PLY MODIFICATIONS TO ALTER DAMAGE INITIATION AND PROGRESSION IN LAMINATES CONTAINING CIRCULAR HOLES

W. Steven Johnson*, Paul J. Treasurer*

***Georgia Institute of Technology**

Abstract

The goal of this research was to evaluate damage suppression in multi-directional notched laminates through the use of slightly off-axis longitudinal plies. These "non-traditional" laminates were compared to laminates with 0° longitudinal plies for quasi-isotropic and hard lay-ups, for open hole tension, filled hole tension, and single-shear bearing loadings. In-situ radiographic inspections were performed to evaluate damage initiation, progression, and suppression.

In notched tension, the non-traditional laminates were less strong and stiff than their traditional counterparts, but X-ray images clearly showed the suppression of longitudinal splitting and delamination. Under single-shear bearing loads, the non-traditional laminates demonstrated increased bearing resistance compared to traditional laminates, and the non-traditional laminates were less prone to damage in the longitudinal plies.

1 Introduction

In typical aerospace applications, composite laminates with 0°, ±45°, and 90° fiber orientation angles are utilized. The use of these orientations in notched specimens results in several well-documented damage types, namely longitudinal fiber-matrix splitting, matrix cracking, delamination, and fiber breakage [1-4]. The type of damage that occurs, as well as how the damage progresses, is lay-up and loading dependant. The goal of this research is to evaluate possible damage suppression through the use of non-traditional off-axis plies. It is believed that by replacing the strong, stiff 0° longitudinal plies with ±5° or ±10° plies, some damage could be suppressed, altering the stress state at the notch and perhaps leading to an increase in notched strength.

For this research, traditional and non-traditional laminates were fabricated for quasi-isotropic and hard lay-ups, and tested in open hole tension, filled hole tension, and single shear bearing. Mechanical properties were compared, and damage was monitored via in-situ X-ray to determine any change in damage type or progression due to the nontraditional laminates.

2 Experimental Techniques and Procedures

The following paragraphs details the procedures used for this research. The first section describes the material used, the lay-ups considered, and the specimen geometry. Next, the experimental equipment and procedures are described.

2.1 Material, Lay-ups, and Specimen Configuration

The specimens were fabricated from a carbon fiber / toughened epoxy prepreg. Panels were made with three-inch tape laid up by hand, and then cured at 177°C. The two baseline lay-ups were a 16 ply $[+45/90/0/-45]_{2s}$ quasi-isotropic lay-up, and a 20 ply hard $[45/0_2/-45/0_2/90/0_2/\pm45]_s$ lay-up consisting of 60% longitudinal plies, 30% ±45° plies, and 10% 90° plies. In addition to the baseline laminates, for each lay-up type panels with ±5°, and ±10° longitudinal plies were fabricated.

The panels were cut into specimens using a diamond saw. The open hole tension and filled hole tension specimens were cut to measure 38.1mm by 304.8mm, and contained a 6.35mm center hole. The single shear bearing specimens were composed of two 31.8mm by 184.2mm coupons, plus two shims, and contained a 6.35mm hole. The filled hole specimens had a fastener consisting of a threaded pin, washer, and frangible collar inserted in the center hole. The head of the frangible collar broke off at a torque of 8.14 N-m, ensuring consistent clamping force. The single shear bearing specimens utilized the same fastener but at half clamp-up torque.

2.2 Experimental Equipment and Procedures

The tests utilized a 100kN and a 250kN servo-hydraulic test frame. Each machine had a computer control and data acquisition system. Both frames were equipped with a 2.54cm extensometer. In-situ die-penetrant enhanced X-ray inspections were performed using a 120kV x-ray unit in conjunction with the 100kN. The unit and x-ray enclosure are shown in Figure 1.

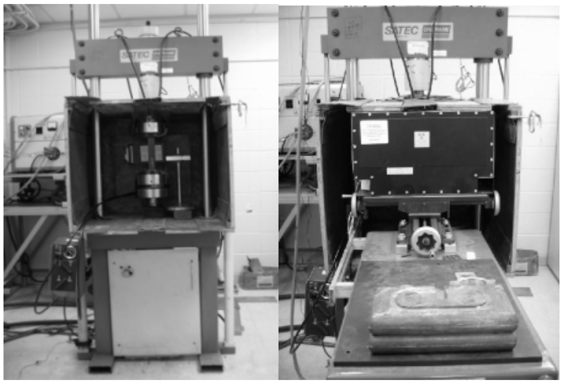

Figure 1 X-ray Enclosure

Initial modulus data was generated on unnotched coupons using a face mounted extensometer. Notched testing was performed at a constant displacement rate of 1.27mm/min until failure, with an extensometer was mounted across the notch.

