EFFECT OF PULLOUT AND TORSIONAL STRENGTH OF COMPOSITES WITH CO-MOLDED THREAD INSERTS

by

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Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
AUGUST 2008

ACKNOWLEDGEMENTS

In support of furthering my academic education and providing unconditional love throughout the long and tedious masters degree program, my wife Christy is the first and foremost person to be recognized. You are an angel and I love you “my heart”.

My graduate advisor, Dr. Wen Chan, provided me with a plethora of knowledge towards the topic at hand and gave me guidance through out the academic process.

Two colleagues from Bell Helicopter that helped me immensely throughout the thesis process are Dr. Ben Chiou and Mr Ed Lee. Dr. Ben Chiou helped me understand phenomenons that I was seeing in my data gathering and Mr. Ed Lee helped me understand and quantify composite fiber waviness behaviors. I appreciate the time both of you spent with me and I thank you.

July 22, 2008

ABSTRACT

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Rotorcraft transmission housings and drive system components are typically made from cast metals due to their highly complex geometries. Utilizing composite materials offers potential to reduce weigh and manufacturing cost while increasing corrosive resistance and extending part life. Traditional compression molded composites have not been utilized in aerospace because they typically experience low fiber volume fraction. Currently there are numerous materials which offer opportunities for composites in drive system housing applications and also offer the ability to co-mold details to reduce post mold operations.

One of the issues associated with composite structures is the ability to fasten them to one another and to metallic structures because of issues concerning corrosion. Directly threading homogeneous materials, such as aluminum, produces strong threads; however, non-homogeneous based materials such as carbon fibrous composites raise concern about permanently damaging the structure or not providing enough holding strength to maintain structural integrity. Co-molding metallic inserts into a composite structure not only reduce part labor costs, but could also eliminate much of the thread strength concerns because thread shear is transferred through the homogeneous material. Unlike composite machining operations, there is no localized damage to the material. Co-molding inserts into composite structures has been done using processes such as Resin Transfer Molding (RTM) but the process comes with challenges.

This thesis intends to experimentally observe composite fiber behavior associated with co-molded insert geometry and the effects on mechanical strengths, namely torsion and pullout. Co-molding processes often induce fiber waviness. The presence of fiber waviness reduces structural stiffness, strength and fatigue life. The lack of a mechanical strength database associated with co-molded inserts in composite molding compounds leads to a comparison with co-molded continuous fiber specimens and traditional tapped laminates. The measures of success for co-molded inserts in composite compression molded panels include pullout and torsional strength compared to the continuous fiber traditional materials specimen with embedded inserts.

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LIST OF ABBREVIATIONS AND SYMBOLS

Term	
Bulk Molding Compound	BMC
Compression Molding Compound	CMC
Finite Element Model	FEM
General Linear Model	GLM
Long Fiber Injection	LFI
Resin Injection Molding	RTM
Resin Transfer Molding	RTM
Sheet Molding Compound	SMC
Structural Reaction Injection Molding	SRIM

CHAPTER 1

INTRODUCTION

Drive system components in rotorcraft applications are often highly dimensionally complex, contain tight tolerance bearing race surfaces, cored passages, o-ring seal grooves, threads and/or bushings and are exposed to corrosive environments. Parts are often made of cast metallic such as aluminum or magnesium, and then machined in tight tolerance areas. Composites offer benefits over metallics such as reduction in weight, cost, and corrosive resistance as well as an increase in stiffness with reduced density as shown in figure 1.1. Utilizing a net molding process such as composite compression molding, further reduction in overall part cost is accomplished by eliminating a significant amount of post bond machining since the parts are produced to a net shape. Post machining operations like drilling, boring of holes and removing flashing can also cause localized damage to the material. The part count can also be minimized within a given assembly if bolted joints can be eliminated. The compression molding process also can produce parts at much faster production since cure times are a few hours rather than tens of hours like traditional autoclave cured parts.

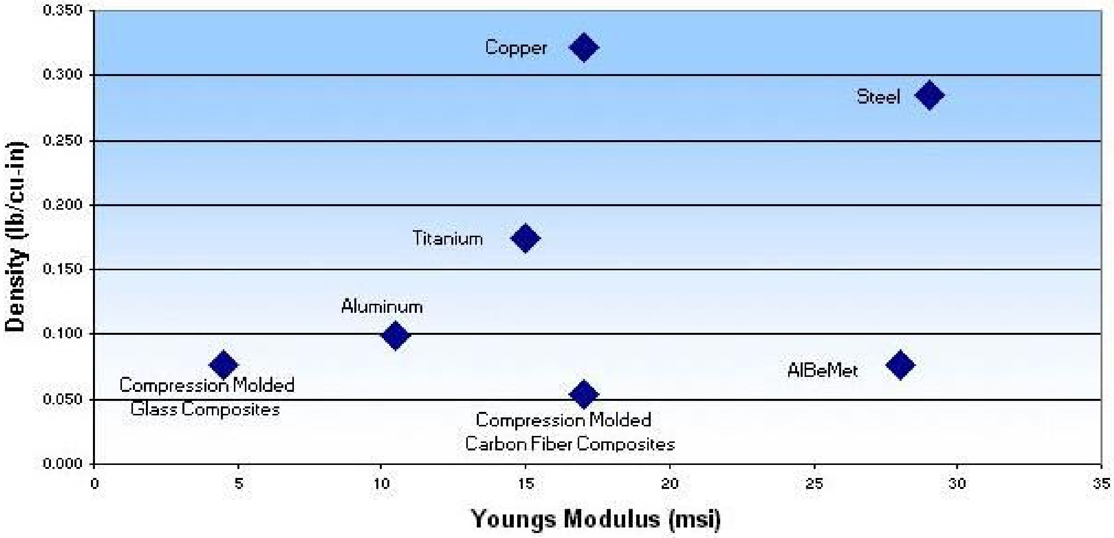


Figure 1.1- Density vs. Stiffness for Various Materials

This research focuses on the co-molding of threaded inserts into a high flow carbon/epoxy composite molding compound. The interaction between the high flow resin and fiber flow of new Sheet Molding Compounds (SMC) with co-molded threaded inserts is correlated to insert pullout strength, torsional strength and laminate fiber waviness which is important for design. The objective of this experiment is to understand the behavioral aspects of fiber distortion and insert geometry as related to mechanical properties of co-molded inserts.

In traditional composite laminates, fiber waviness induces reduced strength, stiffness and fatigue life characteristics. With the randomness of SMC fiber orientation and molding process in fabrication, it is necessary to experimentally examine the effects of fiber waviness on mechanical strength in order to understand the effects of such defects. A study in the area of co-molded insert strength as related to composite materials is the first of its kind.

The co-molded details in such composite specimens will be subjected to both pullout and torsional loading conditions. One goal is to create a General Linear Model for the experimental mechanics characterized by the test parameters. A General Linear Model (GLM) is used to perform univariate analysis of variance with balanced and unbalanced designs, analysis of covariance, and regression for each response variable. Calculations are done using an ANOVA regression approach. An ANOVA or Analysis of Variance [1] is a collection of statistical models and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables.

1.1 Literature Survey and Molding Compounds

The structural demands of composites in the aerospace industry often drive the use of continuous fiber reinforcements such as fabrics, tapes, and roving with epoxy resin systems. Continuous fibers do not lend themselves well to complex geometries because of their low drape-ability. Sheet Molding Compounds or SMCs are short fiber composite materials in a sheet form consisting of randomly oriented chopped fibers and thermoset resin systems. Therefore, Sheet Molding Compounds are often used in parts with highly complex geometry. Typical thickness of a single SMC compound is comparable to 16 to 20 layers of uni-directional pre-preg tape or around .100" thick. Current molding compounds have characteristics of traditional materials in that they lend themselves well to cost effective composite manufacturing. Since process yields can be very high and due to their ability for fiber and resin flow, post molding operations such as machining can be reduced.

The typical compression molding process of composites starts with placing the material into a cavity of the desired part shape. The mold is usually pre-heated by platens and then closed by a hydraulic ram. Sheet molding compound (SMC) are then conformed to the mold shape by the applied pressure and heated until the curing reaction occurs. Heat and pressure are maintained until the molding material has cured. If more complex geometries are to be molded, the sheet molding compounds are usually pre-cut to conform to the surface area of the mold. This process is critical depending on part geometry. More traditional layup processes for composites use material can be in the form of unidirectional tape, woven fabrics, randomly oriented fiber mat or chapped strand.

Consistently manufacturing parts from a SMC method involves understanding and predicting forces during the compression molding process. Such forces are functions of ram speed, tool gap, material resistance, etc. Understanding fiber flow as a function of time and distance is very important in these processes. Predictions like those developed by Abrams [2] have been experimentally validated and shown in figure 1.2 for one particular example. In the illustration, C1 and C2 represent the two measured trails. The predicted curve is based on several parameters such as mold closing speed, material viscosity and friction coefficients to name a few.

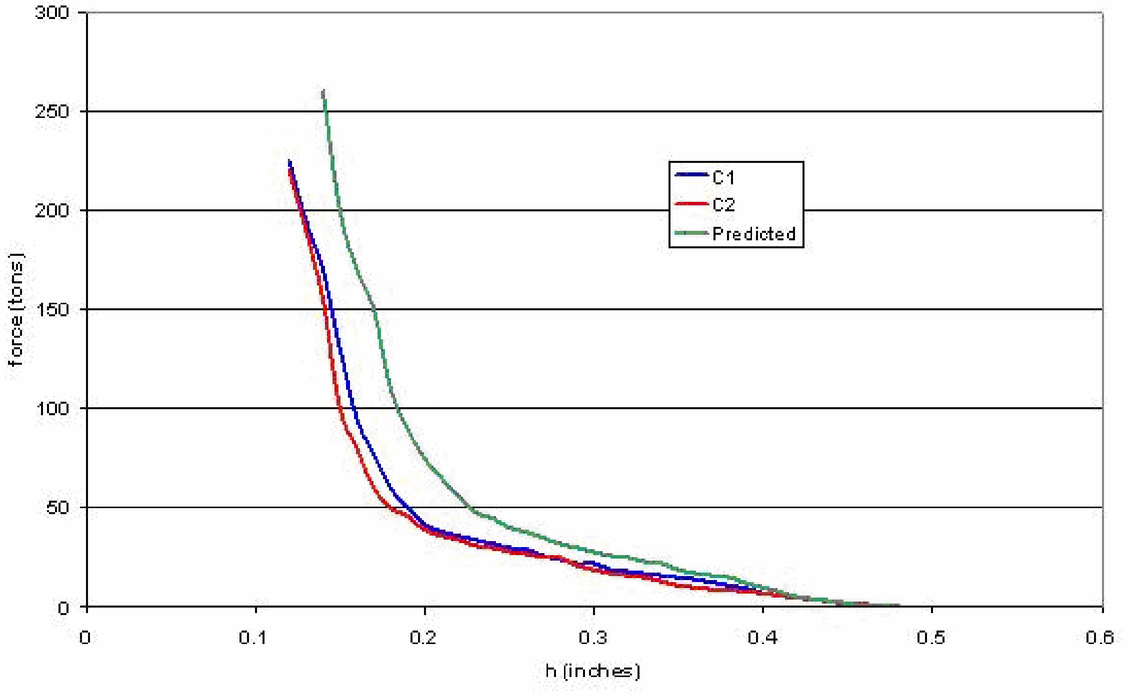


Figure 1.2- Predictions vs. Experimentally-Measured Forces, SMC

The problem associated with such flow predictions is that the flow models examine the material behavior on a global scale since the end goal is to fill a particular mold cavity. These planar models do not consider fiber behavior analysis through the thickness especially around unique part features.

During early modeling, SMC was treated as an isotropic continuum. However, when the mold geometry becomes complicated or has more constraints, the anisotropic nature of SMC causes the flow model to fail. Modifications to Hills [3] anisotropy theory were made and predictions and calculations made as part of the Lin-Weng method [4]. Manufacturers of high-performance components commonly perceive SMC (typically compounded from chopped glass fiber and polyester resin) to be a commodity material, used primarily in nonstructural components. Experienced compression molding vendors have enjoyed some processing latitude when working with conventional glass-reinforced SMC. Conventional SMCs, LFI and SRIM processes feature fiber loading of only 22 to 30 percent by weight, and their polyester resins exhibit favorable flow characteristics.

These new structural grade SMCs are also innovative compression molding materials which have been developed utilizing small 1"x2" sections cut from uni-directional pre-preg tape which are randomly oriented into a mat. Sections can be customized to suit mechanical needs. The mat can then be cut, preformed and placed into a cavity for compression molding. This process solves much of the fiber-distortion and resin control issues associated with traditional forming techniques. Some issues associated with traditional compression molding are controlling fiber orientation, fiber dispersion, high and low fiber volume and consistent resin control through out the part. Advanced molding compounds which have similar molding properties to traditional SMC's now use aerospace pre-pregs instead of dry fibers and resin films which result in performance gains nearly as high as quasi-isotropic laminates. Better resin control reduces cracking and stress concentration since the resin content is lower in pre-pregs than in Bulk Molding Compounds (BMC). The use of pre-pregs can substantially improve performance by providing higher volumes and fibers that are uniformly straight instead of being distorted. Fiber flow predictions do not have to be heavily considered since each lamina layer takes the mold shape with little to no gap between the layer and tooling. These new materials are also compatible with traditional tapes and fabrics because they can use the same resin systems. The advantage here is that thick buildups or tailored stiffness areas can be preformed using traditional pre-preg materials.

Compression molding tends to produce fewer knit lines and less fiber-length degradation than injection molding and can handle more complex geometry than traditional Resin Transfer Molding (RTM). RTM is a process where a performed dry fibers are placed into a closed cavity mold and resin is injected into the mold under very high pressures. RTM parts are typically 5% to 7% heavier than traditional pre-preg materials because the resin content is higher. Tooling costs are higher and resin flow has to be predicted. The RTM process also does not lend itself well to high production rates since cure times are usually much higher unlike compression molding. Like compression molding, RTM also offers net shape molding which reduces labor and machining efforts after the resin has cured. Issues can also arise with resin flow around co-molded inserts and in preventing resin from overflowing out of the closed cavity tool into the threaded inserts [5]. Porosity and lack of resin flow into lower plies can also raise concerns. Other low cost composite manufacturing methods include Long Fiber Injection (LFI) and Structural Reaction Injection Molding (SRIM).

