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Investigation into toughness improvement in graphite/epoxy composites using teflon powder

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**Investigation into toughness improvement in graphite/epoxy
composites using Teflon powder**

Chafey, Daniel Allen, M.S.

San Jose State University, 1993

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Ann Arbor, MI 48106**

**INVESTIGATION INTO TOUGHNESS IMPROVEMENT
IN GRAPHITE/EPOXY COMPOSITES
USING TEFLON POWDER**

**A Thesis
Presented to
The Faculty of the Department of Materials Engineering
San Jose State University**

**In Partial Fulfillment
of the Requirements for the Degree
Master of Science**

**By
Daniel A. Chafey
May, 1993**

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ABSTRACT
INVESTIGATION INTO TOUGHNESS IMPROVEMENT
IN GRAPHITE/EPOXY COMPOSITES
USING TEFLON POWDER

by Daniel A. Chafey

This project investigates a method of improving composite toughness by additives in the form of Teflon powder. The additives improve energy absorbing mechanisms by providing numerous and small defects for the formation of cracks smaller than the critical crack size. The Teflon provides a ductile phase in the matrix that relieves stress and induces cracks to form convoluted paths as the crack tip reaches sites that will plastically deform. An experiment was conducted using graphite/epoxy composite three point bend specimens. The control samples had virtually no measurable strain after yield. With Teflon additions the samples displayed additional strain. The failure modes changed from predominantly single cracks, to a mode of multiple cracks forming delamination before failure. The additional strain is important because it increased the non-linear portion of the stress-strain curve, delaying the propagation of catastrophic cracks, and the material becomes more tolerant to limited damage preceding total failure.

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CHAPTER 1

INTRODUCTION

1.1 Composite Design

A composite is a physical combination of two or more separate materials, designed to use advantageous properties from each component. In the case of fiber reinforced plastics (FRP), desirable properties of greatest interest usually are high strength, high elastic modulus, and low density. This is important because strong, stiff, and lightweight materials are necessary for many advanced high performance applications. In FRP the fibers provide strength and a high elastic modulus, and the plastic matrix provides cohesiveness and load transfer from fiber to fiber. The construction of FRP composite materials can be tailored such that the fibers carry the majority of the load.

Small diameter graphite fibers are considerably stronger than the bulk material because they can be fabricated nearly defect-free with the highly ordered hexagonal plane parallel to the fiber axis. New grades of graphite fibers have tensile strengths of 5.5 GPa, and a elastic moduli of 320 GPa.⁽¹⁾ With a density of 1.8 g/cm³, graphite fibers fabricated into composite materials provide excellent strength, stiffness, and low weight. The specific strength (strength per specific gravity) and specific tensile modulus of various

materials is shown in Figure 1. This figure shows the advantages of composites in weight sensitive structures. The composite material properties shown are for unidirectional fibers where strength is maximized.

Figure 1. Specific Tensile Modulus and Specific Strength for Various Materials.⁽²⁾

The matrix binds the fibers together and acts as the medium to transmit and distribute applied stress to the fibers. The elastic modulus of the matrix is much lower than the fiber, and it is capable of yielding in a plastic manner, allowing the majority of the load to be carried by the fibers. The matrix also acts to protect the fibers from surface damage capable of forming cracks, which may lead to failure at a relatively low stress level. The plastic matrix deters

the propagation of brittle cracks from fiber to fiber. Even though some individual fibers may fail at relatively low stress levels, premature composite fracture will not occur since the matrix phase acts as a barrier to crack propagation. As individual fibers break, the matrix deforms and redistributes the load to surrounding fibers. It is important that the adhesive bonding strength between fiber and matrix be sufficiently high to maximize the stress transfer and prevent fiber motion. Epoxy resins are used frequently because of their excellent balance of properties such as corrosion and solvent resistance, good adhesion, dimensional stability, hardness, and low shrinkage with cure. The fibers are surface treated and a sizing material is applied as a primer to promote good adhesion between the graphite and the epoxy.

A typical continuous FRP composite is shown in Figure 2 as an exploded view of layers called laminae. The fibers are commercially available in either unidirectional form, as a tape, or bi-directional as a woven fabric. Continuous fibers in woven fabric have two directional terms. Warp is the direction down the roll of fabric, and fill is the direction across the width. These directions are important in designing the load carrying capability of the finished composite material. Weavers can vary the tow size, number of tows per meter, and even the continuous reinforcement in either direction, to create unbalanced fabrics. Unidirectional tape and woven fabric are commercially available impregnated with a

partially cured polymer matrix in a form called a prepreg. The prepreg is ready for cutting and forming into a laminated composite.

Figure 2. Exploded View of an FRP Laminate.⁽²⁾

During manufacturing the laminae are pressed together under elevated temperature and pressure to cure the matrix. The epoxy reacts and flows to bond the laminae together, resulting in a single structure. The cured epoxy provides cohesiveness, transfers load from fiber to fiber, and fixes the geometry of the part. Usually the optimum ratio of fibers to matrix, called the fiber volume, is 60%. Another important advantage of composites in design also is illustrated in Figure 2, in that each lamina can be oriented to maximize the load carrying capability of the resulting manufactured

part. This allows the part to be specifically tailored to meet the requirements of a design with a minimum of ancillary weight. The laminate must be balanced, or symmetric about the centerline, to prevent thermal warpage after cure, due to the coefficient of thermal expansion mismatch of the composite materials.

1.2 Toughness in Composites

Two advantages of FRP composite materials are high strength and high elastic modulus. However, a major obstacle to more widespread application of these materials in structural components is the problem of low toughness of the matrix which promotes delamination (lamina separation). Because of low toughness, composites have been restricted to uses outside of primary load bearing structures where they must withstand impact or cyclic loading close to the yield limit of the material.

Toughness indicates the amount of work expended to fracture the material. However, the term toughness should be regarded as a class of properties rather than a single property. This means that there are several measurable properties related to the amount of work required to produce failure in a material. Usually the most direct way to measure the work of fracture in un-notched specimens is the total area under the stress-strain curve up to the point of

failure. This gives the energy of fracture per unit volume. Other toughness properties that can be measured are impact-resistance, delamination-resistance, strain-to-failure, and tear-resistance. Another important characteristic of toughness in materials is the ability to withstand limited fracturing without catastrophic failure. This property is called damage tolerance.

The fracture process generally takes place in three stages. First, a crack is initiated, or an initial flaw is present in the material under load. Second, the crack grows in a stable fashion and may link with other cracks. Third, the crack reaches a critical size at the applied stress level, and propagates to failure in an unstable manner. In brittle materials the second stage is repressed, or may be absent. The basis for many techniques to improve toughness is to modify the matrix to absorb a greater amount of strain energy during crack propagation.⁽³⁾ This can be done by forcing the crack to follow a convoluted path or allowing multiple cracks to be formed. This permits increased deflection of the material with less crack propagation. Another method for increasing the energy absorbed during fracture is for cracks to be arrested at small sites that are able to deform plastically. This lowers the stress present at the crack tip.

Fracture and failure in FRP composites can occur in a number of complex ways because of their laminated construction. Unlike

homogeneous isotropic materials, fracture can be caused by the failure of individual components, or a separation at the interface between the components. The modes of failure depend on both the direction of the applied load and the orientation of the fibers. Generally, there is not a single, self-propagating crack, as in metals. The typical FRP fracture is characterized by matrix cracking, fiber breakage, and delamination, all of which ultimately combine to produce component failure. Also, internal stresses generally develop when the laminate cools after the matrix has been cured because of differences in the coefficients of thermal expansion. Residual stresses cause uneven fiber loading, causing some fibers or the matrix to fail at low loads. This is evident when test specimens are put under load; it is often reported that prior to failure the specimen will emit acoustic energy characteristic of cracking.

Fractures in FRP can be divided into three basic types: interlaminar, intralaminar, and translaminar.⁽⁴⁾ The fracture types are shown in Figure 3, and describe the plane of the fracture with respect to the orientation of the laminae. Translaminar fractures are transverse to the laminated plane, interlaminar fractures are oriented between the laminae, and intralaminar fractures are located internally within a lamina. Translaminar fracture involves significant fiber breakage, while interlaminar and intralaminar fracture occur in the laminate plane, and involve primarily matrix

fracture. The type of failure reflects the type of load the component was subjected to, such as tension, compression, or shear.

Figure 3: Planes of Separation in Fiber Reinforced Composites: (a) Intralaminar, (b) Interlaminar, (c) Translaminar.⁽⁴⁾

Tensile loading in the fiber direction produces predominantly translaminar fractures with a rough, fiber dominated morphology, and fibers protruding out of the fracture plane. Usually little or no delamination is evident near the fracture surface. Brittle tensile failure of fibers is the primary failure mechanism, and fracture of the surrounding matrix is secondary. Fibers tend to fracture in

bundles, and the fibers within each bundle have a relatively flat and common fracture phase. Consistent with brittle failures, the fracture origins are primarily located at surface flaws on the fibers.

Both interlaminar and intralaminar fracture occur on a plane parallel to the fiber reinforcement. For the majority of thermosetting matrices in use, such as epoxy, cohesive matrix failure occurs in a brittle manner. Therefore, flexural and shear fracture mechanisms in FRP tend to be dominated by matrix failure and fiber to matrix interface separation. The cohesive fracture characteristically shows a relatively flat fracture plane with very little evidence of material deformation. For this reason, the interlaminar and translaminar failure modes provide excellent opportunities to study toughening mechanisms. A typical method for improving toughness is to improve the matrix ductility which increases resistance to crack propagation. This project examines a proposed toughening mechanism by additives to the epoxy matrix. The toughness is then tested by interlaminar failure in prepared specimens. The objective of the project is to improve FRP toughness without decreasing the strength or the elastic modulus.

CHAPTER 2

PREVIOUS INVESTIGATIONS IN TOUGHNESS

2.1 Review of Relevant Investigations

The approach to improving toughness of composites has been focused on the mechanisms that absorb energy during loading. In general, toughness can be described as the sum of all the contributions to energy dissipation related to fibers, matrix, and the fiber-matrix interface.⁽⁵⁾ Some energy dissipation mechanisms related to the matrix and interface are elongation, crazing, crack bridging, matrix-fiber debonding, and friction during fiber slippage. Cairns⁽⁶⁾ developed a finite element model to describe the role of individual phases during delamination, and predicted that a more convoluted fracture pattern will require greater energy to fracture. As a result of the convolution, more surface area is created during the fracture. This is shown to be a possible mechanism for toughening brittle materials.

One method for increasing interlaminar toughness is to introduce tough layers interleaved in the composite matrix. Several methods using this technique were examined by Masters⁽⁷⁾, and Sela and Ishai⁽⁸⁾. They were able to show increases in impact damage resistance with layers of ductile material interleaved with the

laminae. They used compressive strength after a standardized impact as the measure of toughness. The effect was that test panels with the tough interlayers had roughly 50% greater compressive strength after impact than panels without the interleaf. A graph of the results of this investigation is shown in Figure 4. The major disadvantage of this system is a weight penalty. The tough layers add weight without increasing the stiffness and the strength of the laminate.

Figure 4. Effect of Interleaving on Impact Damage Resistance.⁽⁸⁾

The value of a low elastic modulus third phase dispersed as particles in the matrix was investigated by Pottick.⁽⁹⁾ This investigation used discrete rubber particles widely dispersed in the

matrix, rather than using tough interlayers. The study showed that the dispersion helped convolute the crack propagation by generating additional plastic deformation at the crack tip. The experimental technique used a moderate amount of rubber which reduced the strength properties. Figure 5 shows the results of adding two blends of rubber up to a weight percent of 15%. The study also showed that an improvement in the toughness was possible with a minor effect to the glass transition temperature. However, this method was accompanied by a 20% decrease in the flexural modulus.

Figure 5. Fracture Energy and T_g Changes Versus Rubber Content.⁽⁹⁾

An extension of the theory of convoluting the growth of cracks was demonstrated by Thorfinnson, et al.⁽¹⁰⁾ Thorfinnson's objective was to improve impact resistance without decreasing the elastic modulus of the composite. The method used glass microfibers added to the epoxy matrix. Instead of using a low elastic modulus filler, such as rubber, the glass microfibers were high modulus, and likely had a strong bond to the epoxy. The importance of this investigation was the size of the microfibers, being less than 70 nm in diameter, and lengths from 1 to 10 μm (aspect ratios of 10 to 100). This particle size was much smaller than that used in previous investigations. The proposed effect of the microfibers was to disrupt crack propagation by creating discontinuities in the matrix. The small size was important in that a very large number of discontinuities can be generated in the matrix with a minimum of added weight or volume. The elastic modulus of the resulting composite material was not decreased because the epoxy content only marginally reduced the cohesiveness and bonding of the fibers. The small size also ensured that the defects formed were smaller than the critical crack size for a given level of stress. Thorfinnson reported that with an 8% addition of microfibers the FRP toughness, measured in damage tolerance to impact forces, was improved by 15%.

Other investigators have examined the effects at the fiber-matrix interface to improve toughness. Saghizadeh and Dharan⁽¹¹⁾

developed a model to estimate the relative contributions from the matrix and the fiber-matrix interface to the overall delamination crack energy. The theoretical crack propagation is illustrated in Figure 6. The study showed that there is a large amount of surface area involved in bonding the fibers, and therefore cracks propagating with both matrix failure and interface failure absorb more energy. This study concluded that increasing the interface energy absorption during crack propagation was more efficient in improving the overall toughness than improving the toughness of the neat* matrix resin alone.

Figure 6. Delamination Model Showing an Assumed Fracture Surface Through a Stylized Hexagonal Array of Fibers.⁽¹¹⁾

* "neat" refers to the unfilled, unmodified resin.

Other studies have shown the fiber-matrix interface to be an important contributor to energy absorbing mechanisms. Piggott and Reboredo⁽¹²⁾ showed that the interface often has properties greatly different from both the polymer and the fiber. The interface appears to be very brittle, often markedly more brittle than the polymer, having a work of fracture only about 20% of the polymer. The investigation showed that if ductility can be increased at the interface, then overall composite toughness should be improved. This supports the conclusions of Saghizadeh and Dharan. Piggott and Reboredo also showed that important friction interactions can take place on the fiber after failure of the interface bond. This is because pressure exists due to the cure shrinkage of the polymer, and that slippage of the fiber after debonding is resisted. The study used single fiber pull-out tests, and showed that due to the large number of fibers, a significant increase to the energy absorbed can be associated with slippage. Figure 7 shows results describing the energy involved in fiber slippage. The study also concluded that fiber interface failure does not necessarily lead to composite failure. A failure in the interface can still transmit stresses by friction. Interfacial pressures may be small, but are significant when coupled with high friction coefficients, giving substantial shear stresses to the fiber. The study reported that increases in the energy absorbed during fracture is provided by allowing the fibers to slip.

