Quasi-three-dimensional Quasi-isotropic woven composites

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1. Motivation

Many modern composite materials are made up of either unidirectional plies or two-dimensional bi-axial woven layers held together by a matrix. While these kinds of composites have been used with great success, there is potential for improvement in performance through the use of different weave patterns. The composites of tomorrow will be more resistant to delamination, more isotropic, and stronger than current generation composites. It is with the goal of attaining these properties that the weave examined in this study was created.

The weave examined in this study was tri-axial, and quasi-three-dimensional (Q3D). This weave varies from traditional weaves in two distinct ways. The first of which is the quasi-three-dimensional (Q3D) woven arrangement. Q3D weaves are weaves where fibers from one layer are woven into the layers above or below the layer. When this pattern is repeated through every fiber layer, the result is multiple layers that are physically attached to each other. In this arrangement, even without a matrix, multiple layers of fibers are physically held together, forming one three-dimensionally woven specimen. Research into the effects of Q3D weaves on the physical properties of composites have been made. [Q3D Testing, Liu, Rosario] showed that bi-axial Q3D weaves had "lower impact-induced damage, higher specific energy absorption, lower impact-induced structural degradation, and competitive in-plane properties than the laminated counterparts." The second difference between the studied weave and traditional weaves is its tri-axial arrangement. In this arrangement, every layer of woven fibers has fibers that run in three directions, along three axes. It is hoped that increasing the number of in plane axes will lead to greater isotropy in the final composite material, allowing for use in more varied applications. It is also hoped that the smaller angles between fibers will result in better resistance to delamination during impacting, as has been seen in other studies [Impact Response of Woven Composites with Small Weaving Angles, Atas, Liu].

2. Objective

The objective of this experiment was to analyze the physical response during impact testing, of a novel tri-axial, quasi-three-dimensional woven composite, and compare the results to composites lacking a complete quasi-three-dimensional arrangement.

3. Literature Review

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4. Specimen Preparation

It was first necessary to develop a tri-axial Q3D weave. The most basic, 2D, form of the weave used is is known as a "tri-axial weave".

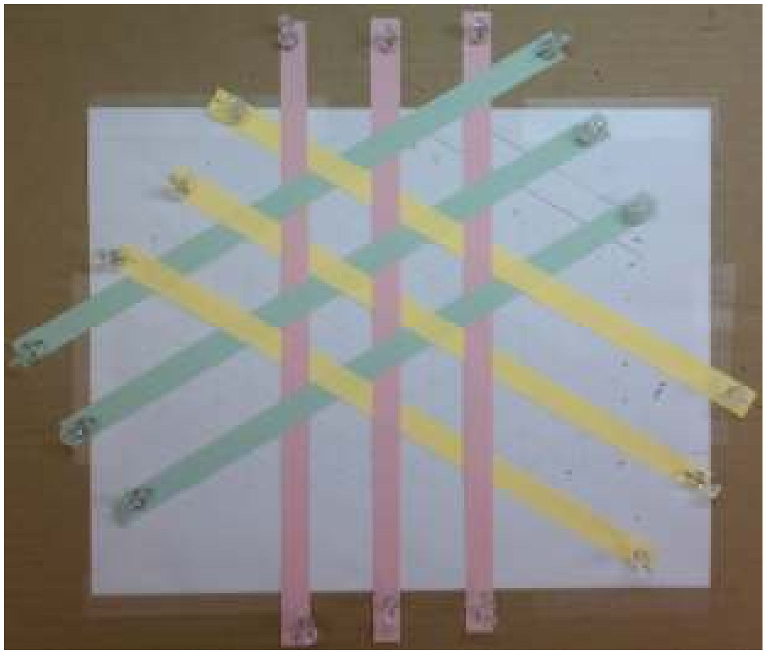


Figure 1: “Base” 2D Weave

In this weave, the “Pink” strands run above the “Yellow” strands, and below the “Green” strands. The “Yellow” strands run above the “Green” strands, and below the “Pink” strands. Finally, the “Green” strands run above the “Pink” strands and below the “Yellow” strands. When constructed so that the angle between all strands is sixty degrees, the weave creates regular hexagonal gaps with a width, from parallel face to parallel face, of twice the strand's thickness. This is the base, 2D weave, used for the creation of the tri-axial Q3D weave.

The next step in the manufacture of this tri-axial Q3D weave is the insertion of the strands that will run through the lower layer while also remaining part of the next layer in the Q3D weave. In this instance, “Yellow” strands were used as this connecting agent. Starting in the space directly to the left of the “Yellow” strands in layer one (Y1), the Y2 strand was woven below all G1 strands. These Y2 strands then form the basis for the second layer of the Q3D weave. The original weaving order is followed for Layer 2, with G2 inserted next, immediately to one side of the G1 strands, so that it runs below Y2, but above all strands in Layer 1. Finally, the P2 strands are inserted so that they run below the G2 strands, and above both the Y2 and Layer 1 strands. All colored strands in Layer 2 are arranged so that they are immediately to the side of their first layer counterparts.

