A COMPARATIVE EVALUATION OF QUASI-ISOTROPIC LAMINATES COMPOSED OF EITHER BRAIDED TRIAXIAL FABRIC OR WOVEN FABRIC, INCLUDING IMPACT AND LAMINATE PERFORMANCE

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ABSTRACT

Braided quasi-isotropic (0°, +/-60°) fabric has enabled easy lay-up and provided superior performance for a variety of composite applications, but to date the test data characterizing the benefits of quasi-isotropic fabric has been application specific. Quasi-isotropic laminates composed of prepregged woven fabric were compared to laminates composed of prepregged quasi-isotropic braided fabric. Both fabrics were produced with the same fiber type and were prepregged with the same resin. The coupon test matrix included: tension and compression in multiple directions; in-plane shear; CAI; open-hole tension and open-hole compression. Panel testing included impact testing using a soft gelatin projectile. The panel testing performed bracketed the containment threshold. Analysis of the two material systems studied and the impact testing performed will be examined, for the first time, in this presentation.

1. INTRODUCTION

Beginning in the early 1990's braid has increasingly become a common reinforcement in advanced composite structures. Initially utilized in the recreational and industrial markets, performance of the composite system was typically measured at the full scale product level. As use of the material proliferated to the aerospace sector a significant number of material property characterization programs were conducted by industry at the coupon level to qualify product performance. Industry characterization often included impact testing to quantify the impact performance benefits that are often realized with braid reinforced composites. Historically very little of this information has been available in the public domain. Much of this characterization work (coupon and impact) was greatly informed by the research conduct on test methods at NASA Glenn in Cleveland Ohio [ref. 1,2,3]

Until recently most of the product development for braid reinforced structures was for resin infused composites. Recent development effort with TenCate Advanced Composites has enabled successful fabrication of a pre-impregnated form of braided fabric. The subject of this study is QISO/ TC275-1 triaxial quasi-isotropic (0°, +/-60°) braided fabric pre-impregnated with a high performance epoxy resin. This study investigated both a heavy (12K, 536 gsm) and light (3K, 272 gsm) braided Qiso architecture. Each braided fabric was benchmarked against laminates reinforced with a woven architecture. Great care was taken to eliminate variables between the braided and woven laminates other than the fabric architecture.

2. EXPERIMENTATION

Laminate Fabrication

Table 1 describes the four fabrics in their dry, unimpregnated state. In order to keep the fabric sets directly comparable, both the quasi-isotropic QISO light and the light woven analog use the same carbon fiber, as did the QISO heavy and the heavy woven analog.

Table 1. Summary of Dry Fabrics prior to prepregging.

Material ID	**Fiber Type**	**Fiber Angles**	**Areal Weight (gsm)**	**Fabric Width (m)**
QISO-L	AS4C-GP 3k	0° / -60° / +60°	272	1.32
Light Plain Weave	AS4C-GP 3k	0° / 90°	205	1.27
QISO-H	T700SC 12k 50C	0° / -60° / +60°	536	1.50
Heavy Plain Weave	T700SC 12k 50C	0° / 90°	400	1.40

The four dry fabrics were then prepregged with TC275-1 epoxy resin system to a nominal 38%wt resin content. After prepregging, balanced, symmetric, quasi-isotropic laminates were fabricated for all four material types. Each panel was fabricated with a 63.5 cm length and a 63.5 cm width. The number of plies per laminate was closely selected to ensure that the total fiber areal weight was equivalent between comparable fabric sets. During hand layup, due to the quasi-isotropic nature of the QISO fabrics, all plies were nested in the same 0° direction. To achieve a quasi-isotropic laminate using the woven materials, it is necessary to cut 45° plies, which were then laid up in conjunction with 0° plies. Table 2 summarizes the laminate stacking sequences and the total fiber areal weight of each laminate type.

Table 2. Summary of Laminate stacking sequence.

Material ID	**Number of Plies**	**Ply Orientation**	**Total Fabric Areal Weight (gsm)**
QISO-L	9	$[0°]_9$	2448
Light Plain Weave	12	$[0°/45°]_{3s}$	2460
QISO-H	6	$[0°]_6$	3216
Heavy Plain Weave	8	$[0°/45°]_{2s}$	3200

The laminates were cured in an autoclave using the following cure cycle.

