Manufacturing and Material Characterisation of Carbon Fibre Reinforced Thermoset Composites in Sandwich Panels

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The fabrication of Carbon Fibre Reinforced Thermosets has enabled new limits to be reached in both structural design and performance of components in many industries. With strength and lightweight construction being heavily desired in the aeronautic and automotive worlds it is easy to see why extensive research into the realm of composite materials is underway. With this in mind, the aim of this project was to characterise Carbon Fibre Reinforced Thermoset Laminates as well as in Sandwich Panel form with a Nomex core. The methodology behind the project involved utilising UNSW equipment, testing machines, and laboratories, in order to demonstrate the quality and effectiveness of thermoset prepreg composite manufacturing and experimental characterisation here on campus. Throughout the project both literature reviews and ASTM standards were used to guide the fabrication, testing and characterisation of the different testing samples. Once results were gained from the characterisation tests undertaken, the data was compared to that of published data found through literature reviews to gain a comparison of results.

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1 MIDN, School of Engineering & Information Technology. ZEIT4500
The structural properties of the final composite material can be heavily affected by the manufacturing processes utilised. As such the correct method which created the desired properties for this project have been used. Many different processing techniques exist for utilisation with prepreg material due to its versatility, such as Vacuum Bag moulding, Autoclave moulding, pressure bag moulding and many more (Lavender, 2012). For this project the joint technique of the hot bonder and vacuum bagging has been utilised demonstrating their effectiveness here at UNSW.

Once the fabrication and manufacturing processes were completed the final step which was vital to the success of this project were the characterisation tests. The purpose of these tests was to provide a basis for accurately testing the manufactured specimens to obtain its material properties. By utilising the ASTM standards for the test conduct, accuracy, minimal error and standardisation across the tests was ensured enabling comparisons to be made to published data.
B. Aim
To manufacture and develop material characterisation tests for CFRP sandwich panels with a Nomex honeycomb core and its individual components, while only utilizing the equipment available at the UNSW campus and comparing the obtained results with published data. Experimental testing methods were conducted as well.

C. Methodology
Composite materials have been proven to compare to that of metals in terms of strength, rigidity and resistance to impact and corrosion. With Carbon Fibre reinforced Polymers being one of the leading composites in the aeronautics industry, automotive and many others, their light weight and high strength capability is highly sort after. Thermoset composites have a higher tensile strength and higher resistance to heat in comparison to thermoplastics and therefore was the main focus for this project in the form of sandwich panels with a Nomex honeycomb core (Martinez, 2014). The main intentions of the project were to prove that CFRP Nomex sandwich panels can be manufactured and characterised within the UNSW campus in order to aid a PhD student’s research. The material characterisation is a method used to describe material properties by using the results from a range of physical tests including experimental test methods. The results obtained from the tests are useful for future references.

II. Fabrication Processes

A. Hot Bonding and Vacuum Bagging Techniques
The manufacturing method for this project involved the use of a Hot Bonder as well as a process known as Vacuum Bagging. Both the CFRP laminates and the CFRP sandwich panels were manufactured with these methods. To create a composite using these methods which had the correct curing process, the hot bonder and the vacuum bagging techniques were set to provide the correct temperatures and pressures. The hot bonder is a unit which controls many elements of the cure cycle during manufacturing, including the vacuum bag pressure, the ramp rate, cure cycle itself and the cool down. Each of these elements were unique to the composite being manufactured and it was vital to achieving the correct composite properties. The overall setup can be seen in figure 1.