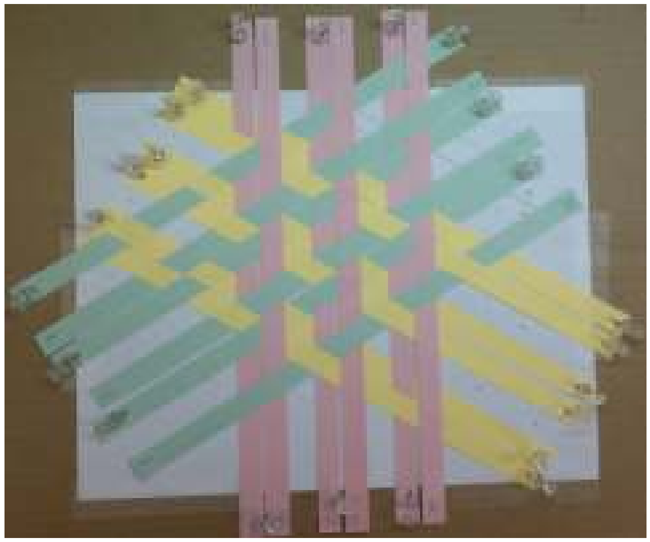


Figure 2: Addition of Layer 2 Fibers

This process can then be repeated once more to create a third layer of the weave. As in the creation of the second layer, Y3 strands are woven below G2 strands, and above everything else. G3 strands are woven below Y3 strands and above everything else, and P3 strands are woven below G3 strands and above all others. After the completion of this third layer, there are no remaining holes in the weave. Additionally, at any point in the weave, the strands are three deep, meaning that as long as a specimen woven using this weave pattern has a number of layers divisible by three, it will have a constant thickness.

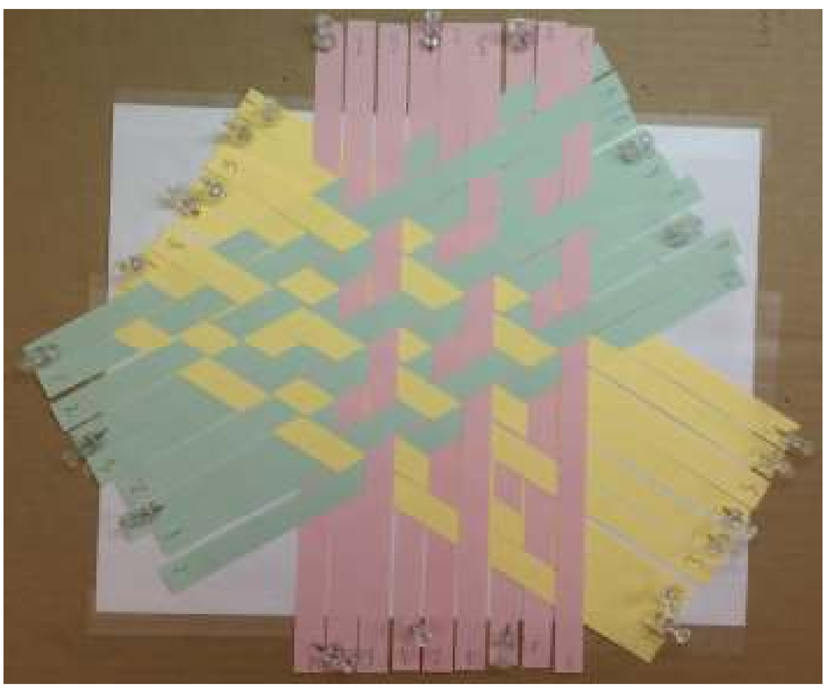


Figure 3: Complete Q3D Sheet

This experiment will compare several different types of strand arrangement in order to determine the effects of the Q3D weave on the specimen.

First, the most basic, will be a specimen, 12 layers deep, with [0/60/-60]4 arrangements of unwoven strands. These layers will be held together only by the matrix of the composite. A single [0/60/-60] sheet is shown below.

Figure 4: Single Laminated Sheet

Next, will be an arrangement of four Q3D panels, each 3 layers deep. These were notated as [0/60/-60]4 Each panel is woven Q3D, but the four panels are not woven together, and will be held together by the matrix. A single [0/60/-60] sheet is shown below.

Figure 5: Single 2D Woven Sheet

Finally, a completely interwoven Q3D panel, a total of 12 layers deep, notated as Q3D[0/60/-60]$_4$ will be created. An entire panel in this arrangement is shown below.