1. Apply 586 MPa pressure and heat 1.1°C per minute to 82°C.
2. Hold at 82°C for 45 minutes.
3. Heat 1.1°C per minute to 135°C.
4. Hold at 135°C for 300 minutes.
5. Cool at 2.8°C per minute to 60°C, then release pressure.

After the laminates were fabricated, ultrasonic C-scans were performed to check uniformity, and panel weight and thickness were measured. Additionally, theoretical fiber volume and cured ply thickness were calculated using the measured thickness. The laminate averages are summarized in table 3 below. Acid digestion testing was later completed to confirm the fiber volume and to analyze the void volume.

Table 3. Average laminate measurables.

Material ID	**Weight (g)**	**Thickness (mm)**	**Theoretical Fiber Volume (%)**	**Cured Ply Thickness (mm)**
QISO-L	1618	2.74	49.6	0.30
Light Plain Weave	1616	2.74	49.9	0.23
QISO-H	2149	3.66	48.8	0.61
Heavy Plain Weave	2068	3.43	51.8	0.43

Mechanical Testing

Table 4 shows the test matrix that was performed by Cincinnati Testing Laboratories to characterize the in-plane static mechanical properties of the four laminate types: QISO light, light weave, QISO heavy, and heavy weave.

Table 4. Mechanical coupon test matrix.

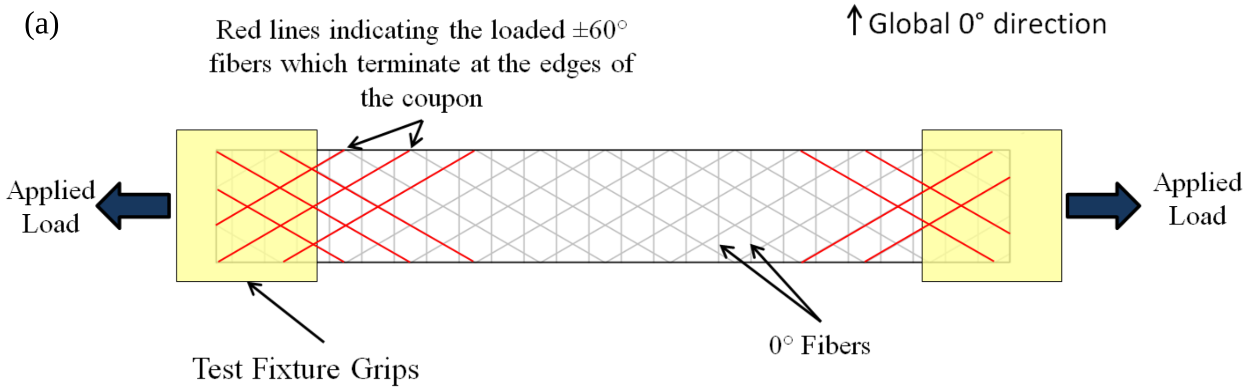
Test Mode	**Method**	**Length (0°) (cm)**	**Width (90°) (cm)**	**Replicates**
0° Tension	ASTM 3039	25.4	3.6	3
90° Tension	ASTM 3039	3.6	25.4	3
90° Tension Notched	ASTM 3039*	7.6	15.2	3
45° Tension	ASTM 3039	25.4 (+45°)	3.6 (-45°)	3
45° Tension Notched	ASTM 3039*	15.2 (+45°)	7.6 (-45°)	3
In-plane Shear	ASTM D7078	5.6	7.6	3
0° Compression	ASTM D6641	14.0	1.8	3
90° Compression	ASTM D6641	1.8	14.0	3
Compression After Impact	ASTM D7136/D7137	15.2	10.2	3

Open Hole Tension	ASTM D5766	30.5	3.8	3
Open Hole Compression	ASTM D6484	30.5	3.8	3
Acid Digestion	ASTM D3171	1.3	3.8	4