Figure 7. Pull-out Curve For Kevlar Treated with Acetone.⁽¹¹⁾

A study by Friedrich⁽¹³⁾ into the mechanisms of fracture at the interface includes the effects of a cohesive failure as well as adhesive failure*. The study concluded that a greater amount of energy was absorbed for fiber pull-out having cohesive failure. Frictional forces then are greater because they are generated by both overcoming the adhesive bond between the matrix and fiber, and the physical interlocking and subsequent plastic deformation of pull-out. Interlocking is missing in a pure adhesive failure, and so only frictional forces absorb energy during strain. A schematic of

* A "cohesive failure" refers to a rupture of an adhesive bond, such that the separation appears to be within the bulk adhesive. An "adhesive failure" refers to a rupture at the adhesive-adherend interface.

this action is shown in Figure 8 as a crack tip extends through fibers producing zones of yielded matrix.

Figure 8. Continuous Fibers Which Fail in the Crack Plane. The Interface is Loaded in Shear and Yields in the Region Close to the Crack.⁽¹³⁾

2.2 Summary of Previous Investigations

Investigators in the field of improving toughness in FRP materials have used various techniques to increase energy absorbing mechanisms. One of the successful methods is the application of a second phase of more ductile material added to the matrix to retard crack propagation. Other methods have included the use of small defects in the matrix designed to disrupt crack propagation. This results in an increase in the surface area of the fracture. Still other methods have examined the effects of improving the ductility at the fiber-matrix interface. This project uses these previous investigations to develop a method of improving toughness by adding a second phase of ductile plastic to the matrix. The second phase is in the form of small discrete particles that would retard crack propagation by being ductile, and increase the surface area generated by being numerous.

CHAPTER 3

EXPERIMENTAL OBJECTIVES

Improvements in the toughness of FRP composites can be achieved by introducing additional mechanisms that absorb energy during crack formation and propagation under an applied load. Some investigations, as described in Chapter 2, examined methods to improve toughness by adding a second, more ductile, phase to the matrix. Other studies showed it was possible to improve toughness by introducing small defects below the critical crack size. This causes propagating cracks to follow a more convoluted path, and thus generate more surface area.

This project uses the previous research, and proposes that if numerous, well distributed, and very small defects are introduced into the composite matrix an improvement to toughness will be achieved. Defects can be added to the matrix in the form of small particles of a ductile material. As the total weight percent of the added defects remains low, improvements to toughness are not expected to be accompanied by decreases to the composite strength and elastic modulus.

The increase in toughness can be realized because cracks will initiate at many small sites, consuming part of the energy that

otherwise would be available for propagation of a main crack. Cracks that form can remain small, below the critical crack size, for a given amount of strain because there are more of them. Also, if the added defects are in the form of a ductile third phase material, a propagating crack will tend to form a convoluted path as the crack tip reaches sites that will plastically deform. The convoluted path increases the absorbed energy by increasing the amount of surface area generated.

An experiment supporting this thesis was conducted to test the effectiveness of small, 0.1 to 5 μm , Teflon® particles dispersed in the matrix to improve the toughness in a graphite fiber reinforced plastic (GFRP). The objective was to disperse the small particles uniformly in the matrix, generating numerous sites of a third phase low elastic modulus material. The experiment used Teflon particles because of the excellent ductility of Teflon, the small particle size, and because the low bonding properties of Teflon ensured the formation of defects in the matrix. This allows the Teflon particles to retard the propagation of cracks by being ductile, and also to convolute the crack path and generate more surface area by being very numerous. The particle size distribution for the Teflon powder was such that for a 1% addition to the prepreg, approximately 4×10^8 particles per cm^3 were introduced into the resin. Since the volume percent of added material was small, the surface area of debonded fiber was expected to be negligible, leaving the fiber

dominated properties of strength and elastic modulus relatively unaffected.

In this project Teflon powder was added to the prepreg laminae before lay-up in the amounts of 0, 1, 2, 4, and 6% by weight. The 0% test panels were used as the control sample for comparison. A more complete description of the calculations and the methods of measuring the toughness is given in Section 4.8.

CHAPTER 4

EXPERIMENTAL DETAILS

This project extends the investigation reported by Thorfinnson⁽¹⁰⁾ by making some important changes. In Thorfinnson's study, very small particles of glass fibers, less than 70 nm in diameter, were used to introduce defects into the matrix. The defects were generated by a high elastic modulus material, and were applied by blending directly into the liquid epoxy prior to impregnating the graphite fibers. In this project the defects were added to the matrix using a thermoplastic polymer of low elastic modulus in the form of very fine Teflon powder. The powder was applied directly to each lamina before lay-up and cure of the panels. The particle size of the Teflon powder was typically 3 μm , and the particle shape was roughly spherical. Although the previous study was able to introduce a greater number of defects per weight percent of added material, the use of a low elastic modulus particle, instead of high modulus glass, was expected to have the effect of allowing greater matrix deformation to occur in the region of high stress surrounding each particle. In Thorfinnson's study the glass fibers likely had a strong bond to the epoxy when forming the defects, whereas the Teflon particles in this project did not bond to the epoxy. This was expected to have the effect of generating a large number of very small cracks under the critical crack size.

The experimental work for this project was performed in the following sequence:

1. Acquire raw materials;
2. Cut prepreg into panel size for lay up;
3. Weigh each ply, and add Teflon powder;
4. Lay up lamina into panels;
5. Assemble and bag panels for cure;
6. Autoclave cure panels;
7. Cut panels into 3 point bend specimens, identify warp and fill directions;
8. Mechanical test each specimen in flexure;
9. Reduce and analyze data, and report results.

Significant items for these steps are described below.

4.1 Raw Materials

The choice of a graphite epoxy composite for this study was made because of the wide industrial use of such materials. Graphite fiber reinforced plastics (GFRP) are also widely known for relatively low toughness properties, and as such provide excellent sensitivity for measuring small changes. A woven fabric of graphite fibers was desirable both because of its common usage, and the ability to test toughness changes in warp and fill directions. The GFRP used in this

project was a commercially available product from Fiberite Corporation, HMF 2409/34. This system has T300 graphite fibers pre-impregnated with Fiberite 934 resin. The weave pattern is 5HS Satin, with 1000 fibers per tow, and balanced in the warp and fill directions. The fabric weave pattern is shown in Figure 9.

Figure 9. HMF 2409/34 Prepreg, with 5HS Satin Weave Pattern (5X). Warp direction is across the width of the page. The warp face is shown up.

The Teflon powder used in this project was selected for its small particle size, and because it was available as a dry product ready to add to the prepreg without chemically affecting the epoxy resin. A commercially available product, MP1100, with particle size distribution in the range of 0.1 μm to 5 μm , was obtained from E.I. duPont de Nemours and Company, Inc.

4.2 Material Preparation

The prepreg was obtained in rolls from a single lot number which assured consistency of properties. The prepreg was cut into plies of 24 cm by 30.6 cm to prepare for lay up. To add the Teflon powder in the desired amounts, each ply was first weighed, then the powder was brush applied to the prepreg surface by hand. A quantity of powder was added and the ply weighed again to verify the weight gain. Powder was added in small quantities until a target value was reached. A ply typically weighed 17 grams, so for a 1% sample 0.17 grams of powder would be added. It was desirable to add the powder in several light coats to reach the target value more accurately, and to cover the surface more uniformly. The uniformity of the powder was able to be checked visually because of the contrast from the white powder against the black prepreg. On a macroscopic scale the uniformity of the powder appeared quite good. A magnified view of the surface of the prepreg before the application of Teflon is shown

in Figure 10. Views showing prepreg surfaces after the application of powder are illustrated in Figures 11, 12, 13, and 14, for 1%, 2%, 4%, and 6% Teflon, respectively. The Teflon becomes progressively more dominant on the surfaces as white deposits filling in depressions, and accumulating against the fiber tows in the weave pattern. The Teflon distribution on a large scale appeared generally uniform, but on the scale of the size of the weave pattern the distribution was not uniform because of the roughness of the surface.

Figure 10. Prepreg Surface Before Application of Teflon Powder(32X).

Figure 11. Prepreg Surface After Application of 1% Teflon Powder (32X).

Figure 12. Prepreg Surface After Application of 2% Teflon Powder (32X).

Figure 13. Prepreg Surface After Application of 4% Teflon Powder (32X).

Figure 14. Prepreg Surface After Application of 6% Teflon Powder (32X).

After each ply was prepared with Teflon powder, the panels were stacked up for curing with 16 plies per panel to produce a target thickness of 0.25 cm. All panels were fabricated exactly the same with the Teflon added to the side opposite the peel ply, and then stacked with the peel ply side up for autoclave curing. Later, when the panels were cut into specimens and tested, the same orientation was always maintained for each panel with the peel ply side down (warp face up). A total of 16 panels were produced, with 4 panels each at Teflon concentrations of 0%, 2%, and 4%, three panels at 1%, and one panel at 6%. The panels were identified by assigning a letter to each panel in the order fabricated. All pertinent fabrication data was kept with the assigned identification letter. Since the weight gained by adding Teflon was not precise the actual concentration varied slightly from the target value. The Teflon concentrations are given in Table 1. Panels I, J, K, and L were not used because a leak developed in the vacuum bagging during the autoclave cure and complete compression of the laminate did not take place. During cure some resin would flow, bleeding out of the panel, and carrying with it a small amount of Teflon. The amount of resin lost was measured by weighing the panels before and after cure. The average value of lost resin was 0.75 g , and for a 4% panel that would carry with it approximately 0.09 g of Teflon (assuming a uniform distribution of Teflon in the resin). Since a typical panel

weighed 300 g, the 4% added Teflon weighed 12 g. This meant that the loss of Teflon by resin bleed-out was negligible, and did not need to be accounted for.

Table 1. Teflon Concentrations added to Each Panel.

<u>ID</u>	<u>Teflon (%)</u>	<u>ID</u>	<u>Teflon (%)</u>
A	0	M	0
B	1.99	N	1.14
C	1.16	O	2.02
D	4.25	P	4.04
E	0	Q	6.16
F	1.28	R	0
G	2.17	S	2.18
H	4.13	T	4.08

4.3 Cure Cycle

The panels were bagged for autoclave cure. The vacuum bagging assembly is shown schematically in Figure 15.

Figure 15. GFRP Lay Up Prepared for Autoclave Cure.

Four panels were cured together in each autoclave cycle. The arrangement of panels on the caul plate for the autoclave is shown in Figure 16. To produce 16 panels, four separate autoclave cycles were run. The temperature, pressure, and vacuum for each cycle were controlled by a microprocessor. The settings were the same for each cycle. The autoclave and control system tolerance on the temperature and pressure is $\pm 6^{\circ}\text{C}$, and $\pm 70 \text{ KPa}$.

Figure 16. Four Panel Arrangement on Autoclave Caul Plate.

The cure is typical for a Fiberite 934 resin system and has several important steps, as shown in Figure 17. The resin is cured at 182°C for two hours under 690 KPa pressure. The autoclave first stages the parts at 121°C for 55 minutes to start the cure of the resin. This increases the viscosity of the resin, and thus prevents excessive flow at elevated temperatures, before the epoxy has a

chance to fully cure. At 15 minutes into the 121°C stage the autoclave pressure is increased to 690 KPa to compact the laminate. At this stage excess resin bleeds out of the panels, through the perforated FEP film, and is absorbed by the bleeder cloth as shown on Figure 15. The process is designed to provide low flow of the resin to achieve a fiber volume of 60%. A vacuum of approximately 100 KPa below ambient is applied on the parts throughout the duration of the cure cycle. This removes trapped gases, moisture, and residue solvents from the prepreg as it cures.

Figure 17. Autoclave Cure Cycle.

4.4 Specimen Preparation

After cure the panels were trimmed to 21.6 cm by 28 cm and cut into five blanks labeled A through E, as shown in Figure 18. All cutting was done with a diamond saw to produce clean edges, and smooth surfaces. Twenty 3 point bend specimens were then cut from each panel, with 10 specimens in the warp direction from blank A, and 10 specimens in the fill direction from blanks C and D. The size of the specimen, and the configuration of the test is per ASTM D 790⁽¹⁴⁾. The dimensions of the specimen are illustrated in Figure 19. This provides a span to thickness ratio of approximately 25. Each 3 point bend specimen was identified with two letters specifying the panel and blank, then numbered sequentially in the order cut.

Figure 18. Panel Cutting Diagram.

Figure 19. Three Point Bend Test Specimen.

4.5 Three Point Bend Test

The three point bend test is an accurate method for determining the flexural properties on flat specimens of GFRP. The test is standardized in ASTM D 790. The specimens are relatively easy to fabricate, and the test is readily performed on an instrumented mechanical tester configured in flexural compression mode. A disadvantage of this type of test is that the volume of the specimen under load is small. This means that if the samples are not uniform in properties there may be a large amount of scatter in the data as defects (voids, inclusions, broken fibers, and

misalignment of laminae) have random probabilities of being included in the volume under load.

The three point bend test has several advantages when being used to test for toughness. The test produces a well defined load-deflection curve, and has well defined points for measuring specimen yield and break. The amount of strain after yield is readily calculated from this data. Since the three point bend test generates shear forces in the specimen, the failure mode is primarily by delamination, fiber fracture, and pull-out. This is the same mode of failure generated by impact tests on GFRP. However, because it is capable of producing a well defined stress-strain curve, the three point bend test can produce toughness data in a more quantitative and repeatable basis than Charpy or Izod impact tests.⁽¹⁵⁾ Results from the three point bend test do not directly correlate to the impact type tests because of differences in the test parameters, such as crosshead speed.

4.6 Experimental Test Variables

This experiment was designed to test the relationship between the amount of Teflon powder added to the GFRP and the toughness of the resulting samples. All other variables in the fabrication process were held constant, except the amount of Teflon added. All sample

panels were made from the same manufacturing lot number of prepreg. All panels were prepared, cured, and cut into specimens using the same process. As mentioned in Section 4.2, Teflon was always added to the side opposite the peel ply, and the same orientation for all panels was maintained throughout the experiment. The Teflon was added to the test panels in concentrations ranging from 0% to 6%. The 0% test panels became the control samples. Three point bend tests were performed on the test specimens in the warp and fill directions to test the effectiveness of the Teflon in both directions.

4.7 Data Acquisition System

The three point bend test was set up on an Instron Series IX, Model 4505. The Instron system has a computer control for setting the test parameters, and recording data.

Each specimen was loaded to failure, and the data recorded and stored on magnetic disk. The crosshead speed was 1.27 mm/minute. The Instron was programmed to measure and record load and displacement at a rate of 10 data points per second. The measurement accuracy of the Instron system is ± 0.013 mm in displacement, and ± 4 Newtons in load. The system was programmed to calculate stress and strain at each data point using the input

parameters of specimen gauge length, width, and thickness. The calculated stress is the maximum stress in the outer fibers occurring at midspan. Likewise, the strain is the maximum strain in the outer fibers occurring at midspan. The flexural modulus is the stress divided by strain calculated from the maximum slope in the elastic region before yield.

Stress, in MPa, for a 3 point bend sample was calculated by the formula:

$$\sigma = \frac{3 \cdot P \cdot L}{2 \cdot w \cdot t^2} \quad (\text{Eq. 1})$$

with P = load (N)
 L = gauge length (mm)
 w = specimen width (mm)
 t = specimen thickness (mm).