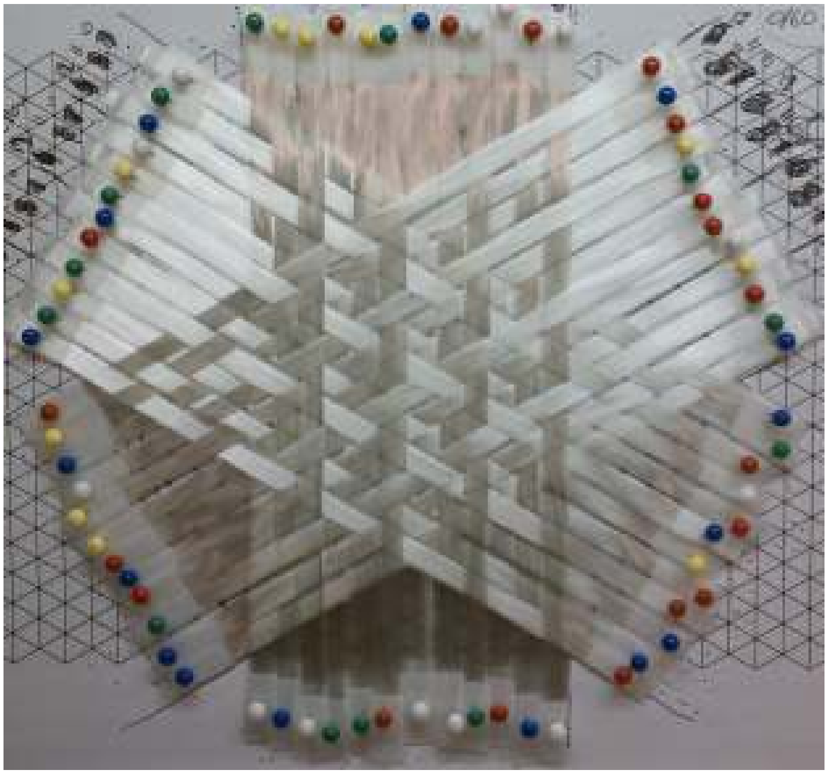


Figure 6: Complete Q3D Specimen

The hexagonal centers of the specimens is twelve layers deep. In order to be covered by the drop weight tower's specimen mount, the hexagon must be able to contain a three inch diameter circle. As such, each specimen features twelve fibers along every axis direction, which allows for the specimens to meet this criteria.

5. Material Characterization and Processing

The roving used for weaving in this study was made of 1102 tex E-glass, and the epoxy matrix was made up of SC-15A resin and SC-15B hardener. Originally, pre-preg fibers were investigated for use in weaving, but were deemed unsuitable due to their un-weavablility presented by their stickiness. The E-glass roving had a width of about .5 to .8 cm, with variations due to “wave” in the roving as it came off the spool. During preparation of the roving, the E-glass was cut into strands about 7” in length. Both ends of the strand were taped using Scotch tape, and the tape was trimmed using scissors so that it was about as wide as the strands.

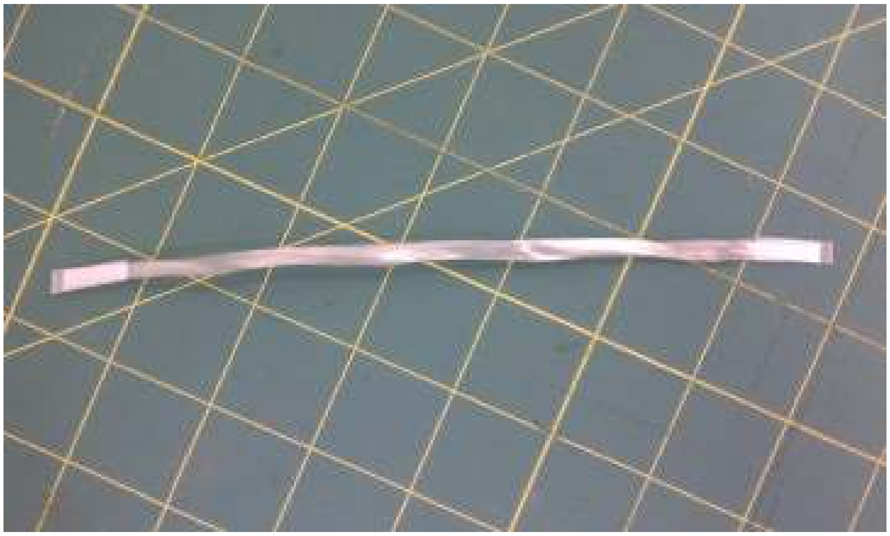


Figure 7: Prepared Fiber Strip

Using these strands, the Q3D panels could then be carefully woven. When woven, the hexagonal center of each specimen was slightly larger than 3” when measured between the parallel faces of the hexagon.

The VARTM process was used to impregnate the specimens with resin. Initial panels displayed poor surface finishes. At first, it was believed that the resin was not dispersing through the fibers, which left gaps as seen below.


