Experimental and Analytical Study of Delamination Arrest
by
Multiple Fasteners in Composite Structures

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Abstract

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The effectiveness of shifting the failure mode away from delamination by the installation of multiple fasteners in series which arrests and stabilizes mixed mode interlaminar failure in composite structures has been demonstrated through analytical and experimental investigation. Based on the novel mixed mode axially loaded specimen, a multi-fastener specimen was manufactured using a quasi-isotropic $[(0/45/90/-45)_{3S}]_2$ layup. Testing showed that the damage tolerance of the structure was improved by the inclusion of a second fastener in the crack arrest feature, with laminate failure occurring before significant delamination propagation past the second fastener. Concurrently, finite element models were developed with good agreement of the results. Parametric studies were performed which aid in the optimization of the feature by studying the relative effect of various parameters such as fastener spacing and stiffness as well as laminate thickness and layup. Additional modeling investigated the crack curvature caused by the installation of a fastener, and the possibility of modeling the system with one dimensional elements. It is recommended that the finite element solution be used to aid in the design of alternate specimen configurations which would increase the crack length prior to total laminate failure.

LIST OF FIGURES

LIST OF TABLES

Page

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Chapter 1
INTRODUCTION

1.1 Introduction

Offering significant improvements in specific stiffness and strength over metallic materials, composites have been increasingly incorporated into aircraft structures. To maximize these benefits, an increasingly wide variety of fiber reinforced composite materials have been developed for use in structural applications; starting in earnest in the 1960s. Recently, carbon fiber composites application has expanded from secondary structures to primary airframe structures to utilize the advantages of the anisotropy of the materials.

Composite materials have many desirable qualities for their use in primary aircraft structures. In particular, the anisotropic properties can generate a directional dependency of the strength and stiffness of structures which is advantageous for components such as spars and stringers that primarily carry longitudinal loads. Additionally, due to their resistance to fatigue cracking, composite structures can be manufactured in large sections, reducing part counts and allowing for the more efficient transferal of stresses through the large bonded area between components. Theoretically, a composite structure can be engineered without the need of fasteners for assembly, however considerations of delamination arrest require the use of fasteners in the structure for fail-safety. Manufacturing defects, impact damage, fatigue, as well as geometric discontinuities all contribute to bond failures which will unstably propagate, resulting in structural failure if steps are not taken to actively prevent this. Since delamination can result in critical structural failure, it is imperative to understand the delamination behavior of structures and how crack arrest features such as fasteners interact with the propagating crack. Through the development of predictive tools for crack arrest features, the efficiency of structures can be increased by minimizing the extraneous usage of fasteners for delamination suppression.

Additionally, crack arrest fasteners are often employed for other tasks, such as load transfer and are rarely installed in isolation, indicating a need to understand the interplay between multiple fasteners installed in series as a crack propagates and is arrested. This thesis is an experimental and analytical study of how two fasteners installed in series affects the delamination behavior of a composite structure.

1.2 Objective

The objective of this thesis is to conduct experimental research to extend prior research by Lin et al. [1-4] to crack stabilization and arrest by two fasteners installed in series in composite structures and develop stable accurate two dimensional finite element predictive tools for varying structural configurations.

1.3 Background

With the migration of composite materials into primary aircraft structures there has been much research into the fracture characteristics of bolted and bonded (hybrid) joints. Initial testing focused on the tensile strength of hybrid single lap joints [Jen and Lin 5, 6] with varied stacking sequence, overlap length, fastener properties, rivets and clamping force. This testing produced disbonding of the joint prior to tensile failure. Depending on the configuration, the resultant disbonding caused loading of the fastener, which continued to carry the joint load. Due to the asymmetry of the load path inducing bending, one of the most common joints, a single lap joint, has disbonding or delamination that occurs in a mixed-mode (modes I and II). Due to this complication, significant research has been conducted into composite hybrid double lap joints [Lee et. al 7] because the symmetric load path results in pure mode II delaminations. The testing indicated that failure consistently occurred as disbonding, propagating to the fastener, where the load began to be transferred. Further development of these concepts resulted in a mode II interlaminar failure test specimen [Gray, 8]. Subsequent testing and modeling validated the idea that a double lap specimen will provide an interlaminar failure specimen which fails in pure mode II and will accommodate crack arrest features such as a fastener. However, the specimens consistently failed in tension at the fastener before significant propagation occurred.

Building on the shortcomings of the mode II fracture specimen, a mixed mode sample was developed for the testing of fastener crack arrest effectiveness in bolted and bonded composite structures [Bruun 1]. Similar to the mode II specimen, which consisted of three plates, one of which was unloaded, the mixed mode sample consisted of two plates, one of which was unloaded. This approximated the configuration of the stringer and skin of a composite aircraft in service that had suffered a delamination. Analytical and experimental studies utilizing the mixed mode crack propagation and arrest sample indicated that while the crack begins to propagate in a mixed mode, the clamping force of the fastener effectively suppresses mode I, the opening mode. This results in a significant increase in load required to propagate the delamination because the fracture toughness in mode II is appreciably greater than in mode I. As well, the propagation is stabilized by the installation of the fastener, which is indicated by the upward slope of the crack length vs. load curve. However the isolated fastener does not fully arrest the delamination.

In relation, research has been conducted on load transfer by fasteners in multi-row fastener joints. Initial research, such as that by Tate and Rosenfeld [9] concerned themselves with metallic butt joints, and gave the fastener compliance as the sum of four individual compliances; fastener shear, fastener bending, fastener bearing, and plate bearing. Subsequently, Huth [10] developed a simpler expression for fastener compliance in multi-row single and double lap joints, derived from empirical data. Multiple experiments were conducted which showed the analytical expression is valid for bolted graphite/epoxy joints as well as bolted and riveted metallic joints. Huth stated that his solution provided higher accuracy compared to existing expressions. The inverse of the fastener compliance, the fastener flexibility can be utilized as a spring constant to reduce the complexity of the modeling by representing the shear stiffness of the fastener as a spring. It is critical to have an accurate expression for fastener flexibility in multi-row fastened joints for this research. Work by Cheung indicated that the shear flexibility of the fastener is the principle driver of crack arrest. Interestingly, the same research by Cheung, utilizing the mixed mode crack arrest specimen indicated that Huth's expression did not accurately predict the fastener flexibility for the specimen configuration in question [2-4]. It has not been investigated why, but utilizing a scale factor of 0.7 for the spring stiffness of the shear fastener significantly improved the agreement of the experimental and analytical results.

As disbond and delamination are a critical failure mode in composites, significant research has been conducted into determining onset and the modeling of this failure mode. A commonly utilized method which has a wide variety of applications is the Virtual Crack Closure Technique (VCCT) [Mabson 11]. The technique is based on the concept that the force required to close a crack at a short distance from the crack tip is equal to the load required to propagate the crack by the same distance. Thus, when the force at the crack tip reaches the load required to close the crack, the crack is assumed to propagate the same distance. The method is very powerful as it allows for a full mode decomposition of the strain energy release rates (SERRs) from relatively simple expressions. This mode decomposition subsequently allows for the understanding of the influence of the two main arrest capabilities that a fastener provides, mode I suppression, by clamping, and mode II resistance through shear flexibility. Because it relies on local crack tip information, such as the force between two nodes of elements on the bondline, VCCT is very well suited for finite element modeling (FEM) and has been implemented in the commercial FEM code ABAQUS [Mabson, 11]. Although research has been performed to develop closed-form expressions for the SERR mode I and II decompositions [Wang and Qiao, 12], which resolve the local behavior at the crack tip in addition to the global behavior, research on single fastener crack arrest specimens has indicated that this adds unnecessary complexity and the VCCT provides accurate predictions.

Chapter 2

DESIGN OF MULTIPLE FASTENER CRACK ARREST SPECIMEN

2.1 Existing Crack Arrest Specimens

A crack arrest specimen has been developed and demonstrated for single fastener crack arrest testing [Cheung, 2-4]. Evolving from the three-plate mode II fracture specimens, a two plate specimen produces a mixed mode crack propagation behavior and more consistently allows the crack to propagate beyond the fastener in testing. Although the crack originally propagates in a mixed mode manner, after a fastener is encountered mode I is effectively suppressed, which allows for the assumption of a purely mode II propagation behavior. Through the testing program, two main areas were identified to improve the fidelity of the data provided by the sampling. Initial samples were tested without using a tab, causing a bending load to be applied to the sample when it was installed in the tension testing machine due the asymmetric gripping of the sample. Consequently, a tab was bonded to subsequent sample sets, removing the extraneous bending of the sample. Second, the samples were cured under vacuum, which caused both global curvature in the plate from which the samples were cut and a curved termination of the unloaded plate. It was suggested that a hot press be utilized in the future.

2.2 Design of Multiple Fastener Crack Arrest Specimen

Leveraging the specifications of the two plate single fastener specimen, the sample design for the two fastener test article was generated. The principle change in the configuration was an increase in length to accommodate the second fastener while maintaining adequate area for the crack to propagate away from the influence of the grips. Since the fastener to grip spacing of the single fastener specimen seemed adequate, the additional length for the two fastener specimen was equal to the spacing between fasteners. The spacing was determined utilizing finite element analysis to locate a spacing which would provide some separation of the influences of each fastener, but also capture possible interaction between the two fasteners. The analysis was performed using the material properties summarized in Table 2.1. A two-dimensional plane strain model was developed by Wenjing Liu, and simulations of varying fastener spacing were then performed. It was determined that a spacing of 2 inches met these specifications, as it was greater than the typical fastener spacing of 5D for a 0.25 inch fastener, but the second fastener was located within the area which remained clamped together due to the first fastener.

Two main improvements in the sample manufacturing were included. The first was the creation and co curing of tabs, which made the two sample ends of equal thickness. This prevented unintended bending loads and simplified the sample manufacture by eliminating one step in the process. The second main improvement was the insertion of material in the gap between the tab and the plate termination. This section was wrapped in release film to aid in its removal after the curing of the sample, and was included to reduce the curvature of the shorter, unloaded plate at the point of its termination. Finally, the samples were cured using a hot press rather than of an autoclave to ensure the plate from which the samples were cut was flat.

Table 2.1: Composite lamina material properties (AS4/3501-6) [7].

	English Units	**SI Units**
Ply thickness	0.0075 in	0.1905 mm
E_1	18.5×10^6 psi	127.5 GPa
$E_2 = E_3$	1.64×10^6 psi	11.3 GPa
$G_{12} = G_{13}$	0.871×10^6 psi	6.0 GPa
G_{23}	0.522×10^6 psi	3.6 GPa
$\nu_{12} = \nu_{13}$	0.3	
ν_{23}	0.4	
G_{IC}	1.5 in-lb./in^2	262.7 J/m^2
G_{IIC}	7.0 in-lb./in^2	1226 J/m^2
η	1.75	1.75
$a=b=c$	1	1
Length	20 in	508 mm
Width	1.25 in	31.75 mm
Layup	$(0/45/90/-45)_{3S}$	

2.3 Sample Specifications

The specimen layup was chosen to be quasi-isotropic $(0/45/90/-45)_{3S}$. Because propagation load is correlated with the layup stiffness, a quasi-isotropic sample would provide an adequate baseline crack arrest effectiveness measurement from which different layups could be compared. To aid in the comparison between multiple and single fastener tests, the ply count mirrored the single fastener specifications and the width was the same value, 1.25 inches or 5 times the fastener diameter (5D) for a 0.25 inch fastener. The single fastener testing showed this thickness and width were appropriate and are representative of a standard thickness and fastener spacing. Finally, as detailed earlier, the sample length is 2 inches greater than that of the single fastener specimens to accommodate the installation of the second fastener. The layout is summarized in Figure 2.1.