When compared to these other low cost manufacturing alternatives, pre-preg utilization methods tend to cost more per part but can also offer higher structural integrity. Figure 1.3 was observed in a review of a comparative analysis performed in the automotive industry [6]. The material cost for the pre-preg material systems, Hexcel HexMC and Quantum Composites systems are to be considered slightly dated. In the case of the Quantum Composites molding compound, it is important to note that energy, capital costs, and labor are relatively low. The materials used in this study are most like the materials from Quantum Composites as far as expenditure costs are concerned.

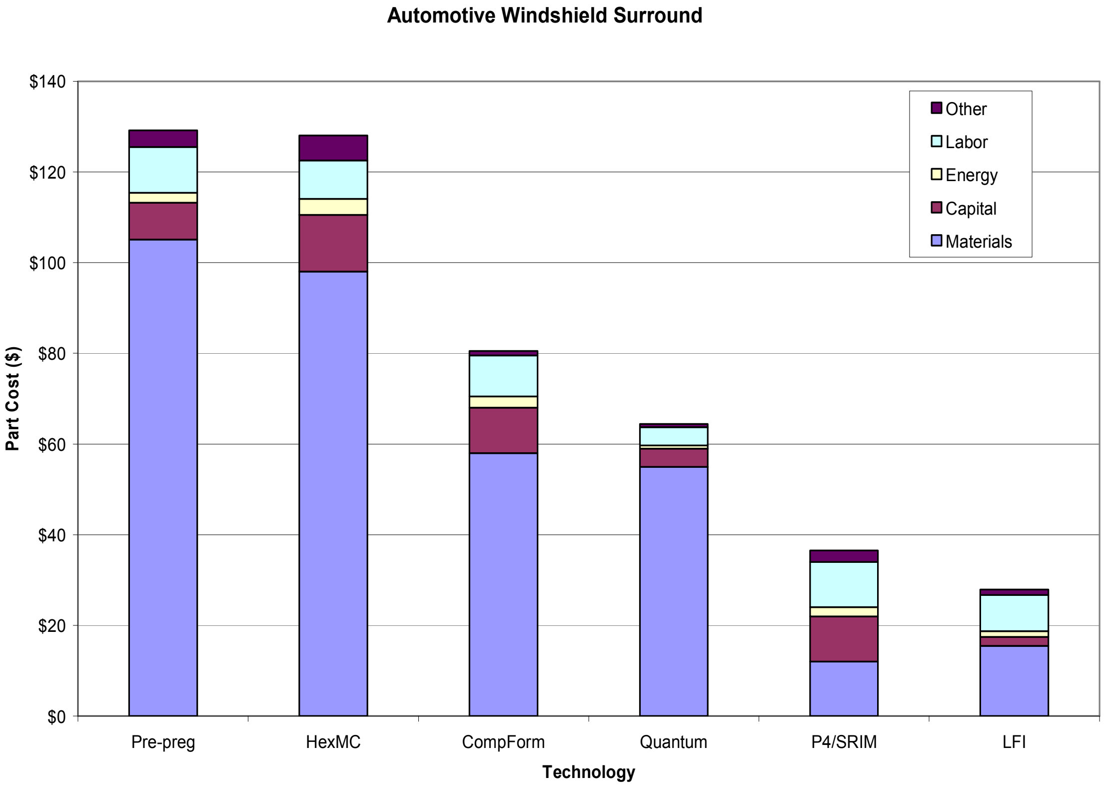


Figure 1.3- Cost Comparative Assessment

Although the SRIM and LFI processes are cheaper they also pose some issues. Long Fiber Injection processes typically use fast-curing two-part polyurethane and glass fibers. Fiber volume fractions have been known to reach 45% however typical fiber volume is around 25% and fiber dispersion is a concern. Structural Resin Injection Molding or SRIM is a process that uses two resin components which are combined and mixed together, then injected into a mold cavity containing reinforcement. In the mold cavity, the resin rapidly reacts and cures to form the composite part. In both instances, performance aerospace applications generally require epoxy resin systems and fiber volume fractions around 55% or higher.

1.2 Traditional Laminate Composites

In order to further reduce cost in each part, machined threads are replaced with co-molded inserts. These compression molded co-molded inserts must comply with the same strength characteristics as the tapped laminates and co-molded inserts embedded within traditional continuous fiber composite materials.

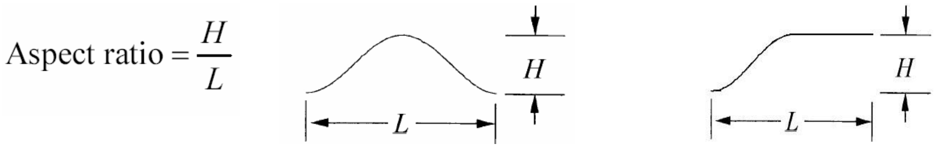
During design of a part, thread pullout and torsional strength are the most common strength parameters. A database for pullout and torsional strength of co-molded details does not currently exist for such a process or is just not available in the public domain. Pullout test data developed in this experiment will be compared to past data generated through threaded quasi-isotropic carbon laminate and EPON 862 resin system made through Resin Transfer Molding (RTM). A second specimen containing molded inserts and traditional uni-directional IM6 carbon pre-preg tape and Hexcel 8552 resin in a quasi-isotropic laminate will also be fabricated.

These specimens are designed to be an extreme points since neither the tapped laminate or continuous fiber specimen is truly representative to a co-molded insert embedded in compression molded composite materials. The torsional data generated will be stand alone since existing data does not exist, but it is hopeful that general trends are shown from which conclusions can be drawn.

1.3 Fiber Waviness

Fiber waviness, or sometimes called fiber distortion, can cause increase local strains and are very similar to typical stress concentration factors in metallic structures such as holes or sharp radii. The difference between metallics and composites is that metals have similar strength characteristics in all directions meaning they are isotropic. Composites on the other hand have strength capabilities that vary significantly in various directions.

Fiber waviness can be in plane or out of plane meaning in the fiber direction or out of fiber direction. When fiber distortions are induced in composite laminates, the strains in resin dominated directions increase significantly [7]. Fiber waviness often leads to degradation in mechanical strength and lower fatigue limits especially in planar situations. Fiber waviness is often found to be a failure initiation spot in a structural part. Laminates with fiber waviness are found to have a reduction in stiffness, strength, natural frequency, fatigue life expectancy and an increase in the deflection in a given direction [8,9]. The severity of fiber waviness both in-plane and out-of-plane is measured by the aspect ratio.



Bell Wave

Step Wave

Figure 1.4- Graphical Representation of Fiber Waviness

Figure 1.4 illustrates the dimensional features which comprise the aspect ratio definition. An example of aspect ratio of .1 means fiber distortion of 0.1 inch in a span of 1 inch. A step wave is used when a fiber path does not follow the typical bell shape.

Analyzing and predicting the behavior of fiber distortions within composites has been widely investigated. Finite Element Models (FEM) which contain fiber distortions have been built to evaluate the sensitivity with respect to thickness and width along with aspect ratio. Most models assume linear behaviors and are based on traditional fabrics and tape lamina [10]. In molding compounds however, the irregularity of the fiber flow and lack of fiber distortion models around co-molded features has lead to experimental mechanics.

Often times in the aerospace community, fiber waviness is separated into classes. Depending on the stress criterion for specific areas within a given part, the classifications and acceptance levels may change [8]. There is no industry standard criterion for classification however companies concerned with such effects on critical part structures often generate test data for which quality control groups can determine accept or reject criteria during inspection.

1.4 Outline of Thesis

The general format of this thesis is separated into three chapters. The first described background research and the subsequent chapters are outlined below.

Chapter two outlines the overall scope of the experimental work including the description of materials used, the specimen configurations and manufacturing methodologies as well as the test setup and procedures.

The third chapter summarizes the results concluded from pullout and torsional testing as well as fiber waviness reviews of several cross-sections. The results of the comparative specimens will also be correlated to test specimens and discussed. Finally a discussion about failure modes typically seen within this application will wrap up chapter three.

The last chapter, four, provides project conclusions, recommendations and directions for further studies.

Following chapter four is an appendix containing detailed analysis pertaining to the statistical analysis and main effects plots for mechanical strength characteristics associated with other molding compounds. Lastly a brief summary of the authors' education and technical background is discussed.

CHAPTER 2

EXPERIMENTAL PROGRAM

The experimental mechanics approach to this set of test methodology is aimed at the preliminary investigation of fiber behaviors around co-molded inserts and the effects on mechanical strength. With all the variables associated with the compression molding process, no computer programs are available to simulate the flow or forming process so test specimens were fabricated. The empirical data acquired with the less expensive trial runs can help to guide modifications to change lamina shapes, detail configurations of co-molded details or tooling approaches and part cure cycles.

2.1 Approach

A compression molded panel was fabricated using a carbon/epoxy based molding compound material from YLA Inc. in Benicia, CA and various unique co-molded embedded inserts from several vendors. Controlled mechanical testing was performed on the co-molded inserts which includes tensile pullout and torsional strength. Each unique insert was analyzed quantifying fiber distortion both before and after mechanical testing. Fiber distortion is analyzed through software specifically designed to quantify aspect ratio based on cross-sectional views.

The aspect ratio for each unique insert was analyzed in three unique sectors around the insert to understand trends in flow characteristics of the molding compound and how they link to insert failure modes. The three sections included one on each side of the insert and one region directly below the insert base.

2.2 Composite Materials Used

The compression molding compound in this study was selected due to its low cost per strength and stiffness. Figures 2.1 and 2.2 illustrate the comparative stiffness and strength differences respectively between other commercially available composite materials. YLA Inc. offers advanced composite materials for performance structural applications and some of their newest materials include hybrid compression molding compounds. One of these hybrid molding compounds is MS-4H which contain T700 fibers (Standard Modulus) with RS56 resin.

YLA can custom tailor the material to meet the needs of specific mechanical or thermal properties. Some of the alternate fibers available for use in YLA molding compounds include HS40 (High Modulus). Alternative resin systems include those similar to Mil Handbook 17 such as 3501-6 minimally toughened epoxy (designated RS36), 8552 intermediate toughened epoxy (designated RS47), High Temperature Cynate Esters (RS49), and High Temperature BMI (RS8HT). Most of the YLA resin systems can also be impregnated into traditional uni-directional or woven materials which offers more latitude when a part requires regions not made from the chopped fiber molding compound such as higher strain regions.

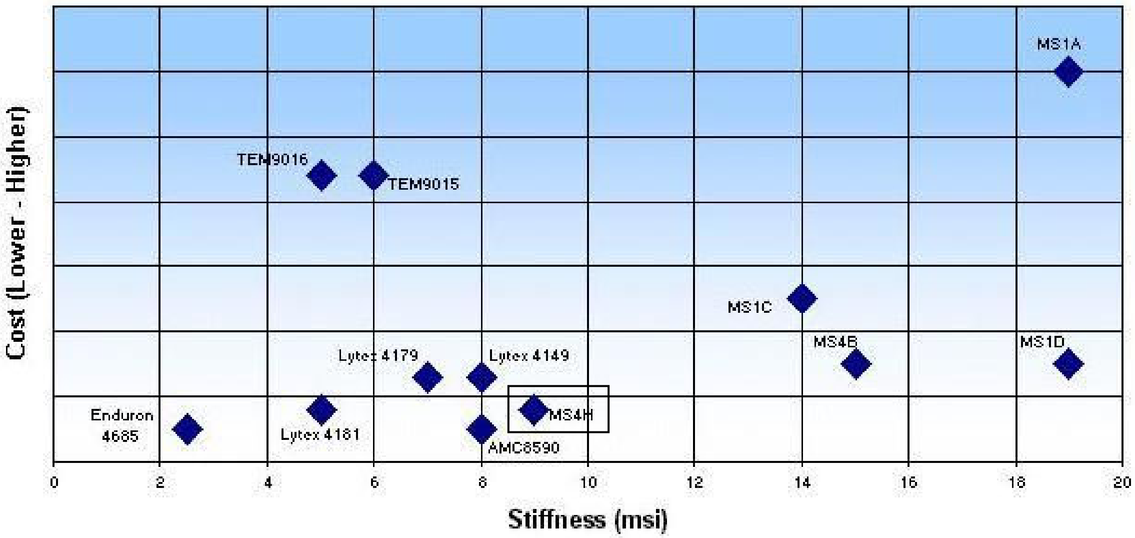


Figure 2.1– Cost vs Stiffness for Molding Compounds

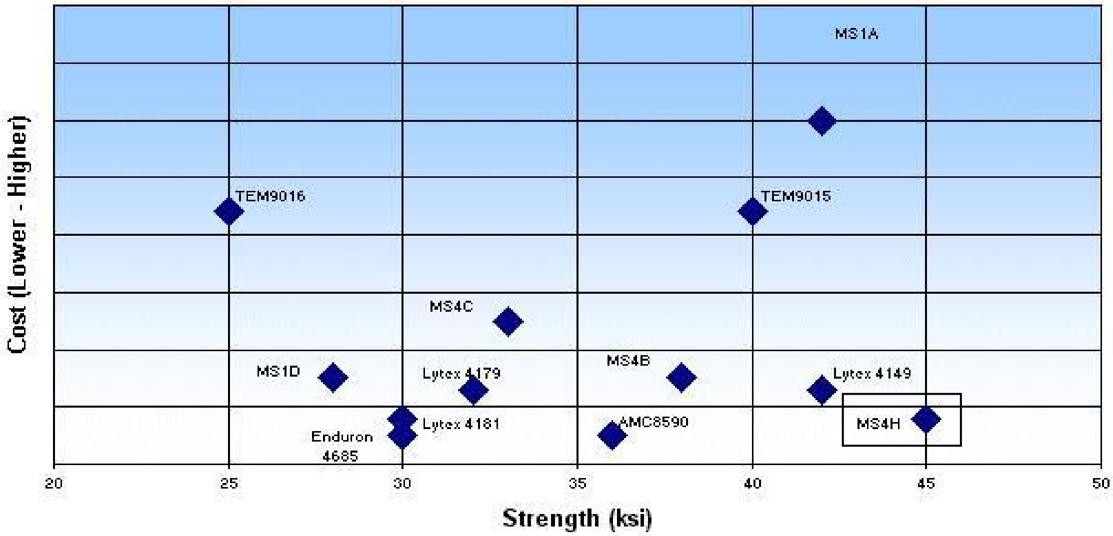


Figure 2.2– Cost vs Strength for Molding Compounds

Consideration should be given to the desired fiber length. In general, fiber length is selected based on flow and performance characteristics of the part. Longer fibers provide improved performance and shorter fibers provide better flow properties but in general, vendors have found that fiber lengths of 1” are a good compromise although computational validation should be attempted for a primary structural part to avoid quality rejection concerns. Strength and stiffness are also affected by both fiber length and flow characteristics. Poor fiber flow can cause excessive fiber waviness in critical high strain regions. The strength vs. stiffness for various molding compounds is shown in figure 2.3.