The vacuum bagging layup can be seen in figure 2. The composite materials which were the 4 sheets of prepreg were layered up on top of the heater mat with non-perforated film beneath it. Once the layup was constructed, i.e. the 4 prepreg sheets or in the sandwich panel case, the prepreg sheets as well as the honeycomb core, a perforated sheet was placed on top to allow for excess resin to soak out and into the next layer which is the peel ply. An absorbent material known as breather fabric was placed on top to soak up the excess resin before the vacuum bag was sealed and connected to the compressed air pump. The hot bonder regulated the temperature with the use of thermocouples and the vacuum line sucked the air from the airtight bag and mould, thus making the atmospheric pressure force the bag onto the materials inside with even pressure over the whole surface. (West System, 2004)

Figure 1. Hot Bonder and Vacuum Bag setup demonstrating the various elements involved (Lkovaios, 2014)

Figure 2. Vacuum Layup demonstrating the layers involved in the vacuum bagging setup (Fibre Glast Corp)
B. Sample Preparation for Testing

Once the manufacturing processes were completed both the sandwich panels and the laminate sheets needed to be accurately cut according to the ASTM standards. Just like the manufacturing processes can affect the material properties gained, so can the cutting method. Unlike metals, composites are known to be very sensitive to damages when cutting. This is particularly evident to the edges which have direct contact to the cutting method. In order to alleviate these effects as much as possible whilst still maintaining all processing within the UNSW precinct as much as possible, the diamond tile saw within the civil engineering labs was chosen. The wheel itself is impregnated with diamonds, allowing for a very hard and fine wheel to cut the specimen with friction rather than serration, which keeps edge damage to a minimum. The main problem which was expected to be encountered with this cutting method was the running water which the saw runs over the specimen to keep the heat to a minimum. Although it effectively absorbs the heat, it was also capable of effecting the specimen properties. If water soaks into the porous region of the composite material, it can weaken the microstructure (Selzer, 1996). However, to alleviate these effects it was deemed sufficient to use the saw without the running water as the specimens were very thin and easily cut without causing significant frictional heat to damage the blade or the specimens themselves.

As will be discussed later in this report, there was a need to cut the sandwich panel into a dog bone shape in order to gain accurate results from the experimental testing method. In order to do this, a water jet cutting tool was used which was capable of cutting through the 12.5mm thick specimen with the specified dimensions. Previously a 40W laser cutter had attempted to cut the specimen however was unable to penetrate through the first layer of laminate. The water jet cutter was highly effective in this application leaving a flawless finish on the cut edges which would later play a factor in receiving highly accurate results. Table 1 shows the final dimensions of all specimens for each tensile test.

<table>
<thead>
<tr>
<th>Coupon (mm)</th>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
<th>Gauge Length</th>
<th>Gauge Width</th>
<th>Fillet Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 90 Rectangular</td>
<td>200</td>
<td>24</td>
<td>1.2</td>
<td>30</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>+ - 45 Rectangular</td>
<td>200</td>
<td>24</td>
<td>1.2</td>
<td>30</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Honey Comb</td>
<td>160</td>
<td>80</td>
<td>0.9</td>
<td>Depends on cell orientation</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Sandwich Panel Rectangular</td>
<td>150</td>
<td>50</td>
<td>12.5</td>
<td>25</td>
<td>47.5</td>
<td>-</td>
</tr>
<tr>
<td>Sandwich Panel Dog Bone</td>
<td>150</td>
<td>50</td>
<td>12.5</td>
<td>25</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 1. Dimensions of all specimens.

III. Material Testing

A. Characterisation Tests and ASTM

The characterisation tests are an important method for testing a material through a range of physical tests in order to objectively gain its material properties. It allows for an in depth understanding of the material which is being tested and allows for an informed decision as to the materials application in a structural sense based on the properties acquired from testing. Another significant advantage to the ATSM standards being utilised for this project, was the ability to compare the data gained to other materials and published data. Due to the standardisation of the testing criteria, comparisons can now be easily drawn to allow for the best material choice when considering the required application.

