

Thermally Induced Effects on Carbon Fiber

by Tiegen Fern Lillicrap

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Thermally Induced Effects on Carbon Fibre

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Abstract

In many applications components are subject to heat treatment of some level. This report aims to determine the effects of such heat on carbon fibre.

An initial study was held into the extent of expansion achieved by subjecting carbon fibre to high temperatures. Also discussed is the possible benefits of such deformation in relation to aerodynamics and whether it is a viable option to use within motorsport applications.

Further discussions were also had on the effects of thermal cycling. Research and practical testing were conducted to determine if, and to what extent repeated exposure to heat treatment has on the structure of carbon fibre based composite test samples from both a macro and micro level.

Both investigations found that significant changes occur to carbon fibre when exposed to different kinds of heat treatments, although it was concluded that the changes that occur result only in detrimental outcomes and as such cannot be used for benefit within component design.

Declaration of Authenticity

This thesis is the sole work of the author and is the result of original research. All practical tests have been carried out by Tiegien Lillicrap with the use of University of Wales Trinity Saint David facilities. It has not been previously submitted for examination which has led to the award of a degree.

Signed: T.Lillicrap

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1. Introduction

The principles of using carbon filaments as a composite dates back to 1879 when Thomas Edison first experimented with the lightbulb. Moving forward 100 years and McLaren Racing decide to use it to create the MP4/1 Formula 1 car (Mackenzie, 2011). To begin with McLaren faced many setbacks given that most carbon manufactures believed it was too ambitious to work and feared it would break into carbon dust during a high impact crash. However, the American firm, Hercules Aerospace took the risk and in 1981 the first F1 car to feature a composite tub took to the tracks (Mackenzie, 2011). As a result of the considerably lighter tub the car began to win races, leaving the rivals to play catch up. Looking forward to modern day F1 cars and carbon fibre is now the main material used in production of the vehicles especially within aerodynamic devices.

The popularity of carbon fibre within motorsport inspired this investigation, as many components are subject to high thermal loading during race scenarios, hence investigating how carbon fibre responds to differing thermal scenarios is important. Two key aspects were investigated: the extent of deformation caused by heating the carbon fibre with the aim of using it for an aerodynamic advantage and the effects of thermal cycling on the mechanical properties of the carbon fibre.

Multiple research papers including those by (Elanchexhian, et al., 2014) and (Weaver & Williams, 1975) detail the extent of deformation that occurs to a composite when under a mechanical load such as a tensile test (up to 800N load) or a pressure (up to 500Mpa). However, research into the deformation caused by thermal loading is still relatively new. Often engineers aim to reduce the levels of deformation caused by temperature change. This is particularly evident within the aerospace industry where the risk of wings fracturing as a result of varying temperatures induced by changing altitudes needs to be minimized (Heath-Smith & Kiddle, 1977). For this project achieving the opposite was necessary. Getting a composite to deform to a large extent without fracturing is a difficult challenge particularly as heating a material causes the chemical structure to change, allowing it to behave in different ways. However, if carbon fibre can deform to a desirable amount it could yield benefits for the motorsport industry. This has already been proven the case, where before the regulation changes in 2000, manufactures of F1 cars modified the wing structure to include composites which not only made them lighter but meant the wings could also flex backwards when heated by the exhaust gases (Mcbeath, 2000). Consequently, manufacturers were able to achieve better deflection of the rear wing which in turn reduced drag and thus improved lap times (Diasinos, et al., 2017).

Replacing components every time a race vehicle is driven is both expensive and time consuming. Therefore, determining the extent at which the mechanical properties change when subjected to multiple thermal cycles is important as it allows engineers to find the optimal time to replace components thus saving both time and money. More importantly, investigating how carbon fibre reacts prevents the likelihood of the components failing during application, which for motor racing is the worst-case scenario.

2. Aims and Objectives

Carbon fibre is found in multiple applications around the world and its popularity within the motorsport industry is unwavering, with (Thomas, 2013) stating that 85% of modern F1 cars are made from a fibre reinforced composite. Its potential to offer the strength of metallic components but with a reduced weight, makes it the first choice for many applications. Currently there are numerous investigations into the uses of carbon fibres, with the focus being on the effects that different mechanical loadings have on the mechanical properties of the material. However, an important area that needs further investigating is the potential effects that are caused by thermal loading. The first aspect to be investigated was the extent of thermal deformation seen and whether this could potentially be used to give an aerodynamic benefit in relation to a brake duct. The composite chosen to study was unidirectional carbon fibre as it is often used within the motorsport industry and unlike woven carbon fibre it is more likely to deform to a greater amount. The deformation is expected to be higher with unidirectional materials as the Young's modulus is considerably different than those of woven materials. The Young's modulus (also known as modulus of elasticity) determines a materials resistance to elastic deformation under loading, as such materials with a high Young's modulus are considered stiff and vice versa (Callister & Rethwisch, 2011). Therefore, materials that are much stiffer such as woven carbon fibre fabrics require higher loads (mechanical or thermal) to achieve the same amount of deformation. Hence unidirectional carbon fibre was chosen for the application within this report as it is not as stiff, therefore the deformation values were expected to be greater and thus more beneficial.

Secondly given that most race vehicles compete in multiple events without the ability to adjust or replace every component after each race, it is important to determine the likelihood of component failure. Subjecting various test pieces to thermal cycling helps to determine the materials fatigue life, and how many races, test sessions or qualifying sessions can be completed before components must be replaced. With the current financial climate ensuring the durability of components is critical, to prevent excess money being wasted on unnecessarily replacing components and labour cost for replacing them.

3. Project Timings

Figures 1-3 depict the varying Gantt charts for the project, with figure 1 being the projected time scale, figure 2 being timescale at the mid-way point of the project and figure 3 being the actual timings of tasks. Gantt charts were first created in the early 1900's by the American engineer, Henry Gantt, as a form of time management which allowed both successes and failures to be clearly portrayed (Maylor, 2001). As (Wilson, 2003) states, the Gantt chart simply highlights where issues are likely to occur and boast possible solutions to problems, thus supporting the reasoning for using them within this project. It is evident across all three figures that the timescale of the project has varied massively from each step of the project. Figure 1 shows the initial plan for the project with the tasks in orange to show that they are pending completion. Certain tasks appear to take a much longer time than others however this is due to some of them, such as the supervisor meetings, being repeated weekly. This initial Gantt chart shows less tasks than the final one due to the nature of the project changing over its duration.

The mid-way Gantt chart shown in figure 2 clearly highlights the change in direction of the project due to the initial results. By now certain tasks such as the design studio tests have been delayed and others such as manufacturing of test samples have begun earlier than predicted. Delays began to arise at this section of the project due to two main factors. Firstly, as Design Studio software had never been used before, time was taken to learn the process applied by the system and how to correctly input the necessary information to run the appropriate tests. This caused delays as the number of people who know how to use the programme is limited so the training of the programme was also limited. Although as stated by (Roensch, 2013) the importance of correctly inputting values for FEA testing software's such as Design studio, is highly important, particularly as this is often a limiting factor in the results achieved. The second factor that induced delays to the initial timescale was that due to the material used for practical testing certain material properties for instance, the coefficient of thermal expansion (CTE) values of the fibres and matrix were unknown thus the CTE values for the complete composite were unknown. This caused delays as the CTE value was required for the FEA to be applied and subsequently further practical testing had to be applied to determine these values.

In comparison, the final Gantt chart shows two key points. All tasks by now have either been completed (shown in green) or rejected (shown in red diagonal stripe). Rejected tasks are tasks which due to the project evolving, are no longer necessary. The rejection of such tasks meant that new tasks were added, many of which involved practical testing. Since practical testing required the lab to be booked in advance, most of the related tasks were completed

within the predicted time. However, there were issues with the machine used for tensile testing (these issues are discussed further in section 6.2) so despite the testing being completed within the dedicated time, the testing could have been completed quicker had the machine worked sufficiently for all tests. Further to this, the NDT testing was originally discussed in January with the aim of commencing testing by the end of February, this was to allow a minimum of 40 days to complete the testing. However due to uncontrollable factors such as the equipment being elsewhere the testing was delayed to the 27th of March subsequently the time for this task was greatly reduced.

3.1 Projected Timescale

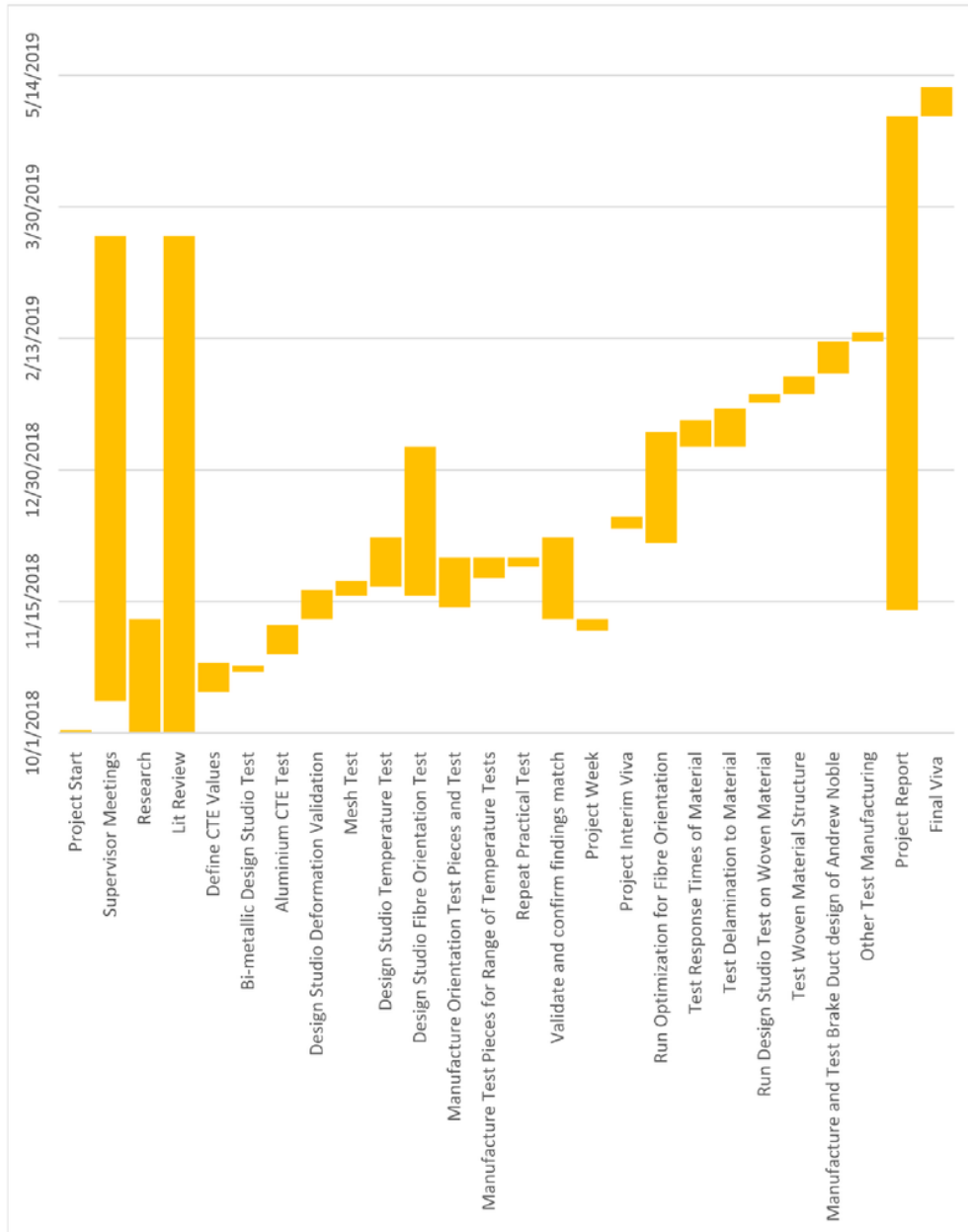


Figure 1: Predicted Gantt Chart (Lillicrap, 2019)

3.2 Mid-Way Timescale

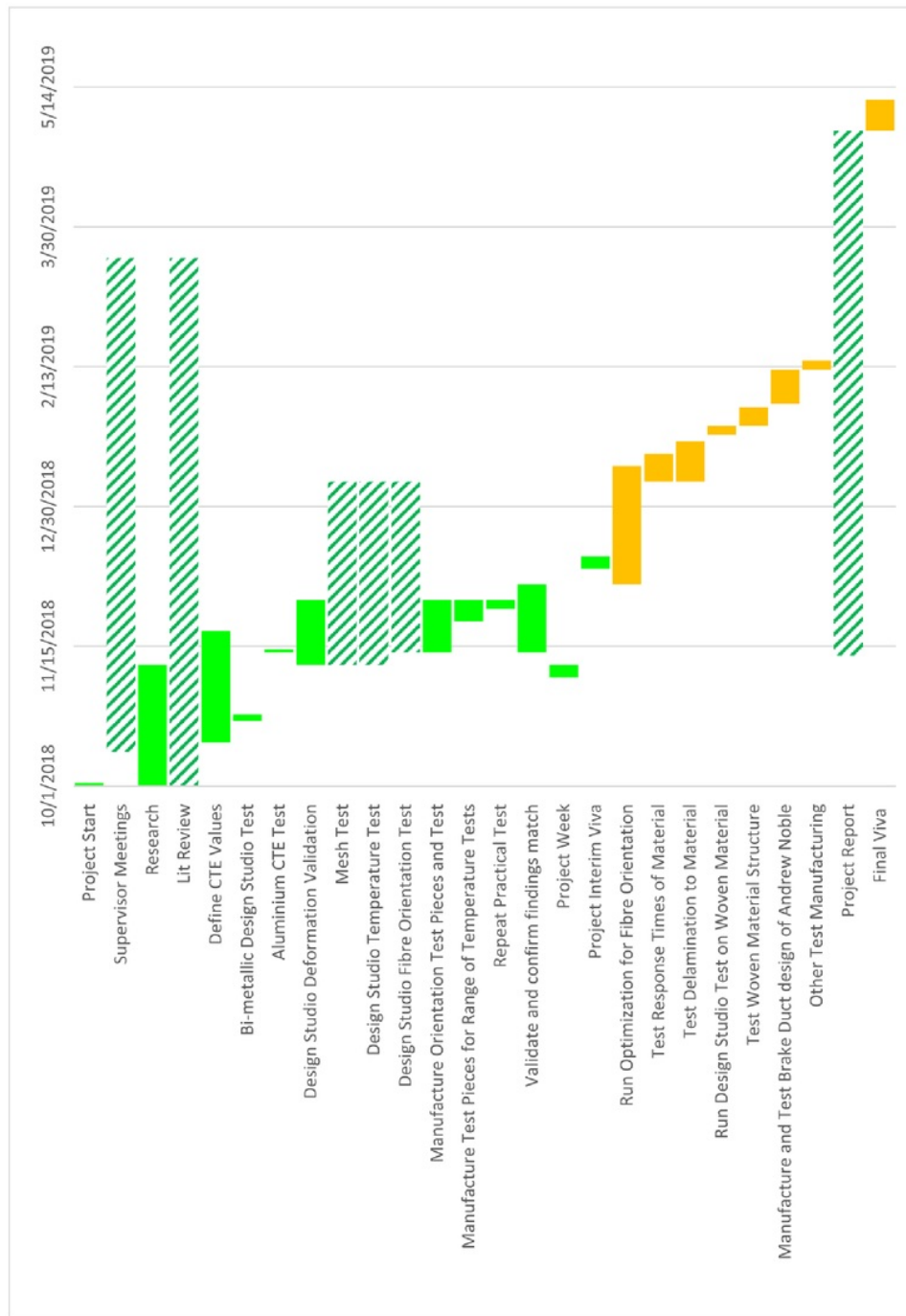


Figure 2: Mid-Way Gantt Chart (Lillicrap, 2019)

3.3 Final Timescale

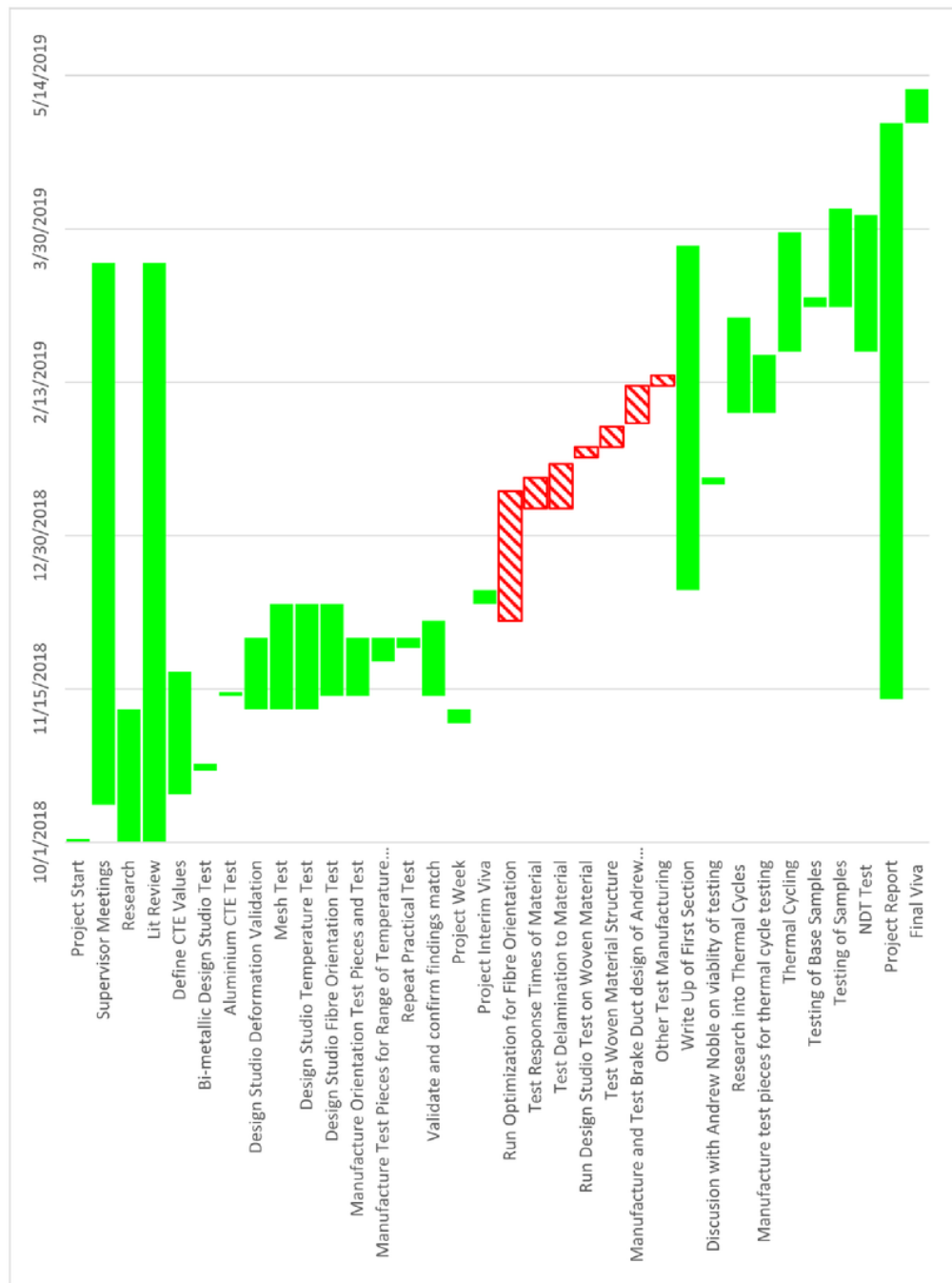


Figure 3: Final Gantt Chart (Lillicrap, 2019)

