Effects of ply drops on the fatigue resistance of composite materials and structures
by Mark Ethan Scott

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

Abstract:
Material thickness variations are required to optimize the design of laminated composite structures. These thickness variations are accomplished by dropping layers of material (plies) along the structure to match the load carrying requirements. Unfortunately, these ply drops produce internal stress concentrations as a consequence of material and geometric discontinuities. This thesis provides a parametric experimental investigation of ply drops in E-Glass stranded fabric reinforced polyester composites and structures. These parameters include: ply drop location, laminate thickness, number of plies dropped at one location, fabric type, loading condition, fiber content, and spacing between ply drops. The damage which develops at ply drops is typically delamination cracks which propagate between the layers of reinforcing fabric.

There were two parts to this study: (1) to examine delamination propagation rates at ply drops and determine crack growth threshold levels, and (2) to determine the effect of ply drops on the lifetime of various composite materials. Tests were conducted on both small coupons of material and beam structural elements with ply drops in the flanges.

A strong sensitivity to ply drop position and manufacturing details is shown for fatigue damage initiation and growth. The results indicate that it will be difficult to completely suppress damage and delamination initiation in service. For 0° plies, single internal ply drops provide the greatest delamination resistance. Multiple ply drops should be spaced at correct intervals so that the delaminations from each do not overlap prior to arrest. It was found that, in most cases, there is a threshold loading under which little growth after initiation is noted. Delamination retardation techniques such as ply edge feathering, "Z-Spiking" and adhesive layers improve the delamination resistance in many cases. After delamination has occurred, especially with exterior ply drops, it can be repaired with adhesives. Ply drops adversely affect fatigue lifetime of low fiber content laminates more severely than for high fiber content laminates. The choice of fabrics used in a laminate can have a significant impact on delamination rates, but the lifetime of the laminate is insensitive to fabric type.

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APPROVAL

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Mark Ethan Scott

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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Date 8/18/97

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ABSTRACT

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There were two parts to this study: (1) to examine delamination propagation rates at ply drops and determine crack growth threshold levels, and (2) to determine the effect of ply drops on the lifetime of various composite materials. Tests were conducted on both small coupons of material and beam structural elements with ply drops in the flanges.

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CHAPTER 1

INTRODUCTION

Today's need for stronger, lighter and cheaper structures has generated much interest in materials development, especially in composite materials. Fiber-reinforced composites have played a leading role in the technological advancement of structural material systems. Typically, fiber-reinforced composites are known for being light weight, high strength materials which are more durable than conventional materials. The use of composite materials in structural applications is rapidly increasing for commercial applications. With this increased use comes the need for a better understanding of the performance of the structures fabricated from composite materials, called composite structures. A large portion of composite structures are comprised of layered, laminated composite materials; thickness variations in such laminates are achieved by changing the number of plies in proportion to the thickness change. This requires the termination of layers, or plies, within the laminate, which then introduces a characteristic flaw into the material.

Laminated composites typically are fabricated from planar sheets of material, so that all fibers are oriented in a plane. Careful design and selection of the in-plane fiber orientation can create a laminate that is designed to carry the loads very efficiently in the plane of the fiber reinforcement. However, an inherent weakness of the laminate is the lack of fiber reinforcement in the direction normal to the fiber orientation . Consequently, the interlaminar direction, normal to the plane of reinforcement, is the weakest direction of the laminated material system. Therefore, any interlaminar loads that are applied to or induced within the structure are of particular concern in terms of structural integrity.

Figure 1, from Ref. 1, illustrates five structural elements used in laminated composite structures that produce interlaminar stresses. These common elements are the free edge, the open hole, the ply drop, and bonded or bolted joints. Free edges are unavoidable in many structures. Open holes are commonly employed to allow access to the internal parts of the structure. When the design calls for a laminate that is tapered in thickness, discontinuous layers or plies are utilized. It is also common to insert

