University of Southern Queensland

Faculty of Engineering and Surveying

Temperature Effects on a Fibre Reinforced Polymer Material

A dissertation submitted by

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towards the degree of

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Abstract

This dissertation details an investigation into the physical effects that temperature has on a specific fibre composite material. The investigation is based on a fibre reinforced polymer material that has been successfully developed and integrated into various applications in the civil and electrical industries. This project has investigated the effects that elevated temperatures up to 105°C have on the strength and elastic properties, the temperature variations observed within structural members in a natural environment and an analysis of changes in strength of a structural design due to temperature variations.

Using practical and accurate methods of experimentation it was found that between the temperatures of 20°C and 105°C, the flexural strength of the material decreases linearly to approximately 28% of its initial strength, thus tensile strength, compressive strength and bending moment capacity are expected to also decrease linearly at a proportional rate. Results for flexural modulus confirmed an expected behaviour and displayed a relatively small drop in modulus over the temperature range.

In collaboration with these results, temperature data recorded over an approximate 4 day period and a brief analysis of a small foot bridge constructed from the composite material confirmed that at high operating temperatures it is not likely that the stresses created at maximum loading will exceed the strength capacity of a composite structure, however modifications may be required to compensate for losses in modulus at elevated temperatures, depending on the structure requirements and specifications.

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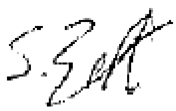

Signature

29 October 2009

Date

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1. Introduction

The core of this project loosely relates to the 'effects that temperature has on both the physical states and mechanical properties of fibre composite materials'. The term 'loosely' is used in this description as there are countless materials in production and research that can be considered 'fibre composites', and for each of those materials there are numerous applications that utilise the material in different ways. This means that the above statement does not accurately describe specific conditions of temperature, material state and mechanical properties.

In specific terms, this project will investigate the key mechanical properties and physical behaviour of a single specific composite material as it is subjected to varying temperature conditions that could be expected in normal service applications. Given that the conditions during testing aim to accurately represent the conditions that are encountered in practical applications, the experimental results will be used to determine if and how the material applications are altered depending on the operating conditions.

1.1 Research Significance and Objectives

As composite materials and in particular polymer matrix composites are quickly becoming a viable alternative in civil applications where accurate structural design is quite complex, deep understanding of the behaviour of such materials is necessary. Furthermore, 'civil design' covers an extremely broad range of applications, thus service conditions for composite materials being used in civil applications are also extremely broad.

In any one civil application, both environmental conditions and design conditions need to be assessed and depending on those conditions, suitable materials for the design can be selected. Environmental conditions include exposure to wind, moisture and humidity, heat, unnatural light, UV light, corrosion etc. In consideration of these along with design conditions such as static loading, dynamic loading, and various fittings and fixings, the overall design specifications of a structure or member can become quite complex, and slight changes in any of these considerations may introduce a need for design modifications.

One particular environmental condition that composite structures are exposed to that tends to vary quite significantly is operating temperature. A significant cause for variation in operating temperatures of composite structures is its general exposure to temperatures generated in service. Examples of such exposure include exposure to sunlight, applications in heated areas such as machinery workshops, use in temperature conditioning vent systems etc. The other governing cause of temperature variation is the global location of the structure itself. It is generally known that between polar and tropical regions the temperature generally varies between extreme temperatures of -30^{o}C and 45^{o}C, as depicted in Figure 1.1.

(a) (b)

Figure 1.1: Examples of small scale civil infrastructure that commonly utilize composite materials. (a) In sub-zero/freezing conditions (b) In tropical conditions (Into the Mist.Org n.d).

An established company that produces a composite material has designed and manufactured numerous composite bridge decks for use on public roads in both polar and tropical regions of the world (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008). Though the designs are currently in service in these areas, the design specifications of these structures were calculated using material data obtained in ‘normal’ operating conditions i.e. ‘room temperature’, which is generally considered to be 23^{o}C (Standards

Association of Australia 1978). The origin of this project formed from the uncertainty that materials will behave the same and retain the properties that were observed at room temperature when they are applied and exposed to operating temperatures different to that at room temperature. It was decided that any such uncertainty should be investigated and any accurate findings may be used to modify or optimise the design of various structures depending on their application and exposure to varying conditions.

As the result of these considerations it was determined that for such an investigation, the objectives are to primarily determine the physical and mechanical properties of a particular composite material that is used in civil structures in various temperature conditions; and secondarily use the findings to determine any effects that the varying temperature conditions may have on composite structures in service.

1.2 Dissertation Outline

As with any research based project, there is a substantial amount of information that needs to be considered. Of these, the most important information to be displayed is the objectives, results and conclusion, however, relative background information, various calculations and methods also need to be included for a full understanding. With such inclusions, appropriate sections of the dissertation and relevant information must be emphasised so that an accurate representation of the work involved in the project is conveyed with clarity. For this reason, the information within this dissertation has been separated into appropriate chapters, each listed below with a brief overview.

- Chapter 1 – Introduction
- Chapter 2 – Literature Review

This chapter includes information that both directly and indirectly relates to the work conducted in this project. Within this chapter is necessary information that is needed to calculate, predict and estimate results, as well as the provision of information that aids in interpreting and explaining the results gathered.

- Chapter 3 – Experimental Methodology

Within this chapter both the theoretical and practical methods used for testing, data gathering and result processing are outlined. These methods include practices and processes of all steps undertaken throughout the duration of the project to ensure that the results obtained whilst using such methods are accurate in gathering correct and valid values and observations.

- Chapter 4 – Test Results and Observations

This chapter displays the results obtained through experimentation in various formats which make the interpretation, discussion and conclusions of the project much simpler.

- Chapter 5 – Results Analysis and Discussion

In this chapter the results and observations displayed in Chapter 4 are processed and analysed, which allows for discussion and interpretation of the results and forms the basis of the final conclusions.

- Chapter 6 – Conclusions

As the final section of the dissertation, clear and concise conclusions to the project objectives are given. These conclusions are primarily based on the information given in Chapter 5 and conclude all of the work and research completed over the duration of the project.

1.3 Summary

The information presented in this dissertation allows a full and clear understanding into the project topic. Through a combination of the study of background information, practical experimentation, observation and data analysis, the objectives of this project will be achieved.

2. Literature Review

2.1 Introduction

This chapter outlines directly and indirectly relevant information relating to the physical behaviour of polymer materials under various temperature conditions, previous research on the topic and structural design details.

All of the information displayed in this chapter is considered valid and accurate, which will be used to predict and explain the results obtained, form the basis of results discussion and help aid in reaching accurate and valid conclusions.

2.2 Fibre Reinforced Polymers

2.2.1 Introduction to Fibre Composites

For many applications in all areas of engineering, material selection is one of the most important factors in the design process, manufacture, installation, servicing and functioning of a product. In consideration of the specific application, basic materials such as woods, metals, plastics, ceramics etc may not hold the optimum physical properties for that application. This lack of material properties not only means that development of innovative projects becomes difficult, it leads to investigations and research into developing materials that combine the desired properties of two or more base material. This research and development forms the basis of what we know as composite materials.

In brief, fibre composites can be defined as a wide group of materials that contain two or more elements that combine the desired properties of each base element into a new material (Morgan 2005).

$$Material\ A + Material\ B = Composite\ Material\ C$$

These fibre composite materials characteristically consist of a matrix polymer or resin which is combined with a reinforcement material in fibre form to enhance the mechanical properties of the matrix (Electrick Publications

2006). For this reason most composites are generally referred to as Fibre Reinforced Polymers (FRP). Though the concept of fibre composite materials is relatively simple, there are endless combinations of fill-in matrices and fibre reinforcement materials. Not only are there countless combinations of materials, there are numerous configurations in which the reinforcement materials can be arranged including continuous, wound, chopped strand and woven configurations which can be combined with each other and also utilized in a number of axis (Electrick Publications 2006).

Though most composite materials used today utilise relatively modern research and development techniques and have only recently been applied in commercial production, the concept of composites has been around for thousands of years. The earliest example of composite materials being used can be dated back to ancient Egypt, where straw was used within mud and clay bricks for strengthening (Electrick Publications 2006). The biblical book of Exodus makes reference to Israelites being oppressed by the Pharaoh by being forced to mass produce bricks without the use of straw fibres.

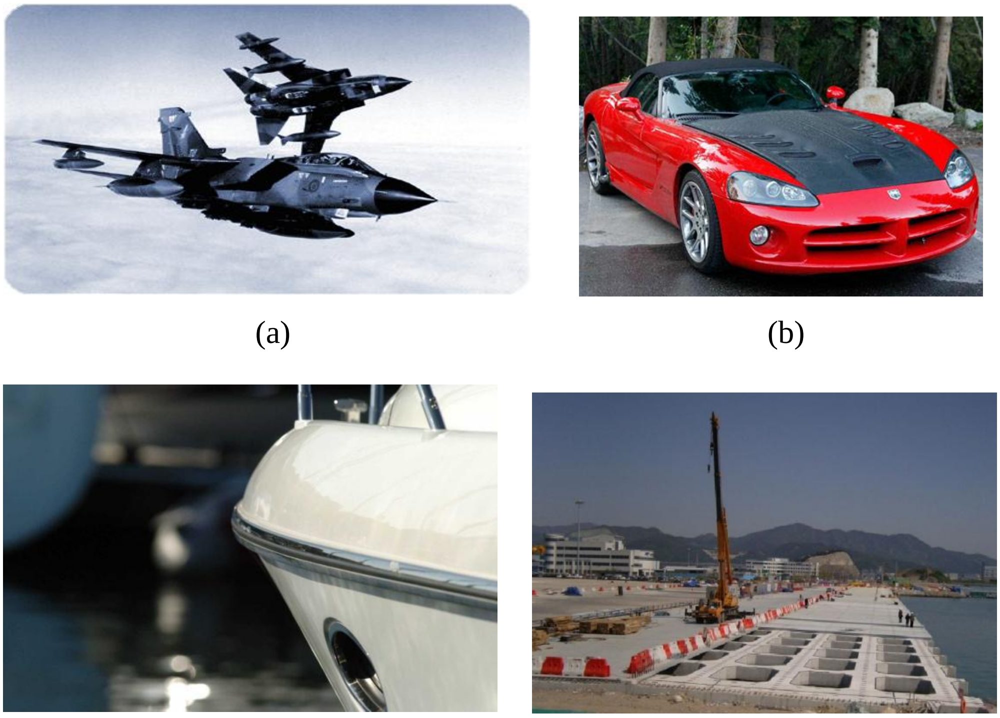
Figure 2.1: Depiction of the earliest use of composite materials by ancient civilizations (Electrick Publications 2006).

Figure 2.2: Application of very basic composite materials in domestic construction (Earth Architecture 2009).

As seen in Figure 2.2, composite materials are utilised in the most domestic applications. The success of fibre composite materials becoming an integral part of modern development comes down to the limitless versatility that composite materials offer. Having the significant amount of material combinations and configurations that it does, and utilizing numerous effective and efficient manufacturing methods makes it viable to produce composite materials for so many applications in modern industry.

As stated, composite materials are generally designed and created to fulfil a requirement that is unable to be met by conventional materials such as wood, plastic, metal and ceramics. Civil applications usually utilize metal and/or wood members, however neither hold optimum properties. Timber and metal, although cheap, are subject to corrosion, degradation and decay over time, thus it is necessary to develop a composite material that attains similar strength properties yet is corrosion resistant and readily available. For similar reasons, composite materials are useful in high moisture and marine environments due to high corrosion resistance.

An application in which the development of composite materials has allowed for technological advancement is in the aerospace industry, where lightweight, high strength and temperature resistant materials are essential. The lightweight and advanced mechanical property advantages also make composite materials a suitable material for automotive design. The primary commercial industries utilising composite materials can be seen in Figure 2.3.



(a) (b)

(c) (d)

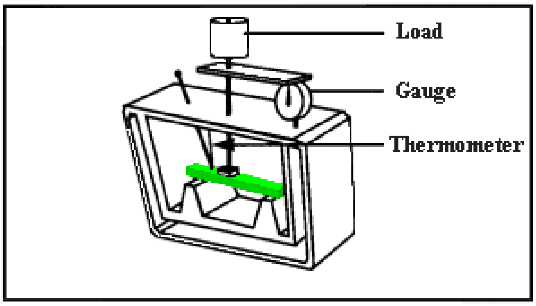
Figure 2.3: Applications in modern industries (a) Aerospace (SES n.d) (b) Automotive (4Car 2008) (c) Marine (Sea-cubed Composites 2009) (d) Structural (Cobrae 2004).

2.2.2 Glass Transition Temperature (T_g) and Heat Deflection Temperature (HDT)

When considering the effect of temperature on the physical properties of polymer materials, two values are generally referred to; Glass Transition

Temperature (T_g) and Heat Deflection Temperature (HDT). When used in context the 2 terms are often confused with each other as it is generally believed that both terms refer to a specific temperature at which the mechanical and physical properties of a material begin to change. This common misconception can be eliminated by fully understanding the definitions of each term.

The ‘heat deflection temperature’, also known as ‘heat distortion temperature’ or ‘deflection temperature under load’ (DTUL), is a measure of the resistance to deflection or distortion of a plastic polymer material under a specific load at elevated temperatures (Wikipedia 2009a). The determination of this value involves testing that is governed by the standard ASTM D648, which specifies that a material specimen shall be loaded in 3-point bending so that the outer fibre stress is equal to 0.455MPa or 1.82MPa, depending on the material (MatWeb 2009). Under this specific load, the HDT is defined as the temperature at which the additional strain reaches 0.2%, generally 25mm considering the standard dimensions of the specimen. This amount of deflection is an arbitrary value, thus it does not have any physical meaning or define changes in material properties.



(a) (b)

Figure 2.4: Equipment used in determining heat deflection temperatures of plastics materials. (a) A basic setup diagram (MatWeb 2009), (b) A HDT testing machine (Ray-Ran Polytest n.d).

Unlike the HDT, the glass transition temperature does have a physical meaning and can be defined as the temperature at which a material changes from a glassy state to a leathery state through molecular structure transformations (Wikipedia 2009b). This transformation does not occur instantaneously rather it is a gradual change with a rising temperature; therefore the value is an average point within the transformation period.

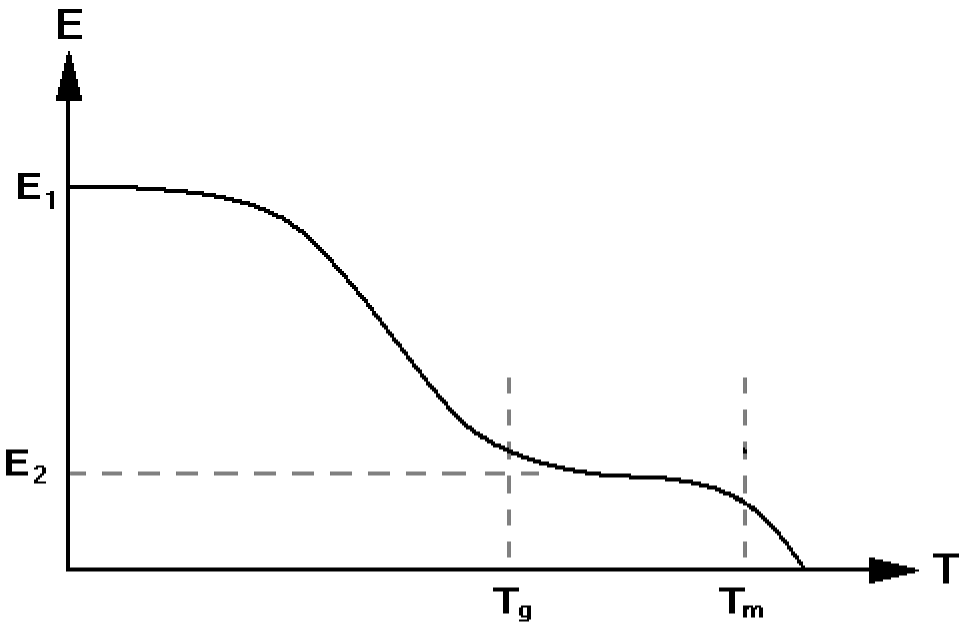


Figure 2.5: Graphical method in which the T_g value is found and general behaviour of modulus with increasing temperatures.

Figure 2.5 shows the expected behaviour of the elastic modulus of a thermosetting polymer as the temperature increases, and shows how the T_g represents the relevant physical changes.

2.2.3 General Behaviour of Thermosetting Polymers

As previously mentioned, composite materials consist of a fill-in material which is reinforced with fibres in order to attain selected properties from multiple materials and optimise its characteristics for particular applications. It is for this reason that investigation into the general behaviour of the individual polymer matrix and the fibre reinforcement are necessary to gain an understanding of the behaviour of that particular material when it is applied in a composite material. In the composite industry there are extensive choices in polymer materials depending on the application; however in structural applications there are generally only 3 types of resins used; epoxy resins, polyester resins and vinyl ester resins. All of these are ‘thermosetting polymers’ (Electrick Publications 2006).

From previous studies on modelling the stiffness of FRP composites under elevated temperatures (Bai 2008) it is clear that the mechanical properties of these materials vary with changes in temperature, as expected. These variations in properties are not so much related to the reinforcement fibres, but are dependent on the microstructure of the resin which changes with varying temperatures. The differences in microstructure between thermoset polymers and thermoplastic polymers can be seen in Figure 2.6, where thermosets consist of cross-linking between polymer chains which define its characteristics.

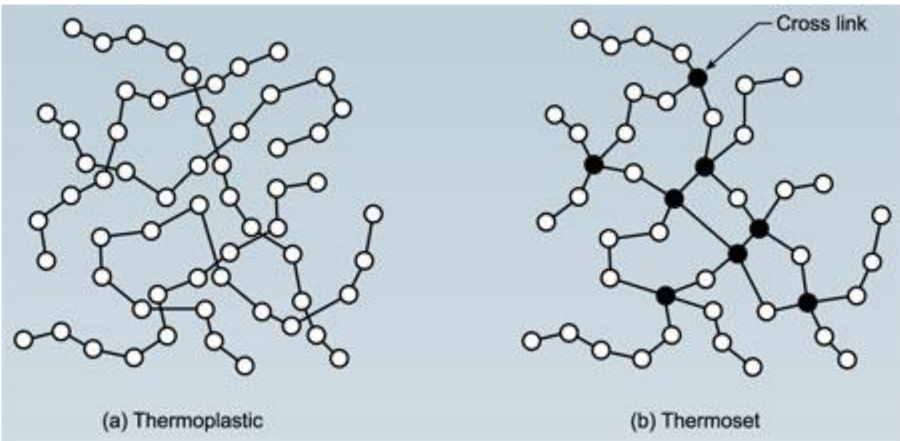


Figure 2.6: Basic microstructure of thermoplastic and thermoset polymers (Paroli 1999).

The microstructure bonds within thermosetting polymers can be divided into 2 types; primary bonds and secondary bonds. The primary bonds consist of strong covalent intra-molecular bonds within the polymer chains along with cross-link bonds between these chains. Unlike the primary bonds, secondary bonds are relatively weak and include hydrogen bonds, dipole interaction and van der Waals interaction. All thermosetting polymers experience similar property changes due to the breakdown of these bonds as the temperature increases.

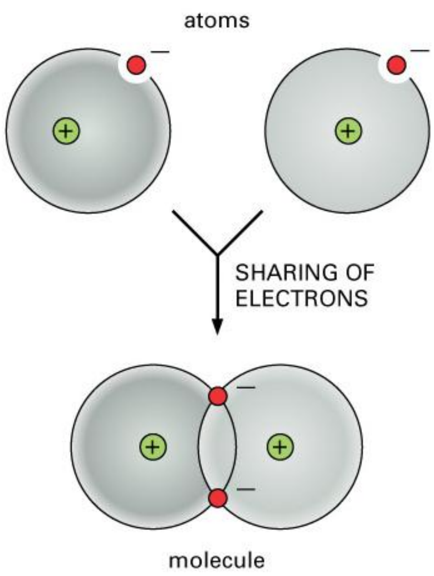


Figure 2.7: The forming of covalent bonds via electron sharing, as seen in polymer microstructures (Connexions 2007).

At lower temperatures, both primary and secondary bonds are intact thus giving the material its highest possible strength properties. This is referred to as the 'glassy' state (Bai 2008). As the temperature increases, enough energy is introduced to the material to break the secondary bonds but leave the primary bonds intact which in turn reduces the strength properties and consequentially leaves the polymer in the 'leathery' state. During this change known as the 'glass transition' the viscosity of the material increases while the elastic modulus, E, decreases. With further increases in temperature the primary bonds remain intact; however the polymer chains form entanglement points when they become knotted together. In this state known as the 'rubbery' state, the E-modulus remains similar to that in the leathery state due to the primary bonds being intact. However the difference in structure allows the viscosity to decrease. As expected, greater increase in temperature causes the primary bonds to break, leaving the material in a 'decomposed' state (Bai 2008).