Figure 2.1: Specimen Dimensions (units are inches)

Chapter 3

EXPERIMENTAL PROCEDURE

3.1 Test Matrix

Due to material limitations and the preliminary nature of the testing, an initial set of four samples was created and tested, as summarized in Table 3.1. While a larger sample set was desired, a material shortage limited the scope, and resulted in the material choice being a surplus Toray T-800S pre-preg, obtained from the Material Science & Engineering department. The subsequent goal for the testing section was to validate the finite element model predictions for a single data point; 40 in-lbs. of torque which represents the assumed torque of a fastener in service or ½ of the specified installation torque for the fastener in question and a 2 inch fastener spacing. However, as seen in Table 3.1, the actual testing did not proceed in the planned manner due to difficulties occurring after the testing of the first two specimens.

Table 3.1: Sample Test Matrix

Sample	*Install Torque*	*Fastener Spacing*	*Special Treatment*
1	40 in-lb.	2 in	None
2	40 in-lb.	2 in	Local Doubler Added
3	20 in-lb.	2 in	450^0F Post Cure
4	20 in-lb.	2 in	450^0F Post Cure

3.2 Sample Preparation and Testing Procedure

One of the principle assumptions in the Finite Element modeling was that the fastener hole had zero clearance, resulting in immediate engagement of the fastener when the crack had passed the fastener shank. Increasing clearance delays the engagement of the fastener shank, which results in a less effective crack arrest feature. As such, the clearance of the fasteners was controlled to replicate this behavior. This was accomplished by utilizing a new carbide tipped ¼ inch drill, which had the same diameter as the fasteners used. Additionally, guide plates were manufactured from aluminum to prevent walking of the drill bit and plywood was utilized as a backing material for the specimen to be drilled. This assembly was subsequently clamped to the table of a milling machine to enhance the accuracy of the drilling process. All eight holes were drilled in this manner. The close fit permitted the sliding of the fastener into the hole with slight resistance and prevented the bolt from falling due to gravity. This was believed to approximate a zero clearance hole for comparison between the experimental and finite element results.

The second important parameter to control was the installation torque of the fastener. Single fastener research indicated that the fastener torque, which generates preload in the fastener, thereby increasing the load transfer due to the frictional force at crack interface, has a significant influence on the crack arrest effectiveness of the fastener. However, preload cannot be directly measured, but only inferred through bolt equations or measuring the strain of the bolt. Because the equations for estimating the preload generated by a given torque are only approximate, and a strain gage could not be installed on the bolt during testing, the same two bolts were utilized for all of the testing to control for variance in installation torque,. As bolts are installed and removed, the threads become worn down and smoother, increasing the preload for a given torque by reducing the friction between the bolt and nut. The bolts chosen had been worn in through the installation and removal during single fastener testing, thus the preload generated by a given installation torque was expected to be consistent from test to test for these fasteners. This torque was measured by a click-type torque wrench which had been recently calibrated to sub 3% accuracy. For future testing, it is suggested to measure the change in length of the bolt due to installation, and infer the preload through the strain, assuming the original length is equal to the distance between the head and halfway up the engaged threads.

Another lesson learned from the single fastener testing was that the loading rate required for the successful tracking of the crack tip was significantly lower than typical for a destructive tension test. The crack tip was tracked visually and the position and load recorded for each extension. This required a loading rate of 0.1mm per minute during the propagation of the crack, otherwise the crack extension would be too rapid to provide an adequate number of data points. Prior to the propagation of the crack, the loading rate was 0.5 mm which provided an adequate compromise between stable initial propagation of the crack and rapidity of crack initiation.

A final concept borrowed from the testing of crack propagation and arrest with a single fastener was the method of tracking the crack tip. First the sides of the sample were painted white to visualize the crack extension, which appeared as a black line. It is critical to lightly but adequately paint the surface such that the paint does not bridge the gap created by the crack. An even white surface allows the crack to be easily seen. This is shown in Figure 3.1. After the sample side is painted, a scale is marked on the white surface utilizing a fine point pen. While previous testing employed a 0.125 inch scale, with careful penmanship, a 0.1 inch scale was created, simplifying the recording of the crack location in decimal values and allowing for a small increase in precision.

3.3 Initial Sample

The initial sample provided some information of the propagation characteristics of the delamination under the effects of two fasteners, however failure occurred at the first fastener before the crack passed the second fastener. Seen in Figure 3.1 the failure mode, occurring at the first fastener hole, is representative of the failure of all samples. For the limited data gathered during the test, the propagation behavior as seen in Figure 3.2 was highly similar to the single fastener testing up until the crack reached the second faster. This good comparison validated the sample manufacturing process and concept that the fasteners do not have significant influence until the crack tip approaches them. As well, since failure of the laminate occurred at approximately the same value as the failures in the single fastener testing, it was assumed that the failure was not a result of manufacturing defects introduced during the creation of the samples, but instead due to the stress concentration introduced by the hole.

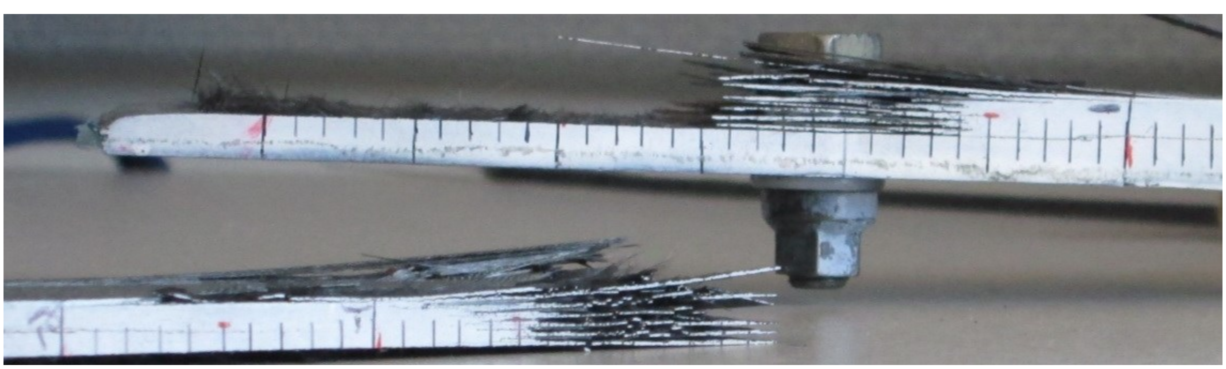

Figure 3.1: Sample Failure

3.4 Local Reinforcement of First Fastener Hole

A model of the local reinforcement was created in order to test whether this would provide adequate support to a specimen, based on the known failure stress at the first fastener. Modeling indicated a stress reduction at the first fastener which was considered adequate to prevent the failure of the specimen prior to adequate crack propagation. Although the behavior prior to the first fastener was now changed, the propagation past the second fastener was minimally affected, which was the desired effect.

Based on the failure mode of the first sample tested; filled hole tension failure at the first fastener, it was decided that a local reinforcement of the first fastener area had the potential to delay failure at the critical location long enough for the crack to pass the second fastener. The doubler was constructed utilizing a section removed from a cured sample. This was ground to an angle of approximately 15 degrees and bonded to the specimen utilizing Hysol EA9303, which is advertised as having high shear strength, a critical characteristic for this application. Unfortunately, while the doubler did slightly delay the failure of the specimen, the crack did not propagate past the second fastener, as the second specimen failed at the first fastener. Inspection of the sample after failure indicated a bond line failure occurred. As a result, the local reinforcement method of delaying the failure at the first fastener was discarded.

3.5 Post-Curing to Modify Bond Strength

Due to the failure of a local reinforcement to provide an adequate delay in sample failure, the second method of increasing the crack length utilizing the existing samples was devised; post-curing of the sample to modify the bond strength. Research has shown that overheating carbon fiber composites leads to a degradation in material properties, particularly in the matrix material. It was determined that one hour of heat at 450^o F would be sufficient to weaken the matrix, reducing the value of G_{IIC}, leading to an increase in crack length at an equivalent load level. Although this method was successful in increasing the crack length prior to failure, it was not for the predicted reason. Instead the post-curing increased the failure strength of the specimens, potentially indicating that the first curing cycle was not sufficient. After the success of the first post-cured sample, the remaining sample was post-cured as well and exhibited a similar response as seen in Figure 3.2.

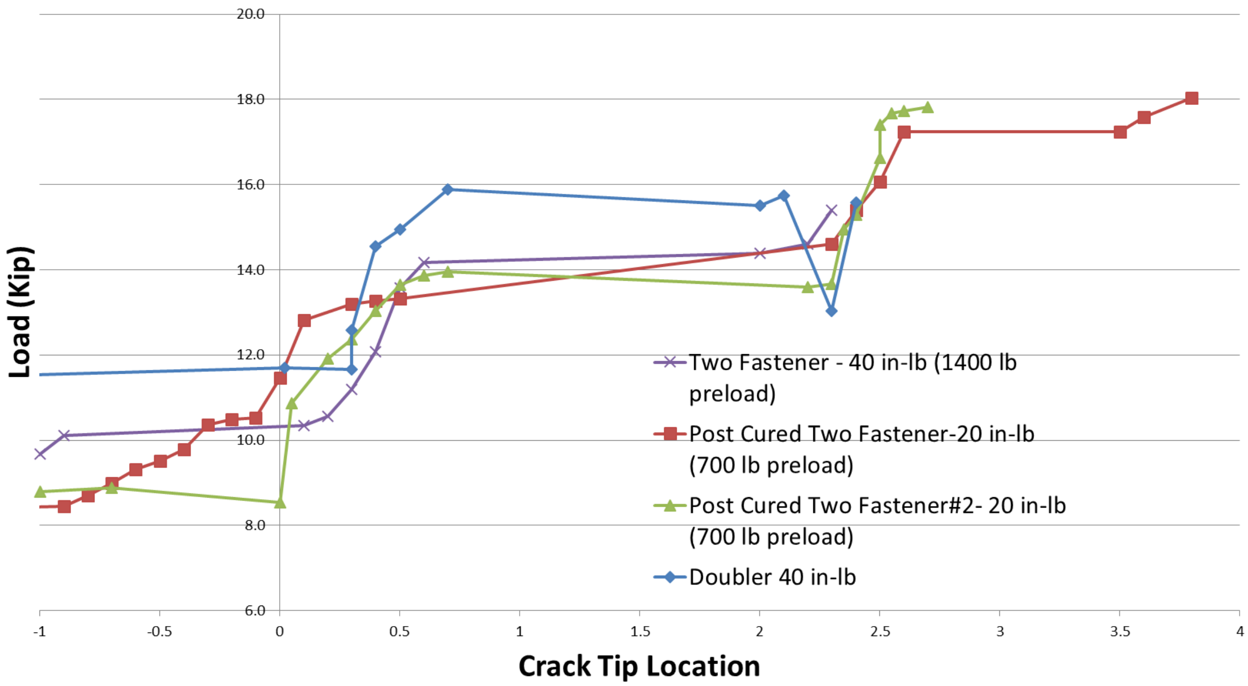

Figure 3.2: Experimental Load vs. Crack Length Results

Chapter 4

CRACK PROPAGATION CHARACTERISTICS

4.1 Test Results of Sample Set

As seen in Figure 4.2, the crack propagation is stabilized by the presence of the fasteners, visualized by the generally increasing propagation load. The doubler results are omitted as the test was considered a failure and the propagation response was significantly altered as seen in Figure 3.2. One of the principle reasons for the increase in propagation load at the first fastener is the removal of the mode I component of crack extension. This can be seen in Figure 4.1, as far away from the fastener the two plates are able to separate, but nearer to the fastener the plates remain clamped together by the fastener. Additional arrest capability occurs as the crack propagates past the fasteners when the shank becomes engaged in shear, transferring load to the unloaded plate. The third method of resisting crack propagation is the transfer of load via friction at the crack face. Combined, these three methods of transferring load into the unloaded plate reduce the value of G at the crack tip for a given applied load, leading to an increase in load required to propagate the crack. As the mode I component remains eliminated well past the first fastener, the initial fastener provides a noticeably larger increase in propagation load, approximately 5,000 lbs. of additional load is required compared to only 3,000 additional pounds of force to propagate the crack past the second fastener.