One of each type of open-hole tension specimen was x-rayed at incremental loads. Based on previous research [5], a voltage of 43kV, amperage of 3mA, and exposure time of 73s were used with Polaroid type 55 P/N sheet film. The specimen was loaded to the desired level and a zinc iodide solution consisting of 60g zinc iodide, 8mL water, 10mL isopropyl alcohol, and 6mL of Kodak PhotoFlow was applied around the hole and at the free edges using a syringe. The load was held for 5 minutes to allow for capillary action of the die penetrant into any cracking, and the film was exposed at the aforementioned levels. The film was according to manufacturer specifications, and a stereomicroscope was used to create a digital image from the negative. Initial x-rays were made at 4.45kN increments until damage was observed. Following the first observable damage, specimens were x-rayed at larger increments to determine overall damage progression.

The procedures for the filled hole and single shear bearing specimens were slightly different. In both cases fasteners had to be removed prior to x-ray. Thus, the specimens were loaded to the desired load level, and then completely unloaded. Specimens were then removed from the machine so the fastener could be removed. In the case of the filled hole tension loading, the specimen was then placed back in the machine and loaded to 4.5kN to provide an opening load without causing any additional damage. In the case of the single shear bearing specimen no load was applied due to specimen geometry. In both cases zinc iodide was then applied around the hole, and given 5 minutes for capillary effects. Following exposure, the specimen removed from the machine, a new fastener was installed, the specimen was re-inserted into the machine, and loaded to the next load increment.

3 Results and Discussion

The subsequent paragraphs describe the findings of the open hole tension, filled hole tension, and single shear bearing tests for the quasi-isotropic and hard laminates. Following the results is a discussion of the differences between traditional and non-traditional laminates and on the effects of notch constraint and lay-up on these laminates.

3.1 Experimental results

For each lay-up and loading case, the mechanical results will be presented first, followed by the in-situ x-ray images. For each type of specimen and lay-up, 3 specimens were loaded to failure, and one specimen was x-rayed under incremental loads. The strengths of each laminate will be given as an average of the four tests, with deviation also provided. Additional images and results can be found in [6].

3.1.1 QUASI-ISOTROPIC OPEN HOLE TENSION

Figure 2 and Figure 3 illustrate the open hole tension performance of the quasi-isotropic laminates. As would be expected, the traditional laminate has the highest modulus, with the ±5° plies resulting in a slight reduction, and the ±10° plies causing a slightly larger reduction. As shown in Table 1, these reductions were accurately predicted by classical lamination theory using properties given in [7]. Slight reductions in failure load occurred in the non-traditional laminates, but there was an increase in strain to failure.

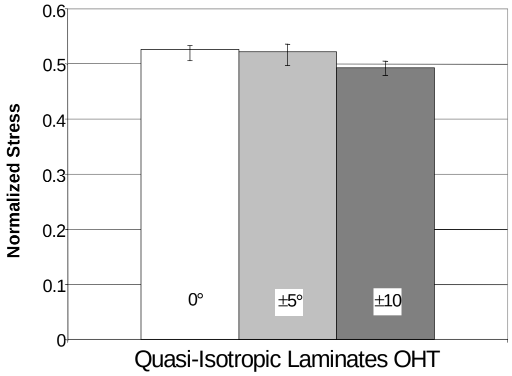

Figure 2: Average Quasi-Isotropic Open Hole Tensile Strengths

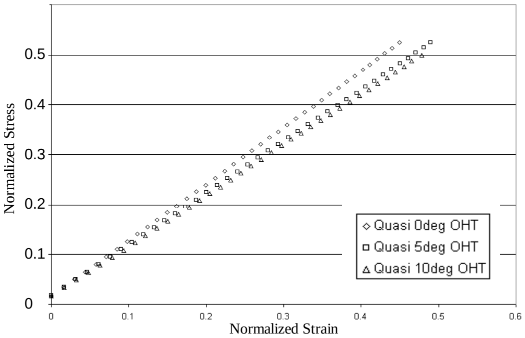

Figure 3 Comparison of traditional and non-traditional quasi-isotropic open hole tension response

Table 1. Experimental and Theoretical Quasi-Isotropic Laminate Moduli

	Quasi (0°) (GPa)	Quasi (±5°) (GPa)	Quasi (±10°) (GPa)
Experimental	55.51	55.16	51.40
Theoretical	53.23	52.54	50.61

X-ray images showing the damage progression in the quasi-isotropic OHT specimens with the 0°, ±5°, and ±10° longitudinal plies are shown in Figure 4, Figure 5, and Figure 6 respectively. In each case, damage initiated at approximately 33% of the failure load, in the form of 90° and ±45° ply cracks. In each specimen, the density of 90° cracks increased with load, with the longest cracks eventually reaching from the hole edge to the free edge of the laminate. The ±45° cracks also increased in number and length with load in all specimens, with lengths exceeding 13mm for each type. There was no significant difference in ±45° and 90° damage between the traditional and non-traditional laminates.