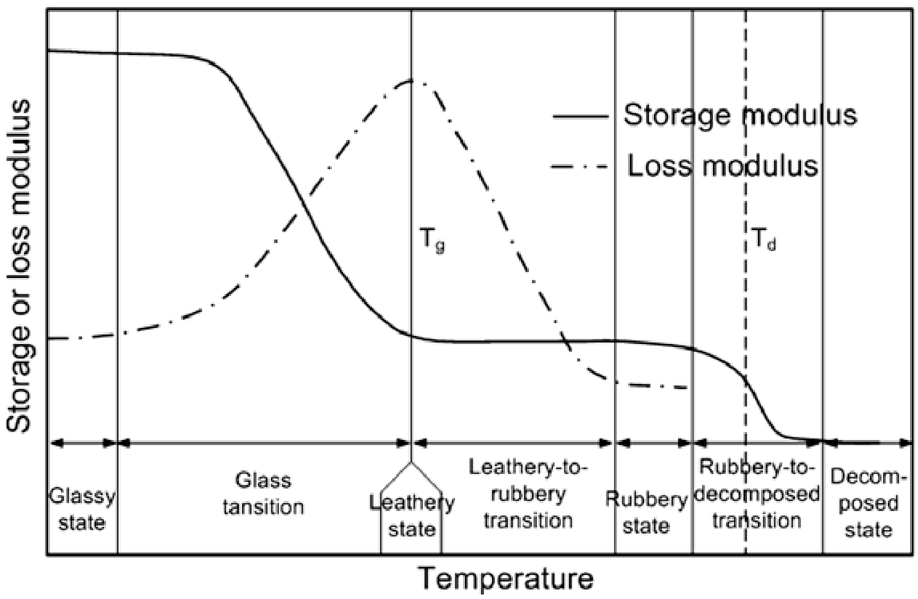


Figure 2.8: The general behaviours of the storage modulus and loss modulus of thermosetting polymers as temperature increases, and the physical states and transition phases which occur during the increase (Bai 2008).

In order to measure the storage modulus and loss modulus, a test procedure known as Dynamic Mechanical Thermal Analysis (DMTA) must be conducted. This involves mechanical testing of plastics specimens under sinusoidal fluctuating loads while measuring the load applied and deflection of the specimen at that load as in normal mechanical testing. However, using dynamic loads rather than static loads allows a 'damping' property, δ, to be determined. This value can be described as a time lag between when the force is applied and when deflection occurs, which is calculated as an angle that represents a 'phase lag' between stress and strain (Guide to Rheological Nomenclature n.d). This lag behaviour is shown in Figure 2.9. The value 'tan δ' is generally shown as the characteristic property.

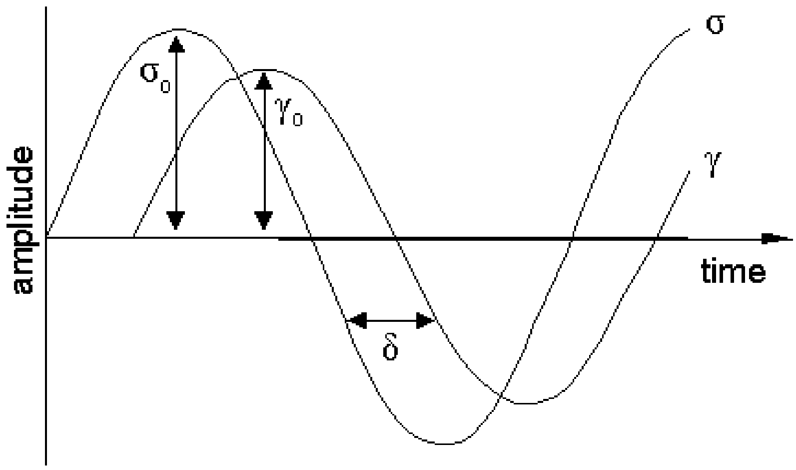


Figure 2.9: A graphical representation of delta (δ) with respect to stress (σ) and strain (ε) (Guide to Rheological Nomenclature n.d).

The Storage Modulus, E', can be described as a measurement of energy stored during deformation;

$$E'' = \left(\frac{\delta_o}{\varepsilon_o}\right)\cos\delta \qquad (2.1)$$

Loss Modulus, E'', similarly represents the amount of energy lost during deformation, usually in the form of heat;

$$E'' = \left(\frac{\delta_o}{\varepsilon_o}\right)\sin\delta \qquad (2.2)$$

From these values the Modulus of Elasticity can be calculated;

$$E = \sqrt{E'^2 + E''^2} \qquad (2.3)$$

One particular set of experimental data shown below in Figure 2.10 shows the typical results for a dynamic mechanical analysis on a silicone based sample. It can be seen that this plot confirms the form of the diagram shown in Figure 2.8 and thus further results on thermosetting polymers can be expected to show similar behaviour.

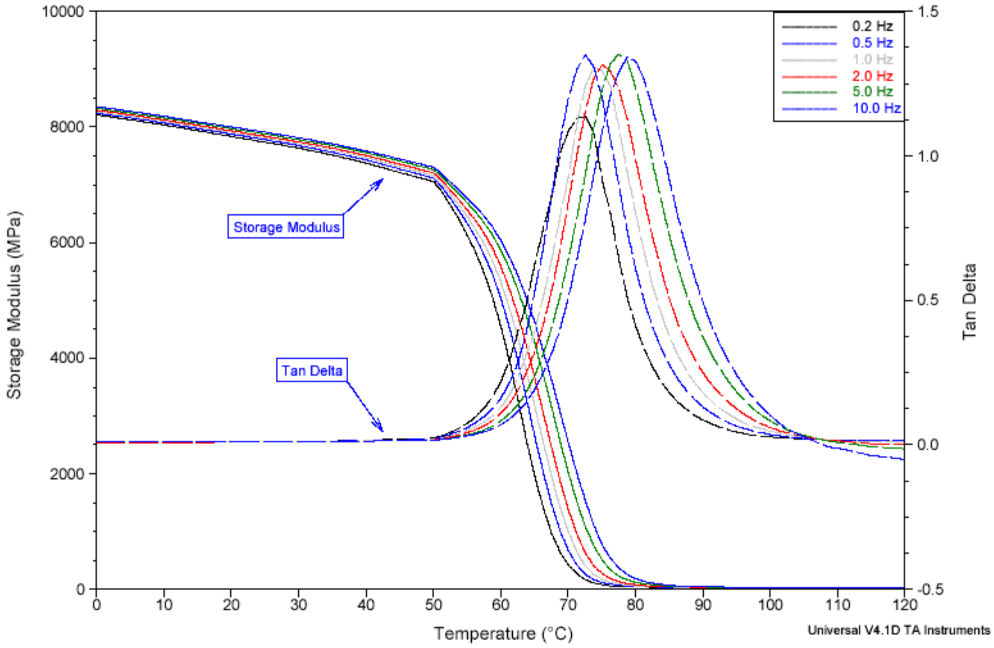


Figure 2.10: Experimental results for loss modulus and storage modulus of a silicone based composite material (The University of Texas at Austin 2008).

Generally with thermosetting materials, the loss modulus is very small relative to the storage modulus, thus the modulus of elasticity tends to follow the same trend as the storage modulus with respect to temperature.

2.2.4 General Behaviour of E-Glass and ECR-Glass

E-Glass is a traditional type of glass fibre that was originally developed for 'electrical' insulation products, but is now widely used in FRP production (FSE Inc. n.d) after it was found to have suitable mechanical properties and very good fibre forming capabilities. Varieties of E-Glass are used nearly exclusively in glass FRP materials.

(a) (b)

Figure 2.11: (a) Various sizes and forms of E-glass as manufactured (), (b) E-glass used in a pultrusion machine during material manufacture (Bedford Reinforced Plastics Inc. 2009).

The production of E-Glass melt spinning and extrusion processes to eventually form spindles of continuous glass fibre. Although the addition of boron and fluorine to the manufacture process simplifies the production, particles released during the melting of the material making the production of E-Glass harmful to the environment (The A to Z of Materials 2009). The development of ECR-Glass (corrosion resistant E-Glass) eliminated the addition of harmful elements while maintaining effective production and use of glass fibres. It was found that the removal of boron and fluorine from the formulation not only reduced the environmental impact, but the chemical corrosion resistance, temperature resistance, electrical properties and mechanical strength were all improved.

Because of its high temperature resistance ECR-Glass is suitable for use in temperatures up to 600°C (Lance Brown Import-Export 2009), however mechanical properties tend to begin decreasing after around 400°C. The strength of ECR-Glass can reach up to approximately 3500 MPa. ECR-Glass generally has a softening point around 880°C.

2.3 Previous Research

2.3.1 Study of Pultruded Glass Fibre Reinforced Plastics Channel Columns at Elevated Temperature

A study conducted by Wang et. al. (2007) aimed to determine the suitability of glass fibre reinforced plastic (GFRP) channels as construction members in low rise house construction and its performance with exposure to fire. Considering all elements of housing construction including protection of construction members against fire, the study utilised controlled experiments to determine compressive strengths of short pultruded GFRP channels and hence determined the Young's modulus at elevated temperatures. Long member compressive testing was also conducted to determine Euler buckling loads and thus confirm modulus values determined in other experiments.

The results of this study concluded that at temperatures that accurately represent those encountered by construction members during a fire, the GRP columns retain a substantial proportion of their strength properties at ambient temperature, confirming that they are suitable for use in low rise housing. It was also observed that at temperatures higher than the resin heat deflection temperature (HDT), GRP sections encounter major reductions in compressive strength, with approximately only 16% of the ambient temperature strength retained at 120°C. Results show that the compressive stresses of the GFRP channels at 60°C and 90°C were respectively 63% and 31% of that at ambient temperature, and the Young's modulus values at 60°C, 90°C and 120 °C were respectively 90%, 78% and 120%.

2.1 ECR-Glass/Vinyl Ester Composite

For the purposes of this research project it is important to note the basic composition and properties of the material undergoing testing.

The composite material is commercially available and produced by an established company for use in electrical cross-arms, small scale footbridges, boardwalks and road bridges, as displayed in Figure 2.12.

(a)

(b)

(c)

Figure 2.12: Applications of an ECR-Glass/Vinyl Ester composite (a) Bridge deck (b) Electrical Cross-arm (c) Footbridge (Wagners 2007).

The material itself is produced as a square hollow section (SHS) pultrusion consisting of a vinyl ester matrix and continuous ECR-glass fibres wound at optimum orientations.

The specifications provided by the vinyl ester manufacturer and supplier state that the T_g is 125°C and the HDT is 115°C, when cured for 24 hours at room temperature and 2 hours at 150°C (Derakane 2004).

Testing on a 100 mm x 100 mm section of composite material conducted found the following strength properties (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008):

Table 2.1: Strength properties of ECR-glass/vinyl ester composite (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008).

Property	**ASTM Test**	**Orientation**	**Characteristic Value**	**Units**
Ultimate Tensile Stress	D3039	Longitudinal	650	MPa
Ultimate Tensile Stress	D3039	Transverse	41	MPa
Ultimate Compressive Stress	D3410	Longitudinal	550	MPa
Ultimate Compressive Stress	D3410	Transverse	104	MPa
Ultimate Shear Stress	D2455	Longitudinal	84	MPa

Additional properties of the material can be viewed in the proceeding section.

2.2 Composite Material Boardwalk Design

2.2.1 General Design Structure

For an investigation into the effects that temperature has on civil structures constructed from FRP pultrusions, it is necessary to gain an understanding in the basic structure of such designs. It is for this reason that an overview of the design and construction of composite a structure is given.

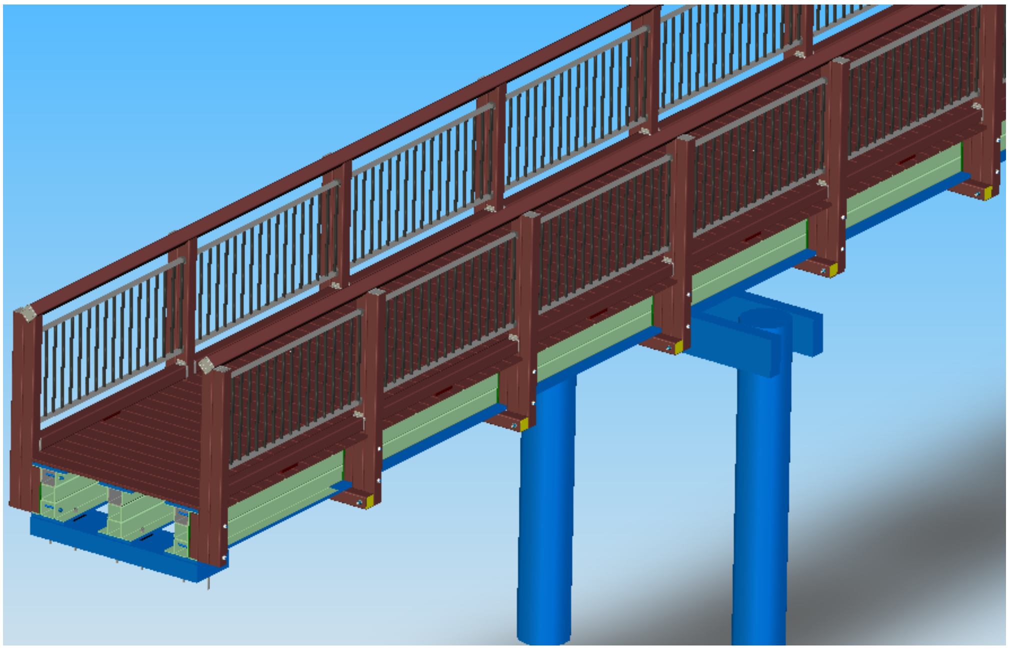


Figure 2.13: 3-D model of a typical composite footbridge (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008).

Figure 2.13 shows an example of a 3-D composite footbridge model, where the primary function of various components of a small structure can be seen and the importance of the mechanical properties of the structure materials and any variations of such properties with temperature will be better understood.

It can be also seen that much of the support strength of the structure comes from the three composite girders supporting the length of the deck. These girders primarily consist of webs formed by FRP square hollow section (SHS) pultrusion lengths bonded with an epoxy resin and top and bottom flat FRP flanges. The construction and design of these girders maximise overall flexural strength, with the flanges designed to hold tensile and compressive stresses while the web is designed primarily for shear stress created during flexural loading. The base components of these girders can be seen separately in Figure 2.14.

Figure 2.14: 375 mm x125 mm web, 125 mm x125 mm pultrusion and 300 mm x 6 mm pultrusion (Wagners CFT 2008).

Though the overall design of the structure takes into consideration loading on all components including handrails and decking, it is only necessary to analyse the loads and capacities of the girders as they not limited to use in this application only, and are the primary support in most similar civil structures.

The property capacities and geometry of various pultrusion members and beams are shown below.

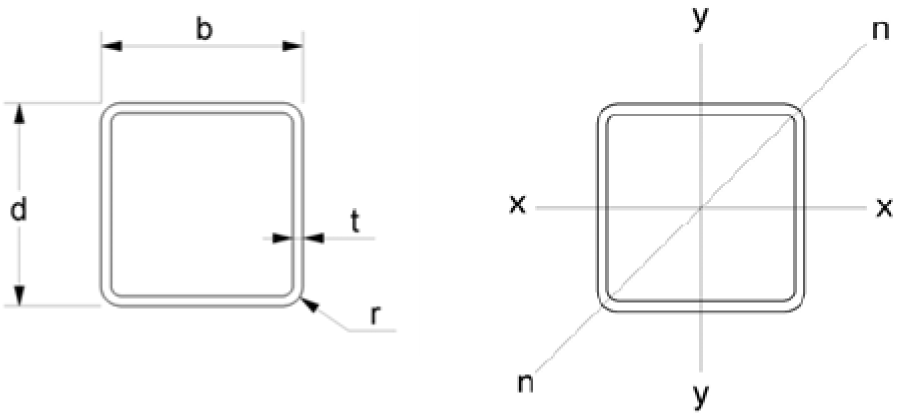


Figure 2.15: SHS Pultrusion geometry.

Table 2.2: Section properties for various composite material structural members (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008).

Joist	Joist Designation			Radii		Gross	About x-, y- and n- axis			
	Width	Depth	Thickness	Internal	External	Section	Moment of Inertia about the x axis	Moment of Inertia about the y axis	Polar Moment of Inertia about the n axis	Torsion
Designation	b'	d	t	R_i	R_e	Area A_g	I_x	I_y	Z_n	Constant J
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm^2)	10^6 mm^4	10^6 mm^4	10^6 mm^4	10^6 mm^4
100x100x5 SHS	100.40	100.40	5.25	4.75	10	1931.68	2.86	2.864	5.73	4.65
100x200x5 SHS	100.40	200.80	5.25	4.75	10	3863.35	15.46	5.727	21.19	12.75
125x125x6.5 SHS	125.00	125.00	6.50	4.75	10	3014.53	6.98	6.979	13.96	11.07
I Beam	300.00	423.00	6.50	4.75	10	23443.58	688.96	128.936	817.89	-

Table 2.3: Strength properties for various composite material structural members (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008).

Joist Designation	Gross Section Area A_g (mm^2)	Density (kg/m^3)	Mass per metre (kg/m)	Modulus of Elasticity (N/mm^2)	Moment Capacity* (kN.m)	Compressive Strength, s_d (MPa)	Shear Strength, s_d (MPa)/N
100x100x5 SHS	1931.68	1970.00	3.81	35400.00	13.63	550.00	84.00
100x200x5 SHS	3863.35	1970.00	7.61	35400.00	36.81	550.00	84.00
125x125x6.5 SHS	3014.53	1970.00	5.94	35400.00	26.69	550.00	84.00
I Beam	23443.58	1970.00	46.18	39796.50	778.54	-	435.00

It must be noted that the properties listed are those of a particular composite material manufactured for the use in civil structure design.

2.2.2 Design Considerations

Composite structures, like any other structures using conventional material are designed to particular standards relating to infrastructure design and loads, however, there are no specific standards for composite structure design alone. Though these standards must still be followed, composite materials generally display a much higher flexibility, or modulus, in comparison to steel and concrete (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008). Hence conventional material structure designs are generally limited by strength properties while composite structures are designed to meet a maximum deflection standard, and generally utilise only small amounts of their strength capacities.

For this purpose, civil structures generally follow a different design code, and for the specific composite material investigated in this project the design structures are based on the Eurocomp Design Guide and Handbook.

Design of composite structures consider many various types of loading including self weight loads, imposed loads, wind loads, dynamic loads and also consider strength reduction factors for short and long terms loading. These various factors can be seen within the Eurocomp Design Guide and Handbook.

For a particular structure, the span-deflection ratio under maximum load cannot exceed 250.

$$\frac{span}{deflection} \geq 250 \tag{2.4}$$

With the maximum live load is considered to be 5.0 kPa, the deflection-span ratio and bending moments are presented below.

Table 2.4: Properties of I Beams in a specific application (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008).

Member Properties				
Item	Description	E (MPa)	I (mm4)	Span (mm)
Outside Girders	I Beam	39796	6.89E+08	13140
Inside Girders	I Beam	39796	6.89E+08	13140

Table 2.5: Calculation of deflection-span ratio and bending moment under live load (Wagners Composite Fibre Technologies Manufacturing Pty Ltd 2008).

Deflection Calculations		
Type of Support	Simply Supported	
Outside Girder Deflection		
Width supported by one girder	300.00	mm
Load on that width per metre	1.50	kN/m
Bending Moment	32.37	kNm
Deflection	21.24	mm
Member span / deflection ratio	619	
Inside Girder Deflection		
Width supported by one girder	600	mm
Load on that width per metre	3	kN/m
Bending Moment	64.75	kNm
Deflection	42	mm
Member span / deflection ratio	309	
BM Capacity of Member	779	kNm
% Utilisation	8	%

The above calculations confirm that at maximum loading, the inner girder has a deflection-span ratio of 309 which is in compliance with the standard, and the deflection of 42 mm is approximately 80% of the allowable deflection. It is also seen that the maximum bending moment created is only 8% of the bending moment capacity of girders. Should the structure be loaded so that the maximum deflection is at the allowable limit, still only approximately 10% of the bending moment capacity will be used.

Though this is only one example of design calculations of a composite structure, it gives an indication of the amounts of the material capacities that are used at full load and confirms the previous statement that composite structures are limited by elastic properties and use only small amount of their strength capacity.

2.3 Summary

The information presented in this chapter is deemed relevant and important in understanding the research topic, the basis of the research and any information that will be additional to the project topic. Much of the information presented will be later used in discussion to compare with experimental results, thus verifying or dismissing any conclusions that are found.

3. Experimental Methodology

3.1 Introduction

In a research based project such as this it is important that the preparation, testing and data calculation that is undertaken is correct and that the results of these procedures accurately represent the required information. This chapter firmly outlines the methods and principles required to achieve such results.

3.2 Test Specimens and Setup

3.2.1 Standards for Testing

For the specific testing of flexural properties of plastics at elevated temperatures, there are no standards for testing procedures. In this case it was considered appropriate and necessary that the testing specifications used were to comply with a general standard for testing in which the specimen environment conditioning was to be modified to suit the requirements.