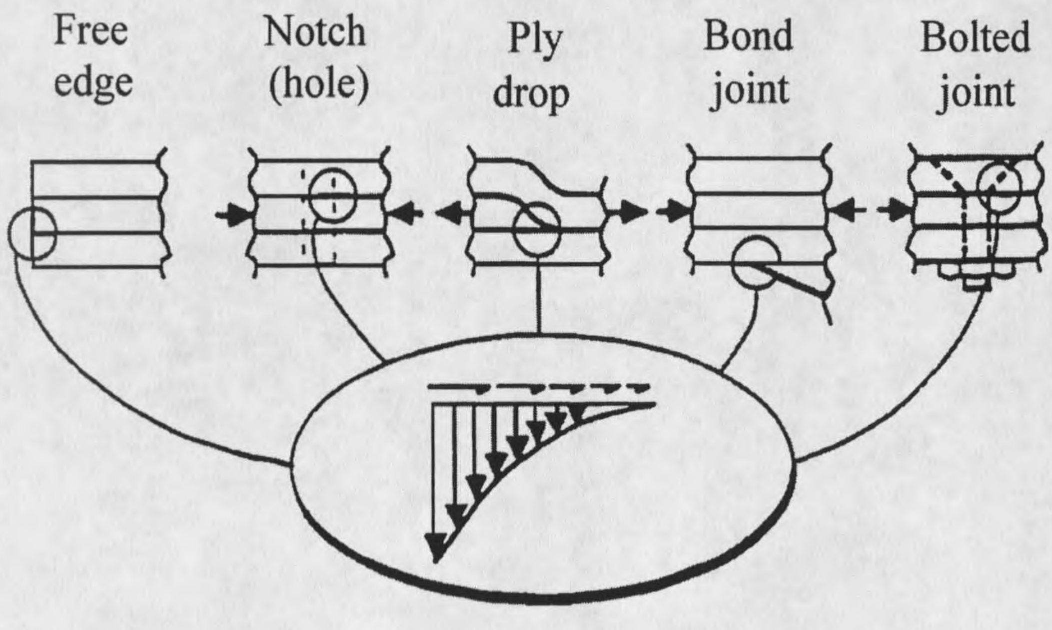

Figure 1. Common structural elements with discontinuities from Ref. 1

discontinuous plies to create a local build-up or thickening at high stress points. Finally, bonded or bolted joints are required to attach multiple sub-components of the structure. Each of the structural elements shown in Figure 1 develop significant out-of- plane normal and shear forces when the component is under load. These interlaminar loads are acting on the plane of minimum strength and toughness of the laminated structure. Therefore, each of these structural elements have the potential to cause a delamination of the individual layers. In addition, most analyses and failure models do not account for these interlaminar loads. The interlaminar performance of these critical structural elements provides a limit to the structural performance of the composite structure. It is important to note that the approach taken in this thesis is also directly applicable to some degree to all of the interlaminar stress risers illustrated in Figure 1.

The approach in this work was to focus on the ply-drop configuration. This is an unavoidable flaw if the thickness is to be tapered, and has received limited attention in the literature with respect to low cost composites of this type under fatigue loading. A parametric experimental study of the influence of various geometric details of ply drops was carried out using laminate coupons, in terms of both the delamination resistance and the reduction in fatigue lifetime. The work is then extended to ply drops in the flanges of larger I-beam structures.

CHAPTER 2

BACKGROUND

This Chapter reviews the basic mechanics of delamination in terms of the strain energy release rate. Several key problem areas associated with thickness transitions in composite laminates are then identified and discussed. Issues in need of an increased research effort are identified.

Strain Energy Release Rate

Once a crack is initiated in a structure it can be further propagated in any of three different modes, or a combination of these. Figure 2 shows the three modes of crack growth. Mode I is an "opening mode" crack, which is caused by normal stresses. In-plane shear causes Mode II or "sliding mode" cracks and Mode III cracks are caused by out-of-plane shear and are known as "tearing mode" cracks [2].

The strain energy release rate, G, is based on the Griffith criterion [2]. Griffith stated that crack propagation will occur if the energy released upon crack growth is sufficient to provide all the energy that is required for crack growth. The Griffith equation can be represented as

$$\frac{dU}{da}=\frac{dW}{da} \qquad \textbf{(1)}$$

where U is the elastic strain energy and W the energy required for crack growth. G is equal to dU/da and is sometimes called the crack driving force. The energy consumed during crack propagation is denoted by R, which is equal to dW/da, and is called the crack resistance. Thus, R is equal to the critical strain energy release rate to cause crack extension.

There is a different critical strain energy release rate for each mode of crack growth. A subscript denotes the particular mode. The critical strain energy release rate is

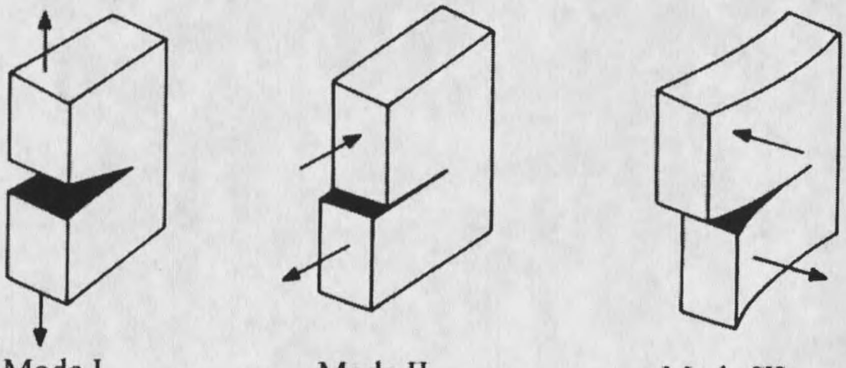

Figure 2. The three modes of fracture from Broek [2].

denoted with a "c" in the subscript following the mode designation. Above this value of G, in simple linear elastic fracture mechanics [2], a crack will propagate unstably in the structure. If there is a mechanism which produces increased crack resistance as the crack extends, the crack will propagate according to some R-curve behavior, requiring higher G values as crack extension occurs [2].