At approximately 50% of failure load, longitudinal ply cracking appeared. The x-ray images clearly show a reduction of this type of damage in the non-traditional quasi-isotropic laminates. Prior to failure the length of the longest longitudinal split in the traditional laminate was measured as 5.6mm, and 3.6mm in both non-traditional laminates, a reduction of 37%. However, since splitting is not a major factor in laminates with a small percentage of longitudinal plies, there is not a significant difference in the overall performance of the traditional and non-traditional laminates. The reductions in strength and modulus found in the non-traditional laminates can most likely be attributed to changes in unnotched properties, as opposed to differences in stress distribution around the notch.

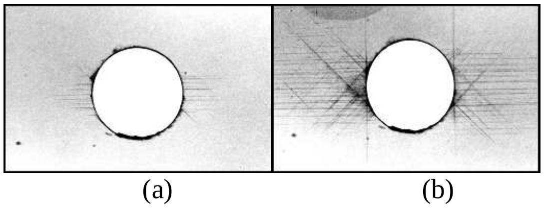
(a) (b)

Figure 4 Radiographic images of traditional quasi-isotropic open hole tension specimen at a)36% failure load, and b) 93% failure load

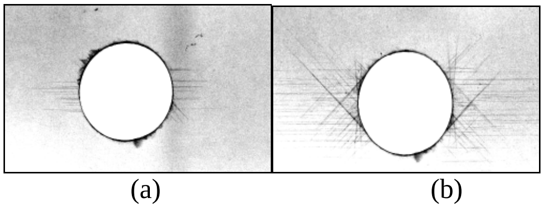
(a) (b)

Figure 5 Radiographic images of non-traditional (±5°) quasi-isotropic open hole tension specimen at a)36% failure load, and b) 93% failure load

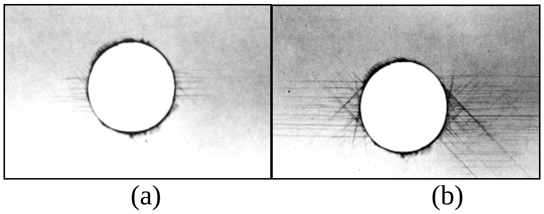
(a) (b)

Figure 6 Radiographic images of non-traditional (±10°) quasi-isotropic open hole tension specimen at a)40% failure load, and b) 100% failure load

3.1.2 QUASI-ISOTROPIC FILLED HOLE TENSION

Figure 7 and Figure 8 present the results of the quasi-isotropic filled hole tension tests. As in the open hole tension case, the non-traditional laminates are less stiff than the traditional laminates. However, the filled hole tensile strength of the non-traditional quasi-isotropic laminates were slightly higher than the filled hole tensile strength of the traditional laminate. Additionally the strains-to-failure of the non-traditional laminates were higher.

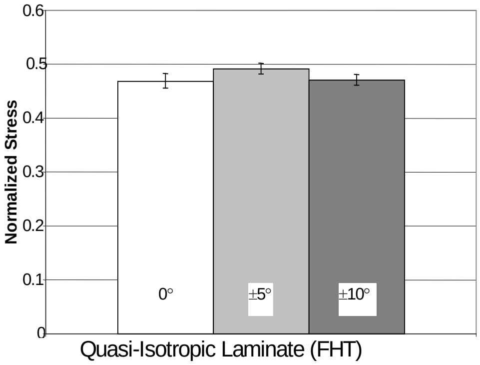

Figure 7 Average Quasi-Isotropic Filled Hole Tensile Strengths

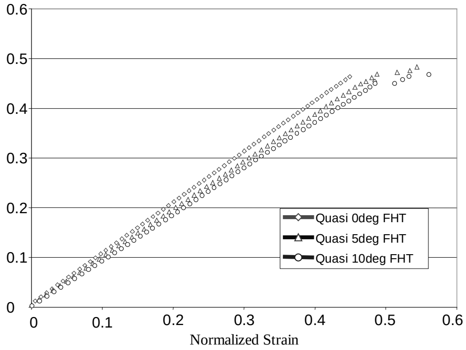

Figure 8 Comparison of traditional and non-traditional quasi-isotropic filled hole tension response

X-ray images of the quasi-isotropic filled hole tension specimens are shown in Figure 9, Figure 10, and Figure 11. As would be expected, the presence of a fastener with clamp-up force reduced damage around the notch, due to the constraint imposed by the fastener [4, 5]. Damage was not observed in any of the specimens until approximately 90% of the failure load, in the form of ±45° and 90° ply cracking. For each specimen, a prominent +45° and -45° crack formed and overlapped, creating a triangular region at the hole edges approximately 1.4mm in width by 2.9mm in height. Fiber breakage and notch delamination occurred shortly thereafter. In the traditional quasi-isotropic FHT specimens, slight longitudinal ply cracking is evident prior to failure, but none was discernable in the non-traditional laminates. Most damage occurs in the area under the washer, and only progresses from under the washer just prior to failure. There does not appear to be significant difference between the traditional and non-traditional laminates in this case.

