DELAMINATION ARREST FEATURES IN AIRCRAFT COMPOSITE STRUCTURES UNDER STATIC AND FATIGUE LOADING

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ABSTRACT

Delamination suppression is critical for large integrated composite structures as there exists no natural arrest mechanism within the laminate. As a result, one common solution is to install fasteners, clamping the laminate together in order to arrest the delamination. While this reduces the danger of critical delamination growth, research has indicated that while fasteners help limit the growth of delaminations, under certain conditions, the interlaminar cracks can extend past these fasteners. These arrest features slow and redirect the propagation of the crack, first by compressing the lamina together and second by transferring load via shear engagement of the fastener. In conjunction, work has found that fastener spacing can be increased beyond the typical spacing of 5 fastener diameters, with each additional fastener installed in series providing increasing benefit. Experimental and computational studies have indicated that the failure mode can be shifted away from delamination under both static and fatigue loading with proper arrest mechanism design.

Nomenclature

\[ CLT = \text{Classical Lamination Theory} \]
\[ D = \text{Fastener Diameter} \]
\[ \frac{da}{dN} = \text{Crack growth per cycle} \]
\[ \Delta G = \text{Range of } G \text{ for one fatigue cycle } \Delta G = G_{\text{max}} - G_{\text{min}} \]
\[ G = \text{Total Strain Energy Relapse Rate} \]
\[ G_c = \text{Critical Total Strain Energy Release Rate} \]
\[ G_I = \text{Mode I Strain Energy Release Rate} \]
\[ G_{II} = \text{Mode II Strain Energy Release Rate} \]
\[ G_{IC} = \text{Critical Mode I Strain Energy Release Rate} \]
\[ G_{IIIC} = \text{Critical Mode II Strain Energy Release Rate} \]
\[ G_{\text{max}} = \text{Maximum value of } G \text{ for a fatigue cycle} \]
\[ G_{\text{min}} = \text{Minimum value of } G \text{ for a fatigue cycle} \]
\[ \text{VCCT} = \text{Virtual Crack Closure Technique} \]

I. Introduction

Fasteners are one of the more robust and easily installed delamination arrest features for laminate carbon/epoxy structures. Their primary benefits over comparable methods such as z-pins and stitches is that they can be installed in thicker structures as well as post curing and in service if needed. Furthermore,
these fasteners are commonly employed in a dual use role; both as a delamination arrest mechanism and a mechanical fastener. Properly understanding the delamination growth and arrest through these features can then allow for more optimal design and possible elimination of single use, delamination arrest only fasteners, reducing the weight of the structures and improving efficiency.

To this end, work was initiated by Cheung [1] which first understood the key mechanisms of arrest for quasi-static loading using a single fastener. As this research showed continued crack growth in mode II, further work by Richard has been conducted using multiple fasteners which showed additional benefits are provided by additional arrest features [2]. Further work by Richard, Lin and Rodriguez [3][4] has focused on accurately capturing the crack front through modeling as well as understanding the arrest of fatigue delaminations, with good agreement between the analytical and experimental results.

II. Analytical Studies

A. Modeling

Representing the experimental design of a tension test specimen which generates an initially mixed mode delamination front, the finite element model consists of two carbon/epoxy split beams joined together by two 0.25 inch (6.35mm) titanium fasteners installed in series, as shown in Figure 1. The design represents a simplified skin-stringer delamination arrest. The analysis is primarily conducted using a one dimensional beam-column model, with the crack along the centerline of the sample. Comparison with prior modeling using a two dimensional model, as well experimental results, has supported this models accuracy.

Each plate is 10 inches (254 mm) long; sensitivity studies found this length sufficient to avoid boundary condition effects in the model. Each plate was 0.18 inches (4.6mm) thick, derived from the nominal thickness of the experimental samples. The primary material system being utilized was T800/3900-2 with the material properties summarized in Table 1.