4. Literature Review

4.1 Carbon Fibre in Motorsport

March 5th, 1981, a date any composite specialist within motorsport will have imprinted in their minds. As John Watson took the win at the British grand prix, he made history by doing so in the MP4/1 (see figure 4) McLaren's first carbon fibre monocoque car (McLaren Group, 2018). This was the start of carbon fibre's evolutionary development within motorsport and after Watson walked away from a high impact crash during the Monaco Grand Prix, the popularity of the material rocketed (McLaren Group, 2018). Almost four decades later and now 85% of a Formula 1 car (Thomas, 2013) is made from fibre reinforced composite (see figure 4), many chassis components, the monocoque, suspension, wings, engine cover and seats are just to name a few. Its ability to combine lightweight properties with contrasting high strength, stiffness and ease of malleability to into different mouldings makes the material highly versatile and applicable to a variety of components within motorsport (Spurgeon, 2017). Despite originally being expected to disintegrate in to carbon dust its first application was, for John Bernard, a no brainer (Mackenzie, 2011). He once stated that in relation to improving vehicle efficiency it is necessary to reduce weight and that the only material appropriate for doing so is carbon fibre (Mackenzie, 2011).



Figure 4: From Original F1 Car to Modern Day F1 Car (Denbar, 2019) & (Smith, 1981)

As listed in table 1 the application of composites within motorsport has many advantages and outweighs the uses of metals. Despite there being no restrictions preventing the use of composites in production cars, their use in this area is limited as a result of the high cost and slow production times although in recent years its affordability has improved and it can be found in more production cars (Brosius, 2003). One such component that has been remade using a carbon fibre composite is the tailgate on the Toyota Prius Hybrid, the aim of this

modification was to reduce weight (by roughly 8lbs) which in turn assisted the vehicle in meeting current fuel economy standards (Milberg, 2017).

Its uses are not limited to formula one and can be found in a range of disciplines, currently multiple components within WRC cars are manufactured from it, and it is a distinct material used throughout Hillclimb cars particularly as the regulations are less restrictive allowing for more varied designs. Regulations are the limiting factor in carbon application and enforce many restrictions where design is concerned. This is essentially due to safety and prohibits extreme designs being fitted to competition vehicles. One such discipline where regulations limit design is the World Rally Championship where in the mid 80's group B cars were equipped with excessive designs and were later banned to improve competitor safety.

Table 1: Advantages and Disadvantages of Materials (Lillicrap, 2018) with information from (Process Industry Forum, 2015), (Herakovich, 1998) and (Kaw, 2005)

	Carbon Composite	Aluminium	Steel
Advantages	• Failure is gradual – its resistance to fatigue is greater than that of metal • Withstands high temperatures • Structures can be tailor design to meet a specified strength and stiffness • High Thermal conductivity • If necessary, the material can be designed to be fire proof, non-conductive and corrosion proof. • Low density • Easily moulded in to various shapes	• Light weight • Malleable • Durable • Thermally conductive • Fairly Corrosion resistant	• Strong • Heavy • Relatively low cost
Disadvantages	• High Cost • Low Shear Strength • Materials are susceptible to oxidisation at high temperatures • Delamination	• Strength of the material isn't high • Expensive • Electrically conductive	• Electrically conductive • Heavy

Given that the majority of an F1 car is now constructed from a composite material, it is no surprise that the aerodynamic devices fitted are also made from the material. The front and rear wings are both produced from composites and as seen in figure 4 the benefit of using this material allows more complex designs to be formed and thus it is possible to redirect air to create better flow characteristics (Kennedy & Martins, 2012). The structural make-up of the composites allows the aerodynamic devices to withstand high levels of pressure and loads without fracturing during a race or adding massively to the overall weight of the vehicle (Oxyzoglou & Nerantis, 2017).

4.1.1 Carbon Fibre Brake Ducts

One specific aerodynamic component made from carbon fibre composites is the brake duct (as shown in figure 5). The brake duct is designed to offer a significant amount of cooling to the brake system by circulating air around the surface of the pads, discs and through the radial centre vents within the discs, this is to try to reduce the temperature experienced by these components which usually reaches in excess of 1000°C (De Groote, 2008). Throughout a race season multiple sizes of brake ducts will be installed on the vehicle depending on the level of braking for each circuit, however the aerodynamic efficiency also changes by up to 1.5% when switching between ducts (Sam, 2014).

Typically, the brake duct is made from carbon fibre composite as it boasts aerodynamic advantages without contributing excessively to the weight of the vehicle. Due to the position of the brake duct, the low mass properties of composites help to maintain a low unsprung mass on the vehicle and so handling characteristics are improved (G.Savage, 1993). Its ability to stay rigid and withstand distortions give the material a durability and so the level of wear is reduced, and a consistent performance can be achieved (Sam, 2014). It is worth noting that in modern day brake ducts, a thermal barrier is often used to coat the composite material to prevent the likelihood of delamination and fatigue caused by the heat exerted from other brake components (Zircotec, 2016).



Figure 5: Carbon Fibre Brake Duct (Formula1.com, 2018)

4.2 Carbon Fibre as a Composite

Over the years the application of carbon fibre in motorsport has advanced the materials development dramatically, new fibres and resin systems have benefited the sport by allowing better mechanical and thermal properties to be achieved.

There are two main types of fibres used within motorsport: Unidirectional and Woven. Unidirectional fibres all run in the same directions, even though plies can be layered on top one another at varying degrees to improve the material stiffness, the fibres in each ply will always run the same way (Herakovich, 1998). Figure 6 show unidirectional carbon fibre on both a macro and micro level where it is evident that from a macro view the material appears to flow in one direction yet on a micro level there is little linearity between the fibres.

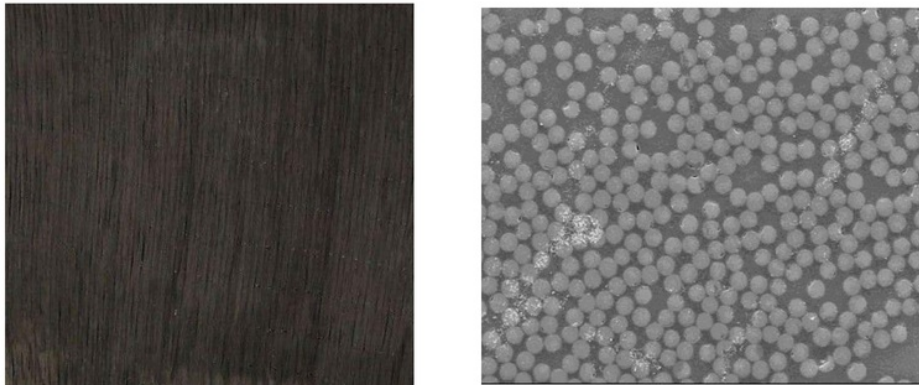


Figure 6: (a) Carbon Fibre from a Macro Level (Carbon.EE, 2015) and (b) Carbon Fibre from a Micro Level (Sahin & Baets, 2017)

Contrastingly, woven fabrics are usually used within motorsport where the pattern appears to be more complex, this is as a result of fibres running at 0 and 90 degrees or mutually perpendicular to each other, the two directions are commonly referred to as the warp or weft direction (Gay, 2015). Woven materials are preferred over unidirectional materials as the interlocking pattern provides greater strength along with a more desirable drapeability, allowing the material to mould easier to more complex shapes (Gay, 2015). The three most commonly used weaves are shown in figure 7:

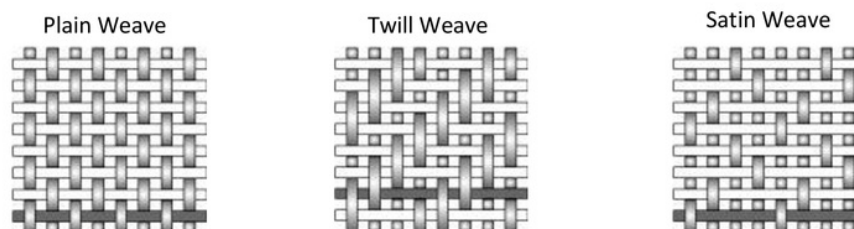


Figure 7: (a) Plain Weave Pattern, (b) Twill Weave Pattern, and (c) Satin Weave Pattern (Cripps, 2018)

Plain Weave

The plain weave follows the more traditional method of weaving in the sense that it follows the under, over pattern making it symmetrical. This style of weave offers good stability and is porous however it is deemed to be the most difficult of weaves to mould and when compared to other weaves its mechanical properties are much lower (Cripps, 2018).

Twill Weave

Commonly seen throughout motorsport components, this weave, as shown in figure 7 comprises of one or two fibres being alternated over either one or two perpendicular fibres and thus gives a diagonal look to the material. Although it is slightly less stable than the plain weave its ability to be draped is considerably better and with the reduction in crimp it is much smoother and better mechanically (Cripps, 2018).

Satin Weave

This is the most complex of the three weaves, designed to have low in-plane shear movement, this weave typically appears very flat and can offer a much higher drapability (Gay, 2015). The pattern is usually repeated after either 4, 5 or 8 fibres have been over lapped. Within motorsport, the 5-harness satin is favoured as it offers high strength whilst remaining relatively inexpensive (Cripps, 2018). The mechanical strength of this weave is considered good as a result of the low crimp and tight weave that can be produced. However, (Cripps, 2018) states that consideration must be taken when layering a satin weave to prevent excess stress being built into the component.

Another factor besides the weave of the fabric to consider is the make-up of each ply. Although more plies do typically mean the manufactured sample is more rigid, the composites strength and stiffness are not solely dependent on thickness (Vasiliev & Morozov, 2007). In fact, the strength and stiffness of a composite is reliant on the volume of fibres, as such there is an 'ideal' medium amount of fibres desired when forming a composite. Too high a fibre content results in lower ply strength when subject to longitudinal compression and increases the inter-plane shear as there is less matrix and thus the bonding between fibre is poor (Vasiliev & Morozov, 2007). Similarly, too low a fibre content and both the strength and stiffness of the ply under tension will reduce (Vasiliev & Morozov, 2007).

For the purpose of testing within this project, prepreg unidirectional carbon fibre was used as it was readily available from university stock and as stated by (Hatton, 2018) prepreg has been utilized by the motorsport industry for nearly 40 years. Prepreg relates to the way in which the carbon fibre material has been manufactured. Composites which are classified as prepreg mean that the fibres have been preimpregnated with a polymer resin and partially cured

(Callister & Rethwisch, 2011), thus allowing the material to be easily moulded into shape and cured without the need for additional resin. These styles of materials then finish curing when both pressure and heat is applied to them, this is normally done using a hot press or autoclave. Typically cure temperatures lie between 120°C and 180°C, this excess heat is what results in the molecular structure of the resin undergoing a chemical reaction and thus the fibres 'glue' together (Loos & Springer, 1982). It is necessary to also apply pressure: to ensure any excess resin is squeezed out of the composite, to aid with the 'gluing' of plies, and to try and mitigate any air or vapour bubbles from within the resin (Loos & Springer, 1982). The cure temperatures of the composites must be considered when carrying out thermal testing as heating composites in excess of the set cure temperatures can result in the epoxy of the composite test sample 'melting' (Dotson, 2018). In addition, as the prepreg material is also considered a thermoset, the polymers which make up the resin are insoluble and infusible (Kaw, 2005) after curing has occurred. Consequently, the polymers form strong covalent bonds and rigidly join (Kaw, 2005), this is an area of concern when trying to achieve deformation from a composite as these covalent bonds provide structural integrity and as such do not easily deform.

Another area for consideration is the levels of crimp that a material experiences. This must be monitored as it relates to the undesirable distortion of the fibres that occurs when creating a weave from warp and weft tows which can be problematic for mechanical properties hence a low crimp value is desired (Fleetcroft, 2014). Due to this, spread tow fabrics (STF) have been developed which instead of forming fibres in narrow and thick tows, they are spread into thin and wide tapes (Borg, 2015). (Fleetcroft, 2014) summarizes that this new style of layering fibres minimises the crimp angle and improves the resin wet-out, in turn the fibre volume increases with more straight fibre and thus ultra-light fabrics can be made. This process restricts the amount of excess resin without being detrimental to the mechanical properties. Therefore, the material is popular within formula 1 particularly as (Fleetcroft, 2014) suggests possible weight savings of 20-30% are achievable compared to woven composites. Further to this the mechanical abilities of STF is like that of a cross-ply lay-up from UD tapes (Fleetcroft, 2014), but offers greater drapability and higher resistance to delamination. Given the excess temperatures often experienced by Formula 1 components its resistance to delamination is critical. Delamination occurs when individual plies separate from each other, as stated by (Gay, 2015), this results in compressive strength of the laminate reducing and subsequently buckling is more likely to occur.

4.3 Understanding the Science

Before discussing the two main aims of the project, an understanding of key thermodynamic principles must be gained. The following section details two key aspects of the thermodynamic principles which relate to the main body of the project.

4.3.1 Heat Transfer

If a temperature difference exists between two bodies then energy is transferred between the two bodies, how this energy transfer is defined in three principles: conduction, convection and radiation (Kreith, et al., 2011). Similarly to studies by (Joven, et al., 2012), the test samples in this project are subject to heat transfer due to convection where heat from the bottom of the autoclave warms the surrounding air, this results in a temperature difference between the air and the test sample, as such the temperature of the test sample increases to equal that of the autoclave. Convection occurs due to the first law of thermodynamics which states all energy can be changed from one form to another, yet it cannot be created nor destroyed (Kreith, et al., 2011). Research suggests that the heat transferred is dependant of three factors: the temperature change, the items mass, and the specific heat capacity of the material (Helmenstine, 2018). The relationship of these three factors is shown in the equation below.

$$Q = mc\Delta T$$

The specific heat capacity is the amount of heat required to cause a temperature change of 1°C to 1Kg of the material (Helmenstine, 2018). In relation to a carbon fibre composite the specific heat capacity and conductivity of a composite can vary depending on the following factors as stated by (Joven, et al., 2012): the epoxy, the fibre orientation/configuration and the volume fraction. These factors also determine how fast the test sample will heat and consequently determine the length of time test samples are subject to heating in the two investigations within this project.

4.3.2 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) relates to a value which determines the extent at which a materials dimensions will change when subject to a temperature change (Elert, 2018). (Callister & Rethwisch, 2011) defines thermal expansion atomically as the increase in distance between each atom. For a unidirectional carbon fibre composite, expansion can occur in two directions giving α_1 and α_2 . As such the following equations from (Kaw, 2005) can be applied to determine the CTE value in each direction, it is worth noting that the equations derive from the thermoelastic extremum principle.

$$\alpha_1 = \frac{1}{E_1} (\alpha_f E_f V_f + \alpha_m E_m V_m)$$

$$\alpha_2 = (1 + \nu_f) \alpha_f V_f + (1 + \nu_m) \alpha_m V_m - \alpha_{12} V_{12}$$

The above equations are more commonly classed as α_1 being in the fibre direction and α_2 being perpendicular to the fibres (or in the matrix direction). Given the above equations and since (Cripps, 2018) states that carbon fibre composites are anisotropic, it can be said that a composite has the ability to be designed in such a way that it holds direction specific properties. As such the properties can be adapted to allow for significant thermal deformation in the desired direction.

4.3.3 Material Specific Thermal Properties

As discussed above, the thermal expansion of unidirectional carbon fibre can vary in two directions. This is a result of the composite being made of two separate entities: the fibres made from carbon and the matrix which is more commonly known as the resin. The next section discusses how the thermal properties of the two entities vary.

Carbon (Graphene)

The following section shall refer to graphene. Although the carbon used for the composites within this report is classified as carbon strand, the material will still behave in the same manner as graphene due to its similar atomic structure.