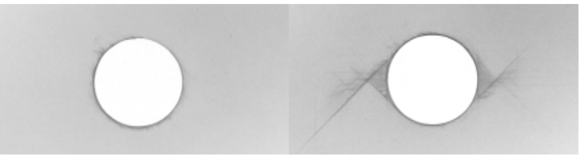
(a) (b)

Figure 9 Radiographic images of traditional quasi-isotropic filled hole tension specimen at a) 81.3% failure load, and b) 97.6% failure load.

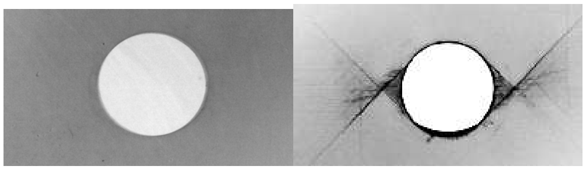
(a) (b)

Figure 10 Radiographic images of non-traditional (±5°) quasi-isotropic filled hole tension specimen at a)84.6% failure load, and b) 96.2% failure load

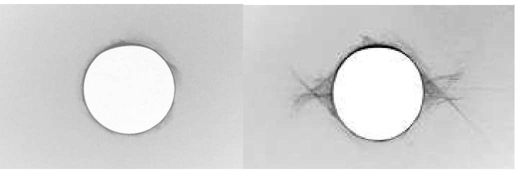
(a) (b)

Figure 11 Radiographic images of non-traditional (±10°) quasi-isotropic filled hole tension specimen at a)82% failure load, and b) 98.4% failure load

3.1.5 Quasi-Isotropic Single Shear Bearing

Figure 12 and Figure 13 give the results of the quasi-isotropic single shear bearing tests. The response of the non-traditional laminates is less stiff than the traditional laminates, but an overall increase in maximum load is observed with the use of non-traditional plies, with the ±10° plies providing the highest strength.

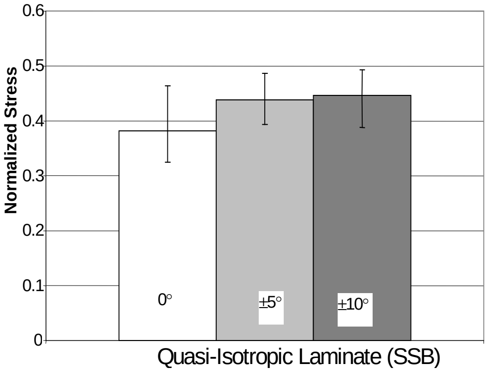

Figure 12 Average Quasi-Isotropic Single Shear Bearing Strengths

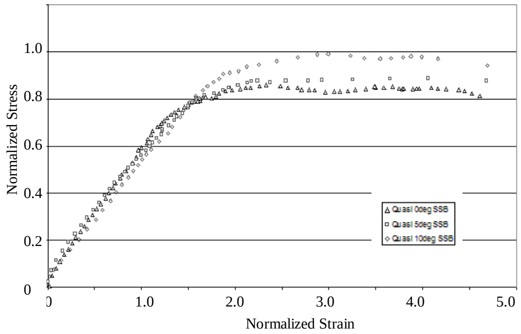

Figure 13 Comparison of traditional and non-traditional quasi-isotropic single shear bearing response

X-ray images of the quasi-isotropic SSB specimens are given in Figure 14, Figure 15, and Figure 16. In each case, longitudinal, ±45°, and 90° damage occurs in the linear portion of the load response. The longitudinal damage is in general less pronounced in the non-traditional laminates. Eventually bearing damage begins to accumulate on the bearing surface in each specimen, and the resulting hole elongation causes non-linearity in the load response. Fastener rotation causes additional surface damage, through-thickness damage, and delamination.

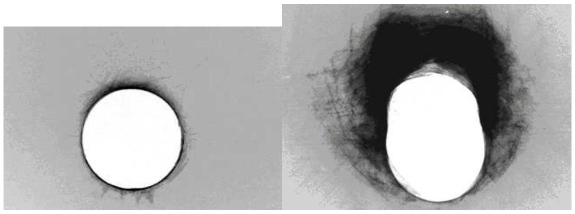
(a) (b)

Figure 14 Radiographic images of traditional quasi-isotropic single shear bearing specimen at a) 69% maximum load, and b) 96% maximum load

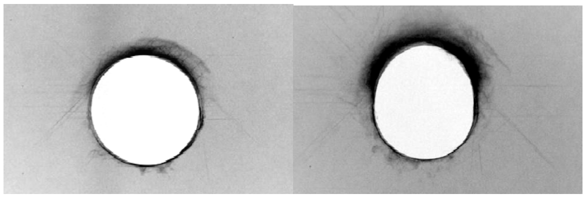
(a) (b)

Figure 15 Radiographic images of non-traditional (±5°) quasi-isotropic single shear bearing specimen at a) 60% maximum load and b 84% maximum load