Strain, in mm/mm, was calculated by the formula:

$$\varepsilon = \frac{6 \cdot D \cdot t}{L^2} \quad (\text{Eq. 2})$$

with D = displacement (mm).

The flexural modulus, in MPa, was calculated by the formula:

$$E = \frac{P}{D} \cdot \frac{L^3}{4 \cdot w \cdot t^3} \quad (\text{Eq. 3})$$

These formulas calculate an apparent flexural modulus that is approximately 12% lower than the tensile elastic modulus for this size specimen with a span to thickness ratio of 25.⁽¹⁶⁾ The primary method of evaluating of the data was by comparing the test samples with the control samples. Since all data were calculated using the same formula, this approximation did not affect the results.

The instrumented mechanical test machine was programmed to measure and record the maximum stress, strain, and flexural modulus for the linear elastic region of the stress-strain curve. The Instron detected the yield point by the offset method, as shown in Figure 20. The offset is a user-defined value, and was selected for this test after a set of trial specimens were run to determine the shape of the stress-strain curve.

Figure 20 Offset Yield Method

The offset value used was 0.02 mm of displacement from the slope, which is roughly equivalent to 0.01% strain. The value represented a compromise between a lower value, which could prematurely detect yield when small deviations occur while the test is still in the linear elastic region, and a larger value, which could be delayed in detecting delamination. The small strain value of the offset detect point is characteristic of a brittle material, such as the GFRP. Once the offset value was defined it was held constant throughout the test.

The instrumented mechanical test machine was also programmed to detect and record stress (σ_b) and strain (ϵ_b) at the specimen break point. The break point criteria also is a user-defined value specifying the decrease in load from the maximum load. Again, this value was selected after some trial runs. The value selected was 20% because in a typical structure a loss of load bearing capability on that order would be defined as a failure. This value fit well into the data set because for the fully brittle specimens the break point showed loss of load clearly in excess of 20%, and for specimens showing delamination before break the loss of load was less than 20%.

4.8 Method of Calculating Toughness and Damage Tolerance

The toughness was measured quantitatively as energy per unit volume by the area under the stress strain curve for a three point bend specimen. This is identified as the total energy of failure:

$$E_T = \int \sigma \cdot d\epsilon \quad (\text{Eq. 4})$$

A measure of the energy of deflection in the linear elastic region of the stress-strain curve is the resilience, and is defined as:

$$\text{Resilience} = \frac{\sigma_y * \epsilon_y}{2} \quad (\text{Eq. 5})$$

Two additional relative measures of damage tolerance were calculated from the three point bend test data: delta-strain from yield to break, and the delta-strain times stress at break. The delta-strain ($\Delta\epsilon$) is the strain at the break point (ϵ_b) minus the strain at the yield point (ϵ_y):

$$\Delta\epsilon = \epsilon_b - \epsilon_y \quad (\text{Eq. 6})$$

The $\Delta\epsilon$ times stress at break (σ_b) is a measure of the energy absorbed after yielding begins, and is identified as the energy of fracture:

$$E_f = \Delta\epsilon * \sigma_b \quad (\text{Eq. 7})$$

All three measures of toughness were used to compare the performance of the test panels against the control panels. The three point bend test was used as a simple and effective method to measure delamination toughness of interlaminar and intralaminar fracture.

CHAPTER 5

EXPERIMENTAL RESULTS

Sixteen panels were fabricated with concentrations of Teflon ranging from 0% to 6% added to the resin. Three point bend test specimens were cut from each panel, and loaded to failure with the instrumented mechanical test machine and the method described in Section 4.5. Stress and strain measurements were obtained for each specimen. Values for the flexural modulus, fracture energy, and total energy of failure were calculated from the stress and strain data. The data for all specimens are presented in Appendix 1.

In general, all the test specimens behaved in a brittle manner. The elastic portion on the stress-strain curve was relatively straight, and ended with a discontinuous portion in a delamination fracture. There was an increased amount of deflection from the point of initial yielding to the point of failure in specimens with added Teflon. This is measured as increased damage tolerance. However, it is important to recognize that the yielding is not plastic deformation of the GFRP material. The mechanism of yielding is one of progressive delamination, where the material under load fails by partial delamination, while the remaining plies continue to carry the load. This is observed during testing as the specimen under load will emit acoustic reports. It is more appropriate to define the

stress-strain curve in terms of a linear elastic region, and a non-linear progressive delamination region.

5.1 Test Results

Data for the warp direction specimens are presented in Table 2, and data for the fill direction are presented in Table 3. Each value in the table presented here is the average of ten tests, as ten specimens each in the warp direction and ten in the fill direction were tested for each panel. The data in Tables 2 and 3 are given in order of increasing Teflon, and show values for the maximum stress, standard deviation for the maximum stress, flexural modulus, standard deviation for the modulus, strain at the yield point, and strain at the break point.

Table 2. Warp Direction 3-point Bend Test Data

ID	FEP (%)	σ_{max} (MPa)	σ_{max} Std.Dev. (%)	Flexural Modulus (MPa)	Modulus Std.Dev. (%)	ϵ_y (mm/mm)	ϵ_b (mm/mm)
Aa	0	795.4	5.6	83890	1.7	.0166	.0166
Ea	0	747.0	5.6	81720	0.9	.0162	.0161
Ma	0	772.9	6.0	82510	1.8	.0165	.0165
Ra	0	750.2	5.3	82650	1.1	.0160	.0160
Na	1.14	764.3	5.3	82570	1.9	.0158	.0163
Ca	1.16	774.3	2.9	82250	0.9	.0160	.0164
Fa	1.28	723.8	3.8	80150	1.8	.0147	.0160
Ba	1.99	756.5	7.2	82870	1.5	.0145	.0163
Oa	2.02	750.2	5.3	81470	3.1	.0153	.0165
Ga	2.17	726.8	4.9	81266	0.6	.0134	.0157
Sa	2.18	774.3	7.1	83290	2.6	.0162	.0167
Pa	4.04	699.6	3.2	78850	1.3	.0128	.0158
Ta	4.08	749.1	4.8	82070	1.7	.0157	.0160
Ha	4.13	693.2	5.0	83260	1.4	.0120	.0152
Da	4.25	660.9	6.5	81630	1.1	.0124	.0151
Qa	6.16	692.7	8.2	80930	1.3	.0128	.0157

Note: Each data entry represents an average of ten specimens.

Table 3. Fill Direction 3-point Bend Test Data

ID	FEP (%)	σ_{max} (MPa)	σ_{max} Std.Dev. (%)	Flexural Modulus (MPa)	Modulus Std.Dev. (%)	ϵ_y (mm/mm)	ϵ_b (mm/mm)
Ac-d	0	823.8	5.9	88180	0.9	.0165	.0165
Ec-d	0	822.9	3.9	84420	1.4	.0172	.0172
Mc-d	0	743.9	6.4	84560	1.7	.0156	.0155
Rc-d	0	862.0	3.0	85370	1.9	.0176	.0178
Nc-d	1.14	690.6	3.8	82990	1.2	.0145	.0146
Cc-d	1.16	743.1	6.6	84700	2.1	.0154	.0154
Fc-d	1.28	729.0	6.8	84850	1.2	.0152	.0151
Bc-d	1.99	757.9	4.4	87950	1.3	.0148	.0151
Oc-d	2.02	673.3	4.9	83200	1.5	.0138	.0146
Gc-d	2.17	626.0	5.9	82460	1.4	.0132	.0132
Sc-d	2.18	705.2	8.3	84290	3.0	.0146	.0148
Pc-d	4.04	655.1	4.9	82620	1.9	.0134	.0142
Tc-d	4.08	697.5	5.7	85820	2.0	.0141	.0153
Hc-d	4.13	663.5	3.0	86750	1.0	.0135	.0134
Dc-d	4.25	661.2	4.6	83960	1.4	.0133	.0138
Qc-d	6.16	676.5	3.8	83160	1.4	.0139	.0145

Note: Each data entry represents an average of ten specimens.

All samples fractured in a manner characteristic of a generally brittle material, and with a considerable amount of scatter in the data. The amount of scatter in the data was measured by the standard deviations in the averages of the strength and flexural moduli. As shown in Tables 2 and 3, the standard deviations did not increase with added Teflon in either the warp or fill directions. This implies that adding the Teflon powder did not increase the inherent defect population caused by the manufacturing process. Inherent defects, such as broken fibers, voids, laminae misalignment, rough cutting edges, or contamination, are largely responsible for variations in the test data that are observed in all test samples. Frequently, a measure of the processing quality is the standard deviation of the average of the test samples. A large value in the standard deviation implies non-uniformity, and random defects in the material, which leads to scatter in the test data. This shows that the measured effects were not biased by additional factors in the sample fabrication process, and indicates that the additions of Teflon were uniform at least on a macroscopic scale.

Toughness and damage tolerance values in terms of $\Delta\epsilon$, fracture energy, and total failure energy, were calculated from the data in Tables 2, and 3. These values are presented in Table 4 for the warp direction, and Table 5 for the fill direction. In Tables 2 and 3 some of the ϵ_b values are larger than the ϵ_y values. This is typically the case for brittle specimens, and is a result of the

programming used to detect the yield and break points on the instrumented mechanical test machine, as explained in Section 4.7. When ϵ_b is larger than ϵ_y it results in a negative value for $\Delta\epsilon$, which then results in a negative value for the fracture energy, $\Delta\epsilon \times \sigma_b$. This is avoided by recognizing that in reality there is no additional strain, and ϵ_b is equal to ϵ_y , meaning that we may simply assign a zero value to $\Delta\epsilon$.

Table 4. Warp Direction, With Calculations for Toughness and Damage Tolerance

ID	FEP (%)	$\Delta\epsilon$ (mm/mm)	σ_b (MPa)	$\Delta\epsilon \times \sigma_b$ (MJ/m ³)	Resilience (MJ/m ³)	Total Energy (MJ/m ³)
Aa	0	0	767.5	0	6.602	6.602
Ea	0	0	745.2	0	6.051	5.976
Ma	0	0	760.9	0	6.376	6.376
Ra	0	0	748.2	0	6.002	6.002
Na	1.14	0.0005	762.3	0.381	6.038	6.419
Ca	1.16	0.0004	768.8	0.308	6.194	6.502
Fa	1.28	0.0013	720.8	0.937	5.320	6.257
Ba	1.99	0.0018	724.8	1.305	5.485	6.789
Oa	2.02	0.0012	735.6	0.883	5.739	6.622
Ga	2.17	0.0023	712.7	1.639	4.870	6.509
Sa	2.18	0.0005	767.1	0.384	6.272	6.655
Pa	4.04	0.003	691.0	2.073	4.477	6.550
Ta	4.08	0.0003	734.0	0.220	5.880	6.101
Ha	4.13	0.0032	665.0	2.128	4.159	6.287
Da	4.25	0.0027	612.5	1.654	4.098	5.751
Qa	6.16	0.0029	657.9	1.908	4.433	6.341

Note: Each data entry represents an average of ten specimens.

Table 5. Fill Direction, With Calculations for Toughness and Damage Tolerance

ID	FEP (%)	$\Delta\epsilon$ (mm/mm)	σ_b (MPa)	$\Delta\epsilon \times \sigma_b$ (MJ/m ³)	Resilience (MJ/m ³)	Total Energy (MJ/m ³)
Ac-d	0	0	809.4	0	6.796	6.796
Ec-d	0	0	821.6	0	7.077	7.077
Mc-d	0	0	742.2	0	5.802	5.728
Rc-d	0	0.0002	860.2	0.172	7.586	7.758
Nc-d	1.14	0	688.8	0.069	5.007	5.076
Cc-d	1.16	0	738.6	0	5.722	5.722
Fc-d	1.28	0	726.1	0	5.540	5.468
Bc-d	1.99	0.0003	747.0	0.224	5.608	5.833
Oc-d	2.02	0.0008	654.5	0.524	4.646	5.169
Gc-d	2.17	0	616.5	0	4.132	4.132
Sc-d	2.18	0.0002	690.6	0.138	5.148	5.286
Pc-d	4.04	0.0008	643.6	0.515	4.389	4.904
Tc-d	4.08	0.0012	673.9	0.809	4.917	5.726
Hc-d	4.13	0	661.6	0	4.479	4.413
Dc-d	4.25	0.0005	641.6	0.321	4.397	4.718
Qc-d	6.16	0.0006	652.2	0.391	4.702	5.093

Note: Each data entry represents an average of ten specimens.

It is evident from Table 4 that for the warp direction, an increase in $\Delta\epsilon$ and fracture energy ($\Delta\epsilon \times \sigma_b$) is produced by adding Teflon powder. Table 5 shows that for the fill direction $\Delta\epsilon$ and fracture energy increases are slight. Tables 4 and 5 also show the total failure energy, which is the fracture energy plus the resilience. The resilience is defined as the work to strain the specimen elastically. It is shown that for the warp direction the total energy is a slightly decreasing function of added Teflon, but for the fill direction the total energy decreases a much larger degree, primarily because of the decrease in $\sigma_{\max}$.

Examples of stress-strain curves for some representative warp direction specimens are shown in Figures 21, 22, and 23. Examples of stress-strain curves for some representative fill direction specimens are shown in Figures 24, 25, and 26.

Figure 21. Stress-Strain Curve for a Warp Direction Specimen from Panel A with 0% Teflon

Figure 22. Stress-Strain Curve for a Warp Direction Specimen from Panel F with 1% Teflon

Figure 23. Stress-Strain Curve for a Warp Direction Specimen from Panel P with 4% Teflon

Figure 24. Stress-Strain Curve for a Fill Direction Specimen from Panel A with 0% Teflon

Figure 25. Stress-Strain Curve for a Fill Direction Specimen from Panel O with 2% Teflon

Figure 26. Stress-Strain Curve for a Fill Direction Specimen from Panel D with 4% Teflon

Figure 21 shows a brittle fracture with no measurable strain past the yield point. This graph is from a warp direction specimen from panel A, with 0% added Teflon. The GFRP has properties as expected and provides essentially no fracture energy. This is typical of all the control samples. Figure 22 shows a well behaved linear portion, but with 1% Teflon added the specimen now shows progressive delamination producing additional strain after the point of deviation from the linear elastic portion. As explained in Section 4.8, this is measured as $\Delta\epsilon$ and represents damage tolerance in the material. Also evident in Figure 22 is that the strength of the specimen, σ_{max} , is slightly decreased from the control sample. Figure 23 shows even greater $\Delta\epsilon$ with 4% added Teflon. This specimen also shows that when initial cracking begins, the curve deviates from the straight line portion, but there is still additional stress that can be supported by the specimen. This is evident by σ_b being greater than σ_y . This is representative of specimens containing higher concentrations of Teflon. Warp direction specimens in the experiment clearly have greater values of $\Delta\epsilon$ with added Teflon powder.