In recent years, graphene has become popular for its high thermal conductivity values, with both (Mertens & Peleg, 2019) and (Pop, et al., 2012) stating that the thermal conductivity for freely suspended samples is approximately between 2000 W/mK and 4000 W/mK, making it one of the most conductive materials at room temperature. For comparison, the thermal conductivity of aluminium is stated by (HyperPhysics, 2019) as 205 W/mK hence graphene is ten times more conductive. Graphene's ability to be highly conductive at room temperature makes it the perfect choice for thermal applications particularly within motorsport where excessive temperatures are unable to be reached without causing danger to the surrounding participants. This suggests that for applications such as the rear wing, using graphene would allow the wing to conduct large amounts of heat from the exhaust gases and as a result deform. Further to this it shows that within the conducted experiments the test samples should adequately conduct heat from the autoclave.

The thermal conductivity (κ) of graphene also directly links to the specific heat capacity (C), the relationship is stated by the equation below:

$$\kappa = \Sigma C v \lambda$$

Where v = is the phonon group velocity and λ is the mean free path (Pop, et al., 2012).

The specific heat capacity of both pure solid carbon and graphene cannot be accurately determined, as such the specific heat capacity of graphite will be discussed. (Pop, et al., 2012) states that for graphite the specific heat at room temperature is $0.7 \text{ Jg}^{-1}\text{K}^{-1}$ and that matches with the value stated by (Engineering Toolbox, 2003) of $0.71 \text{ Jg}^{-1}\text{K}^{-1}$. Again, when comparing this to the value stated by (Engineering Toolbox, 2003) for aluminium ($0.91 \text{ Jg}^{-1}\text{K}^{-1}$), the values match with expected trends that suggest graphene requires less energy to change temperature by 1 degree.

Furthermore, the CTE for graphene can also be determined. Research by (Balandin, 2011) suggests that graphene has a negative thermal expansion coefficient of $(-4.8 \pm 0.1) \times 10^{-6} \text{ K}^{-1}$ but the research also states that this value becomes positive after the temperature exceeds 900K. Similarly, research by (Shaina, et al., 2016) states a coefficient of $-3.75 \times 10^{-6} \text{ K}^{-1}$, although slightly lower this value is to the same magnitude as the previous value stated. Data from (Autodesk, 2017) suggests that the coefficient for the T800 fibres used within the materials for this report is -1.37×10^{-6} , as expected this is to the same magnitude as the graphene although it is slightly smaller suggesting its expansion will be slightly less. All the previously stated coefficient values are negative which suggest that the fibres used in composites will constrict rather than expand when heated. The exact cause of negative coefficients of expansion is still to be discovered however many including (Balandin, 2011) and (Shaina, et al., 2016) suggest that it is a result of the phonon distribution. Phonons are sound waves produced as a result of the atoms oscillating, if the atoms stop, then the phonons disappear (Balaguru & Jeyaprakash, 2017). At higher temperatures atoms vibrate more which gives a higher wave amplitude and thus more phonons are created (Balaguru & Jeyaprakash, 2017), the opposite is true for low temperatures. (Mittal, et al., 2017) states that the anharmonicity of the phonons and the Grüneisen parameter are the two key factors that cause negative coefficient values. Further to this, (Callister & Rethwisch, 2011) suggests that from an atomic level the thermal expansion is related to a change in the average distance between atoms.

Figure 8 shows how the potential energy varies with interatomic distance; the graph clearly follows a trough like trend. For materials such as graphene, where the atoms have strong covalent bonds, the potential energy trough would appear much narrower and deeper (Callister & Rethwisch, 2011). This would consequently increase the distance between atoms for each rise in temperature, as such lower expansion values are expected (Callister & Rethwisch, 2011).

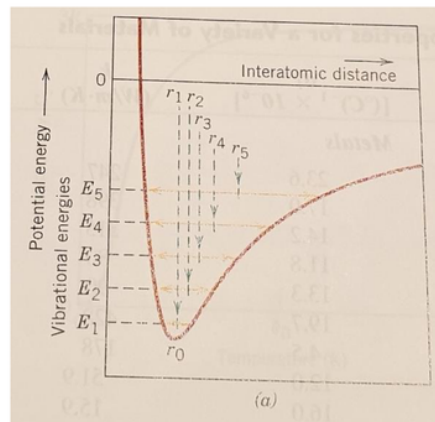


Figure 8: Graph Showing How Potential Energy Varies with Interatomic Distance (Callister & Rethwisch, 2011)

Epoxy Resins

Similarly, to carbon, finding exact values for the thermal properties of individual resins is difficult and instead resins will be discussed from a more general view.

Firstly, the thermal conductivity of epoxy resins is much lower than that of graphene, with (Lee & Neville, 1982) and (Garrett & Rosenberg, 1974) stating that the conductivity value is between 0.15 W/mK and 0.25 W/mK almost 10,000 times smaller than figure stated for graphene. Hence the thermal conductivity of the epoxy resin is poor, which is why (Chung & Lin, 2016) explains that epoxies should be paired with highly conductive materials to form composites with improved conductivity values. In relation to thermal testing, it is expected that due to the lower thermal conductivity values of the epoxy, the test samples would need to be subject to higher temperatures for longer to see any significant changes.

The specific heat capacity of epoxy resins is higher than that of the graphene stated previously, with (Engineering Toolbox, 2003) and (SubsTech, 2012) stating that the specific heat capacity is approximately $1-1.1 \text{ Jg}^{-1}\text{K}^{-1}$. These values further support the previously made statement which suggested that the epoxy would require more heat, and thus more energy before changes would significantly occur to the epoxy structure. Consequently, it is hypothesised that the thermal cycling tests will highlight variation in the epoxy after a high number of cycles.

Finally, the CTE of the epoxy, similarly to the other two values, the coefficient can only be taken as an approximation. Research by (Zhiguo, et al., 2014) which studied a range of epoxies, determined that on average the CTE value for epoxy resins at room temperature lies between $43 \times 10^{-6}/K$ and $64 \times 10^{-6}/K$, which match with the values stated by (Engineering Toolbox, 2003). Unlike the graphene, the CTE values for the epoxy is expected to follow a linear expansion, as such it is expected to expand the same in all directions. Furthermore, it is always quoted as positive which shows that when heated through thermal testing it should positively expand. However, it is expected that due to the difference in CTE values for the graphene and the epoxy that cracking will occur within the material (Nawab, et al., 2013). This is due to a conflict between the graphene constricting and the epoxy expanding. This is to be investigated further with non-destructive testing.

4.4 Deformation

As characterised by the discussion on the CTE value in section 4.3.2 it is evident that some level of expansion can be achieved through heating, however to what extent this deformation occurs and whether it is viable during a race application is still for debate. Despite currently being used within F1, the idea of 'active' aerodynamics which expand and contract depending on the heat applied is relatively new. If a suitable level of deformation could be achieved, then it could be highly beneficial. For example, if it was used in a wing application on an F1 car to improve the angle of attack, then according to (McBeath, 2015), it would allow more downforce which means better grip and consequently the vehicles performance improves. Further to this current research by (Balandin, 2011) suggest that carbon fibre contracts when heated, yet it does state that this only occurs at temperature below 300K (26°C), suggesting that it is possible to achieve a level of positive extension beyond this temperature. As previously stated, the material can be engineered to be direction specific so it would be possible to engineer a carbon-based composite to achieve greater deformation results. This, however, does rely to an extent on the epoxy which from section 4.3.3 is known to have a CTE of approximately $43 \times 10^{-6}/K$ (Zhiguo, et al., 2014) which should allow the material to deform to a beneficial level.

4.5 Thermal Cycling

Thermal cycling is defined by (Hancox, 1998) as repeatedly exposing a test sample to varying temperatures for example between 30C and 100C, with an adequate dwell time at each extreme to allow for thermal equilibrium to be achieved. It is important to consider how thermal cycling effects carbon fibre, particularly within a motorsport application as during a components life it is likely to be repeatedly subjected to high temperatures and cooling especially if the component is installed on a F1 car for example.

By using data from (Formula 1, 2018) the number of cycles that a component is likely to experience can be determined, the cycles are shown in table 2. This is based on one duration on track being equal to one cycle.

Table 2: Number of Cycles for an F1 Race Weekend (Lillicrap, 2019)

Activity	Number of Cycles
Free Practice	3
Qualifying	3
Race	1

Table 1 shows that for one race weekend a component would experience at least 7 cycles, if this was spread across the 21 races for the season it would equal 147 cycles not including testing or promotional events. Therefore, determining the effects induced by thermal cycling is important to determine the fatigue life and durability of components. (Hancox, 1998) and (Shang, et al., 2012) have previously conducted research into this area where the results suggest that after repeated cycling the tensile strength of the component begins to reduce. This is also supported by (Daguang, et al., 2013) who found that the thermal cycling of a Cf/Al composite caused microcracks between the fibres to appear as a result of the epoxy expanding. (Daguang, et al., 2013) further explains that if a couple of single fibres break then the load is redistributed to the surrounding fibres, as such the composite adjusts to withstand the load, hence it is concluded that the reduction in strength must be as a result of the hardening/softening of the matrix caused by thermal cycles.

It is worth noting that (Hancox, 1998) highlights potential factors that could result in resistance to thermal cycling and are as follows: fibre properties; resin properties; number of cycles; stacking sequence; temperature differential; bond strength; stress/strain at micro/macro levels; and matrix morphology. It is already clear from previous discussion in section 4.3.3 that fibre and resin properties will influence thermal cycles especially from a CTE aspect. Research conducted by (Hancox, 1998), suggested that compressive and tensile stresses, which are proportional to the difference between the CTE values, are induced into the fibre and matrix. Subsequently theses stresses cause reductions in both tensile and bending strength.

Therefore, it is expected that by applying similar testing methods, the same trends should appear with the test samples that have been thermally cycled the most being deemed the weakest.

4.5.1 Non-Destructive Testing

Much of the previously discussed research also used non-destructive testing to determine the effects of thermal cycling. Non-destructive testing (NDT) allows for the microstructure of the carbon-fibre test samples to be analysed without impacting on the structural integrity of the sample (ASNT, 2017). Commonly NDT is applied to determine the quality of materials or inspect joins which could be deemed as 'weak' points on the component. In a paper by (Unnþórsson, et al., 2019), many forms of NDT for carbon fibre purposes are discussed, with the paper concluding that the best possible methods are acoustic emission and electrical properties, both of which are unavailable for this project. Similarly (Schwartz, 1997) discusses the benefits of using NDT for carbon fibre, the diagram in figure 9 shows the different features that (Schwartz, 1997) states NDT should highlight. One of the main features highlighted is the appearance of cracks within the matrix, as such NDT is useful when assessing the issues caused by thermal cycling as often microcracking occurs.

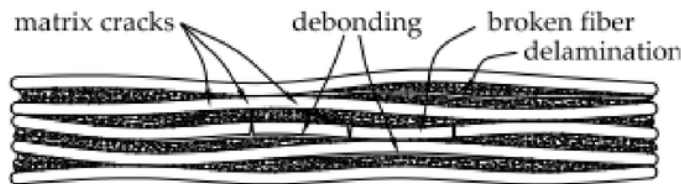


Figure 9: Diagram of NDT Features of Carbon Fibre Composite (Schwartz, 1997)

In research by (Liu, et al., 2019) and (Daguang, et al., 2013) either transmission electron microscopes (TEM) or scanning electron microscopes (SEM) were used to determine the thermally induced effect on the heat cycled composites. This type of testing allowed the microcracks or microvoids between the fibres to be analysed, as such it was concluded that test samples exposed to more thermal cycles had more microcracks. Examples of both the SEM (a) and TEM (b) images are in figure 10. Another form of testing used to distinguish the induced effects from thermal cycles is X-ray CT which was applied in research by (Zhang, et al., 2013). As before this form of NDT highlights the microcracks that form after prolonged cycling, (c) in figure 10 shows an example of the test done by (Zhang, et al., 2013) where the white lines are the microcracks. Although the NDT discussed is not available for the project, the same principle can be applied to determine if microcracking has occurred. Hence by applying a thermography camera and light box test as explained in section 6.1.3, it is expected that results similar to those by (Zhang, et al., 2013) will be achieved.

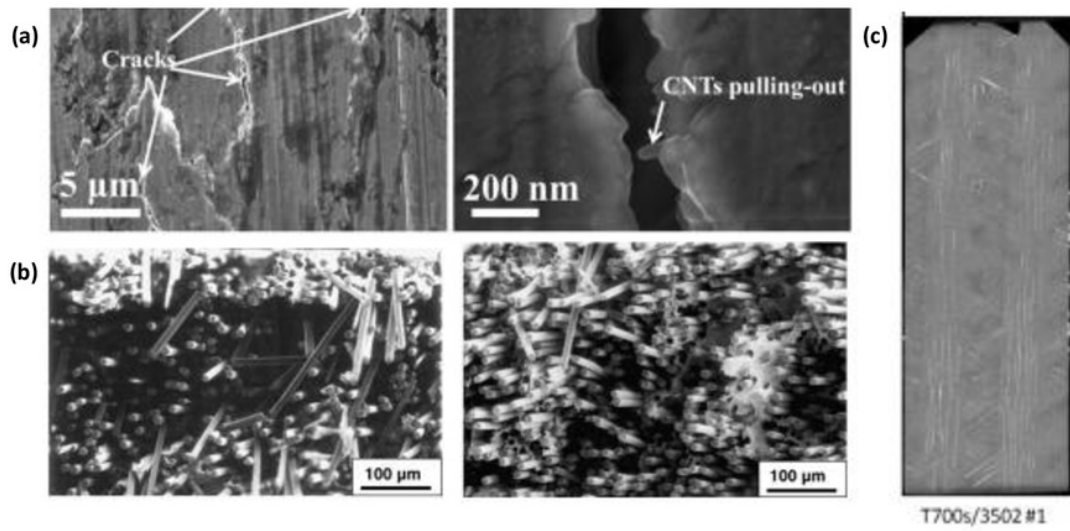


Figure 10: (a) Example of SEM images (Liu, et al., 2019), (b) Example of TEM Images (Daguang, et al., 2013), (c) Example of X-Ray CT Scan (Zhang, et al., 2013)

5. Deformation Study

5.1 Bi-Metallic Strip Test

Using a tutorial from (Dlubai, 2017), a Design Studio test of a bimetallic strip was completed to ensure the computer software could accurately model thermal deformation. The tutorial used copper and invar as the two metals with differing thermal expansion coefficients and heats them to 100°C so matched with the planned tests for the carbon fibre composite. Figure 11 below shows the schematic of the bi-metallic strip, with the relating details shown in table 3. Note properties relating to invar are denoted with subscript (i) and copper denoted with subscript (c).

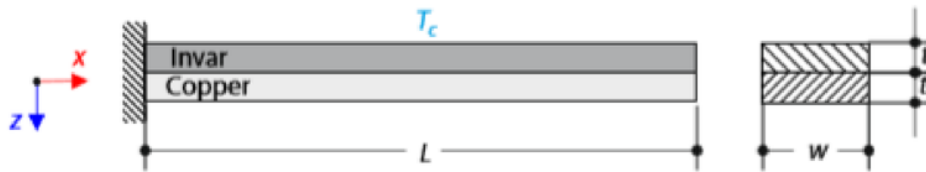


Figure 11: Schematic of Bi-Metallic Strip (Dlubai, 2017)

Table 3: Specifications for Bi-Metallic Strip (Dlubai, 2017)

		Specification	Symbol	Measurement
Material	Invar	Modulus of Elasticity - <i>MPa</i>	E_i	137000
		Poisson's Ratio	ν_i	0.280
		Coefficient of Thermal Expansion - $^{\circ}C^{-1}$	α_i	1.2×10^{-6}
	Copper	Modulus of Elasticity - <i>MPa</i>	E_c	130000
		Poisson's Ratio	ν_c	0.354
		Coefficient of Thermal Expansion - $^{\circ}C^{-1}$	α_c	2.0×10^{-5}
Geometry		Cross-Section Width – <i>mm</i>	w	5.0
		Layer Thickness - <i>mm</i>	$t_i = t_c = t$	1.0
		Length - <i>mm</i>	L	100
Load		Thermal Loading - $^{\circ}C$	T _c	100

The tutorial states the following equation for calculating the extent of deformation.

$$U_{z,max} = \frac{6(\alpha_i - \alpha_c)(t_i + t_c)T_c L^2}{t_s^2 K_1} \frac{1}{2}$$

Where K is the stiffness coefficient and is calculated by applying the following:

$$K_1 = 4 + 6\frac{t_c}{t_i} + 4\left(\frac{t_c}{t_i}\right)^2 + \frac{E_c}{E_i}\left(\frac{t_c}{t_i}\right)^3 + \frac{E_i t_i}{E_c t_c}$$

Applying the properties for invar and copper gives the following results:

$$\begin{aligned}
 K_1 &= 4 + 6\frac{1}{1} + 4\left(\frac{1}{1}\right)^2 + \frac{130 \times 10^9}{137 \times 10^9} \left(\frac{1}{1}\right)^3 + \frac{137 \times 10^9 \times 1}{130 \times 10^9 \times 1} \\
 &= 4 + 6 + 4 + 0.948905 + 1.053849 = 16.0275 \\
 U_{z,max} &= \frac{6(1.2 \times 10^{-6} - 2.0 \times 10^{-5})(1 + 1)100}{1^2 \times 16.0275} \frac{100^2}{2} \\
 &= -7.049\text{mm} = 7.049 \times 10^{-3}\text{m}
 \end{aligned}$$

This can be compared to the results from Design Studio (see figure 12), which were achieved by using the same values as above although the mesh size in the design studio test is slightly different as it was set to a standard medium mesh from Solidworks. This variation in mesh size accounts for the slight variation in results. The Design Studio results are shown in meters, at maximum deflection (red section of the scale), Design Studio gives a value of $7.1 \times 10^{-3}\text{m}$ (7.1mm) which is a difference of 0.7% from the values stated by (Dlubai, 2017). This variation is so small that it is reasonable to conclude that the computer software accurately models the thermal deformation.

