Effects of manufacturing defects on the strength of toughened carbon/epoxy prepreg composites
by Luke Everett Turoski

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University

Abstract:
Fiber reinforced prepreg composites are used extensively in the aerospace industry. Several manufacturing techniques have been implemented to automate the part lamination process. One such process is contour tape layup. A contour tape layup machine (CTLM) lays relatively narrow (75-150 mm) prepreg tapes beside one another to form a large composite. During layup, gaps and/or overlaps form between these tapes. This research examined the effects of gaps formed within each layer and the interaction between multiple ply gaps. Experimental and numerical analyses were performed.

Several types of failure tests were performed: unnotched tension, open hole tension, unnotched compression, and open hole compression. Virgin, ungapped samples and samples containing gaps were tested in each of these areas. Compression tests proved problematic, and a compression fixture was machined on site to help alleviate bending/buckling during the tests. An open hole compression scenario often drives a design at Boeing, so a more detailed test regime of this geometry was performed. This included strain field and damage initiation tests.

Finite element models were created for the unnotched and open hole-compression cases. Gaps were modeled as pure resin. Two models were created that varied the gap relationship to the hole in the open hole models. Several gap cases were analyzed for each of the models.

Nearly all of the experimental tests showed a reduction in failure strength with the introduction of gaps. The maximum experimental reduction was 16%. The numerical models predicted both increases and decreases in the failure strains, depending on the gap/hole geometry. The maximum reduction predicted numerically was 6%; most of the experimental reductions were higher than this. This discrepancy led to examination of other factors that may have further reduced the strength. Probable factors were bending caused by sample thickness variations and out-of-plane ply waviness, both artifacts of the gapped geometry.

Design and test method recommendations were made.

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APPROVAL

of a thesis submitted by

Luke Everett Turoski

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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STATEMENT OF PERMISSION TO USE

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Date 17 July, 2000

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Pascal in his Pensees wrote, "Certain authors, speaking of their works, say, 'My book,' 'My commentary,' 'My history,' etc. They would do better to say, 'Our book,' 'Our commentary,' 'Our history,' etc., because there is in them usually more of other people's than their own."

My thanks goes out to the entire MSU composites group and my family. Special thanks goes to Boeing, NASA, and the Montana Space Grant Consortium, whose support made this work possible.

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ABSTRACT

Fiber reinforced prepreg composites are used extensively in the aerospace industry. Several manufacturing techniques have been implemented to automate the part lamination process. One such process is contour tape layup. A contour tape layup machine (CTLM) lays relatively narrow (75-150 mm) prepreg tapes beside one another to form a large composite. During layup, gaps and/or overlaps form between these tapes. This research examined the effects of gaps formed within each layer and the interaction between multiple ply gaps. Experimental and numerical analyses were performed.

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CHAPTER 1

INTRODUCTION

The aerospace community uses fiber reinforced composite materials extensively in structural designs. Unidirectional composite plies are one layer of parallel continuous fiber reinforcement, with a matrix or binder surrounding the fibers. Composite laminates are made from several layers of variously oriented plies. A description of basic motivations and principles for composite materials is found at the beginning of almost every introductory composites textbook [e.g. Mechanics of Composite Materials, Robert Jones, (1975)].

There are many material options for both the fibers and the matrices. However, the dominant fiber in recent years for structures requiring high stiffness and strength is carbon/graphite [Agarwal and Broutman, (1990)]. Most glass fiber composites are made from dry woven fiber fabrics that are impregnated with resin at the time of the laminate fabrication. These materials are robust in that glass fibers can tolerate high strain to failure. The stiffer, lower strain to failure carbon or graphite fibers abrade or break when woven. The weaving can also introduce waviness and inconsistency in the fibers, reducing the strength of the composite [Pirrung, (1987)].

A preimpregnated ply, or prepreg, requires no weaving of the fabric. The prepreg ply is produced in rolls of tape that contain the unidirectional fibers already impregnated with the matrix. Prepreg materials generally perform better structurally than the corresponding dry fabric/resin impregnation method as a consequence of better manufacturing controls [Dominguez, 1987]. Due to their success, these materials have been implemented into thousands of applications, including commercial aircraft. The drawback of prepreg is that it can have considerably higher manufacturing costs.