Specimens in the fill direction also show an increase in $\Delta\epsilon$ with added Teflon, but to a lesser degree. Figure 24, with 0% Teflon, shows the brittle characteristics typical of GFRP with no

measurable toughness in the non-elastic region. Figure 25, with 2% Teflon, shows a specimen with a very small amount of $\Delta\epsilon$, such that it is not readily measured. This figure shows a typical example of a fill direction specimen where progressive delamination does not occur. Instead, an incomplete fracture causes a large drop in the stress, and the material continues to deflect at a lower load. Even though the material does not fail, the drop in the stress is large enough to be detected by the Instron as the break point, so the Instron does not measure any $\Delta\epsilon$. At higher Teflon concentrations the fill direction specimens do show some small increase in damage tolerance, as shown by Figure 26.

5.2 Toughness and Damage Tolerance Evaluation

Damage tolerance, in terms of strain after yield and before failure, and toughness in terms of the total energy required to fracture a specimen, were calculated for each panel from the data given in Tables 2 and 3. The results for additional strain in the warp direction are presented in Figure 27, and for additional strain in the fill direction in Figure 28. The results for energy of fracture in the warp direction are presented in Figure 29, and for energy of fracture in the fill direction in Figure 30. The total energy of failure for the warp and fill directions is presented in Figures 31 and 32.

Figure 27. Warp Direction $\Delta\epsilon$ as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 28. Fill Direction $\Delta\epsilon$ as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 29. Warp Direction Fracture Energy as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 30. Fill Direction Fracture Energy as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 31. Warp Direction Total Energy of Failure as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 32. Fill Direction Total Energy of Failure as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

With the addition of Teflon, it can be seen from Figures 27 and 28 that the warp direction has a significant increase in $\Delta\varepsilon$, but in the fill direction the increase is much less. The $\Delta\varepsilon$ starts at essentially zero for the control sample, and for the warp direction increases to an amount roughly 20% above the amount of elastic strain. In the fill direction the added strain is about 4% above the elastic strain.

The fracture energy, as defined in section 4.8 as $\Delta\varepsilon \times \sigma_b$, is shown to be zero in the control samples in Figures 29 and 30, and increases to roughly 2 MJ/m³ with 4% added Teflon in the warp direction. In the fill direction the fracture energy increases from zero to roughly 0.5 MJ/m³ with 4% added Teflon.

5.3 Effects on Strength and Flexural Modulus

Figures 33 and 34 show the effects of adding Teflon on the strength in the warp and fill directions, and Figures 35 and 36 show the effects on the flexural modulus in the warp and fill directions. Here it is shown that the strength in the warp direction (Fig. 33) decreases by roughly 7% with a 4% addition of Teflon. In the fill direction (Fig. 34) the strength decreases by roughly 13% with a 4% addition of Teflon. Fill direction the flexural strengths were found

to be slightly higher than the warp direction, and delamination occurred more rapidly with the addition of Teflon. The fracture characteristics in the fill direction are still primarily brittle after the addition of Teflon, as shown in the stress-strain curves of Figures 25, and 26. The flexural modulus for specimens in both directions shows a small decrease of roughly 1% with the addition of 4% Teflon.

Figure 33. Warp Direction Strength as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 34. Fill Direction Strength as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 35. Warp Direction Flexural Modulus as a Function of Added Teflon.
Note: Each data point represents an average of ten specimens.

Figure 36. Fill Direction Flexural Modulus as a Function of Added Teflon.
 Note: Each data point represents an average of ten specimens.

5.4 Effects on Panel Thickness and Density

As the sample panels were fabricated, and Teflon added, each panel was weighed and the thickness measured as part of the test procedure. It was noticed that the density and thickness of the samples increased slightly with the addition of Teflon. The relationship of density and thickness to Teflon amount is shown in Figures 37 and 38. The reason for the increased thickness was not

tested, but it is suspected that the very high number of particles in the Teflon powder acted as a filler and increased the resin viscosity. The filled resin did not flow as much during cure, producing slightly thicker panels. The reason for the increased density is primarily due to a rule of mixtures with the Teflon having a higher density than both the fiber and the resin.

Figure 37. Post-Cure Panel Density as a Function of Added Teflon.

Figure 38. Post-Cure Panel Thickness as a Function of Added Teflon.

5.5 Effects on the Mode of Failure

A qualitative evaluation of the toughness can be obtained by an examination of the 3-point bend specimens after testing. This was done and the results are shown in Figures 39, 40, 41, and 42 for the warp direction, and Figures 43, 44, 45, and 46 for the fill direction.

Figure 39 shows a representative set of warp direction specimens with 0% Teflon. As shown with the stress-strain curve in Figure 21, these specimens are characterized by a brittle fracture. The fracture in these specimens is mainly a single translaminar crack that propagated to failure. The specimens shown in Figures 40, 41, and 42 are typical of samples with added Teflon, and correlate well with the stress-strain curves displaying greater toughness and damage tolerance. The fractures shown here have a greater amount of multiple cracking.

Figure 39. Three Point Bend Specimens Fracture Zone. Warp Direction, Panel E, 0% Added Teflon.

Figure 40. Three Point Bend Specimens Fracture Zone. Warp Direction, Panel F, 1.28% Added Teflon.

Figure 41. Three Point Bend Specimens Fracture Zone. Warp Direction, Panel O, 2.02% Added Teflon.

Figure 42. Three Point Bend Specimens Fracture Zone. Warp Direction, Panel H, 4.13% Added Teflon.

Figure 43. Three Point Bend Specimens Fracture Zone. Fill Direction, Panel M, 0% Added Teflon.

Figure 44. Three Point Bend Specimens Fracture Zone. Fill Direction, Panel N, 1.14% Added Teflon.

Figure 45. Three Point Bend Specimens Fracture Zone. Fill Direction, Panel G, 2.17% Added Teflon.

Figure 46. Three Point Bend Specimens Fracture Zone. Fill Direction, Panel D, 4.25% Added Teflon.

The fill direction specimens maintained a relatively low level of toughness, and damage tolerance, even with the addition of Teflon. This is shown also in the stress-strain curves of Figures 24, 25, and 26. The small amount of fracture area in these curves confirms the low level of toughness and damage tolerance. The fractures in the fill direction, even with the Teflon additions, are mainly characterized by a brittle appearance of a single dominant fracture, as shown in Figures 44, 45, and 46. This appearance is shown in the control samples, and not much additional fracturing is evident in the test samples with Teflon. The graphs in Figures 28, and 30, showing $\Delta\varepsilon$ and fracture energy, also confirm the lack of toughness and damage tolerance improvement in the fill direction specimens.

CHAPTER 6

SUMMARY OF SIGNIFICANT RESULTS

Some of the salient aspects in this investigation are that damage tolerance improvements, measured by strain after yield, were achieved with the addition of Teflon powder into the epoxy matrix. The improvements were seen primarily in the warp direction and the strength of the composite decreased. Since the strength decreased, the resilience and total energy of failure also decreased. The control samples had virtually no measurable strain after yield, but the test samples with Teflon additions displayed significant additional strain after yield. The additional strain is important because it increased the non-linear portion of the stress-strain curve, delaying the propagation of catastrophic cracks. Although cracking initiated at lower stress levels, and the resilience of the material decreased, the material becomes more usable in designs requiring tolerance to limited damage preceding total failure.

All specimens failed in a characteristically brittle manner. Each specimen had a relatively well behaved linear elastic region on the stress-strain curve, and ended in delamination failure of the composite. The introduction of Teflon powder changed the character of the fracture from an abrupt and complete failure, to one of a progressive and incomplete delamination of the laminae. The

progressive delamination character is visible qualitatively in the warp direction by comparing Figure 39 with Figures 40, 41, and 42. Fractures in the samples without Teflon additions were characterized by single, predominantly translaminar, cracks. Fractures in the test samples with Teflon had multiple fractures occurring, and the mode of failure changed to interlaminar and intralaminar. It appears that the Teflon powder was able to provide sites for crack growth, and was able to increase the surface area generated by the cracking. The effect of this is that the Teflon powder dispersed in the matrix established a non-elastic portion to the stress-strain curve. Without additions of Teflon powder, the non-elastic portion to the stress-strain curve was not present.

The damage tolerance was measured quantitatively as $\Delta\epsilon$ and $\Delta\epsilon \times \sigma_b$ on the stress strain curve for each sample. It was seen that increases in $\Delta\epsilon$ were greater for warp direction samples, and only slight for fill direction samples. However, damage tolerance was improved even in the fill direction, because some additional strain before failure was produced. This is evident by the stress-strain curves showing multiple fracture edges at the end of the linear elastic region for these specimens. It appears that the Teflon particles, located in the matrix at a large number of sites and able to deform plastically, were able to improve damage tolerance. Cracks were able to form at numerous sites, which provided greater strain for a given stress. Also, it appears that the Teflon was able

to arrest some crack propagation by deforming plastically in the matrix, as is shown by the characteristic of progressive delamination. Cracks that formed at stress levels close to $\sigma_{\max}$ did not immediately propagate to failure.

Delamination strength decreased for both warp and fill directions. With a 4% addition of Teflon powder, it was shown that there was roughly a 7% loss in $\sigma_{\max}$ for the warp direction, and 13% loss in the fill direction. This is believed to be due to the dispersion of particles on a small scale not being uniform. With high concentrations of Teflon powder in localized regions of the prepreg weave pattern, delamination cracking can initiate and propagate to failure at lower stress levels. The powder was intended to act as discrete particles, generating numerous and small defects uniformly in the matrix. In a concentrated group the Teflon can act as a relatively large defect. It is possible that this is responsible for the decrease in strength. The Teflon powder was able to arrest some propagation of cracks in the warp direction, but not as much in the fill direction. The reason for this effect is not clear from these tests. However, it is possible that during the manufacturing process for the prepreg material, a greater amount of fiber damage is caused in the fill direction due to the weave process. This makes the fill direction fibers more sensitive to cracking and crack propagation.

In both the warp and fill directions the flexural modulus decreased slightly, roughly 1%. This can be attributed to the fact that the Teflon additions made up only small volume percentages of the matrix, and so the loss in bond strength to the fibers was minimal. The fibers then were still the dominant contributor to the stiffness of the material, and the flexural modulus remained roughly unchanged. The flexural modulus is determined by the linear portion of the stress-strain curve, before delamination cracking begins to occur.

The relative merits of the damage tolerance improvement can be evaluated by comparing $\Delta\epsilon$ with the elastic strain, and by comparing $\Delta\epsilon \times \sigma_b$ with the resilience, the elastic energy of deflection. An addition of 4% Teflon powder increased the warp direction strain from an average value of 0.013 mm/mm to 0.016 mm/mm, which is approximately a 20% increase above the elastic strain. In the fill direction only a 4% increase above the elastic strain was achieved. Likewise, in evaluating the fracture energy, the 4% Teflon powder addition in warp direction samples showed an average increase from 4.6 MJ/m³ for the elastic strain energy, to 6.2 MJ/m³ for elastic strain energy plus delamination energy. This is an increase of 33% for the warp direction specimens. For the same conditions in the fill direction, an 11% increase in energy from 4.6 MJ/m³ to 5.1 KJ/m³ was achieved. The control samples showed no measurable non-elastic delamination energy.

Combining the increase in delamination energy with the decrease in $\sigma_{\max}$, it was shown that the total energy of failure (the total area under the stress-strain curve) remained roughly constant for the warp direction specimens, but decreased by roughly 21% in the fill direction. This is attributed to the relatively large decrease in $\sigma_{\max}$ for the fill direction, without significantly increasing $\Delta\varepsilon$.

Adding the Teflon powder apparently did not increase the inherent defect population caused by the manufacturing process. Inherent defects, such as misalignment of plies, broken fibers, voids, or contamination, are largely responsible for variations in the test data that are observed in all test samples. The standard deviation of the average for a set of test samples frequently is a measure of the processing quality. A large value in the standard deviation implies non-uniformity and random defects in the material, which leads to scatter in the test data. It was shown in this experiment that the standard deviations for the averages of the strengths and moduli did not increase with added Teflon. This implies that the measured effects of toughness and damage tolerance were not biased by additional factors in the sample fabrication process.

CHAPTER 7

CONCLUSIONS

This study has shown that GFRP damage tolerance, measured as additional strain after yield, can be produced with the addition of Teflon powder into the epoxy matrix. The control samples had virtually no measurable strain after yield, but the test samples with Teflon displayed significant additional strain after yield. The additional strain is important because it increased the non-linear portion of the stress-strain curve, delaying the propagation of catastrophic cracks. Although cracking initiated at lower stress levels and the resilience of the material decreased, the material may be more usable in designs requiring tolerance to limited damage preceding total failure. Toughness, as measured by the total area under the stress-strain curve, did not increase. With the addition of the Teflon particles, the strength of the composite decreased. The decrease in strength was greatest in the fill direction, and when combined with the small increase in strain before failure, the fill direction showed a decrease in the total energy of failure.

The test specimens showed qualitatively that by the addition of Teflon particles in the matrix, there is a greater degree of multiple fracturing in the material under load. The visual appearance of the fractures correlated with the measured values of additional strain, showing that the additional strain is due to

progressive delamination of the material without total failure. Fractures in the samples without Teflon were characterized by single, predominantly translaminar cracks. Test samples with Teflon had multiple fractures, and the mode of failure changed to interlaminar and intralaminar. It appears that the Teflon powder was able to provide sites for crack growth, and was able to increase the surface area generated by the cracking.

Test specimens in both the warp and fill directions showed only a slight decrease in flexural modulus. The quantity of Teflon used in this experiment was sufficiently small so that the loss in bond strength to the fibers was minimal, and the fibers still dominated the stiffness properties. Even though the strength of the composite decreased, and delamination cracking was initiated at lower stress levels, the modulus is measured in the linear elastic region of the stress-strain curve, before delamination fracturing begins to occur.

Adding the Teflon powder did not increase the inherent defect population caused by the sample fabrication process. A measure of the processing quality is the value of the standard deviation of the average of the test samples. For both the warp and fill directions, the standard deviations did not increase with added Teflon. This implies that the measured effects in toughness and damage

tolerance were not biased by additional factors in the sample fabrication process.

It appears that the effectiveness of the Teflon was limited by the degree of uniformity in the distribution of the particles in the composite. The decrease in strength accompanying the improvement in strain to failure is most likely attributed to the Teflon not being dispersed uniformly on a small scale. Using Teflon powder appears to be a viable method for improving damage tolerance and toughness by introducing a large number of small and ductile defects. However, future studies should improve on the method of dispersing the particles. Future studies may examine processes for adding the particles directly to the epoxy prior to the prepreg stage. If this can be done, it will ensure dispersion not subjected to the geometry of the fibers in the weave pattern.

This project also was not able to distribute defects directly onto the fibers. Application of the particles after the prepreg stage did not assure defects would be located directly at the interface. The literature survey showed that additional toughness may be achieved by small defects at the fiber-matrix interface. The defects may generate localized yielding on fibers under load and that would increase the strain to failure. Future studies may examine processes for locating the defects at the fiber-matrix interface.

These processes may include adding defects to the sizing material as applied to the fibers.

A related project would be to increase the level of adding Teflon to the matrix above 6%. This project produced only one panel at 6%, and it is possible that additional improvements can be realized at higher levels. At higher levels of Teflon in the matrix, the loading eventually will be large enough to decrease strength and flexural modulus beyond acceptable levels. It is not clear from these tests that 6% is the maximum level for achieving acceptable results, and higher levels may be tried, especially if the uniformity of the distribution is improved.