The requirements for the preparation, testing and data calculation involved in the material testing were specified by the international standard ISO 14125:1998 (E) Fibre-reinforced plastic composites – Determination of flexural properties (Internation Organization for Standardization 1998). This is based upon the international standard ISO 178 Plastics – Determination of flexural properties and modified for application to fibre-reinforced plastic composite materials.

The principle of this standard states that the test specimen, supported as a beam, is deflected at a constant rate until the specimen fractures or until the deformation reaches a pre-determined value. During this procedure, the force applied to the specimen and the deflection are measured.

3.2.2 Test Specimen Dimensions and Loading Rate

The above standard states that for flexural testing of plastics the dimensions of the test specimen shall be as follows:

Length *(l)*: 80 mm minimum

Width *(b)*: 10 ± 0.5 mm

Thickness *(h)*: 4 ± 0.2 mm

As the specimens shall be cut from the wall of a pultrusion member and the thickness criteria cannot be met, it is specified that the specimen dimensions are as follows:

Thickness h (mm)	**Width b (mm)**
$1 < h \leq 10$	15
$10 < h \leq 20$	35
$20 < h \leq 35$	50
$35 < h \leq 10$	80

Table 3.1: Suggested dimensions for flexural test specimens of reinforced plastics (International Organization for Standardization 1998).

It is also stated within the standard that the support span, L, shall be between 15 and 17 times the thickness of the specimen.

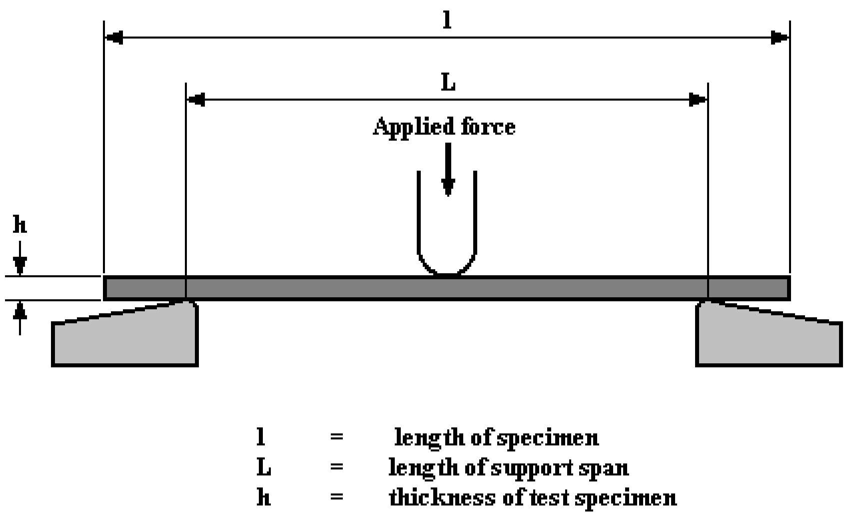


Figure 3.1: Dimension of specimen and position during testing.

Considering the nominal wall thickness of the pultrusion member to be approximately 5 mm, the following dimensions apply to the specimen and test position:

Length *(l)*:	100 mm
Width *(b)*:	15 mm
Thickness *(h)*:	5 mm
Support span *(L)*:	85 mm

The relative rate of movement of the loading nose and supports can be calculated by:

$$V = \frac{S_r L^2}{6h} \tag{3.1}$$

where: V = relative rate of movement of the loading nose and supports (mm/min)

S_r = strain rate of the outer fibre (mm/mm.min)

= 0.1 for semi-rigid materials

L = span length (mm)

h = thickness of test specimen (mm)

The actual machine loading rate should be set to the nearest speed so that it is within ±25% of the calculated value. In this case that value is 3 mm/min.

3.2.3 Testing Equipment and Apparatus

For the testing of flexural properties of material specimens, precision equipment specifically designed for the purpose of materials testing was required. The two primary components of a typical testing system are a material testing system (MTS) machine and a computing system, generally a PC, installed with compatible control software.

Figure 3.2: Typical PC and MTS used for material testing.

As represented by the arrows in the above figure, the position and loading rate of the MTS is controlled by manual inputs on the PC, and the position and load data recorded by the MTS is transferred back to the PC for display and processing.

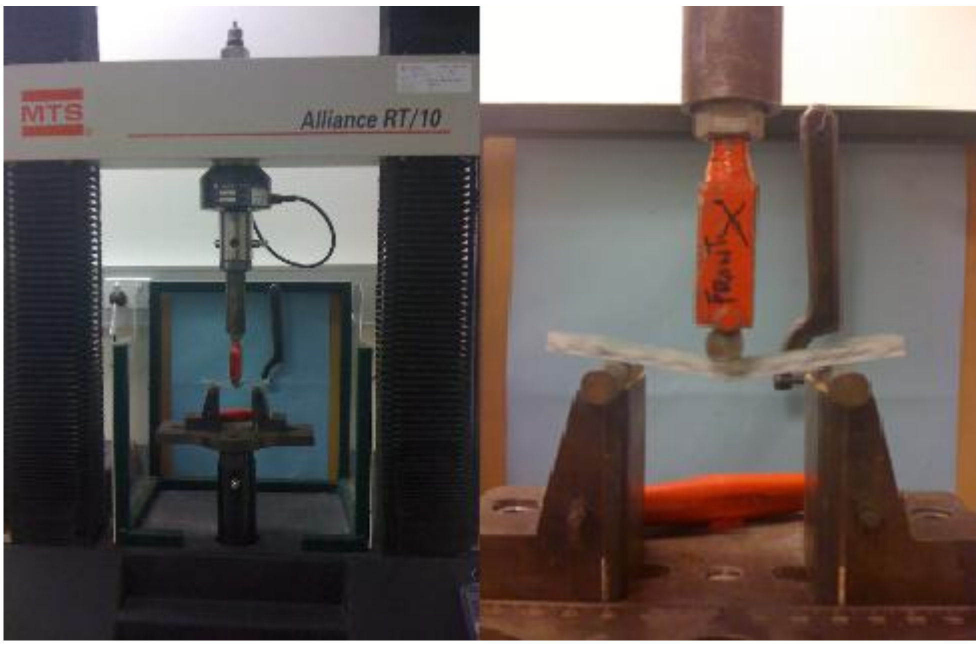


Figure 3.3: Flexural testing in MTS and close view of specimen.

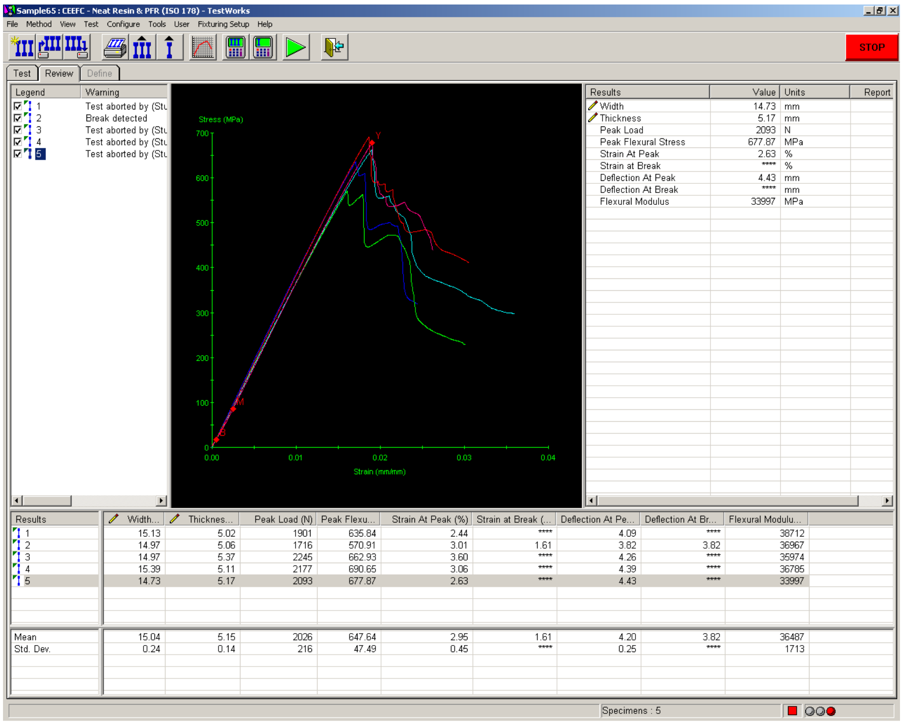


Figure 3.4: The TestWorks 4 review screen which shows a plot of stress vs. strain along with calculated values in tabular form after specimen testing is complete.

As seen in Figure 3.3, the program used for flexural testing uses load and deflection data recorded by the MTS to calculate various mechanical properties such as stress, strain and modulus for each specimen and average values for the whole sample. This data can be exported to an electronic file along with each load and deflection point recorded.

For the specimens to be tested for flexural properties at elevated temperatures, the above equipment must be fitted with an environmental chamber specifically designed to be installed with a standard MTS.

Figure 3.5: Environmental chamber fitted to a MTS

(source http://www.instron.com.au/wa/).

This environmental chamber shown in Figure 3.5 is controlled manually and separately to the MTS and PC via a small control panel located on the side of the chamber. During testing, the chamber will be set to a specific temperature to heat the specimens to an approximate steady state and will remain at that temperature during testing.

3.2.4 Sample Conditioning

As previously stated in Section 3.2.1, the required conditioning of the specimens for testing at elevated temperatures could not be defined by a standard, thus a suitable pre-conditioning procedure was determined. This procedure was required to produce accurate results and to not contradict any specifications previously stated in the general standard.

Based on the recommendations of the material manufacturers and in accordance to the project specification, it was determined that samples should be tested under temperature conditions ranging from a standard room temperature to a temperature considerably higher than what could be predicted in extreme natural conditions. This resulted in a total of 7 samples being tested at temperatures between 20°C and 110°C with 15°C increments.

The capabilities of the environmental chamber allow a stable environmental temperature to be achieved, however for any material exposed to that environment for any amount of time is difficult to predict due to variations between the environment and material temperature. This difference is a function of initial temperatures, time, geometry and material thermal properties. Figure 3.6 shows the typical behaviour of material temperature as air temperature increases.

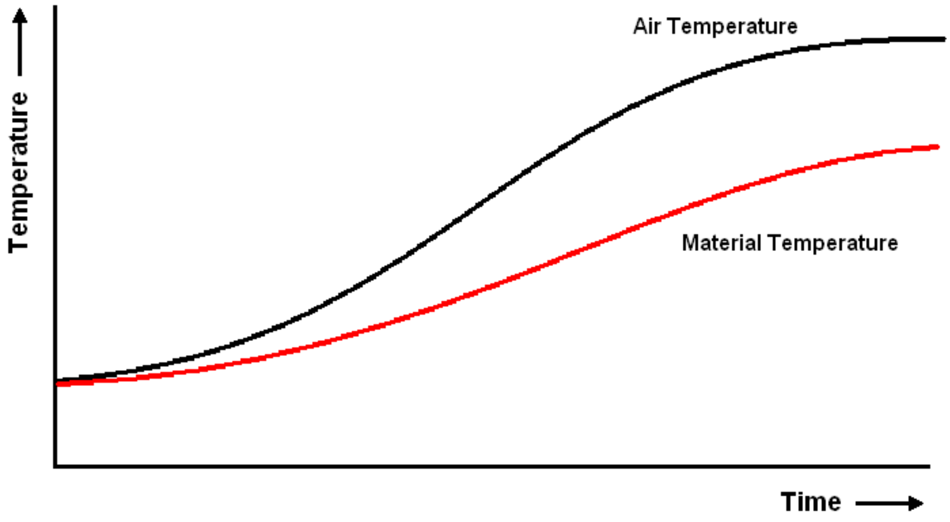


Figure 3.6: The behaviour of material temperature with relation to air temperature as it increases over time.

Given a stable environment temperature, initial material temperature and specific material property values, the uniform temperature of the exposed material can be calculated at any given time using a mathematical model.

This method only predicts the uniform temperature of the material and with estimated material property data it is likely that the results will not be accurate. A more accurate alternative method of acquiring the uniform material temperature is by practical measurement using a thermocouple temperature monitoring device, which can be installed within a specimen.

This will measure the actual uniform temperature of the material at any time and when it is exposed to the same conditions as the samples an accurate temperature reading will be given.

To achieve accurate material temperature reading and eliminate any uncertainty and complexities of mathematical modelling, the practical temperature monitoring method was chosen. For purposes of simplicity, a 1mm hole was drilled into the center of a specimen and a thermocouple was placed inside. This ‘monitoring specimen’ was placed in the stable environment along with all of the samples to be tested so that the exposure time was the same for the sample specimens and the monitoring specimen. For each sample, the chamber temperature was set to a specific temperature and once the material reached a relatively stable temperature, it was recorded and mechanical testing was conducted.

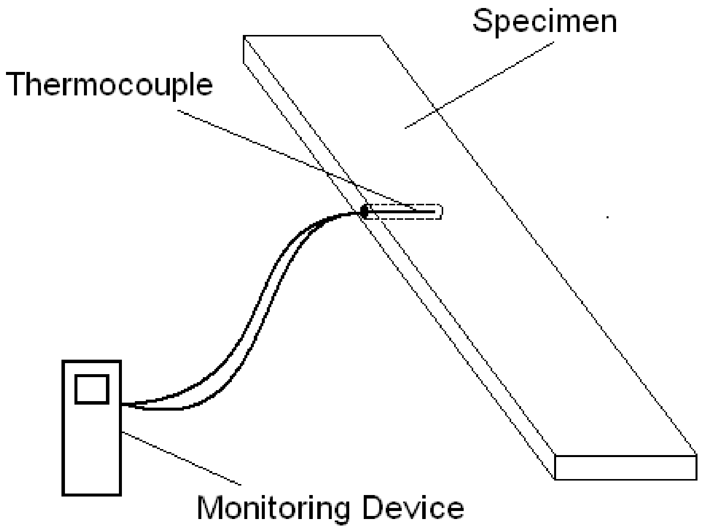


Figure 3.7: Basic diagram of the material temperature monitoring method.

3.3 Data Processing and Calculation

3.3.1 Flexural Stress, Strain and Modulus

The standard used for testing outlines methods for both 3-point bending and 4-point bending, as shown in the schematic diagrams below.

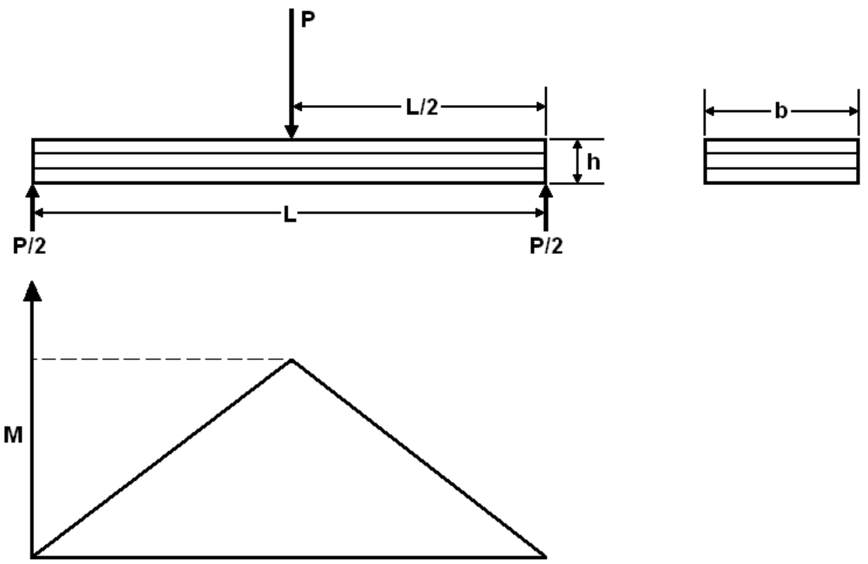


Figure 3.8: Schematic diagram of a 3-point loading.

Figure 3.3 shows a schematic diagram of a 3-point bending test setup and the bending moment diagram that corresponds to 3-point loading. As seen the maximum bending moment occurs at the point load.

Although through experimentation a 4-point flexure test is appropriate for finding the bending moment capacities, 3-point bending can also be used and is recommended for finding flexural strength and modulus. It is for these reasons that 3-point flexure tests will be conducted. Various mechanical properties can be calculated by the following (International Organization for Standardization 1998):

For Flexural Stress (3-point loading);

$$\sigma f = \frac{3PL}{2bh^2} \tag{3.2}$$

where: σ_f = flexural stress

P = load (N)

L = span (mm)

h = thickness (mm)

b = width (mm)

For Flexural Strain (3-point loading);

$$\varepsilon f = \frac{6Dh}{L^2} \tag{3.3}$$

where: ε_f = flexural strain

D = midpoint deflection (mm)

L = span (mm)

h = thickness (mm)

For Flexural Modulus (3-point loading);

$$E_f = \left(\frac{L^3}{4bh^3}\right)\left(\frac{\Delta P}{\Delta s}\right) \tag{3.4}$$

where: E_f = flexural modulus

L = span (mm)

b = width (mm)

h = thickness (mm)

ΔP = maximum change in applied load between initial and final deflection (N)

Δs = difference between initial and final deflection (mm)

The method used in TestWorks 4 is pre-programmed to calculate the flexural stress, σ_f, flexural strain, ε_f and flexural modulus E_f.

As previously stated, another property value that is important to note during flexure of a material is the maximum bending moment.

For Bending Moment (3-point loading);

$$M = \frac{PL}{4} \tag{3.5}$$

where: P = load (N)

L = span (mm)

For each sample 5 specimens will be tested and from the results of each specimen test a standard value for each of the above properties needs to be derived. This is found by finding the average value of the 5 specimens tested.

3.3.2 Relationship between Flexural and Tensile Properties

In many general and practical applications of composite fibre materials and in particular, glass FRP materials, the shape, form and loading of the material results primarily in tensile loading, rather than flexural loading. For this reason, properties for both flexural and tensile loads are desirable.

Though it is through unfortunate circumstances that tensile tests were unable to be conducted at elevated temperatures, it is possible to use the flexural data obtained through experiment to estimate the corresponding tensile data using a mathematical model.

A study of the relationship between tensile strength and flexural strength in fibre reinforced composites (Whitney 1979) used a statistical strength model to determine that for glass/epoxy composites undergoing 3-point bending, the relationship between flexural and tensile strength is as follows;

$$\frac{S_b}{S_t} = 1.52 \tag{3.6}$$

where: S_b = bending stress

S_t = tensile stress

Using this relationship, the tensile strength of the composite material can be determined from the flexural data collected.

3.4 Determination of Temperature Gradient

This area of the research topic aims to investigate the temperature gradients and variations that occur with FRP pultrusions when exposed to natural conditions and heat exposure from the sun. It is assumed that when exposed to natural sunlight, as many civil structures are, a temperature gradient will occur within the structure and more specifically within the individual members.

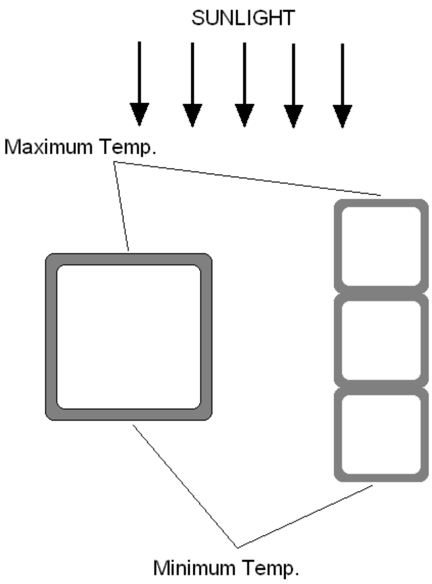


Figure 3.9: Basic diagram explaining temperature gradients with pultrusions.

In understanding the thermal behaviour of the product and gathering practical data and figures from experimentation, any effects in mechanical properties due only to the gradients may be determined.

In order to gain maximum information while utilising efficient and effective experimental methods, it was decided that two tests for this section should be conducted; one that monitors temperature variations within a basic girder consisting of three 125 mm x 125 mm pultrusion sections bonded vertically, and one single 100 mm x 100 mm pultrusion member. These two configurations do not represent the ways in which all composite structures are utilised and exposed to heat in every situation, however together they give an indication into the magnitude of temperature variations within many possible configurations when exposed to heat.

Due to time constraints, the experiments were conducted in mid spring over a 4 day period. Though this short testing period will not produce temperature ranges that can be observed at any given time during the year, the temperature fluctuations during this period are expected to occur at similar rates as any other period.

3.4.1 Equipment

As this experiment is quite simple, the equipment requirements are quite minimal. The basic objective of this experiment is to effectively record the temperature of in different locations within the pultrusion, meaning that a practical and accurate temperature recording device was required. It was decided that small data loggers fitted with thermocouples shown below were suitable for this purpose given their capabilities simplicity.