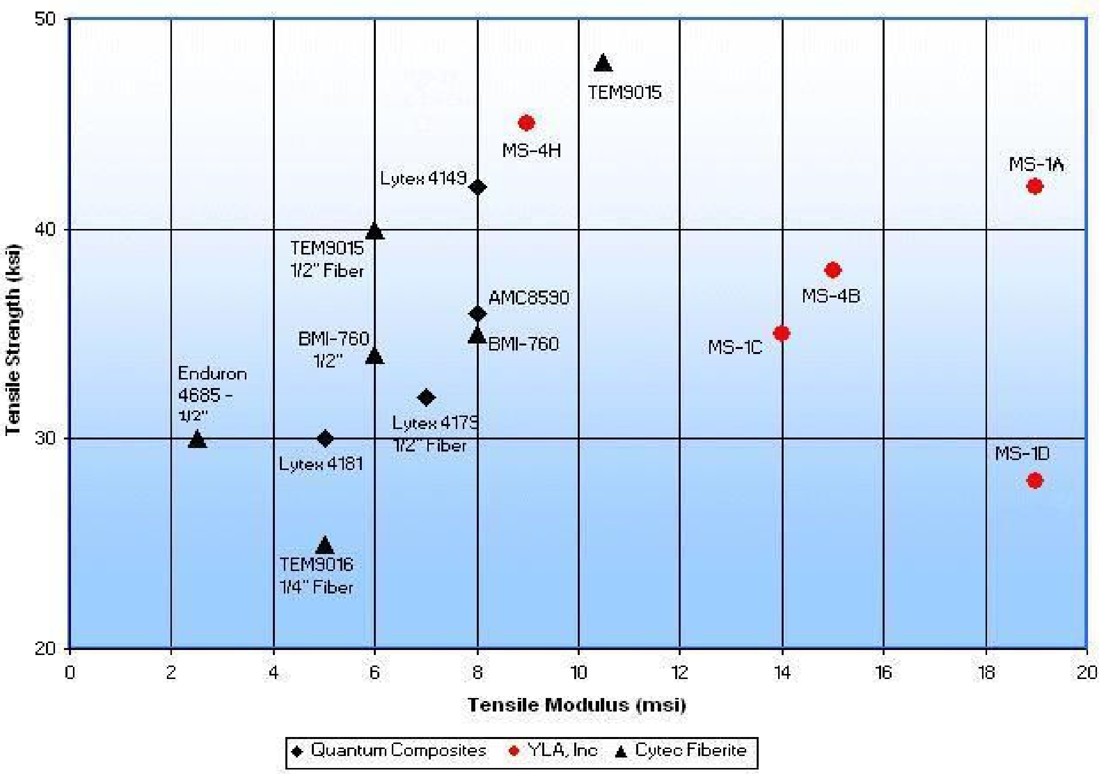


Figure 2.3- Strength vs Stiffness Plot

A charge is the SMC lamina trimmed to fit within a desired region of the tooling mold. When creating the charge of material to be placed into the mold, careful design and placement should be considered to anticipate mold-flow challenges by minimizing flow. The material charge typically will cover at least 95 percent of the mold, compared to conventional SMCs charges which only typically cover 50 to 90 percent [13]. This high percent coverage not only accommodates the high viscosity of the material, but also maintains the integrity of the reinforcement [11].

2.3 Experiment Outline

A controlled laboratory experimental setup approach was used during these tests. Five replication blocks were used to validate data taken from mechanical pullout and torsional testing of four different style inserts co-cured into the same YLA MS-4H material. Cross sectional analysis was performed on all unique style inserts as well as replication points.

All tests were conducted at standard room temperature and typical standard humidity conditions. MTS structural loading frame test equipment was used to conduct the mechanical testing as well as record the data. Data analysis was done using both standard graphing techniques and sophisticated commercially available statistical software called MINITAB Version 14 by MINITAB Inc. The fiber waviness portions of the experiment were conducted using separate software specifically designed for examining aspect ratios.

2.4 Insert Descriptions

An industry survey of candidate inserts for co-molding within the composite laminate panel was performed. Inserts had to meet several criteria to be considered before down selection could begin. Candidate inserts must be able to withstand 350°F cure temperature and they should be designed to reduce fiber migration from entering the threaded cavity. Since high flow molding compounds are being used, the use of a blind insert, meaning closed bottom end, is important to keep fiber from entering the threads during fabrication and prevent possible leakage through the molded laminate. In order to compare with past threaded composite laminate mechanical pullout data, a ¼-20 UNC thread is preferred. To maintain the lower cost objective, the insert should be an off-the-self item or could be easily modified to satisfy the design objectives.

Various materials were investigated including stainless, brass, aluminum, and composite. A total of ten candidates were put into a determination matrix from each was graded on cost, weight, thread size, and ease of manufacturability. Figure 2.4 illustrates the building block selection technique were a Pugh matrix was created to determine the final candidate inserts.

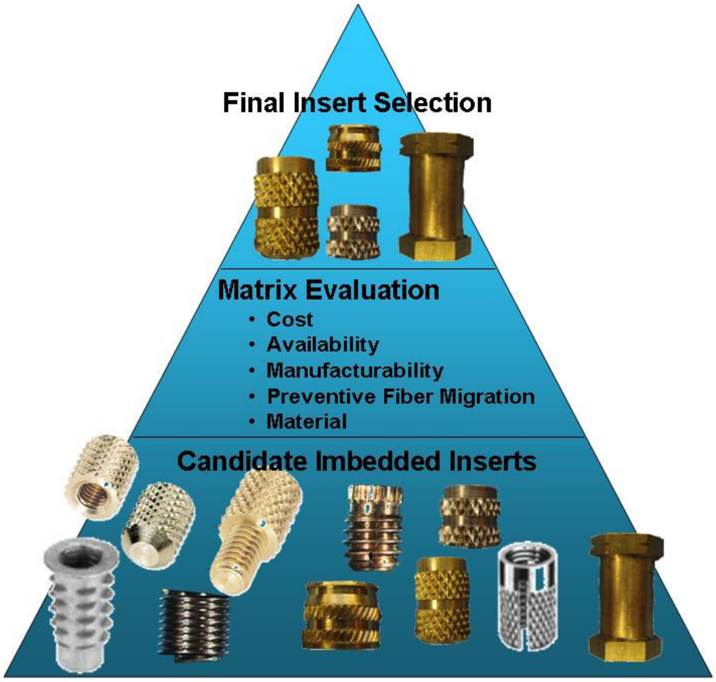


Figure 2.4 - Insert Selection Building Block

Four inserts were selected in this study and were chosen based on availability, outside surface characteristics and the alignment with previously recorded data. The selected inserts are shown in figure 2.5 by outside surface area. The selected inserts have various outside bondable areas and varied outside surface texture. Three of the four inserts utilize the same ¼-20UNC thread size while the fourth insert used a #10-32 thread. Unfortunately an industry survey yielded an extensive amount of brass inserts but very few stainless steel. Typically stainless steel would be preferred over brass because the enhanced corrosive resistance properties, however the mechanical behaviors of the molding compounds being studied should be less dependent of the insert material. All insert vendors have stated that specialty inserts can be made to suit customer needs.

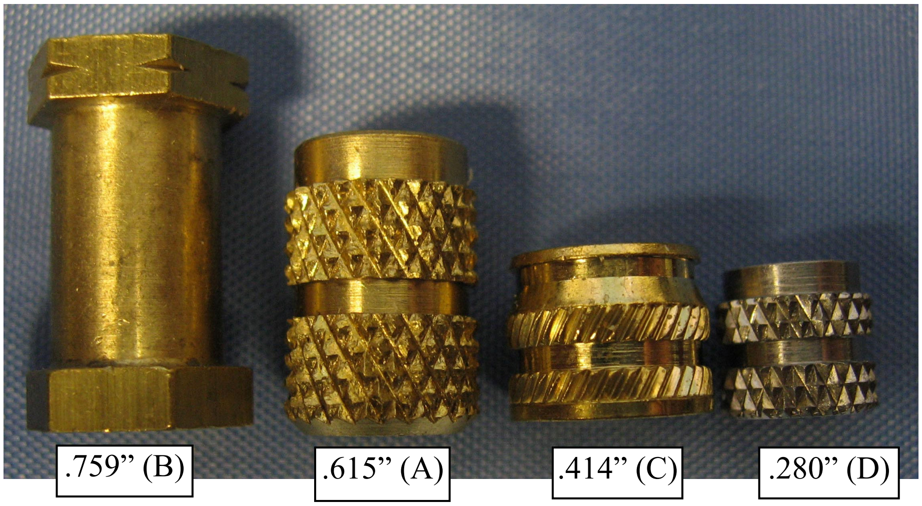


Figure 2.5 - Final Selected Inserts

2.5 Compression Molded Panel

The composite SMC was chosen from YLA Composites was to remain consistent throughout the test sequences for this study. The molding compound used from YLA was MS-4H which has a good balance between mechanical properties and cost and is therefore a widely used material in the aerospace industry. The specific material characteristics will be discussed in the following section.

The four unique inserts with different outside bondable surface areas were chosen to study the fiber distortion behavior at the neighborhood of the inserts. For statistical purposes, five specimens of each insert are co-molded in the composite panel. All outside surfaces are slightly different in an attempt to see how the affects of surface finish on mechanical behaviors. The goal is to examine the interaction between the composite and the insert rather than the insert thread itself.

The panel fabrication process begins by spreading chopped fibers, randomly oriented, into a sheet. The fibers can be distributed by hand or through an automated machine operation. The buildup of the sheet thickness is based on weight of the chopped fibers. Figure 2.6 illustrates the charge being formed. This perform sheet made up of the random oriented fibers are then heated and pressed. This hot compaction makes the sheet much easier to handle and transfer into the tool. YLA Inc. materials need to be oriented on site of part fabrication; other vendors such as Hexcel Inc. and Quantum Composites offer their products already in the sheet form and ready for cut and cure.

Figure 2.6- Chopped Fiber Loaded in SMC Ply

The inserts are located and held in place with integrated tooling features in the bottom of the mold. Each ply is cutout around the inserts before being loaded into the now heated closed cavity mold. The cutout is based on the inserts outside diameter and was consistently held at .125” over the outside diameter which varied slightly for each insert. After all the plies have been placed into the mold, the upper tooling detail is located and an 80 bar pressure is applied. The mold is preheated to reduce overall cure times since exothermic behaviors do not seen to be important with these resin systems.

The cure cycle for such a molding operation can be as low as 5 minutes at 275°F for thin parts. Typical cure temperatures are around 250°F for 2.5 minutes for every millimeter of the part thickness. A cure cycle is part specific to reduce resin exotherm as much as possible. The panels in this study were compression molded in a heated platen press. After cure the resultant specimen is shown in figure 2.7.

Figure 2.7- YLA MS-4H Molding Compound with Embedded Inserts

2.6 Continuous Fiber Molded Panel

For a comparative analysis specimen, traditional continuous fiber pre-impregnated materials were used in a molding operation in which to compare the molding compound panel data. The attempt was to fabricate a panel with little to no fiber waviness around the co-molded inserts. By eliminating fiber waviness, the effect of fiber waviness on mechanical strength could be quantified. These panels were used to develop a mechanical comparison. The following sections discuss the materials used, inserts, and manufacturing process.

2.6.1 Composite Materials Used

Since the molding compound being used in this study is made from chopped pre-preg fibers, it seemed appropriate to use a comparable fiber and resin. A structural grade C/EP IM6/8552 pre-preg tape was used in a quasi-isotropic layup. The Hexcel 8552 resin system is a low flow system however it was the most readily available material for this continuous fiber panel. Ideally a high flow resin like those found in molding compounds would have been preferred because of the excessive bulk factors and desired flow around the inserts.

2.6.2 Insert Descriptions

The same inserts which were used in the molding compound panels will be used in this baseline panel. The insert descriptions are revisited in section 2.4. Due to availability, only the ¼” brass inserts were used. Two specimens from each of the three inserts were co-molded.

2.6.3 Layup / Panel Fabrication Process

This continuous fiber carbon/epoxy composite panel was made in a closed cavity tool and cured in a heated INSTRON press from which pressure and temperature could control the cure cycle. The 6”x6”x 0.72” specimen contained 6 molded inserts. A tooling plate on the bottom of the cavity tool held each insert and pre-cut plies were loaded into the mold around the inserts. A room temp debulk vacuum compaction was performed after 20 plies were placed into the mold, the total laminate contained 100 plies.

A slightly modified cure for the Hexcel 8552 resin system was used which extended the time duration during the first 200°F dwell. Standard ramp rates of 5°F/min to the first and second dwell were used. The change in the cure cycle was an attempt to decrease any exothermal behaviors since the laminate is .75” thick. The cure cycle for the baseline co-molded insert panel is shown in figure 2.8 and contains pressure, temperature and vacuum all as a function of time.

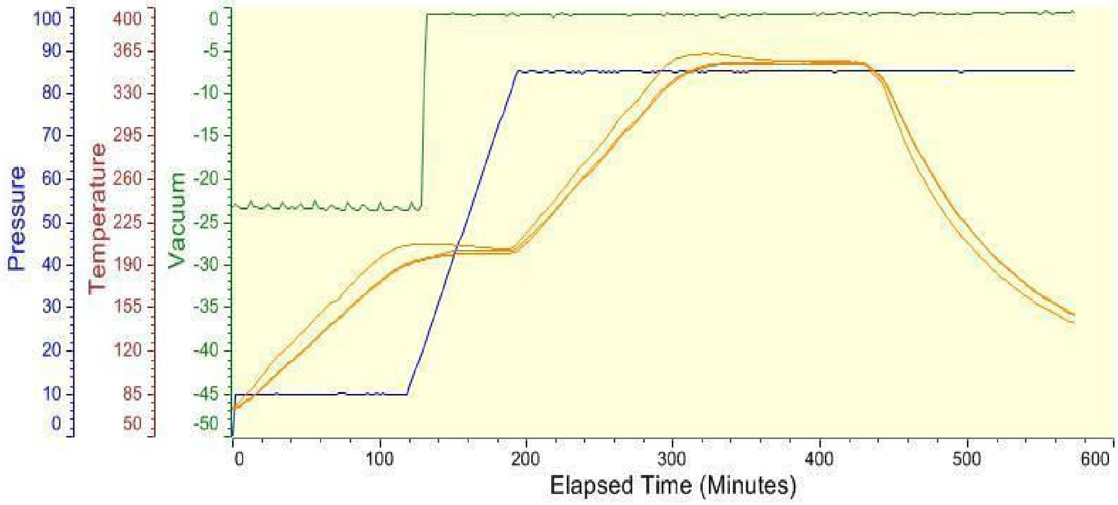


Figure 2.8- Cure Cycle for Thick Laminate IM6/8552 with Inserts

Two steps in the build sequence of the continuous fiber panel are illustrated in figure 2.9 and 2.10. Figure 2.9 shows how the fasteners were located to the bottom molding plate via threaded nylon rod. Figure 2.10 shows the layup approximately half way through the ply stackup.