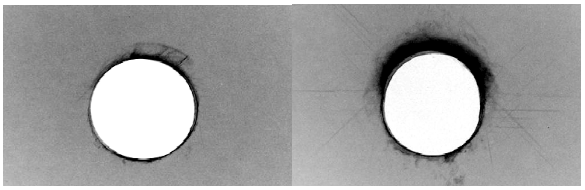
(a) (b)

Figure 16 Radiographic images of traditional quasi-isotropic single shear bearing specimen at a) 58% maximum load and b) 81% maximum load

3.1.3 HARD OPEN HOLE TENSION

Figure 17 and Figure 18 give the results of the hard open hole tension tests. As before, modulus decreases with increasing longitudinal ply angle as shown in Table 2. There also is a significant difference in the OHT strength and strain-to-failure of the traditional and non-traditional laminates.

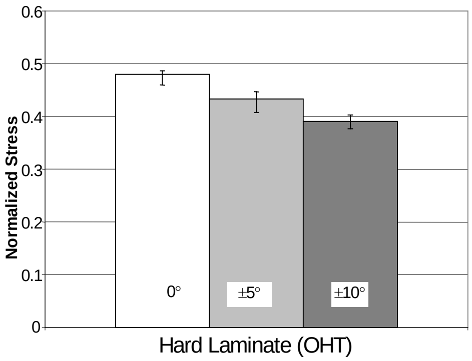

Figure 17 Average Hard Laminate Open Hole Tensile Strengths

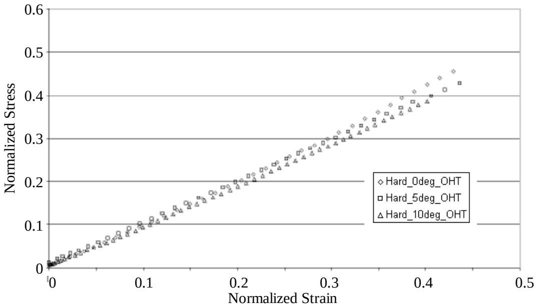

Figure 18 Comparison of traditional and non-traditional hard open hole tension response

Table 2 Experimental and Theoretical Hard Laminate Moduli

	Hard (0°) (GPa)	Hard (±5°) (GPa)	Hard (±10°) (GPa)
Experimental	94.32	91.08	89.01
Theoretical	94.67	93.01	88.05

The x-ray images showing damage progression in the hard open hole tension specimens with 0°, ±5°, and ±10° longitudinal plies are shown in figure 6, 7, and 8 respectively. Early damage consisted of ±45° and 90° cracking. 90° cracking increased in density and length with load, and eventually reached the free edge of the specimen for each type. ±45° cracks also increased in number and size with load, but little difference was noted between traditional and non-traditional laminates. As expected, the traditional hard OHT specimens developed severe longitudinal ply cracking. The use of the ±5° or ±10° longitudinal plies greatly reduced the extent of this damage. Prior to failure, the length of the longest longitudinal ply crack in the traditional laminate was 9.1mm, versus 4.8mm in the laminate with ±5° plies and 4.3mm in the laminate with ±10° plies. However, in the traditional laminate this splitting at the hole essentially eliminated the notch effect, resulting in two unnotched ligaments and thus a higher failure stress. In contrast, the notch effect remained present throughout loading in the non-traditional laminates resulting in a significant decrease in failure stress.

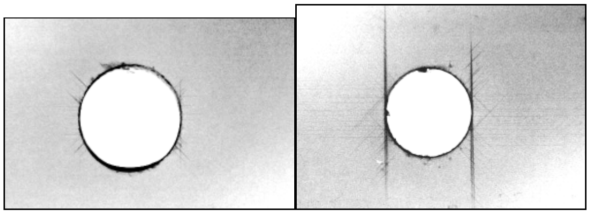
(a) (b)

Figure 19 Radiographic images of traditional hard open hole tension specimen at a)32% failure load, and b) 76% failure load

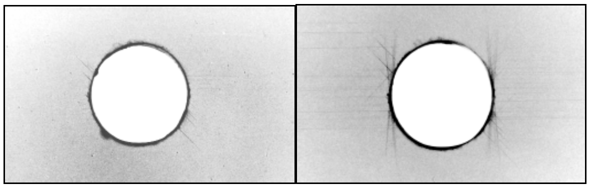
(a) (b)

Figure 20 Radiographic images of non-traditional (±5°) hard open hole tension specimen at a)36% failure load, and b) 88% failure load

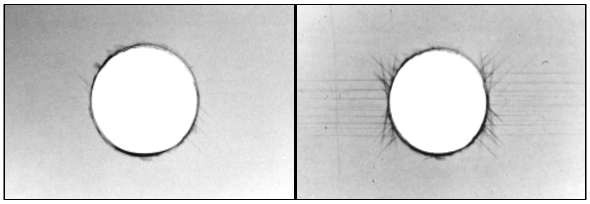
(a) (b)

Figure 21 Radiographic images of non-traditional (±10°) hard open hole tension specimen at a)40% failure load, and b) 79% failure load

Edge delamination is evident in the x-ray images, but was difficult to quantify the amount present. As such, one of each type of hard OHT laminate was sectioned during post-failure inspection of the specimens. The specimen was cut into 1.25cm sections using a Silicon Carbide cutting disc on a water-cooled abrasive saw. Damage length was then measured at these points under a stereomicroscope, and are given in Figure 22. A definite reduction in delamination occurred in both non-traditional laminates, and no delamination was apparent in the specimen with the ±10° plies.