*Indicates modified ASTM test method

All of the mechanical testing follows standard ASTM test methods, except the 90° and 45° notched tensile tests. The standard straight sided ASTM 3039 coupon fails to capture the global strength benefits of a braided architecture when testing coupons in these off axis directions, as demonstrated in figure 1. Specifically looking at the 90° tensile test, using the standard straight sided coupon, no single carbon fiber spans the entire gauge section of the coupon leading to artificially low strength data. With a typical quasi-isotropic plain weave layup, this issue is avoided due to the presence of 90° fibers that span from grip to grip. Additionally for the braid, the bias ±60° fibers that are gripped in the test fixture terminate at the edges of the test coupon inducing negative edge effects which can also lead to artificially reduced strength values. The notched coupon realizes the global effect of the ±60° fibers, allowing them to span the gauge section of the coupon, and eliminates the negative edge effects. Due to the complex strain field created by this coupon, no strain or modulus is recorded for the notched tensile tests, only tensile strength.

(a)



(b)

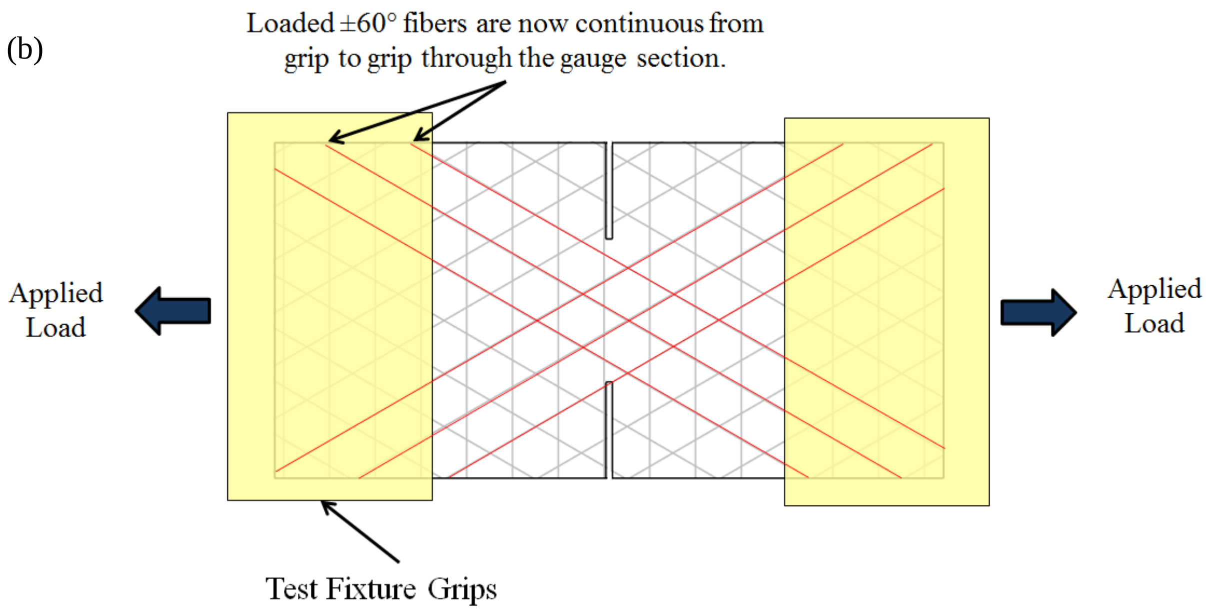


Figure 1. (a)Demonstration of the inadequacies of the ASTM 3039 straight sided coupon for tensile testing of braided composites in the 90° direction. (b)The notched coupon developed to give accurate strength measurements of braided composites in the 90° direction.

In addition to this testing, for the QISO heavy and heavy woven fabric, one test panel was purposefully laid up with a ply that was misoriented by 5°. The purpose of this test panel was to simulate human error during layup, and study the effects that this has on mechanical properties. For both laminates, one of the 0° plies at the midplane of the laminate was misoriented. Table 5 summarizes the tests conducted on the misoriented ply laminates. Again for this testing, a notched coupon was used to capture the 90° tensile strength.

Table 5. Test matrix for misoriented ply QISO heavy and heavy weave.