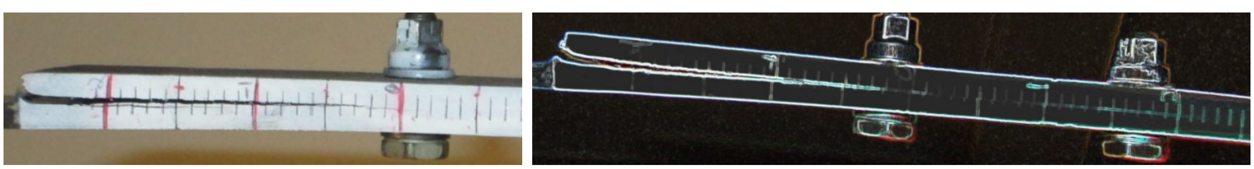

Figure 4.1: Delamination Side View

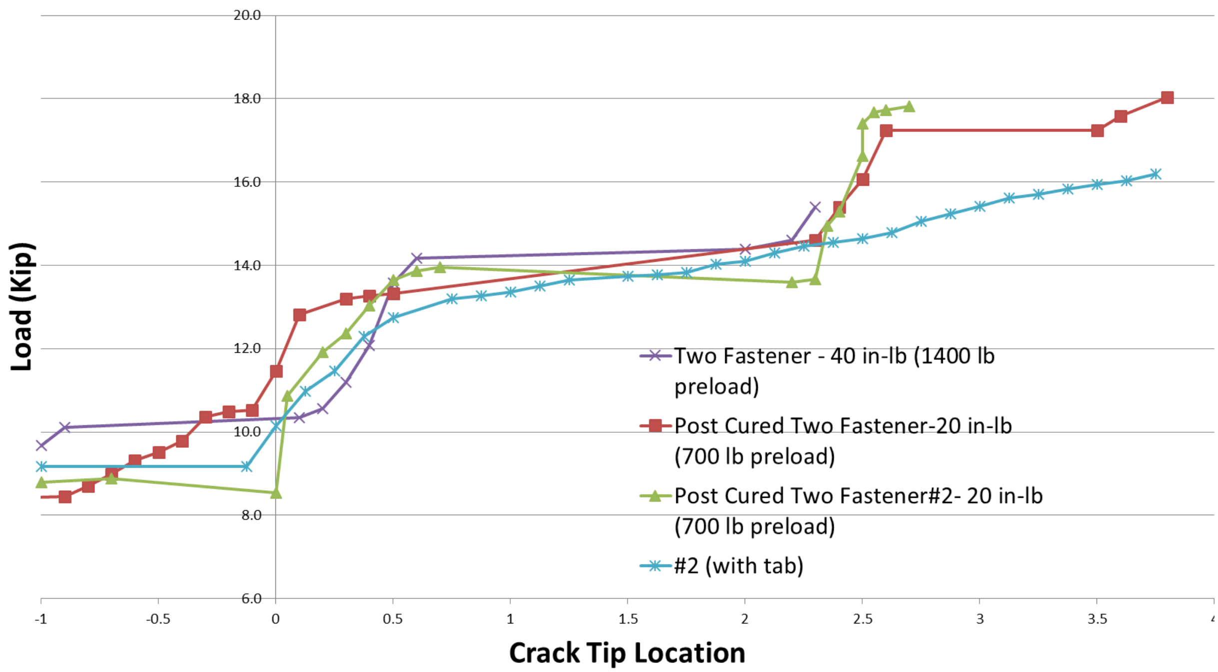

Figure 4.2: Two Fastener Results overlaid with Typical Single Fastener Result

Despite the generally favorable results from the installation of the second fastener, the installation of the additional bolt caused greater crack growth when propagation events occurred. As seen in Figure 4.2, where each marker represents a data point, the crack extensions are unstable as the crack extends from near the first fastener to the second fastener, seen by the flat or negatively sloped lines. One potential reason for this is that a stress concentration exists at the fastener holes, which presents a possible explanation for the loss in stability between the fasteners, which does not occur during single fastener testing. Additionally visualized in Figure 4.2 is the stability recovers once the crack reaches the second fastener, where there is a second increase in propagation load. Because mode I has been eliminated, this increase in propagation is hypothesized to occur due to the engagement of the fastener shank and the increased transfer of load through friction at the crack face as the delamination passes the bolt.

4.2 Comparison of Single Fastener Testing

As seen in Figure 4.2, when comparing the testing of two fastener samples with those utilizing only one fastener, the second fastener has minimal influence as the crack extends to the first fastener.

Once the crack extends slightly past the first fastener, the inclusion of a second fastener begins to play a role in the propagation behavior. When comparing the two different test scenarios, the propagation is less stable past the first fastener, leading to a larger unstable zone. However, once the crack reaches the second fastener, there is a significant increase in propagation load. This is caused by the engagement of the second fastener shank in shear, as well as the transfer of load via friction, both of which obviously don’t occur in a test with only one fastener. This increase in required load for crack extension leads to a laminate failure at approximately the same load levels as that of the single fastener testing, but with a distinctly shorter crack. Thus, the experimental results suggest that the inclusion of a second fastener is highly efficient in shifting the failure mode away from delamination by reducing the crack length.

Chapter 5

FINITE ELEMENT ANALYSIS

5.1 Initial Finite Element Model Description

Leveraging the success of prior model designs by Bruun, Cheung and Lin [1-4], a two dimensional model was built in the finite element software Abaqus which depicted a delaminating skin/stringer system with parameters summarized in Table 5.1. The model is built of two identical carbon/epoxy split beams joined together with titanium fasteners in series, shown in Figure 5.1 Both plates are 12 inches long and 0.18 inches thick, which represents a 24-ply layup, in this case quasi-isotropic $(0/45/90/-45)_{3s}$. The grips are not modeled; instead both beams are fixed at one end, while a load is applied to one beam at the other. The crack tip is initially 1 inch from the first fastener. This fastener is located 9 inches from the model end which is fixed. The second fastener is typically located 7 inches from the model's fixed end to present a 2 inch fastener spacing, however this spacing was now varied to investigate the delamination response.

Table 5.1: Lamina and Model Properties

Composite Lamina Material Properties (AS4/3501-6)		Model Properties	
Ply Thickness	.0075 in	Layup	$(0/45/90/-45)_{3S}$
E1	$18.5*10^{6}$ psi	Element	CPE4R (2D) C3D8R (3D)
E2=E3	$1.64*10^{6}$ psi	Plate Thickness	0.18 in/plate
G12=G13	$0.871*10^{6}$ psi	Layup	(0/45/90/-45)3S
G23	$0.522*10^{6}$ psi	Width	1.25 in
$\nu_{12} = \nu_{13}$	0.3	Length	12 in
ν_{23}	0.4	Fastener Spacing	2 in
GIC	1.5 in-lb./in^2	Fastener Stiffness	$1.6*10^{5}$ lb./in (shear)
GIIC	14.0 in-lb./in^2		$2.24*10^{6}$ lb./in (tension)
η	1.75	Preload	0 or 1000 lb
a=b=c	1	Friction Coefficient	0, 0.25 or 0.5

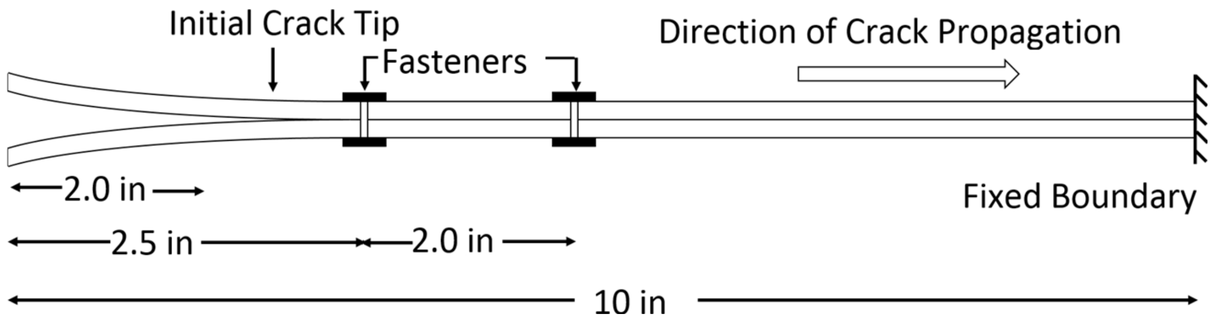

Figure 5.1: Two Fastener Model

To reduce the model complexity, each 0.25 inch diameter Titanium fastener is represented by two springs which enable the decoupling of the tensile and joint stiffness. The extensional stiffness of the fastener is calculated as $2.24986*10^6$ lb./in, based on the fastener area and elastic modulus. Meanwhile the joint stiffness is 160,883 lb./in; calculated using the fastener flexibility formula by Huth [10] with the 0.7 correction factor found by Cheung [4]. The springs are non-linear in their response to account for preload (tension spring) and clearance (shear spring). Preload is accomplished by establishing a non-zero load at zero extension. Similarly, as fastener clearance is assumed to simply delay the engagement of the fastener, the stiffness is set to zero for an extension range determined by the clearance and assumption that the fastener is centered in the hole. For the rest of the spring's response it is assumed to behave in a linear manner.

The model was meshed with 4-node plane-strain quadrilateral elements (Abaqus element CPE4R) of varying size. Initial modeling utilized one element per ply, resulting an element size of 0.0075 inches high and 0.015 inches long. Subsequently, the elements were assigned anisotropic element properties based on the AS4/3501 material system, with properties modified to indicate the rotation of the plies. Modeling which combined plies had elements 0.0225 inches high and 0.045 inches long.

The Virtual Crack Closure Technique (VCCT) is used to calculate the crack-tip energy release rates [Mabson, 11]. The disbond/delamination is assumed to propagate in a self-similar fashion, thus the crack tip always remains at the prescribed interface between the two beams regardless of load conditions. The B-K law [Benzeggagh, 13] as well as the power law are used for the mixed-mode fracture with the parameter η shown in Table 5.1. Finally, friction is modeled either as a constant value ranging from 0 to 0.5, or as stick-slip.