To determine an opening mode, or Mode I, strain energy release rate for delamination, a double cantilever beam (DCB) specimen is used. The critical strain energy release rate can be obtained by determining the area enclosed by the loading and unloading curves on a load-displacement diagram, which is the incremental change in stored strain energy, U, with crack extension Δa. A typical loading-unloading diagram for a DCB specimen can be seen in Figure 3. Another method to determine G_I values

$$G_{Ic}=\frac{12P_c^2a^2}{EB^2h^3} \qquad \textbf{(2)}$$

uses an analytic formula (Eq. 2) proposed by Benbow and Roesler [3] and Gilman [4] which takes into account the strain energy generated due to the bending moment of the DCB test, where a is the crack length, E the modulus parallel to the crack direction, B the laminate width, h is the half height and P_c is the critical load. Many G values can be obtained from a single DCB specimen which allows a crack resistance (R) curve to be generated, indicating how (and if) the resistance to crack growth changes with increasing crack length.

To determine Mode II crack growth resistance, it is necessary to use a different test method to determine the corresponding strain energy release rate. End notched flexure (ENF) tests apply a load to the center of the coupon; when the applied load

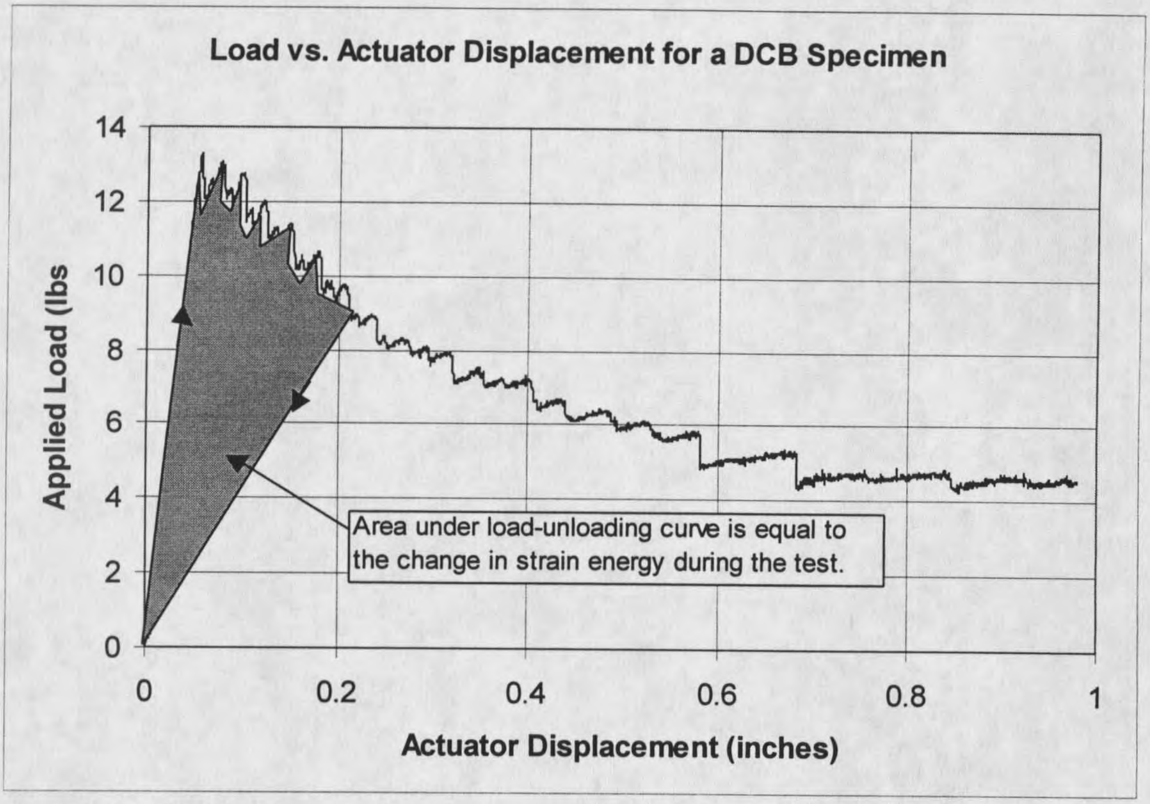

Figure 3. Typical load vs. actuator displacement for DCB specimen.

reaches a critical value, the crack propagates suddenly toward the center where the load is applied. In this type of test, there is only one data point collected as compared with the many points for the DCB specimen due to the instability of crack growth in the ENF specimen. A typical load-actuator displacement graph is shown in Figure 4. Since the load-displacement diagram is unstable for Mode II tests, an analytic formula is necessary to determine a G value. The formula proposed by Russell and Street [5] to calculate G_{IIc} is

$$G_{IIc} = \frac{9{P_C}^2 a^2}{16 E_x w^2 h^3} \qquad \textbf{(2)}$$