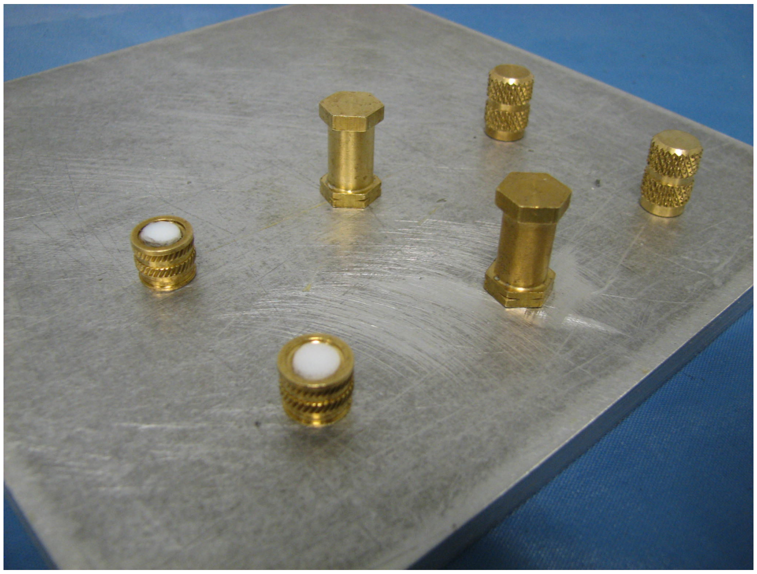


Figure 2.9– Bottom of Continuous Fiber Molded Plate with Inserts

2.10– Continuous Fiber Laminate 50% Completed

2.7 Tapped Laminate Composite Panels

A series of quasi-isotropic composite panels were made as another data set for mechanical pullout strength. The first laminate was blank compression molded (CMC) panel made of YLA MS-4H. The second panel was from traditional autoclave (A/C) cure materials from Hexcel which was an IM6/8552 system. The third panel is a Resin Transfer Molding RTM specimen made from a quasi-isotropic weave and EPON 862 Resin. The fourth panel is a metallic comparison made from 6061-T6 aluminum. Each panel was constant at .32” thick and the threads were tapped with a ¼-20 UNC two flute tap. A two-flute tap is commonly referred to as a gun tap. One specimen was made in each configuration and contained three tapped holes per panel. Figure 2.11 illustrates the autoclave, aluminum and RTM panels with gun tapped threads. Figure 2.12 illustrates a cross-sectional view of the tapped RTM panel.

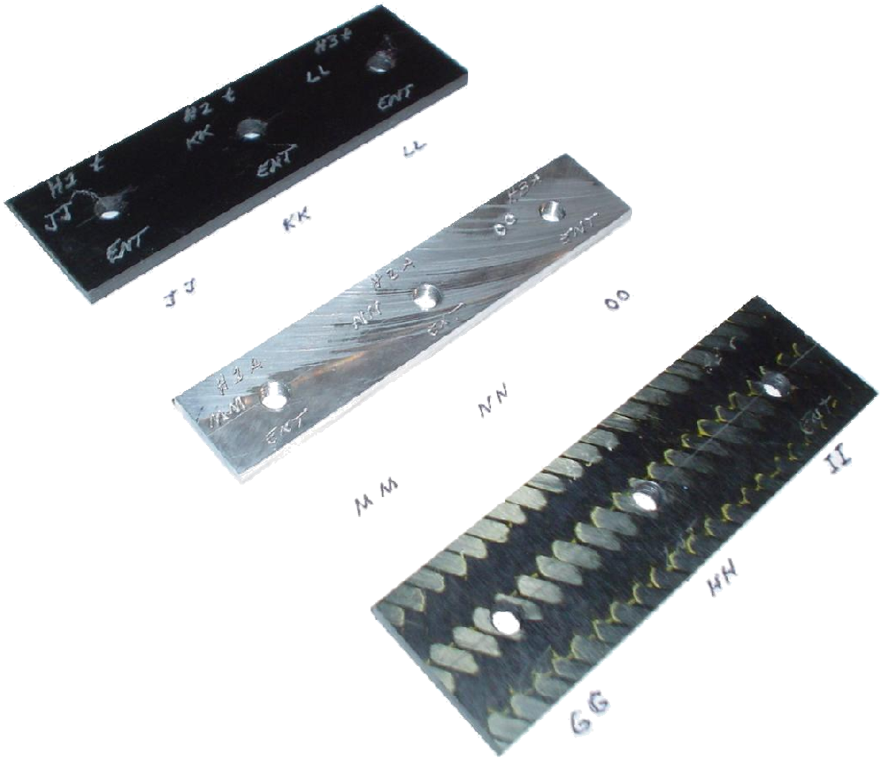


Figure 2.11- Tapped Laminate and Metallic Panel

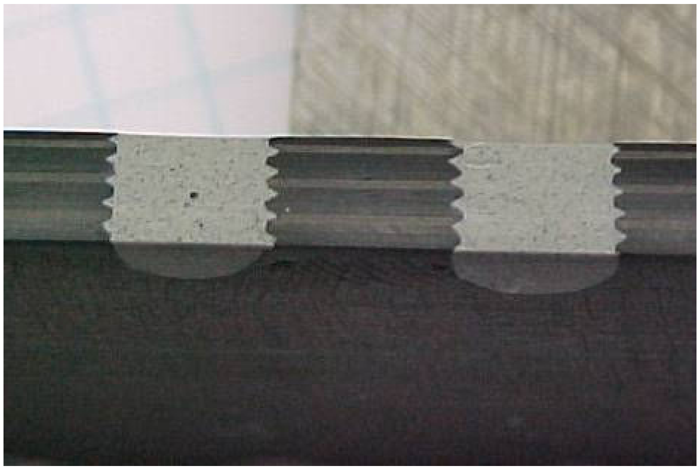


Figure 2.12- Cross Sectional View of Tapped RTM Panel

2.8 Test Setup and Process

The pullout and torsional testing accomplished in this experiment was performed in a controlled test environment. Both tests were performed at room temperature and in low humidity environments. The pullout testing was performed in a MTS hydraulic tensile test machine capable of tensile forces up to 50,000 lbs. The machine was setup with a computer control system capable of managing force and displacement to the user specified values. No secondary data acquisition system was used for these tests. To support the coupons, a previously designed holding fixture was used. Each pullout test coupon was 2”x2” square. Since all the inserts were co-molded into the same test laminate, each coupon thickness was molded constant to .75” thick.

The apparatus had a large bolt secured to its top which was clamped into the upper grips of the tensile machine and supported the test block. The force of the test was reached by the resistance apparatus shown in figure 2.13 which had a .375” hole through it providing a passage for the test bolt to pass. A region surrounding the insert was covered to isolate the bonding interface rather than inducing interlaminar failure elsewhere in the panel.

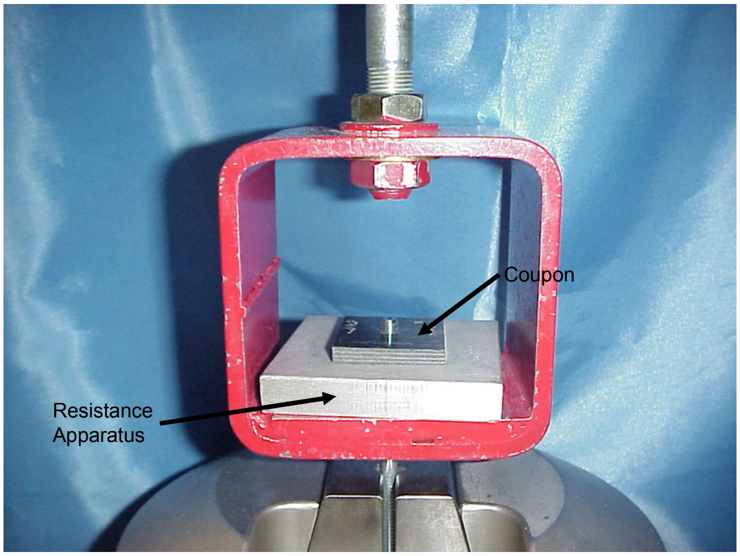


Figure 2.13– Pullout Test Apparatus and Setup

The test was designed as a constant rate of displacement test, .050 inches per minute. The applied load was continually increased until the tensile dropped 10% below the maximum value during the test. Composite testing experience has shown that failure will occur soon after peak loads have been reached, thus tests are usually concluded when tensile loads have dropped 10%. The constant rate of displacement test was chosen for this test because of its widely used industry acceptance.

The torsional testing was also performed on test specimens containing five inserts of the same type. A single insert was tested at a time and maximum torque taken was recorded. The specimen was clamped to a flat granite table. A bolt was threaded into the insert being tested and the thread length was .040” to .060” short of total thread depth available. As seen in figure 2.14, a calibrated dial in-lb torque wrench was used to apply load. The dial torque wrench displays maximum load reached after failure occurs.

Figure 2.14- Calibrated Dial in-lb Torque Wrench

The next piece of critical data to observe was the out-of-plane fiber distortion around molded inserts. The fiber waviness was quantified using the aspect ratio approach and a software package called Volume Graphics, by VG Studio [12] via the cross-sectional view of the specimen.

The cross section was separated into three different sectors, A, B and C, to determine trends in fiber distortions and connections to failure modes. Sectors A and C used the Step Wave criterion and Sector B used the Bell Wave criterion. Figure 2.15 illustrates the location of the three sectors in a cross-sectional view.

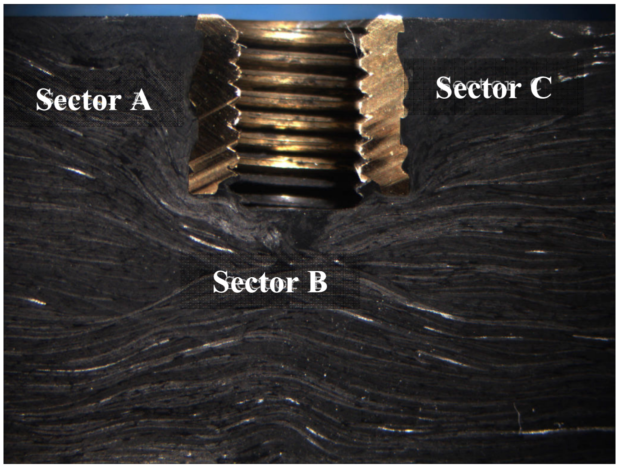


Figure 2.15- Cross Sectional Analysis Division

CHAPTER 3

RESULTS AND DISCUSSION

Pullout and torsional strength data was taken on each co-molded insert. Visual characterization of fiber distortion around the co-molded inserts was also conducted before and after mechanical testing. The data was analyzed to understand the correlations between the mechanical behaviors of the inserts associated to fiber characteristics at the bonding interface and the physical parameters of the inserts themselves ie. size, shape and surfaces.

3.1 Pullout and Torsional Strength Data

One of the response parameters associated with these tests is the pullout strength of the co-molded inserts. Five specimens of each unique insert were mechanically pulled and torsionally tested. As previously mentioned, each unique insert was co-molded into a flat compression molded composite panel. Figure 3.1 correlates the insert bondable area to pullout and torsional strength.

Interestingly enough, the data suggests that the greater the bondable area, the more pullout and torsional load it can endure. This analysis does not consider the effects of the outside diameter surface texture of pattern as relevant to mechanical strength. It is intuitive however that the outside surface of the insert performs better when some texture is available for the composite fiber to bind to. This variable is not taken into account in the data analysis but rather is an observational analysis. The raw experimental data is summarized in Table 3.1.

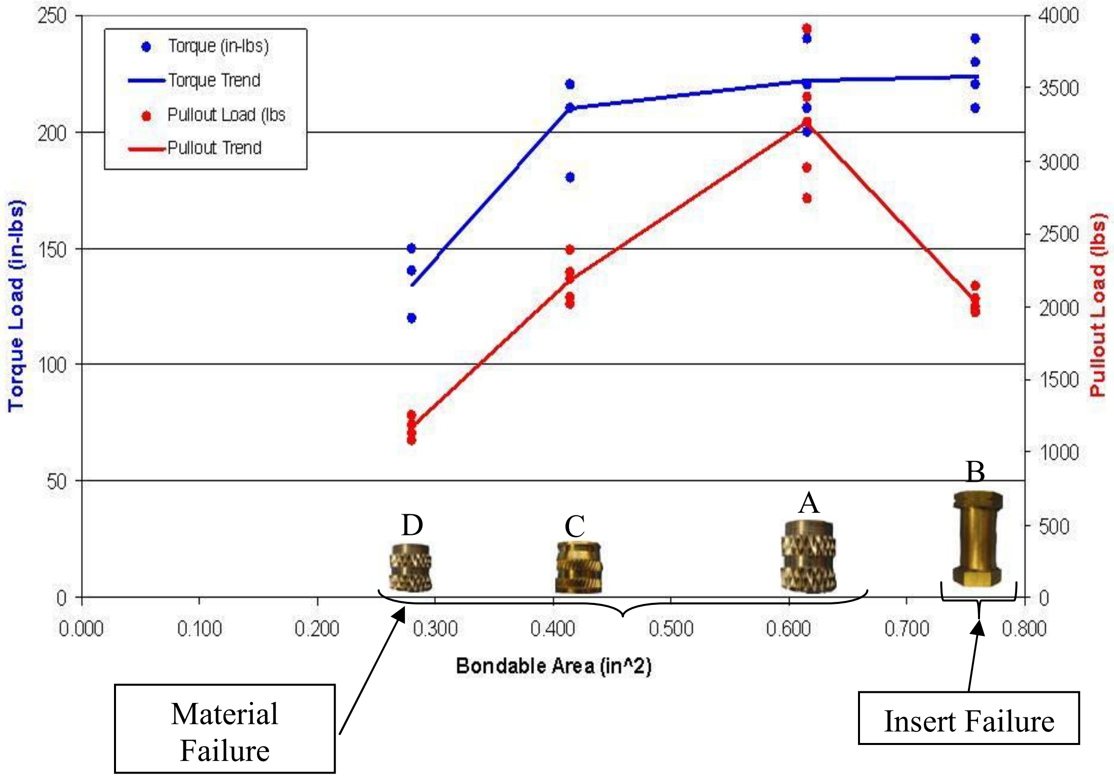


Figure 3.1- Mechanical Load Plots

Table 3.1- Pullout / Torsioanl Load Raw Data

Insert	OD Area (in^2)	Insert Height (in)	Pullout Sp.	Mean Pullout Ld (#)	Pullout Std. Dev	Torque Sp.	Mean Tors. Load (in-lbs)	Torsion Std. Dev
A	0.615	.530	5	3262	450.6	4	222	17.9
B	0.759	.688	5	2023	74.7	4	224	11.4
C	0.414	.300	5	2176	146.6	4	210	17.3
D	0.280	.281	5	1177	77.8	4	134	13.4

The torsional aspect of the mechanical tests performed in a very similar fashion to the pullout studies. The same trends were observed as in previous pullout studies.