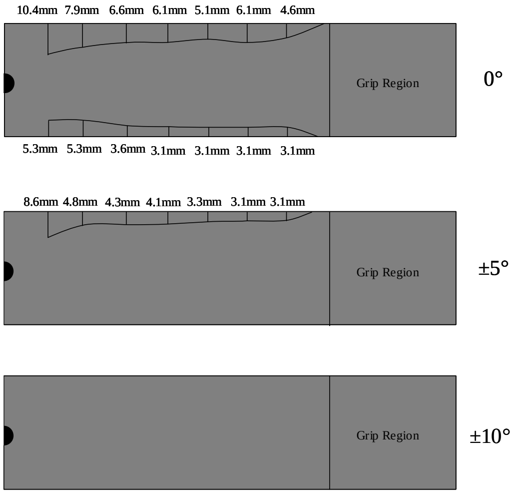

Figure 22 Edge Delamination in Hard OHT Specimens

3.1.4 *HARD FILLED HOLE TENSION*

The results of the hard filled hole tension tests are given in Figure 23 and Figure 24. There is a reduction in average strength in the non-traditional laminates, although the difference between traditional and non-traditional laminates is not as pronounced as in the open hole tension case. There is a significant reduction in the strength of all laminates when compared to the open hole case, with a fastener resulting in an approximate 20% decrease in strength in the traditional laminate.

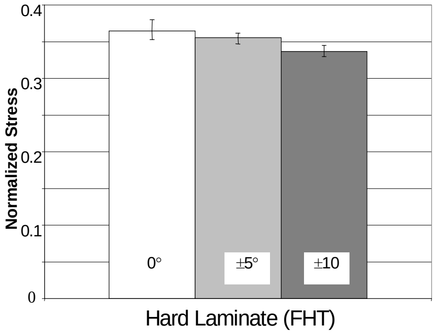

Figure 23 Average Hard Filled Hole Tensile Strengths

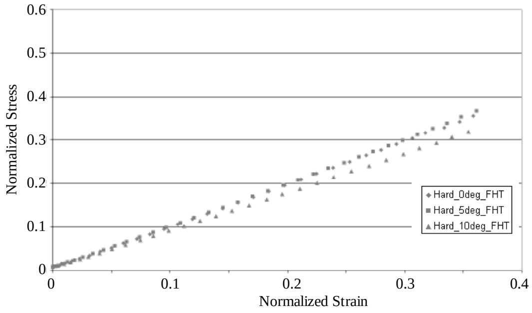

Figure 24 Comparison of traditional and non-traditional hard filled hole tension response

The x-ray images of the hard filled hole tension specimens are shown in Figure 25, Figure 26, and Figure 27. Longitudinal splitting occurred earliest in the traditional laminate, and propagated outside the washer region, exceeding 11.3mm. In the non-traditional laminates, the splitting was largely suppressed. In general, damage in the traditional laminate appeared much more severe at every load increment compared to the non-traditional laminates.

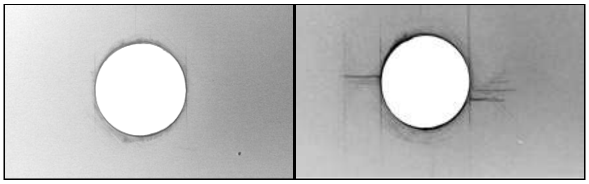
(a) (b)

Figure 25 Radiographic images of traditional hard filled hole tension specimen at a)70% failure load, and b) 96% failure load

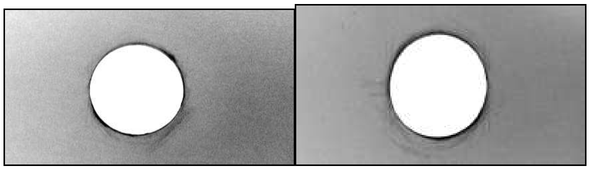
(a) (b)

Figure 26 Radiographic images of non-traditional (±5°) hard filled hole tension specimen at a)80% failure load, and b) 96% failure load

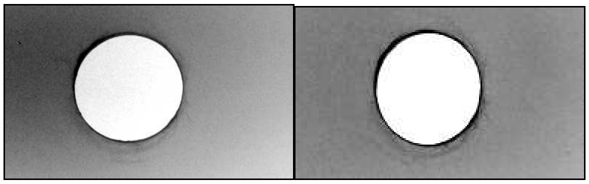
(a) (b)

Figure 27 Radiographic images of non-traditional (±10°) hard filled hole tension specimen at a)74% failure load, b) 95% failure load

3.1.6 Hard Single Shear Bearing

Figure 28 and Figure 29 present the results of the hard single shear bearing tests. The response of the non-traditional laminates is less stiff than the traditional laminates but average strength increased through the use of non-traditional plies. As in the quasi-isotropic single shear bearing tests, the ±10° plies provided the highest strength.