Figure 8: Specimen After Curing with Poor Impregnation

This problem was solved by cutting the taped ends of the specimen after weaving, as seen below.

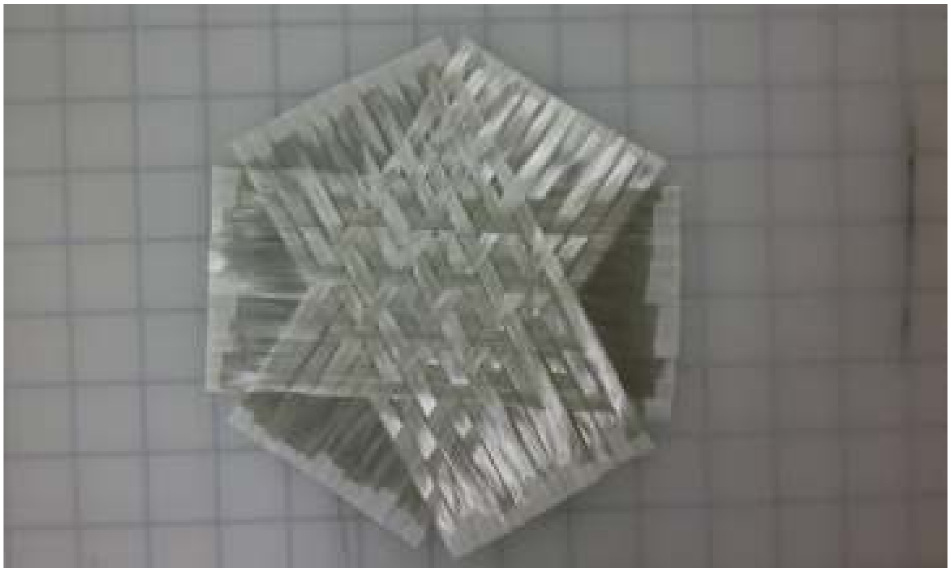


Figure 9: Specimen with Taped Edges Removed

Although the implementation of this technique solved the resin dispersion problems, another problem appeared. Additional panels had poor surface finishes that were pocked with what appeared to be air bubbles. Prior to impregnation, the VARTM setup was carefully checked for leaks, so it was determined that the the air was not due to a poor vacuum seal. Rather, it was hypothesized that after the exit hose was sealed off, some of the air remaining inside it entered the specimen during the curing cycle. In the image below, notice the bubbles within the distribution media at the top, and the poor surface finish below.

Figure 10: Specimen After Curing with Poor Surface Finish due to Bubbles

Several methods were attempted to combat this issue, but the method that proved to stop the problem was a continuous resin infusion setup. In this setup, the tubing was arranged so that both the inlet and outlet tubing are run out of the exit hole in the back of the oven. This allows the panel to be placed in the oven, while both tubes are accessible. In this setup the vacuum is run for the entire curing process. The inlet tubing is placed into a resin filled bucket and secured. The resin impregnates the specimen, and after it is visually determined to have done so, the oven is turned on for the curing cycle. The vacuum pump is left on, and the inlet tubing is left in the resin filled bucket. The continuous flow of resin prevents any air seepage, and the flow is reduced to zero as the epoxy inside the oven cures. The image below shows a panel created in this way. Note the smooth bottom finish, and lack of any air bubbles in the red distribution media.

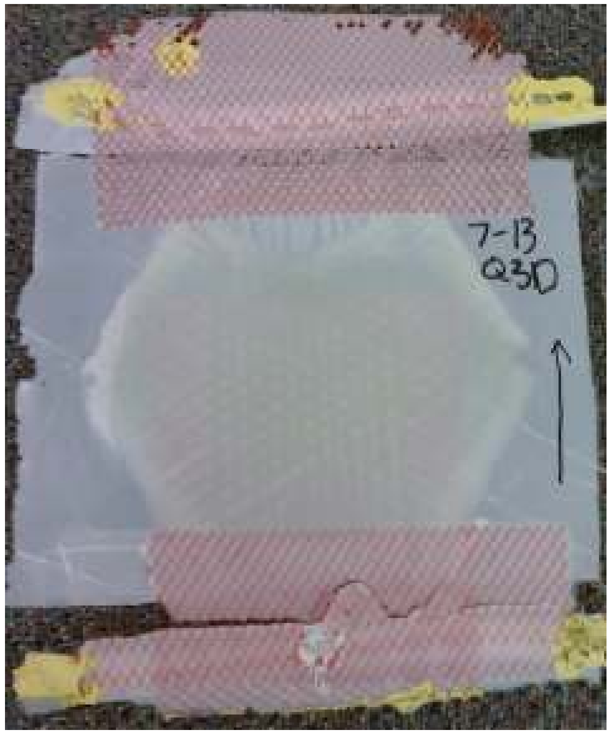


Figure 11: Specimen After Curing with Successful Surface Finish

It is hypothesized that the original infusion process was not successful due to the physical size and thickness of the specimens manufactured. Previous specimens created using the original technique tended to be much larger and thicker. It is possible that the air seepage occurred in the specimens, but their physical size and thickness made its impact negligible.