As each component of the sandwich panel was tested, ASTM standards D3039 and D3518 were used to provide the guidance for testing of the 0 90 and + - 45 CFRP laminate skins respectively as well as provide input into the experimental testing of sandwich panels and honey comb.
ASTM D3039 provides the ‘Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials’. ASTM D3518 provides the ‘Standard Test Method for In-Plane Shear Response of Polymer Matrix Composites by Tensile Test of ± 45 degree Laminate’. Through these methods of testing, quality assurance was ensured whilst providing the following properties:

Ultimate Tensile Strength –

\[ F_{tu} = \frac{P_{max}}{A} \]

Ultimate Tensile Strain –

\[ \varepsilon_{max} = \frac{\delta_{max}}{L_g} \]

Modulus of Elasticity –

\[ E_{chord} = \frac{\Delta\sigma}{\Delta\varepsilon} \]

Poisson’s Ratio –

\[ \nu = -\frac{\Delta\varepsilon_t}{\Delta\varepsilon_l} \]

Maximum in-plane shear stress –

\[ \tau_{max} = \frac{P_{max}}{2A} \]

Maximum in-plane shear strain –

\[ \gamma_{max} = \varepsilon_{lmax} - \varepsilon_{lamax} \]

Shear Modulus of elasticity –

\[ G_{12} = \frac{\Delta\tau_{12}}{\Delta\gamma_{12}} \]

A. Laminate Tensile Tests

With the above ASTM standards used as guidelines the laminate tensile testing of both the 0 90 specimens and the ± 45 specimens were conducted. The equipment utilised was the 50KN Shimadzu machine equipped with a laser which could measure displacement in the longitudinal direction. Due to displacement measurements only being capable in the one direction, the 100KN Shimadzu was utilised with its edge detection camera in order to gain poison ratio values. These two machines were utilised concurrently depending on availability. As specified within the ASTM standards the tests were conducted at a displacement rate of 2mm/min for all tests as was reflected within the TrapeziumX program which controls the Shimadzu machines (Shimadzu, 2017).

The 0 90 specimens with their previously mentioned dimensions were used to calculate the Ultimate Tensile Strength, Ultimate Tensile Strain, Modulus of Elasticity and Poissons Ratio. To achieve the 0 90 specimen, the laminate was cut directly along or perpendicular to the fibre orientation.

The ± 45 specimens with their previously mentioned dimensions were used to calculate the Maximum in-plane shear stress, Maximum in-plane shear strain and Shear Modulus of Elasticity. To achieve the ± 45 specimen, the laminate was cut at an angle to achieve a 45 degree orientation across all fibres.

For the tensile tests ASTM standards clearly state that failures within the grips themselves, or at a point of an obvious flaw need to be re-evaluated in order to gain accurate results. To achieve this requirement, 80 grit sand paper was wedged within the grip on the tab area of the specimen. By doing this stress concentration was minimised within the grip and slippage of the specimen during the test was prevented. The final test set up can be seen in figure 3. The specimens all broke within the acceptable failure modes as can be seen in figure 4.

The results for these tests have been calculated and are presented within the ‘Results and Discussion’ section of the report.
B. Experimental Honeycomb Tensile Test

The Nomex Honeycomb Core as seen in figures 5 and 6 is fabricated from a Nomex paper which is made from aramid fibres and is known as AH-HC-4.8-48 (Cripps, 2017). For the experimental tensile test of the honeycomb, there was requirement to manufacture a test rig which could hold the honeycomb in place within the jaws of the Shimadzu. In order to achieve this the required dimensions of the honeycomb were first established which have been previously mentioned and the test rig was built to suit. This involved manufacturing a brace for either end of the honeycomb which was capable of holding the specimen in either cell orientation. The rig is made from easily purchased materials and was manufactured within the student workshop. The basic manufacturing process involved bending aluminium triangular rods which were thin enough to fit in the Shimadzu grips. Secondly, bending aluminium sheeting to allow for locating pins to be drilled through both sides in order to support the honeycomb. As the honeycomb was not expected to hold a significant amount of force (less than 100N), structural load carrying ability was not a priority for the clamps. The final test setup can be seen in figure 5. Again acceptable failure modes meant that breakages within the mounts made the data void. By having locating pins for each cell, stress concentration within the mounts was minimised and the failures were acceptable as can be seen in figure 6.