Two manufacturing techniques have been used extensively to fabricate laminates from prepreg materials: hand layup and automated tape or tow-laying. Hand layup affords low initial set up costs and the use of large sheets of prepreg. However, it is labor intensive, time consuming, and can produce an inconsistent quality in final parts [Pirring, (1987)]. All of these factors lead to expensive manufacturing costs and so companies developed machines to automate the process [Williams, (1987)].

Automated tape and tow-laying in composite fabrication has increased significantly in recent years [Grant, (2000)]. Automated tape laying machines use relatively narrow (25-150mm) tapes to build composite parts. Several adjoining tapes are then required to build a large composite part. As the tapes are laid together, three manufacturing conditions arise.

First, the tapes can be laid perfectly beside each other, causing no discontinuity of prepreg material. However, width variance exists in the machine laid tape, so this variance translates to inaccuracy of the tape placements. This leaves two options. Either an overlap or a gap must exist between the adjoining tapes. Previous research on the geometric asymmetries and perturbation of reinforcing fibers caused by fiber overlaps led Boeing to implement a no overlap design specification. This leaves a gap between the tapes as the remaining option, as shown in Figure 1.

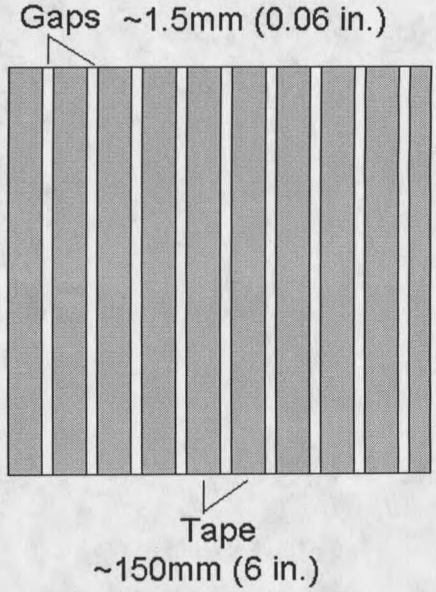

Figure 1. Formation of gaps.

As the layup proceeds, the gaps of each ply cross the others. The formation of the gap regions is shown in the two layer, simplified schematic of Figure 2.

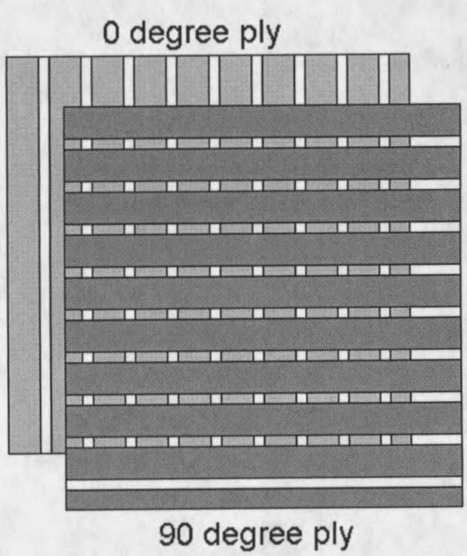

Figure 2. Formation of gap interaction regions.

Here, the small white squares represent the gap regions formed as a 0° layer is laminated with a 90° layer. These regions contain no reinforcing fibers and will be comprised of resin, voids, or both. In addition to the resin rich regions, the gaps also perturb the layer geometry; this is manifested in out of plane layer waviness and overall laminate thickness variations.

Little published research and testing have been done on these "gapped" composites, although the manufacturing techniques have been implemented. This lack of knowledge forces companies to conservatively knockdown the composite strengths. This motivates the research presented in this thesis.

The research objectives are to study the effects of the gapped regions on the material behavior with a series of mechanical tests and computer simulations. Then, design and manufacturing recommendations can be made for these gapped material.