After curing, each specimen had its peel-ply removed, was cut to size using a wet saw, and then drilled to fit the fixture of the drop weight impact tower, as seen below. The fixture holes were aligned so that the 3” diameter circle of the mounting plate was able to fall within the hexagonal center of the specimen.

Figure 12: Specimen Cut and Drilled for Impact Testing

In the end, eight specimens were created and tested. Several of the specimens tested had surface defects. The specimens, the designations, weave style, and any defects are noted below.

Table 1: Summary of Samples Tested

Type	Date	Test	Problems
Laminated	07/18/11	T4	-
	07/19/11	T2	Strips missing from top of specimen
	07/20/11	T1	Poor resin filling
2D Woven	07/18/11	T3	-
	07/19/11	T1	Poor resin filling
	07/19/11	T3	Bubbles
Q3D	07/18/11	T5	-
	07/20/11	T3	-

6. Testing Results

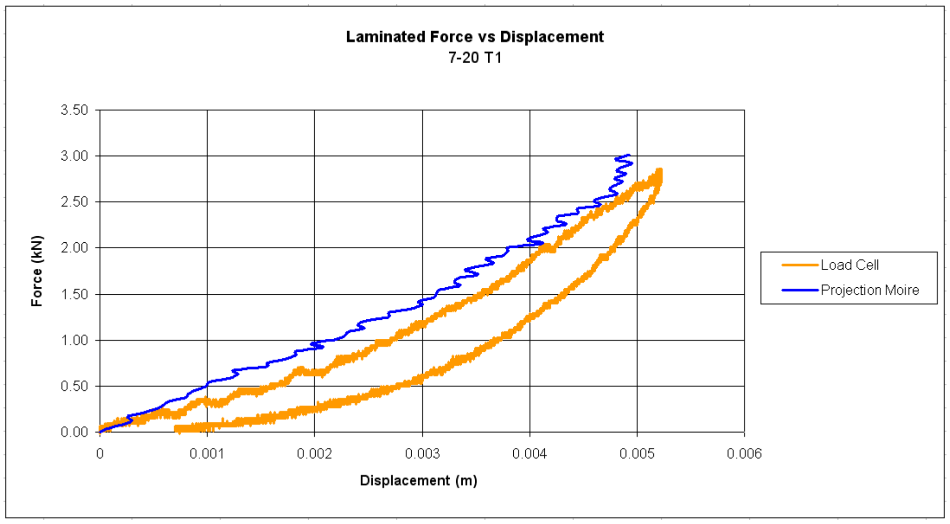
Drop weight impact testing was carried out on the eight specimens. The impact height was set at six inches, a height that would cause deformation during loading, but minimal fiber breakage.

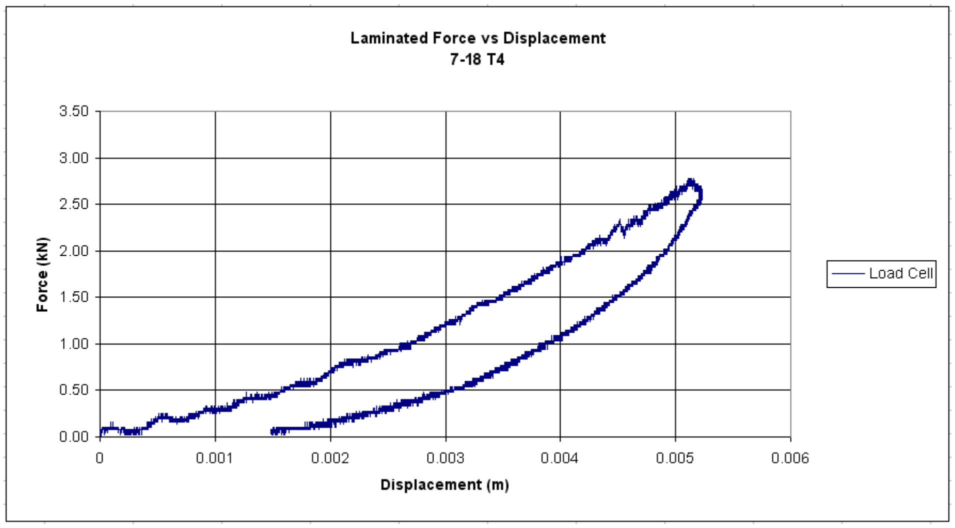
Two setups were used to gather data. The first was the load cell attached to the impacting tup on the drop weight tower. The data was output as a voltage over time, and with a conversion factor, was transformed to force-time data for the point of impact. The data was trimmed to only include the impact event. The velocity before impact was found using an optical sensor. Using this and the force-time data, velocity-time, and then displacement-time data was determined through numerical integration. For the numerical integration, the trapezoidal rule was used.