The data which was gained from this test was Ultimate Tensile Strength, Ultimate Tensile Strain and Modulus of Elasticity for each cell orientation and are presented within the ‘Results and Discussion’ section of the report.

C. Experimental Sandwich Panel Tensile Test

For the experimental tensile test of the sandwich panel, there was again a requirement to manufacture a test rig which could hold the sandwich panel in place within the jaws of the Shimadzu whilst under a tensile load. Previously this experiment has been attempted at UNSW, however to no success. Therefore for this test method, the lessons learned were taken on board and had a significant influence on the design of the test rig. Two attempts were made in order to gain accurate tensile data for a sandwich panel as well as provide a future tensile test method which can be successfully implemented to not only this project but others as well. Problems which were faced in previous attempts included, slipping in the grips, stress concentration regions, as well as getting inaccurate data due to the test rig failing under load rather than the specimen itself.

In order to improve on previous attempts the test setup in figure 7 was manufactured here at UNSW with easily purchased materials. The tabs were 5mm thick MPG350 grade steel held together by 10mm thick class 8.8 high tensile bolts. Both of which were capable of withstanding significantly more tensile load than the sandwich panel without deforming. This was proven during the test conduct and was calculated within the final technical report. Another important factor was the adhesive which was chosen to bond the steel tabs to the CFRP skins. Gorilla epoxy glue was chosen as it provided the highest bond strength of any available adhesive with a rating of 232kg/cm² at maximum strength. This meant that for the tab size of 5cm x 4cm there was a theoretical maximum adhesive load rating of 232 x 20 = 4640 kg (45,518 kN). If this value was physically achieved during the test conduct then the first square specimen would have had a much greater chance of success. However as will be discussed within the ‘Results and Discussion’ section of the report this was not the case and the adhesive gave out before the specimen failed.
Attempt two involved the dog bone specimen, thus allowing the specimen to keep the same tab size and maximise the adhesive area whilst reducing significantly the maximum tensile load. With the previously mentioned dimensions, the final test setup can be seen in figure 7 above. The test was a success with acceptable failure within the narrow section of the specimen as can be seen in figure 8 and no deformation to the test rig itself.

The data which was gained from this test was Ultimate Tensile Strength, Ultimate Tensile Strain and Modulus of Elasticity.

IV. Results and Discussion

A. Tensile Properties (Laminates)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ultimate Tensile Stress (MPa)</th>
<th>Ultimate Tensile Strain (%)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Poisons Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>408.30</td>
<td>0.92</td>
<td>43.9</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>449.54</td>
<td>0.69</td>
<td>69.45</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>488.64</td>
<td>1.03</td>
<td>49.95</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>427.78</td>
<td>0.72</td>
<td>61.95</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>499.98</td>
<td>0.94</td>
<td>40.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Average</td>
<td>454.85</td>
<td>0.86</td>
<td>53.08</td>
<td>0.092</td>
</tr>
</tbody>
</table>

Table 2. Calculated properties for the 0 90 specimens as per the ASTM Standards

As can be seen from figure 9, the 0 90 specimens showed almost no transition region which was expected due to the load being applied either perpendicular or parallel to the fibres. As this was the case, ASTM standards suggest that a strain range of 1000με to 3000με be used to represent the data in which both poisons ratio and Modulus of Elasticity could be calculated. This graph can be seen in figure 10.