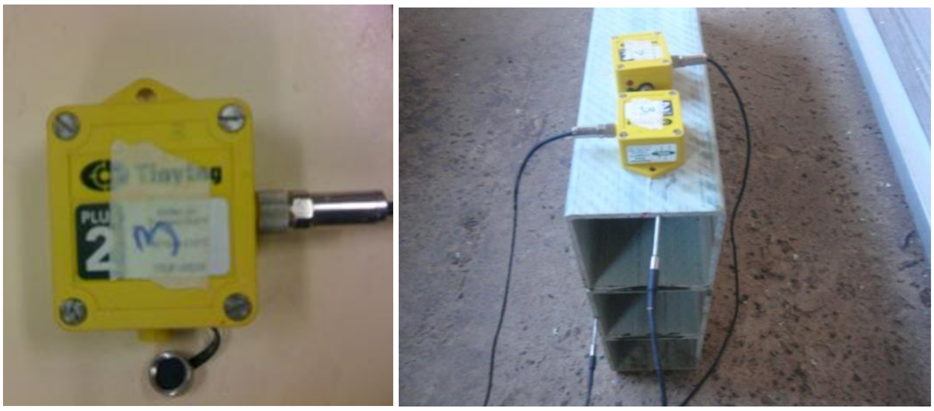


Figure 3.10: Temperature data logger and bonded pultrusion beam used for thermal gradient testing.

Previous to installation, each data logger was set up via a PC to record the temperature every 10 minutes before being activated.

The small thermocouples were installed by drilling small holes only big enough to fit the thermocouple shaft inside approximately 50 mm into the ends of the walls to ensure that heat entering the material was only conducted through the walls and not the ends.

3.4.2 Test Setup

As seen in figure 3.4, it is generally assumed that due to the way that a structure will be exposed to sunlight, the maximum temperature difference within a structure or member will be between the top and bottom surfaces. For this reason, the thermocouples were placed in locations within the pultrusion that were expected to have either relatively high, low or largely varying temperatures. Again considering the way that the sun moves across the sky, from East to West, it was decided that the top, bottom, Eastern and Western walls off the test pieces were to be monitored, along with the ambient air temperature.

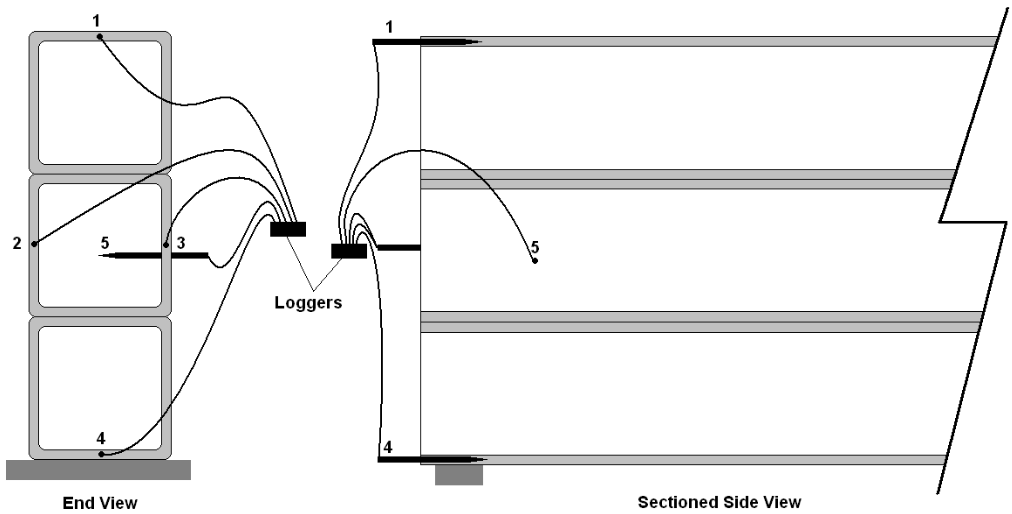


Figure 3.11: Schematic diagram of the test piece and locations of the thermocouples within 3 x 125 mm x 125 mm girder.

Similarly, the setup for the single 100 mm x 100 mm pultrusion member allowed the monitoring of the top and bottom surface temperatures as well as the ambient air temperature.

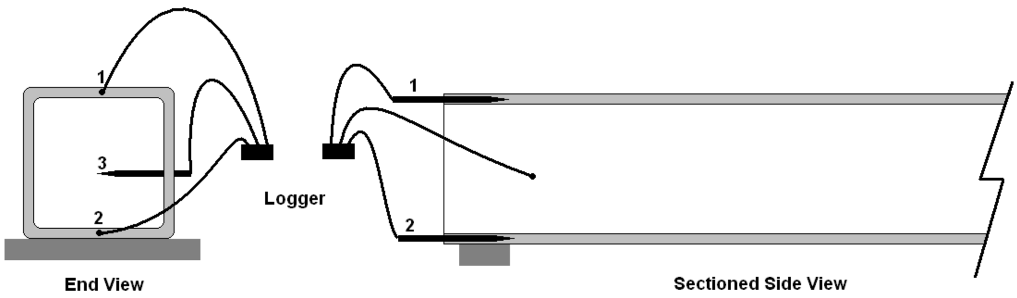


Figure 3.12: Schematic diagram of the test piece and locations of the thermocouples within 100 mm x 100 mm member.

After the test pieces, thermocouples and data loggers were installed and prepared, the setup was placed in an appropriate place where it was not shielded from sunlight by and objects throughout the duration of the monitoring. To simulate natural conditions, the test pieces were raised from the floor of their location, and also placed on wooden panels to reduce any temperature effects caused by reflection or conduction from the floor surface.

Figure 3.13: The experimental test setup for bonded pultrusion beam.

Figure 3.14: The experimental test setup for single pultrusion member.

4. Test Results and Observations

4.1 Introduction

In order to achieve an accurate and in depth analysis of the project topic, data obtained from the practical tests must be carefully collected and displayed in forms that are interpretable and visually representative. This chapter displays the data recorded during testing in ways that endeavour to use observations and mathematical methods to analyse the material behaviour.

4.2 Flexural Testing

4.2.1 Flexural Property Data

As the principle of the standard ISO 14125:1998 states, the data recorded by the MTS during flexure testing consists of a deflection value and the corresponding force required to that deflection. Due to the frequency of these value measurements, there are tens of thousands of data values between the total of 35 specimens tested. In consideration of this large amount of values it is inappropriate to display a tabulated representation of this data; however a graphical representation is both appropriate and allows for visual analysis.

As discussed in Chapter 3 of this dissertation, the method used in TestWorks 4 is pre-programmed to calculate and represent the flexural stress, σ_f, flexural strain, ε_f, and flexural modulus E_f using the mathematical equations displayed. The table below shows these average property values recorded and calculated for each sample, and the complete tables including individual specimen property values, average property values and standard deviations are shown in Appendix B.

Table 4.1: Average values collected for each of the 7 samples.

Sample #	1	2	3	4	5	6	7
Air Temperature (°C)	20	35	50	65	80	95	110
Material Temperature (°C)	20	35	50	63	77	91	105
Peak Load (N)	3392	2797	2421	2026	1906	1370	980
Extension at Peak Load (mm)	6.11	5.76	4.74	4.2	4.06	3.26	3.31
Peak Flexural Strength (Mpa)	995.7	890.65	737.96	647.64	592.26	415.49	299.48
Peak Strain (%)	2.69	2.9	3.04	2.95	2.33	2.24	2.28
Flexural Modulus (MPa)	38389	36498	36209	36487	36207	34480	31563

The following plot shows the data points for the five (5) specimens tested at each of the seven (7) temperatures. Note that this plot uses the average values shown in Table 4.1 and only represents data recorded up until the peak load and subsequent failure of each specimen. Again, the load-deflection plots for each specimen within the seven samples can be seen in Appendix B.

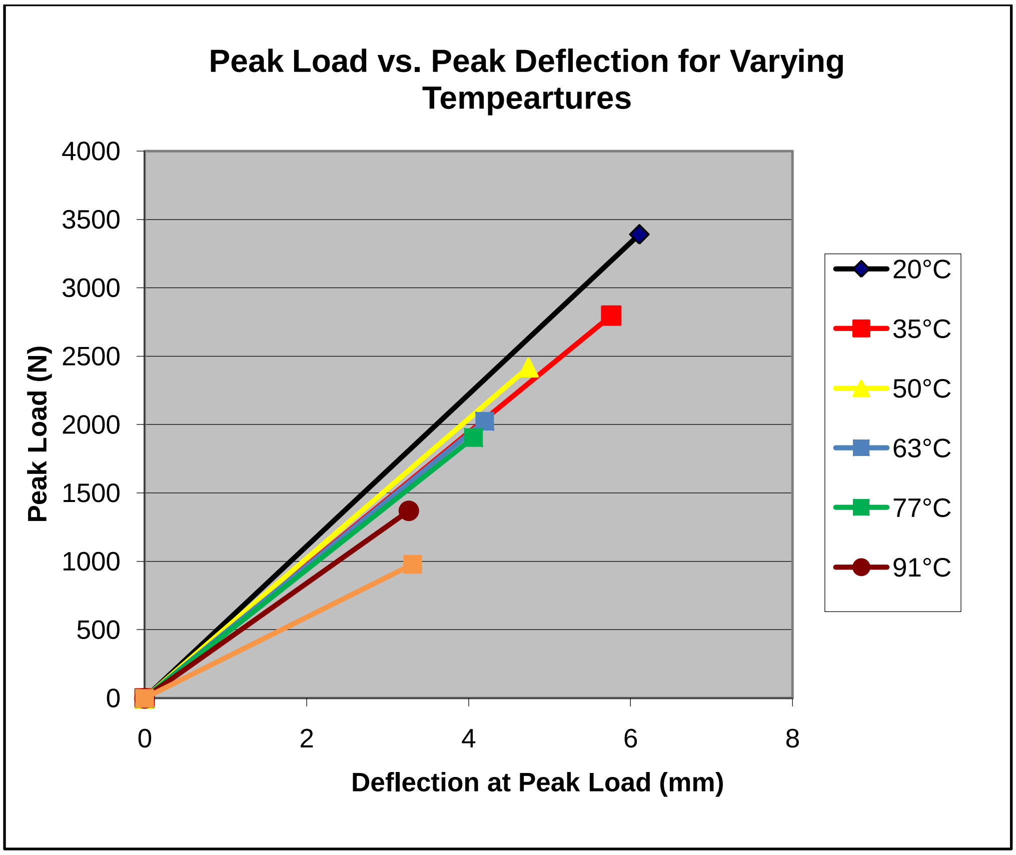


Figure 4.1: Plot of peak load and corresponding deflection for samples a 7 different temperatures.

While both Table 4.1 and Figure 4.1 show the important property values to a certain extent of accuracy, it is difficult to interpret any patterns or trends by simply reading them. It can be seen that the properties, particularly the peak flexural stress, tend to decrease with the increase in temperature; however any specific patterns in the values cannot be made obvious whilst avoiding further calculations. It is for this reason that a graphical representation of these values is necessary to determine any specific patterns.

The below plot shows the average peak flexural stress, σ_f, and the flexural modulus, E_f, for each sample temperature as displayed in Table 4.1. The modulus values have been scaled down for display purposes.

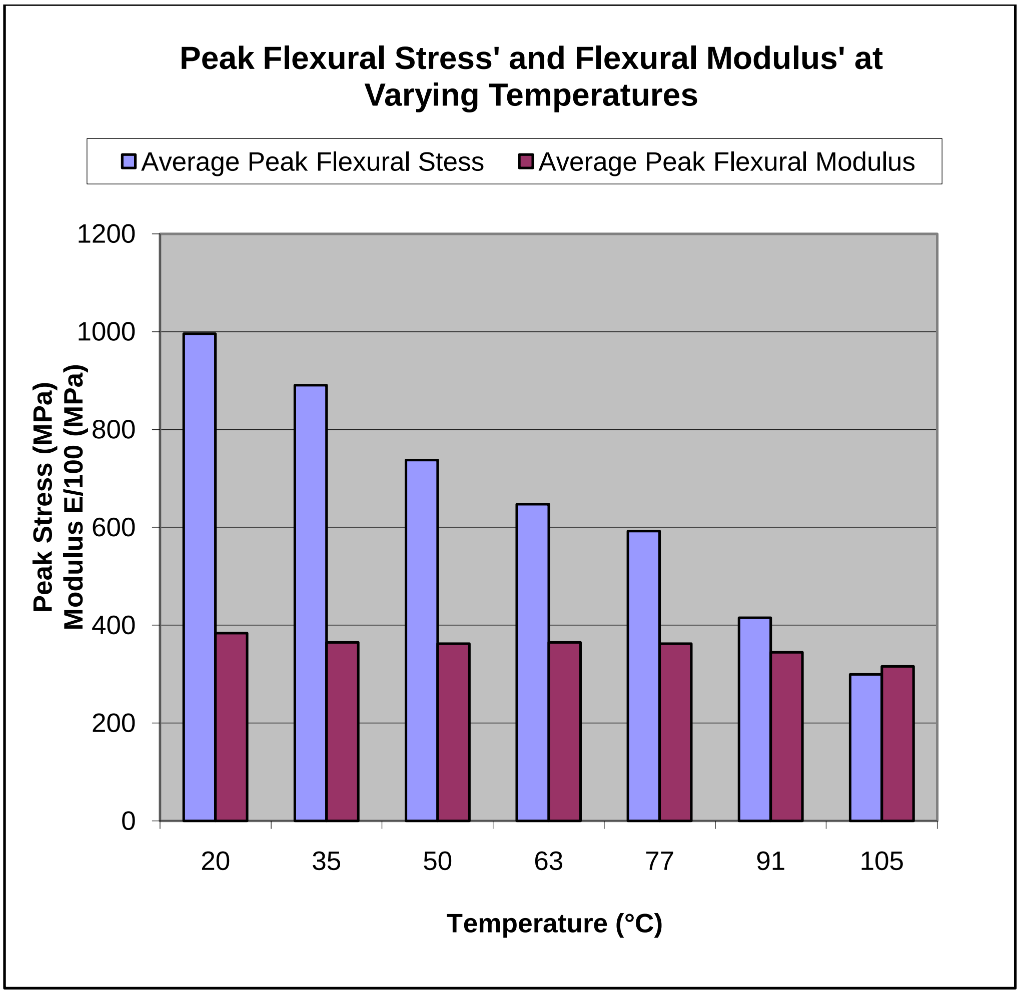


Figure 4.2: Bar chart for average peak flexural stress and average flexural modulus for samples at 7 different temperatures.

With the data represented in a graphical form, obvious trends can be seen and initial evaluation of the plot concludes that a steady decrease in peak flexural stress occurs with an increase in temperature. This plot also initially indicates that the flexural modulus does not display any behaviour or large variations with temperature that could be described by a simple mathematical model.

4.2.2 Flexural Failure Observations

The results of flexure testing conducted will later be used to estimate the tensile properties of the material in order to analyse the behaviour of pultrusion members. It is for this reason that for the pultrusion analysis it is not necessary to investigate the modes of failure during flexure testing as the failure mechanisms are quite different in tensile and flexural loading. However, it is very important to note the failure modes in order to determine the interaction between the matrix polymer and the fibres and predict the behaviour and mode of failure during flexural loading of the material at elevated temperatures.

Although it is difficult to determine the governing mode(s) of failure during flexure testing, it is possible to examine the failed specimens after testing is complete to determine the way in which failure occurred. During the visual examination of the failed specimens, it was noted whether failure occurred primarily due to compressive failure on the top surface, tensile failure on the bottom surface or a combination of both.

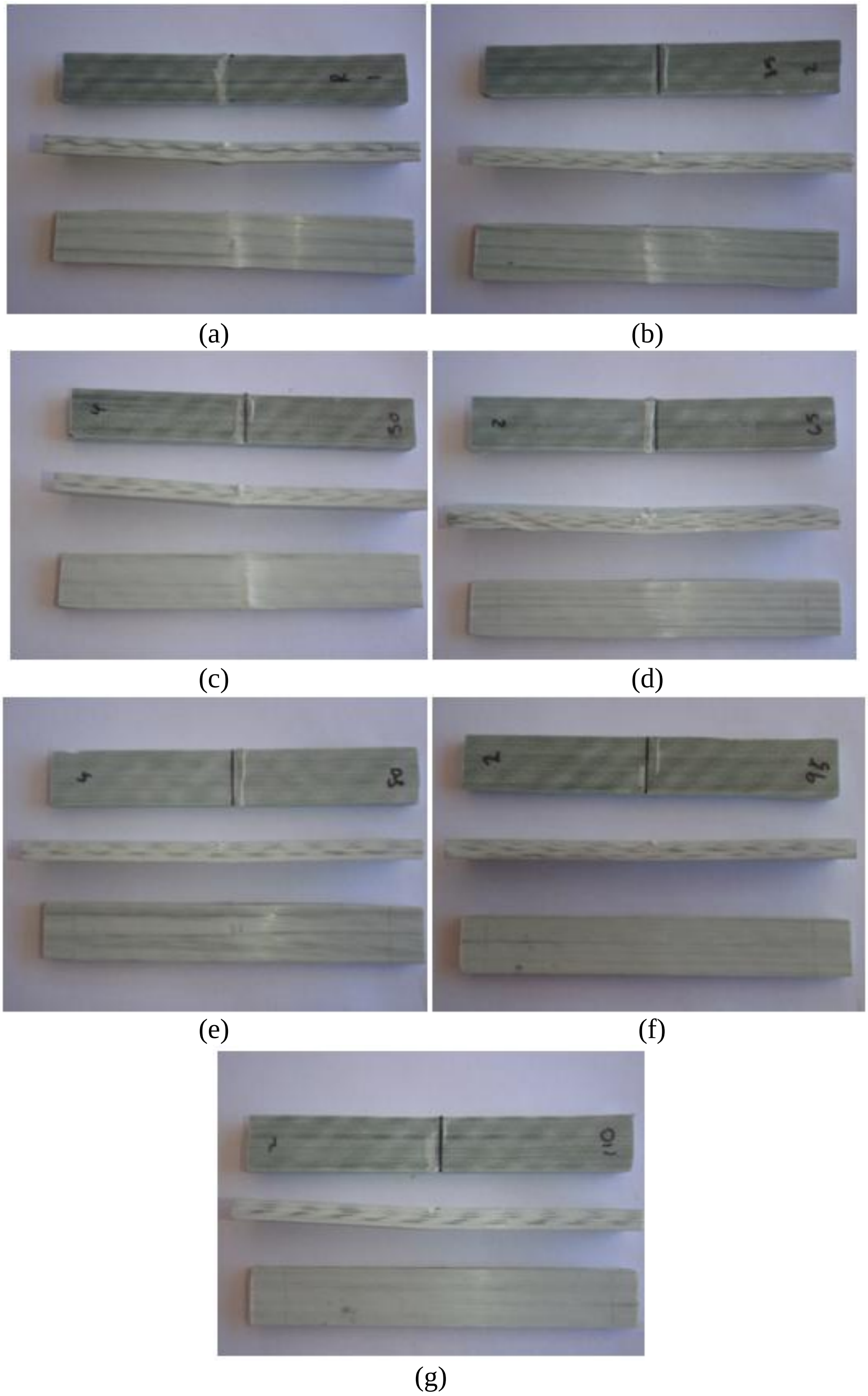


Figure 4.3: Top, side and bottom views of specimens after failure for flexure tests at: (a) 20°C (b) 35°C (c) 50°C (d) 63°C (e) 77°C (f) 91°C and (g) 105°C.

Though it is difficult to see, all of the samples failed primarily through compression of the top surface, and only those at lower temperatures failed through a combination of compression on the top surface as well as tensile failure on the bottom surface.

Figure 4.4: Bottom surface of samples tested from 20°C (closest) to 105°C (farthest).

Figure 4.4 shows that for samples between 20°C and 63°C, tensile failure of the bottom surface occurred, and samples between 77°C and 105°C display little or no tensile failure. At closer inspection it can be seen that very small amounts of tensile failure of the outer surface occurred within the specimen tested at 77°C, and no tensile failure occurred within the samples tested at 91°C and 105°C.