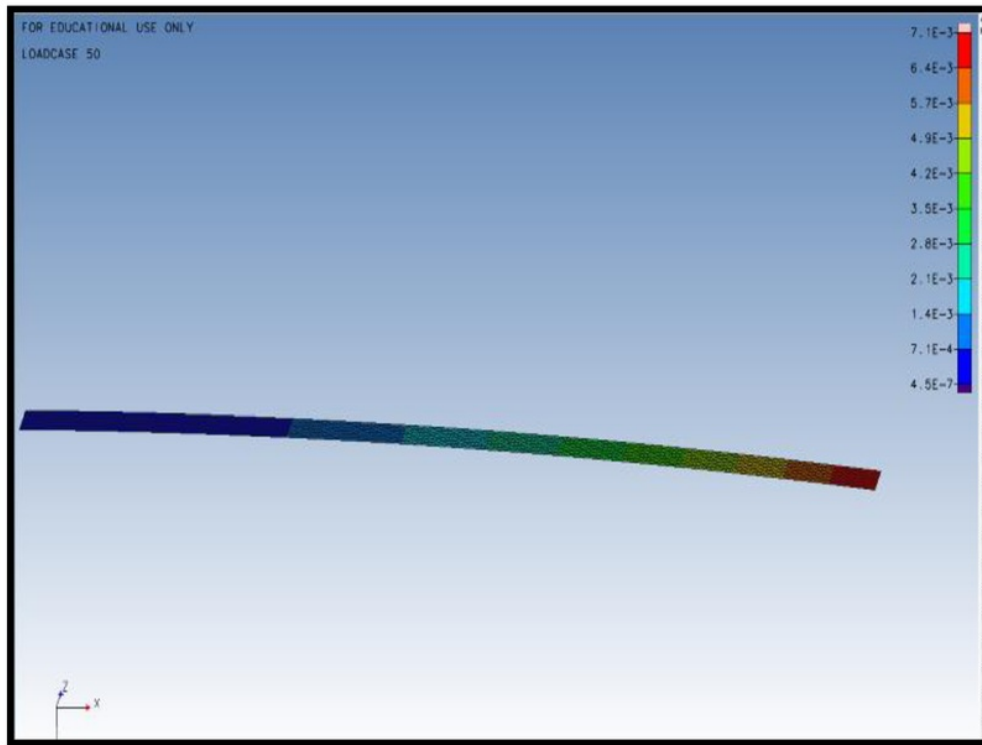


Figure 12: Design Studio Print Screen of Bi-Metallic Strip (Lillicrap, 2018)

5.2 Aluminium Test

As explained in section 4.3.2, obtaining the exact specifications for the CTE values of both the matrix and fibres is extremely difficult and despite many phone calls and emails to the manufacturers the exact micro properties of the composite remain unknown. However, the CTE value of the overall composite could be determined from practical testing, thus allowing the material to be analysed from a macro point of view.

Before testing the carbon fibre composite, testing was done with an aluminium test sample to ensure that both the test procedure and mathematical calculations could correctly calculate the CTE value for a known substance. Unlike carbon fibre composites, aluminium is isotropic and should react linearly in all directions (DEXCRAFT, 2015). The aluminium test was done using T6 60/61 grade with the following dimensions: 200.17mm x 282.68mm x 1.24mm. These dimensions differ from those used for the composite as this was the only size of known material that was readily available for testing.

When heated to 100°C the aluminium deformed by 0.3/0.22mm ($3/2.2 \times 10^{-4}$ m) in the width/length directions. This can be inserted into the following, more simplified, equation below to calculate the CTE.

$$\alpha = \frac{\Delta L}{L_1 T_c}$$
$$\alpha = \frac{0.3}{200.17 \times 71.6} = 2.09 \times 10^{-5} K^{-1}$$

(Engineering Toolbox, 2003) states the CTE for aluminium is between $2.1 \times 10^{-5} K^{-1}$ and $2.4 \times 10^{-5} K^{-1}$ hence the values calculated from the practical test are within 0.01 of the lower end values, meaning that the practical/mathematical procedure will accurately determine CTE values. These values were then further substituted into design studio to validate the findings. Again, the Design Studio results are given in meters, and as seen by the area highlighted in green in figure 13 which gives a deformation value ranging between $2.3 \times 10^{-4}m$ and $3.3 \times 10^{-4}m$, the Design Studio values match almost identically with those calculated previously and those stated by (Engineering Toolbox, 2003).

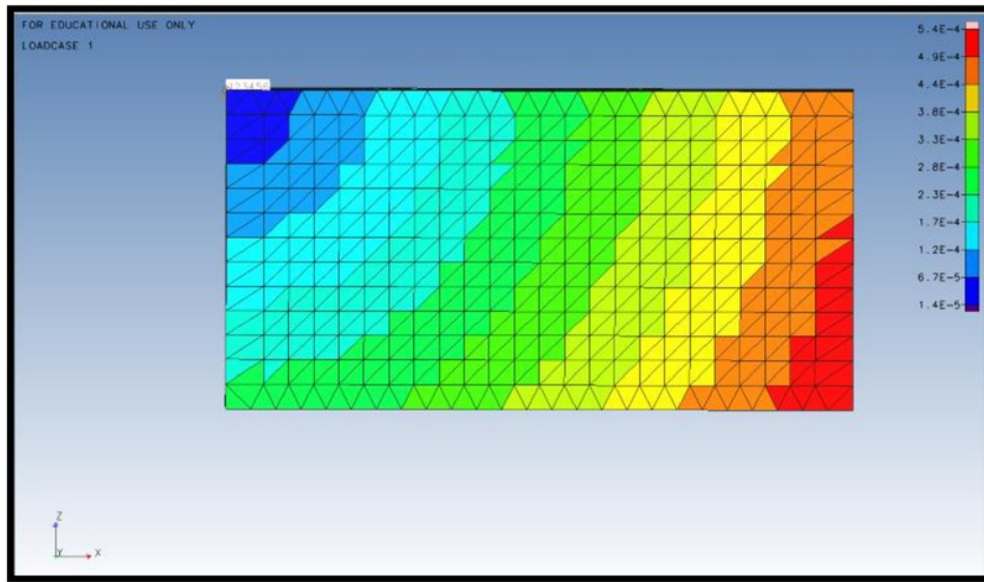


Figure 13: Design Studio Print Screen Aluminium Block (Lillicrap, 2019)

5.3 Carbon Fibre Deformation Test

Given the two previous investigations validate both the practical test and the computer software the processes could be applied to carbon fibre test sheets. A test sheet of MTC400 T800 UD carbon fibre with 0-degree fibre orientation, of 8 ply thickness with dimensions of 280mm x 280mm was made. The reasons behind these specific choices were as follows, the MTC400 T800 material was readily available, testing at 0-degree allowed for baseline data to be obtained and the dimensions were chosen as these were the largest dimensions that the hot press (used for curing) could accommodate. It was decided to make the test sample as large as possible, after discussions with (Tibbott, 2018), who stated that any deformation would be clearer to see on larger test samples. This test piece was then placed in an autoclave with thermocouples attached (see figure 14 (a) for example) and heated to 100°C. The test piece was measured using a digital height gauge (2dp of accuracy) before and after the test, these measurements were taken whilst the test sample was placed on a smooth, level bed (see figure 14(bi&ii) for example). The deformation was then calculated as the difference between the first and last measurements.

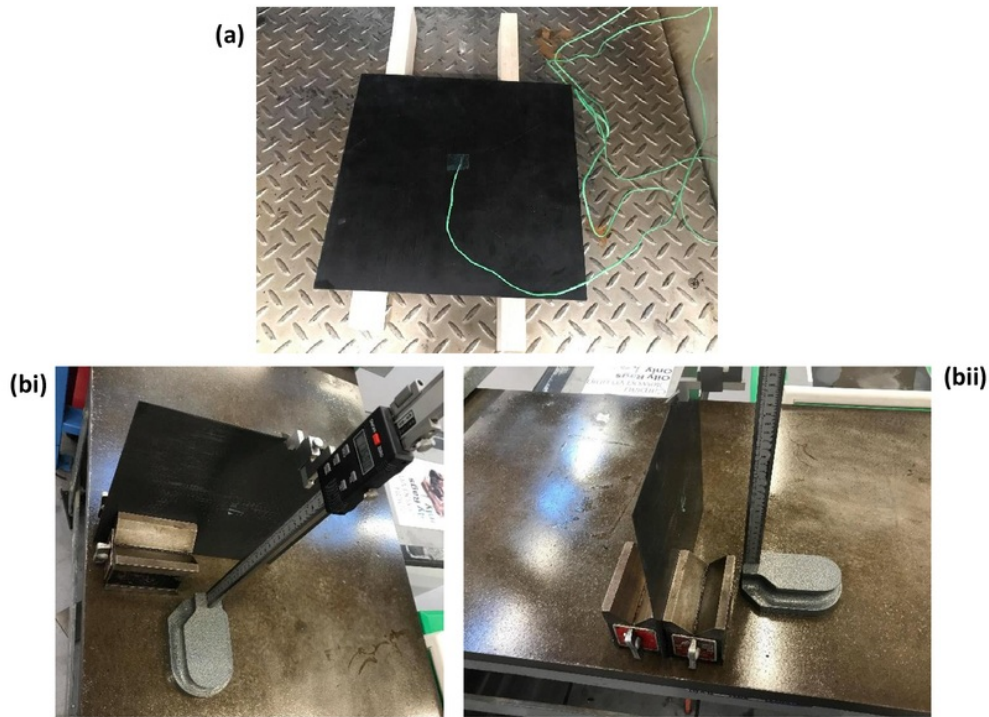


Figure 14: Photos of Deformation Test: (a) Thermocouple Attached to Square Test Plate in Autoclave (bi) and (bii) Measuring of Expansion with Digital Height Gauge at Different Angles (Lillicrap, 2018)

Initially a comparison was to be made between the expected deformation and the achieved deformation. However due to the issues previously mentioned in section 4.3.2, an expected deformation value could not be calculated as a result of the micro properties being unavailable. Instead the practical testing of the carbon fibre was done with the aim of calculating the CTE value for the overall composite. Despite this, comparisons can still be made to researched values given from (Autodesk, 2017), a computer software which has preprogramed data and can calculate properties of specified composites.

Table 4: Results of Carbon Fibre Deformation Test (Lillicrap, 2018)

	CTE Values		Deformation (mm)	
	Fibre	Matrix	Fibre	Matrix
Test 1	7.758×10^{-7}	1.2×10^{-5}	0.016	0.273
Repeated Test	1.287×10^{-6}	7.076×10^{-5}	0.026	0.143
(Autodesk, 2017) CTE Value with Design Studio Deformation	8.843×10^{-7}	2.772×10^{-5}	0.012	0.300

It is evident from the results (see table 4) that all the test gives values of the expected magnitude suggesting a level of accuracy in the test procedure. However, this is contradicted by the difference in the initial and repeated test results. The difference within the CTE values calculated is roughly 60% in fibre direction and 600% in the matrix direction. When comparing

the practical test results with those determined by design studio for the similar material from (Autodesk, 2017), the CTE values vary by 14% and 230% suggesting that although the CTE values are of an appropriate magnitude they are exceedingly different from expected. The difference between the sets of values is so large that it suggests the test procedure is inaccurate.

One element that is not recorded with this test procedure is the rate of cooling between the test sample being removed from the autoclave and it being measured with the digital gauge. This could result in some inaccuracy in the CTE calculations as the temperature is being taken as exactly 100°C when in fact the temperature is much lower, closer to 90°C. This in turn means that the temperature change value used in the calculations would be inaccurate. The cooling rate also contributes to the difference between the first and repeated test, because it is not monitored, there is no way of knowing if both final measurements are being taken at the exact same temperatures. Consequently, the value for the change in temperature used in the equations for both tests could be completely different to the real temperature difference.

Another factor that could have contributed to the difference in the initial and repeated test is that there was a slight variation in the test procedure due to the autoclave breaking after the initial test. Due to this, the repeated test was done using the hot press which meant that unlike the first test where the test sample was laid flat on top of an aluminium block and free to expand in all directions, it was now clamped between two plates. Despite this it could still expand longitudinally and laterally and was heated to 100°C so the expansion was expected to remain the same. Given this expectation, and the differences that occur it is more likely the cooling that creates such significant difference than the heating process.

By considering the aforementioned factors, it is recommended that for future testing thermal imaging cameras be utilised to monitor the exact temperature before it enters the autoclave chamber and after it leaves the autoclave chamber. This would allow for more accurate values to be obtained and used in the CTE calculations which improves the accuracy of both the practical testing and the Design Studio model as these CTE values are used to form the model.

Despite the issues discussed in the practical testing, it is evident that the achievable deformation is only around 0.3mm which is too small to be deemed beneficial for aerodynamic purposes. This is further supported by the effects cooling had on the achievable results, as in many instances the components will be subject to both hot and cold air simultaneously making it difficult to achieve an exact level of deformation.

5.4 Design Studio Modelling of Carbon Fibre Test

The practical results were also modelled within Design Studio to validate the deformation values. These models are shown in figures 15 and 16.

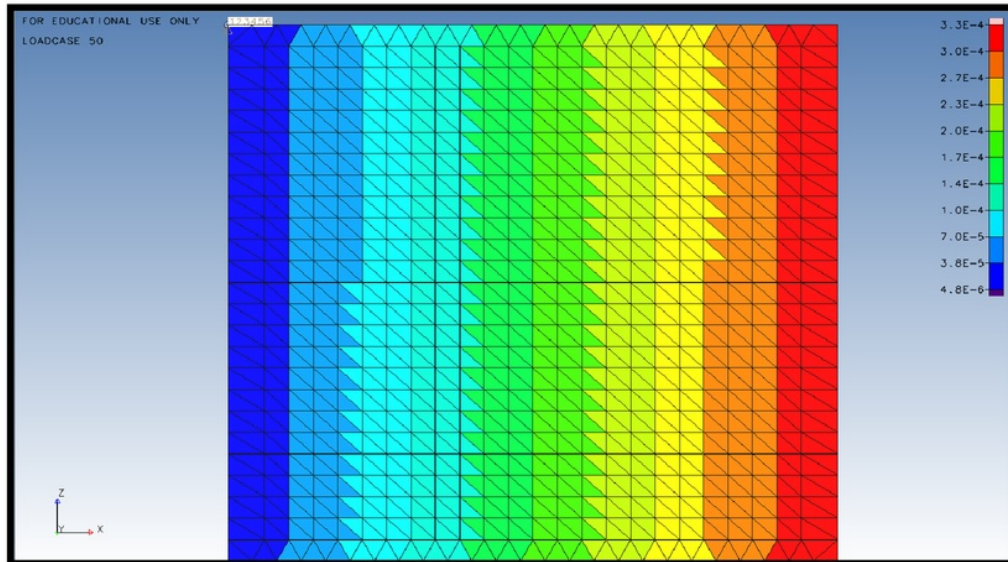


Figure 16: Design Studio Print Screen of Back Calculated CTE Values from Initial Test (Lillicrap, 2018)

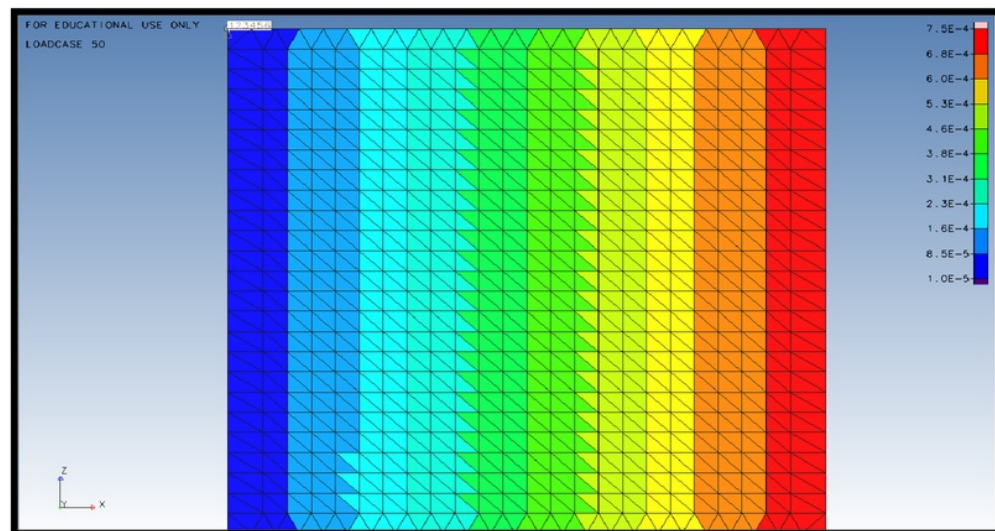


Figure 15: Design Studio Print Screen of Autodesk Helius CTE Values (Lillicrap, 2018)

Again, discrepancies appear between the achieved deformation in the practical tests and those modelled in Design Studio. The model from the back calculated CTE values from the initial test, suggest a deformation value between $1.4 \times 10^{-4} \text{m}$ (0.14mm) and $3.3 \times 10^{-4} \text{m}$ (0.33mm) in the matrix direction which is about expected although as shown by the varying colours in

figure 16, it does suggest the test sample barely deforms along one edge (shown in blue) which is unrealistic. Similarly, the model from the (Autodesk, 2017) data, also shows a small deformation along one edge, however the variation in deformation values is now much larger with it experiencing a deformation between $2.3 \times 10^{-4} \text{m}$ (0.23mm) and $7.5 \times 10^{-4} \text{m}$ (0.75mm). This is unrealistic given the max deformation modelled is over twice the level achieved during practical testing.

As explained earlier, these errors are believed to appear as a result of the inaccurate test procedure, although there is a possibility that the errors in the modelled results could be induced from the computer software being inappropriately set up. As (Roensch, 2013) discusses, there are many factors that could contribute to software issues, from lack of memory or processing power to user induced errors. (Roensch, 2013) further explains that often insufficient training of the programme or not appropriately defining the variables/design criteria is the cause of many issues. These user errors include issues with both design constraints and meshes both of which are explored further in the following section.