Additional studies to continue this investigation should include separating and examining the fracture surfaces under high magnification. This may reveal more information about the crack propagation processes that were affected by the Teflon particles. Also, a highly magnified view of a section of the matrix may show if the distribution of particles is uniform after cure. The resin flows during the cure process, and it is not known what effect that has on the particle distribution. This investigation showed a significant difference in the results in the warp direction compared to the fill direction samples. The exact reason for this effect was not apparent from these tests. From micrographs that were taken, it was proposed that the effect was due to accumulation of Teflon

powder against the fill direction fibers. The accumulation was due to the weave pattern on the warp face up fabric, which was the orientation when the powder was applied. This could be verified by repeating the experiment and applying the powder to the fill face up. In that case the weave pattern would be reversed, and then the powder would accumulate against the warp direction fibers. A reversal of the directional effects seen in this project would confirm the importance of the uniform distribution of powder on a scale smaller than the weave pattern.

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APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive

Instron Corporation
Series IX Automated Materials Testing System 1.08
Test Date: 03 Feb 1993

Operator name: CHAFEY

Sample Type: ASTM

Sample Identification: A

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00
Crosshead Speed (mm/min): 1.270

Humidity (%): 50
Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	Aa1	2.896	.7113	753.6	81500.	713.60	.0162	713.6	.0162	.6735
2	Aa2	2.921	.7282	771.5	83100.	17.12	.0163	769.9	.0163	.7266
3	Aa3	2.870	.7113	753.6	83180.	36.68	.0160	751.7	.0159	.7095
4	Aa3	2.921	.7344	778.1	82560.	667.90	.0162	667.9	.0162	.6504
5	Aa5	3.175	.8056	853.5	83910.	19.16	.0177	852.3	.0177	.8044
6	Aa6	2.946	.7451	789.4	83210.	19.47	.0165	787.5	.0164	.7432
7	Aa7	3.277	.8380	887.9	84580.	22.79	.0183	887.0	.0182	.8371
8	Aa8	3.023	.7722	818.2	84860.	24.75	.0169	816.0	.0169	.7701
9	Aa9	2.870	.7344	778.1	85830.	44.81	.0161	777.2	.0160	.7335
10		2.862	.7270	770.3	86130.	651.80	.0160	651.8	.0160	.6152
Mean:		2.976	.7507	795.4	83890.	221.80	.0166	767.5	.0166	.7244
Standard Deviation:		.142	.0420	44.5	1464.	315.10	.0008	75.1	.0008	.0709
Minimum:		2.862	.7113	753.6	81500.	17.12	.0160	651.8	.0159	.6152
Maximum:		3.277	.8380	887.9	86130.	713.60	.0183	887.0	.0182	.8371

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.06
	Test Date: 03 Feb 1993
Sample Identification: BA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	BA1	3.048	.7202	730.4	79870.	533.1	.0116	749.2	.0167	.7190
2	BA2	2.667	.6672	675.2	81500.	653.8	.0138	659.6	.0151	.6532
3	BA3	2.718	.7042	733.7	82990.	587.9	.0122	710.9	.0151	.6823
4	BA4	3.175	.8220	856.5	83820.	847.9	.0175	760.8	.0176	.7302
5	BA5	3.048	.7945	827.8	84010.	141.1	.0170	827.4	.0170	.7940
6	BA6	2.972	.7540	785.6	83490.	749.2	.0158	784.8	.0165	.7532
7	BA7	2.743	.7068	736.5	83210.	707.3	.0153	735.5	.0159	.7059
8	BA8	2.819	.7295	760.1	83260.	709.5	.0148	693.6	.0164	.6657
9	BA9	2.845	.6539	681.3	83500.	636.5	.0133	678.1	.0159	.6508
10	BA10	2.946	.7082	737.9	83000.	656.1	.0136	648.1	.0167	.6220
Mean:		2.898	.7260	756.5	82870.	622.4	.0145	724.8	.0163	.6956
Standard Deviation:		.166	.0522	54.4	1255.	189.9	.0019	57.3	.0008	.0550
Minimum:		2.667	.6539	681.3	79870.	141.1	.0116	648.1	.0151	.6220
Maximum:		3.175	.8220	856.5	84010.	847.9	.0175	827.4	.0176	.7940

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.05
	Test Date: 03 Feb 1993
Sample Identification: CA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3800	2.3800	2.3800	2.3800	2.3800	2.3800	2.3800	2.3800
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (Autyoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	CA1	2.997	.7277	767.8	81500.	741.40	.0162	766.8	.0167	.7268
2	CA2	2.972	.7393	780.0	81590.	744.20	.0166	744.2	.0166	.7054
3	CA3	2.896	.7277	767.8	83290.	105.10	.0161	766.5	.0161	.7265
4	CA4	2.972	.7415	782.4	82130.	765.20	.0162	782.2	.0166	.7414
5	CA5	3.099	.7651	807.2	83290.	742.60	.0156	805.3	.0173	.7632
6	CA6	2.769	.7024	741.1	82900.	734.20	.0154	740.0	.0155	.7013
7	CA7	2.870	.7197	759.4	81370.	730.50	.0154	750.4	.0164	.7113
8	CA8	3.048	.7664	808.6	81750.	787.20	.0166	807.3	.0170	.7652
9	CA9	2.819	.7064	745.3	82540.	98.74	.0157	743.5	.0157	.7047
10	CA10	2.972	.7424	783.3	82150.	770.70	.0163	781.6	.0166	.7408
Mean:		2.941	.7339	774.3	82250.	622.00	.0160	768.8	.0164	.7280
Standard Deviations:		.102	.0216	22.8	725.	274.70	.0005	24.9	.0006	.0220
Minimum:		2.769	.7024	741.1	81370.	98.74	.0154	740.0	.0155	.7013
Maximum:		3.099	.7664	808.6	83290.	787.20	.0166	807.3	.0173	.7652

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units,Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 04 Feb 1993
Sample Identification: DA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4500	2.4500	2.4500	2.4500	2.4500	2.4500	2.4500	2.4500
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	DA1	2.540	.6392	655.2	81700.	601.9	.0142	601.9	.0142	.5872
2	DA2	2.438	.6147	630.1	81740.	609.2	.0130	629.0	.0136	.6137
3	DA3	2.438	.6272	642.8	81800.	572.4	.0121	636.7	.0137	.6212
4	DA4	2.667	.6472	663.4	82400.	576.0	.0123	662.9	.0149	.6467
5	DA5	2.642	.6388	654.7	81090.	555.7	.0120	551.2	.0170	.5376
6	DA6	2.946	.7286	746.8	82520.	572.1	.0121	726.7	.0167	.7090
7	DA7	2.692	.6901	697.1	82190.	578.4	.0123	634.3	.0151	.6189
8	DA8	2.743	.6797	696.6	82320.	619.1	.0132	695.7	.0153	.6788
9	DA9	2.565	.6672	622.3	80900.	530.0	.0114	506.7	.0147	.4944
10	DA10	2.540	.5849	599.5	79650.	534.3	.0116	479.8	.0160	.4682
Mean:		2.621	.6448	660.9	81630.	574.9	.0124	612.5	.0151	.5976
Standard Deviation:		.153	.0419	42.9	879.	29.7	.0008	79.2	.0012	.0775
Minimum:		2.438	.5849	599.5	79650.	530.0	.0114	479.8	.0136	.4682
Maximum:		2.946	.7286	746.8	82520.	619.1	.0142	726.7	.0170	.7090

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units,Raw Data

Test type: Compressive

Instron Corporation

Operator name: CHAFEY

Series IX Automated Materials Testing System 1.08
Test Date: 04 Feb 1993

Sample Identification: EA

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutoYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	EA1	3.073	.7335	787.1	79700.	27.55	.0172	784.0	.0171	.7305
2	EA2	2.718	.6566	704.6	81420.	17.42	.0152	701.4	.0152	.6530
3	EA3	2.845	.6890	739.4	82360.	15.59	.0158	738.0	.0158	.6878
4	EA4	2.743	.6550	700.7	82200.	74.78	.0153	698.4	.0152	.6508
5	EA5	2.896	.6948	745.0	81750.	16.53	.0161	742.9	.0161	.6923
6	EA6	3.073	.7384	792.4	81570.	25.17	.0171	792.2	.0171	.7383
7	EA7	3.048	.7384	792.4	81900.	12.69	.0170	791.4	.0170	.7375
8	EA8	2.769	.6659	714.6	81990.	38.88	.0153	712.3	.0154	.6636
9	EA9	2.718	.6481	695.5	82130.	68.66	.0152	695.0	.0152	.6482
10	EA10	3.073	.7433	797.6	82140.	15.51	.0172	795.4	.0171	.7412
Mean:		2.896	.6961	747.0	81720.	31.28	.0162	745.2	.0161	.6944
Standard Deviation:		.157	.0397	42.2	766.	22.73	.0009	42.3	.0009	.0394
Minimum:		2.718	.6481	695.5	79700.	12.69	.0152	695.6	.0152	.6482
Maximum:		3.073	.7433	797.6	82360.	74.78	.0172	795.4	.0171	.7412

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 76-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive

Instron Corporation

Series IX Automated Materials Testing System 1.08

Operator name: CHAFEY

Test Date: 04 Feb 1993

Sample Identification: FA

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3600	2.3600	2.3600	2.3600	2.3600	2.3600	2.3600	2.3600
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (kN)	Stress at Max. Load (MPa)	Modulus (Autotuning) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	FA1	2.896	.6877	731.7	79260.	715.20	.0158	731.7	.0162	.6877
2	FA2	2.743	.6681	710.9	79990.	635.40	.0137	709.1	.0153	.6664
3	FA3	2.870	.6904	734.6	79090.	654.90	.0143	731.9	.0160	.6878
4	FA4	2.845	.6944	738.8	81860.	97.23	.0159	736.4	.0159	.6921
5	FA5	3.048	.7429	790.4	82770.	463.10	.0170	789.6	.0170	.7421
6	FA6	2.718	.6530	694.8	81400.	236.00	.0151	691.6	.0151	.6500
7	FA7	2.819	.6663	709.0	79000.	622.10	.0137	708.2	.0158	.6656
8	FA8	2.896	.6761	719.4	79890.	632.80	.0138	706.8	.0169	.6643
9	FA9	2.819	.6681	710.9	79830.	632.30	.0140	708.0	.0157	.6654
10	FA10	2.896	.6552	697.2	78400.	638.50	.0141	694.7	.0162	.6529
Mean:		2.835	.6802	723.8	80150.	532.70	.0147	720.8	.0160	.6774
Standard Deviation:		.092	.0261	27.8	1408.	205.60	.0012	28.7	.0006	.0270
Minimum:		2.718	.6530	694.8	78400.	97.23	.0137	691.6	.0151	.6500
Maximum:		3.048	.7429	790.4	82770.	715.20	.0170	789.6	.0170	.7421

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 04 Feb 1993
Sample Identification: GA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 8 specimens, 0 excluded.

Sample comments: OUT OF MEMORY ON DISK, TRY TO RESUME TEST WITH A NEW DISK

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (Autrong) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user break (MPa)	Strain at user break (mm/mm)	Load at user break (KN)
1	GA1	2.794	.6868	715.6	81560.	647.2	.0139	715.7	.0156	.6869
2	GA2	2.769	.6646	692.4	81700.	560.5	.0119	606.0	.0155	.5816
3	GA3	2.591	.6343	660.9	80380.	504.9	.0109	606.8	.0144	.5816
4	GA4	2.718	.6828	711.4	81260.	697.8	.0149	709.7	.0153	.6811
5	GA5	2.921	.7313	762.0	81320.	627.5	.0134	759.2	.0163	.7287
6	GA6	2.769	.6784	706.8	81730.	588.9	.0125	651.9	.0155	.6256
7	GA7	2.794	.6797	708.2	81310.	590.9	.0125	705.9	.0156	.6775
8	GA8	2.819	.7157	745.7	81090.	651.0	.0137	744.5	.0158	.7145
Mean:		2.772	.6842	712.9	81290.	608.6	.0130	694.0	.0155	.6660
Standard Deviation:		.093	.0296	30.9	430.	60.2	.0013	51.3	.0005	.0492
Minimum:		2.591	.6343	660.9	80380.	504.9	.0109	606.0	.0144	.5816
Maximum:		2.921	.7313	762.0	81730.	697.8	.0149	759.2	.0163	.7287

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-5.1. Units:Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Autosaved Materials Testing System 1.08
	Test Date: 05 Feb 1993
Sample Identification: GA-2	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3
Width (mm)	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60

Out of 3 specimens, 0 excluded.

Sample comments: CONTINUATION OF TEST GA FROM DISK #1

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	GA-2-9	3.150	.7433	774.5	81930.	666.6	.0141	773.5	.0175	.7423
2	GA-2-10	3.023	.7362	767.1	80960.	679.2	.0144	766.3	.0168	.7354
3	GA-2-11	2.870	.7202	750.4	80690.	699.4	.0148	747.8	.0160	.7177
Means:		3.014	.7332	764.0	81200.	681.7	.0144	762.5	.0168	.7318
Standard Deviations:		.140	.0119	12.3	652.	16.5	.0004	13.2	.0006	.0127
Minimum:		2.870	.7202	750.4	80690.	666.6	.0141	747.8	.0160	.7177
Maximum:		3.150	.7433	774.5	81930.	699.4	.0148	773.5	.0175	.7423

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOW-SPEED MISSILES : SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-1)

1 Point Compressive Test-5... Units:raw Data

Test type: Compressive

Instron Corporation

Series IX Automated Materials Testing System 1100

Operator name: CHAFFE

Test Date: 06 Feb 1993

Sample Identification: HA

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFFE

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4600	2.4600	2.4600	2.4600	2.4600	2.4600	2.4600	2.4600
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Flatten Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (Autotune) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	HA1	2.819	.7157	730.6	81020.	605.8	.0129	730.1	.0157	.7152
2	HA2	2.413	.6187	631.6	84040.	549.2	.0111	516.0	.0162	.5055
3	HA3	2.489	.6450	658.4	85620.	590.1	.0118	551.2	.0139	.5400
4	HA4	2.692	.6966	711.1	83490.	632.6	.0130	710.3	.0150	.6958
5	HA5	2.692	.6935	707.9	82870.	606.4	.0127	708.0	.0150	.6925
6	HA6	2.819	.7242	739.2	82310.	529.6	.0111	737.3	.0157	.7223
7	HA7	2.816	.6703	684.3	83490.	541.0	.0113	669.2	.0151	.6556
8	HA8	2.769	.6730	707.4	82630.	569.3	.0121	668.2	.0157	.6546
9	HA9	2.692	.6721	706.5	83360.	553.3	.0117	704.7	.0150	.6904
10	HA10	2.515	.6419	655.2	83450.	600.5	.0126	655.0	.0141	.6417
Mean:		2.632	.6791	692.2	83260.	577.8	.0120	663.0	.0152	.6515
Standard Deviation:		.141	.0342	34.9	1184.	34.1	.0007	74.7	.0007	.0722
Minimum:		2.413	.6187	631.6	81020.	529.6	.0111	516.0	.0129	.5055
Maximum:		2.819	.7242	739.2	85620.	632.6	.0130	737.3	.0162	.7227