The data was calculated in accordance with procedures from the ASTM standards and formulas which have previously been seen. Whilst processing the results, verification and comparisons to published data were made in order to ensure the values fell within acceptable ranges for the composite and test method. For example a current PHD student has previously tested specimens with the same manufacturing process and received results within 5% - 15% of those gained in table 2. Furthermore according research 0 90 samples of CFRP laminate usually exhibit a poisons ratio of 0.10 and an Ultimate Tensile Strain of 0.85 (Performance Composites, 2009). Both of these values are very similar to...
values gained from this experiment and further validate the results. Please note a full results discussion is included in the final Technical Report.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum in-plane Shear Stress (MPa)</th>
<th>Maximum in-plane Shear Strain</th>
<th>Shear Modulus of Elasticity (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.04</td>
<td>0.22</td>
<td>2247.5</td>
</tr>
<tr>
<td>2</td>
<td>77.71</td>
<td>0.19</td>
<td>1427.5</td>
</tr>
<tr>
<td>3</td>
<td>74.07</td>
<td>0.21</td>
<td>1579.5</td>
</tr>
<tr>
<td>4</td>
<td>75.81</td>
<td>0.20</td>
<td>2182.5</td>
</tr>
<tr>
<td>5</td>
<td>74.40</td>
<td>0.18</td>
<td>1870.0</td>
</tr>
<tr>
<td>Average</td>
<td>75.61</td>
<td>0.20</td>
<td>1861.4</td>
</tr>
</tbody>
</table>

Table 3. Calculated properties for the +45 specimens as per the ASTM Standards

As can be seen from figure 11, the +45 specimens show significant deformation when under a tensile load. This was expected due to the fibre orientation allowing the ‘scissoring effect’ to occur. Fibre scissoring causes the initial fibre angle to change, thereby decreasing the load carried by the fibres and increase the load carried by the matrix (Shuart, 1989). As this was the case ASTM standards suggest that a shear strain range of 2000με to 6000με be used to represent the data in which the In-plane Shear Modulus of Elasticity could be calculated. This graph can be seen in figure 12.

The data was calculated in accordance with procedures from the ASTM standards and formulas which have previously been seen. Whilst processing the results, verification and comparisons to published data were made in order to ensure the values fell within acceptable ranges for the composite and test method. Again the above results are within 10% to that of previous tests conducted by a PHD student. Secondly to further verify these results against published data a comparison to CYTEC data sheets for VTM 264 carbon fibre prepregs can be made. The specimens which were tested within CYTEC’s experiments were conducted according to ASTM D3518 which is the same as the tests conducted within this experiment and therefore are relevant for comparison. A value of 95 MPa for in-plane shear stress and a value of 3900 MPa for in-plane shear modulus was obtained. Although these values vary quite significantly (up to 50%) to those from table 3, the variation can be attributed to a difference in manufacturing methods used by CYTEC and those used within this test.

Please note further discussion and comparisons are included in the final Technical Report.
B. Tensile Properties (Honeycomb)

<table>
<thead>
<tr>
<th>Cell orientation</th>
<th>Max Force (N)</th>
<th>Max Displacement (mm)</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>94.77</td>
<td>22.11</td>
<td>0.917</td>
</tr>
<tr>
<td>2</td>
<td>120.95</td>
<td>33.12</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Table 4. Calculated properties for the honey comb specimens

The results for both cell orientations of the 4.8mm cell size Nomex honey comb cores can be seen here in Table 4. The stress Strain graphs as seen in figures 13 and 14 clearly show the behaviour of each specimen as a tensile displacement rate of 5mm/min was applied. As seen in figure 13 a maximum stress of 0.13 MPa was achieved however before it reaches this value the graph shows significant fluctuation in stress values. As noted during the conduct of the experiment, these fluctuations reflect the individual rupture of cells within the specimen before the whole specimen fails. This kind of behaviour was noted during a similar tensile test of Nomex honey comb cores conducted by Nanyang Technological University (Foo, Chai, Seah, 2007).

Again as can be seen in figure 14 there are stress fluctuations before a maximum stress of 0.27 MPa was reached. The reasons for this is the same as was discussed previously for the tensile tests of Nomex honey comb cores. As can be seen from table 4, cell orientation 2 was able to hold a larger force and had significantly more displacement than cell orientation 1. This reflects that of previously conducted tensile tests of Nomex honey comb cores and further validates the results. For example the tensile tests conducted by the by Nanyang Technological University which had a 13mm cell size, produced a max load of 120N with a displacement of 40mm for cell orientation 1 and a max load of 160N with a displacement of 80mm for cell orientation 2.