<table>
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<tr>
<th>Ply thickness</th>
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<th>SI Units</th>
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<tr>
<td></td>
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<tr>
<td>$E_1$</td>
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<td>142.0 GPa</td>
</tr>
<tr>
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<td>$0.58 \times 10^6$ psi</td>
<td>3.99 GPa</td>
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<tr>
<td>$G_{23}$</td>
<td>$0.52 \times 10^6$ psi</td>
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<tr>
<td>$\nu_{23}$</td>
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<tr>
<td>$G_{IC}$</td>
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<td>280.2 J/m$^2$</td>
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<td>$G_{IIc}$</td>
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<td>2452 J/m$^2$</td>
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Table 1. Composite laminar material properties (T800/3900-2) [5]

The stiffness values of the bars were generated utilizing CLT and the above material properties. To capture the fastener’s influence, two springs are employed at each fastener to represent the shear and tensile stiffness, determined from the fastener flexibility equations proposed by Huth [5] for the shear stiffness and the assumption that the fastener acts as a constant diameter bar under tensile loading. However, for static loading, it was found that the Huth equation had a tendency to over predict the joint stiffness. Cheung noted that his equations are derived from taking the joint to failure, but in these cases, the joint is not brought near failure. While the samples consistently failed at the first fastener, this was due to filled hole tension failures, with little to no joint damage observed. Testing utilizing delaminated specimens supported Huth’s predictions for single lap shear but showed that for this specific configuration, the shear stiffness was reduced by a factor of 2.5 [2]. In contrast, for the fatigue modeling,
the full stiffness version of the fastener flexibility was utilized and provided good agreement with the results.

In order to propagate the crack down the length of the model, VCCT and the BK law is used to determine the mixed-mode crack propagation behavior [7] for quasi-static loading. For fatigue loading, VCCT was utilized to extract the value of $\Delta G$ and the Paris Law. In this case, $\text{da/dN vs. } \Delta G$ instead of $\text{vs. } \Delta K$ was utilized to extrapolate the damage forward. The $\text{da/dN vs. } \Delta G$ curves for this material system were derived from material testing utilizing a pure mode II specimen with twin crack fronts, originally employed in quasi-static testing by Cheung et. al [1]. As the delamination is a matrix governed process, fatigue evaluation techniques similar to those used in metallic structures can be utilized [9]. The common mode II method of using a flexure specimen was not employed as research has shown that friction plays an important role in the delamination propagation under fatigue, and the loading of bending specimens will introduce a non-negligible amount of friction. Under fatigue loading, pure mode II delaminations were assumed as no current models exist for the fatigue propagation of mixed mode cracks. This is supported by experiments which show that the delamination, once past the fastener, propagates in pure mode II.

![Figure 1. The Two-beam Model for ABAQUS modeling](image)

In addition, a three dimensional models was developed further by Rodriguez [4]. Three dimensional models were utilized to investigate the curvature of the crack front which was visible through C-scans of the specimens when the crack front is around the fastener. One and two dimensional models assume a flat crack front and do not capture this effect, which can become important when designing non-square fastener patterns. The three dimensional model, using shells or solid elements, allowed for the analytical investigation of this crack curvature [4]. Current work is focused on extending this modeling technique to investigate how crack curvatures will respond to fastener arrays, particularly those using non-square fastener pattern.

An additional key inclusion in the modeling was that of a fatigue threshold for the delamination. The predictions, without a fatigue threshold, tended to show the crack slowly growing continuously, out to hundreds of thousands of cycles. Meanwhile, experimental results tended to show that the crack was fully arrested and runouts to an additional 500,000 cycles did not result in further growth. An experimentally derived fatigue threshold of $\Delta G_{II} = 5 \text{ lb/in} \ (875 \text{ J/m}^2)$ was then utilized.

**B. Modeling Results**

Mode I is effectively eliminated for all reasonable loading conditions by the first fastener and Mode II becomes the dominant mode, seen in figure 3. Under compressive loading, mode I remained suppressed even post-buckling due to the clamping of the fastener, although for different configurations, it is distinctly possible that mode I would reappear due to the buckling. Meanwhile, as shown in figure 2, crack propagation will continue to occur until laminate failure for quasi-static loading. In the modeling, failure is not incorporated, the additional computation cost was deemed unnecessary as failure was consistently net section at the first fastener hole. Using the published $G_{II}C$ data for the material system consistently overpredicted the propagation loads, testing showed a more accurate value of $G_{II}C = 12 \text{ lb/in}$ which showed excellent agreement with experimental results.
After mode I elimination, the two primary methods of arrest are load transfer through fastener shear and friction. As noted in Figure 2, because clearance delays the engagement of the fastener in shear, the two curves diverge at the first fastener. Furthermore, modifying the stiffness of the fastener yields a dramatic difference in the load vs. propagation curve as well as the final crack length at which the laminate fails. This indicates the need to accurately predict the fastener flexibility in order to capture the final delamination length at failure.