Test Mode	**Method**	**Length (0°) (cm)**	**Width (90°) (cm)**	**Replicates**
Longitudinal Tension	ASTM 3039	25.4	3.6	3
Transverse Tension	ASTM 3039	3.6	25.4	3
Transverse Tension Notched	ASTM 3039*	7.6	15.2	3
Acid Digestion	ASTM D3171	1.3	3.8	2

*Indicates modified ASTM test method

Impact Testing

In addition to the static mechanical testing, dynamic impact testing was conducted by the University of Dayton Research Institute (UDRI) impact physics division. 5 QISO heavy laminates and 5 heavy woven laminates were tested via impact, and the panels used were identical to those used for mechanical testing (63.5 cm by 63.5 cm). The purpose of the impact testing was to bracket the penetration threshold of the braid and the weave by varying the velocity of the projectile. For this testing, the projectile was a gelatin cylinder with a 7.0 cm diameter, a 12.7 cm height, and 453.6 gram mass. The projectiles were encased in a polyurethane sabot, and then fired using an 8.9 cm diameter smooth-bore compressed-gas gun. The projectile was in free flight to the target over a distance of 1.65 meters, during which the velocity was measured using laser photodetector stations positioned in front of the target. The test panels were bolted into place around the perimeter leaving a 50.8 cm x 50.8 cm unsupported area in the center, and high speed video of the impact event was recorded.

3. RESULTS

Mechanical Testing Results

Table 6 shows the fiber, resin, and void volume percentages from the acid digestion testing on the laminates used for mechanical testing.

Table 6. Acid digestion results for the 4 laminate types

Material ID	Percent Fiber Volume (%Vf)	Percent Resin Volume (%Vr)	Percent Void Volume (%Vv)
QISO-L	52.88 ± 1.74	46.71 ± 1.79	0.4 ± 0.05
Light Weave	52.42 ± 0.37	47.38 ± 0.26	0.2 ± 0.11
QISO-H	49.07 ± 0.62	51.08 ± 0.8	-0.15 ± 0.19
Heavy Weave	51.52 ± 0.95	48.38 ± 0.93	0.1 ± 0.02

In order to compare the reinforcement types, the fiber volume was normalized to 55% for all tension and compression testing. The only testing that was not normalized for fiber volume was the in-plane shear testing as in-plane shear is not known to scale linearly with fiber volume. The mechanical test results for QISO heavy and the heavy weave are summarized in table 7, and the results for QISO light and the light weave are summarized in table 8.

Table 7. Mechanical test results for QISO heavy and heavy woven laminates, normalized to 55% fiber volume.

Material Property	**QISO Heavy**	**Heavy Weave**
0° Tensile Strength - MPa (ksi)	930 (135)	638 (92)
0° Tensile Modulus - GPa (Msi)	45.2 (6.6)	44.8 (6.5)
90° Tensile Strength - MPa (ksi)	881 (128)	690 (100)
90° Tensile Modulus - GPa (Msi)	43.7 (6.3)	42.6 (6.2)
45° Tensile Strength - MPa (ksi)	771 (112)	711 (103)
45° Tensile Modulus - GPa (Msi)	45.5 (6.6)	45.2 (6.6)
0° Compressive Strength - MPa (ksi)	569 (83)	380 (55)

0° Compressive Modulus - GPa (Msi)	43.2 (6.3)	41.7 (6)
90° Compressive Strength - MPa (ksi)	424 (61)	362 (53)
90° Compressive Modulus - GPa (Msi)	41.8 (6.1)	40.9 (5.9)
Compression After Impact - MPa (ksi)	245 (36)	201 (29)
Open Hole 0° Tensile Strength - MPa (ksi)	676 (98)	484 (70)
Open Hole 0° Tensile Modulus - GPa (Msi)	45.7 (6.6)	43.7 (6.3)
Open Hole 0° Compressive Strength - MPa (ksi)	423 (61)	297 (43)
Open Hole 0° Compressive Modulus - GPa (Msi)	41.3 (6)	45.4 (6.6)
In Plane Shear Strength - MPa (ksi)*	236 (34)	264 (38)
In Plane Shear Modulus - GPa (Msi)*	16.4 (2.4)	15 (2.2)
Misoriented Ply 0° Tensile Strength - MPa (ksi)	849 (123)	656 (95)
Misoriented Ply 0° Tensile Modulus - GPa (Msi)	45.4 (6.6)	44.8 (6.5)
Misoriented Ply 90° Tensile Strength - MPa (ksi)	859 (125)	663 (96)
Misoriented Ply 90° Tensile Modulus - GPa (Msi)	43.6 (6.3)	44 (6.4)

*Indicates data not normalized to 55% fiber volume.