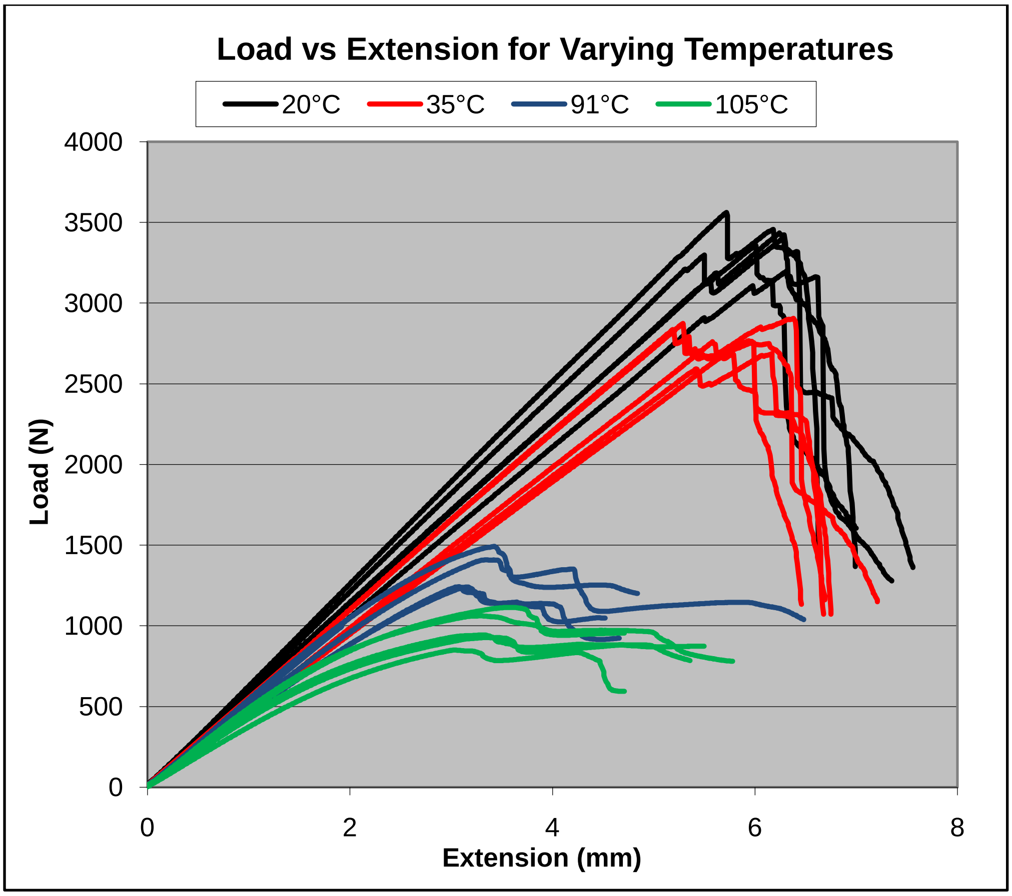


Figure 4.5: Load vs. Extension plot for all specimens tested at 20°C, 35°C, 91°C and 100°C, showing brittle and ductile failure.

As seen in Figure 4.5, the specimens tested at lower temperatures display sudden failure at their peak load, indicating brittle failure, while those tested at higher temperatures display ductile failure. It can confirmed from this plot and the visual inspection that the amount of tensile failure contribution to the overall failure is a governing factor in whether the specimen fails in a brittle or ductile behaviour.

4.3 Temperature Gradients within Pultrusions

As with previous results, the data obtained from monitoring the temperatures within FRP pultrusions was too much to be displayed in tabular form, and was not easy to interpret by looking at data values. The following plots represent the data obtained for each of the 2 experiments over an approximate 24-36 hour period.

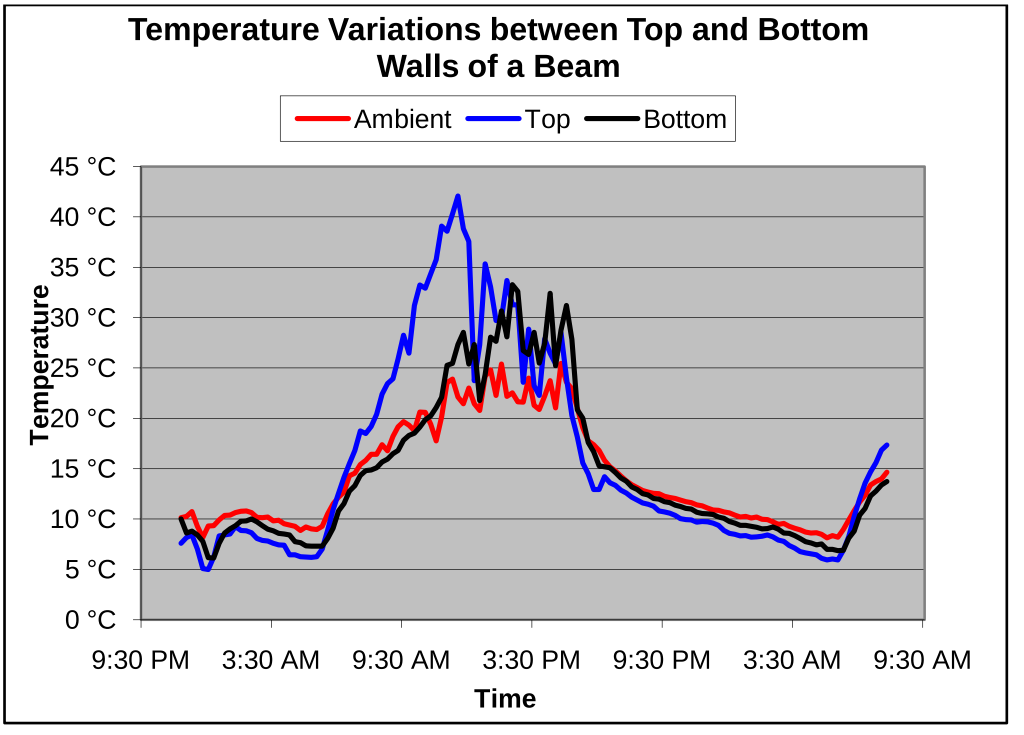


Figure 4.6: Plot of ambient temperature, top wall temperature and bottom wall temperature for a 3 x 125 mm x 125 mm pultrusion beam over a 1.5 day period.

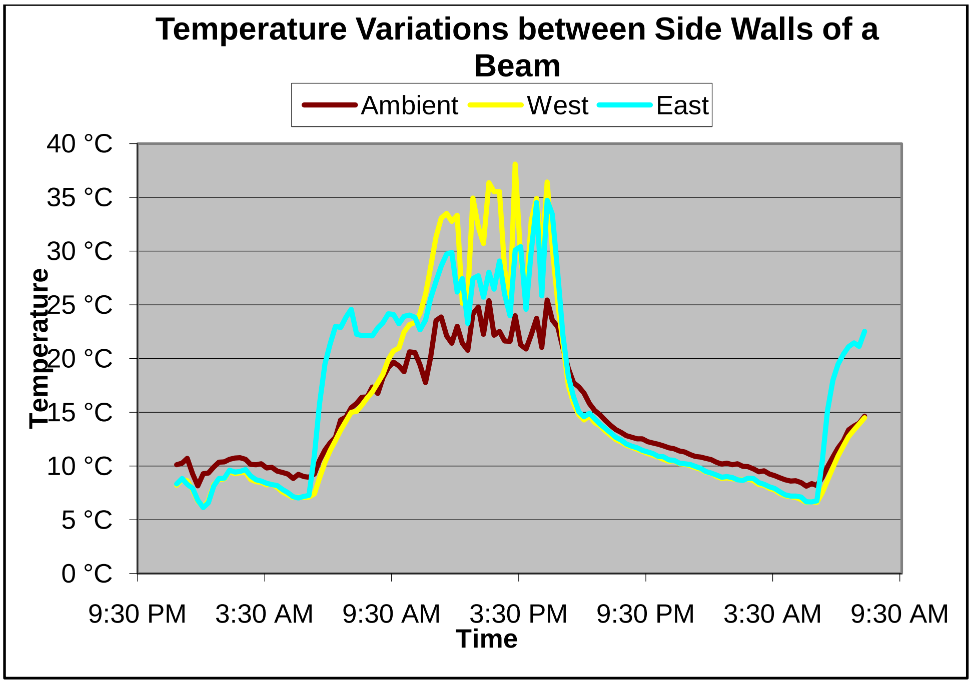


Figure 4.7: Plot of ambient temperature, eastern wall temperature and western wall temperature for a 3 x 125 mm x 125 mm pultrusion beam over a 1.5 day period.

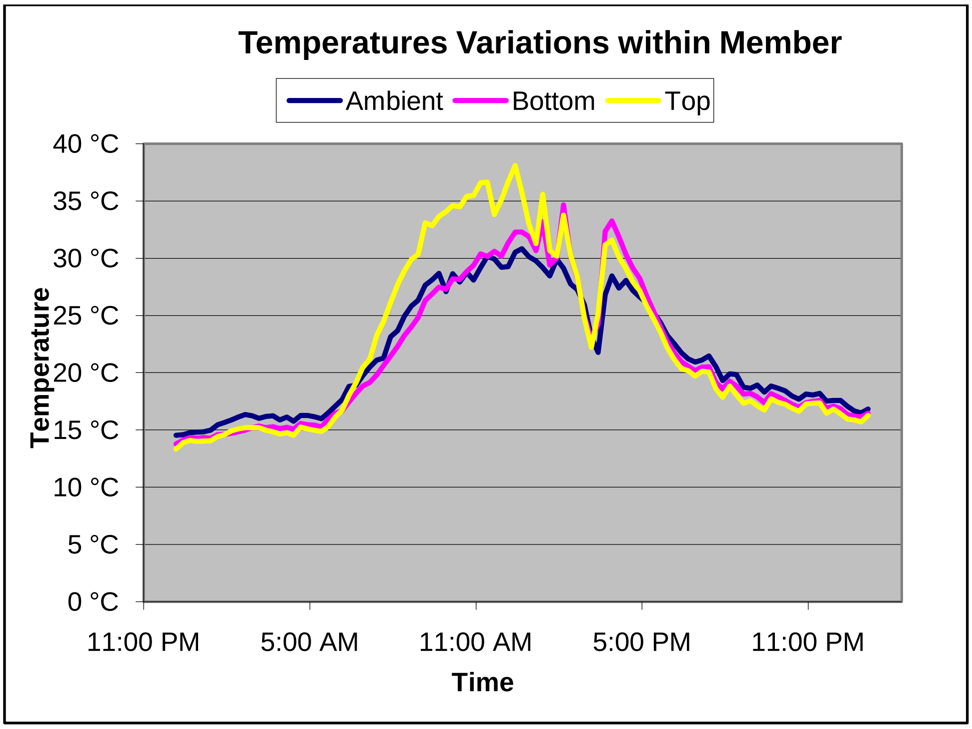


Figure 4.8: Plot of ambient temperature, top wall temperature and bottom wall temperature for a 100 mm x 100 mm pultrusion member over a 1 day period.

4.4 Summary

This chapter aims only to represent the direct data that has been recorded without any analysis or processing. The following chapter uses the information shown to calculate specific values and use them to discuss and analyse and reach conclusions from.

5. Results Analysis and Discussion

5.1 Introduction

In order to draw conclusions to the research and testing conducted throughout the project, it is necessary to critically analyse the results gathered. The results presented in chapter 4 alone do not provide a sufficient conclusion to the research, thus this chapter will use background information, mathematical methods and analytical judgments to discuss and analyse the results. In doing so, an in depth understanding of the results will be gained and clear and precise conclusions can be drawn.

5.2 Strength Property Analysis

5.2.1 Flexural Strength

The results for flexural strength displayed in chapter 4 can be used to draw an initial conclusion that the average peak flexural stress of the material does decrease steadily with increases in material temperature. This conclusion however was an expected behaviour and does not assist in determining the magnitude of strength variation nor allows us to predict the behaviour of the material at any given temperature.

Similar to Figure 4.2, a plot of average peak flexural strength versus material temperature is required to firstly gain an understanding of the amount of decrease in the strength with increases in temperature; and secondly use mathematical analysis to find the relationship between the two in order to predict the peak flexural strength of the material at any given temperature.

The below plot shows the calculated average peak flexural strength of the material for each of the 7 samples tested at different temperatures.

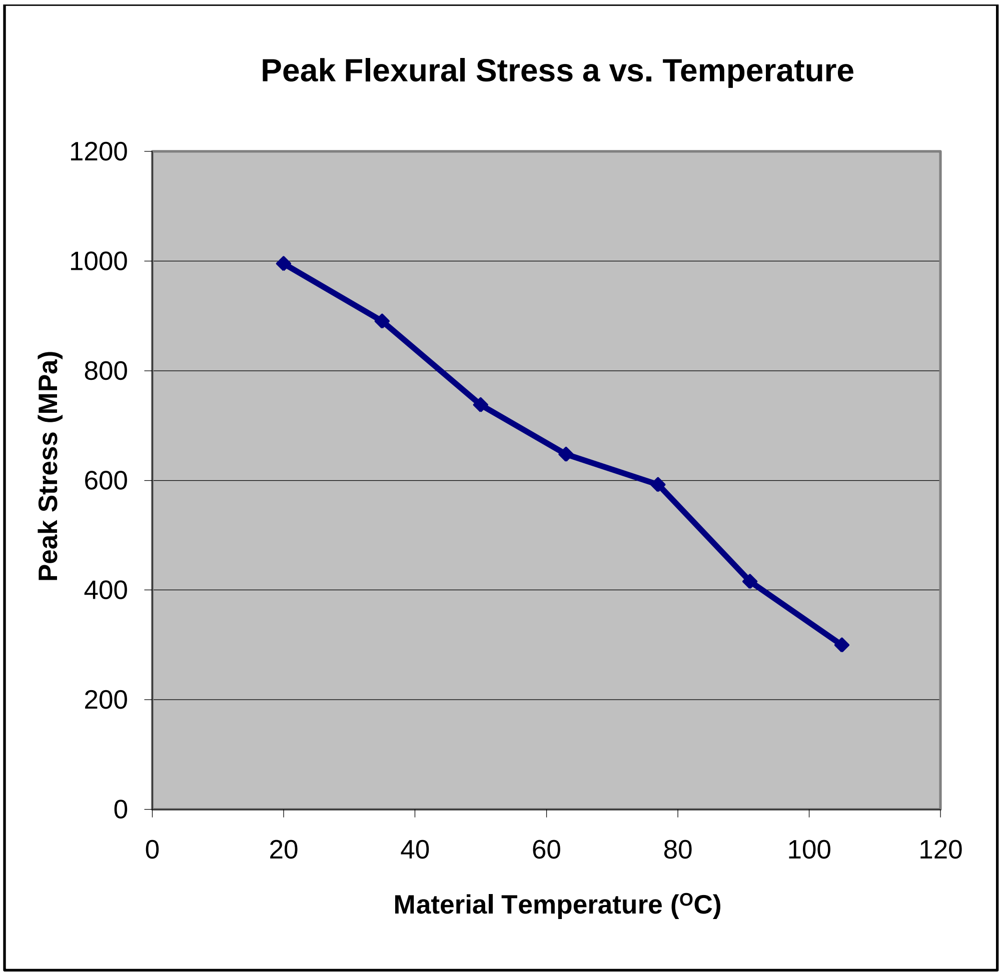


Figure 5.1: Plot of average flexural strength of samples as material temperature increases.

Again, only a small amount of information can be drawn from this plot. It appears that the relationship between peak stress and temperature is linear, and the flexural strength decreases by approximately 700 MPa between temperatures of 20°C and 105°C.

These values can be compared to the strength of the material at room temperature (20°C).

Table 5.1: Percentage of the material flexural strength at room temperature retained by the material at elevated temperatures.

Temperature	20°C	35°C	50°C	63°C	77 °C	91°C	105°C
Percentage of Strength Retained	100%	89%	74%	65%	59%	42%	28%

In comparison to previous studies reviewed in Chapter 2, which showed that for a GRP channel, the compressive strengths at 60°C and 90°C were respectively 63% and 31% of that at ambient temperature, the results obtained in this experiment are relatively similar.

Although this small amount of information is valuable in predicting the strength behaviour of the material within the temperature range tested, the addition of a 'regression line' or 'line of best fit' can confirm the mathematical relationship between flexural strength and material temperature and allow estimations of flexural strength to be made for any given material temperature within a certain range.

When plotted in Microsoft Excel, a regression line can be automatically calculated to best fit the data points according to the type of function fitted i.e. liner, exponential, polynomial etc, in the form of $\sigma_f = f(T)$.

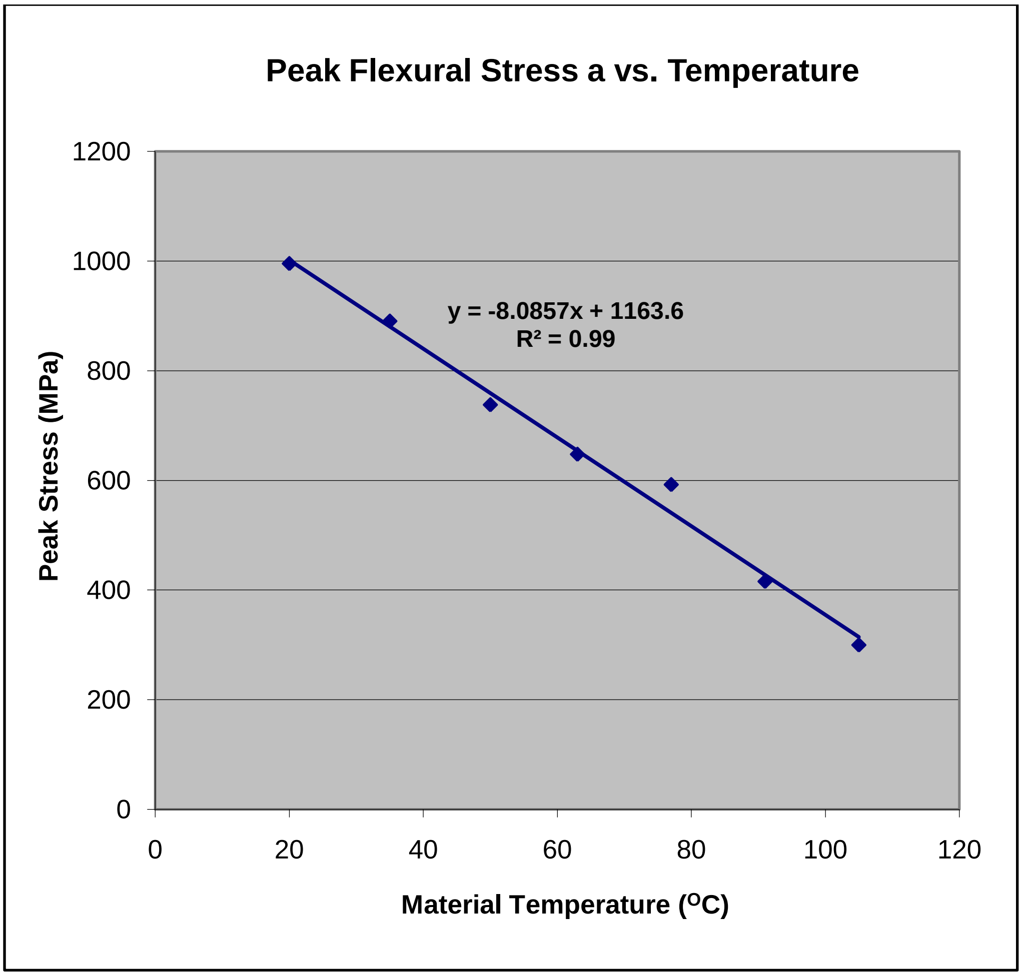


Figure 5.2: Plot of average flexural strength of samples as material temperature increases including linear regression line.

The above plot is identical to Figure 5.1 only included in it is a line of best fit which was automatically calculated and plotted using Microsoft Excel. In this particular plot, a linear function was chosen to represent the 7 data points.

Given this linear function, the peak flexural stress of the composite material can be estimated as;

$$\sigma_f = -8.0875T + 1163.6 \qquad (5.1)$$

where: 20°C < T < 105°C

Disregarding the final term of the equation, it is interpreted that the peak flexural strength of the material decreases by approximately 8.1 MPa for a temperature increase of 1°C for any temperature between 20°C and 105°C.

Also calculated automatically by Microsoft Excel is the R^2 value, which uses the deviance of the data points from the regression line to determine the viability of the function. For $R^2 = 1.0$, it can be said that data points and regression line perfectly coincide; and for decreases in the R^2 value, the viability of the regression line being used to predict patterns in the data points also becomes less. Using the data obtained during testing, a linear regression line results in a R^2 value of 0.99. Considering that a R^2 value of 1.0 indicates a perfect prediction, it can be confirmed that the linear function previously calculated can be used to predict the peak flexural stress for any temperature between 20°C and 105°C.

Though a linear function accurately represents the data points, the function type is not restricted. The following plot shows a 2nd order polynomial regression line.