The pullout load probability test results from the normality tests evaluation of the null hypothesis (H_o) that the data follow a normal distribution. This data is summarized in table 3.2. If the p-value for the test is less than the chosen α-level, then one must reject the H_o and conclude that the data does not follow a normal distribution. The most commonly used α-level is 0.05 because the chance of finding an effect that does not really exist is only 5%.

Table 3.2- Pullout Load Data Summary

N = 5 for all α= .05
(D).280 Bondable Area Insert….p-value=.493, std. dev=77.80, Mean=1177,
(C) .414 Bondable Area Insert…. p-value=.817, std. dev=146.6, Mean=2176
(A) .615 Bondable Area Insert….p-value = .862, std dev= 450.6, Mean=3262
(B) .759 Bondable Area Insert…. p-value = .357, std dev= 74.66, Mean=2023

3.2 <u>Fiber Waviness Analysis</u>

Each co-molded insert was cut through the center, polished and analyzed to quantify out-of-plane fiber distortion on the cross-section. Five specimens' samples for each insert used were analyzed in three sectors. The data suggests that fiber behaviors for each unique insert is fairly consistent over the five specimens however the aspect ratio varies greater based on the insert geometry. Sectors A and C should be nearly identical as they are symmetrical assuming perpendicular flow, however the data does not support this. These two sectors are analyzed as a step wave whereas sector C is analyzed as a wrinkle similar to that of a standard bell curve. The schematic outline of the three sections is shown in figure 3.2.

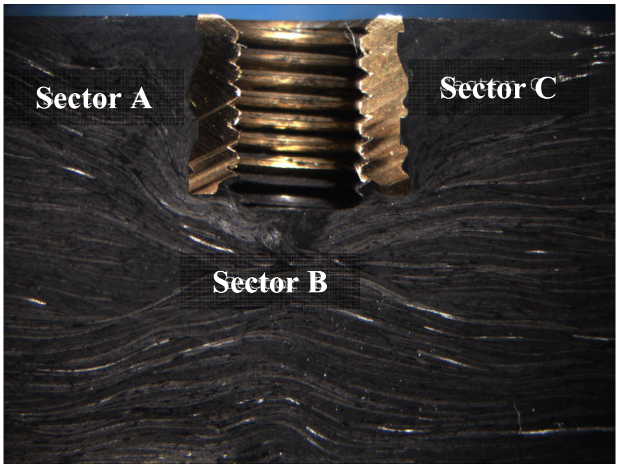


Figure 3.2- Cross Sectional Division of Insert C

Figure 3.3 shows an example of two of the four inserts and the typical fiber distortions associated with each one. Interesting enough, some cross sections showed fiber distortions towards the bottom of the insert. The reverse fiber distortion in sector B happens when the last composite SMC charge around the insert is loaded into the cavity tool and its bulk exceeds the insert height.

The visible lines shown in figure 3.3 are actually the modeled fiber paths based on black and white contrast. The software calculates fiber length, height and angles for both legs and the combined fiber path. The top insert is (D) and the bottom insert is (B). As step wave analysis is done because the L-direction must be perpendicular to the loading direction.

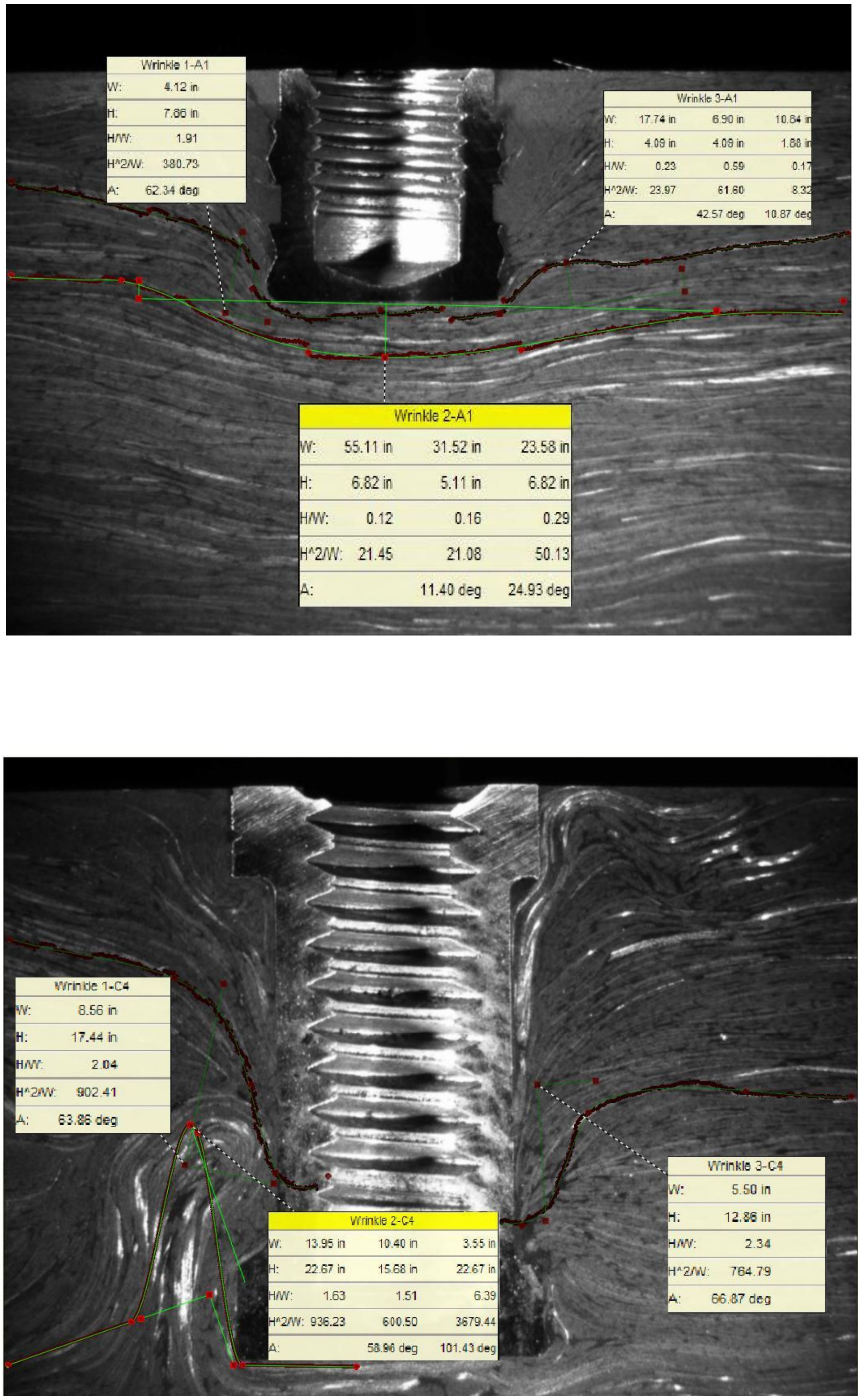


Figure 3.3- Examples of Cross Section Fiber Waviness Analysis

The reverse fiber flow phenomenon seen under the base of the insert is caused when the open clearance area in cut in each lamina is filled with subsequent plies creating a reverse fiber flow. This reverse action can be examined as a fiber flow to the path of lease resistance when curing pressures are applied. The molded insert is then forced to move enough material bulk to nest. Too much nesting could cause voids or resin pockets along side the insert walls.

Figure 3.4 summarizes the fiber waviness in each of the three sectors surrounding the molding insert. The data is summarized over five specimens per each insert. It is important to note that sector A is on the left side of the insert and sector C is the right side whereas sector B is directly underneath the insert base. Refer back to figure 3.2 if needed. Although sector A and C should intuitively follow the same general trends, the data suggests that waviness is random and is not easily predictable in any of the three regions. Again sector A and C were analyzed using a step wave method and sector B used a bell shape method. The bell shape behavior seen in sector B should less of a contributor to the mechanical loading condition than that of the step waves on either side of the co-molded detail. The median raw data is shown in Table 3.3.

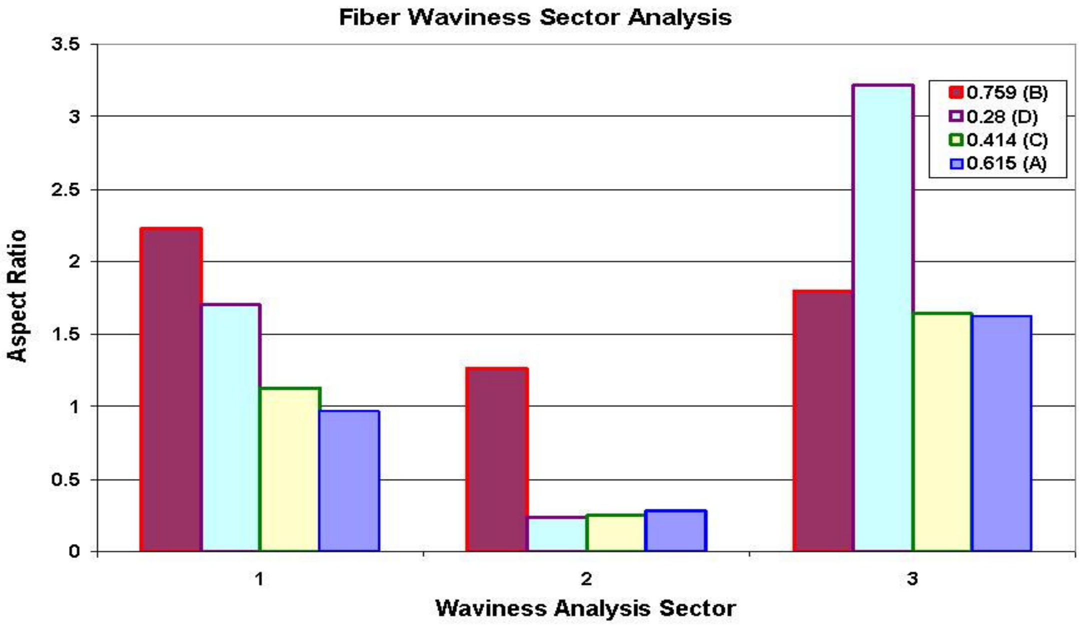


Figure 3.4- Main Effects Plot for Fiber Waviness in all Sectors

Table 3.3- Sector Analysis Data

Insert Style	Bondable area (in^2)	Pullout (lbs)	Torsional Moment (in-lbs)	Waviness Sector A (h/L)	Waviness Sector B (h/L)	Waviness Sector C (h/L)
A	0.615	3262	222	4.582	0.278	1.626
B	0.759	2023	224	3.884	1.264	1.800
C	0.414	2176	210	1.132	0.250	1.640
D	0.280	1177	134	1.702	0.232	3.220

Intuitively analyzing the two symmetric sides of the cross section, sectors A and C should be close in fiber waviness aspect ratio however the data says otherwise. It becomes apparently clear that the true randomness of this material in the X-Y axis contributes to the out-of-plane fiber behaviors in the Z-direction. In most cases the mechanical data band is tight enough to show that the out-of-plane fiber waviness spread has little to no impact.

3.3 Continuous Fiber Configuration

Due to the limited baseline data found, baseline panels were made using traditional uni-directional IM6/8552 material. This is a fairly standard material used throughout industry and is often involved in operations requiring post machining and installation of bushings and inserts. This low flow resin system material is not intended in this situation however the purpose of this specimen is to attempt to reduce fiber distortion as much as possible around the insert interface.

Tensile data presented by Ferret [11] regarding co-molded inserts in a composite RTM panel, showed 0.37” diameter and 0.47” tall or 0.654 in^2 bondable area, averages 2000 lbs. This data compared to the presented data in this thesis is approximately equal which is satisfactory. The paper also describes much of the manufacturing issues associated with the process such as perform construction, injection flow modeling, excess resin areas, dry fiber regions, voids around inserts, and inserts entering the elastic region prematurely. For those reasons, compression molding surpasses the RTM process in this situation.

Figure 3.5 shows a cross-sectional view of the molded insert in traditional pre-preg material. It is important to note that the fiber waviness is significantly reduced but because the quasi-isotropic laminate contained continuous fibers and a low flow resin system, a significant amount of voids were visible around the molded insert walls.

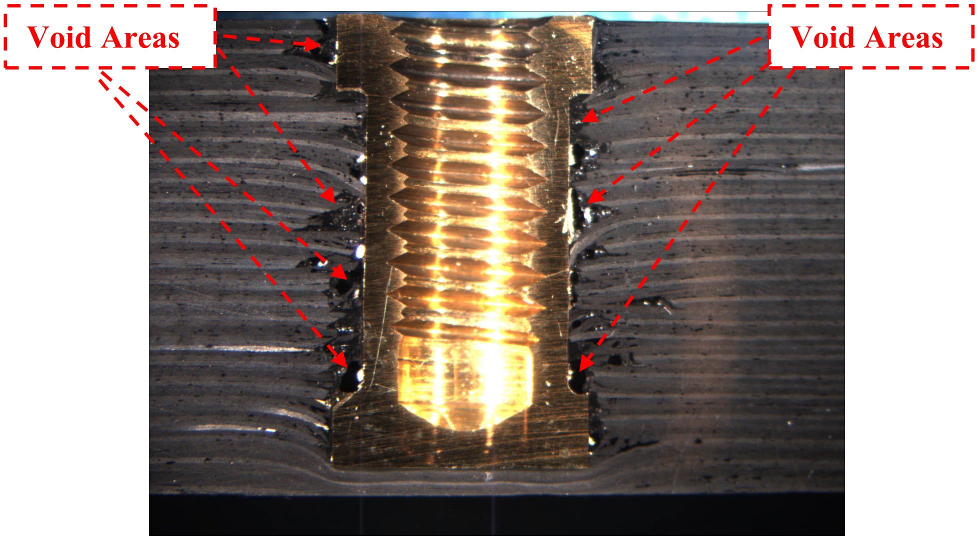


Figure 3.5– IM6 / 8552 Molded Insert in Quasi-Isotropic Layup

While fiber distortion was reduced further away from the insert to composite interface, there was an increase in localized void content and some fiber distortion. Due to the localized voids, the pullout and torsional strength was significantly lower than expected. This phenomenon was seen in all three insert styles tested. The failure mechanisms seem again reiterate the fact that the load transfer between co-molding insert and fiber in a molding compound is much better is some amount fiber waviness is present.