$$\int_a^b f(x)\,dx \approx (b-a)\left[\frac{f(a)+f(b)}{2}\right] \tag{1}$$

The second method of data capture was Projection Moiré. Projection Moiré allows for a model of the displacement-time for the entire bottom of the specimen to be generated through image analysis done by the MATLAB program Joshua. The point of impact can be examined to compare the results of Projection Moiré with the load cell data. The displacement-time data from Projection Moiré can be curve fit by a third power polynomial, which can then be differentiated to yield velocity-time, and acceleration-time graphs. By multiplying the acceleration-time graph by the mass of the impactor, a force-time plot can be created for the specimen.

With force-displacement data from both the load cell and Projection Moiré, force-displacement graphs were created for each specimen. These are shown below. Note that the initial Q3D specimen does not have Projection Moiré data, and several have not yet been curve fit to an acceptable degree. The Projection Moiré curves currently calculated, one for each weave type, are shown.





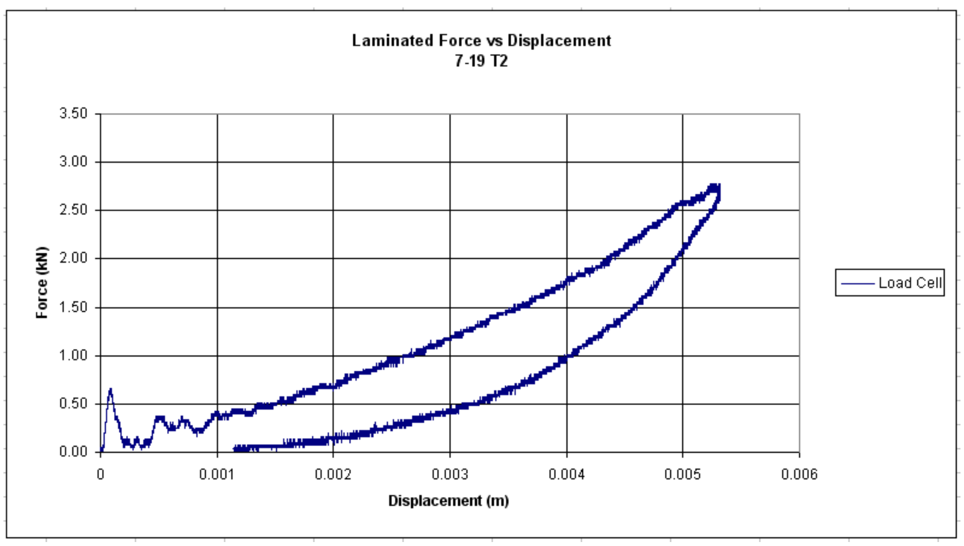


Figure 13-15: Force-Displacement Curves for Laminated Specimens

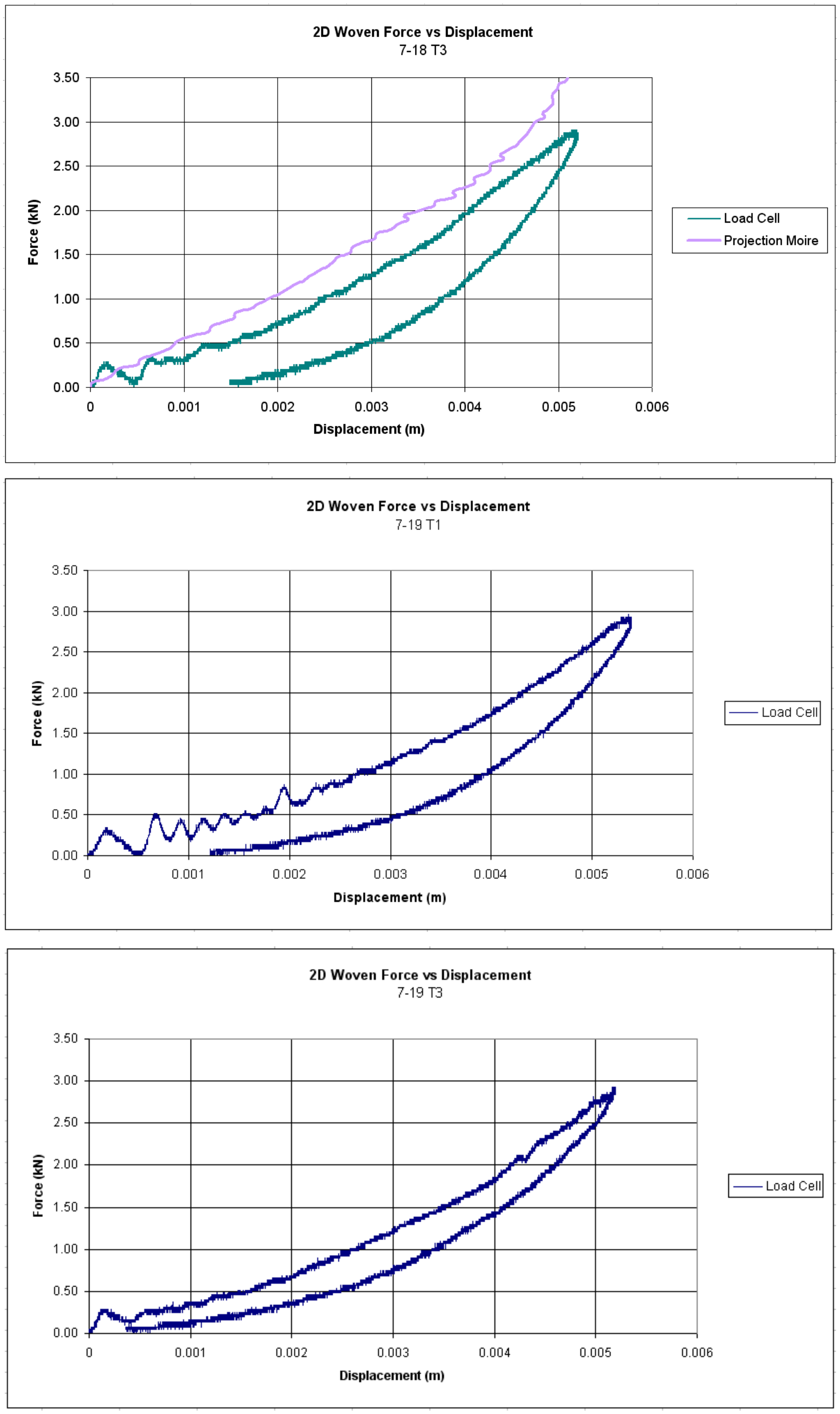
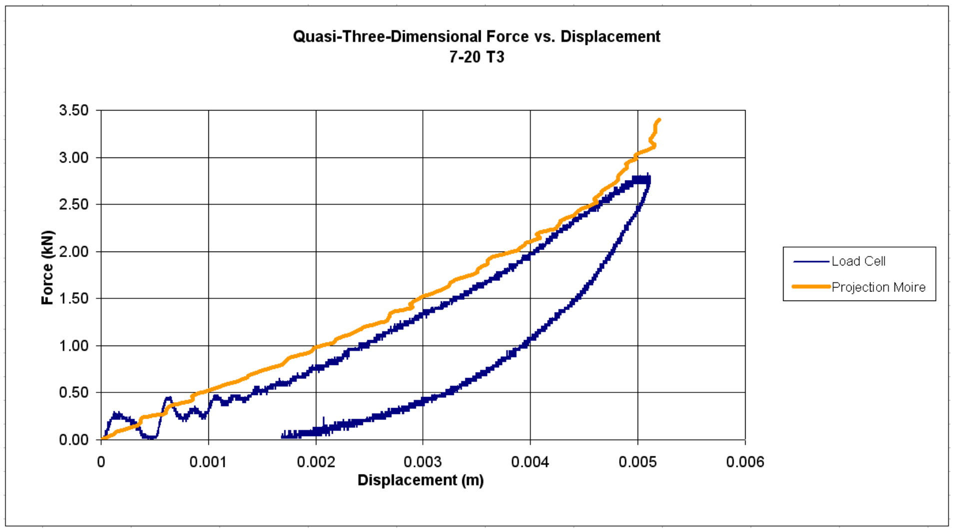


Figure 16-18: Force-Displacement Curves for 2D Woven Specimens



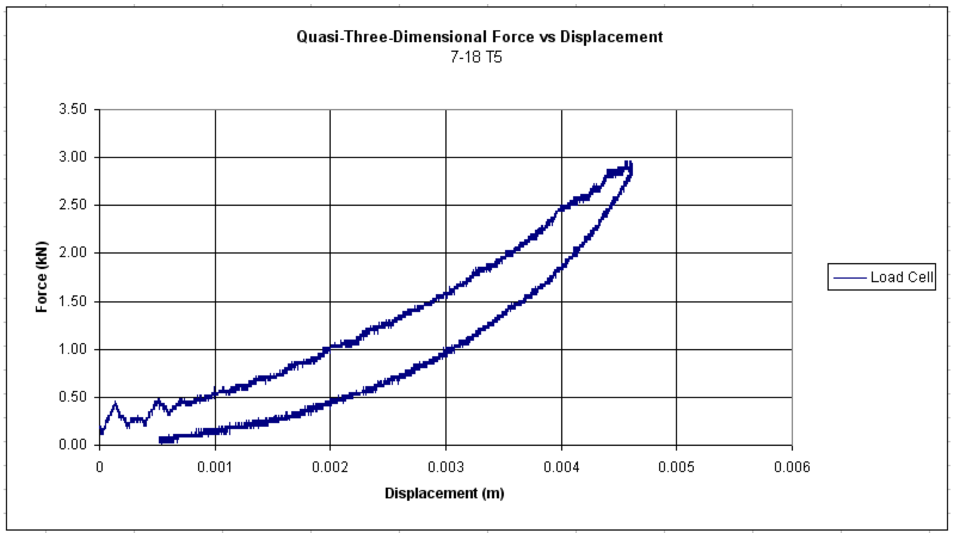


Figure 19-20: Force-Displacement Curves for Q3D Specimens

From these graphs, the following load cell data was gathered.