Table 8. Mechanical test results for QISO light and light woven laminates, normalized to 55% fiber volume.

Material Property	**QISO Light**	**Light Weave**
0° Tensile Strength - MPa (ksi)	775 (112)	657 (95)
0° Tensile Modulus - GPa (Msi)	47 (6.7)	46.2 (6.7)
90° Tensile Strength - MPa (ksi)	681 (99)	648 (94)
90° Tensile Modulus - GPa (Msi)	43 (6.2)	44.6 (6.5)
45° Tensile Strength - MPa (ksi)	565 (82)	657 (95)
45° Tensile Modulus - GPa (Msi)	44 (6.4)	44.6 (6.5)
0° Compressive Strength - MPa (ksi)	603 (87)	465 (67)
0° Compressive Modulus - GPa (Msi)	42 (6.2)	41.8 (6.1)
90° Compressive Strength - MPa (ksi)	464 (67)	425 (62)
90° Compressive Modulus - GPa (Msi)	43 (6.2)	43.1 (6.2)
Compression After Impact - MPa (ksi)	240 (35)	227 (33)
Open Hole 0° Tensile Strength - MPa (ksi)	494 (72)	378 (55)
Open Hole 0° Tensile Modulus - GPa (Msi)	46 (6.7)	43.6 (6.3)
Open Hole 0° Compressive Strength - MPa (ksi)	374 (54)	298 (43)
Open Hole 0° Compressive Modulus - GPa (Msi)	43 (6.2)	41.5 (6)
In Plane Shear Strength - MPa (ksi)*	305 (44)	360 (52)
In Plane Shear Modulus - GPa (Msi)*	16 (2.4)	17 (2.5)

*Indicates data not normalized to 55% fiber volume.

