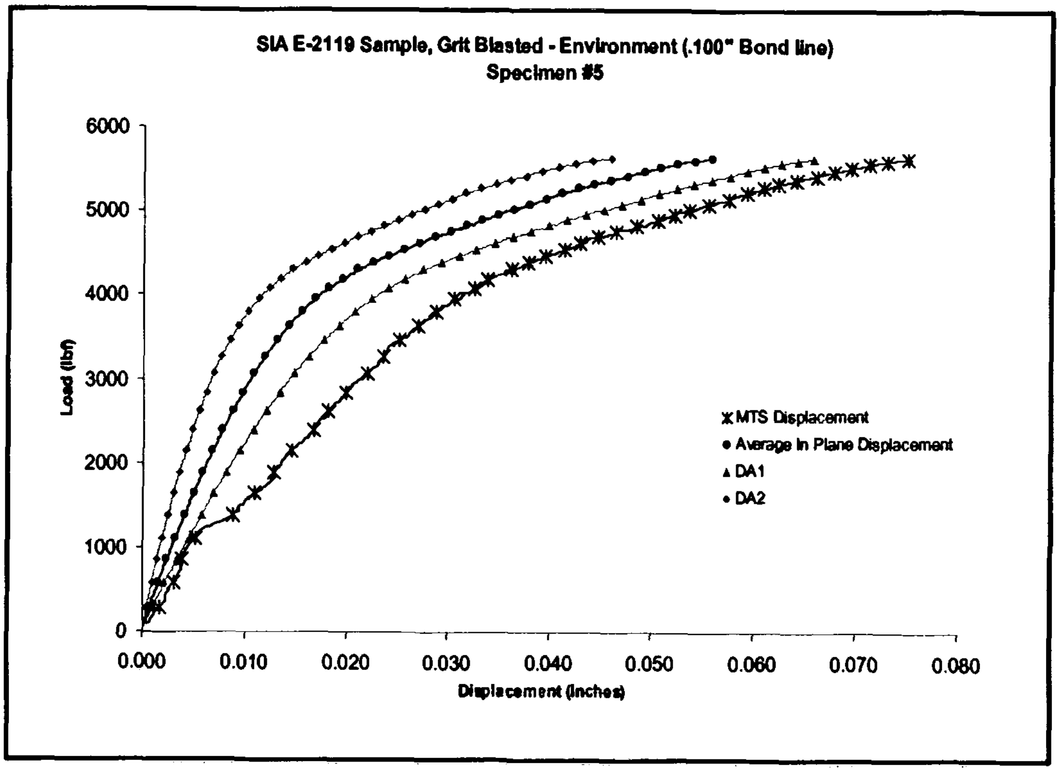
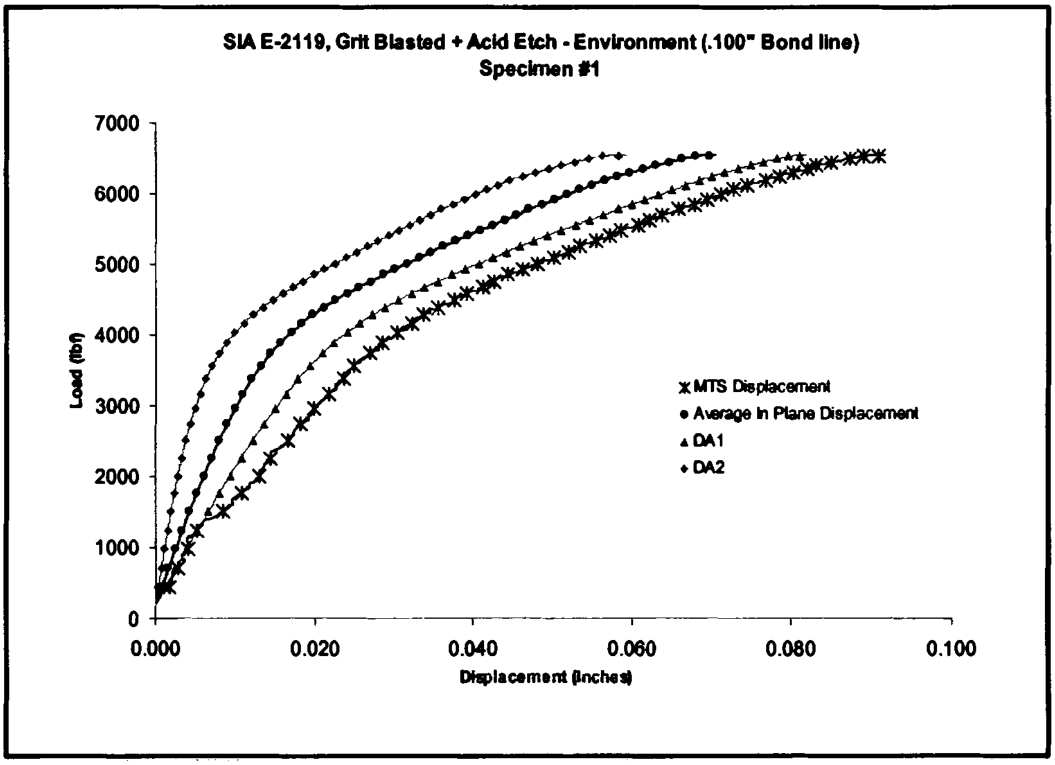