5.2 Development of 2D Finite Element Model

After the initial model was developed and refined to provide consistent convergence of the solution, further refinements were required to improve the accuracy of the predicted response due to the second fastener. Generally, the predicted crack arrest capability of the second fastener obtained from the finite element model was significantly larger than what was expected. Since the mode I component had been eliminated, the load increase required to propagate the crack due to the second fastener was expected to be equal or less than the load step at the first fastener, however this was not the case. This inaccuracy was generated by singularities created by the methods of modeling the shear spring, which interestingly did not affect the results of single fastener modeling. Prior to the refinement of the fastener modeling, the layup of the laminate was simplified to drastically reduce the simulation run time without compromising accuracy.

5.2.1 Simplification of Layup

When the model consisted of 48 plies, the same count as the experimental specimens, the simulations took approximately one day to complete when running on a desktop computer, due to the complexity of the problem. Additionally, when a failure of the solution to converge occurred it was typically near the simulation conclusion as the crack tip reached the second fastener, resulting in a full day spent without useful data. A faster model was desired to reduce the downtime waiting for simulations to complete in order to more efficiently model and perform parametric analyses. Based on the modeling technique of having 1 element per ply, the driving factor of the model complexity was the limitation that the element thickness be equal to the ply thickness. The logical conclusion was to reduce the ply count, thereby increasing the element size for a model of the same dimensions. As simulations had indicated that there is minimal bending deformation of the specimen, seen in Figure 5.2, the stacking sequence of the laminate should not contribute significantly to the elastic response of the test. The resultant layup was simplified to two plates of 8 plies each, the minimum number possible to still produce a symmetric quasi-isotropic layup. The results of the two simulations are shown in Figure 5.2.

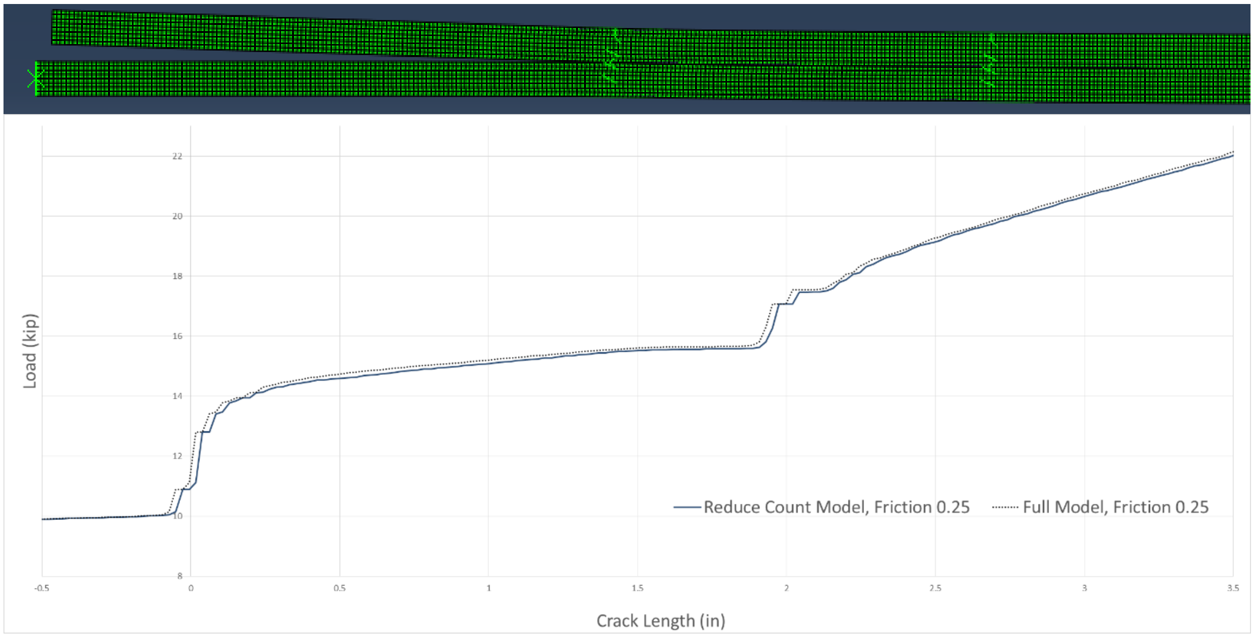

Figure 5.2: Bending Response (upper) and Propagation Comparison of 48 and 16 Ply Models (lower)

As seen in Figure 5.2, the 48 and 16 ply models have good agreement. The small deviation between the two laminate configurations can be explained by the slightly different bending stiffness values of the laminates. Because the 8 ply plates have the 0^o lamina clustered on the outside, the bending stiffness of the simplified model is larger, which results in slightly different propagation characteristics. As well, the model run time was reduce to approximately one hour as the number of degrees of freedom was reduced by an order of magnitude. The further research of quasi-isotropic laminates was conducted utilizing the simplified model since it enhanced the rapidity with which results could be delivered. Finally, simulations were evaluated for large bending deformations which could cause inaccuracies in the results.

5.2.2 Modification of Fastener Spring Location

Previous research in the propagation characteristics of delaminations in specimens with multiple arrest fasteners by Wenjing Liu indicated that the second fastener spring system was significantly more sensitive to the modeling methodology. In particular, while successful in single fastener designs, the inclusion of a fastener wall, designed to distribute the load generated by the shear fastener, created an artificial spike in propagation load. This was caused by the fastener wall rod increasing the shear stiffness of the laminate at the point of the fastener, a phenomena which does not occur in actuality. The removal of this wall subsequently reduced the load spike at the second fastener to a reasonable level. However, when running various models with zero friction, a jump in load remained present at the second fastener as seen in Figure 5.3's un-revised model.

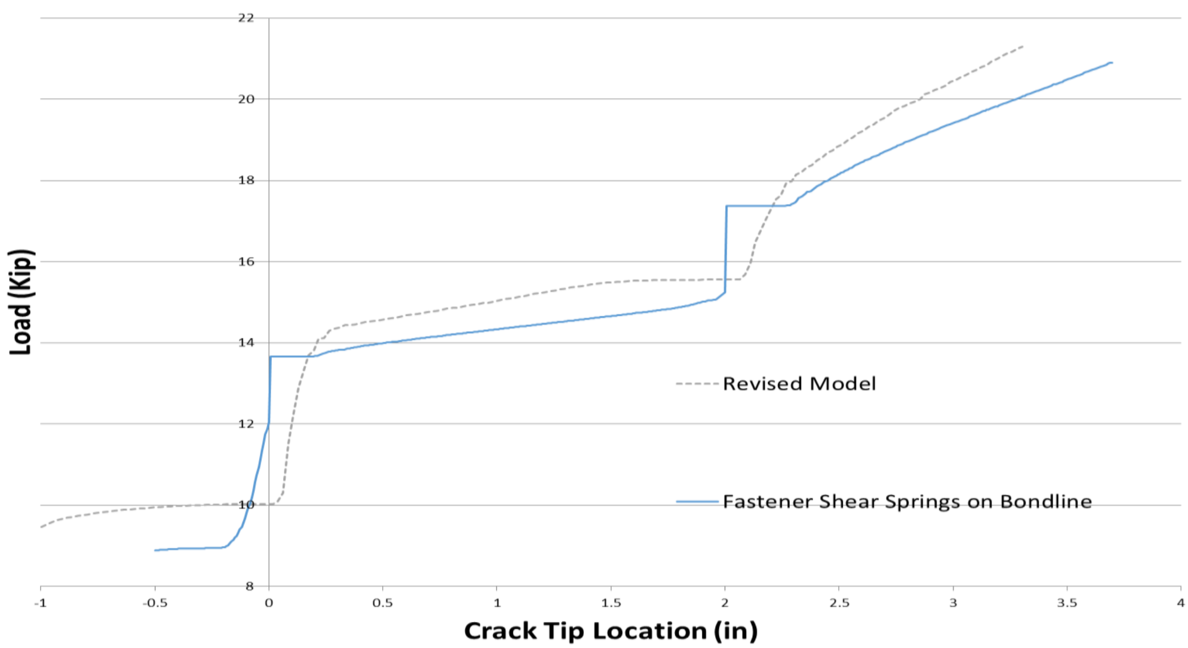

Figure 5.3: Comparison of Model Revision

Considering that the only propagation mode occurring at the second fastener was mode II, when friction was not included, the only way the fastener should be resisting the delamination is through shear stiffness. But this resistance should only occur after the crack has passed the fastener and the spring begins to extend, not prior to the crack reaching the fastener. Further investigation indicated that the application of the shear spring on the bondline of the specimen created a singularity at the node of interest. For this, the shear spring was moved 1 element off of the bondline, which resulted in more realistic predictions as seen in Figure 5.3. Demonstrated with the inclusion of friction, the fastener is able to become effective prior to the crack tip reaching it. The distribution of the preload through the laminate allows for the transfer of load through friction before the crack tip reaches the fastener.

5.3 Comparison of Modeling and Experimental Results

As seen in Figure 5.4, the experimental and computational results compare well. One of the most noticeable differences is the rightward offset of the experimental results compared to the analytical predictions. This is presumed to be due to the crack curvature. The propagation occurs faster near the edges of the laminate where it is tracked during the experiments, compared to the centerline, where it is measured during the simulations. Also, the finite element model tends to over predict the propagation load and stability. This can be attributed to three possible phenomena; unknown frictional forces at the crack face, clearance in the fastener hole and imperfect prediction of the fastener flexibility. The exact value of friction is still being researched, and better frictional modeling could improve convergence. Zero clearance was assumed for the simulations as the fastener holes were drilled to a close fitting tolerance, but the fastener may not engage as rapidly as assumed in the simulations. However, overall the modeling provides a satisfactory predictive capability for laminates with multiple arrest features.

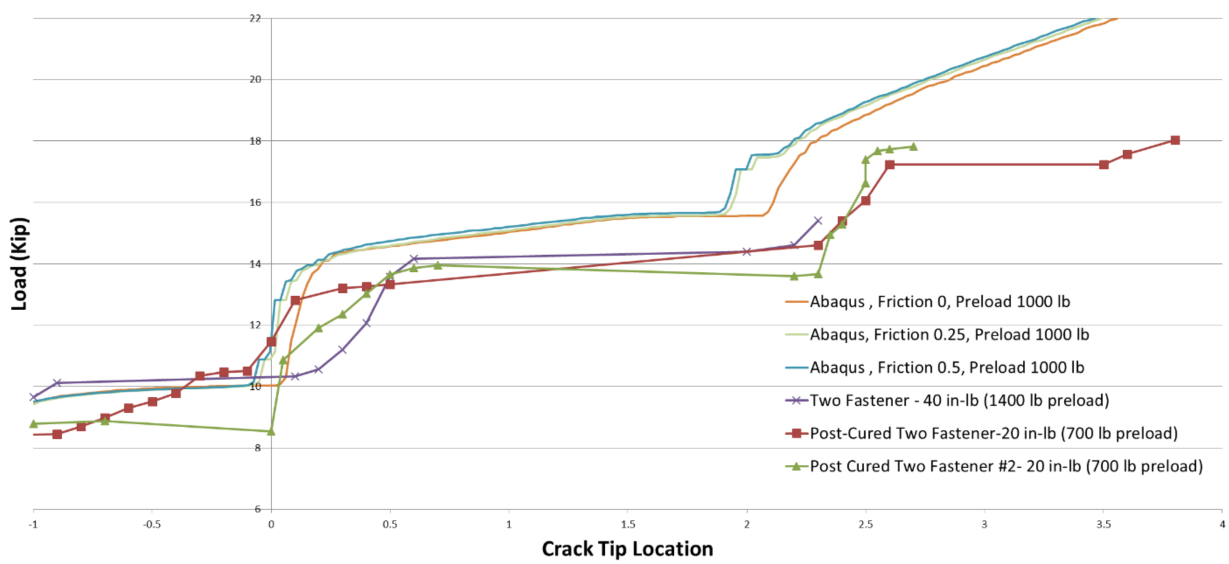

Figure 5.4: Propagation Load of Experimental and Finite Element Tests

5.4 Development of 1 Dimensional Model

Preceding research into the delamination of composites with arrest features had developed single dimensional beam models based on the Principle of Minimum Potential Energy (PMPE). However, with the inclusion of a second fastener, this methodology becomes untenably complex, particularly when trying to account for a varying fastener spacing. To explore the possibilities of a one dimensional model which could provide rapid and accurate results, a beam based finite element model was developed. Development of this model used Abaqus to take advantage of the stability of the program and advanced VCCT capabilities in order to investigate the design of a custom code for calculating the response of a beam model.