5.4.1 Constraint Study

There was some variation within the practical test results and those from design studio, particularly when looking at the different ways that the software models both stress and deformation caused by thermal loading. When the practical test was carried out the test sheet was free to expand in all directions however when modelling the test sheet within design studio the sheet must be constrained. The location of the constraint however does highly impact the results given by Design Studio.

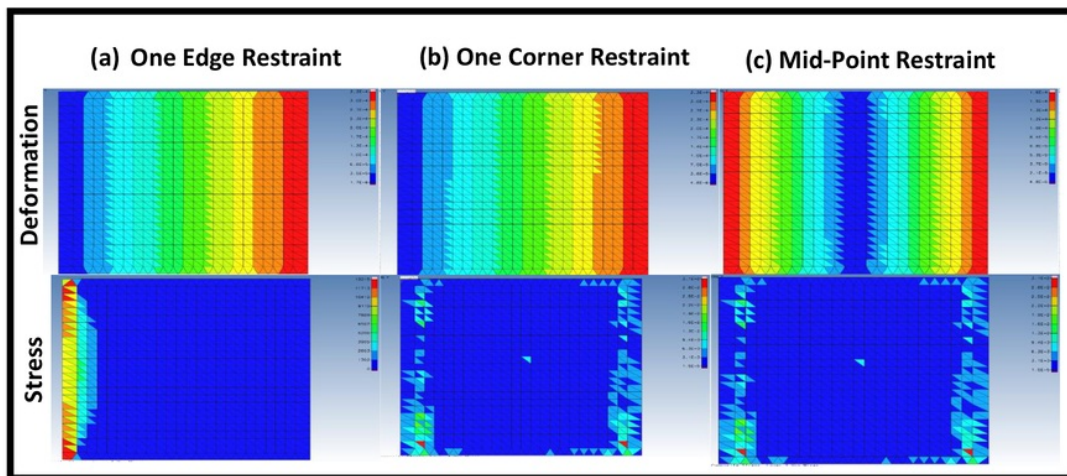


Figure 17: Results of Constraint Study in Design Studio: (a) One Edge Restraint (b) One Corner Restraint (c) Mid-Point Restraint (Lillicrap, 2018)

Figure 17 shows how varying the constraint effects the results. The three constraints modelled were constraining one edge (a), constraining one corner (b) and constraining a mid-point (c). When constraining one edge the test piece can only expand in one direction away from the constraint and is an unrealistic model of the practical test. In comparison the corner and mid-point constraint does allow the test piece more freedom to expand. Unlike the one edge constraint, the other two constraints spread the stress evenly across the entire test piece rather than concentrating it to one edge. Although it does show one element with slightly increased stress in the middle of the test sample (see bright blue triangle in figure 17). This is expected as it is a result of the software modelling the test sample expanding in all directions and so there will be a slight increase in stress at the midpoint. Clearly modifying the constraint of the model significantly improves the accuracy of the model and the deformation value matches closer with those achieved during practical testing. It is worth noting that the difference between the results from the corner and mid-point constrain is so minor that either constraint is recommended for the Design Studio model.

5.4.2 Mesh Study

An investigation into the effects of the mesh size on the Design Studio model was also carried out. As the test sheet is considered a simple model, it is expected that the mesh size will have no detrimental effect on the results. This is supported by technical paper from (Liu & Glass, 2013) which concluded for static analysis such as the ones carried out in this project, there was a 1% difference between the results for the coarse and fine mesh. (Liu & Glass, 2013) deemed this as an acceptable variation limit within engineering simulation and as such it was summarized that the mesh size has no detrimental effects on simple models.

Figure 18 shows the varying mesh sizes that were tested, these vary from coarse triangular mesh to fine 3mm squares mesh. The results of the study are shown in table 5 All the mesh sizes give the same magnitude of maximum deformation and all lie around $0.14\text{mm} \pm 0.03\text{mm}$ which is a variation of 20% although in terms of the deformation experienced the variation is so small that either a fine tri or quad mesh will yield the same results and so either are appropriate for the given application. Therefore, it can be summarized that the mesh size has no significant effect on the Design Studio model.

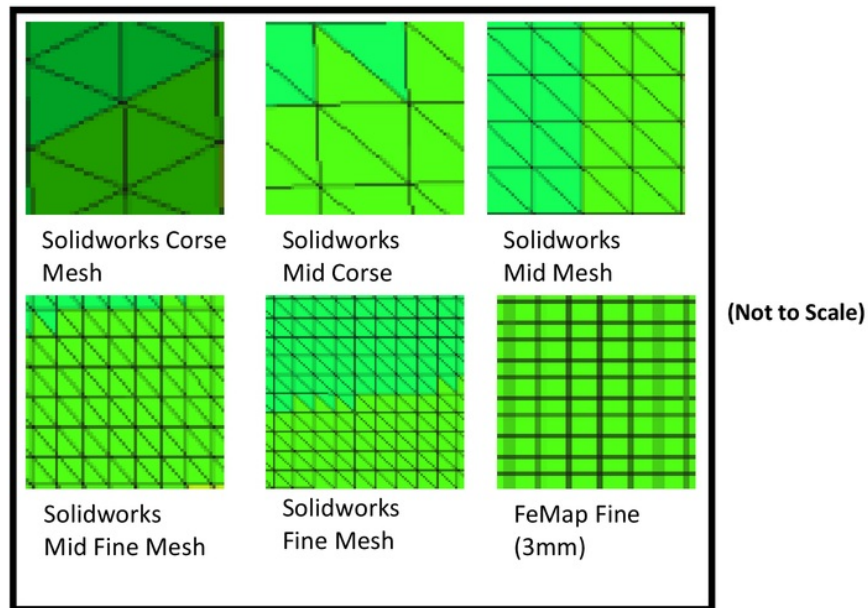


Figure 18: Comparison of Mesh Sizes (Lillicrap, 2019)

Table 5: Results of Mesh Study (Lillicrap, 2018)

Mesh	Max Deformation (M)	Max Deformation (mm)
Solidworks – Corse	1.7×10^{-4}	0.17
Solidworks – Mid Corse	1.6×10^{-4}	0.16
Solidworks – Mid	1.4×10^{-4}	0.14
Solidworks – Mid Fine	1.1×10^{-4}	0.11
Solidworks – Fine	1.1×10^{-4}	0.11
FeMap – Fine (3mm Quad)	1.4×10^{-4}	0.14

5.5 Discussion of the Carbon Study

As the previous few sections show, being able to accurately obtain deformation values is particularly difficult especially with a material such as carbon-fibre. There are so many varying factors to account for during testing that without specific material properties at a micro level, it is almost impossible to accurately model the behaviour of carbon fibre when studying achievable deformation. Discussions in section 4.3.2 show the influence of the CTE value on the expansion achieved and as typical CTE values as stated by (Balandin, 2011) and (Shaina, et al., 2016) are shown to be negative it is no surprise that larger deformation values have not been achieved.

Many reasons for the errors have been discussed and despite modifications to both the constraint and mesh of the Design Studio model, these were found to not significantly affect the overall results. Therefore, it can be concluded that the issues within the test data are more than likely a result of errors within the test procedure, with the main concern being the effects of cooling on the final measurements. Possible solutions to the expected issues have been discussed, with the main aim of monitoring the effects of cooling.

From a motorsport perspective, the results (despite the errors) show that only a small level of deformation can be achieved from heating the carbon fibre, consequently it is not viable nor practical for aerodynamicists to use the deformation for any kind of aerodynamic benefit. However, from repeatedly testing the samples for the deformation test, questions were raised about the effects the repeated testing would have on the carbon fibre, initially whether there would be any changes to the deformation or CTE values achieved. The effects of repeated thermal cycling of test samples is discussed further in the next section. Although due to the issues discussed in relation to the deformation study and lack of micro properties, it was decided to study the carbon fibre from a macro point of view instead.

6. Thermal Cycling Study

The following section details the methodology, results and analysis of the thermal cycling study. As discussed previously the main aims of thermal cycling is to determine the induced effects on the carbon fibre and to what extent these influence the fatigue life of components within a motorsport application.

6.1 Experimental Procedure

The experimental procedure for the thermal cycling study has been separated into three sub-sections as follows: Thermal Cycles, Tensile Test, NDT.

The test samples used were the same for both the tensile test and NDT test. To manufacture the test samples, 6 sheets of MTC400 T800 UD laid up in 500mm x 30mm rectangles with 8 ply (roughly 1mm) thickness. These sheets were then cured in the autoclave. The sheets were then cut into individual test samples which were made to meet tensile test standards ASTM D 3039. The details of this standard were quoted in (Hodgkinson, 2000) which states the dimension of 250mm x 15mm x 1mm for 0° fibre orientation. Despite this standard suggesting the use of tabs on either end of the test strip, initially the test samples were made without tabs as after discussions with (Tibbott, 2018) it was concluded unnecessary for 0° fibre orientation. However, tabs were later attached to all test samples used for tensile testing as a way of resolving issues with slip. The total number of test samples created was 180.

6.1.1 Thermal Cycling

Research into thermal cycling suggests many different methods for testing, with some focused on repeated steady test and others discussing the effects of shock testing materials. A paper by (Liu, et al., 2019) suggests placing each test sample into a pot of liquid nitrogen for 5 minutes, then removing the test sample and inserting straight into a boxed container with a temperature of 200°C. The test samples were then cycled 10, 20 or 30 times with tensile testing occurring at the end of each cycle. This 'fast dipping method resulted in micro-voids and crack which subsequently reduced the strength and Young's modulus of the test samples after numerous cycles. In contrast (Daguang, et al., 2013) ran thermal cycles from -70°C to 120°C and from -196°C to 120°C with the test sample being held at the lowest temperature for 20 minutes and at the highest temperature for 40 minutes. The result of this study showed changes to the bending stress and modulus were most evident and that inter-laminar sliding was happening. Furthermore, (Daguang, et al., 2013) ran cycles of 0, 5, 10, 20, 50, 100 and 200 intervals, which is like that of (Ghasemi & Moradi, 2017) who ran cycles of 0, 50, 100, 150, 200 and 250. (Ghasemi & Moradi, 2017) also ran prolonged thermal cycling with cycles

starting at 0°C and finishing at 100°C, with tensile tests at 50Kn. Again, the results suggested that as the polymer matrix composite was exposed to more cycles it became more brittle. Given the test methods discussed, it was decided to test at similar intervals to match with previous testing, however due to the autoclave cooling system not functioning and liquid nitrogen being an unviable option, the test temperatures were slightly different but still within range of the researched methods.

The thermal cycling was defined as: A thermal cycle from ambient (21°C) to 120°C with a heating rate of 50°C a minute. Each test sample was held at either extreme for 20 minutes. The number of cycles were 0, 5, 10, 20, 50, and 100.

Before commencing thermal cycling 40 test pieces were removed from the grouping so that both tensile testing and NDT could be completed to collect baseline data of the test samples. 10 of these 40 test pieces were used for investigating select issues with the tensile machine, which are discussed later in section 6.2.

As previously mentioned, the cooling function on the autoclave was broken, as such the door of the autoclave had to be open at the end of each cycle to allow each test samples to be removed and cooled to ambient. However, the test samples were fitted with thermocouples to monitor the temperature of each test sample and as such the test samples were held at temperature when the thermocouple read either 21°C $\pm$ 0.5 or 120°C $\pm$ 0.5. On average one complete cycle would take 1 hour and 20 minutes, meaning to complete all thermal cycling it would take 133.4 hours or 5.6 days, consequently to save time all test samples were placed into the autoclave together with a set number being removed at each interval (see table 6 for details). Figure 19 shows how the test samples were laid out in the autoclave and how multiple thermocouples (green wires in figure 19) were attached to the test samples.



Figure 19: Test Samples in the Autoclave with Thermocouple Attached (Lillicrap, 2019)

Table 6: Test Plan for Thermal Cycling (Lillicrap, 2019)

Total Number of Test Pieces in Autoclave	Cycle Duration (Time in Hours)	Number of Cycles	Total Number of Cycles Test Pieces Have Completed	Number of Test Pieces Removed	Number of Test Pieces Remaining
140	6.7	5	5	28	112
112	6.7	5	10	28	84
84	13.3	10	20	28	56
56	40	30	50	28	28
28	66.7	50	100	28	0

6.1.2 Tensile Testing

As stated earlier all test pieces were made to comply with the ASTM D 3039 tensile test standard. Research into the tensile tests used by (Liu, et al., 2019) and (Ghasemi & Moradi, 2017) did not specify exact testing methods although both discussed the use of standard tensile test machines. As such the test standard used in this project was selected after discussions with (Tibbott, 2018) which deemed it the most common and suitable testing standard.

For the completion of the tensile tests a Denison Tensile Test Machine was used, which according to the UWTSO equipment directory is an Electromechanical Universal Testing Machine which was manufactured in compliance with the National and ASTM E4 standard. Further specification of the machine is detailed in table 7 below. The machine applied a displacement at a rate of 20mm/sec. An example of the test machine is shown in figure 20 below. It is worth noting that the service sticker on the front of the machine indicates that the machine was last calibrated on the 15 June 2015, this could possibly cause errors within the results and is discussed further in section 6.2.1. The computer software that links to this test machine is MaxTest.exe, which gives out both graphical (BMP file) and text data of results.

Table 7: Denison Tensile Machine Specification (Lillicrap, 2019)

Machine Specification	Details
Max Load	100 kN
Load Accuracy	±0.5%
Deformation Resolution	±0.5%
Crosshead Displacement Accuracy	0.01 mm
Crosshead Speed	0.005-500 mm/min
Stiffness	164 kN/mm



Figure 20: Denison Tensile Test Machine (Lillicrap, 2019)

As mentioned previously, the test samples were initially manufactured without tabs. After the excessive slip that occurred with the first tests it was decided to add tabs to either end of the test sample. Multiple variants of tabs and adhesives were tested to determine the most successful combination. The results of these are in table 8.

Table 8: Results of Tab Investigation (Lillicrap, 2019)

Tab Test	Result of Test
Carpet Tape (Only)	The tape stretched resulting in the test sample slipping.
Sand Paper and Carpet Tape	Tape is not strong enough, as such the tape stretch, and the test jaws eventually pull the sand paper away from the test sample.
Emery and Gorilla Glue	Gorilla glue resulted in the emery cloth moving due to too much free movement in the glue. Test sample slipped.
Emery Cloth and LOCKTITE Super Glue	Emery cloth remain in place throughout. Jaws could sufficiently clamp to the test sample.

Clearly the best combination was the emery cloth and LOCKTITE Super Glue, which (Henkel, 2014) states has an ethyl cyanoacrylate base, allowing a fixture time of 15-30 seconds. Consequently, to attach the tabs, either end of the test sample was rubbed with sandpaper to roughen the surface, the emery cloth was then glued to one end of the test sample and clamped in place to ensure the glue set and the emery cloth was sufficiently attached. An example of the process and test pieces are shown in figure 21. To further ensure the jaws clamped the test samples between each test both sets of jaws were removed and brushed off to remove any build-up of carbon dust.

The tests were completed as such that the 0 cycle, 50 cycle, and 100 cycle tests were completed first. This was decided upon to save time because if the 50 cycle or 100 cycle tests showed no change in ultimate tensile strength or break load then there would be even less chance of differences being seen in the 5, 10 or 20 test pieces.

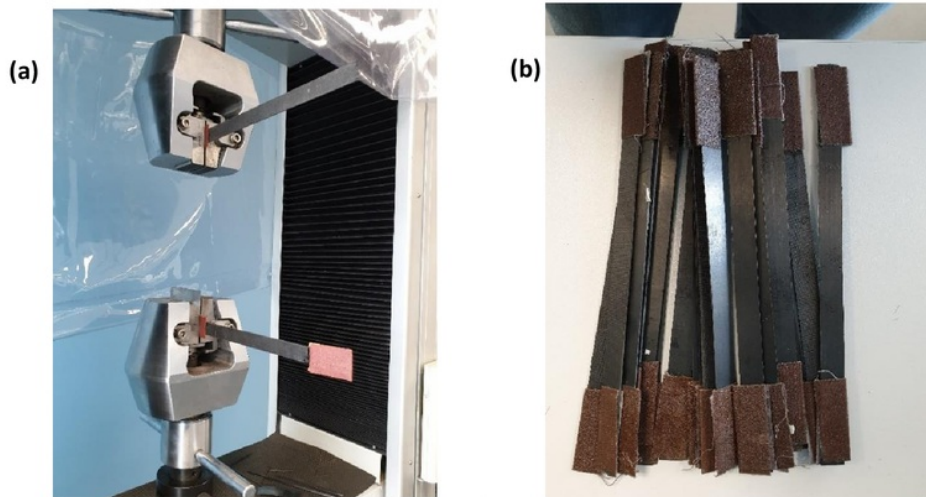


Figure 21: (a) Example of Manufacturing Process, (b) Example of Manufactured Test Samples with Tabs (Lillicrap, 2019)

6.1.3 Non-Destructive Testing

As discussed in section 4.5.1 most research utilised SEM, TEM or X-ray CT scans as the form of NDT. However, the university facilities do not have the appropriate test equipment to carry out such in depth tests, as such an adapted test using a light source and thermography camera was completed.