Figure A.3 – Continued



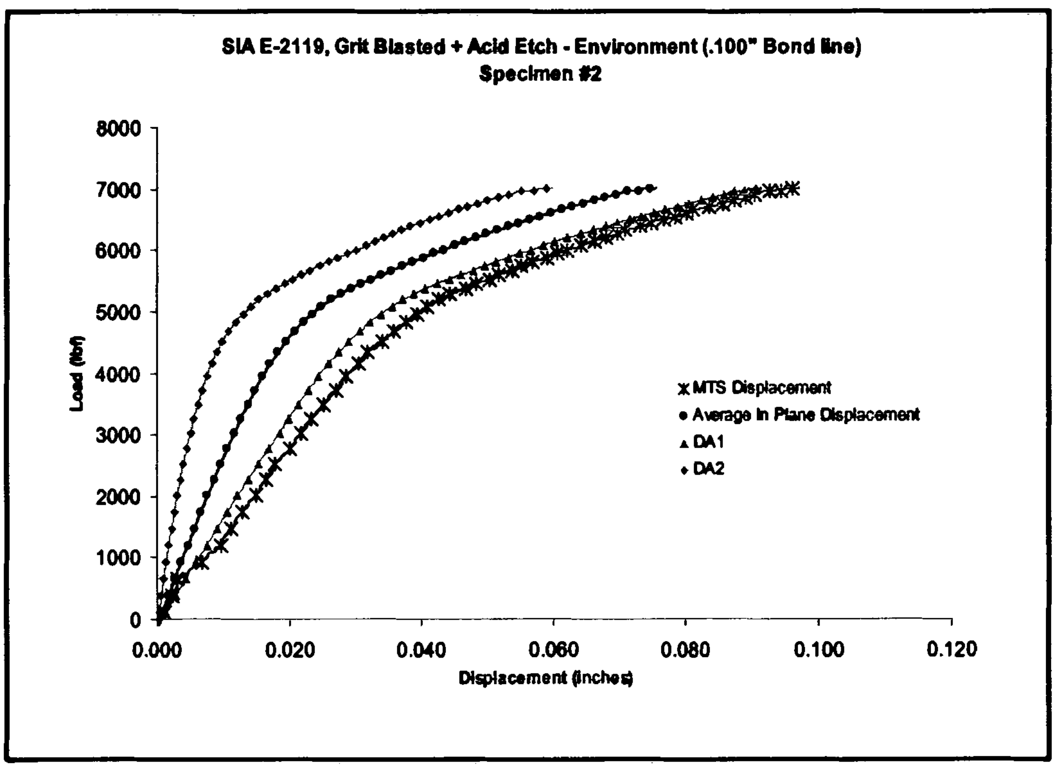
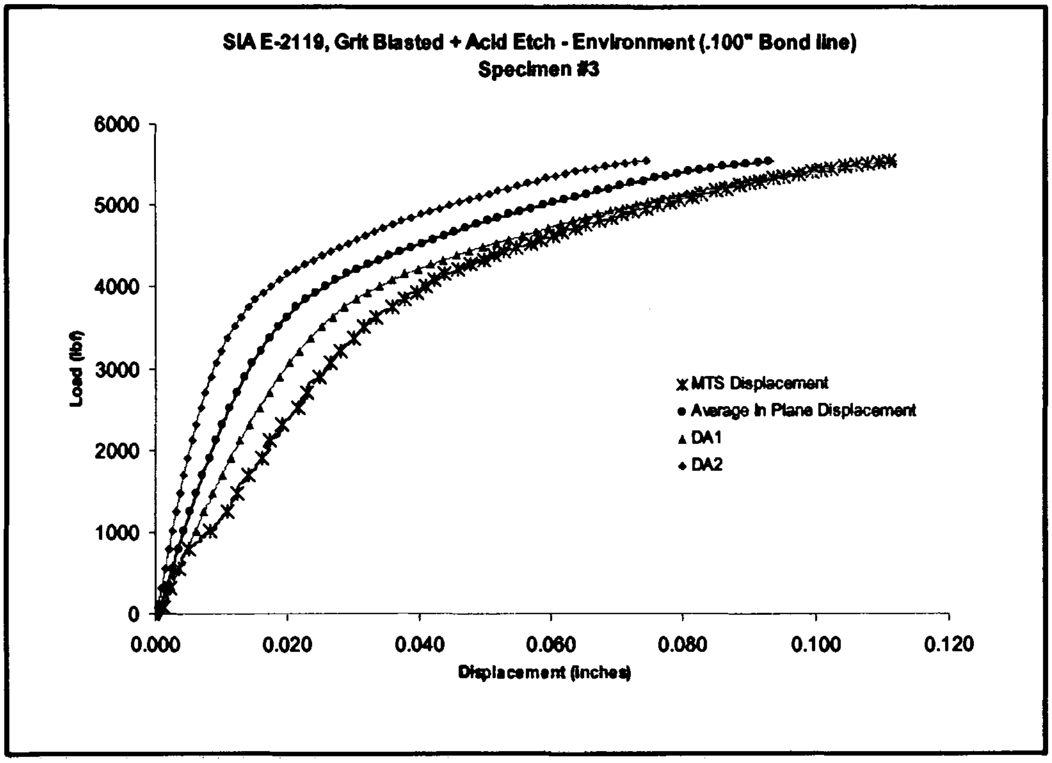