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 76-30

3 Point Compressive Test-B.I. Units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFFEY	Series IX Automated Materials Testing System 1.06
	Test Date: 06 Feb 1993
Sample Identification: NA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Flaten Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (At Young's) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	MA1	3.048	.7157	768.1	80140.	70.67	.0169	766.1	.0169	.7119
2	MA2	2.972	.7095	761.4	80130.	44.49	.0166	760.4	.0166	.7085
3	MA3	3.099	.7424	796.7	81600.	43.37	.0172	794.4	.0172	.7401
4	MA4	2.692	.6419	688.8	81780.	85.65	.0150	687.3	.0150	.6405
5	MA5	2.921	.7153	767.6	83030.	46.91	.0163	764.8	.0162	.7127
6	MA6	2.718	.6681	717.0	83280.	90.53	.0151	714.8	.0151	.6661
7	MA7	2.895	.7148	767.1	83960.	34.96	.0162	766.3	.0162	.7141
8	MA8	3.200	.7909	848.7	83830.	31.89	.0178	846.3	.0177	.7886
9	MA9	3.048	.7562	811.5	82860.	45.85	.0171	810.8	.0171	.7553
10	MA10	3.048	.7473	801.9	84280.	697.60	.0170	697.6	.0170	.7451
Mean:		2.964	.7202	772.9	82510.	119.20	.0165	760.9	.0165	.7190
Standard Deviation:		.162	.0429	46.0	1502.	204.30	.0009	50.0	.0009	.0466
Minimum:		2.692	.6419	688.8	80130.	31.89	.0150	687.3	.0150	.6405
Maximum:		3.200	.7909	848.7	84280.	697.60	.0178	846.3	.0177	.7886

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units-Raw Data

Test type: Compressive

Instron Corporation

Series II Automated Materials Testing System 1.06

Operator name: CHAFEY

Test Date: 09 Feb 1993

Sample Identification: NA

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3500	2.3500	2.3500	2.3500	2.3500	2.3500	2.3500	2.3500
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	NA1	2.794	.6708	716.8	82370.	112.50	.0157	715.7	.0156	.6698
2	NA2	2.921	.7108	759.6	79010.	517.00	.0112	759.2	.0162	.7104
3	NA3	2.870	.7055	753.9	82730.	140.20	.0160	750.9	.0160	.7028
4	NA5	2.997	.7308	780.9	81340.	94.18	.0167	778.5	.0167	.7286
5	NA4	2.692	.6503	694.9	82560.	383.40	.0150	693.2	.0149	.6487
6	NA6	3.175	.7744	827.5	82330.	111.30	.0177	826.9	.0177	.7739
7	NA7	2.819	.6877	734.8	84910.	117.90	.0157	733.8	.0157	.6867
8	NA8	3.023	.7446	795.7	83640.	787.20	.0170	790.3	.0170	.7396
9	NA9	3.048	.7491	800.4	82750.	44.37	.0170	799.2	.0170	.7480
10	NA10	2.921	.7286	778.6	84070.	102.20	.0163	775.5	.0163	.7258
Mean:		2.926	.7153	764.3	82570.	241.00	.0158	762.3	.0163	.7134
Standard Deviations:		.141	.0380	40.6	1605.	243.30	.0018	40.4	.0008	.0378
Minimum:		2.692	.6503	694.9	79010.	44.37	.0112	693.2	.0149	.6487
Maximum:		3.175	.7744	827.5	84910.	787.20	.0177	826.9	.0177	.7739

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. units-Faw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 09 Feb 1993
Sample Identification: QA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (kN)	Stress at Max. Load (MPa)	Modulus (Aut Young) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	QA1	3.048	.7160	709.0	78960.	762.40	.0108	767.1	.0107	.7149
2	QA2	2.896	.7006	751.8	80310.	500.20	.0108	712.6	.0163	.6640
3	QA3	2.870	.6979	749.0	80990.	737.70	.0158	738.3	.0162	.6880
4	QA4	2.946	.6877	738.0	83460.	705.90	.0157	737.8	.0165	.6676
5	QA5	2.972	.7286	781.9	84590.	46.48	.0166	779.3	.0165	.7262
6	QA6	2.946	.7251	778.1	83570.	48.20	.0165	776.3	.0164	.7234
7	QA7	2.946	.7264	779.5	83920.	150.80	.0165	777.6	.0164	.7246
8	QA8	2.972	.7266	780.0	82690.	66.96	.0165	778.5	.0165	.7255
9	QA9	2.845	.6726	721.8	78500.	714.90	.0157	717.9	.0162	.6690
10	QA10	2.591	.6085	653.0	77650.	543.00	.0120	570.9	.0168	.5320
Mean:		2.903	.6991	750.2	81470.	427.80	.0153	735.6	.0165	.6855
Standard Deviation:		.124	.0371	39.8	2506.	312.90	.0021	63.4	.0002	.0691
Minimum:		2.591	.6085	653.0	77650.	46.48	.0108	570.9	.0162	.5320
Maximum:		3.048	.7286	781.9	84590.	762.40	.0168	779.3	.0167	.7262

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFFEY	Series 1A Automated Materials Testing System 1.08
	Test Date: 09 Feb 1993
Sample Identification: PA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (Autyoung) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	PA1	2.972	.7019	731.4	77120.	612.5	.0136	730.2	.0166	.7008
2	PA2	2.845	.6610	688.7	79390.	548.4	.0119	662.2	.0164	.6355
3	PA3	2.769	.6534	680.9	79360.	455.9	.0100	660.1	.0155	.6235
4	PA4	2.718	.6437	670.7	77580.	594.3	.0133	650.7	.0161	.6245
5	PA5	2.769	.6792	707.7	79390.	696.3	.0152	705.1	.0154	.6767
6	PA6	2.667	.6428	669.7	77910.	620.8	.0137	661.6	.0150	.6349
7	PA7	2.819	.6761	704.5	78520.	561.8	.0121	702.7	.0157	.6744
8	PA8	2.819	.6810	709.6	80070.	616.5	.0133	708.2	.0157	.6797
9	PA9	2.769	.6703	698.5	79660.	542.7	.0117	696.6	.0155	.6686
10	PA10	2.972	.7046	734.2	79520.	613.7	.0133	732.2	.0165	.7027
Mean:		2.812	.6714	699.6	78850.	586.3	.0128	691.0	.0158	.6671
Standard Deviation:		.099	.0217	22.6	1004.	63.8	.0014	30.1	.0005	.0280
Minimum:		2.667	.6426	669.7	77120.	455.9	.0100	650.7	.0150	.6245
Maximum:		2.972	.7046	734.2	80070.	696.3	.0152	732.2	.0166	.7027

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units,Raw Data

Test type: Compressive

Instron Corporation

Series 11 Automated Materials Testing System 1.08

Operator name: CHAFEY

Test Date: 10 Feb 1993

Sample Identification: QA

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4800	2.4800	2.4800	2.4800	2.4800	2.4800	2.4800	2.4800
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Sample comments: 0.16% FEP

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	QA1	2.819	.6984	707.1	79070.	648.5	.0143	707.2	.0157	.6984
2	QA2	2.819	.7157	724.7	79530.	605.0	.0130	722.4	.0158	.7134
3	QA3	2.464	.6414	649.5	81370.	640.6	.0136	649.0	.0138	.6410
4	QA4	2.896	.7420	751.3	80770.	715.9	.0154	749.0	.0161	.7397
5	QA5	2.997	.7655	775.1	82470.	721.9	.0155	775.2	.0167	.7656
6	QA6	2.794	.7322	741.4	81690.	583.5	.0123	740.8	.0156	.7317
7	QA7	2.642	.6641	672.4	81600.	473.1	.0100	670.4	.0146	.6621
8	QA8	2.565	.6641	672.4	81730.	569.8	.0120	557.7	.0148	.5508
9	QA9	2.515	.6263	634.2	80230.	526.3	.0111	519.8	.0179	.5134
10	QA10	2.311	.5912	598.6	80810.	506.0	.0106	487.9	.0159	.4819
Mean:		2.682	.6841	692.7	80930.	599.0	.0128	657.9	.0157	.6498
Standard Deviation:		.217	.0559	56.6	1064.	84.2	.0019	102.1	.0011	.1008
Minimum:		2.311	.5912	598.6	79070.	473.1	.0100	487.9	.0138	.4819
Maximum:		2.997	.7655	775.1	82470.	721.9	.0155	775.2	.0179	.7656

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 76-30

2 Point Compressive Test-0.1. Units, Raw data

Test type: Compressive	Instron Corporation
Operator name: CHAFEI	Series IX Automated Materials Testing System 1.06
	Test Date: 10 Feb 1993
Sample Identification: RA	Sample Type: ASTM
Interface Type: 450v Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR: DAN CHAFEI

Dimensions:	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Flatten Bear. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.
Sample comments: 0% FEF, WRF DIRECTION SAMPLES

Specimen Number	ID#	Displacement at Max. Load (mm)	Load at Max. Load (kN)	Stress at Max. Load (MPa)	Modulus (Autotuning) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	RA1	3.048	.7388	792.9	81000.	40.670	.0170	791.4	.0170	.7374
2	RA2	2.876	.7024	753.7	82020.	34.740	.0162	751.4	.0162	.7002
3	RA3	2.870	.6979	749.0	81990.	24.890	.0161	747.1	.0160	.6762
4	RA4	2.794	.6775	727.0	83750.	54.290	.0156	725.2	.0156	.6755
5	RA5	3.124	.7678	823.9	82880.	2.989	.0175	821.9	.0175	.7655
6	RA6	2.769	.6766	726.0	82550.	53.640	.0155	725.1	.0155	.6755
7	RA7	2.972	.7295	782.9	83270.	10.530	.0160	780.6	.0160	.7274
8	RA8	2.769	.6744	723.7	84270.	17.260	.0155	720.8	.0154	.6737
9	RA9	2.819	.6877	736.0	82400.	17.800	.0158	736.3	.0157	.6867
10	RA10	2.642	.6388	685.5	81790.	35.260	.0147	682.2	.0146	.6357
Means:		2.870	.6991	750.2	82650.	29.210	.0160	748.2	.0160	.6772
Standard Deviations:		.145	.0374	40.1	862.	17.490	.0008	40.4	.0008	.0776
Minimum:		2.642	.6388	685.5	81600.	2.989	.0147	682.2	.0146	.6357
Maximum:		3.124	.7678	823.9	84270.	54.290	.0175	821.9	.0175	.7655

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-5.1. Units, Raw Data

Test type: Compressive

Operator name: CHAFET

Sample Identification: SA
Interface Type: 4500 Series
Machine Parameters of test:

Sample Rate (ots/sec): 10.00
Crosshead Speed (mm/min): 1.270

Instron Corporation
Series IX Automated Materials Testing System 1.08
Test Date: 11 Feb 1993

Sample Type: ASTM

Humidity (%): 50
Temperature (deg. F): 73

REQUESTOR DAN CHAFET

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Sample comments: 2.18% FEF, WARP DIRECTION SAMPLES

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	SA1	2.845	.6165	653.2	77860.	604.80	.0132	594.5	.0174	.5511
2	SA2	2.794	.6921	733.4	82060.	693.80	.0147	731.4	.0155	.6903
3	SA3	2.921	.7357	779.5	84730.	93.71	.0164	778.1	.0163	.7343
4	SA4	2.896	.7184	761.2	82840.	526.60	.0161	759.2	.0161	.7166
5	SA5	3.150	.7767	822.9	82890.	52.44	.0175	821.7	.0175	.7755
6	SA6	3.175	.7940	841.3	83490.	98.54	.0178	841.2	.0178	.7940
7	SA7	3.023	.7544	799.3	85460.	116.40	.0168	798.3	.0168	.7534
8	SA8	3.124	.7762	822.4	84630.	806.80	.0170	820.9	.0173	.7748
9	SA9	2.946	.7344	778.1	84020.	141.80	.0165	776.0	.0164	.7324
10	SA10	2.870	.7095	751.7	84890.	147.90	.0160	749.4	.0159	.7073
Mean:		2.974	.7508	774.3	83290.	328.30	.0162	767.1	.0167	.7240
Standard Deviation:		.136	.0516	54.6	2188.	293.40	.0014	69.9	.0008	.0669
Minimum:		2.794	.6165	653.2	77860.	52.44	.0132	594.5	.0155	.5511
Maximum:		3.175	.7940	841.3	85460.	806.80	.0178	841.2	.0178	.7940

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units,Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 11 Feb 1993
Sample Identification: TA	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4300	2.4300	2.4300	2.4300	2.4300	2.4300	2.4300	2.4300
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Sample comments: 4.08% FEP, WARP DIRECTION SAMPLES

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (Autotune) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	TA1	2.946	.7371	761.7	80030.	757.80	.0164	738.1	.0165	.7143
2	TA2	2.718	.6899	712.9	81680.	452.90	.0151	710.0	.0151	.6871
3	TA3	2.642	.6561	678.0	80520.	656.90	.0142	675.5	.0147	.6536
4	TA4	2.769	.7064	730.0	84740.	102.70	.0154	730.1	.0154	.7065
5	TA5	3.048	.7775	803.5	83130.	139.50	.0170	802.8	.0170	.7769
6	TA6	2.845	.7251	749.3	81930.	193.40	.0159	747.7	.0159	.7236
7	TA7	2.896	.7251	749.3	81040.	721.40	.0155	748.1	.0162	.7239
8	TA8	2.972	.7562	781.4	82660.	732.10	.0156	664.6	.0166	.6432
9	TA9	2.946	.7522	777.3	82500.	129.50	.0165	775.9	.0165	.7508
10	TA10	2.819	.7237	747.9	82430.	98.67	.0158	747.3	.0157	.7232
Mean:		2.860	.7249	749.1	82070.	398.50	.0157	734.0	.0160	.7103
Standard Deviation:		.126	.0349	36.0	1362.	293.10	.0008	42.0	.0007	.0407
Minimum:		2.642	.6561	678.0	80030.	98.67	.0142	664.6	.0147	.6422
Maximum:		3.048	.7775	803.5	84740.	757.80	.0170	802.8	.0170	.7769

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive

Instron Corporation

Operator name: CHAFEY

Series IX Automated Materials Testing System 1.08

Test Date: 03 Feb 1993

Sample Identification: AC

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	AC1	2.819	.7424	786.6	88500.	742.50	.0158	742.5	.0158	.7008
2	AC2	3.073	.8039	851.7	88620.	20.60	.0171	851.4	.0171	.8036
3	AC3	2.667	.6979	739.5	88120.	90.50	.0150	738.8	.0149	.6973
4	AC4	3.175	.8243	873.3	87790.	11.15	.0177	872.1	.0176	.8231
5	AC5	3.251	.8518	902.6	88610.	22.25	.0181	901.0	.0181	.8504
6	AD1	2.845	.7540	798.9	87940.	34.15	.0158	797.6	.0158	.7527
7	AD2	2.972	.7922	839.4	88840.	43.75	.0166	838.6	.0166	.7914
8	AD3	2.870	.7615	806.9	87480.	54.73	.0160	805.4	.0159	.7602
9	AD4	2.845	.7437	788.0	86910.	696.30	.0159	696.3	.0159	.6572
10	AD5	3.048	.8033	851.2	86970.	474.10	.0170	850.5	.0170	.8027
Mean:		2.957	.7775	823.8	88180.	219.00	.0165	809.4	.0165	.7639
Standard Deviation:		.180	.0457	48.4	810.	297.50	.0010	63.8	.0010	.0621
Minimum:		2.667	.6979	739.5	86910.	11.15	.0150	696.3	.0149	.6572
Maximum:		3.251	.8518	902.6	89480.	742.50	.0181	901.0	.0181	.8504