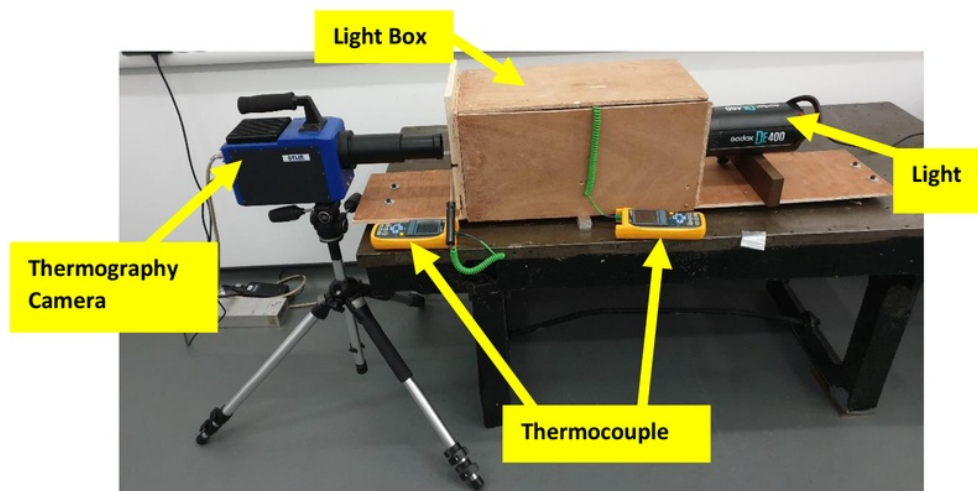


Figure 22: Non-Destructive Test Rig (Lillicrap, 2019)

Figure 22 shows the test rig used for the NDT, with the arrows indicating each piece of equipment. The thermography camera used was a FLIR Systems camera, and the light was a Godox DE 400. Despite figure 22 showing the use of two portable thermocouples, these were later removed. Initially the thermocouples were attached to validate the thermography camera readings.

This NDT functions by allowing each test sample to reach a base temperature, for this project it was set at 27°C, which was indicated from the mean value given by the thermography camera. The light was then turned on for 5 minutes, this acted as a heat source and warmed the test piece. After the 5 minutes the live stream from the thermography camera was frozen and the mean temperature recorded. The light source was turned off and the box, which held both the test sample and directed the heat from the light, cooled back to ambient.

The basic principles behind this test can be broken down into two key aspects. Firstly if cracks have occurred between the fibres and matrix, then more light will seep through these areas, as such the thermography image will show areas of intense heat, which matches with tests discussed by (Unnþórsson, et al., 2019). Secondly, as the test samples are subject to the thermal cycles it is expected that the epoxy will spread, as explained in section 4. Research conducted by (Liu, et al., 2019) suggest this expansion forms microvoids (air pockets) within the epoxy. Given that (Engineering Toolbox, 2009) states the conductivity of air as 0.0022 W/mK, it is expected the test samples undergoing the most thermal cycles, will experience more expansion within the epoxy, as such there will be more air in the test sample so the resulting mean temperature after 5 minute will be lower.

6.2 Results of Thermal Cycling

6.2.1 Tensile Test Results

The following section details the results of the tensile testing. For all of the comparisons any tests that were deemed to be 'fails' have been removed from the results. Typically, failed tests are a result of the test samples experiencing slip. Slip occurs when the jaws cannot sufficiently clamp the test sample. The problem with slip arose in the first set of tensile testing with the un-cycled test samples.

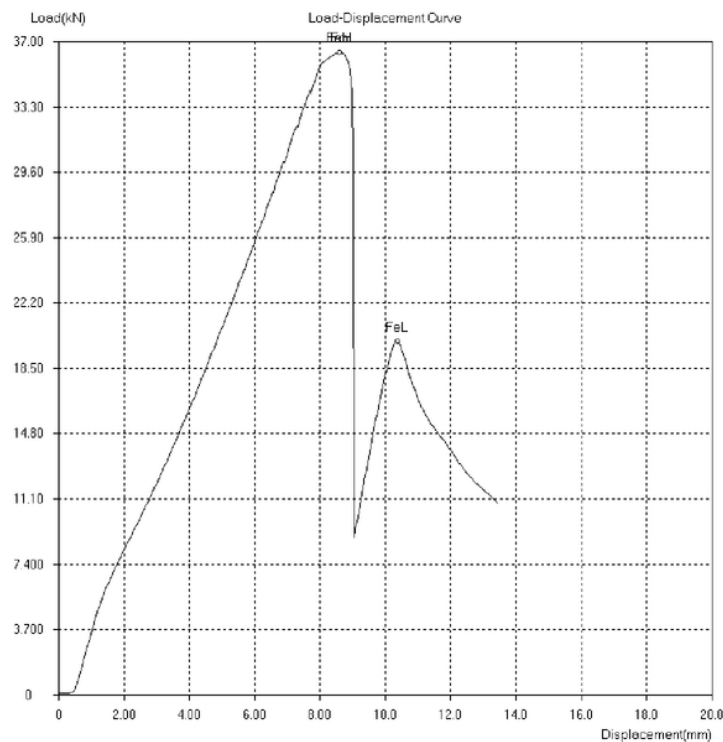


Figure 23: Example of Slip on Graph from MaxTest Software (Lillicrap, 2019)

Figure 23 shows an example of the graphs output by the MaxTest programme, the beginning on the graph is shallower, and the extension experienced by the component rises much quicker than the load. Further to this, at the end of the test, the graph drops off and then begins to rise again, this is due to the test rig believing the component has failed when in fact the test piece has slipped, so not actually broken. As stated in section 6.1 the test samples initially didn't have tabs, however, due to slip the tabs were added to increase the friction between the jaws of the clamp and the test sample. In addition to this, two inserts were added to either side of the jaw on the bottom of the test rig as it was found that this jaw did not completely shut. These inserts forced the top of the jaws closer together thus allowing the test sample to be

securely clamped in place. Figure 24 shows the jaw with the inserts and an example of both a test piece that has slipped and one that broke correctly.

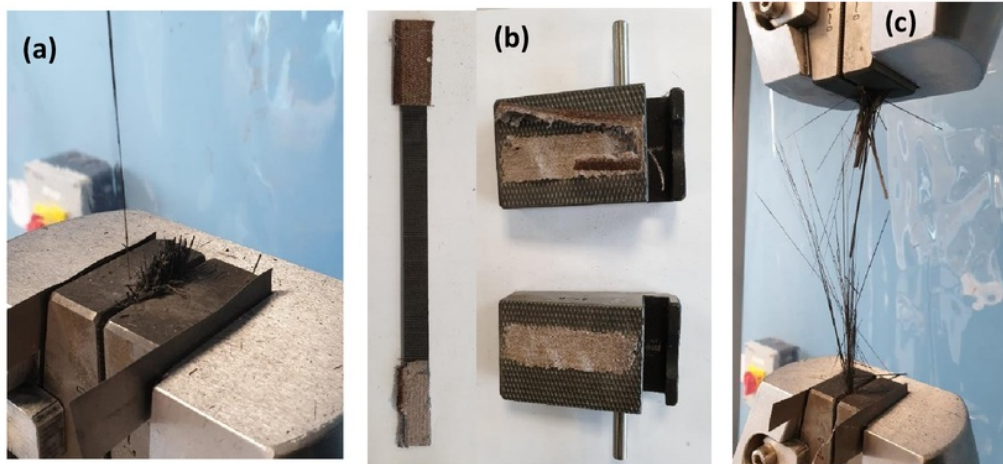


Figure 24: (a) Test Jaw with Inserts Added, (b) Example of Test Sample Experiencing Slip (c) Example of Successful Test (Lillicrap, 2019)

Appendix A details a table that contains the values of the break loads and break times for the 20 tensile tests completed for the 0, 50 and 100 cycled test samples. Also, in appendix A is a photo of all test samples subjected to tensile testing. Figure 25 Below, shows that the test samples all break around the same time which is expected as the tensile test machine was set to displace at a rate of 20mm/min so it would take the roughly the same amount of time to reach the same amount of load.

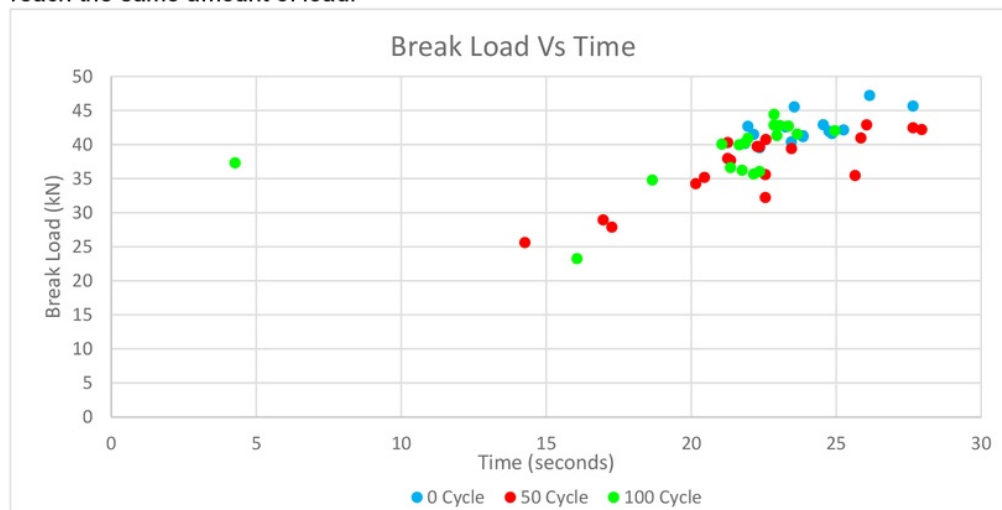


Figure 25: Graph of Break Load Vs Time (Lillicrap, 2019)

Figure 26 shows that the break loads lie between the ranges of 20 kN and 50 kN for all of the load tests which was expected as (Ghasemi & Moradi, 2017) carried out tensile tests at 50 kN and experienced breakages at this point.

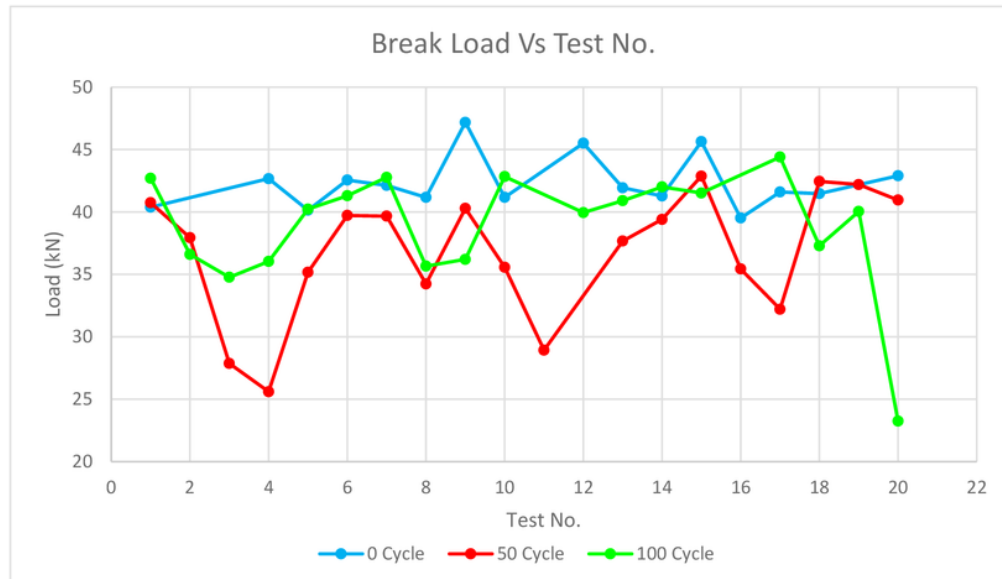


Figure 26: Graph Depicting the Break Loads for Each Test of Varying Thermal Cycles (Lillicrap, 2019)

Also as expected is that the 0 cycled test samples were able to withstand the highest level of loading. Interestingly, the 50 and 100 cycle test samples do not follow the expected trends, with the break loads for the 50 cycles (shown in red) being on average the lowest of all tests. The mean break load of each test is 42.33kN, 36.79kN and 38.80kN, for the 0, 50 and 100 cycled tests respectively. The mean values clearly show that after thermal cycling there is a change in the strength of the composite, with it typically being able to with stand less loading. However, due to the 100 cycles being on average stronger than the 50 cycles, the extent of this change cannot be given an exact value or percentage. Further to this, as the graph in figure 26 shows, the 50 cycle test samples appears to follow no form of linearity with the line depicting large variation in values.

This large variation occurs as a result of the difference between the minimum and maximum values, as such boxplot's showing the variation between the minimum, maximum and median values for the three tests are shown in figure 27. For the 50-cycle test, the maximum and minimum break load was 42.88kN and 25.60kN, respectively, meaning there is roughly a 67% difference between the smallest and largest value. By making the same comparisons with the 100 cycled data, there is roughly a 22% difference between the maximum and minimum values

recorded. This therefore suggests that the predictability of the results achieved for the 50 cycles is far less than that of the 100 cycles.



Figure 27: Boxplot of Results for 0, 50 and 100 Cycle Tests

Furthermore, the box and whisker plot show the location of the data, with the 0-cycle data being slightly lower on average than the median, meaning that the data when plotted on a frequency distribution graph would skew slightly to the left. Contrastingly, the 50 cycle and 100 cycle data, would both appear skewed to the right on a frequency distribution graph due to the box being shifted to the higher end of the whisker. The skewness of both results is also supported by the variance (σ^2) of the data (see appendix B for calculations). The σ for both the 50 cycle and 100 cycle is 26.1 and 25.1 respectively which compares to a variance of 4.5 for the 0 cycled. The much larger values show the level of variance in the thermally cycled tests is over 5 times larger than the 0 cycle tests, further supporting the idea that the thermal treatment has caused changes within the structure of the carbon-fibre test samples.

In addition to the variance, the standard deviation can be considered (see appendix B for calculations). Typically, and as stated by (Klein & Dabney, 2013), statisticians allow for the data to lie with 2 standard deviations of the mean value, for a normal distribution, as this gives a 95% confidence level. By considering this statement then there are few errors within the collected data, with all values collected for the 0-cycle test lying within 2 standard deviations. Both the 50 cycled and 100 cycled tests have 2 tests which lie outside of this range and as such could be deemed as anomalies. It is also worth considering the standard deviation alone, where the three tests give the following values: 0 cycle = 2.1, 50 Cycle = 5.2 and 100 Cycle = 5.0. By noting these values singularly, it is clear that, as the test samples are exposed to excessive number of cycles, the predictability of test sample reduces, meaning it is now much harder to determine when the component will break. For motorsport applications, this is

significant, not only does it suggest the components should be replaced more commonly meaning more expenditure, but it also suggests that determining the precise fatigue life of the component is almost impossible.

To try to determine the point at which the test samples begin to become unpredictable in terms of the break load, further tests were done using the 10 and 20 cycled test samples. A comparison of the break load results is shown in figure 28. For this test only 5 test samples of each cycle are compared.

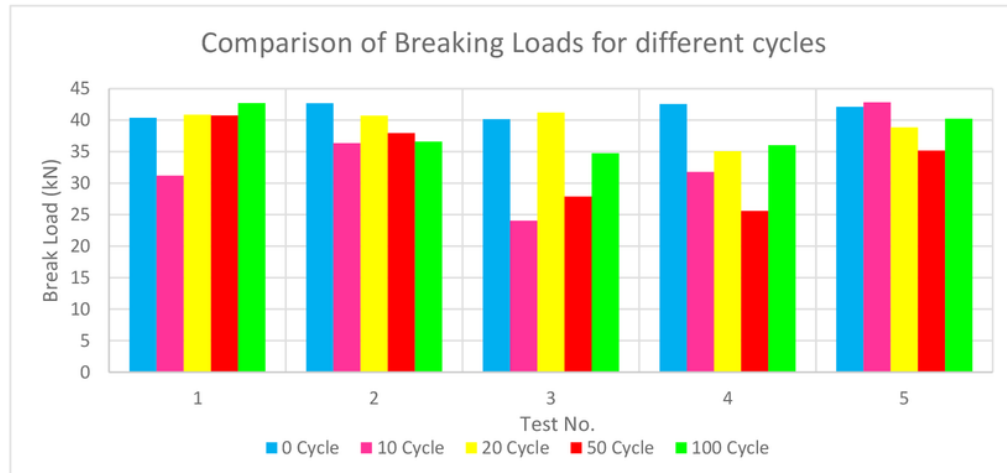


Figure 28: Comparison of Results for Tensile Tests of All Cycles (Lillicrap, 2019)

Interestingly, the break loads are on average lower for the test samples exposed to only 10 cycles, the break load then increases again with 20 cycled test samples before dropping off for the 50 cycles. This break load then increases with the 100 test samples. The break load fluctuates so significantly between each of the cycles it is difficult to conclusively determine whether the test sample improves, weakens or remains unchanged after experiencing thermal cycles. Furthermore, the inconsistency in the test data suggests that there is an underlying error in the testing or manufacturing of the test samples. Although the test procedure remained constant for all tests and the break loads were within the expected region. Similarly, the manufacturing process of the test samples was constant, and despite there being 6 sheets of the composite made, the test samples were mixed together to ensure a random selection of test samples were used for each test. The test samples were randomly selected as suggested by (Klein & Dabney, 2013), to prevent either of the test sets being biased due to a manufacturing defect, thus allowing each test sample the equal opportunity to be exposed to any number of cycles. Given that both the manufacturing and testing processes remain the same throughout the study, the only possible explanation for the 100 cycled test samples breaking at a higher load is that statistically out of all the test samples there were just slightly

stronger. If this was to be investigated further with a larger population of samples, then it is expected that more of the test samples would break at lower loads. Consequently, it is recommended that further testing be carried out with a larger number of samples to determine whether the 100 cycled test samples are stronger than the 50 cycled test samples or if the data collected in this study was just statically higher.