Upon closer inspection of the fiber to metal insert interface, some amount of very localized fiber distortion can be seen. Figure 3.6 shows the interface under magnification but predominate bonding interface is high resin areas.

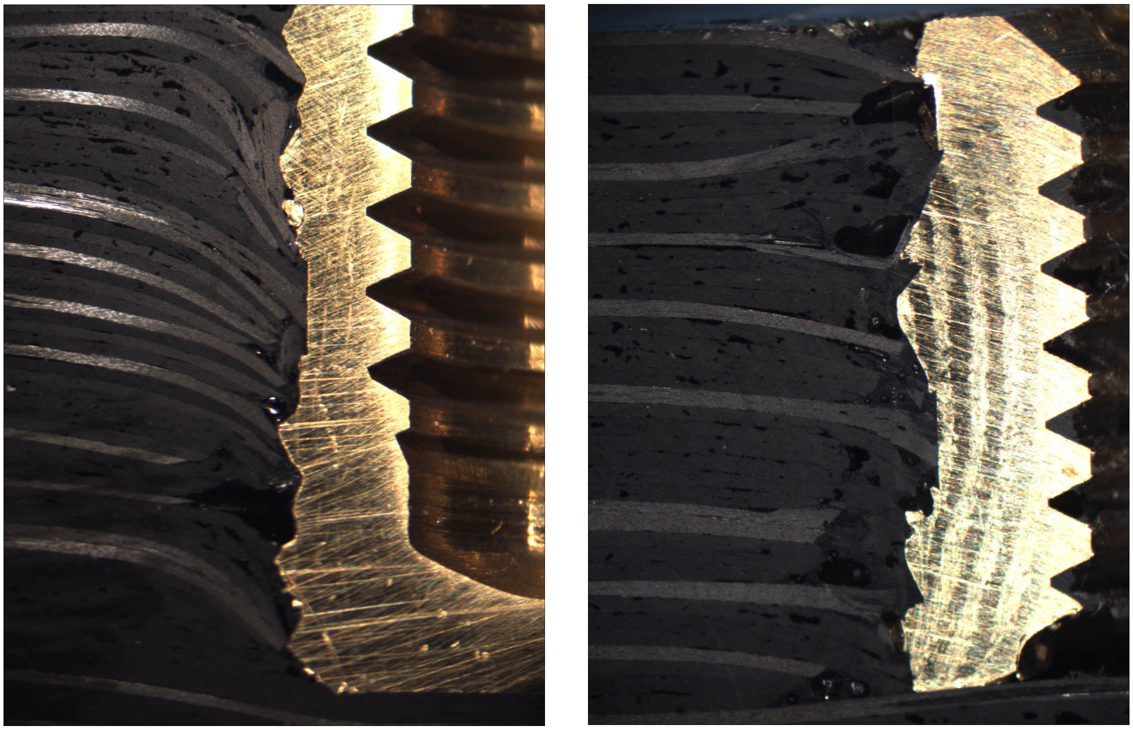


Figure 3.6- Magnification of Laminate to Insert Interface

3.4 Correlation Analysis

Using statistical software to analyze the correlation between the mechanical strengths and fiber behaviors to baseline specimens, statistically significant variables were determined. Insert depth and as a function of fiber waviness in each sector and pullout strength was used to determine a General Linear Model (GLM). Since Insert bondable area is a function of the insert depth, the statistical significance does not change. A GLM is used to perform an Analysis of Variance (ANOVA), analysis of covariance, and regression analysis on balanced and unbalanced data. A GLM is a procedure to test the hypothesis that the means of several populations are equal. In this case, the GLM procedure requires a response, or measurement taken from the units sampled and has one or more factors. Factors for the GLM can be one of two types, fixed or random. In this setup, the fixed or discrete variable of insert depth was selected; this variable is then altered systematically. The ANOVA examines whether the factor level means are the same or different. The significant statistical events from the GLM are shown in Table 3.4. All the statistical terms used in the following table are defined in appendix A.1.

Table 3.4- General Linear Model for Analyzed Fiber Waviness Data

General Linear Model: Pullout Load, Waviness A, ….. versus Insert depth

```
Factor        Type   Levels  Values
Insert depth  fixed       4  0.281, 0.300, 0.530, 0.688
Analysis of Variance for Pullout Load, using Adjusted SS for Tests

Source        DF    Seq SS    Adj SS   Adj MS      F      P
Insert depth   3  10994383  10994383  3664794  62.07  0.000
Error         16    944656    944656    59041
Total         19  11939039
S = 242.984   R-Sq = 92.09%   R-Sq(adj) = 90.60%
Analysis of Variance for Waviness A, using Adjusted SS for Tests

Source        DF  Seq SS  Adj SS  Adj MS     F      P
Insert depth   3   41.68   41.68   13.89  0.67  0.582
Error         16  330.90  330.90   20.68
Total         19  372.58
S = 4.54768   R-Sq = 11.19%   R-Sq(adj) = 0.00%
Analysis of Variance for Waviness B, using Adjusted SS for Tests

Source        DF  Seq SS  Adj SS  Adj MS      F      P
Insert depth   3  3.8358  3.8358  1.2786  16.48  0.000
Error         16  1.2411  1.2411  0.0776
Total         19  5.0769
S = 0.278509   R-Sq = 75.55%   R-Sq(adj) = 70.97%
Analysis of Variance for Waviness C, using Adjusted SS for Tests

Source        DF  Seq SS  Adj SS  Adj MS     F      P
Insert depth   3   8.887   8.887   2.962  1.74  0.199
Error         16  27.221  27.221   1.701
Total         19  36.108
S = 1.30433   R-Sq = 24.61%   R-Sq(adj) = 10.48%
```

Significant….
P-values >
α-Level

An explanation of each of the significant statistical factors can be seen in appendix A. It is important to note that the insert depth is statistically significant on pullout strength and fiber waviness in Sector B which is the region directly under the bottom of the insert.

Upon correlating fiber waviness to mechanical pullout strength, the data suggests tight patterns in most of the test specimens. In three of four test configurations, the 95 percent confidence interval was well within an acceptable range. The insert bondable areas included in this range were the two smallest, .280 and .414 square inches, as well as the largest area insert at .759 in^2. Figure 3.7 illustrates the confidence regions. The median insert bondable area specimen, measuring in at .615 square inches, faired very well in during mechanical testing however the 95 percent confidence region was a bit scatted with a variance of just under 600 lbs or about 24 percent from the median. Although the spread of fiber waviness aspect ratio between all samples was within the range of zero to six with an exception of a few high points, it appears that this variable has little impact on results.

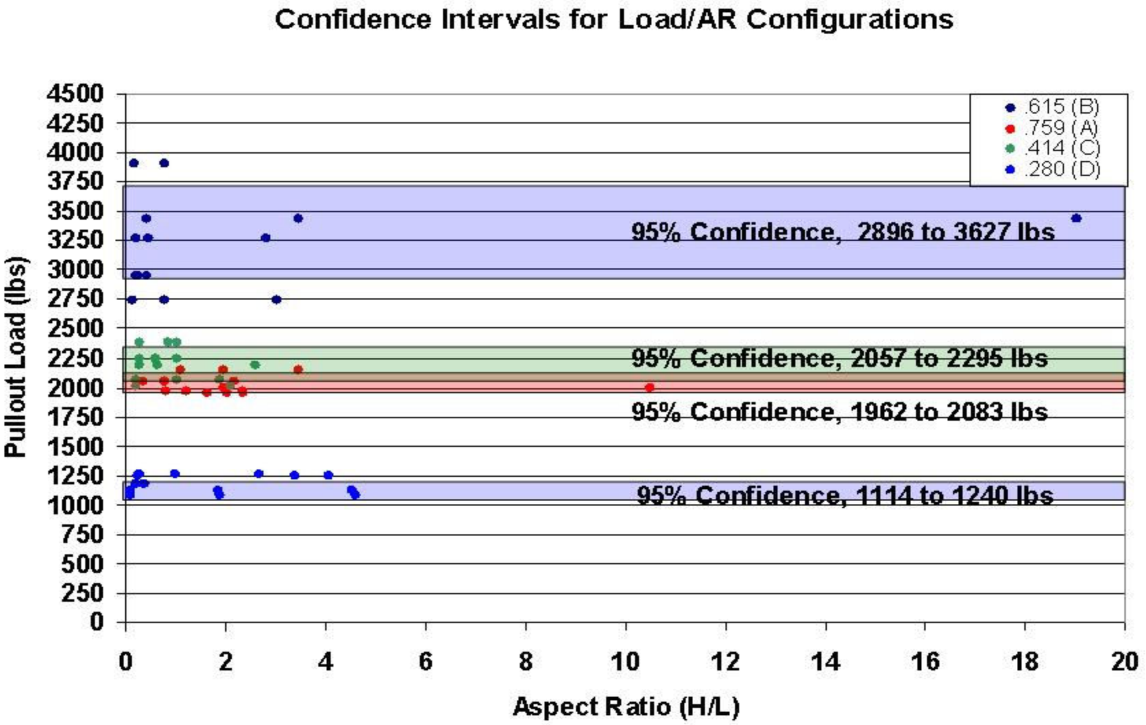


Figure 3.7- Fiber Waviness vs Pullout Load

Both the experimental pullout and torsional mechanical testing was compared to baseline specimens. Figure 3.8 again shows the relationship between torsional load, pullout load and bondable area except that now the baseline quasi-isotrpoic laminate test panel with co-cured inserts is shown on the same graph. The graph shows that the comparative continuous fiber configuration has a significant reduction in strength which can be attributed to the previously discussed amount of void content around the interface. Also the fact that the fibers are loaded almost entirely in shear within the baseline panel also confirms that the amount of fiber distortion within the compression molded materials could also help in these two particular test scenarios.

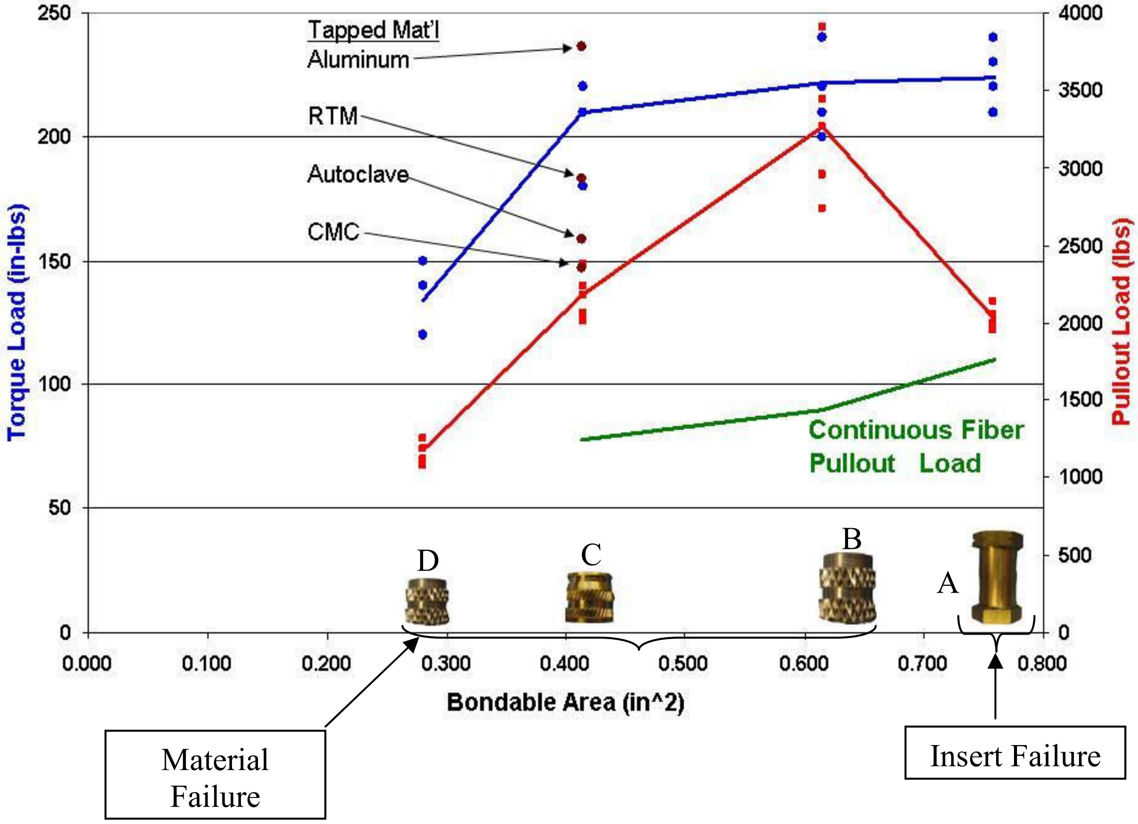


Figure 3.8– Comparison of Continuous Fiber Laminate and SMC Panel

Aside from the continuous fiber composite configuration using traditional pre-preg materials and a quasi-isotropic laminate, the compression molded laminates are also compared to traditional threaded composite laminates. These comparison panels include traditional laminates using ¼-20 UNC gun tapped threaded holes in the same YLA MS-4H compression molded panel (CMC), an autoclave cured IM6/8552 pre-preg laminate (A/C), RTM laminate using Epon 862 resin and aluminum 6061 T-6.

Depending on the mechanical requirement, the molded inserts within the compression molded panel faired well and this does not consider the cost advantage by preventing the post bond work that is required in all the baseline panels. The results of this comparison are shown in figure 3.9.