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units-Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 03 Feb 1993
Sample Identification: BC-D	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement	Load	Stress	Modulus	Stress	Strain	Stress	Strain	Load
		at Max.Load (mm)	at Max.Load (KN)	at Max.Load (MPa)	(AutYoung) (MPa)	at offset Yield 1 (MPa)	at offset Yield 1 (mm/mm)	at user Break (MPa)	at user Break (mm/mm)	at user Break (KN)
1	BC1	2.667	.7073	736.9	87420.	642.10	.0149	642.1	.0149	.6162
2	BC2	2.743	.7509	782.4	88630.	98.68	.0154	779.9	.0153	.7485
3	BC3	2.819	.7486	780.0	86180.	330.20	.0157	777.1	.0157	.7458
4	BC4	2.743	.7371	768.0	87390.	596.90	.0120	766.7	.0152	.7358
5	BC5	2.769	.7517	783.3	87910.	603.30	.0153	782.1	.0155	.7506
6	BD1	2.667	.7104	740.2	86290.	166.40	.0149	739.1	.0148	.7093
7	BD2	2.565	.6832	711.9	88930.	132.50	.0143	709.7	.0142	.6811
8	BD3	2.921	.7784	811.1	88530.	272.20	.0163	810.3	.0163	.7777
9	BD4	2.692	.7246	755.0	88630.	164.20	.0151	754.5	.0150	.7242
10	BD5	2.540	.6815	710.1	89530.	280.90	.0141	708.9	.0141	.6804
Mean:		2.713	.7274	757.9	87950.	328.70	.0148	747.0	.0151	.7170
Standard Deviations:		.113	.0317	33.0	1120.	209.70	.0012	49.0	.0006	.0470
Minimum:		2.540	.6815	710.1	86180.	98.68	.0120	642.1	.0141	.6162
Maximum:		2.921	.7784	811.1	89530.	642.10	.0163	810.3	.0163	.7777

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units,Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 03 Feb 1993
Sample Identification: CD-D	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3800	2.3800	2.3800	2.3800	2.3800	2.3800	2.3800	2.3800
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (Kil)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (Kil)
1	CC1	2.896	.7442	785.2	83690.	162.80	.0162	782.6	.0162	.7418
2	CC2	2.769	.7042	742.9	84010.	154.60	.0155	742.4	.0155	.7036
3	CC3	2.565	.6321	666.9	81830.	192.50	.0143	665.7	.0143	.6309
4	CC4	2.921	.7469	788.0	85640.	110.40	.0163	787.3	.0163	.7462
5	CC5	2.616	.6797	717.1	86900.	218.90	.0147	715.1	.0146	.6778
6	CD1	2.845	.7313	771.6	85850.	101.90	.0159	769.5	.0159	.7293
7	CD2	2.997	.7611	803.0	82940.	57.32	.0167	801.4	.0166	.7576
8	CD3	2.489	.6268	661.3	83430.	260.40	.0139	659.8	.0139	.6254
9	CD4	2.794	.7211	760.8	85870.	729.30	.0156	729.3	.0156	.6912
10	CD5	2.642	.6961	734.5	86860.	158.10	.0148	732.7	.0148	.6945
Mean:		2.753	.7043	743.1	84700.	214.60	.0154	738.6	.0154	.7000
Standard Deviations:		.168	.0466	49.2	1749.	190.10	.0009	48.8	.0009	.0462
Minimum:		2.489	.6268	661.3	81830.	57.32	.0139	659.8	.0139	.6254
Maximum:		2.997	.7611	803.0	86900.	729.30	.0167	801.4	.0166	.7576

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 76-30

Point Compressive Test-S.I. Units-Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.16
	Test Date: 04 Feb 1993
Sample Identification: DC-0	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4500	2.4500	2.4500	2.4500	2.4500	2.4500	2.4500	2.4500
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	DC1	2.515	.6788	695.7	85420.	616.6	.0126	695.6	.0141	.6786
2	DC2	2.565	.6739	690.7	84850.	326.6	.0143	689.0	.0142	.6723
3	DC3	2.515	.6672	683.9	84850.	277.2	.0141	680.7	.0141	.6641
4	DC4	2.489	.6610	677.5	84610.	579.4	.0120	676.7	.0139	.6602
5	DC5	2.464	.6557	672.0	84720.	566.2	.0138	592.0	.0151	.5776
6	DD1	2.261	.5916	606.4	81740.	501.6	.0127	501.6	.0127	.4893
7	DD2	2.337	.6174	632.8	83390.	430.0	.0131	631.4	.0130	.6161
8	DD3	2.515	.6610	677.5	84090.	205.6	.0141	675.9	.0140	.6595
9	DD4	2.413	.6241	639.7	83300.	401.1	.0135	637.1	.0134	.6216
10	DD5	2.413	.6205	636.0	82600.	350.5	.0135	636.1	.0135	.6206
mean:		2.449	.6451	661.2	83560.	425.5	.0133	641.6	.0138	.6260
standard deviation:		.094	.0293	30.1	1169.	138.3	.0008	59.0	.0007	.0576
minimum:		2.261	.5916	606.4	81740.	205.6	.0120	501.6	.0127	.4893
maximum:		2.565	.6788	695.7	85420.	616.6	.0143	695.6	.0151	.6786

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 76-30

2 Point Compressive Test-5.1. Units: Raw Data

Test type: Compressive

Operator name: CHAFFEY

Sample Identification: EC-D

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Crosshead Speed (mm/min): 1.270

Instron Corporation

Series IX Automated Materials Testing System 1.08

Test Date: 04 Feb 1993

Sample Type: ASTM

Humidity (%): 50

Temperature (deg. F): 73

REQUESTOR: DAN CHAFFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens. 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	EC1	2.997	.7179	770.4	82040.	21.02	.0167	768.0	.0167	.7157
2	EC2	3.099	.7718	828.2	84530.	36.95	.0173	825.7	.0173	.7494
3	EC3	3.048	.7571	812.4	84630.	34.31	.0171	811.6	.0170	.7563
4	EC4	3.069	.7749	831.5	84370.	41.94	.0173	829.9	.0173	.7734
5	EC5	3.073	.7624	818.2	84580.	25.38	.0171	817.4	.0171	.7617
6	ED1	3.200	.7718	828.2	82640.	815.70	.0176	827.2	.0178	.7708
7	ED2	2.972	.7482	802.9	85900.	19.60	.0166	802.4	.0166	.7477
8	ED3	2.946	.7420	756.2	85490.	37.00	.0165	794.8	.0165	.7406
9	ED4	3.156	.7971	855.4	84830.	31.15	.0176	854.7	.0176	.7965
10	ED5	3.277	.8247	885.0	85190.	869.70	.0180	884.6	.0183	.8247
Means		3.086	.7668	822.7	84420.	193.30	.0172	821.6	.0172	.7656
Standard Deviations:		.193	.0295	31.7	1200.	342.60	.0005	32.1	.0006	.0299
Minimum:		2.946	.7179	770.4	82040.	19.60	.0165	768.0	.0165	.7157
Maximum:		3.277	.8247	885.0	85190.	869.70	.0180	884.6	.0183	.8247

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

Joint Compressive Test-5.1. units: Raw Data

Test type: Compressive

Operator name: CHAFFEY

Sample Identification: FC-0

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Crosshead Speed (mm/min): 1.270

Instron Corporation

Series IX Automated Materials Testing System 1.08

Test Date: 04 Feb 1993

Sample Type: ASTM

Humidity (%): 50

Temperature (deg. F): 73

REQUESTOR: DWM CHAFFEY

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3600	2.3600	2.3600	2.3600	2.3600	2.3600	2.3600	2.3600
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (kN)	Stress at Max. Load (MPa)	Modulus (Autotuning) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	FC1	2.591	6441	685.3	82820.	145.00	.0145	683.3	.0144	6424
2	FC2	2.464	6147	654.1	84620.	638.40	.0137	638.4	.0137	6000
3	FC3	2.591	6499	691.5	85120.	240.80	.0145	689.7	.0144	6482
4	FC4	2.616	6606	702.9	83570.	161.00	.0147	700.2	.0146	6581
5	FC5	2.616	6628	705.2	84650.	312.00	.0145	704.8	.0145	6624
6	FD1	2.946	7437	791.4	85650.	71.47	.0164	790.4	.0164	7425
7	FD2	2.718	6810	724.6	84980.	117.30	.0152	722.9	.0152	6794
8	FD3	2.870	7262	774.8	86130.	182.40	.0161	772.7	.0160	7262
9	FD4	2.946	7445	797.5	85530.	73.10	.0164	797.0	.0164	7491
10	FD5	2.794	7166	762.3	83480.	193.90	.0156	761.0	.0156	7152
Mean:		2.715	6851	729.0	84850.	213.00	.0152	726.1	.0151	6824
Standard Deviation:		.167	.0465	49.4	1003.	166.30	.0009	52.2	.0009	6491
Minimum:		2.464	6147	654.1	82820.	71.47	.0137	638.4	.0137	6000
Maximum:		2.946	7445	797.5	86130.	638.40	.0164	797.0	.0164	7491

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive

Instron Corporation

Operator name: CHAFEY

Series IX Automated Materials Testing System 1.08

Test Date: 06 Feb 1993

Sample Identification: GC-0

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (Avg Young) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	GC1	2.413	.6081	633.6	81110.	277.4	.0135	631.6	.0135	.6061
2	GC2	2.083	.5342	556.6	82260.	290.0	.0117	554.7	.0116	.5324
3	GC3	2.235	.5671	590.9	82850.	139.6	.0125	587.8	.0124	.5642
4	GC4	2.362	.6041	629.4	82820.	162.4	.0132	628.8	.0132	.6035
5	GC5	2.362	.6072	632.7	82580.	532.8	.0132	532.8	.0132	.5306
6	GD1	2.337	.5916	616.4	80490.	239.4	.0131	614.4	.0130	.5897
7	GD2	2.438	.6219	648.0	83780.	179.3	.0136	646.0	.0135	.6209
8	GD3	2.616	.6721	700.3	83950.	192.3	.0146	698.8	.0146	.6706
9	GD4	2.413	.6076	633.1	83000.	184.0	.0134	632.6	.0134	.6071
10	GD5	2.362	.5943	619.2	81610.	219.4	.0132	617.4	.0131	.5925
Mean:		2.362	.6008	626.0	82460.	243.7	.0132	616.5	.0132	.5917
Standard Deviations:		.138	.0355	37.0	1137.	118.9	.0008	43.4	.0009	.0417
Minimum:		2.083	.5342	556.6	80490.	139.6	.0117	552.8	.0116	.5306
Maximum:		2.616	.6721	700.3	83780.	532.8	.0146	698.8	.0146	.6706

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units-Raw Data

Test type: Compressive

Instron Corporation

Series 1A Automated Materials Testing System 1.05

Test Date: 06 Feb 1993

Operator name: CHAFFEY

Sample Identification: MC-0

Sample Type: ASTM

Interface Type: 450V Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR: DWN CHAFFEY

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4600	2.4600	2.4600	2.4600	2.4600	2.4600	2.4600	2.4600
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Flatten Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (kN)	Stress at Max.Load (MPa)	Modulus (Autotung) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	MC1	2.464	.6672	681.1	86720.	448.6	.0137	678.2	.0136	.6644
2	MC2	2.337	.6343	647.5	86090.	266.3	.0131	646.9	.0131	.6337
3	MC3	2.413	.6610	674.7	87720.	190.5	.0133	671.3	.0133	.6577
4	MC4	2.261	.6170	629.8	87710.	332.8	.0126	628.6	.0126	.6158
5	MC5	2.337	.6365	649.8	87250.	283.6	.0131	647.0	.0130	.6353
6	MD1	2.438	.6423	655.7	86900.	209.2	.0136	653.6	.0135	.6403
7	MD2	2.540	.6752	689.3	86630.	130.2	.0142	687.6	.0141	.6776
8	MD3	2.464	.6574	671.1	85400.	378.2	.0137	670.2	.0137	.6566
9	MD4	2.489	.6735	687.5	87620.	259.3	.0139	686.0	.0139	.6721
10	MD5	2.388	.6352	648.4	85440.	337.4	.0133	646.8	.0132	.6336
Mean:		2.413	.6500	663.5	86750.	285.8	.0135	661.6	.0134	.6482
Standard Deviation:		.084	.0196	20.0	874.	95.7	.0005	19.8	.0005	.0174
Minimum:		2.261	.6170	629.8	85400.	130.2	.0126	628.6	.0126	.6156
Maximum:		2.540	.6752	689.3	87720.	448.8	.0142	687.6	.0141	.6776

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 76-30

3 Point Compressive Test-S.I. units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFE	Series IX Automated Materials Testing System 1.05
	Test Date: 06 Feb 1993
Sample Identification: MC-0	Sample Type: ASTM
Interface Type: 450v Series	
Machine Parameters of test:	
Sample Rate (c/s/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR: DWM CHAFE

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Flatten Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (Aurtrough) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	MC1	2.657	.6619	710.3	84080.	316.40	.0149	709.8	.0149	.6614
2	MC2	2.743	.6984	749.4	86450.	10.20	.0154	747.7	.0153	.6965
3	MC3	2.972	.7388	792.9	84750.	25.34	.0160	791.2	.0165	.7375
4	MC4	2.464	.6099	654.4	83700.	111.80	.0137	652.7	.0137	.6083
5	MC5	2.794	.6825	732.7	83100.	36.09	.0157	732.0	.0156	.6821
6	MD1	2.870	.7117	763.8	84800.	297.70	.0161	761.5	.0160	.7096
7	MD2	2.794	.7050	750.0	86780.	422.30	.0156	754.4	.0156	.7030
8	MD3	3.023	.7477	802.4	84260.	47.26	.0169	801.1	.0169	.7465
9	MD4	2.890	.7322	785.7	85440.	28.36	.0162	782.0	.0161	.7293
10	MD5	2.591	.6441	691.2	82210.	76.88	.0145	689.0	.0145	.6420
Mean:		2.751	.6933	743.9	84560.	137.20	.0156	742.2	.0155	.6916
Standard Deviation:		.172	.0441	47.4	1419.	149.90	.0010	47.2	.0010	.0440
Minimum:		2.464	.6099	654.4	82210.	10.20	.0137	652.7	.0137	.6093
Maximum:		3.023	.7477	802.4	86780.	422.30	.0169	801.1	.0169	.7465