From the break load the ultimate tensile strength (UTS) could also be calculated, this was done using the equation below.

$$UTS = \frac{\text{Break Load}}{\text{Cross Sectional Area}}$$

Data supplied by (Reddy, et al., 2016) and (Hexcel, 2013) suggested that the UTS of carbon fibre, at 0° fibre direction should be between 1200MPa and 2400MPa. From the tensile test break loads the UTS for the 0, 50 and 100 cycled test samples are on average, 2467MPa, 2097MPa and 2283MPa. Similarly, to before the 50 cycled test sample's UTS is lower than the other two cycles, with the 100 cycled UTS being roughly midway between the other two values. Again, these values match with the data supplied which further supports the accuracy of the tensile test and the break loads achieved. Although as with the break loads, it is difficult to say with such a small number of test samples whether these outcomes are a matter of chance or whether there is something else causing the difference especially as all test samples have been treated the same.

Additionally, the Young's modulus was going to be determined however, when analysing the values for Young's modulus given by the MaxTest software the values appear to be wrong, with the software stating a Young's modulus between 12-14Gpa. Since (Performance Composites, 2009) and (Hexcel, 2013) both state that the Young's modulus for carbon fibre composites is typically between 130GPa and 170GPa then there must be an error in the calculations used in the software. To overcome this issue the values of elongation and displacement from the programme were used along with the break load and cross-sectional area to determine by hand the Young's modulus of the composite. However, these calculations were still incorrect with the Young's modulus now being calculated to be 50GPa at most. Thus, an investigation into where the error occur and possible resolutions was carried out. The following section details this investigation.

6.2.2 Young's Modulus Investigation

As previously explained, there were clearly errors with the Young's modulus calculated by the software, however as these values could not be determined from the hand calculations it suggests there is an error with data output by the software. As section 6.2.1 discusses, the values for the break load match those expected, and further checks carried out which involved placing known weights on the load sensors, all matched. Therefore the error was believed to be with the software's measurements of elongation or displacement.

Firstly, the data given by the MaxTest software was plotted in excel to create a stress-strain graph. The gradient of the steepest section of the graph was then taken to determine the Young's modulus from a graphical method. Again, this found the Young's modulus to be, at most, 45GPa. Still too small to match with the expected values.

It was then decided to manually validate the values the tensile test machines' readings. Three separate methods were tried and are as follows:

Installation of a Dial Gauge

By attaching a dial gauge to the bottom set of jaws on the tensile test machine, as shown in figure 29, the displacement could be measured to see if it matches the displacement given by the machine. The result of this test was that the dial gauge matched perfectly, and in some cases was slightly greater than the displacement displayed by the MaxTest software. Consequently, it validates that the machine was moving at the correct displacement but gives no indication as to why the Young's modulus is incorrect.

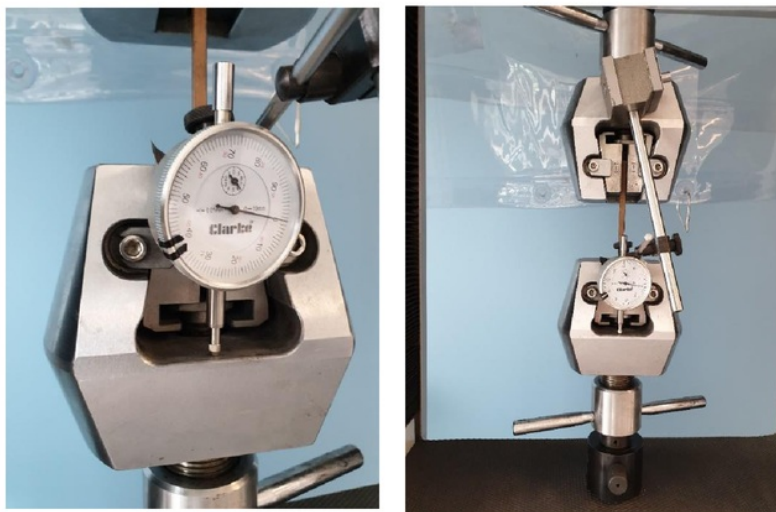


Figure 29: Dial Gauge Attached to the Jaws of the Denison Tensile Machine (Lillicrap, 2019)

Installation of a Strain Gauge

As figure 30 shows, a strain gauge was attached to a piece of aluminium that was placed within the jaws, as this piece of aluminium was stretched the strain was determined. For this investigation the strain was recoded as 1.2mV. It was believed this value was in millivolts however there is a possibility it was given in millivolts per volt. In either case the Young's modulus calculated using the values from the strain gauge still do not match with those expected.



Figure 30: Strain Gauge Attached to Test Sample (Lillicrap, 2019)

Tests of Known Samples

Finally, it was decided to tensile test known samples of materials to determine whether a scaling factor had been automatically applied within the programme and whether the same scaling factor could then be applied to the composite test samples. This investigation was conducted alongside Matthew Powell. Three differing materials were selected for these tests, these were brass, aluminium, and carbon steel (varying percentages). Table 9 shows the results of this investigation, the table states the expected Young's modulus, the scale factor necessary and the achievable Young's modulus after the scale factor is applied. Note the

scale factor was applied to the extension reading from the MaxTest software. Data for the expected Young's modulus is as stated by (Engineering Toolbox, 2003) and (AZO Materials, 2012).

Table 9: Results of Known Test Sample Young's Modulus Investigation (Lillicrap, 2019)

Material	Test Number	Expected Young's Modulus (GPa)	Scale Factor Applied (%)	Achieved Young's Modulus (GPa)
Brass	1	102-125	90.0	120
Aluminium	2	69	91.0	69.8
	3	69	90.2	70
	4	69	90.5	71
	5	69	90.4	68
0.4% Carbon Steel	6	200	90.4	199
	7	200	90.3	204
	8	200	90.2	194
	9	200	90.3	203
	10	200	90.3	203
0.54% Carbon Steel	11	200	90.4	197
	12	200	90.3	202
	13	200	90.3	204
	14	200	90.3	204
	15	200	90.3	202
	16	20	90.4	205

As table 9 shows, a scale factor of 90.5% ± 0.5 results in a Young's modulus that matches closely with those expected. However, if this same scale factor is applied to the results for the composite, for example to the 50GPa, the Young's modulus becomes ten times larger and is now 500GPa, meaning it is now unrealistically too large.

In summary, many investigations were carried out to determine a solution to the Young's modulus errors and despite successfully finding scale factors which work for known materials this same approach cannot be applied to the composite. Due to the set-up of the MaxTest software, the debug settings could not be accessed due to them being password protected, as such these properties could not fully be investigated. As previously stated, the machine was last calibrated in 2015, and given that the machine has since been relocated, it more than likely that this is the cause of such errors. Therefore, the Young's modulus could not be accurately ascertained and discussed for this project and further investigations with a calibrated machine are recommended.

6.2.3 Non-Destructive Test Results

Tables containing the exact details of the NDT results can be found in appendix C.

Figure 31 shows a comparison of the mean temperatures reached for the 8 tests carried out for each set of cycled test samples. Unlike the tensile testing the 50 cycled test samples appear to be much closer matched to the 0 cycled test samples, and instead the 100 cycled test samples appear to vary more greatly. As explain in section 6.1.3 it was expected that the test samples which had been exposed to the greatest number of cycles would conduct less heat due to the test sample having more air within the epoxy. This is supported by the findings of the NDT which show that the 100 cycled test samples on average reach lower temperatures only 31.53°C compared to 31.81°C and 31.75°C of the other tests. This is a decrease of 0.88%, despite being small, especially when the changes expected to happen are on a micro level.

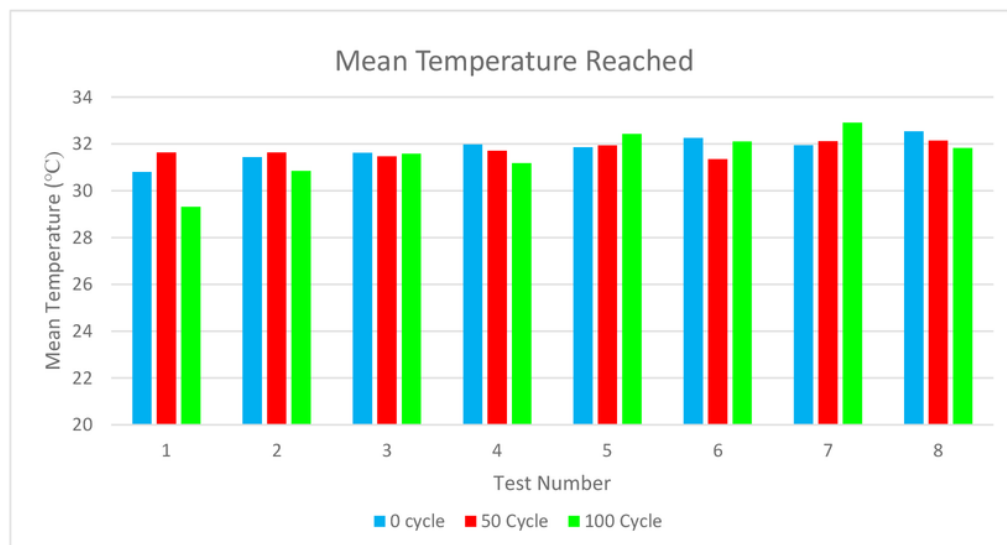


Figure 31: Results of NDT - Mean Temperature Reached Comparison (Lillicrap, 2019)

Furthermore, the standard deviation of the test samples can be discussed. By comparing the standard deviation of each set of cycled samples at the beginning and the end of the NDT, it is clear that, for the 100 cycled test samples the standard deviation has increased. As seen in figures 32 to 34, the standard deviation for both the 0 cycle and 50 cycle test samples lies on average around 0.21 (beginning) and 0.28 (end). Although the 50 cycle samples appear to follow a much more unpredictable trend than the 0 cycle, both sets suggests that no changes from an NDT aspect have occurred. However, for the 100 cycled test samples the standard deviation rises to an average of 0.22 at the beginning to 0.36 at the end. This suggests that as the test sample is being heated there are areas which are conducting more or less heat than others, and in some areas the temperature experienced is much higher. By pairing these

values with an example images from the thermography camera for the 0 and 100 cycled test (see figure 35), it is clear that changes must have occurred to the structure of the composite as there are no areas of bright pink, which mean there are hotter areas.

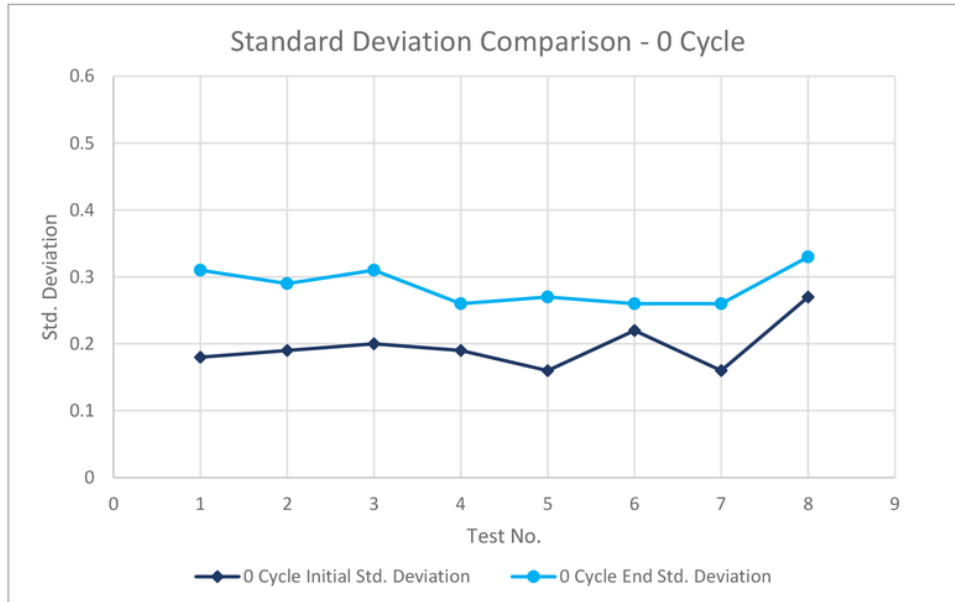


Figure 32: Standard Deviation Comparison of Start and End Results - 0 Cycle (Lillicrap, 2019)

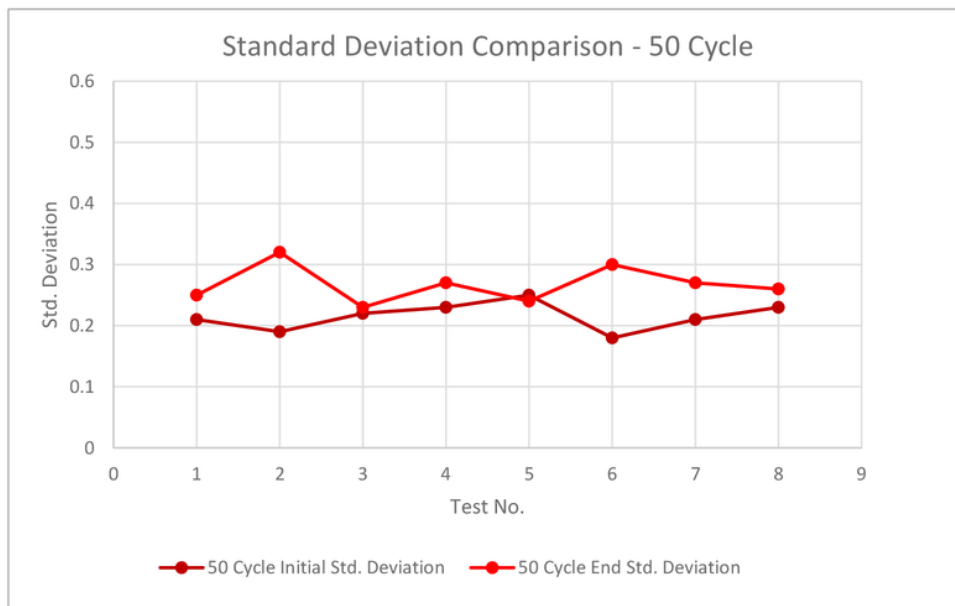


Figure 33: Standard Deviation Comparison of Start and End Results - 50 Cycle (Lillicrap, 2019)

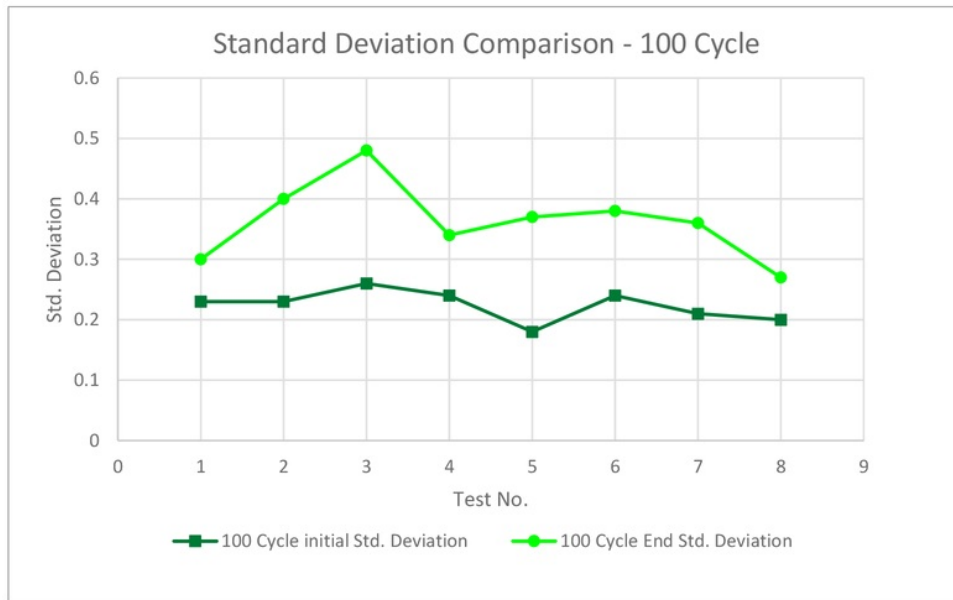


Figure 34: Standard Deviation Comparison of Start and End Results - 100 Cycle (Lillicrap, 2019)

It is worth noting that some of the intense heat shown in green in the middle of the images is a result of the light source being directed at the test sample. It is only areas of intense heat shown in pink that are of interest.

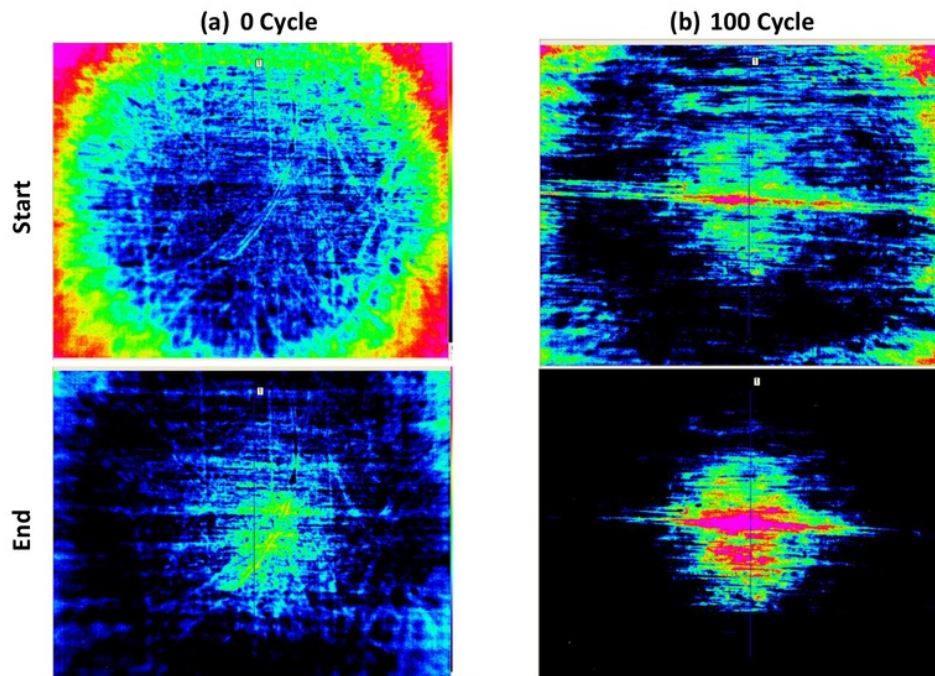


Figure 35: Comparison of Thermography Images at Start and End of Test. (a) 0 Cycle (b) 100 Cycle (Lillicrap, 2019)

A test was carried out to see if extending the time that the test sample was exposed to light source to 10 minutes made any significant effects on the temperatures achieved, the temperatures increased by an extra 2 degrees on average, but the standard deviation trend matched as before. Thus, it was decided that the extended time made no significant change to the temperatures or the trends seen as such all tests were completed with the 5-minute exposure time.