There is also a notable load spike at this first fastener due to the inclusion of frictional load transfer in the models, the elimination of friction would eliminate this non-negligible bump. However, once the fastener becomes engaged in shear, the slope of the curves are identical. This is to be expected because the entirety of the model is linear elastic. The same process occurs at each fastener, with a load spike due to friction, and subsequent engagement of the fastener.

Additional load transfer occurs via crack face friction generated from the clamping of the fasteners. While the frictional transfer aids the arrest of crack propagation, particularly as the preload is increased, the ultimate influence of the frictional load transfer is dependent on the loading and fastener conditions. For a zero clearance hole, the effect is dwarfed by the effects of the fastener shear load transfer, however there is a small but noticeable load spike at each fastener, made more apparent when clearance is introduced into the system. For fatigue testing, frictional load transfer plays a much bigger role, regardless of the clearance value. Load transfer through friction can represent a sizeable fraction of the load transfer between the two pieces, resulting in improved arrest capability. Since it is exceedingly difficult to control the friction coefficient of the interface, this load transfer is thus controlled by the preload of the fastener; higher preloads correlate to improved fatigue performance.

Figure 2. Propagation Load vs. Crack-Tip Location
As seen in Figure 4, modeling agrees with tests that clearance is a critical factor when evaluating the fatigue life. Under cyclic loading, a zero clearance system effectively arrests the crack under subcritical loading at 75% of the failure load of the specimen, however with the inclusion of minimal clearance, the delamination propagates, and with a typical clearance value (0.007 in), as shown in the plot, the effect is worsened. Under the current experimental conditions, the delamination was not arrested while the predictions indicate successful arrest, the test was terminated once the delamination propagated across a sufficient length of the specimen that boundary condition effects may have become an issue.

The underlying cause for this effect is the dramatic change in cyclic stresses at the crack tip when the fastener clearance is included. The relative displacement of the two plates at subcritical loading is small, thus clearance dramatically increases the value of $\Delta G$ by reducing or eliminating load alleviation at the crack tip.

![Figure 3. ERR Components vs. Crack-Tip Location and Experimental Overlay](image)

As seen in Figure 4, modeling agrees with tests that clearance is a critical factor when evaluating the fatigue life. Under cyclic loading, a zero clearance system effectively arrests the crack under subcritical loading at 75% of the failure load of the specimen, however with the inclusion of minimal clearance, the delamination propagates, and with a typical clearance value (0.007 in), as shown in the plot, the effect is worsened. Under the current experimental conditions, the delamination was not arrested while the predictions indicate successful arrest, the test was terminated once the delamination propagated across a sufficient length of the specimen that boundary condition effects may have become an issue.

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![Figure 4. Fatigue Performance of Varying Clearance, cyclic load of 12,000:0 lbs](image)
In comparison, the response of system was simulated and tested at 8,000:0 lbs. The results shown below in figure 5 show that for a lower cyclic load level, the crack is arrested for both a zero clearance as well as a clearance drilled hole. The fastener engagement in shear as well as the frictional load transfer is sufficiently high in this case to reduce the value of $\Delta G$ below the apparent fatigue threshold.

![Figure 5. Fatigue Performance of Varying Clearance, cyclic load of 8,000:0 lbs](image)

In the previous two figures, the predictions were made blind, using purely unfastened material properties that were experimentally derived and not accounting for hole damage. By manipulating the input parameters, in particular the fatigue properties as well as introducing an exponential growth in the clearance from the initial value, it is possible to improve the agreement further, indicating the need for careful establishment of each of these properties and further work in this area.

Finally, comparison of the three dimensional model, shown below in Figure 6, with the experimental C-scans of delaminated specimens shows good agreement between the modeling and experimental crack fronts shown in Figure 9. Accurately capturing this crack shape is important for the subsequent modeling of arrest through fastener arrays and the design of novel crack arrest fastener patterns.
III. Experimental Validation