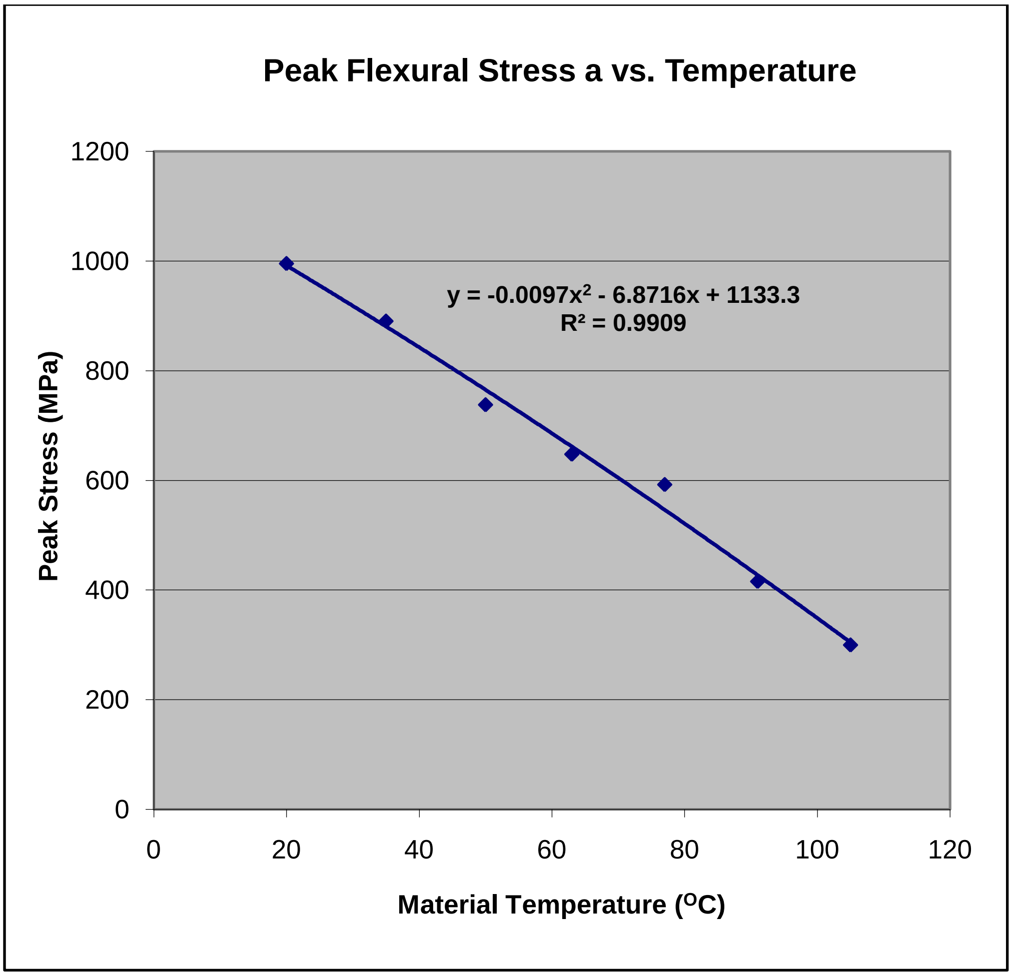


Figure 5.3: Plot of average flexural strength of samples as material temperature increases including 2nd order polynomial regression line.

Similar to the linear function, the polynomial regression line results in a R^2 value of 0.9909 which also confirms that it can be used to predict the peak flexural stress for any temperature within the range tested.

Considering that there are only 7 points in the data series and that both a linear and polynomial function can be used to predict data points with very similar results, the linear regression line will be recognized as the fundamental function used to model the 7 data points obtained.

As previously mentioned, a comparison can be made between the results obtained during this experiment and the results of previous studies on GRP channels at elevated temperatures. As shown in Table 5.1 the percentage of flexural strength retained in pultrusion samples as temperature rises can be compared to the percentage of compressive strength retained in GRP channels. It is with this similarity that a prediction of behaviour of the experimental results can be made, and be expected to follow the trend observed in the previous study. As seen in figure the trend is not linear between ambient and 250°C, however it appears linear up until the HDT as do the experimental results of this project.

5.2.2 Flexural Modulus

Unlike the data obtained for flexural strength, there is no easily recognisable pattern within the 7 data points collected. The following plot shows the Flexural Modulus for each of the 7 temperatures tested.

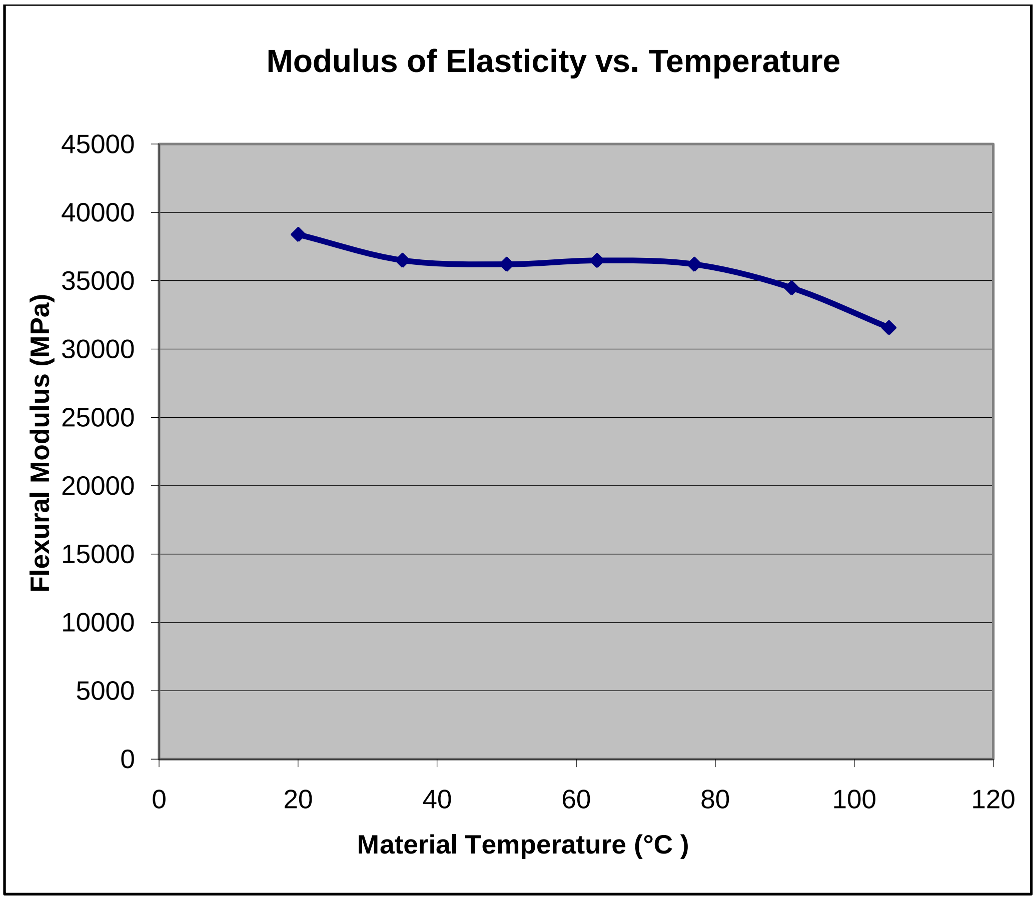


Figure 5.4: Plot of average flexural modulus of samples as material temperature increases.

Although it can be seen that there is a drop in flexural modulus between 20°C and 105°C, a specific trend in which the decrease in values occur cannot be determined as easily as with the data obtained for flexural strength.

Table 5.2: Percentage of the material flexural strength at room temperature retained by the material at elevated temperatures.

Temperature	20°C	35°C	50°C	63°C	77 °C	91°C	105°C
Percentage of Modulus Retained	100%	95%	94%	95%	94%	90%	82%

Using an initial visual analysis, there is an obvious drop in modulus between 20°C and 35°C and more obviously a further from 80°C and 105°C. There is an overall drop of 6826 MPa (18%) over the temperature range tested, which clearly indicates that elevated temperatures have an effect on the modulus of the material; however the results recorded at 35°C, 50°C, 63°C and 77°C are very similar, with the overall difference drop in modulus over this range equalling only 291 MPa. Furthermore, these 4 values fluctuate as the temperature increases, and for these reasons it is considered that the modulus value between 20°C and 77°C is uniform. Together the 7 data points show that approximately 96% of the modulus drop occurs over the first 16% and final 34% of the temperature rise, and only 4% of the modulus drop takes place during the middle 50% of the temperature rise. Due to the reasons indicated and the relatively small amount of data points obtained, it would be inappropriate and inaccurate to fit a regression line to the data.

Whilst the relationship between flexural modulus and material temperature cannot be estimated by a mathematical function, the plot shown in Figure 5.4 still provides an insight into the property behaviour. The shape of the plot shows that there is a definite drop in modulus between 20°C and 35°C and between 77°C and 110°C, whilst there is uniformity from 35°C to 77°C. Given that the testing temperatures do not reach the glass transition temperature, T_g, of the vinyl ester matrix which is approximately 125°C, there is an indication that the behaviour of the composite material and the interaction between the matrix and reinforcement is complex and requires a more detailed analysis.

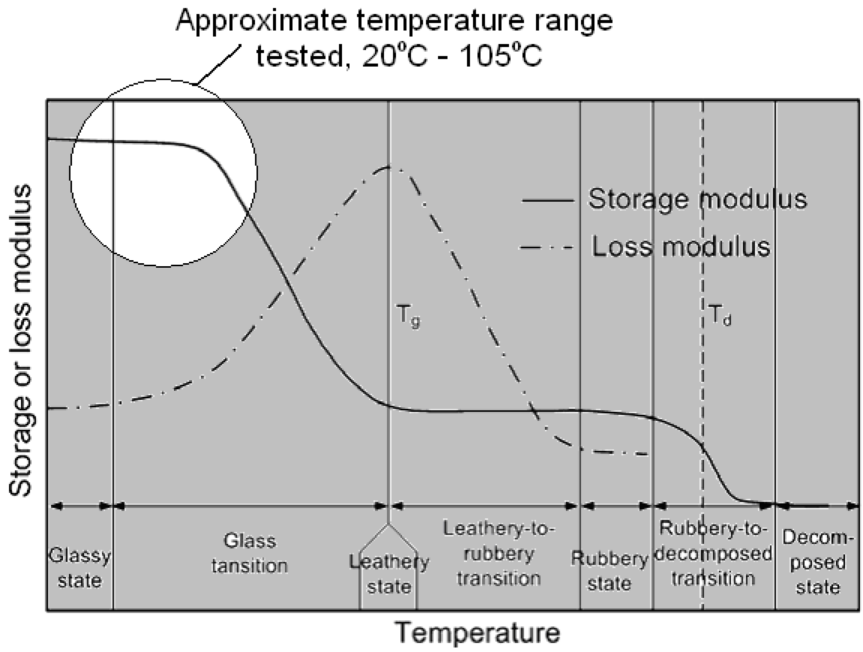


Figure 5.5: The approximate region of collected test data within a modulus vs. temperature plot.

Though any further analysis of this behaviour is outside the scope of this project, the plot form can be confirmed as an expected behaviour by figure 5.5 which shows a uniform modulus in the glassy state and at the beginning of the glass transition before dropping steadily as the T_g is approached. Considering the general behaviour shown in this figure, it is expected that further testing at higher temperatures will result in a uniform modulus value yet again after approximately 125°C. By this analysis and in agreement with previous research, it can be confirmed that at 20°C, the material is in the glassy state, and at a temperature between 20°C and 110°C, the glass transition has begun.

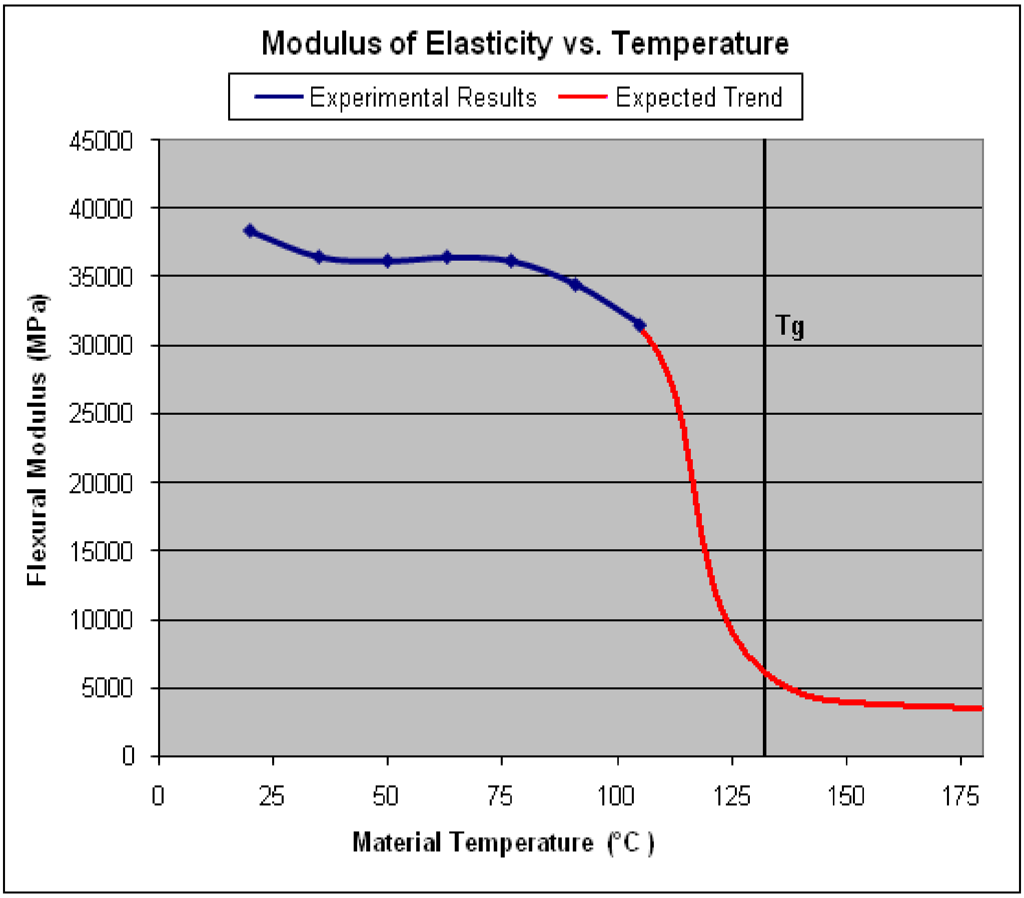


Figure 5.6: Plot of experimental results for strength vs. temperature, and the expected results for higher temperatures.

Figure 5.6 shows the general form of a modulus plot with respect to temperature and although the exact shape of the form is unknown without experimentation, the line demonstrates how the collected data follows a the general shape and the pattern of data points that would be expected with further experimentation at higher temperatures.

5.3 Temperature Variations within Pultrusions

5.3.1 Analysis of Temperature Variations

The temperature values recorded within the bonded pultrusion beam show obvious differences between ambient, top surface and bottom surface temperatures. Though the results shown so far indicate the temperature of the separate locations, it important to note the variation in temperature between these surfaces and their relationship with the ambient temperature.

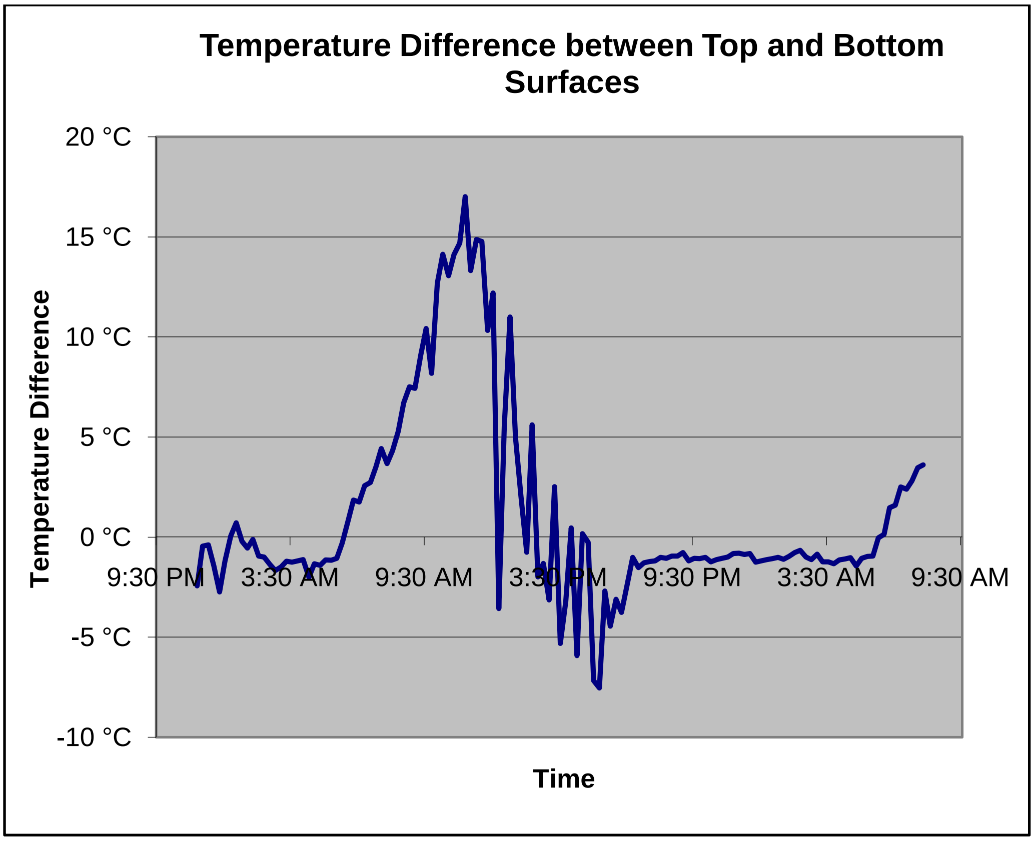


Figure 5.7: The difference in temperature between the top wall and bottom wall of the bonded pultrusion beam.

As seen in Figure 5.7, the difference in temperature between the top wall and the bottom wall reaches approximately 17°C at the approximate peak ambient temperature, and in many instances the bottom wall is at a higher temperature than the top wall. In consideration of previous results, this temperature variation equates to approximately 138 MPa difference in flexural strength between the 2 outer walls.

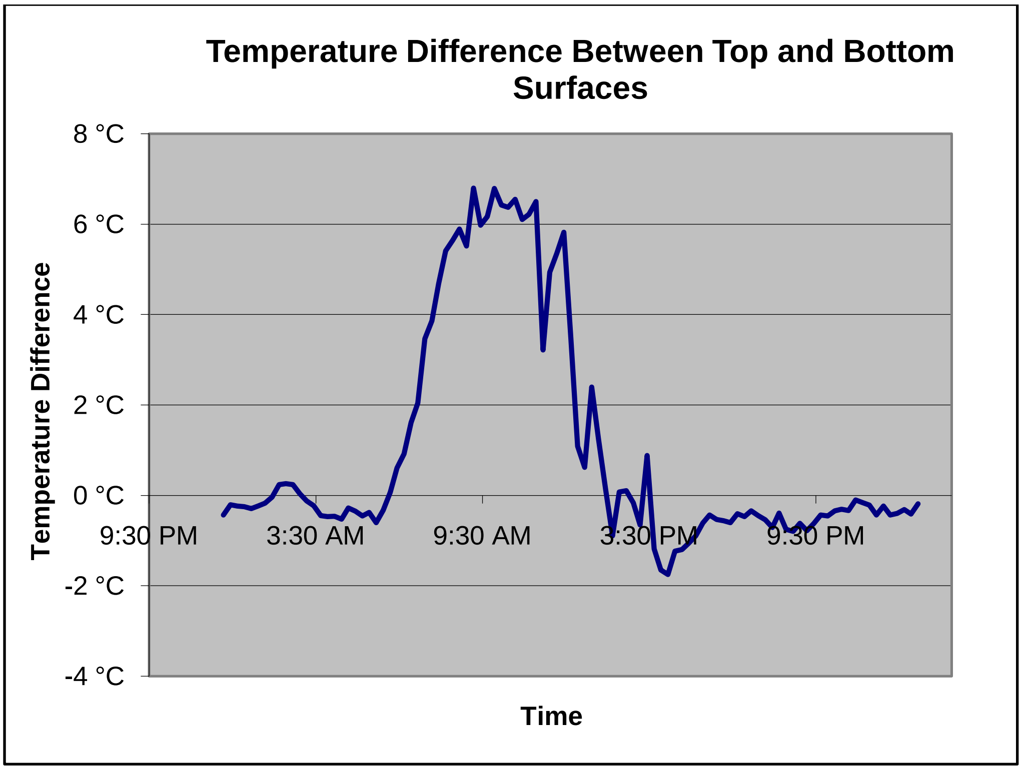


Figure 5.8: The difference in temperature between the top wall and bottom wall of the single pultrusion member.

Unlike in the bonded beam, the temperature difference between the top and bottom walls of the single pultrusion member reached a maximum of approximately 7°C, corresponding to a difference in flexural strength of approximately 57 MPa.

5.3.2 Effect of Ambient Temperature on Material Temperature

In reference to Figure 4.5, there is a considerable difference between ambient temperature and the maximum material temperature. The maximum difference occurs when the ambient temperature is approximately 24°C and the material temperature is approximately 43°C. This difference throughout the monitoring period is important to note in that a relationship between ambient temperature and wall temperatures can be made, thus a prediction of the wall temperature can be made using a measurement of ambient temperature at a given time.