Consequently, it can be said that the 100 cycled test samples must have more air in them allowing for less temperature to be conducted, and that these changes occur but not significantly until after 50 cycles. This matches with the results of research by (Daguang, et al., 2013) and (Liu, et al., 2019) which, as explained in section 4, found microvoids after excessive numbers of thermal cycling. However, the size of these microvoids and their precise location cannot be determined using the thermography camera, as such it is recommended that further NDT be carried out using SEM or TEM to determine the exact details of the micro voids and cracks.

6.3 Discussion of Thermal Cycling Study

Both sets of testing give the same overall conclusion that thermal cycling does affect the structure of the composites, however neither give a conclusive answer as to how much the thermal cycles effect the test samples.

Due to the issues highlighted with the tensile test machine when trying to determine the value of Young's modulus, it is evident that the data collected is only accurate enough for comparison. Without being able to fully resolve the issues with the machine the load values, although believed to be accurate, should as a precaution be taken as estimated values rather than absolute, until further testing has been completed.

Despite that, the data does match to an extent with the findings of (Ghasemi & Moradi, 2017) who stated that polymer matrix composites became brittle after numerous cycles. Similarly, (Shang, et al., 2012) found that more cycles, meant more micro cracking within the layers of the composite and thus the strength of the composite decreased, however the testing within this study does not follow that pattern. Instead as the number of cycles increased to 50 the strength decreased, but by 100 cycles the strength increased again. As explained in section 6.2.1, this could be a result of statics, and the test samples were just on average slightly stronger. However, it could also be a result of the degradation to the fibres occurring after 50 cycles, and instead of it getting worse as the cycle number increases, it remains the same. If this was the case then it is more than likely that the samples tested for 100 cycles were slightly

stronger, and that testing a larger number of samples, say 300, would yield an average that was in fact lower than the 50 cycles.

In contrast, with the NDT testing, significant changes to the test samples could not be detected until 100 cycles. This could be a result of the NDT focusing on the matrix properties, rather than the fibre properties as tested in the tensile test. All the 100 cycled test samples show areas of intense heat, which suggests that the matrix has spread and as discussed previously in sections 6.2.3, microvoids and cracks have formed. Interestingly, the matrix only begins to degrade after the 100 cycles, suggesting that unlike the fibres, the fatigue life of the matrix is much longer.

Furthermore, both the tensile tests and NDT show that after numerous thermal cycles, the composite becomes unpredictable. In both cases, once the test samples reach 50 cycles, it becomes increasingly difficult to determine how the structure has changed. In terms of the tensile tests, the results of the 50 and 100 cycled samples are so varied that the standard deviation for the two test is above 5, this is further reflected by the NDT which clearly shows that as the number of cycles increases so does the standard deviation. Therefore, it is recommended that any component subject to excess temperatures for prolonged number of cycles, is replaced frequently particularly as the exact fatigue life of the component cannot accurately be determined.

7. Conclusion

Reflecting on the results from both the deformation and thermal cycling studies, it is evident that the effects of temperature on the performance, longevity and fatigue of carbon fibre components is almost impossible to accurately determine. This is made even harder as composites are composed of two factors, the fibres and the matrix, both of which react to temperature in different ways.

From a fatigue aspect, the deformation test showed that the expansion that occurs when heated is so minor that in the short term there would be no significant impact on composite components. This is further supported by the thermal cycling study which showed that significant changes to the structure of the composite only occur after high number of cycles. As such, for most general applications where the number of thermal cycles remains low, the component would not fail. However in a motorsport application, the use of unidirectional carbon fibre in areas exposed to high heat for a large number of cycles is impractical, particularly as repeated expansion and constriction will result in cracks, pair this with the microvoids and cracks that are induced from the thermal cycling and the component is likely to fail much quicker.

In relation to the original aim, which was to achieve an aerodynamic benefit from deformation induced from heating the brake duct, both the extent it deforms and rate at which carbon fibre cools makes it an unviable option. Furthermore, the components which could possibly benefit from heating during a race are the wing and the brake duct, in which both are exposed to hot and cool air. Consequently, trying to achieve the precise temperature, for the exact deformation at the right moment on the race circuit is unrealistic, and will most likely create undesirable handling characteristics. As such it is concluded that for aerodynamics the use of thermal induced deflection is not an option.

In addition, designers of motorsport components should also be aware of the issues caused as a result of thermal cycling. Despite the changes in both sets of testing being only minor, the unpredictable nature of the composite is cause for concern, especially in relation to race vehicles where component failure can have devastating consequences for drivers.

To conclude, the response of the carbon fibre to heat treatment in both the deformation and thermal cycling has been significant. Despite some of the data being unreliable, comparison has been drawn which clearly shows that the composite does not react in any beneficial way to heat treatment and as such further testing should be done before utilising carbon fibre based composites in areas exposed to excess or repeated heat.

8. Evaluation

Throughout this report many issues have been discussed and possible solutions found. One main area which could have been improved was the test procedures. Initially the deformation study was not closely monitored from a temperature aspect which allowed for varying CTE values to be calculated. Had this error been noticed sooner, and had the deformation been of a higher value then this could have been mitigated.

In terms of the thermal cycling study, the tensile testing could have been improved had the machine been calibrated after its change in location. As discussed, many steps were taken to reduce the impact of the machine's errors on the result, but despite the best efforts, the results cannot be taken as true values. If the machine was to be calibrated, then the testing could be rerun however this would require remanufacturing the test samples and ensuring that the thermal cycles were completed using the exact same method as before. As mentioned, there were initially issues with slip occurring at the start of the tensile tests however this was resolved, although there were still a couple of tests which were deemed as fails due to the test piece's slipping. There is no exact cause of this slippage as the materials and glue used were the same.

The NDT used within this project was based on the basic principles of physics as explained in section 4.3. Although in theory these tests should yield accurate results, there are many factors to also consider, such as the ambient air temperature in the room and the resolution of the camera. Therefore the test procedure could have been further improved had SEM or TEM equipment been available for use to gain in depth photos of the exact structure of the composite.

In both cases the same MTC400 T800 UD carbon fibre material was used due to it being readily available at the university. However, as explained previously, the exact specifications of this material are unknown making it difficult to analyse the exact matrix and fibre properties of the composite from a micro level. Therefore, had the circumstances allowed, a specified known composite material, whose matrix and fibre properties were known would have been used. This would improve the accuracy of all the results and allowed for a more precise CTE value to be equated.

9. Recommended Further Work

Recommendations have been made throughout this report as to steps that should be taken to further advance the understanding of this area. Primarily, further testing should be done to accurately determine the significant changes induced from thermal cycling to the composite test samples on both a macro and micro level.

Tensile testing with accurately calibrated machines is recommended, with testing of both composite and known samples to ensure that the readings of both correlates. Further testing should be done with test samples cycled to increments between 50 and 100 to determine whether there is any variation in the break loads, or predictability of the test samples. Tests should also be carried out with much higher number of cycles, for example 250 like in the research by (Ghasemi & Moradi, 2017). This would give evidence to determine if the statement made about the fibres changing at 50 cycles is true or not and would show how prolonged cycling effects components.

Further investigation from a micro level should also be carried out with the recommendation of SEM, TEM or X-Ray CT scans that match with those from (Daguan, et al., 2013), (Liu, et al., 2019) and (Zhang, et al., 2013) being completed. This would show the internal structure of test samples and determine the exact extent of the microvoids and cracks. As with the tensile testing, further testing in this area would also help to improve the predictability of the test samples.

Across both tests, it is recommended that the number of test samples be largely increased to obtain a more accurate representation of the entire population of carbon fibre materials. As such it is recommended that the number of test samples be increased to 1000, with this including a range of carbon fibre based composites. This would then allow for a more collective overview of the material to be obtained and comparisons between varying matrix's to be made.

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Appendix

Appendix A

Table 10 details the results of the tensile tests for the 0, 50 and 100 cycle tests. These results are portrayed graphically within the main body of text. The results discussed within section 6.2.1 mitigate failed tests however the results below show the read out of these tests in red. The results for the failed tests appear to be in the same ranges as the other results however this is due to the test being stopped once the MaxTest graphs showing mass amounts of slip.

Table 10: Results of Tensile Tests (Lillicrap, 2019)

Test No.	0 Cycle			50 Cycle			100 Cycle		
	Time (Sec)	Break Load (kN)	Ultimate Tensile Strength (MPa)	Time (Sec)	Break Load (kN)	Ultimate Tensile Strength (MPa)	Time (Sec)	Break Load (kN)	Ultimate Tensile Strength (MPa)
1	23.46	40.39	2375.90	22.58	40.74	2396.47	23.36	42.70	2511.77
2	23.96	34.98	2057.65	21.26	37.94	2231.77	21.36	36.60	2153.24
3	23.86	36.07	2121.77	17.26	27.86	1638.53	18.66	34.77	2045.29
4	21.96	42.67	2510.00	14.27	25.60	1506.18	22.36	36.04	2119.71
5	21.86	40.14	2361.20	20.46	35.17	2069.12	21.86	40.23	2366.47
6	23.26	42.56	2503.53	22.28	39.72	2126.47	22.96	41.30	2429.41
7	25.26	42.13	2392.35	22.36	39.67	2333.82	23.06	42.78	2516.47
8	23.86	41.17	2421.47	20.16	34.24	2014.41	22.16	35.66	2097.65
9	26.16	47.18	2775.29	21.26	40.29	1310.29	21.76	36.21	2129.71
10	23.86	41.17	2421.47	22.56	35.57	2092.35	22.86	42.84	2519.71
11	26.25	43.6	2564.71	16.96	28.93	1701.77	19.76	31.12	1830.59
12	23.56	45.51	2664.41	27.25	36.58	2151.47	21.66	39.95	2350.00
13	24.76	41.94	2467.35	21.36	37.67	2215.88	21.96	40.91	2406.18
14	23.86	41.28	2427.94	23.46	39.41	2317.94	24.96	42.01	2471.18
15	27.66	45.64	2684.71	26.05	42.88	2522.06	23.66	41.52	2442.35
16	22.36	39.52	2318.52	25.66	35.44	2084.41	5.87	11.63	684.12
17	24.86	41.6	2447.05	22.56	32.21	1894.71	22.86	44.41	2612.06
18	22.16	41.47	2439.12	27.65	42.45	2497.06	4.28	37.29	2193.53
19	22.16	38.63	2247.65	27.95	42.20	2473.82	21.06	40.05	2355.59
20	24.56	42.9	2259.12	25.86	40.96	2409.12	16.07	23.25	1367.35

Figure 36, on the following page shows the tensile test samples after the tests have been complete. Other than failed test, most of the test samples broke in the same manner with only a few stands remaining at the end of the test. The samples broke in such a way as a result of test while destroy being turned off on the machine thus allowing all samples to reach their destruction point.



Figure 36: Photograph of All Test Samples Subject to Tensile Testing (Lillicrap, 2019)

Appendix B

The equations used below show the steps taken to determine the variance and standard deviation of the tensile test results. The equations are as stated in (Klein & Dabney, 2013) book.

Variance

$$\sigma = \frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \dots + (x_n - \bar{x})^2}{n - 1}$$

x = measured value, $\bar{x}$ = the average value, and n = number of test samples

Theoretically (Klein & Dabney, 2013) defines the variance as the average of the squared differences from the average, which is why the 50 cycle and 100 cycles variance values are so large because the range from the average is much larger.

The calculations for the 0 cycle, 50 cycle and 100 cycle are shown below, however they have been simplified to show the total deviation squared divided by $n-1$. Where the deviation is distance from the recorded measurement to the average (Klein & Dabney, 2013).

0 Cycle:

$$\sigma = \frac{66.80}{16 - 1} = 4.45$$

50 Cycle:

$$\sigma = \frac{469.51}{19 - 1} = 26.08$$

100 Cycle:

$$\sigma = \frac{401.61}{17 - 1} = 25.10$$

Standard Deviation

The standard deviation (s) is simply the square root of the variance, as such the above equation becomes:

$$s = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \dots + (x_n - \bar{x})^2}{n - 1}}$$

For each cycle, the calculations are as follows:

0 Cycle:

$$s = \sqrt{4.45} = 2.11$$

50 Cycle:

$$s = \sqrt{26.08} = 5.11$$

100 Cycle:

$$s = \sqrt{25.10} = 5.01$$

Appendix C

The results have been broken-up across two tables, with table 11 showing the measured results as given from the thermography camera and table 12 showing the calculated results used for analysis in section 6.2.3

Table 11: Measured Results of the Non-destructive Testing (Lillicrap, 2019)

Test Piece	Start				Finish			
	Min Temp. (°C)	Max Temp. (°C)	Mean Temp. (°C)	Std. Deviation	Min Temp. (°C)	Max Temp. (°C)	Mean Temp. (°C)	Std. Deviation
0-1	26.34	27.46	27.06	0.18	30.04	31.47	30.8	0.31
0-2	26.46	27.62	27.1	0.19	30.53	32.15	31.44	0.29
0-3	26.21	27.43	27.04	0.20	30.89	32.31	31.62	0.31
0-4	26.47	27.6	27.14	0.19	31.07	32.5	31.98	0.26
0-5	26.55	27.55	27.06	0.16	30.97	32.46	31.86	0.27
0-6	26.59	27.64	27.08	0.22	31.52	32.85	32.26	0.26
0-7	26.57	27.43	27.03	0.16	31.31	32.62	31.95	0.26
0-8	25.34	27.64	27.05	0.27	30.59	33.17	32.54	0.33
Averages	26.32	27.55	27.07	0.20	30.87	32.44	31.81	0.29
50-1	26.52	27.56	27.03	0.21	31.08	32.25	31.63	0.25
50-2	26.34	27.58	27.02	0.19	30.84	32.48	31.63	0.32
50-3	26.36	27.66	27.05	0.22	30.87	32.06	31.47	0.23
50-4	26.35	27.52	27.04	0.23	30.82	32.4	31.71	0.27
50-5	26.35	27.68	27.03	0.25	31.29	32.53	31.94	0.24
50-6	26.24	27.42	26.99	0.18	30.35	31.91	31.35	0.3
50-7	26.47	27.69	27.03	0.21	31.4	32.65	32.12	0.27
50-8	26.4	27.61	27.04	0.23	31.36	32.78	32.14	0.26
Averages	26.38	27.59	27.03	0.22	31.00	32.38	31.75	0.27
100-1	26.32	27.47	27.01	0.23	28.59	29.88	29.32	0.30
100-2	25.98	27.66	27.01	0.23	29.54	31.83	30.85	0.40
100-3	25.95	27.5	27.04	0.26	30.03	32.44	31.58	0.48
100-4	26.45	27.93	27.07	0.24	30.58	32.41	31.18	0.34
100-5	26.59	27.49	27.07	0.18	31.61	33.12	32.43	0.37
100-6	26.46	27.72	27.05	0.24	31.16	32.85	32.1	0.38
100-7	26.46	27.6	27.08	0.21	32.06	33.8	32.91	0.36
100-8	26.53	27.63	27.06	0.20	31.1	32.66	31.83	0.27
Averages	26.34	27.63	27.05	0.22	30.58	32.37	31.53	0.36
10 Minute Investigation								
0-8	26.59	27.75	27.03	0.21	32.67	34.09	33.47	0.29
50-8	26.4	27.69	27.02	0.26	32.3	33.81	33.2	0.29
100-8	26.53	27.63	27.06	0.20	32.61	34.4	33.45	0.35

Table 12: Calculated Results from Non-destructive Testing (Lillicrap, 2019)

Test Piece	Temperature Difference from Start to Finish (°C)	Std. Deviation Difference from Start to Finish	Temperature Increase per Minute	Temperature Increase per Second
0-1	3.74	0.13	0.75	0.012
0-2	4.34	0.1	0.87	0.014
0-3	4.58	0.11	0.92	0.015
0-4	4.84	0.07	0.97	0.016
0-5	4.80	0.11	0.96	0.016
0-6	5.18	0.04	1.04	0.017
0-7	4.92	0.10	0.98	0.016
0-8	5.49	0.06	1.10	0.018
Averages	4.74	0.09	0.95	0.016
50-1	4.6	0.04	0.95	0.015
50-2	4.61	0.13	0.92	0.015
50-3	4.42	0.01	0.92	0.015
50-4	4.67	0.04	0.88	0.016
50-5	4.91	-0.01	0.93	0.016
50-6	4.36	0.12	0.98	0.015
50-7	5.09	0.06	0.87	0.017
50-8	5.10	0.03	1.02	0.017
Averages	4.72	0.05	1.02	0.016
100-1	2.31	0.07	0.46	0.008
100-2	3.84	0.17	0.77	0.013
100-3	4.54	0.22	0.91	0.015
100-4	4.11	0.10	0.82	0.014
100-5	5.36	0.19	1.07	0.018
100-6	5.05	0.14	1.01	0.017
100-7	5.83	0.15	1.17	0.019
100-8	4.77	0.07	0.95	0.016
Averages	4.48	0.139	0.90	0.015
10 Minute Investigation				
0-8	6.44	0.08	0.64	0.011
50-8	6.18	0.03	0.62	0.010
100-8	6.39	0.15	0.64	0.011