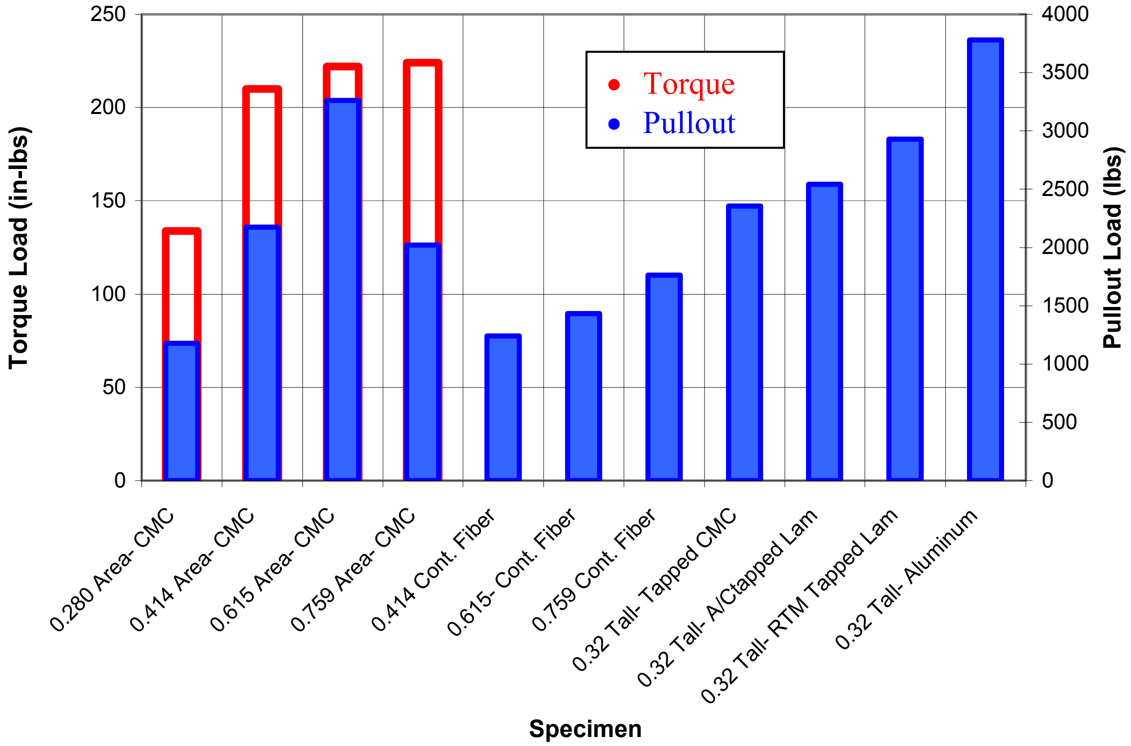


Figure 3.9- Comparative Mechanical Strengths

3.5 Failure Investigation

Quasi-isotropic composite laminates, like the molding compounds used in these studies, have fractures that are essentially controlled by a single parameter, e.g. the fracture toughness or the stress-intensity factor. Whereas anisotropic composites contain at least seven primary controlling failure parameters: (1) crack length; (2) crack orientation with respect to material axis of anisotropy; (3) nature of applied combined stresses; (4) lamination geometry; (5) strain, or deformational, and strength responses of the constituent lamina; (6) three kinematically admissible modes of crack extension and (7) crack trajectory.

Since composites have low stiffness in transverse directions, when out of plane loading exists, separation between plies happens, i.e. delamination. Delamination in composite laminates is defined as the separation of surfaces between adjacent layers. Such delamination crack growth is usually attributed to out-of-plane (plane of laminate) stress components near the vicinity of the crack tip. In particular, crack growth is often dominant due to an interlaminar normal stress (Mode I). Isotropic materials almost always fail in a local opening mode since this generally requires less energy. Shear failures where laminas are in a sliding mode are considered mode II. Out-of-plane tearing failure is categorized into mode III. Figure 3.10 illustrates the three fundamental failure modes seen in material failures regardless of isotropic or composites.

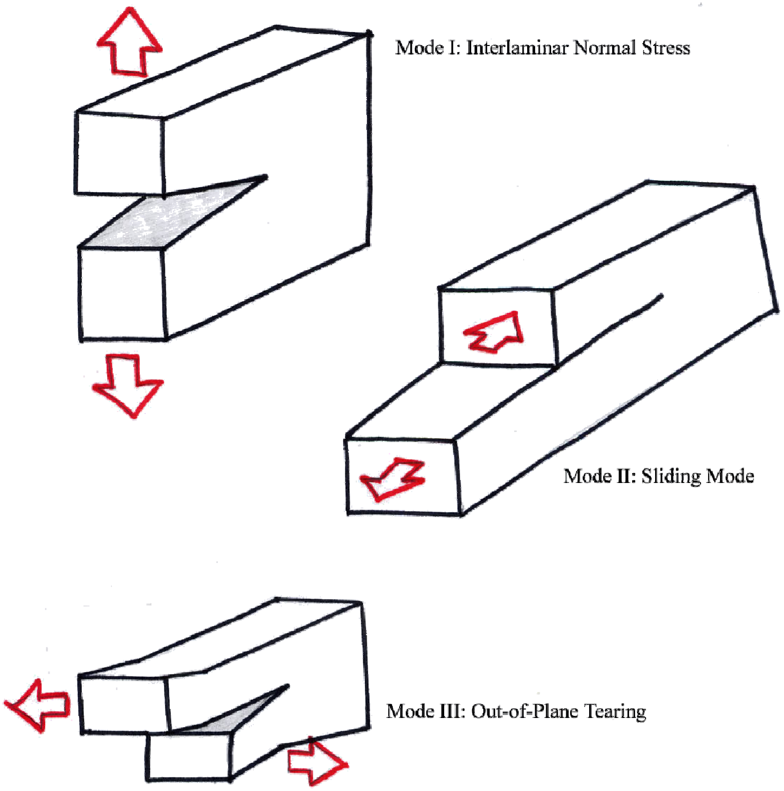
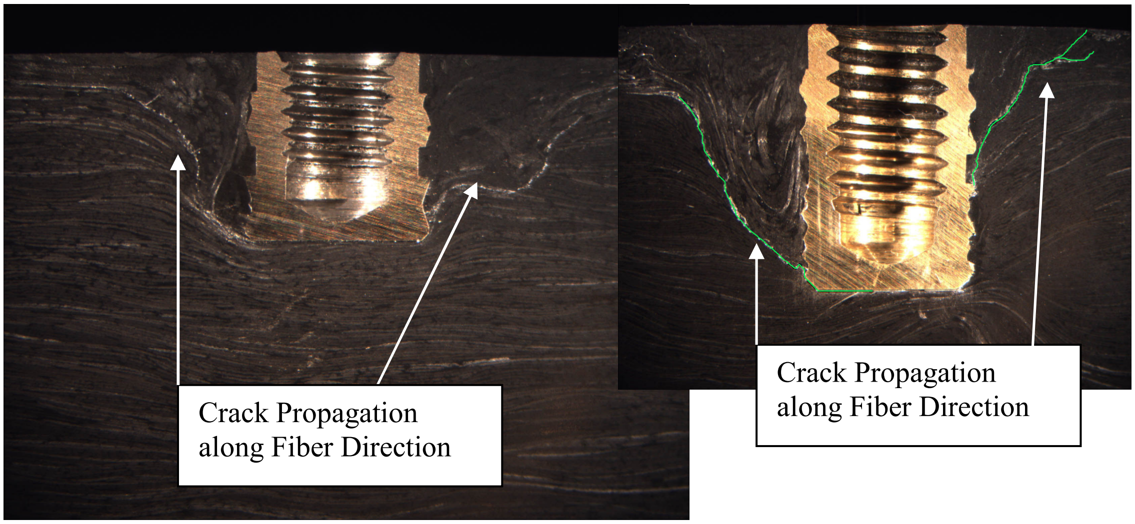


Figure 3.10- Modal Failures in Composite Laminates

In the compression molding compound application where fiber waviness is clearly visible around co-molded features, some mixed mode failure is apparent. In nearly all instances, crack propagation began near the base of the molded insert (Mode I). If the fiber orientation where perpendicular to the molded insert, the attributed failure mode would be Mode I dominant. Due to the fiber waviness, the shear component (Mode II) contributing to delamination is apparent. The material randomness contributes to the out-of-plane tearing seen in Mode (III). All three modes are present in the pullout of co-molded inserts. Figure 3.11 illustrates the interlaminar failures seen in the shortest, barrel style configurations.



Crack Propagation along Fiber Direction

Crack Propagation along Fiber Direction

Figure 3.11- Crack Propagation Around Co-Molded Inserts

The tallest insert, which has an I-shaped cross-section, showed another failure mode not related to laminate failure. During this set of specimen testing, the failure occurred in the narrowest part of the insert itself. In this case the laminate was clearly left in tact. Figure 3.12 illustrates that I-shaped insert, insert A, failure from both a cross sectional view and from the top. It is important to note that the graphical and tablature data shows significant drops in strength around this largest insert and that is due to the fact that the insert is failing before laminate failure.

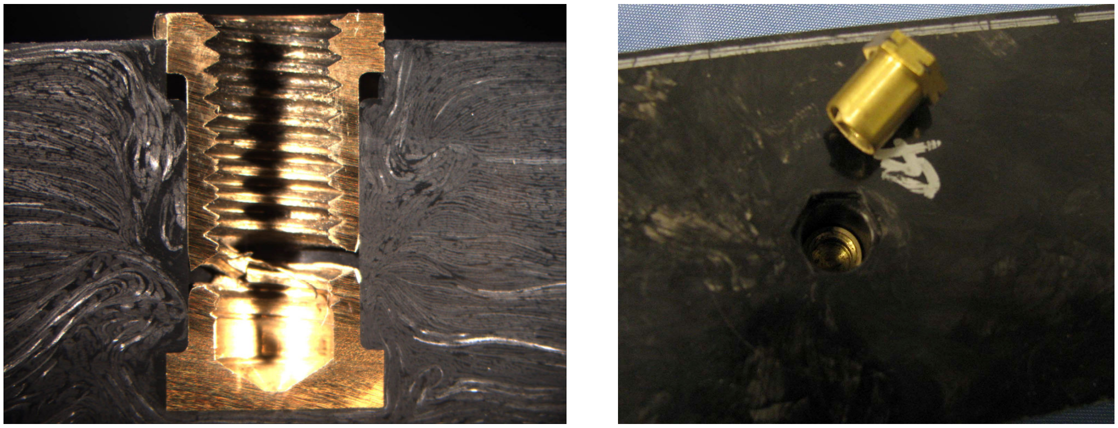


Figure 3.12- 0.759 in^2 Insert Failure

The illustrations shown below, figure 3.13, were taken under a high power microscope to examine the typical fracture lines. It is important to note the fracture along the fiber path and the discontinuous and randomness of the molding compound. All failures were seen in sectors A and C which was the two adjacent sides to the loading path. No visible delamination occurred in the laminate underneath the insert in sector B which is to be expected.

The fact that interlaminar shear is occurring would suggest that the localized fiber distortion around the co-molded details actually enhances the mechanical properties in this particular application and configuration.

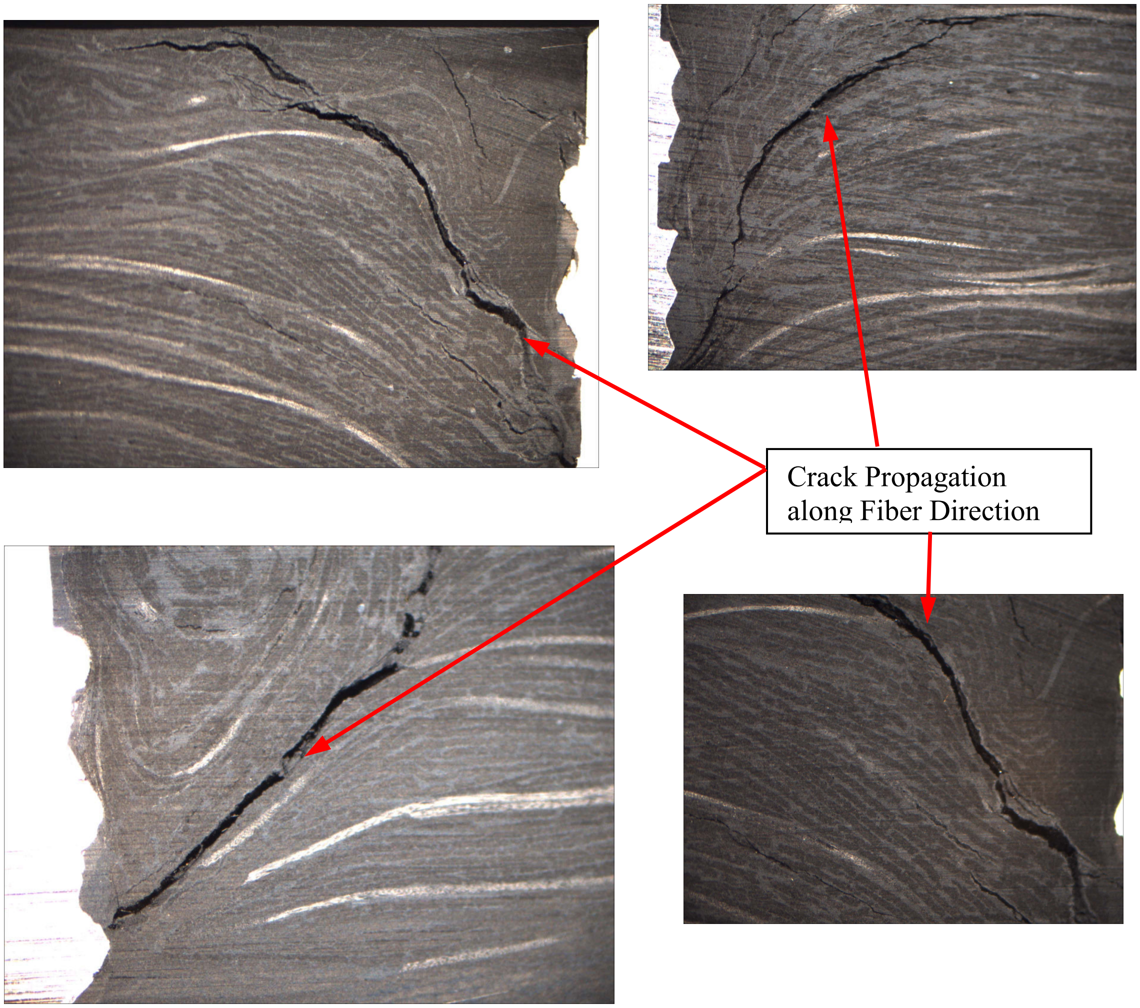


Figure 3.13- Microscopic Fracture Photograph of Co-Molded Insert

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Effects of the pullout and torsional strength on co-molded threaded inserts in a high flow carbon/epoxy composite molding compound were investigated. The results began to provide a better understanding to the strength characteristics seen as a function of fiber behaviors and the bonding area between the inserts and composite panels. The results indicate that the pullout and torsional strength increase as the bonding area increases.