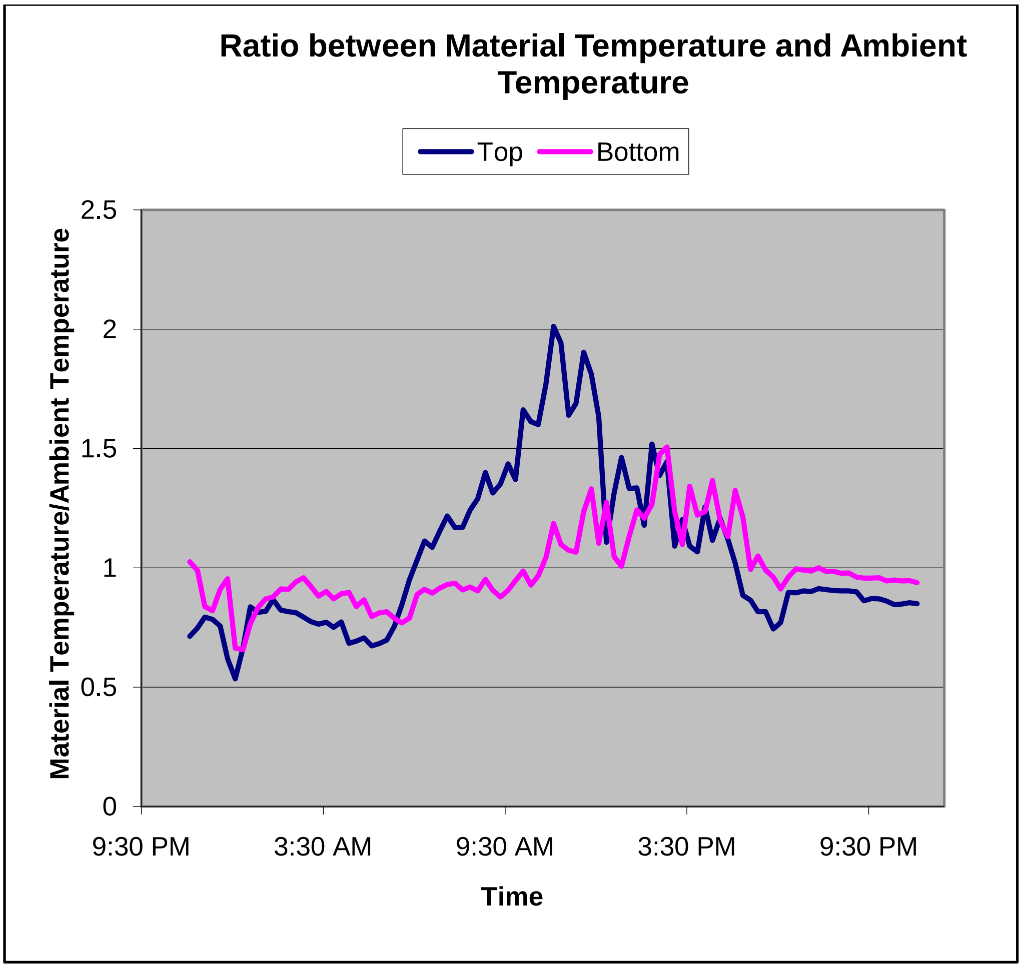


Figure 5.9: Ratio between ambient temperature and material temperatures at top and bottom walls of bonded pultrusion beam.

Though no mathematical relationship can be determined, Figure 5.8 indicates that as the ambient temperature increases, the higher the ratio between ambient temperature and the material temperature increases. This is explained by the data; with a peak ambient temperature of approximately 25°C, the material temperature increased to approximately 2 times that temperature, while when the ambient temperature was 10°C, the material temperature was almost equal to that. From this it can be expected that with ambient temperatures higher than 25°C, ratio between ambient and material temperature will also be greater.

As stated before, no mathematical relationship can be formed; however it can be predicted by the data that on very hot day when the ambient temperature reaches up to 40°C it is possible that the material temperature could reach well over 2 times this temperature, or at least 80°C.

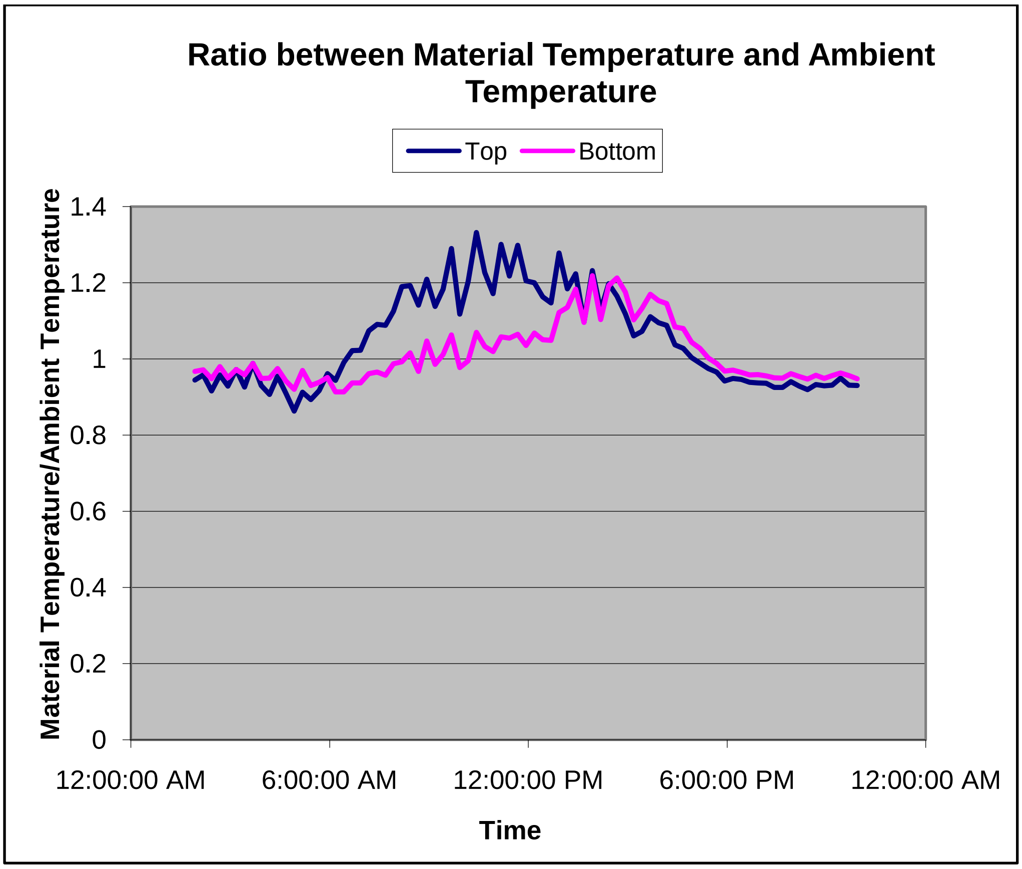


Figure 5.10: Ratio between ambient temperature and material temperatures at top and bottom walls of single pultrusion member.

It is seen that for a single pultrusion member rather than a bonded beam, the ratio between ambient and material temperature is considerably lower, approximately 1.3. This information does not display the same trends as with the bonded beam, as the peak ambient temperature was also approximately 25°C. This variation in behaviour between the bonded beam and pultrusion member indicate that the size and application of pultrusion members alters the effect of ambient temperature on the material temperature.

5.3.3 Conditions Affecting Temperature Variations

Although the experiments conducted give tangible results, the conditions in which the pultrusions were tested represent only one of many situations that would occur while a structure is in service.

Considering that pultrusions are used in 3 primary applications; electrical cross-arms, bridge decks and boardwalks, and each of these applications utilize different designs depending on the specific application, there are countless physical conditions that will affect temperature variations within the structure. These conditions include:

- Open ends: as the pultrusions are continuous hollow tube sections, they are produced with open ends, and can remain open-ended in applications. Depending on the application and positioning of a pultrusion member, various air drafts will flow through the member thus transferring heat through convection.
- The use of end-caps and/or inserts: End-caps are used for both aesthetic purposes and to cover open ends of the pultrusions used in cross-arms and boardwalks. In applications that use end-caps, the air within the pultrusion is static and unable to transfer heat through convection to the outside atmosphere. Similarly, inserts are used within pultrusions for structural purposes and will have similar effects to end-caps.
- Fixing configurations: in boardwalk and bridge deck applications, girder webs can be formed by a number of pultrusion either through mechanical fixings (bolts etc.) or bonding the surfaces with a glue/epoxy. Depending on the type of connection and the configuration of the bonded pultrusions, conduction of heat through the connected members will vary.
- Surface finishes: depending on the application, pultrusion members can be finished with a variety of coatings for a number of purposes including aesthetics, UV protection, electrical insulation etc. Each coat or finish will affect the reflection and absorption of light and heat.

Given that each application will include a number of these factors to varying extents, it is advised that the results of the experiments conducted cannot be used to predict the behaviour in all circumstances; however they do give an indication of the magnitude of any temperature gradients that occur within pultrusion members and structures.

5.3.4 Effect of Temperature Variation on Structure Design

It shall be noted that this section is not intended to represent all composite structures but will only be used as an example to give a broad indication into if and how changes in strength properties with temperature effect will affect a structure design. The values and calculations are based on a composite footbridge reviewed in Chapter 2.

Considering that the bending moment capacity of a pultrusion member is the primary strength property to consider during structural design, it is appropriate to analyse the change in this property with variations in temperature, rather than flexural strength.

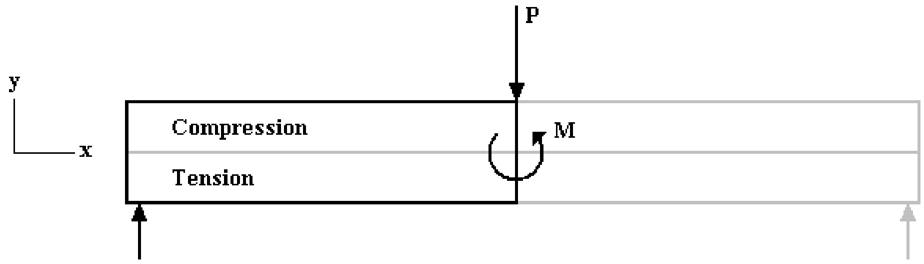


Figure 5.11: Schematic diagram of a member in 3 point loading, showing the reaction bending moment areas of tension and compression.

As shown in the above figure, a member under flexural loading creates a bending moment, which is a combination of tensile and compressive stresses. Established by mathematical modelling, tensile and compressive stresses are directly proportional to flexural stress, thus the bending moment is also proportional to flexural stress.

At any given point along the neutral axis, the longitudinal stress can be found by:

$$\sigma = \frac{My}{I} \tag{5.2}$$

where: σ = stress

M = bending moment

y = vertical distance from neutral axis

I = second moment of area

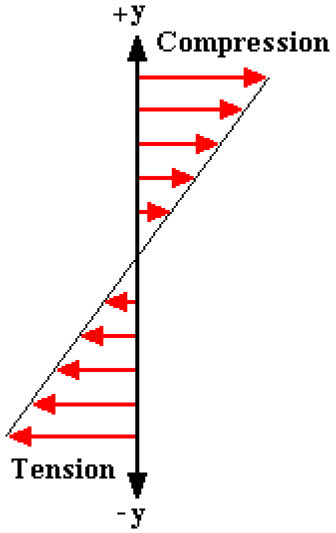


Figure 5.12: The linear force distribution along the y-axis of a member in flexure.

As seen in Table 5.1, the material tested at 105°C retained approximately 28% of its flexural strength at room temperature, so it is assumed that the bending moment capacity of a pultrusion member at this temperature will also be approximately 28% of that at room temperature.

In reference to Table 2.2, it has been established that at maximum load, the maximum bending moment within a typical composite structure is approximately 8%, thus at 105°C a composite girder will still withstand approximately 3.5 times the bending moment created in that example.

Though a composite structure will retain enough strength at high temperatures to withstand the forces created under maximum loading, the modulus may be reduced enough that the deflection exceeds the maximum allowable. It was found that the material retains 82% of its strength at room temperature when heated to 105°C, and that the deflection at of a structure under maximum load is approximately 80% of the allowable deflection. Considering that the deflection is inversely proportional to the modulus, a reduction to 0.82 of the original modulus will yield a deflection of $\frac{1}{0.82}$ of the original deflection:

$$\delta_2 = 1.22\delta_1 \qquad (5.3)$$

where: δ_2 = deflection at 105°C

δ_1 = deflection at 20°C

and:

$$\delta_1 = \delta_m \qquad (5.4)$$

where: δ_m = maximum allowable deflection

Therefore:

$$\delta_2 = 0.98\delta_m \approx \delta_m \qquad (5.5)$$

This shows that the deflection at 105°C can be considered equal to the maximum allowable deflection.

From the analysis of both strength and modulus variations within a structure it is seen that at an operating temperature of 105°C the strength properties of the material remain high enough, however the modulus reduces enough that the structure will reach the allowable deflection under maximum loads, thus improvements to the design should be made.

Again, it should be noted that these calculations and conclusions use data and design calculations from only one structure and cannot be used as general values. Separate and detailed analysis should be carried out each composite structure to determine the effect of property degradation on design specifications as each application is different requires a specific design.

6. Conclusions

In the first chapter of this dissertation, the objectives of this research project were outlined and all relevant information, processes, calculations and discussions that aided in achieving those objectives were presented throughout the chapters following the project introduction. This chapter is a summary of the work completed throughout the project and outlines the important information found during the project.

6.1 Temperature Effects on Material Strength

Based on experimental results obtained during flexural testing of material specimens at temperatures between 20°C and 105°C, it has been determined that the material strength displays a linear relationship to the temperature. This relationship is:

$$\sigma_f = -8.0875T + 1163.6 \tag{6.1}$$

where: 20°C < T < 105°C

Given that the material specimen was cut from a SHS pultrusion length, the flexural strength property is not particularly important in design and application; however the results obtained are useful in determining relationships between more relevant strength properties and material temperature. The relationship between flexural strength, tensile strength, compressive strength and bending moment capacity is directly proportional, thus it can be said that these properties also reduce linearly as temperature increases and in the same proportions as flexural strength.

From Equation 6.1, an approximate value of flexural strength, tensile strength, compressive strength and bending moment capacity can be calculated for any material temperature, if the room temperature (≈ 20°C) is known. This value can be calculated by:

$$S_T = kS_{20°C}T \qquad (6.2)$$

where: T = material temperature, 20°C < T < 105°C

S_T = property capacity at temperature, T

$S_{20°C}$ = Strength capacity at 20°C

k = 8.1×10^3

The relationship can only be considered linear within the temperature range as it is expected that the behaviour of plastic material strength will change after the Tg.

The results obtained for flexural modulus show that over the temperature range tested a maximum value drop of 18% occurred. Like the strength properties, the relationship between flexural modulus and tensile modulus are directly proportional thus it can be expected that this value will also drop a maximum of 18%. Considering the pattern of the results shown in figure 5.6, a sudden drop in modulus can be expected at temperatures exceeding 105°C.

6.2 Response to Temperature Variations of Structural Pultrusion Members

The results obtained show that for a 3 x 125 mm x 125 mm bonded member exposed to sunlight over a 72 hour period, the maximum temperature difference within the member was found to be approximately 17°C, which results in a of approximately 138 MPa difference in flexural strength, or 14% of all strength properties, between the top and bottom walls. For a single 100 mm x 100 mm member this difference was found to be 7°C, which created approximately 57 MPa difference in flexural strength, or 6% of all strength properties.

Analysis of the relationship between material temperature and air temperature showed that over the period tested, the maximum material temperature reached double the ambient air temperature. This occurred when the ambient air temperature was approximately 25°C. It was found that that the relationship between the two temperatures is not proportional, rather the ratio increases as the ambient temperature increases, meaning that for ambient temperatures up to 40°C, the material temperature may reach 80°C or higher.

It should be noted that as discussed in Chapter 5, these values should not be used in practice as they do not represent all applications and conditions, therefore should only be used as an indication of behaviour.

6.3 Consequential Modifications to Civil Structure Design

Using a composite footbridge as an example, it was found that even at temperatures up to 105°C, the material within the major structural members retained 28% of its strength at room temperature and therefore enough needed to support a maximum load. Though at 105°C the structure retains suitable strength, it should be noted that in natural environment when operating temperatures can be expected to exceed 40°C, the strength will reduce by at least 50%.

Though the strength properties remained suitable, the modulus is generally the governing property in composite structure design. It was calculated that at 105°C, the material modulus resulted in maximum load deflections that were approximately equal to the acceptable standard deflection. Given various estimations and assumptions, design modifications would be advised to minimise deflection if the structure were to be operating at temperatures approaching and above 105°C. For general structures exposed to natural environment conditions it is very unlikely that design modifications should be made to accommodate maximum operating temperatures.

Though these recommendations can be made for the composite footbridge that was analysed, a separate and more detailed analysis should be completed for each composite structure as there are numerous considerations differences between each application.

6.4 Further Research

Though the initial objectives of this project were completed, the detail and extent in which the topic of temperature effects on composite materials can be investigated much greater than the work involved in this project. As with any research project there are smaller details that relate to the topic that are not within the scope of the research, but do require a certain level of understanding.

Not only do relevant background studies aid in further researching and understanding the topic, the work completed within this project has formed the basis for further expanded research.

Relevant research that may add to and expand on this project topic include the following:

- Testing of the material in low temperature conditions and temperatures much higher than those tested in this project to view strength properties and behaviour over a relatively large range.
- Investigation into specific civil structure composition, the purpose and behaviour of each component while in service and the effect that variations in temperature have on the individual components.
- Detailed research into the interaction between the polymer matrix and fibre reinforcement, and the behaviour of failure at varying temperatures.
- Investigation into thermal conductivity properties and the relationship between the ambient air temperature and the material temperature when exposed to natural sunlight and various direct and indirect heat sources.

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Appendix A – Project Specification

Sam Zerbst Research Project 2009 10 March 2009

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Samuel Zerbst

TOPIC: Temperature Effects on Fibre Composite Materials

SUPERVISORS: A/Prof Thiru Aravinthan
Dr. Mainul Islam

ENROLMENT: ENG 4111 – S1 2009
ENG 4112 – S2 2009

PROJECT AIM: This project will investigate the change in physical properties of fibre composite materials under various temperatures in both regular and extreme conditions. Temperature gradients within fibre composite pultrusion will also be investigated.

PROGRAMME:

1. Research background information relating to temperature effects on existing fibre composite materials.
2. Gather mechanical property data for existing fibre composite materials.
3. Design an appropriate test arrangement and obtain suitable test pieces (Wagners Composite Fibre pultrusion) to setup in a controlled environment to monitor thermal conductivity and temperature gradient properties.
4. Test coupon specimens in an environmental chamber conditioned to various temperatures and collect test data.
5. Collaborate and arrange test data into a suitable format and find a conclusion based on these results.

As time permits:

6. Further comparison study on FEA and experimental results to provide a recommendation subjected to environmental effects.

AGREED:

________ (student) ________, ________ (supervisors)
Samuel Zerbst Thiru Aravinthan Mainul Islam

24/03/09 24/03/09 24/03/09

Examiner/Co-Examiner: ________________

Appendix B – Sample Data

The following information was collected directly by TestWorks 4 during testing and automatically exported to a Microsoft Word file. A separate report for each temperature sample is given and the values collected for each specimen within the samples are shown in the tables along with the plots of stress and strain data calculated during testing.