In order to reduce the complexity of the model, the plane strain plates were reduced to beams. Classical Lamination Theory (CLT) was utilized to predict the global properties of the beam which were assigned anisotropic properties. While it would be possible to model multiple beams, each a single anisotropic ply, this would cause at least an eight-fold increase in complexity compared to utilizing CLT, without any expected increase in accuracy. One difference that resulted however was that the two dimensional elements were assumed to be in plane strain, which is not an assumption for the formulation of beam elements. Finally, the fastener heads were not modeled, as the inclusion of the heads prevented convergence of the model. This resulted in a more concentrated force applied by the extensional fastener spring, but minimal deviation in the results.

As seen in Figure 5.5, the results for the one and two dimensional models provide reasonable agreement. The most significant difference is that the inclusion of friction causes a different response in the two models. A lack of fastener heads causes the preload, which generates the frictional force, to be concentrated directly under the fastener spring. This results in a significantly sharper spike in the load required to propagate the crack compared to the two dimensional model, as the frictional force is immediately included once the crack has passed the fastener. Secondly, the propagation load is over predicted by the single dimensional model. This requires further investigation, as the two suspected causes are the fastener flexibility and the modeling of the beam properties using CLT. While it had been demonstrated that a single dimensional code could be developed to provide accurate results for the prediction of crack propagation with two arrest fasteners, this method was not developed further due to the consistent failure of standard specimens prior to significant propagation past the second fastener causing a refocusing of efforts elsewhere.

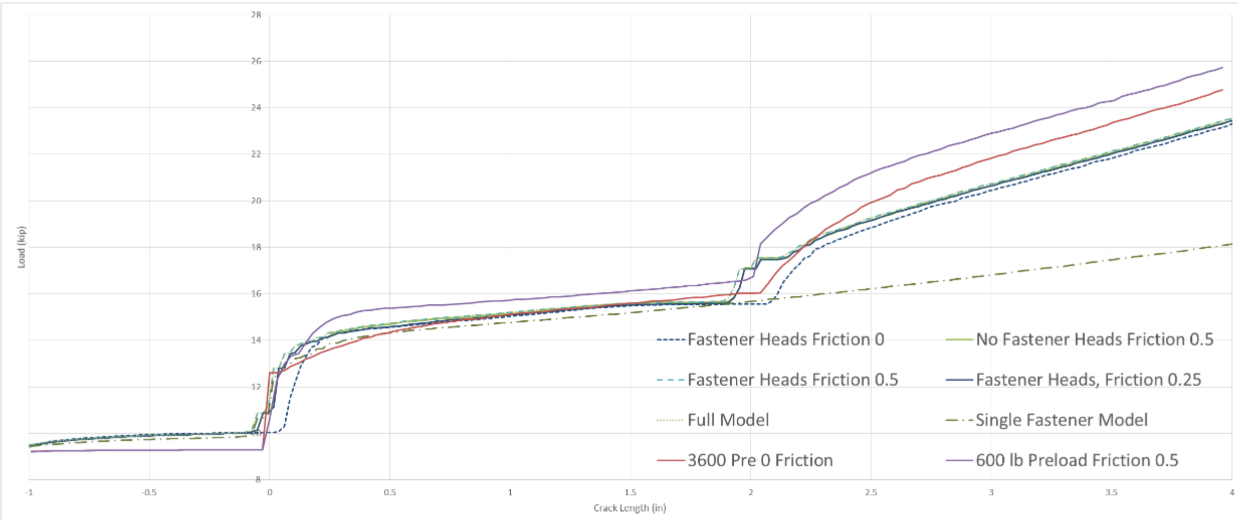

Figure 5.5: Model Comparisons

5.5 Development of 3 Dimensional Model

A three dimensional model was initially developed to investigate the stresses induced by the preload of the fastener on the crack face. This was of interest as the preload distribution could affect the resultant distribution of the frictional force which provides load transfer between plates. Second, the model was increased in size to mirror the two dimensional model specifications to investigate the curvature of the crack front as it propagated down the specimen. This explored the main limitation of the two dimensional model which was the assumption that the crack front did not possess significant curvature.

5.5.1 Fastener Preload Distribution

To investigate the local distribution of the fastener preload in the layup of the specimen, a 1.25 inch square was modeled. This was determined to provide sufficient area for the preload distribution but minimized the computational cost of the model. All 48 individual lamina were modeled similar to the method utilized in the two dimensional model, each ply was one element thick and the elements were assigned anisotropic properties which corresponded to the direction of the layer in question. The model of the fastener was simplified because the intricacies of its response were not of interest; the bolt was modeled as three connected cylinders representing the shank, head, and nut. Thermal effects were included, to account for the stresses generated in the laminate during the curing process, by first solving the thermal problem in the plate and then utilizing the solution as the initial conditions for the preload simulation. This was found to have a negligible effect on the final preload distribution. Finally, the preload was then applied utilizing the Abaqus "Bolt Load" load utility, which adjusts the length of the bolt shank to generate the appropriate load in the fastener shank.

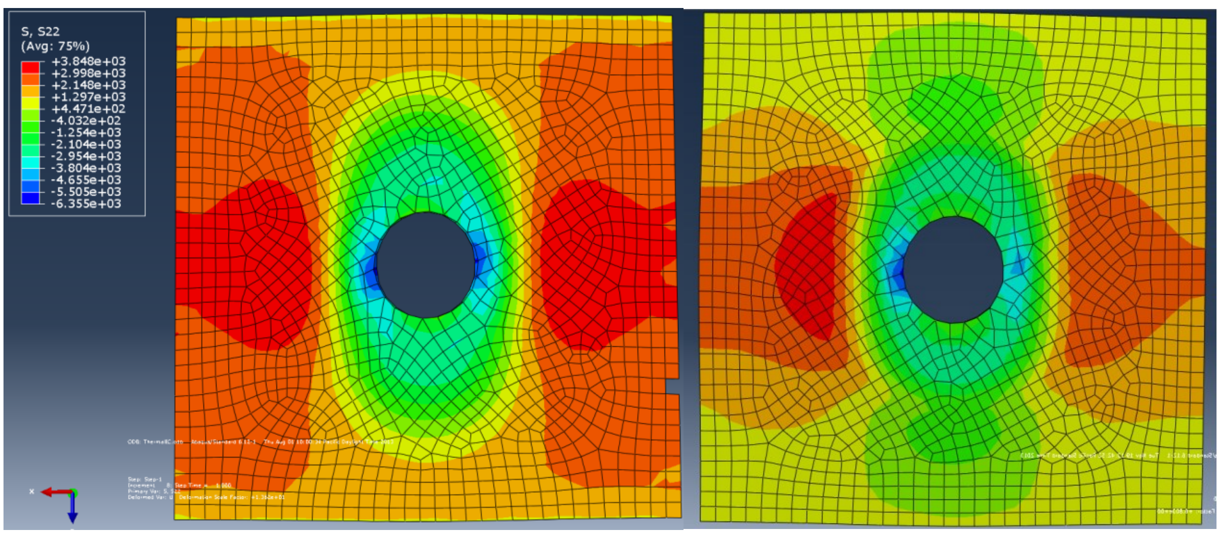

Figure 5.6: Model Preload, 0 Degree Interface on Left, 45 Degree Interface on Right

As seen in Figure 5.6, the preload is asymmetrically distributed with fiber direction of the laminate oriented vertically in the left picture, and at a 45° angle in the right. This distribution is due to the anisotropic properties of lamina which cause an asymmetric preload distribution, despite the layup being quasi-isotropic. This is of particular importance because the distribution of load transferred due to friction will be affected by this distribution, changing the local strain energy release rates compared to an isotropic material. A comparison of the inclusion of thermal effects is not pictured as there is minimal difference between the two cases. While stress is induced through the curing process, this stress is generally in plane, and is dwarfed by the stresses created by the preloading of the fastener.

5.5.2 Fastener Induced Crack Curvature

Prior research [Gray, 8] has shown that the crack has significant curvature near the fastener. This is particularly important as the sample width becomes greater than 1.25 inches, since the delamination could potentially steer entirely around the fastener instead of being forced to propagate through it, dramatically reducing the effectiveness of the arrest feature. Due to the computational requirements for a model incorporating 48 plies, only a simplified 16 ply model was generated. Otherwise the modeling methodology remained the same as the local preload model. Although a mapped mesh was originally implemented to improve the crack propagation characteristics, ultimately the mesh was generated utilizing the Abaqus default settings in order for the model to converge. As seen in Figure 5.7, this results in an oddly shaped mesh. Further development of the model, in particular the mesh, did not occur due to a refocusing of efforts elsewhere.

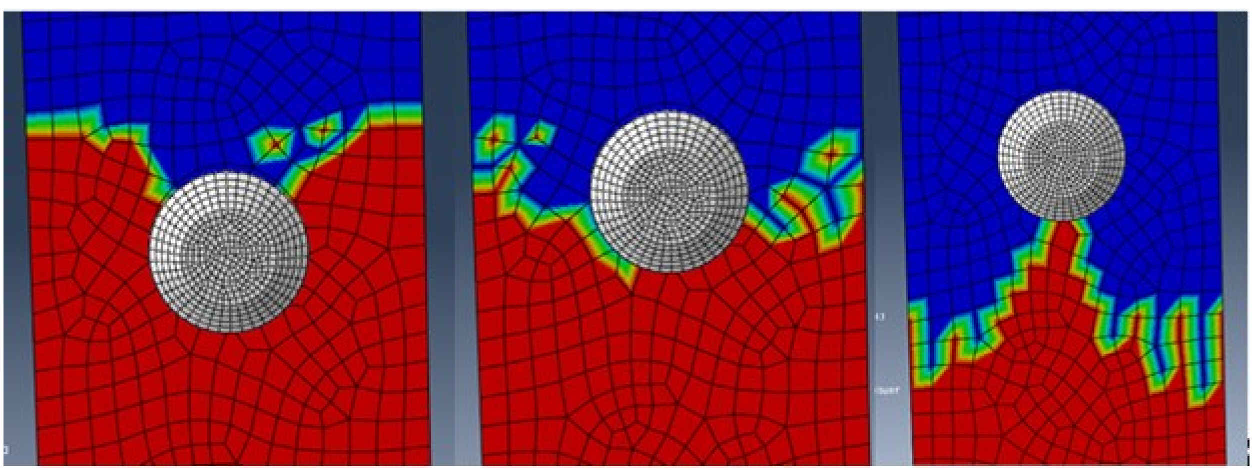

Figure 5.7: Crack Curvature in Three Dimensional Model

Visualized in Figure 5.7, there is clear crack curvature as the crack propagates around the fasteners. The direction of propagation through the laminate is down as pictured. Interestingly the crack initially curves in toward the fastener, before reversing direction as the crack passes the fastener. The “islands” of bonded area visible in the figure are artifacts of the VCCT code interactions with the free-form mesh and should be ignored. To investigate this curvature phenomenon, the fastener was removed and the simulation was again run both as a DCB and a two point ENF specimen. In both cases, the crack front remained flat, which indicated that the fastener had significant influence on the propagation behavior, while the simple inclusion of the hole did not. However, the exact mechanism by which the fastener increases the value of G nearby and in front of the hole is unknown. Conversely, the curvature occurring as the crack passes the fastener can be explained by the engagement of the fastener. This reduces the stress in a localized area behind the fastener, causing it to remain bonded at a higher load compared to areas further away. This has significant implications for crack arrest arrays with a spacing wider than the typical 5D. Obviously, as the bolt spacing becomes larger, a reduction in arrest control may be encountered due to crack propagation around instead of through the arrest features.