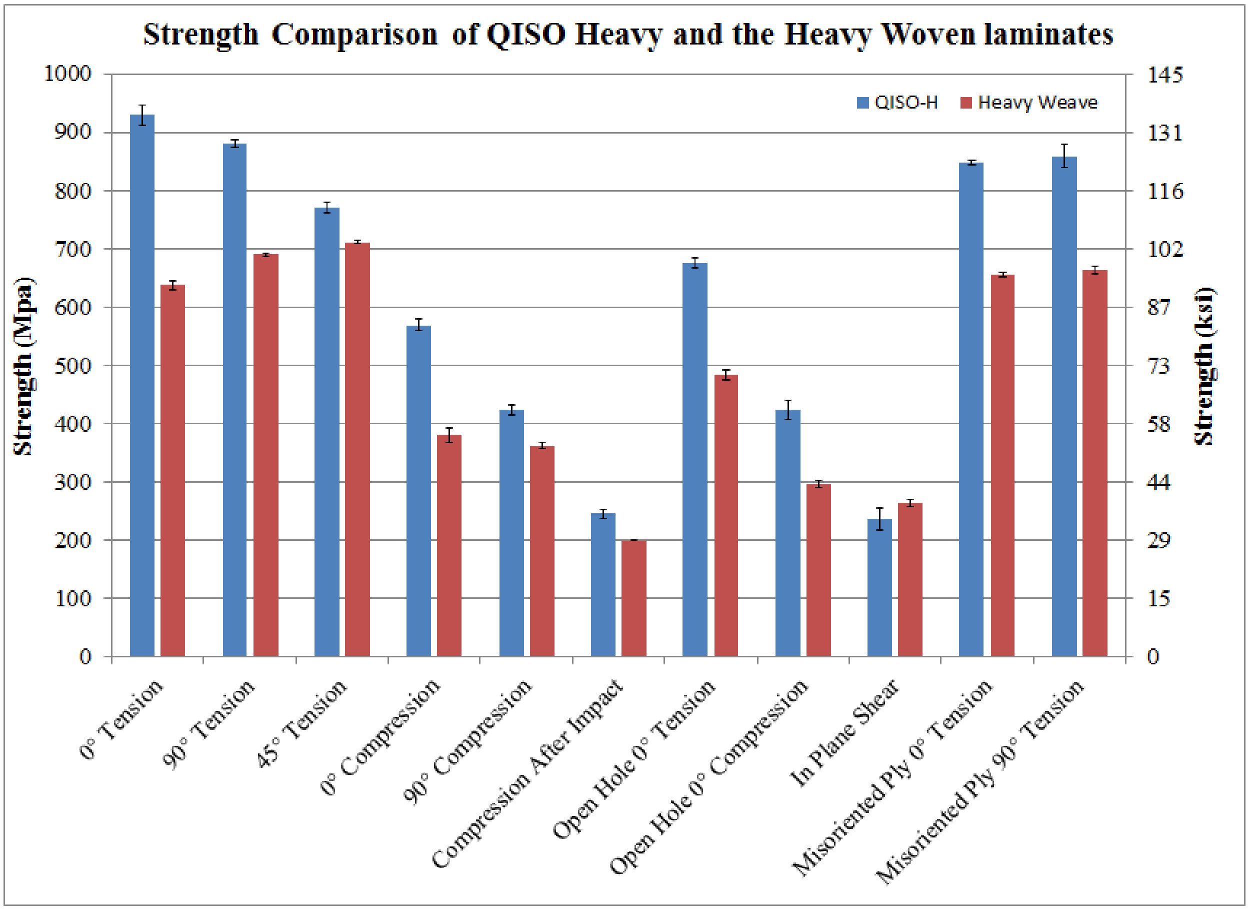


Figure 2. Graphical represenation of strength data comparing the QISO Heavy laminate to the Heavy Woven laminate.