A. Experimental Specimen Specifications

A novel tension delamination arrest experiment has been created to validate the analysis. Figure 1 shows a schematic of the specimen design and Figure 7 shows the experimental specimen, which was retained from previous research. Carbon/epoxy pre-preg laminates with a quasi-isotropic layup, ((0/45/90/-45)3s/Crack)8, or 50% zero layup ((0/45/0/-45/0/90)2s/Crack)8 were tested. The initial crack is implanted via an FEP insert at the mid-plane of the specimen. The holes were drilled using carbide drills of either 0.2500 inch (zero clearance) or 0.2559 inch (6.5mm) (clearance) diameter. Two titanium fasteners, 0.25 inches in diameter are used and tightened to a prescribed torque, typically 40 in-lb (4.5 N-m), approximating a part in service. The standard specimen width was chosen as 5D or 1.25 inches (31.75mm). [2]

Figure 7. Two-Plate Crack Arrest Specimen

Fatigue specimens were of identical configuration albeit undergoing cyclic loading. Testing has been conducted at two different load levels, a high and lower loading, 12,000:0 lbs (53.4:0 kN) and 8,000:0 lbs (35.6:0 kN) respectively. The goal is to compare the fastener arrested configuration against unmodified delamination specimens to determine how the inclusion of arrest features modifies the stability of crack
propagation. The mode II fatigue properties of the composite system were determined experimentally utilizing a quasi-isotropic layup [3] in order to eliminate potential effects of layup.

The curves shown in Figure 4 utilized a maximum load of 12,000 lb. (53.4 kN) with an amplitude of 6,000 lb (26.7 kN), which is approximately 75% of the failure load of the specimen and approximately the load at which the crack grows past the first fastener in quasi-static loading. Additional testing was conducted at lower cyclic stresses, at a load range of 0:8000 lbs. This value was chosen as it represents a maximum load below that of the initial crack propagation load of 9,000 lbs and is approximately 50% of the failure load of the specimen.

Fatigue testing was also done to derive the da/dN curve for the material, which was then utilized in the predictions to enhance the accuracy over the generic material properties derived from literature. [8] However, as seen in figure 10, compared to previous results the fatigue predictions show significantly better agreement. This again can largely be explained by more accurate input parameters. Key inputs such as the fastener flexibility and laminate stiffness were experimentally determined, resulting in a more accurate prediction compared to a blind predictions using formulas.

B. Experimental Results

As seen in Figure 8, there was a consistent stabilization of the crack and superior arrest compared to a single fastener. Greater arrest capability is determined as requiring a higher load or number of cycles for an equivalent crack length. It is important to note that better agreement has been generated with later generations of analysis and test specimens. The improvement is two-fold. Testing of key parameters, such as the fastener flexibility, $G_{IC}$ and laminate stiffness provided more accurate input parameters while improved manufacturing of the test specimens generated stronger specimens which failed under a higher tensile load, providing more crack growth for comparison with analysis.

As shown in Figure 9, C-scans of the specimens continue to support the fact that there is curvature of the crack front around the fastener. Additional C-scans of a 2x2 fastener array also support the strip modeling assumption as the appearance of the crack front when it is near the fasteners is very similar to that of the crack front in a single with specimen. Additionally testing of the 2x2 fastener arrays showed a similar load vs. crack front location curve, when normalized for the doubled width.
Further testing was conducted on another typical laminate configuration, 50% 0, as well as at varying R-Ratios which verified the general applicability of the modeling methodology. It was found that stiffer laminates benefit less from the installation of fasteners because the crack propagates at a lower overall strain, resulting in less shear engagement, and thus less load transfer. However, the fastener was still beneficial, particularly in forcing the crack to propagate in mode II, and did provide some load alleviation.

As seen in Figure 10, the model produces reasonable agreement with purely blind predictions when estimating the final crack length for an R-Ratio of 0.33 and with a stress amplitude of 4,000 lbs (17.8 kN). Average test results are shown for clarity as there was comparatively little data scatter in the experimental results. Further investigations are ongoing to generate better agreement between the test data and predictions. However, as the predictions were made using the modified Paris law which accounts for R-Ratio, the initial results lend credence to the assumption that this methodology is a reasonable method for predicting the delamination growth in composites with arrest features under varied loading.
During testing of these samples, it was found that the second fastener did not engage in the hole but was instead providing arrest purely through load transfer through friction. This was observed by examining the fastener shanks as shown in figure 11. When the first fastener was removed, a mark is visible on the shank where it engaged the fastener hole, but these marks are not visible on the second fastener, suggesting it was not engaging. These results were consistent through multiple fatigue tests of identical configuration. In addition, after the delamination was successfully arrested, the fastener was loosened so it was not providing load transfer through interfacial friction. After loosening, the delamination would resume propagation, and retightening the fastener would again arrest the growth.