5.6 Parametric Analysis Using the Finite Element Model

Employing the two dimensional model, parametric studies were performed to locate areas for further investigation and optimization of the arrest feature. The parameters were chosen to represent possible variations which could be accomplished with relative ease in a manufacturing environment and had the possibility to aid in the improvement of the arrest features. All parametric analyses vary from a base configuration, with parameters previously summarized in Table 5.1. Although failure modes were not included in the modeling, the loads at which alternate failure modes would occur can be extrapolated from test data of equivalent laminates.

5.6.1 Influence of Friction

Friction was found to be a major driver of crack arrest in the current research as well as prior experiments. By transferring some of the load into the unloaded plate through friction, the stress is reduced at the crack tip for a given load, improving the delamination characteristics of a given specimen. Two models of friction were generated; stick-slip which assumes different static and kinetic coefficients as well as a constant value of the coefficient. Because the sliding distance is small but at high speed, the kinetic coefficient was not assumed to be velocity dependent. Many different combinations of friction coefficient and model were simulated in order to represent the bounding and typical cases that would be encountered. The results are summarized in Figure 5.8.

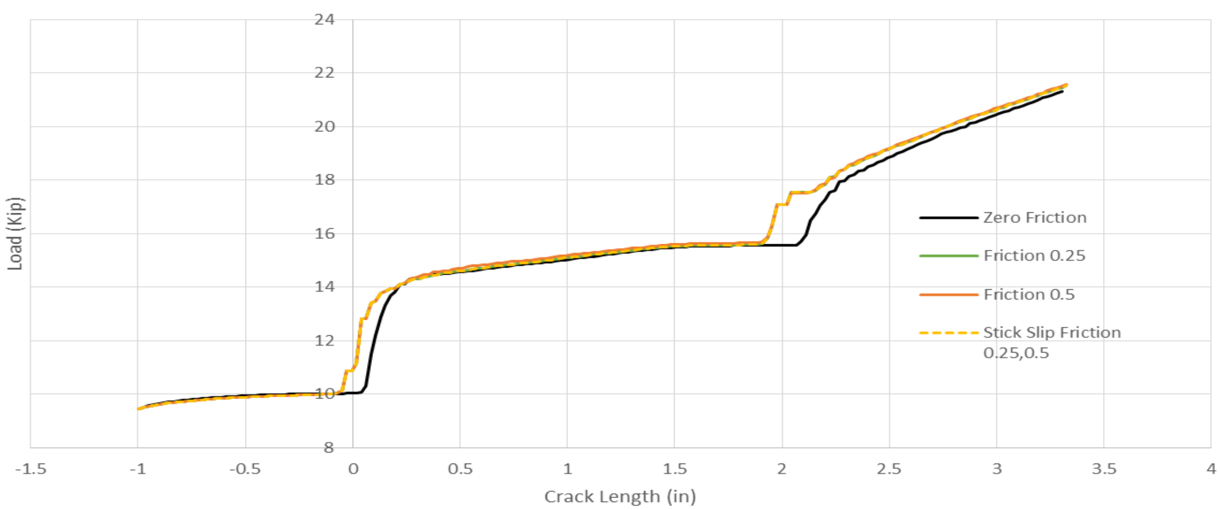

Figure 5.8: Influence of Friction on Propagation Load

As shown in the above figure, the inclusion of friction has a significant influence on the propagation characteristics of the model, however, the value of the friction coefficient does not play a significant role. This may require further investigation because it is expected that the change in friction coefficient would correlate directly to a change in load transfer, and thus a change in propagation load. It is hypothesized that due to the relatively low value of the clamping force, the load transfer due to friction is dwarfed by the transfer through shear engagement of the fastener, and thus is not seen at low clamping levels. Additionally, stick-slip friction was modeled. The results are bracketed by the constant value models but are difficult to discern due to the clustering of the results.

5.6.2 Variation of Laminate Stiffness

The main benefit of composites is that the laminate properties can be tailored by altering the layup. Thus, while quasi-isotropic laminates are commonly utilized in testing programs, this is generally the least efficient configuration. As such, the response of an alternate laminate's stiffness to the installation of a second fastener was of particular interest. The stiffness of both plates were varied at the same time during this testing regime in order to decouple the effects of a globally changing stiffness with plates of different stiffness values. Three additional layups were considered for this analysis, summarized in Table 5.2.

Table 5.2: Parametric Analysis Layups

Layup	Layup Percentage (0/45/90)
[90/45/0/-45/90/45/90/-45/90/45/0/-45]$_s$	[17/50/33]
[(0/45/90/-45)$_3$]$_s$ (base configuration)	[25/50/25]
[0/45/90/45/0/45/0/-45/0/45/90/-45]$_s$	[33/50/17]
[(0/45/0/-45/0/90)$_2$]$_s$	[50/33/17]

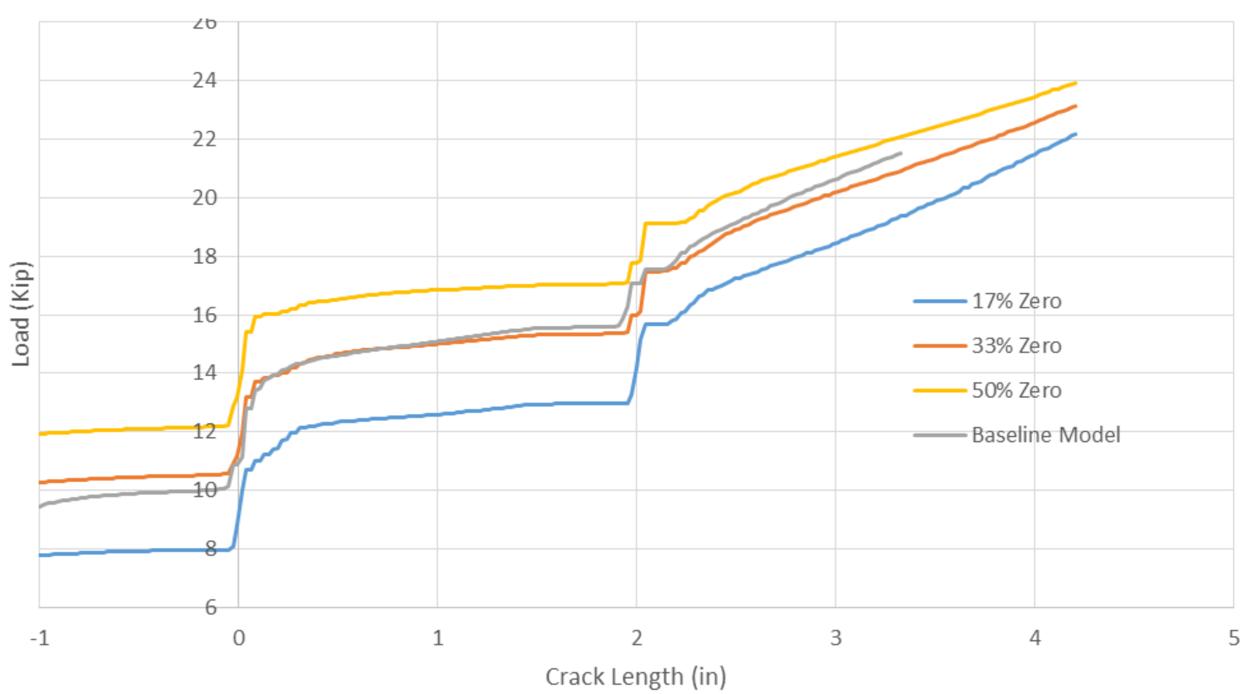

Figure 5.9: Propagation Load for Varying Layups

Shown in Figure 5.9, an increase in laminate stiffness correlates with an increase in propagation load. However, most of the difference in propagation load can be traced to the increased load required to initially propagate the crack, not the effectiveness of the arrest features. At the first fastener, each laminate experienced approximately 4,000 lbs. of propagation load increase, caused by the fastener. Meanwhile, increasing the stiffness of the laminate caused the second fastener to be less effective in arresting the crack propagation, indicated by a smaller increase in load required to propagate the delamination past the second fastener.

5.6.3 Variation of Fastener Stiffness and Preload

In addition to varying the stiffness of the laminate, the fastener spring stiffness and preload values were also individually altered. The extensional, shear and preload properties were altered individually in order to compare the response, but both fasteners were assumed to remain identical in their response, as manufacturing considerations precludes individually varying fasteners in an array. Each parameter was both halved and doubled, which allowed for a rapid comparison of the relative scaling of the crack response with respect to each property. The parameter quantities are summarized in Table 5.3.

Table 5.3: Fastener Analysis Parameters

Parameter	Half Value	Baseline Value	Double Value
Preload	500 lb.	1,000 lb.	2,000 lb.
Shear Stiffness	$8*10^4$ lb./in	1.6 $*10^5$ lb./in	$3.2*10^5$ lb./in
Tension Stiffness	$1.12*10^6$ lb./in	$2.24*10^6$ lb./in	$4.48*10^6$ lb./in

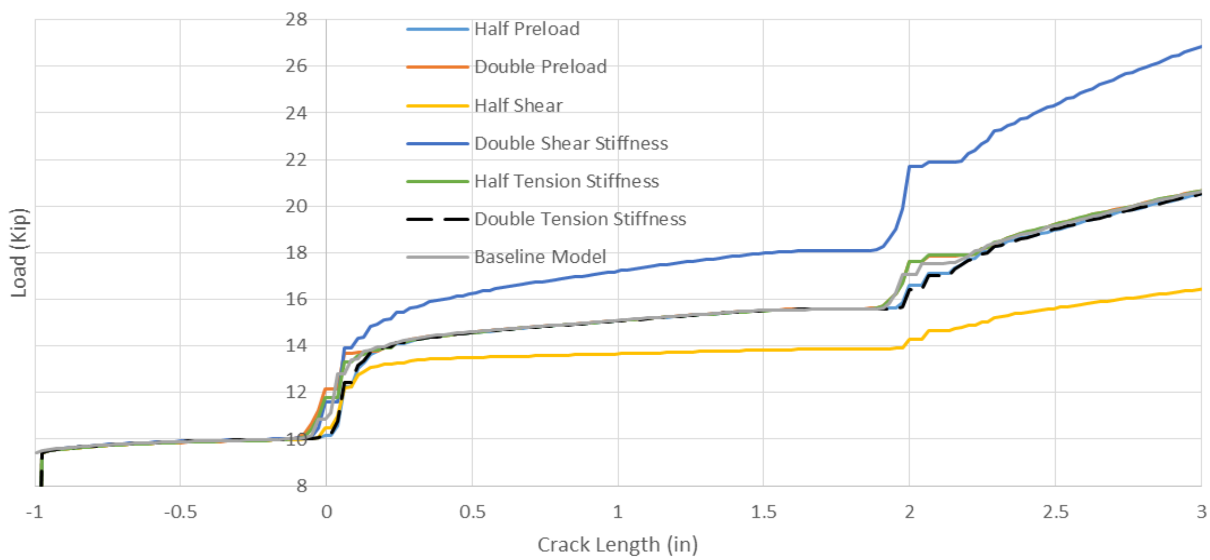

Figure 5.10: Fastener Parametric Analysis Results

Seen in Figure 5.10, the only parameter that has significant influence on the propagation characteristics is the shear stiffness of the fastener. Doubling or halving the effective spring stiffness of the fastener results in an equivalent change in the fastener propagation load. This is to be expected, as most of the load is transferred through the shear engagement of the fastener. Additionally, the tension stiffness and preload have a small effect because the modeling included the effects of friction. Thus, as the plates are clamped together by a greater force, the load transferred by friction is increased, resulting in a greater arrest effectiveness, however, this is dwarfed by the influence of the shear stiffness of the fastener. The tensile stiffness has minimal effects on the propagation load because the main role of extensional stiffness of the fastener is the elimination of mode I. Once the fastener meets this minimum level, the effects are expected to not change significantly.