X-ray images of the hard SSB specimens are given in Figure 30, Figure 31, and Figure 32. In each case, longitudinal, ±45°, and 90° damage occurs in the linear portion of the load response. Severe longitudinal damage occurs in the traditional hard laminate, but this damage is less pronounced in the non-traditional laminates. Bearing damage accumulates and the resulting hole elongation causes non-linearity in the load response.

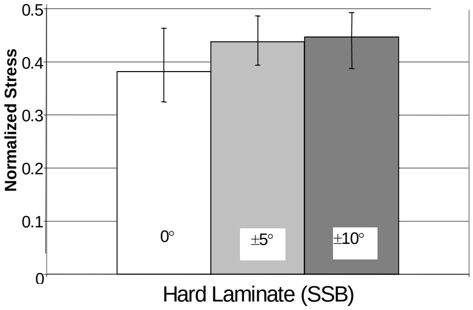

Figure 28 Average Hard Single Shear Bearing Strengths

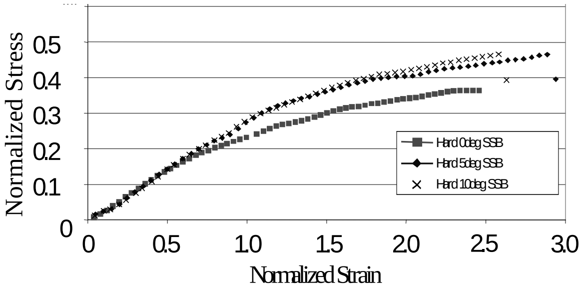

Figure 29 Comparison of traditional and non-traditional hard single shear bearing response

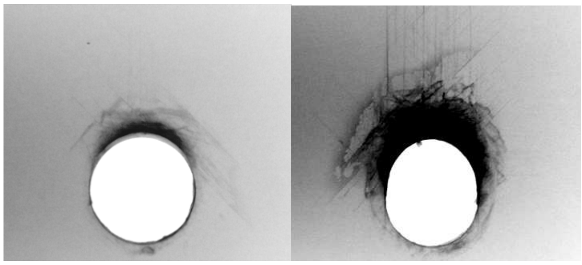
(a) (b)

Figure 30 Radiographic images of traditional hard single shear bearing specimen at a)58% maximum load and b) 75% maximum load

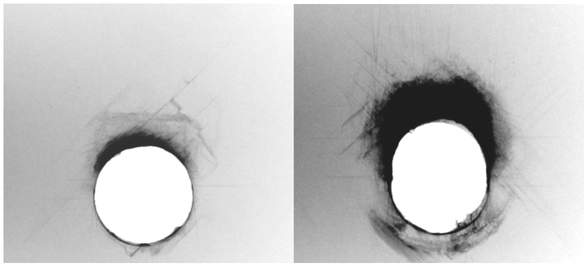
(a) (b)

Figure 31 Radiographic images of non-traditional (±5°) hard single shear bearing specimen at a) 59% maximum load and b) 77% maximum load

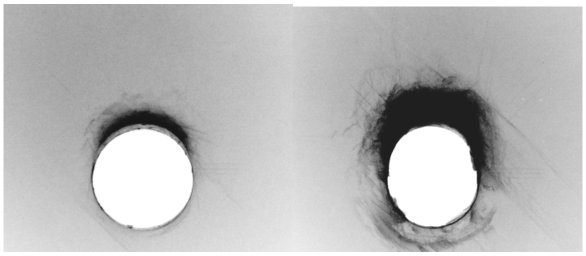
(a) (b)

Figure 32 Radiographic images of non-traditional (±10°) hard single shear bearing specimen at a)58% maximum load and b) 75% maximum load

In the traditional laminates, if loading is continued beyond what is normally considered failure (i.e. 15-20% hole elongation), shear-out of the longitudinal plies can occur, as is shown in Figure 33. No such damage occurred in the non-traditional laminates.