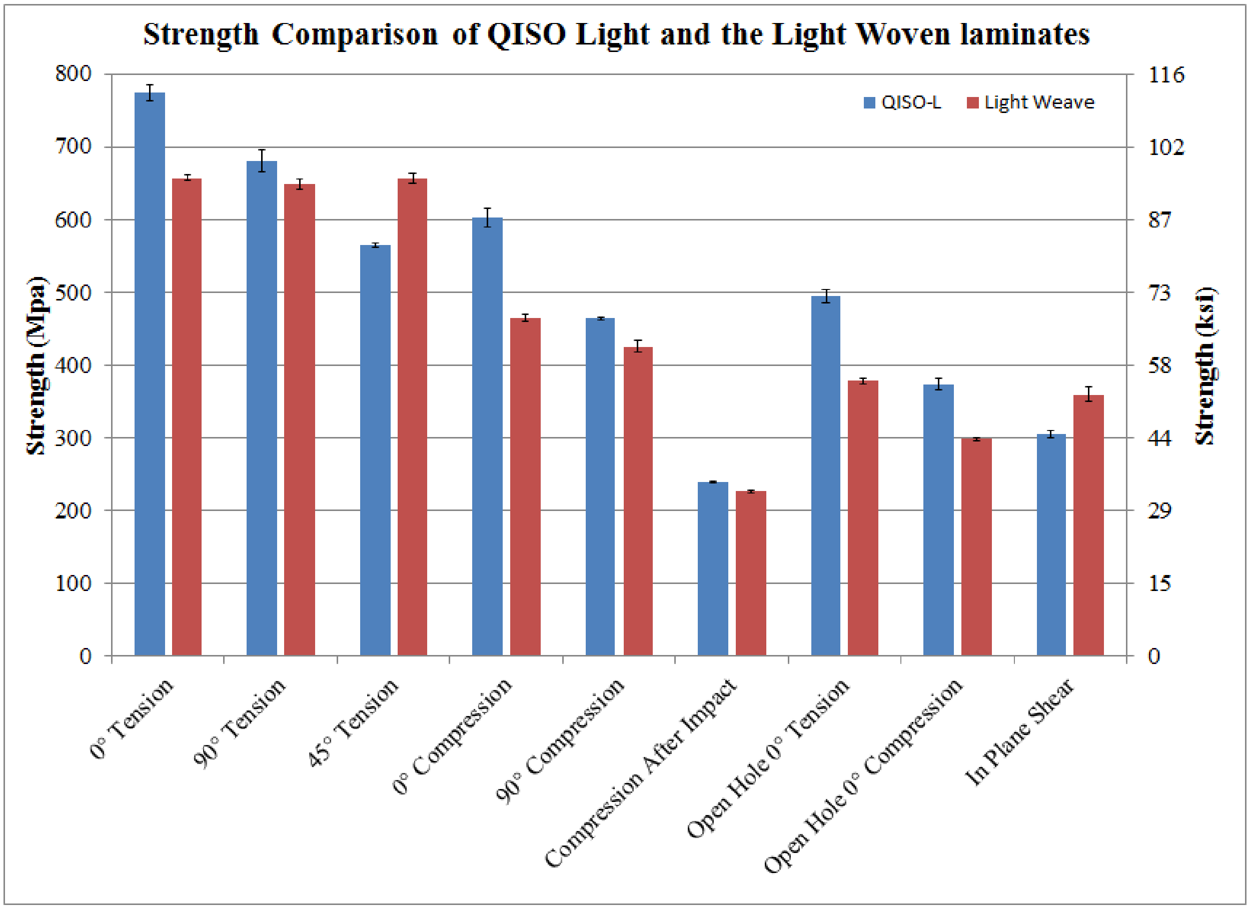


Figure 3. Graphical representation of strength data comparing the QISO Light laminate and the Light Woven laminate.

Impact Testing Results

The results of the impact testing are summarized in table 9. For the braided QISO-H panels, it was determined that an impact energy of 7929 joules was not enough for the projectile to penetrate the panel, but an impact energy of 8037 joules was enough energy for penetration. These two impact energies successfully bracket the penetration threshold between 7929 joules and 8037 joules for the QISO heavy laminates. For the heavy woven laminates, the penetration threshold was bracketed between 6901 joules and 7205 joules. These results demonstrate a 13.2% performance increase in the QISO-H compared to the woven panel in the impact energy required for the specified projectile to penetrate the laminate.

Table 9. Impact testing results for the braided QISO heavy and heavy woven laminates.

Shot #	**Panel Type**	**Projectile Wt. (g)**	**Impact Energy (J)**	**Penetrate (Y/N)**
2-5535	QISO-H	453.6	7636	N
2-5544	QISO-H	455.8	7929	N
2-5543	QISO-H	456.0	8037	Y

2-5537	QISO-H	456.3	8359	Y
2-5536	QISO-H	438.4	9417	Y
2-5539	Heavy Weave	455.9	5971	N
2-5540	Heavy Weave	455.7	6901	N
2-5542	Heavy Weave	456.3	7205	Y
2-5541	Heavy Weave	455.1	7384	Y
2-5538	Heavy Weave	455.9	7828	Y

4. CONCLUSIONS AND FUTURE WORK

Test results from this study show a clear performance benefit to laminates reinforced with braided fabric compared to woven fabric. This benefit applies to both in-plane measurements as well as the ballistic impact testing. Continuing work will focus on developing a more thorough understanding of why there is such a clear advantage to braid versus weave. This work will include:

1) Extensive photo-microscopy parallel to all fiber paths to quantify the out of plane orientation or undulation associated with the two architectures and two fiber sizes. The goal is to establish a correlation between this undulation and resulting laminate performance.
2) Interrupted testing of both material systems where the coupons will be pulled from the load frame at the first audible and inspected for failure onset. These tests will be used to better understand failure mode initiation and progression.
3) Testing of a 2 x 2 twill woven construction to determine performance differences compared to the 1x1 plain weave that was evaluated in this study
4) Off-axis testing to supplement the 45° tensile tests conducted in this study. The next tests will be done at a 30° orientation so that the tensile load is not aligned with a fiber direction in either architecture type.
5) Additional tests for the effect of a mis-aligned ply within the laminate. The current study evaluated the effect of a 5° ply mis-alignment which is the maximum allowable per typical shop practice. The effect of a 10° mis-alignment will be assessed to understand the effect at a local level when the 5° standard can be met globally but not always locally on a complex geometry.
6) Impact testing of higher fiber volume laminates. Failure modes of the ballistic panels in previous evaluations have been more energetic. In this study the panels had a much higher panel bending stiffness given increased thickness which reduced panel deformation during the impact event. It seems that the panels behaved much less like a membrane in tension than in previous evaluations. This will be investigated.

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