5.6.4 Variation of Fastener Spacing

As the experimental and finite element results show [1-4], a single fastener effectively removes the mode I method of propagation for a significant distance, but the crack continues to propagate in mode II, resisted only by fastener bearing and load transfer through friction. The subsequent inclusion of a second fastener doubles the load transfer through the two methods, causing alternative failure modes to occur prior to extensive propagation of the delamination even with a larger than typical fastener spacing. Accordingly, a parametric analysis was performed on the response to an even larger fastener spacing. The spacing was increased by 0.5 inches between cases, reaching a spacing of 3.5 inches, which is approximately equal to the maximum crack length observed in testing when utilizing a single fastener.

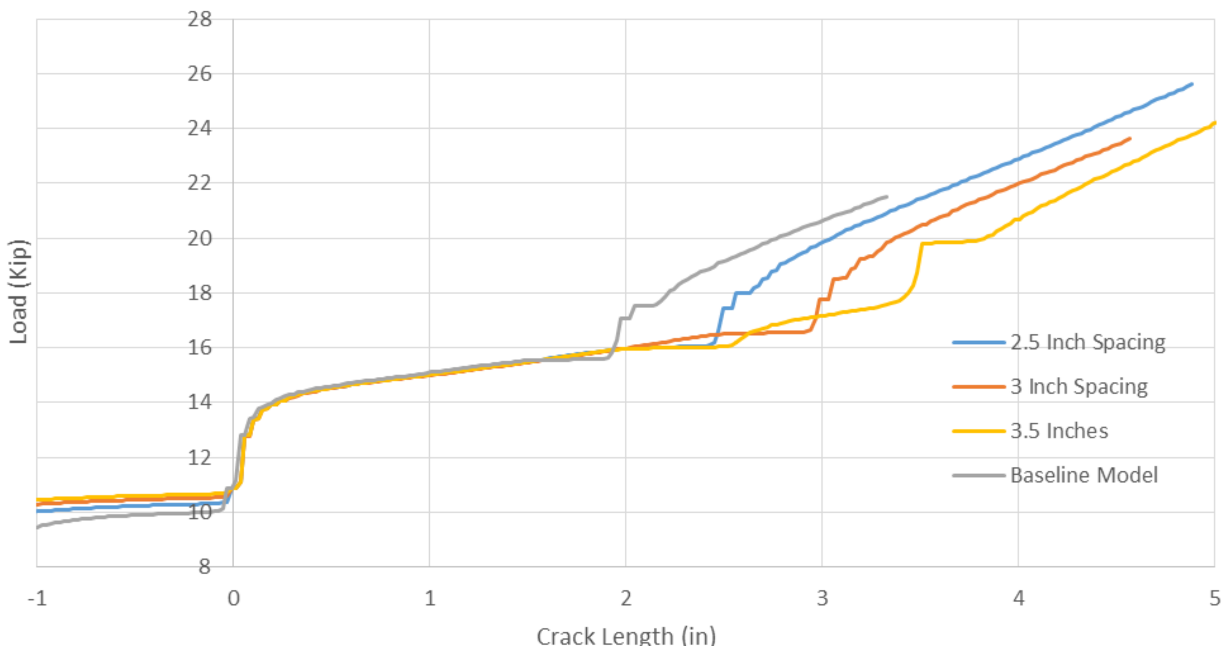

Figure 5.11: Propagation Load for Varied Fastener Spacing

Shown in Figure 5.11, the fastener spacing does not significantly alter the propagation characteristics. The response to the delamination is globally the same, only differing in the length before the second fastener is reached. Other than considerations for the maximum allowable crack length, it appears that the spacing between arrest features may be increased significantly beyond the typical 5D spacing.

5.6.5 Variation of Specimen Width

As the experimental and finite element results indicate, crack arrest fasteners do not have to be spaced at the typical 5D utilized in other applications. The inclusion of a second fastener at 2 inches and subsequent parametric analysis indicate that the simple inclusion of a second fastener will shift the failure mode away from delamination once the crack reaches that second fastener. Consequently, arrays of crack arrest fasteners could have a wider spacing in the direction transverse to the loading as well. This would correspond to a wider specimen compared to the one currently being modeled and tested. Specimens of greater width were chosen. Because a parametric study utilizing the three dimensional model would not be possible, each width was run under two conditions; plane strain and plane stress to approximate the edge and centerline of a specimen. Three additional widths were simulated, 1.5, 2 and 2.5 inches, to check for a significant drop in arrest capability.

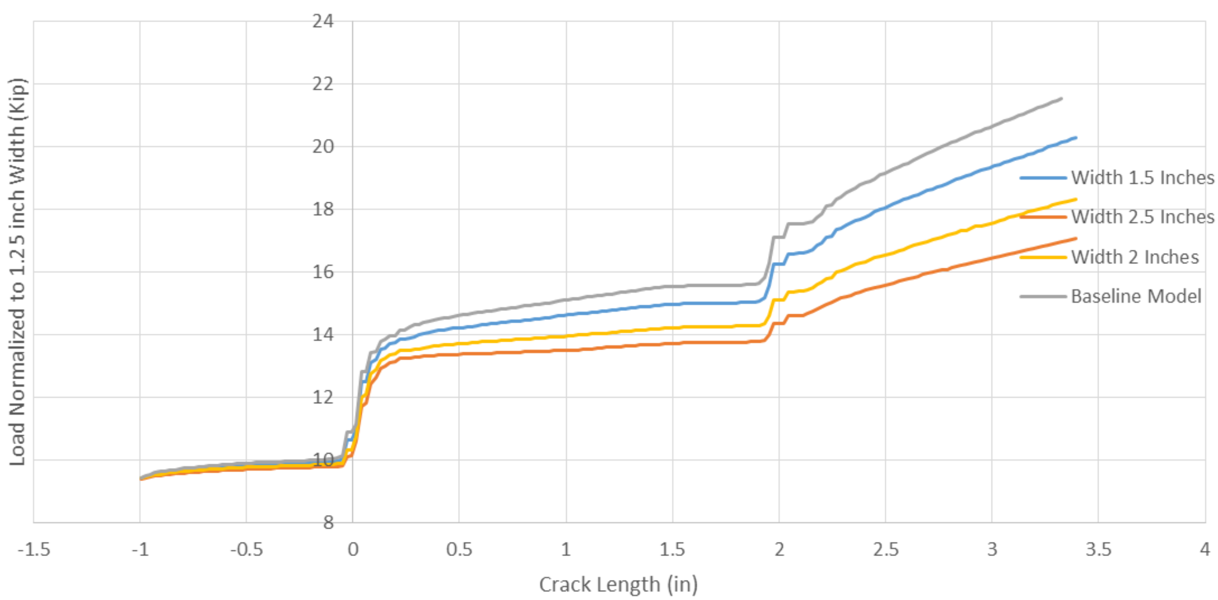

Figure 5.12: 1.25 inch Width Normalized Propagation Load for Varied Specimen Width

As expected, increasing the specimen width causes a decrease in propagation load when normalized to the 1.25 inch baseline specimen. These results are encouraging for the utilization of the two dimensional model for predicting the response of larger specimens. However, as seen in the three dimensional results, there is crack curvature, therefore before employing a two dimensional model for predictions, research needs to be performed to determine the limit where the crack passes around the arrest feature instead of through it.

5.7 Fatigue Loading and Crack Propagation

While it has been demonstrated that the failure mode will be shifted away from delamination by the installation of multiple fasteners under a static loading case, a second consideration is the fatigue properties. Although composites are typically chosen for their superior fatigue life due to their resistance to fatigue cracking, the propagation of delaminations may still occur through cyclic loading.

For this study, the fatigue response of the system was evaluated by Abaqus' direct cyclic approach. This technique utilizes a combination of Fourier series and time integration of the non-linear material behavior in order to obtain the stabilized response of the structure directly. A cyclic load is applied to the specimen, in this case a 10,000 lb. load which oscillates sinusoidally [Abaqus 14]. Subsequently, the principles of linear elastic fracture mechanics are employed, with the Paris law predicting the crack growth due to sub-critical loading. The results of the cyclic analysis are shown below in Figure 5.13.

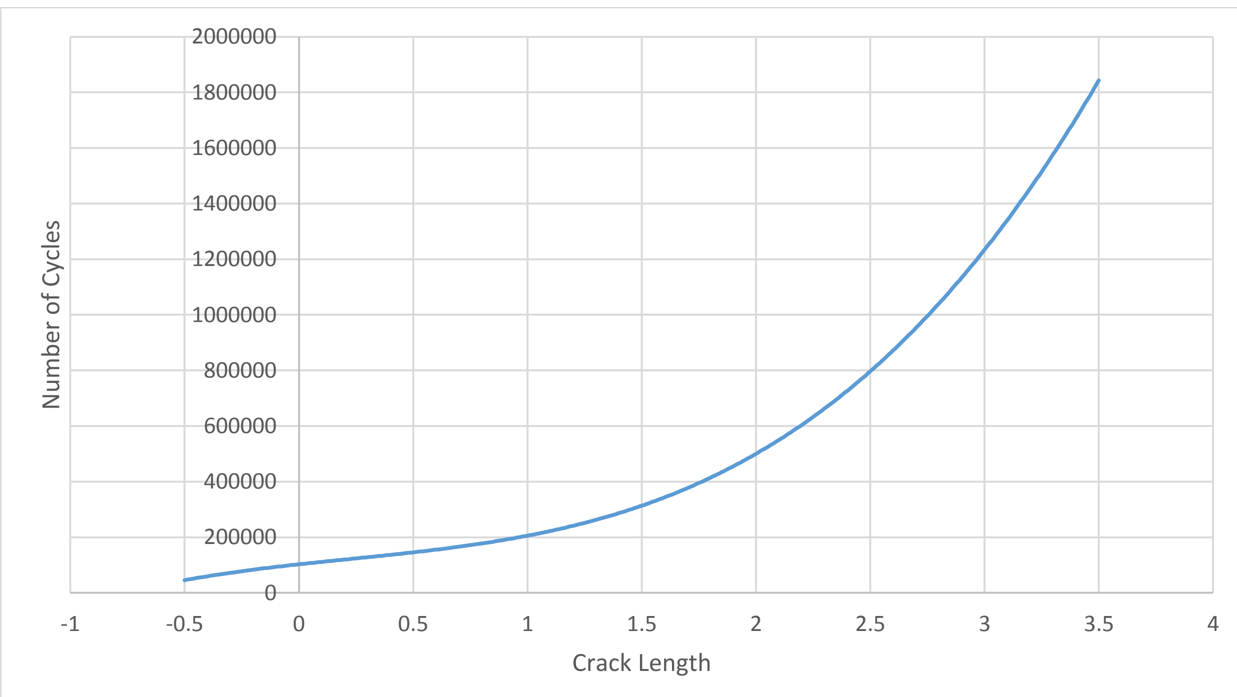

Figure 5.13: Fatigue Crack Propagation

As seen in Figure 5.13, a sub critical load can cause extensive crack propagation in the structure. This is due to the degradation of the interlaminar fracture toughness of the laminate from repeated cycling, potentially shifting the failure mode back to delamination. This is an area for further research, as the service life of aircraft structures is commonly driven by their fatigue characteristics, and it has been suggested that small initial delaminations can propagate under cyclic conditions and degrade the properties of the structural members.