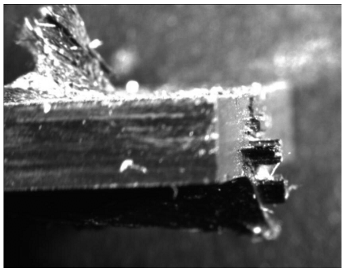

Figure 33 Shear-out of longitudinal plies in traditional hard single-shear bearing specimen

3.2 Discussion of Results

Following is a discussion of the effects of the various test parameters on the notched tension and single shear bearing tests. The different lay-ups resulted in differing responses and damage modes, and within each lay-up, the use of 0°, ±5°, or ±10° longitudinal plies causes further changes in response. Additionally, differences in loading and notch constraint caused significant changes in damage progression and mechanical properties. Following is a discussion of each of these variables.

3.2.1 Effect of non-traditional laminates

The use of slightly off-axis longitudinal plies had several effects. Most notably, the non-traditional laminates suppressed longitudinal splitting. In notched tension, splitting serves to reduce the notch effect, and thus the suppression of splitting resulted in continued notch effect and ultimately lower strengths. When splitting was severe, as in the open hole tension case of the hard laminate, the continued presence of the notch effect in the non-traditional laminates resulted in a considerable reduction in strength. Conversely, there was little difference between traditional and non-traditional laminates for the filled hole case, because splitting was already suppressed by the fastener. Additionally, the non-traditional laminates reduced delamination. Also of interest was the increase of bearing strength through the use of non-traditional laminates. This is most likely the result of small increases in bearing resistance due to the slightly off-axis plies. The off-axis plies also seem to reduce the possibility of fiber shear-out in laminates prone to that behavior.

3.2.2 Effect of lay-up

There were significant differences in performance and damage development in the quasi-isotropic and hard laminates. The hard lay-ups, with a higher percentage of longitudinal plies, were stronger and stiffer in tension. Conversely, because the quasi-isotropic laminates had a higher percentage of 90° and ±45° plies, they demonstrated higher bearing strengths due to increased bearing resistance. Additionally, the hard lay-ups experienced much more severe longitudinal splitting and delamination, as shown in the x-ray images, and the hard traditional laminate was shown to be more prone to fiber shear-out.

3.2.3 Effect of notch constraint

The effect of notch constraint is evident in the difference between open hole and filled hole tensile strengths. For each laminate, the filled hole tensile strength was lower than the open hole tension case.

Because a fastener with a clamp-up load constrains the area around the notch, the softening and stress redistribution that occurs in the open hole specimen does not occur. As such, damage appears later but failure occurs earlier. The difference between OHT and FHT strength is most severe in the hard traditional laminate. The high OHT strength of this laminate results from splitting at the edges of the notch , which leads to the elimination of the notch effect. When this splitting is suppressed by the fastener, the strength is greatly reduced. Since the non-traditional laminates suppress splitting in the OHT case, the effect of the fastener in the FHT case is less pronounced.

4 Conclusions

Non-traditional laminates with slightly off-axis longitudinal plies were evaluated for the possibility of damage suppression. The open hole tension, filled hole tension, and single shear bearing performance of traditional and non-traditional laminates were compared. The damage progression in these laminates was evaluated using radiographic inspection at incremental loads. The effects of notch constraint, lay-up, and off-axis longitudinal plies were discussed.

Under notched tensile loading, the non-traditional laminates were typically less stiff and less strong than traditional laminates. However, depending on design criterion, the increased damage tolerance of the non-traditional lay-ups may make these laminates useful in some applications. Additionally, the suppression of splitting and delamination could have added benefits in laminates with very high percentages of longitudinal plies. Finally, the increased bearing resistance of non-traditional laminates shows promise for increasing bolt-bearing strength.

[1] Argon, A., Fracture of Composites, in Treatise on Materials Science and Technology. 1972. p. 79-114.

[2] Awerbuch, J. and M.S. Madhukar, Notched Strength of Composite Laminates: Predictions and Experiments - A Review. Journal of Reinforced Plastics and Composites, 1985. 4(1): p. 3-159.

[3] Etheridge, G.A., W.S. Johnson, and S. Reeve. Effect of Lay-up and Constraint on Tensile Notch Strength. in 13th Annual Technical Conference on Composite Materials. 1998. Baltimore, MD: American Society of Composites.

[4] Yan, Y., et al., Experimental study on clamping effects on the tensile strength of composite plates with a bolt-filled hole. Composites - Part A: Applied Science and Manufacturing, 1999. 30(10): p. 1215-1229.

[5] Etheridge, G.A., Investigation of progressive damage and failure in IM7 carbon fiber/5250-4 bismaleimide resin matrix composite laminates, in School of Mechanical Engineering 1998, Georgia Institute of Technology: Atlanta. p. xviii, 178 leaves

[6] Treasurer, P.J., Characterization and analysis of damage progression in non-traditional composite laminates with circular holes, in Mechanical Engineering. 2007, Georgia Institute of Technology: Atlanta, GA. p. 175.

[7] Sawicki, A.J. and P.J. Minguet, Failure mechanisms in compression-loaded composite laminates containing open and filled holes. Journal of Reinforced Plastics and Composites, 1999. 18(18): p. 1708-1728.