Table 2: Summary of Load Cell Data for Impact

	Laminated			2D Woven			Q3D	
	7-20 T1	*7-18 T4*	*7-19 T2*	*7-18 T3*	*7-19 T1*	*7-19 T3*	*7-20 T3*	*7-18 T5*
Maximum Displacement (mm)	5.23	5.21	5.32	5.18	5.38	5.22	5.11	4.61
Maximum Force (kN)	2.86	2.75	2.78	2.93	2.96	2.88	2.83	2.96
Bending Stiffness (kN/mm)	0.440	0.464	0.465	0.489	0.480	0.485	0.501	0.591

This data was then averaged for each type of weave.

Table 3: Average Load Cell Data for Each Weave Type

	Laminated	2D Woven	Q3D
Average Maximum Displacement (mm)	5.25	5.26	4.86
Average Maximum Force (kN)	2.80	2.92	2.90

Finally, the loading event of the load cell data was analyzed to determine bending stiffness. The entire loading event was curve fit with a linear trend line. The slope of this trend line was the specimen's bending stiffness. Table 4, below, shows the average bending stiffnesses for each type of weave.

Table 4: Average Bending Stiffness for Each Weave Type

	Laminated	2D Woven	Q3D
Average Bending Stiffness (kN/mm)	0.456	0.485	0.546

7. Discussion

First, let us examine the load cell data in the force-displacement graphs for each individual weave. Within each weave, the individual curves follow similar paths, and have very similar maximum displacement, and maximum forces. Each curve displays some oscillation during the beginning of the loading event, likely due to interactions between the specimen's surface and the tup as they come in contact. The shape of these curves were as expected, based on review of previously created force-displacement graphs.

Furthermore, the shape and size of the loading event section of the load cell curves were further verified using the Projection Moiré curves. These curves had the same general slope as the load cell data, but were offset above load cell curves. The offset is due to the fact that Projection Moiré examines the bottom of the specimen, while the load cell examines its top, allowing for discrepancies due to the specimen's thickness. While the maximum force and displacements of the Projection Moiré curves varied slightly from the load cell data, this was attributed to greater error in the processing of the Projection Moiré data, and the general shape of their graphs helped verify the accuracy of the load cell curves.

As mentioned above, the load cell data for the loading event of every specimen was used to determine each specimen's bending stiffness. This bending stiffness was then averaged with other specimens of the same weave, the summary of which can be seen in Table 4. The results of the study indicate that the Q3D weave was about 13% stiffer than the 2D Woven, and was about 20% stiffer than the Laminated. The 2D Woven was about 6% stiffer than the Laminated.

8. Conclusion

The results of the testing indicate that as a specimen's fibers become more interlocked, its bending stiffness increases. These results warrant further investigation into other physical properties of the Q3D weave with the hopes of other performance increases.

9. Future Recommendations

The largest recommendation with respect to the testing carried out, is that a more suitable roving be selected for further weaving of the composite. The undulation in the width of the roving within individual strands proved troublesome for precise weaving. To create a specimen with less gaps in the weaving, roving of constant width should be used. Secondly, it would be recommended to use a roving of slightly greater thickness. This would allow for thicker specimens without increasing the number of layers, a time intensive task.

With regards to recommendations into future experiments, work can be carried out to continue to determine the physical properties of the Q3D weave. With the specimens already impacted, a scientific analysis of delamination should be carried out to determine the effect of increasingly interwoven layers on the specimen's delamination. Investigation into the isotropy of the specimen is also recommended. One of the assumed benefits of a tri-axial weave is that it will increase the specimen's isotropy versus bi-axial weaves. Tensile testing of new specimens at varying angles should be examined. Additionally, if a resin could be found that would allow for the creation of transparent resins, the effects of stress and strain, with respect to the isotropy of the specimen, could be optically examined.

Many further tests could be performed on the specimen, however, the current largest factor limiting this analysis is the time necessary to prepare the taped strips, perform the weaving, and perform the specimen impregnation and curing. The weaving of a Q3D specimen used in the testing is easily the product of several day's work. In order to produce the number of specimens needed to perform additional analysis and statistical validation, it is recommended that research into a weaving machine be performed. If a specimen were able to be more easily prepared, much research could be done into the weave's properties.