Further experimental work has been conducted under compressive loading, at loads of 0: -8,000 lbs, and 0:-12,000 lbs. The agreement with the tensile loading was reasonable at the lower loading magnitude but not at the higher. This is suspected to be because the sheer quantity of fixturing required to suppress buckling, plus the level of clamping necessary caused additional load transfer through friction, improving the apparent effectiveness of the fasteners. In contrast, the modeling predicted identical responses to compression and tension, ignoring buckling, because mode II delaminations do not depend on the loading direction.
IV. Discussion

As seen in Figures 4 and 10, the experimental and analytical responses show reasonable agreement. Single tests are shown for clarity, but consistency between tests was achieved. The static testing and analysis have better correlation as the results are less sensitive to varying material parameters and have been under development for a longer time period. On particular issue in fatigue is the high sensitivity to frictional load transfer. While experiments have measured the value of frictional load transfer between specimens under static loading, loss of fastener clamping as well as surface polishing may cause the actual value during the testing to be different from these numbers.

The inclusion of clearance in the tested samples and finite element solutions indicates the need to control the clearance tightly as clearance can be seen to lower crack resistance and can cause a loss in stability, indicated by a flat propagation line, and this effect is exacerbated by a low toughness [4]. Furthermore, the accuracy of the simulation is dependent on accurately modeling sensitive parameters with previous work [4] has showing the relative sensitivity to each parameter.

Meanwhile, in compression, as well as fully reversed cyclic loading, the performance is similar, but the requisite anti-buckling fixtures indicate the difficulty in propagating the delaminations in compression and capturing the response accurately. Performance in compression was superior to that of tension, which was an unexpected result and theorized to be a result of the fixturing, not the true performance of the specimens. An interesting addition to this is that under reversed loading, the solution appears to require being broken into two segments; the tension and compression values, with a $\Delta G$ for each. While mode II is independent of loading direction, it is incorrect to assume that the global $\Delta G$ which would be the subtraction of $G_{\text{min}}$ from $G_{\text{max}}$ should be used in the $\frac{da}{dN}$ vs $\Delta G$ curve, instead each single cycle can be thought of as two cycles, with a $\Delta G_{\text{comp}}$ and a $\Delta G_{\text{tens}}$. When using this approach, more accurate agreement has been achieved, with the caveat that the compressive performance is artificially improved due to the anti-buckling fixturing.

V. Conclusion

Arrest capability and the limitations of multiple fasteners installed in series has been demonstrated under static and fatigue loading. Representing common delamination initiation sites such as runouts, the specimen initially generates a mixed mode propagation state which demonstrates the capability of the fastener to eliminate mode I propagation. Variations in laminate configuration have shown that the model retains good predictive accuracy, though the accuracy remains highly sensitive to certain input parameters such as laminate and fastener stiffness.

Due to the clamping of the fasteners, the spacing can be greatly increased if the goal is mode I suppression, with the ultimate spacing being dependent on the configuration and loading. As a general rule, the stiffer the laminate in bending and higher percentage of the loading which is tensile, the greater the fastener spacing is possible before mode I re-initiation becomes an issue. Meanwhile, the analysis has indicated that the fastener joint stiffness and frictional load transfer are the primary forces resisting propagation. As the fasteners only become effective in these modes once the crack has passed them, the spacing is subsequently governed by the maximum crack length, smaller maximum crack lengths necessitate a tighter fastener pitch. Further testing in fatigue has shown that fastener friction is of particular interest as under lower cyclic loads, fasteners installed in clearance have been found to provide arrest prior to engagement in shear.

Current testing compares well to the analysis models which have provided predictions for the performance of the arrest features under varying loading. Compressive loading has been examined, and it can be assumed that the tensile and compressive mode II delamination performance of a bolted-bonded joint is identical, provided additional failure modes such as buckling do not arise.

The results of this research contribute to the understanding of fasteners as a crack arrest feature in composite aircraft structures. Understanding the arrest capability and limitations of fasteners installed
explicitly for arrest, as well as bolts whose secondary feature is providing delamination arrest, will allow for the optimization of fastener features to minimize the fastener weight penalty while maintaining safety by limiting the size of the disbond/delamination, sustaining the component’s structural integrity and possibly extending its certified lifespan.
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