CHAPTER 2

BACKGROUND

Some work has been previously done in the area of gapped regions created during automated prepreg manufacturing. These provide a background for the work presented in this paper. While none of the work specifically examines the question at hand, it helps develop a better foundation for understanding the problem. Following the survey of similar work, a few areas that became important in the research and results are discussed.

Previous Gapped Composite Research

Automated Tow-Placed Laminates

Some research was performed on automated tow-placed laminates. These differ slightly from automated tape layup. Instead of prepreg tapes, individual prepreg tows (about 2.54mm (0.1 in.) wide) are laid by the machine. It is obvious that gap and overlap regions are present. In fact, due to the small widths of the laid tows, gap and overlap regions are much more frequent in a tow-placed laminate compared to a similar laminate built with tapes.

Cairns, Ilcewicz, and Walker [(1993)] published data on the effects of the automated manufacturing defects. Notched tension experimental and numerical results were compared. The experimental failure improvement ratio from tape to tow was reported to be 0.795. This improvement was attributed to a larger damage zone in the tow placed laminates at the crack tip. The notched gapped composites were modeled globally and locally to study the influence of the inhomogeneity on the strain field and damage progression.

A unique finite element method was implemented. Modeling the multilayered composites with solid elements would have been computationally intensive. However, a laminated shell would not allow damage in specific plies of the laminate. So, a stacked shell approach was taken. A set of common nodes could be shared with separate shell elements for each layer. Then, damage was induced by splitting the nodes, giving the required elements separate nodes to act independently from one another, layer to layer.

While numerical results suggested a slight improvement from the effect of the inhomogeneity on the strain field alone, it could not account for the considerable improvement realized experimentally. Damage modeling showed splitting of the 0° ply greatly alleviated the influence of the notch. Delaminations seemed to do the same, and a combination of both provided the most benefit. These analyses showed up to a 36% benefit from these damage combinations.

Possible mechanisms for the experimentally observed improvement due to lap and gap regions for tow-placed composites were shown in this study. However, the improvement was only seen in notched tension samples.

Sawicki and Minguet studied the effect of these intraply gaps and overlaps on compression strength [(1998)]. They also used tow-placed laminates for the study. They studied both unnotched and open hole compression samples. These samples were laid up by hand with a gap and overlap in one of the 90° layers. This is shown in Figure 3. Gaps of 0.76mm (0.03 in.) and 2.54mm (0.1 in.) were studied. Again, each of these defects contained both a gap and an overlap. Laminates were nominally about 4-5mm thick, depending on the layup. Unnotched compression samples 13mm (0.51 in.) wide were tested in a modified IITRI fixture. A Boeing anti-buckling fixture tested samples that were 38mm (1.5 in.) wide with a 6.35mm (0.25 in.) diameter hole OHC.

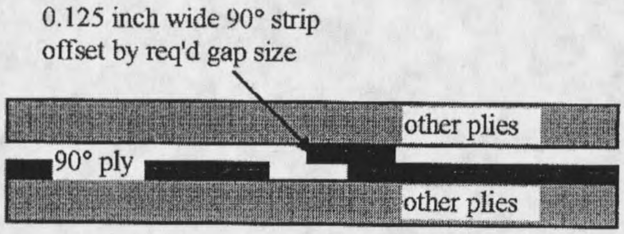

Figure 3. Fabrication of overlap/gap defects in test laminates.
From Sawicki and Minguet.

Unnotched samples with defects produced reductions in mean compression failure strain of 7.5-12.9% for samples at standard conditions. Hot wet samples produced reductions of around 20%. OHC samples produced reductions of 11.6 and 9.5% for standard conditions, and 14.7 and 27% for hot wet conditions. The authors noted that a large reduction was typically seen for the .76mm (0.03 in.) gap, and only a slightly greater one was noticed for the 2.54mm (0.1 in.) gaps. They noted that the hot wet reductions were significantly higher that the standard reductions. They stated that this implied the failure mechanisms which occurred local to an overlap/gap defect were likely to be matrix dominated. The authors discussed previous work studying samples with considerably more frequency of defects in every ply. A significant difference was not observed between the samples with one defect and the work done with samples containing many defects. This indicated that the failures were likely due to out of plane