A major point which can be taken from this experimental test is the lack of tensile load which the Nomex honey comb core is able to hold. Thus validating the purpose for honey comb within a sandwich panel which is for its compressive properties not its tensile properties. Please note further discussion and comparisons are included in the final Technical Report.
C. Tensile Properties (Sandwich Panel)

The rectangular sandwich panel failed to produce accurate data as mentioned previously due to the test rig failing before the actual specimen itself. However with the data gained from this failed attempt it was possible to ensure the second test had a much greater chance of success. The rectangular specimen held a maximum load of 16.1kN when the glue failed. Therefore to ensure the second specimen would fail, calculations were conducted to ensure it would fail before 16.1kN (Calculations included in final Technical Report). The calculations were proven reasonably accurate during the dog bone test with the specimen failing at approximately 15.3kN. The results which can be seen in figure 15 clearly show the expected behaviour of a composite sandwich panel under a tensile load. As the skins were a 0 90 layup, it was expected there would be no transition region and a sudden failure point much like the 0 90 laminates. With the data deemed valid, it was graphed as per ASTM standards to produce the first set of characterised data for a complete sandwich panel under a tensile load here at UNSW. As can be seen from figure 15 and table 5, the calculated stress and Modulus of Elasticity are both quite low. This is because of the increase in cross-sectional area due the Nomex honey comb core. The honey comb has a significant influence within the calculations due to its cross-sectional area, however very little influence in the tensile load carrying ability as shown previously. If just two laminates were tested together, equivalent to the two laminate skins within a sandwich panel, it is highly likely and would be expected that a similar load to that of the sandwich panel would be achieved. Again this is due to the honey comb core having very little influence when subjected to a tensile load. Please note further discussion and comparisons are included in the final Technical Report.

Figure 15. Stress versus Strain graph demonstrating the failure behaviour of the dog bone sandwich panel

<table>
<thead>
<tr>
<th>Ultimate Tensile Stress (MPa)</th>
<th>90.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strain (%)</td>
<td>0.58</td>
</tr>
<tr>
<td>Modulus of Elasticity ASTM (GPa)</td>
<td>13.95</td>
</tr>
</tbody>
</table>

Table 5. Calculated properties for the Dog bone Sandwich Panel Specimen

Figure 16. Stress versus Strain graph as per the ASTM Standards
V. Conclusion

This project has seen a variety of experiments undertaken in order to thoroughly investigate the tensile properties of a CFRP Sandwich panel and its various components. Other than the waterjet cutting all manufacturing, processing and testing was conducted here at UNSW. It has demonstrated the effectiveness of composite manufacturing and testing here at UNSW whilst exploring new testing methods which can be implemented into future projects. Overall the project was effective in producing accurately characterised data for the laminates as well as two successful experimental testing methods for the honey comb and complete sandwich panel specimens. The data gained within this project can now be used within a PHD students simulations to verify theoretical models as well as draw further comparisons to published data and other projects conducted at UNSW. All challenges within this project were overcome by help and assistance from both panel members and mentors and it was this effective collaboration which has led to the successful completion of this project.

VI. Recommendations

This project can be further extended by future students by using a different manufacturing method in order to create the complete sandwich panel. Other manufacturing methods could include using a different adhesive between the Nomex honey comb core and the skins, as well as looking into the use of a different prepreg with a different weave pattern to see how this would compare to the results presented within this paper. Another extension of this project could include the variation of cores used within the sandwich panel such as a foam core to see if this has an effect on the results gained. Furthermore confirmation tests could be conducted for the honey comb and sandwich panel to validate the experimental results presented in this paper.
References