Figure A.3 – Continued



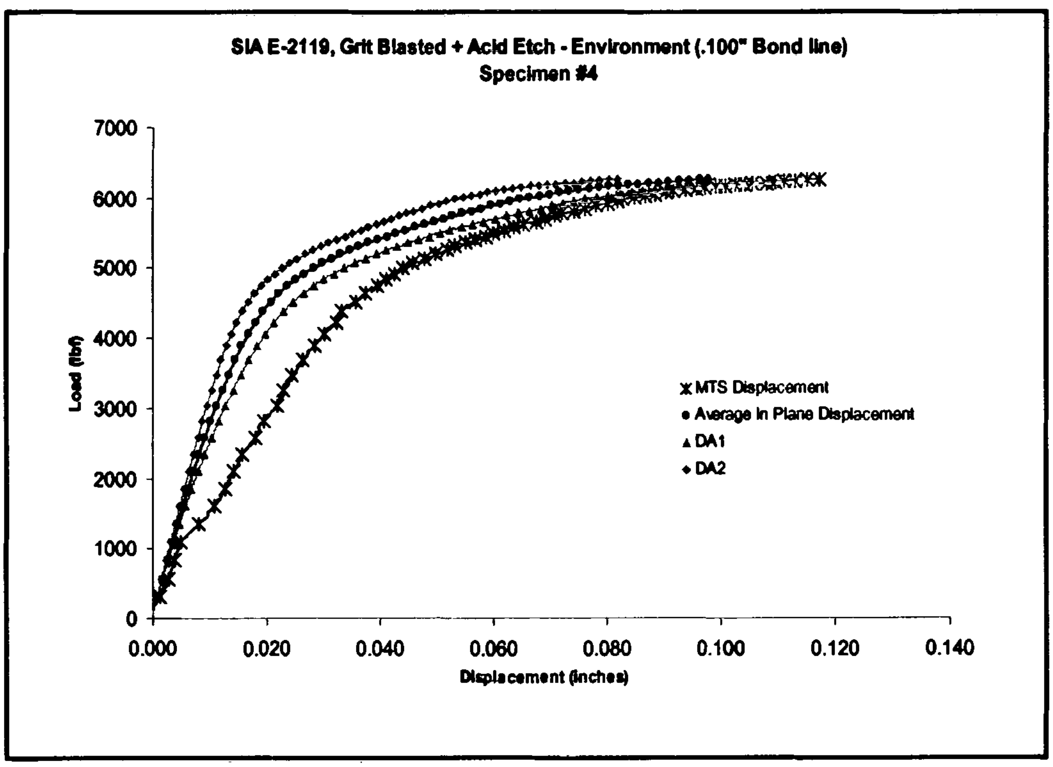
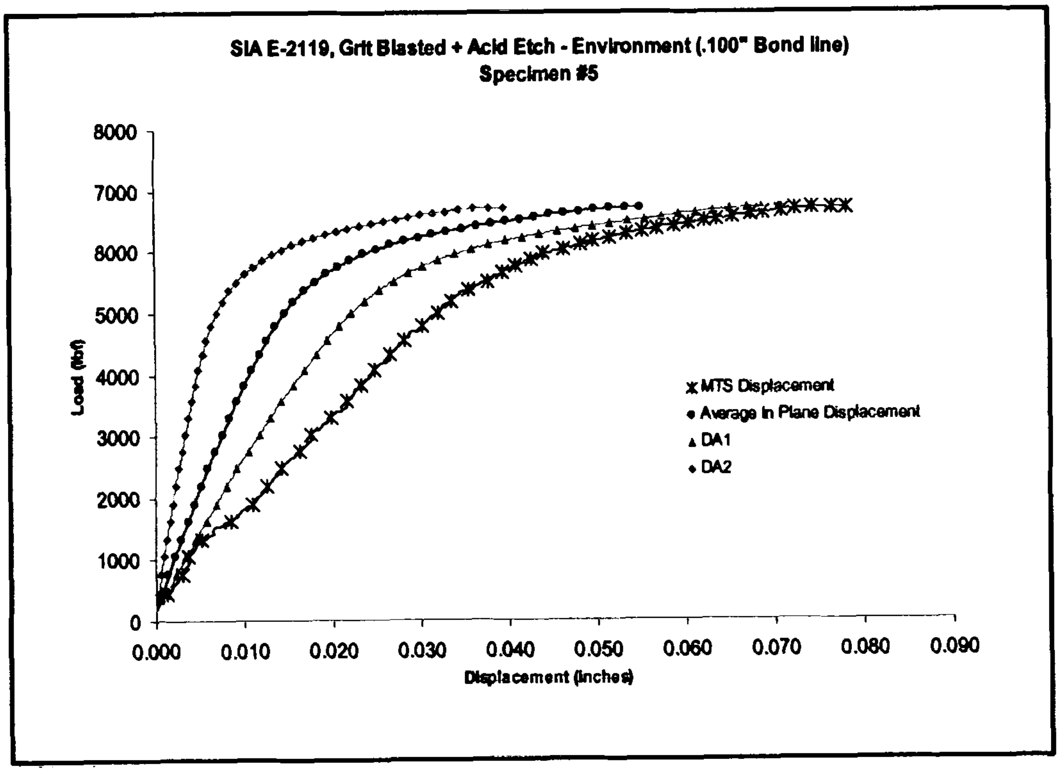


Figure A.3 – Continued



Appendix B – Adhesive Workability

Table B.1 – Adhesive Potlife

	Time Prepared	Time - Cured	Work Time - Tested	Work Time – Manufacturer	Date of Test
Loctite Hysol 9359.3	1:39 PM	4:01 PM	142	50 min	4/ 17/02
Loctite Hysol 9430	2:05 PM	5:30 PM	205	50 min	4/ 17/02
Belzona 1121 Super XL	1:55 PM	3:01 PM	66	35 min	4/ 17/02
Loctite Hysol 9394.2	1:00PM	4:42 PM	222	15-20 min	4/ 24/02
SIA 2119 A/B	1:33 PM	3:13 PM	100	25 min	4/ 24/02
3M Scotchweld 2216	1:15 PM	5:29 PM	254		4/ 24/02

Biography of the Author

Michael James Boone was born in Louisville, Kentucky, on March 15, 1968. He attended Sesser-Valier High School from 1984-1986. After graduating for high school, Michael joined the Navy enrolling in the Naval Nuclear Power Program. Michael successfully completed the Naval Nuclear Power program on 28 April 1990. Michael served in the Navy until August 1991. After discharge from the Navy, Michael went on to attend Maine Maritime Academy. He graduated with a Bachelor's degree in Power Engineering Technology in May 1995. In August 200, Michael enrolled at the University of Maine. Michael was accepted to Phi Kappa Phi honor society at the University of Maine in July 2002. Michael is a candidate for the Master of Science degree in Mechanical Engineering from The University of Maine in December 2002.