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units-Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.06
	Test Date: 09 Feb 1993
Sample Identification: NC-D	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR DAN CHAFEY

Dimensions:	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3500	2.3500	2.3500	2.3500	2.3500	2.3500	2.3500	2.3500
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max.Load (mm)	Load at Max.Load (KN)	Stress at Max.Load (MPa)	Modulus (Autyoung) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	NC1	2.616	.6405	684.5	82800.	217.7	.0146	684.5	.0146	.6405
2	NC2	2.591	.6339	677.3	82640.	244.4	.0145	676.5	.0144	.6331
3	NC3	2.667	.6566	701.6	82720.	233.7	.0148	698.9	.0148	.6541
4	NC4	2.845	.6988	746.7	84470.	300.6	.0158	745.7	.0158	.6978
5	NC5	2.489	.6112	653.1	82740.	246.2	.0140	651.0	.0139	.6093
6	ND1	2.489	.6219	664.5	83040.	140.0	.0140	662.1	.0139	.6196
7	ND2	2.642	.6506	695.4	82750.	119.5	.0147	692.9	.0146	.6464
8	ND3	2.591	.6343	677.8	80810.	588.1	.0126	675.4	.0144	.6321
9	ND4	2.667	.6481	692.5	83530.	243.4	.0148	691.5	.0148	.6471
10	ND5	2.718	.6668	712.5	84390.	253.9	.0151	709.6	.0150	.6640
Mean:		2.631	.6465	690.6	82990.	258.7	.0145	688.8	.0146	.6446
Standard Deviation:		.105	.0246	26.3	1029.	127.6	.0009	26.4	.0006	.0247
Minimum:		2.489	.6112	653.1	80810.	119.5	.0126	651.0	.0139	.6093
Maximum:		2.845	.6988	746.7	84470.	588.1	.0158	745.7	.0158	.6978

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive

Instron Corporation
Series IX Automated Materials Testing System 1.08
Test Date: 09 Feb 1993

Operator name: CHAFEE

Sample Type: ASTM

Sample Identification: OC-0

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (ots/sec): 10.00

Humidity (%): 50

Crosshead Speed (mm/min): 1.270

Temperature (deg. F): 73

REQUESTOR DAN CHAFEE

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	OC1	2.388	.5818	624.4	81340.	532.20	.0115	500.5	.0141	.4664
2	OC2	2.591	.6325	678.8	82600.	231.00	.0145	677.0	.0145	.6308
3	OC3	2.642	.6503	697.9	84260.	306.10	.0148	695.7	.0147	.6483
4	OC4	2.489	.6183	663.5	84450.	233.20	.0139	662.5	.0139	.6174
5	OC5	2.642	.6552	703.1	85430.	268.00	.0147	702.4	.0147	.6546
6	OD1	2.743	.6646	713.2	83020.	116.10	.0154	713.3	.0154	.6647
7	OD2	2.438	.5978	641.6	83110.	242.00	.0136	638.5	.0136	.5950
8	OD3	2.642	.6414	688.3	83120.	91.92	.0148	688.0	.0148	.6411
9	OD4	2.362	.5818	624.4	81540.	482.20	.0103	571.4	.0153	.5325
10	OD5	2.667	.6499	697.4	83130.	314.90	.0149	695.8	.0148	.6484
Mean:		2.560	.6274	673.3	83200.	281.80	.0138	654.5	.0146	.6099
Standard Deviation:		.131	.0308	33.0	1260.	139.30	.0017	68.1	.0006	.0624
Minimum:		2.362	.5818	624.4	81340.	91.92	.0103	500.5	.0136	.4664
Maximum:		2.743	.6646	713.2	85430.	532.20	.0154	713.3	.0154	.6647

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units-Raw Data

Test type: Compressive

Franken Corporation
Series IX Automated Materials Testing System LWB
Test Date: 09 Feb 1992

Tested Part: C-40

Sample type: RETH

Sample Identification: PC-0

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (Hz): 10.00
Crosshead Speed (mm/min): 1.250

Humidity (%): 5
Temperature (deg. F): 73

REQUESTOR: DWA (HAFB)

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100	2.4100
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (kN)	Stress at Max. Load (MPa)	Modulus (Autotough) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	PC1	2.515	.6272	653.5	81730.	291.4	.0140	652.7	.0140	.6265
2	PC2	2.515	.6389	665.6	82940.	335.5	.0141	648.3	.0162	.6222
3	PC3	2.413	.6174	643.3	82190.	562.2	.0135	562.2	.0135	.5395
4	PC4	2.438	.6272	653.5	82360.	465.8	.0098	650.9	.0136	.6247
5	PC5	2.642	.5747	598.8	79830.	498.0	.0122	596.7	.0147	.5726
6	PD1	2.515	.6272	653.5	81680.	333.3	.0140	650.0	.0140	.6238
7	PD2	2.413	.6072	632.7	83610.	235.8	.0135	631.9	.0135	.6064
8	PD3	2.667	.6846	713.3	84330.	194.5	.0150	711.3	.0149	.6826
9	PD4	2.565	.6666	696.6	85480.	298.4	.0144	693.9	.0143	.6660
10	PD5	2.413	.6147	640.5	82690.	348.1	.0134	637.8	.0134	.6121
Mean:		2.510	.6288	655.1	82620.	378.3	.0134	643.6	.0142	.6177
Standard Deviations:		.093	.0308	32.1	1529.	132.6	.0014	42.6	.0009	.0409
Minimums:		2.413	.5747	598.8	79830.	194.5	.0098	562.2	.0134	.5395
Maximums:		2.667	.6846	713.3	85480.	562.2	.0150	711.3	.0162	.6826

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-5.1. Units: Raw Data

Test type: Compressive

Operator name: CHAFE

Sample Identification: QC-0

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00
Crosshead Speed (mm/min): 1.270

Instron Corporation

Series IX Automated Materials Testing System 1.08

Test Date: 10 Feb 1973

Sample Type: ASTM

Humidity (%): 50

Temperature (deg. F): 73

REQUESTOR: DRN CHAFER

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4800	2.4800	2.4800	2.4800	2.4800	2.4800	2.4800	2.4800
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.
Sample comments: 0.16% FEP

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (GPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (N)
1	QC1	2.413	.0170	624.7	80670.	545.5	.0118	515.7	.0140	5693
2	QC2	2.616	.0148	703.5	84010.	331.2	.0146	702.9	.0146	6942
3	QC3	2.489	.0597	667.9	82630.	365.2	.0139	666.7	.0138	6584
4	QC4	2.489	.0601	668.4	83360.	496.9	.0139	542.0	.0151	5752
5	QC5	2.505	.0846	693.2	83560.	354.1	.0144	672.6	.0144	6640
6	QD1	2.515	.0598	667.0	82190.	331.9	.0141	667.2	.0141	6589
7	QD2	2.505	.0921	700.8	84650.	387.8	.0143	699.5	.0143	6968
8	QD3	2.464	.0566	664.8	83890.	352.3	.0137	663.9	.0137	6557
9	QD4	2.645	.0546	663.0	83980.	556.0	.0135	660.8	.0159	6557
10	QD5	2.642	.0728	711.6	82670.	247.1	.0147	710.7	.0147	7915
Mean:		2.500	.0601	676.5	83160.	396.7	.0139	652.2	.0145	6441
Standard Deviation:		.122	.0256	26.0	1155.	101.9	.0008	67.7	.0007	7.007
Minimum:		2.413	.0170	624.7	80670.	247.1	.0118	515.7	.0137	5693
Maximum:		2.645	.0728	711.6	84650.	556.0	.0147	710.7	.0159	7915

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

Point Compressive Test-S.I. Units-Raw Data

Test type:	Compressive	Instron Corporation
Operator name:	CHAFE	Series 11 Automated Materials Testing System 1108
		Test Date: 10 Feb 1973
Sample Identification:	RC-0	Sample Type: ASTM
Interface Type:	4500 Series	
Machine Parameters of test:		
Sample Rate (pts/sec):	10.00	Humidity (%): 50
Crosshead Speed (mm/min):	1.270	Temperature (deg. F): 73

REQUESTOR: DAN CHAFE

Dimensions:

	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400	2.3400
Spec gauge (in (mm))	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Sample comments: ON FEF, FILL DIRECTION SAMPLES

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (Autotung) (MPa)	Stress at offset yield 1 (MPa)	Strain at offset yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	RC1	3.200	.7673	823.4	81930.	811.00	.0176	822.9	.0178	.7668
2	RC2	3.200	.7762	854.5	84310.	24.21	.0179	853.4	.0179	.7952
3	RC3	3.251	.7976	855.9	84020.	813.00	.0173	854.3	.0182	.7961
4	RC4	3.251	.8158	875.5	85640.	48.67	.0181	873.3	.0181	.8158
5	RC5	3.200	.8082	867.3	86340.	828.00	.0171	864.8	.0179	.8059
6	RD1	3.277	.8434	905.1	86960.	24.29	.0182	904.6	.0182	.8430
7	RD2	3.124	.8033	862.1	85200.	23.92	.0175	859.1	.0174	.8005
8	RD3	2.997	.7713	827.7	87340.	48.83	.0167	826.9	.0167	.7705
9	RD4	3.099	.7940	852.1	85730.	109.70	.0173	849.0	.0172	.7912
10	RD5	3.277	.8338	896.5	86190.	134.20	.0182	893.6	.0181	.8027
Mean:		3.188	.8033	862.0	85370.	286.70	.0176	860.2	.0178	.8016
Standard Deviations:		.090	.0243	26.1	1600.	368.20	.0005	25.8	.0005	.0240
Minimum:		2.997	.7673	823.4	81930.	23.92	.0167	822.9	.0167	.7668
Maximum:		3.277	.8434	905.1	87340.	828.00	.0182	904.6	.0182	.8430

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive

Instron Corporation
Series IX Autocoated Materials Testing System 1.06
Test Date: 11 Feb 1993

Operator name: CHAFER

Sample Identification: SC-D

Sample Type: ASTM

Interface Type: 4500 Series

Machine Parameters of test:

Sample Rate (pts/sec): 10.00
Crosshead Speed (mm/min): 1.270

Humidity (%): 50
Temperature (deg. F): 73

REQUESTOR DAN CHAFER

Dimensions:

Spec. 1 Spec. 2 Spec. 3 Spec. 4 Spec. 5 Spec. 6 Spec. 7 Spec. 8

Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700	2.3700
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.

Sample comments: 2.18% FEF, FILL DIRECTION SAMPLES

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (KN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (KN)
1	SC1	2.464	.6259	663.1	81810.	257.9	.0138	662.8	.0138	.6256
2	SC2	2.616	.6588	698.0	83080.	170.0	.0146	694.8	.0145	.6557
3	SC3	2.642	.5689	602.8	80080.	497.9	.0122	600.5	.0147	.5667
4	SC4	2.413	.6085	644.7	83110.	264.2	.0135	642.4	.0134	.6063
5	SC5	2.743	.6993	740.9	88000.	268.6	.0153	738.8	.0152	.6973
6	SD1	2.769	.7050	747.0	86520.	192.3	.0155	743.9	.0154	.7021
7	SD2	2.591	.6508	689.5	82410.	305.0	.0144	689.0	.0144	.6503
8	SD3	2.972	.7477	792.3	85060.	663.7	.0165	663.7	.0165	.6264
9	SD4	2.645	.7255	768.7	85870.	170.8	.0159	767.1	.0159	.7240
10	SD5	2.616	.6650	704.6	86910.	386.0	.0146	703.3	.0146	.6638
Mean:		2.667	.6655	705.2	84290.	317.6	.0146	690.6	.0148	.6518
Standard Deviation:		.169	.0555	58.5	2560.	158.1	.0013	50.7	.0009	.0479
Minimum:		2.413	.5689	602.8	80080.	170.0	.0122	600.5	.0134	.5667
Maximum:		2.972	.7477	792.3	88000.	663.7	.0165	767.1	.0165	.7240

APPENDIX A: INSTRUMENTED MECHANICAL TEST DATA FOR ALL SPECIMENS (continued)

LOCKHEED MISSILES & SPACE CO.
MATERIALS & PROCESSES ENGINEERING
DEPT. 78-30

3 Point Compressive Test-S.I. Units, Raw Data

Test type: Compressive	Instron Corporation
Operator name: CHAFEY	Series IX Automated Materials Testing System 1.08
	Test Date: 12 Feb 1993
Sample Identification: TC-D	Sample Type: ASTM
Interface Type: 4500 Series	
Machine Parameters of test:	
Sample Rate (pts/sec): 10.00	Humidity (%): 50
Crosshead Speed (mm/min): 1.270	Temperature (deg. F): 73

REQUESTOR: DAN CHAFEY

Dimensions:	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Spec. 6	Spec. 7	Spec. 8
Width (mm)	12.700	12.700	12.700	12.700	12.700	12.700	12.700	12.700
Thickness (mm)	2.4300	2.4300	2.4300	2.4300	2.4300	2.4300	2.4300	2.4300
Spec gauge len (mm)	50.800	50.800	50.800	50.800	50.800	50.800	50.800	50.800
Platen Separ. (mm)	101.60	101.60	101.60	101.60	101.60	101.60	101.60	101.60

Out of 10 specimens, 0 excluded.
Sample comments: 4.08% FEP, FILL DIRECTION SAMPLES

Specimen Number	ID:	Displacement at Max. Load (mm)	Load at Max. Load (kN)	Stress at Max. Load (MPa)	Modulus (AutYoung) (MPa)	Stress at offset Yield 1 (MPa)	Strain at offset Yield 1 (mm/mm)	Stress at user Break (MPa)	Strain at user Break (mm/mm)	Load at user Break (kN)
1	TC1	2.413	.6325	653.0	84050.	381.5	.0135	544.1	.0194	.5265
2	TC2	2.362	.6241	644.9	84550.	369.2	.0132	535.0	.0190	.5178
3	TC3	2.642	.6997	723.1	86460.	266.5	.0147	719.0	.0146	.6764
4	TC4	2.692	.7211	745.1	86470.	377.1	.0150	745.0	.0150	.7209
5	TC5	2.515	.6939	717.1	87790.	524.9	.0141	714.2	.0140	.6912
6	TD1	2.616	.6961	719.4	86960.	462.7	.0147	717.2	.0146	.6941
7	TD2	2.607	.7148	738.7	86370.	261.7	.0149	737.2	.0149	.7134
8	TD3	2.616	.6917	714.8	88010.	216.6	.0146	713.5	.0146	.6904
9	TD4	2.388	.6179	638.5	83040.	579.3	.0122	636.2	.0133	.6150
10	TD5	2.515	.6583	680.3	84330.	242.8	.0141	677.4	.0140	.6553
Mean:		2.543	.6750	697.5	85820.	368.2	.0141	673.9	.0153	.6522
Standard Deviation:		.122	.0385	39.8	1722.	124.1	.0009	77.3	.0021	.0748
Minimum:		2.362	.6179	638.5	83040.	216.6	.0122	535.0	.0133	.5178
Maximum:		2.692	.7211	745.1	88010.	579.3	.0150	745.0	.0194	.7209