Fiber waviness was observed in the laminate with co-molding inserts. The degree of fiber waviness, in terms of aspect ratio, was dependent in the size of the insert. Significant amounts of fiber waviness in the aspect ratio range of zero to six were observed. The degree of fiber waviness was correlated back to insert mechanical properties via pullout and torsion loads. The results suggest that fiber distortion could actually help the mechanical advantage when compared laminates made of pre-impregnated composites and are comparable to tapped laminates. Tapped laminates however require post machining efforts which can cause localized fiber fractures. Co-molded inserts better transmit loads into the laminate and in most cases put the fiber in a tri-modal effect rather than straight shear. In the tapped laminate and continuous fiber with co-molded inserts, the subsequent fibers are put into a more shear. The modeling of such complex and random fiber behaviors will be rather hard to quantify and it appears that the significance of the randomness will be minimal. Depending on part specific requirements, insert mechanical property data taken through the experiment could be used as design allowables if a greater database was created. The feasibility concept was not only demonstrated through these tests but will add a significant amount of cost reduction through the reduction in post operations and reduced labor.

4.1 Directions for Future Studies

Upon the completion of this preliminary investigation, there are several topics which could be further investigated. These investigations could lead to a modeling analysis to better predict these new materials which would lead to optimization in the design community.

Subsequent research should study the effects of the laminate properties as a function of a co-molded insert. Although this study focused more on the fiber behaviors about one times the diameter of the co-cured insert, subsequent studies to determine the affects of the laminate properties such as tension, compression and shear. The presumption is that out-of-plane fiber waviness and a co-cured detail could be a recipe for reducing stress concentration on a global scale.

Fractographic investigation is recommended for determination of initial failure of laminates with co-molded composite panels. This will provide a better understanding of failure mechanism of co-molded panels.

Insert surface finish characteristics such as surface treatments of grit blasting, etching, primers, etc, should also be examined. The mechanical lock between the fibers, resins and metallic interface could be crucial to improving the mechanical properties of the co-cured detail if needed.

Although the tapped laminate co-molded insert panel performed much worse than the composite molding compound, perhaps a more representative baseline panel using molding compounds with a significant attempt to reduce fiber waviness could be fabricated, examined and tested. The attempt to reduce fiber waviness would be a processing issue and could make the part cost increase dramatically but this could be investigated to better quantity the effects.

APPENDIX A

BACKUP DATA ANALYSIS

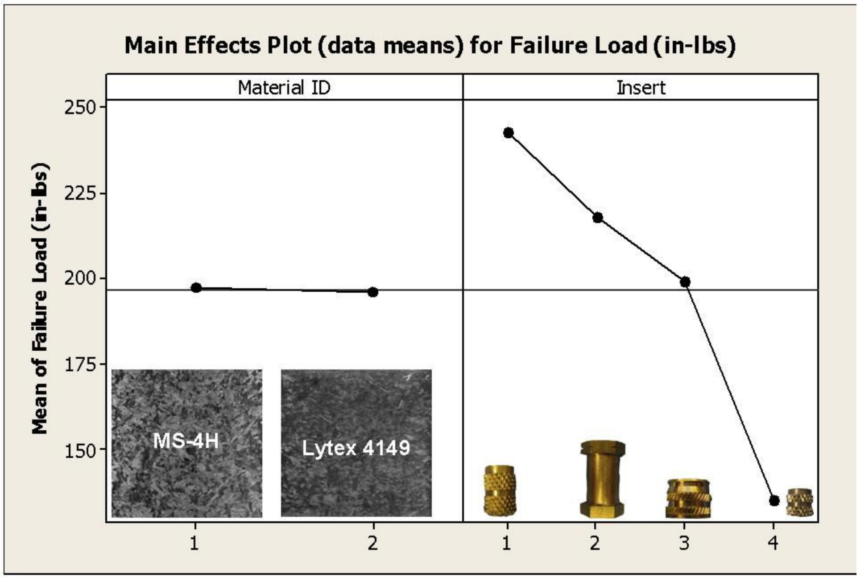
A.1- PARAMETERS USED IN THE GENERAL LINEAR MODEL

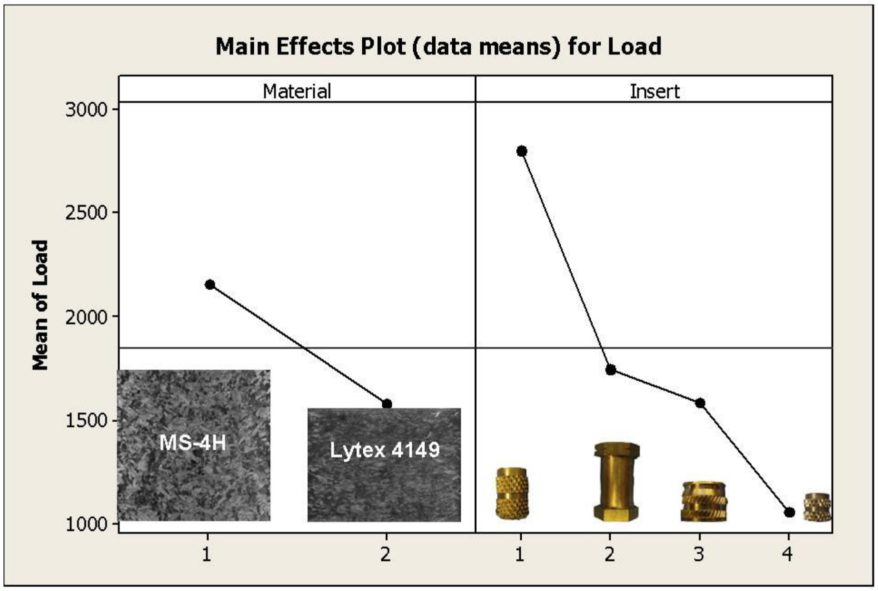
- DF= Degrees of Freedom
- SeqSS= Sequential Sums of the Squares for each term in the model measure the amount of variation in the response that is explained by adding each term, given that all the other terms are already in the model.
- Adj SS= The adjusted sum of the squares for a term in the model measures the amount of additional variation in the response that is explained by the term, given that all the other terms are already in the model.
- P= this is the probability that one would have obtained samples as extreme, if P is less than or equal to the α-level selected, then the term is deemed to have significant effect on the response. Likewise, if P is larger than the α-level selected, the effect is not significant.
- A-level, If one concludes that there is a difference between factor level means and there is not, you make a type I error. The probability of making a type I error is called alpha (α) and is sometimes referred to as the level of significance. When choosing a α-level, the smaller the value, the less likely you are to incorrectly reject the hypothesis. The most commonly used α-level is 0.05 because the chance of finding an effect that does not really exist is only 5%.

A.2-GENERAL LINEAR MODEL DATA SET

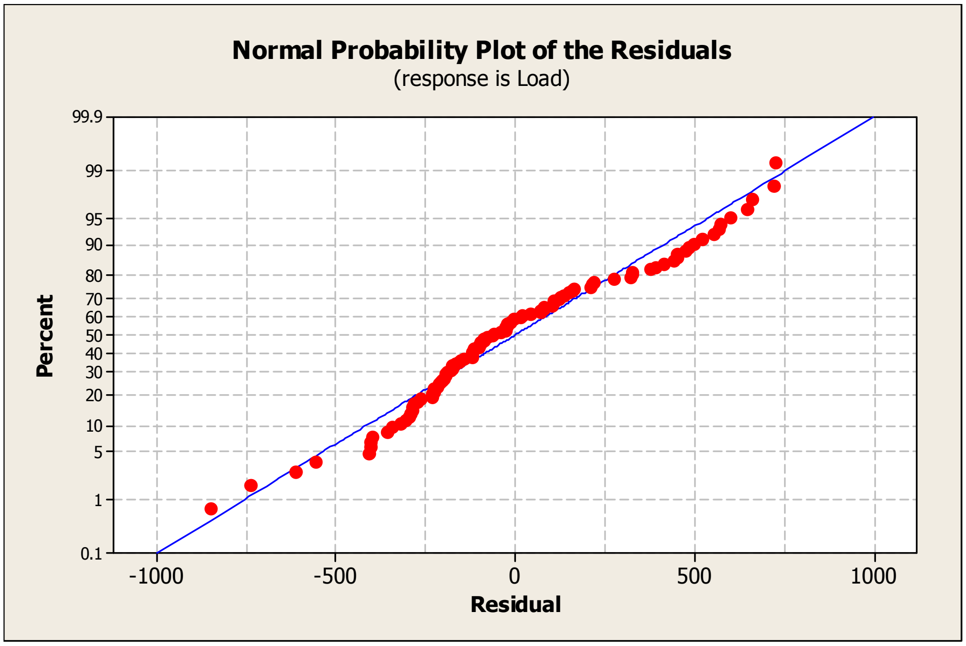
```
General Linear Model: Pullout Load, Waviness A, ... versus Insert depth
Factor        Type   Levels  Values
Insert depth  fixed       4  0.281, 0.300, 0.530, 0.688
_____________________________________________________________________
Analysis of Variance for Pullout Load, using Adjusted SS for Tests

Source        DF    Seq SS    Adj SS   Adj MS      F      P
Insert depth   3  10994383  10994383  3664794  62.07  0.000
Error         16    944656    944656    59041
Total         19  11939039
S = 242.984   R-Sq = 92.09%   R-Sq(adj) = 90.60%
Unusual Observations for Pullout Load
     Pullout
Obs     Load      Fit  SE Fit  Residual  St Resid
  2  2743.00  3262.00  108.67   -519.00     -2.39 R
  5  3908.00  3262.00  108.67    646.00      2.97 R
R denoted an observation with a large standardized residual.
_________________________________________________________________________
Analysis of Variance for Waviness A, using Adjusted SS for Tests

Source        DF  Seq SS  Adj SS  Adj MS     F      P
Insert depth   3   41.68   41.68   13.89  0.67  0.582
Error         16  330.90  330.90   20.68
Total         19  372.58
S = 4.54768   R-Sq = 11.19%   R-Sq(adj) = 0.00%
Unusual Observations for Waviness A
Obs  Waviness A     Fit  SE Fit  Residual  St Resid
  3     19.0400  4.5820  2.0338   14.4580      3.55 R
R denotes an observation with a large standardized residual.
_________________________________________________________________________
Analysis of Variance for Waviness B, using Adjusted SS for Tests

Source        DF  Seq SS  Adj SS  Adj MS      F      P
Insert depth   3  3.8358  3.8358  1.2786  16.48  0.000
Error         16  1.2411  1.2411  0.0776
Total         19  5.0769
S = 0.278509   R-Sq = 75.55%   R-Sq(adj) = 70.97%
Unusual Observations for Waviness B
Obs  Waviness B      Fit   SE Fit  Residual  St Resid
  8     1.98000  1.26400  0.12455   0.71600      2.87 R
R denotes an observation with a large standardized residual.
_________________________________________________________________________
_
Analysis of Variance for Waviness C, using Adjusted SS for Tests

Source        DF  Seq SS  Adj SS  Adj MS     F      P
Insert depth   3   8.887   8.887   2.962  1.74  0.199
Error         16  27.221  27.221   1.701
Total         19  36.108
S = 1.30433   R-Sq = 24.61%   R-Sq(adj) = 10.48%
Unusual Observations for Waviness C
Obs  Waviness C      Fit   SE Fit  Residual  St Resid
 20     0.23000  3.22000  0.58332  -2.99000     -2.56 R
R denotes an observation with a large standardized residual
```

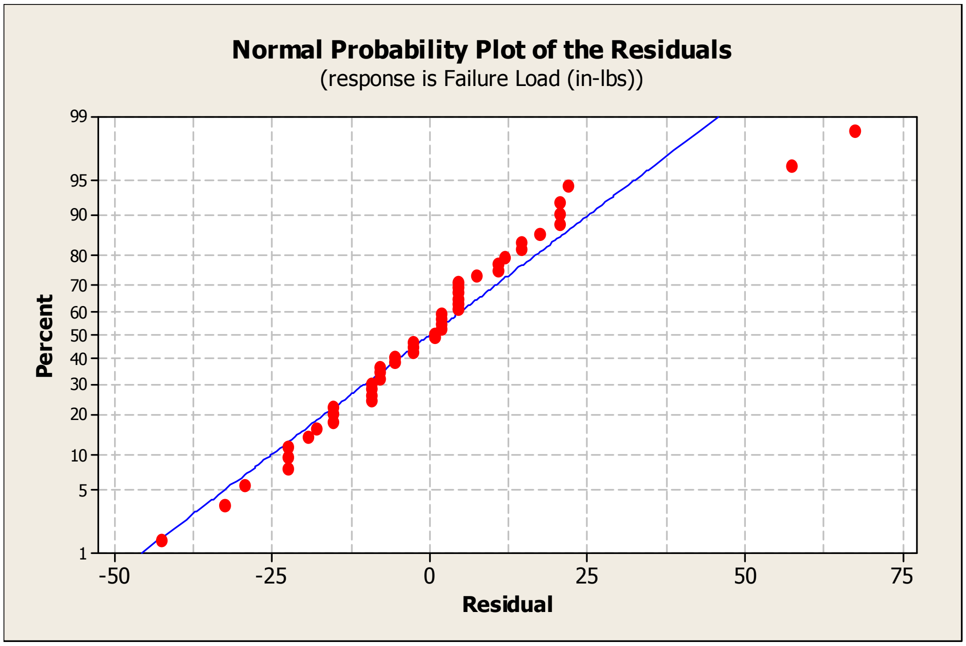
A.3- STRENGTH COMPARISON BETWEEN CMC MATERIALS
YLA MS-4H AND QUANTUM LYTEX 4149





A.4- NORMALITY PLOTS





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BIOGRAPHICAL INFORMATION

Dan Reller is a Senior Research & Development Engineer at Bell Helicopter with background advanced composite automation manufacturing (AFP, ATL), composite structures producability, assembly techniques, composite bonding and composite materials and processes. Recent assignments included UAV prototype airframe assembly, exploration and characterization of large carbon honeycomb sandwich structures, composite compression molding compounds, and single cure composite rotor blades for commercial vertical lift aircraft. Mr. Reller previously worked at Alliant Technology Systems in Salt Lake City as a tool design engineer and development process engineer where he acted as manufacturing, process and tooling engineer for prototype parts in the composite space structure industry. Mr. Reller received a BSME from Washington State University and is currently working towards his MSME from University of Texas at Arlington focusing on advanced composite technologies and experimental test methods.