5.8 Specimen Revision using Finite Element Model

Whereas the failure of the crack to propagate is excellent from a certification standpoint, this does not help in the validation of predictive methods which could be utilized for determining cases in which the delamination will not be arrested. Without designing another entirely novel specimen, there are two mechanisms by which the sample can be revised to increase the crack width prior to failure; by reducing the stress at the first fastener hole, and by increasing the stress at the crack tip.

5.8.1 Reinforcement Around First Fastener Hole

While the first attempt to reinforce the first fastener hole failed, upon further analysis, this was a suboptimal solution at best. When the idea was to put the minimum sized doubler on to accomplish the job, the secondary bonding of the small doubler did little to prevent failure, as the adhesive failed. However, reinforcement in the manner of additional 0^{o} plies incorporated into the design has the potential to increase the failure load enough to cause additional propagation of the crack. These lamina would extend to one inch beyond the first fastener, providing reinforcement, but not changing the laminate, and thus crack response, near the second fastener. Simulations were subsequently performed to characterize the change in response to the addition of three plies along the centerline of the lower plate.

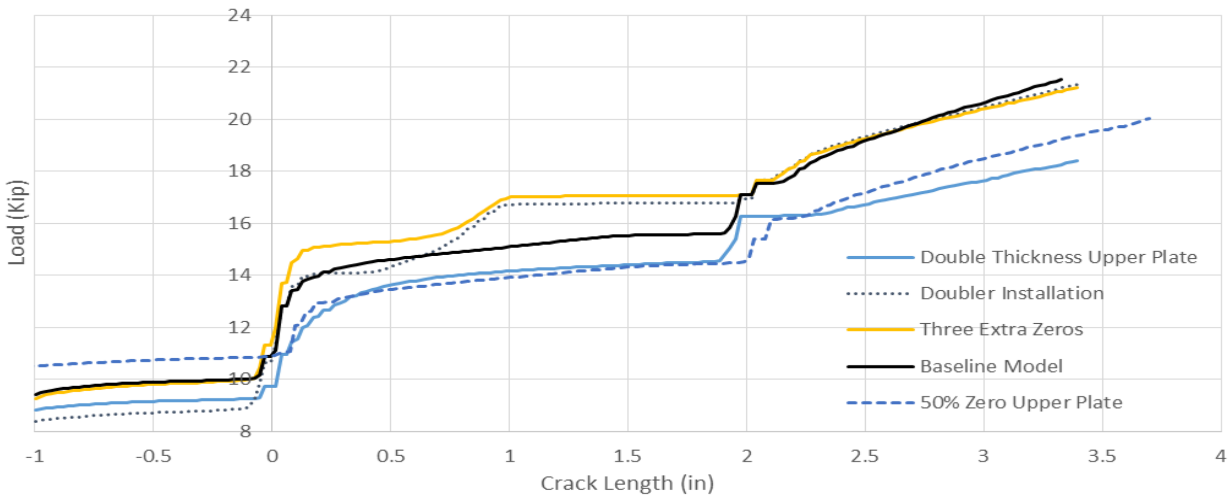

Figure 5.14: Propagation Load for Possible Specimen Revisions

As seen in Figure 5.14, while the propagation load past the first fastener is increased by a significant amount with the addition of 0º plies, the behavior around the second fastener is not significantly affected. Additionally, if the change in load at the first fastener is neglected, the behavior compares favorably with the unmodified specimen. Interestingly, this method is similar to the doubler application, however with the co-curing and distribution of the reinforcement instead of secondary bonding, it is more likely that the extra plies will provide additional reinforcement, without failing prematurely.

5.8.2 Increasing Individual Plate Stiffness and/or Thickness

The second method for altering the specimen reaction is by enhancing the mode II strain energy release rate at the crack tip. One method for accomplishing this task is employing plates of different stiffness and/or thickness. Mode II crack extension relies on a high shear stress between the opposing plates, which can be readily generated by having the unloaded plate be significantly stiffer. Two methods can be employed to fulfill this requirement, increasing the layup stiffness or laminate thickness. These represent two different possible scenarios. The first could be encountered in a stringer/skin combination, where the two sections are tailored to carry different loads, resulting in differing levels of rigidity. The second is typical of a delamination that does not occur on the centerline of the laminate.

Seen in Figure 5.14, the propagation load is lowered by approximately 1,000 lb. at the second fastener both when using a 50% 0º laminate or doubling the thickness of the unloaded plate. As well, the slope of the propagation curve after the second fastener is lower, further improving the crack length prior to specimen failure. Since the loaded laminate is not altered, the failure load should remain the same as in previous experimental results. Utilizing either method appears to be a viable option, however the recommendation is to stiffen the laminate as it requires significantly less carbon fiber and provides a slightly greater drop in propagation load.

Chapter 6

FUTURE AREAS FOR RESEARCH

Many of the parameters necessary for this research are only partially understood, thereby presenting challenges in the development of accurate predictive tools. One particularly poorly understood area is that of crack face friction. While it is commonly assumed that the frictional coefficient between surfaces is independent of the loading conditions, this does not appear to be the case for carbon fiber composites. Deeper understanding of this material could aid in the development of predictive equations or MATLAB modeling of the system, both of which would improve the optimization of arrest features by enhancing the predictive capabilities.

6.1 Crack Face Friction

The common representation of the frictional force using Amontons' law, $F=\mu N$, is an incredible simplification of an impressively complex system. In particular, this assumes that the frictional coefficient is constant. For most reasonably smooth surfaces, this representation of the force generated through friction is valid. However, for rougher surfaces, such as the fracture surface of a carbon fiber composite, the assumption that the coefficient of friction is constant appears to break down.

Research by Schön has indicated that at the minimum, the coefficient of friction is dependent on the fiber angle [15]. Additional research performed by myself on fractured specimens has indicated that the coefficient of friction can also be influenced by mode of delamination and loading area. Fractured specimens that were bolted together exhibited a higher coefficient of friction compared to samples that were subjected to a distributed normal force per ASTM standards for testing friction. Further research it needed to understand the sensitivities of the coefficient of friction, which should prove beneficial to the design of damage tolerant composite structures.

Similarly, the fracture surface of the specimen is different from the surface utilized by Huth to generate the constants employed by his fastener flexibility equation for a bolted graphite/epoxy joint. As noted by Cheung [2-4], the results had significantly superior agreement when a correction factor of

0.7 was employed. Since the fastener flexibility influences the results dramatically, as shown by the parametric studies performed for this thesis, empirically determining more appropriate constants to utilize in Huth's equation have the potential to improve the accuracy of the simulations.

6.2 Predictive Equations

As the current research has shown, the propagation behavior is largely determined by a limited number of parameters; laminate stiffness, fastener flexibility, frictional coefficient, and specimen width. This limited spectrum of influencing factors holds promise for the development of predictive equations for the multi-fastener crack arrest system. This has the potential to provide a significant advancement in the optimization of these arrest features through the understanding of the interplay between the individual influences and their global effect.

Currently, there is no publicly available research which supports the development of this concept. Development is instead focused on computer models which will produce rapid results with acceptable accuracy. This focus is based in the fact that these models have the benefit of lower developmental costs as the fundamental modeling principles have already been developed and tests are required simply to validate the model. Well-constructed equations provide an explicit definition of how each input parameter will affect the solution, allowing for more rapid optimization. However, the significant experimental and analytical work entailed in further developing this concept is outside the scope of this thesis.

6.3 MATLAB Modeling

A slightly less complex option which can be utilized for the optimization of crack arrest fastener systems is the development of MATLAB models of the system. While prior research has used the principle of minimum potential energy as the basis of the model, the shape functions required become untenably complex for a multi-fastener system. However, one dimensional modeling in Abaqus has shown the viability of finite element modeling in MATLAB. Further development was shelved due to a lack of industry interest, although future research could prove useful.

CHAPTER 7

SUMMARY AND CONCLUSIONS

The arrest capability of multiple fasteners under mixed mode loading in composite structures has been investigated both analytically and experimentally. Leveraging the development of the novel two-beam tension test specimen, a lengthened version was employed to investigate the delamination response with the addition of a second fastener. A finite element simulation of the utilized specimen was developed which indicated the secondary fasteners primary role was resisting the crack propagation through friction and fastener bearing.

A preliminary set of samples was manufactured at the University of Washington and made of a quasi-isotropic layup with post-manufacturing modifications applied to enhance the crack length. Testing of the specimens showed that the fracture toughness of the laminate was too great, as the crack propagation load required to extend the delamination significantly past the second fastener was greater than the filled hole tension failure load of the loaded plate. This occurred despite two different approaches employed to either delay the failure mode or reduce the fracture toughness and it limits the data available to verify the crack arrest capability predicted by the finite element solutions. Future specimens will require a revised design to provide a superior data set. However, considering the goal of improving the damage tolerance methodology as it applies to delamination and arrest, these results are encouraging, as the testing indicates that the simple installation of a second fastener will shift the critical failure mode away from delamination.

A finite element model based on the idealization of the specimen has been developed. The simplification of the model allows for the rapid prediction of the crack response with high fidelity and shows good comparison with the experimental data. The solution was utilized to simulate the capability of the system for various parameters. The following parameters were varied individually: crack face friction, laminate stiffness, fastener spring stiffness and preload, fastener spacing, and specimen width. The model indicated that crack stabilization is improved by increasing the stiffness of the laminate and fasteners and fastener preload, while it was relatively unaffected by an increase in fastener spacing.

Further experimental work is necessary to completely study the crack arrestment capabilities of the multi-fastener installation using a modified specimen. Based on finite element simulations of the system, it is suggested that beams of differing stiffness values be utilized to increase the stress at the crack tip for an equivalent load value. Reducing the bond strength is not of particular interest, as it portrays a less realistic scenario. Additionally, a more detailed treatment of the crack face friction would be very useful for further improvements in the predictive capabilities of the fastener arrest effectiveness. Supplementary improvements to the simulations may arise through improving the calculation of the fastener flexibility, allowing for a more accurate picture of the load transfer through bearing.

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