FLEXURE TESTING REPORT

Test Method: User Specified

Test Date:	Test Method:	Operator:
14/08/2009	CEEFC - Neat Resin & PFR (ISO 178).msm	Atul Sakhiya

Sample Information:

(A) Project Name:	Sam
(B) Sample ID:	
(C) Resin Name:	
(D) Curative Name:	
(E) Mix Ratio:	
(F) CastingType:	
(G) Attention:	Sam
(H) Nominal Spec. Dimensions:	100mm x 15mm x 5mm
(I) Casting Cure Schedule:	
(J) Nominal Span (mm):	85
(K) Conditioning Temp. & RH:	N/A
(L) Test Speed (mm/min):	3

Test Equipment Details:

Test Machine:	MTS Alliance RT/10
Location:	P9 110

Appendix B-1 Data Recorded for Sample Tested at 20°C

Specimen Results:

Table B - 1: Data recorded and calculated at 20°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	14.90	5.33	443	133.38	0.36	****	0.81	****	36715
2	14.90	5.33	3405	1025.52	3.35	2.78	6.29	6.29	38343
3	15.50	5.38	****	****	****	****	****	****	****
4	15.50	5.38	3436	976.48	3.13	2.79	6.24	6.24	36386
5	15.60	5.36	3357	955.07	3.11	2.67	6.01	6.01	38297
6	15.50	5.36	3563	1020.02	2.95	2.55	5.72	5.72	40254
7	15.60	5.11	3199	1001.38	3.12	2.68	6.31	6.31	38666
Mean	**15.42**	**5.31**	**3392**	**995.70**	**3.13**	**2.69**	**6.11**	**6.11**	**38389**
Std Dev	**0.29**	**0.11**	**132**	**29.72**	**0.14**	**0.10**	**0.25**	**0.25**	**1376**

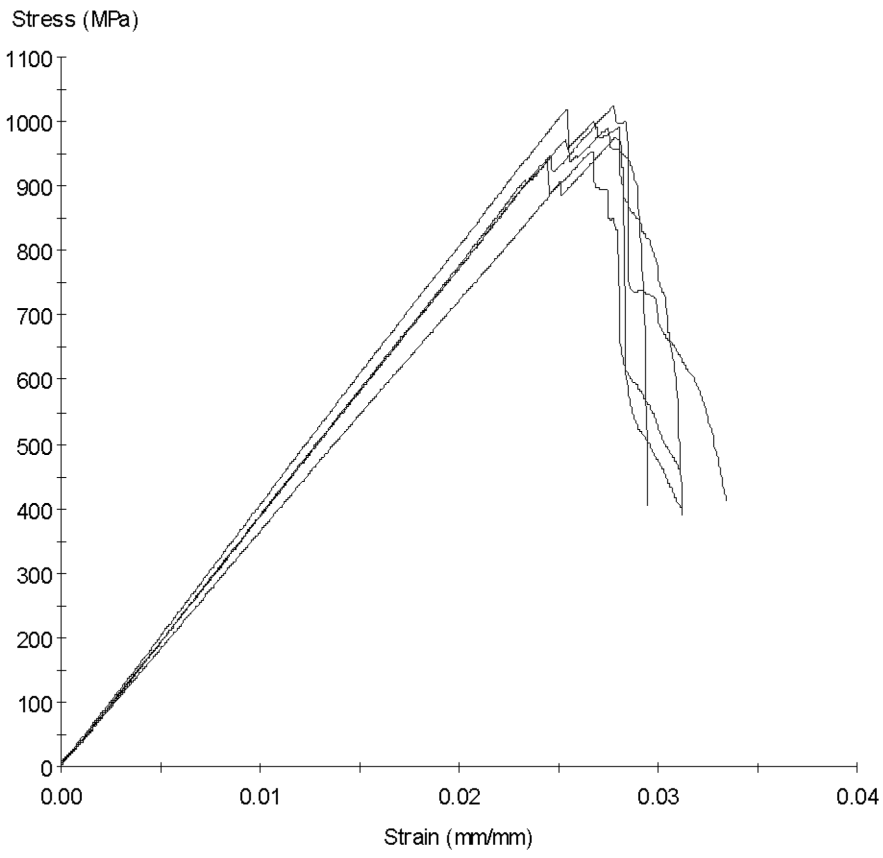

Figure B - 1: Stress vs. Strain plot for samples at 20°C.

Appendix B-2 Data Recorded for Sample Tested at 35°C

Specimen Results:

Table B - 2: Data recorded and calculated at 35°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	15.00	5.37	2875	847.40	3.22	2.36	5.29	5.29	35312
2	14.66	5.07	2682	907.57	2.84	2.43	5.78	5.78	37391
3	15.32	5.01	2906	963.47	2.79	2.66	6.38	6.38	37552
4	15.19	5.00	2687	902.09	2.77	2.56	6.17	6.17	37264
5	15.17	5.35	2836	832.71	2.87	2.31	5.19	5.19	34970
Mean	**15.07**	**5.16**	**2797**	**890.65**	**2.90**	**2.46**	**5.76**	**5.76**	**36498**
Std Dev	**0.25**	**0.18**	**106**	**52.31**	**0.18**	**0.14**	**0.52**	**0.52**	**1248**

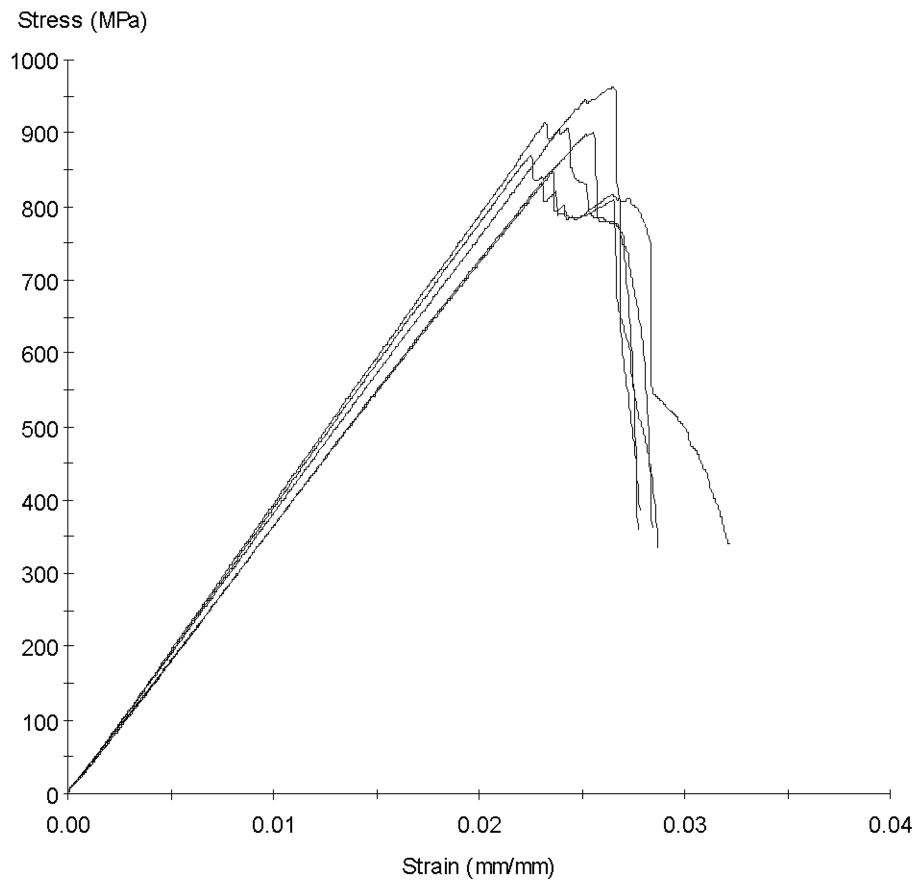

Figure B - 2: Stress vs. Strain plot for samples at 35°C.

Appendix B-3 Data Recorded for Sample Tested at 50°C

Specimen Results:

Table B - 3: Data recorded and calculated at 50°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	14.88	5.29	2574	788.28	3.29	2.24	5.10	5.10	35802
2	15.54	5.33	2561	739.53	3.47	2.25	5.07	5.07	36572
3	14.88	5.16	2189	704.33	2.94	****	4.48	****	34931
4	14.94	5.42	2412	700.75	2.77	****	4.36	****	35045
5	15.39	5.09	2367	756.89	2.72	****	4.67	****	38687
Mean	**15.13**	**5.26**	**2421**	**737.96**	**3.04**	**2.24**	**4.74**	**5.09**	**36207**
Std Dev	**0.31**	**0.13**	**158**	**36.77**	**0.33**	**0.00**	**0.34**	**0.02**	**1535**

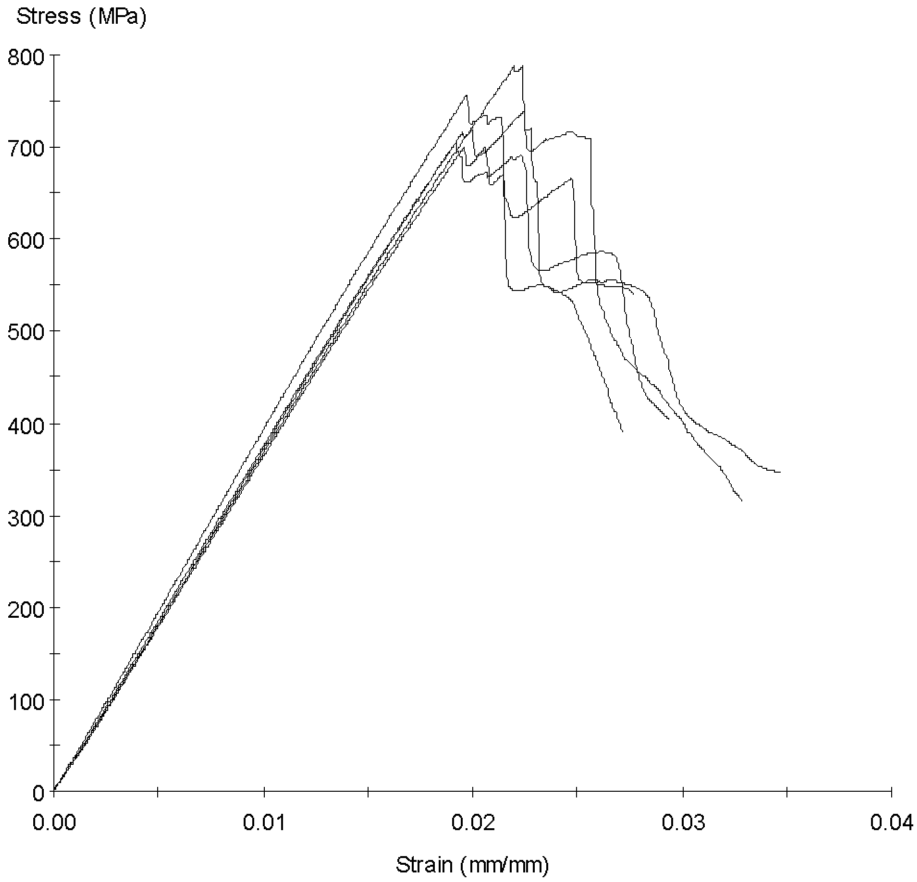

Figure B - 3: Stress vs. Strain plot for samples at 50°C.

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Appendix B-4 Data Recorded for Sample Tested at 63°C

Specimen Results:

Table B - 4: Data recorded and calculated at 63°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	15.13	5.02	1901	635.84	2.44	****	4.09	****	38712
2	14.97	5.06	1716	570.91	3.01	1.61	3.82	3.82	36967
3	14.97	5.37	2245	662.93	3.60	****	4.26	****	35974
4	15.39	5.11	2177	690.65	3.06	****	4.40	****	36785
5	14.73	5.17	2093	677.87	2.63	****	4.43	****	33997
Mean	**15.04**	**5.15**	**2026**	**647.64**	**2.95**	**1.61**	**4.20**	**3.82**	**36487**
Std Dev	**0.24**	**0.14**	**216**	**47.49**	**0.45**	**** **	**0.25**	**** **	**1713**

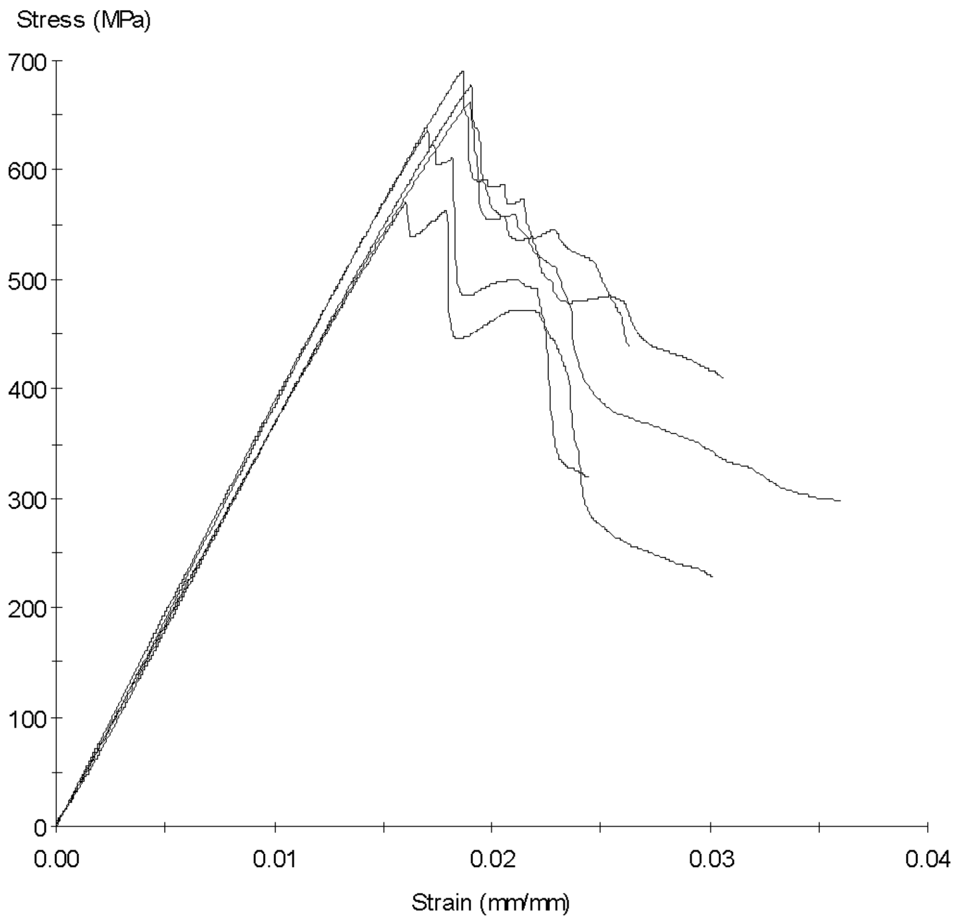

Figure B - 4: Stress vs. Strain plot for samples at 63°C.

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Appendix B-5 Data Recorded for Sample Tested at 77°C

Specimen Results:

Table B - 5: Data recorded and calculated at 77°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	14.47	5.20	1761	573.75	2.28	****	3.90	****	36170
2	14.92	5.12	1879	612.67	2.20	****	4.28	****	36270
3	15.60	5.41	1971	550.41	2.60	****	3.78	****	33593
4	15.38	5.10	1980	631.12	2.30	****	4.03	****	39745
5	15.77	5.14	1939	593.33	2.29	****	4.29	****	35254
Mean	**15.23**	**5.19**	**1906**	**592.26**	**2.33**	****	**4.06**	****	**36207**
Std Dev	**0.53**	**0.13**	**90**	**31.71**	**0.15**	****	**0.23**	****	**2251**

Table B - 6: Data recorded and calculated at 77°C.

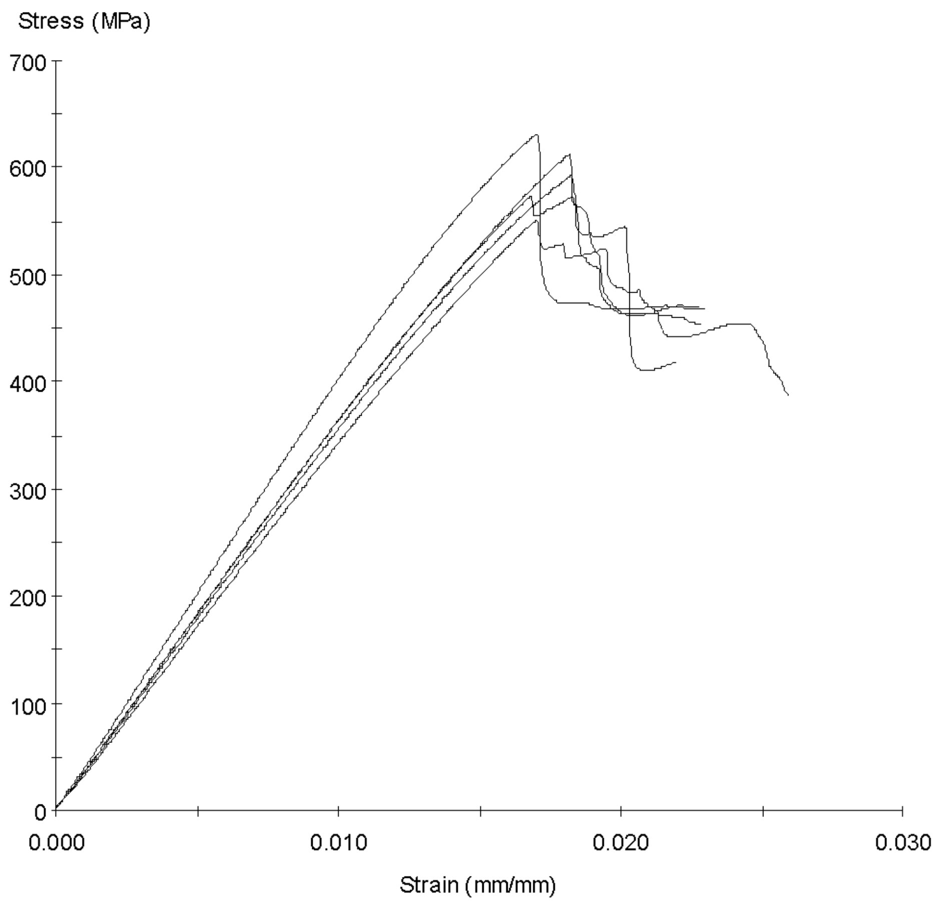

Figure B - 5: Stress vs. Strain plot for samples at 77°C.

Appendix B-6 Data Recorded for Sample Tested at 91°C

Specimen Results:

Table B - 7: Data recorded and calculated at 91°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	14.79	5.08	1241	414.53	1.96	****	3.08	****	35682
2	15.51	5.37	1476	420.78	2.28	****	3.39	****	33821
3	14.98	5.37	1491	440.21	2.16	****	3.43	****	35672
4	15.51	5.02	1231	401.65	1.89	****	3.08	****	35986
5	15.45	5.39	1409	400.30	2.90	****	3.34	****	31239
Mean	**15.25**	**5.25**	**1370**	**415.49**	**2.24**	********	**3.26**	********	**34480**
Std Dev	**0.34**	**0.18**	**126**	**16.30**	**0.40**	********	**0.17**	********	**2004**

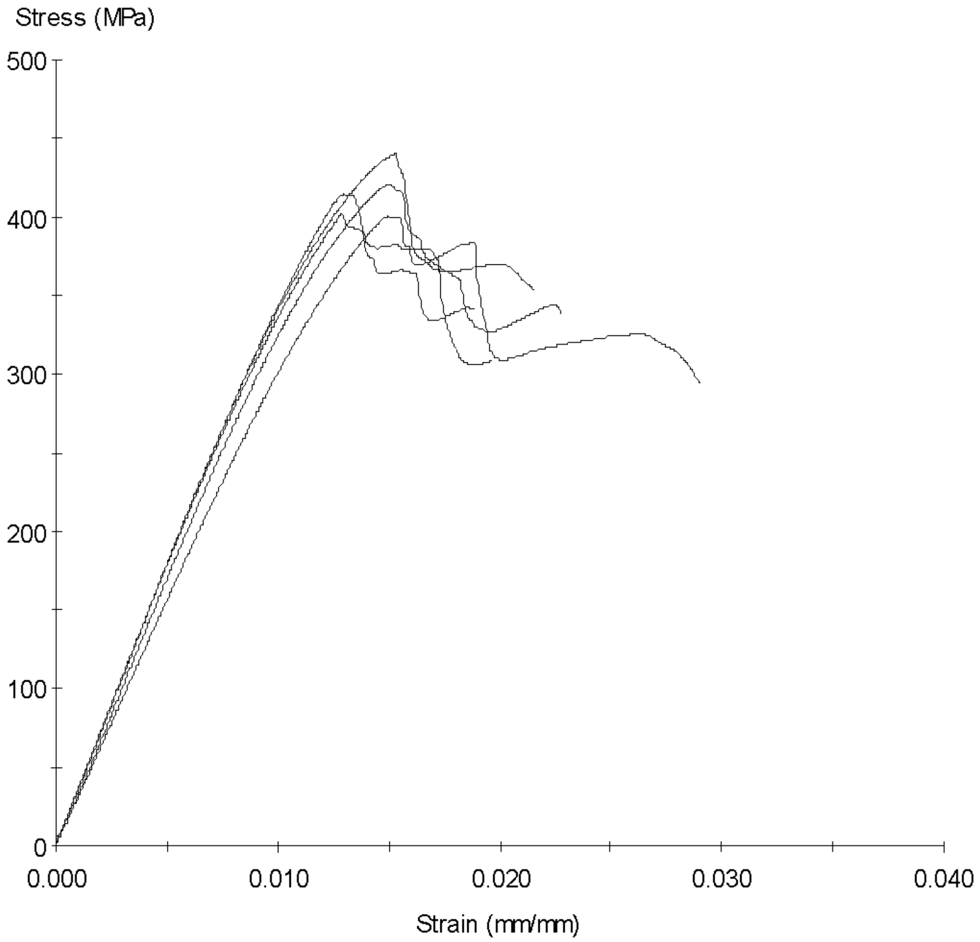

Figure B - 6: Stress vs. Strain plot for samples at 91°C.

Appendix B-7 Data Recorded for Sample Tested at 105°C

Specimen Results:

Table B - 8: Data recorded and calculated at 105°C.

Specimen #	Width mm	Thickness mm	Peak Load N	Peak Flexural Stress MPa	Strain At Peak %	Strain at Break %	Deflection At Peak mm	Deflection At Break mm	Flexural Modulus MPa
1	15.58	5.29	****	****	****	****	****	****	****
2	15.58	5.29	1114	325.87	2.07	****	3.55	****	31758
3	14.81	5.38	1062	315.90	2.58	****	3.31	****	33301
4	15.03	5.00	851	288.81	1.96	****	3.03	****	31044
5	14.92	5.33	944	284.09	2.37	****	3.32	****	31344
6	14.95	5.29	928	282.74	2.42	****	3.33	****	30367
Mean	**15.15**	**5.26**	**980**	**299.48**	**2.28**	********	**3.31**	********	**31563**

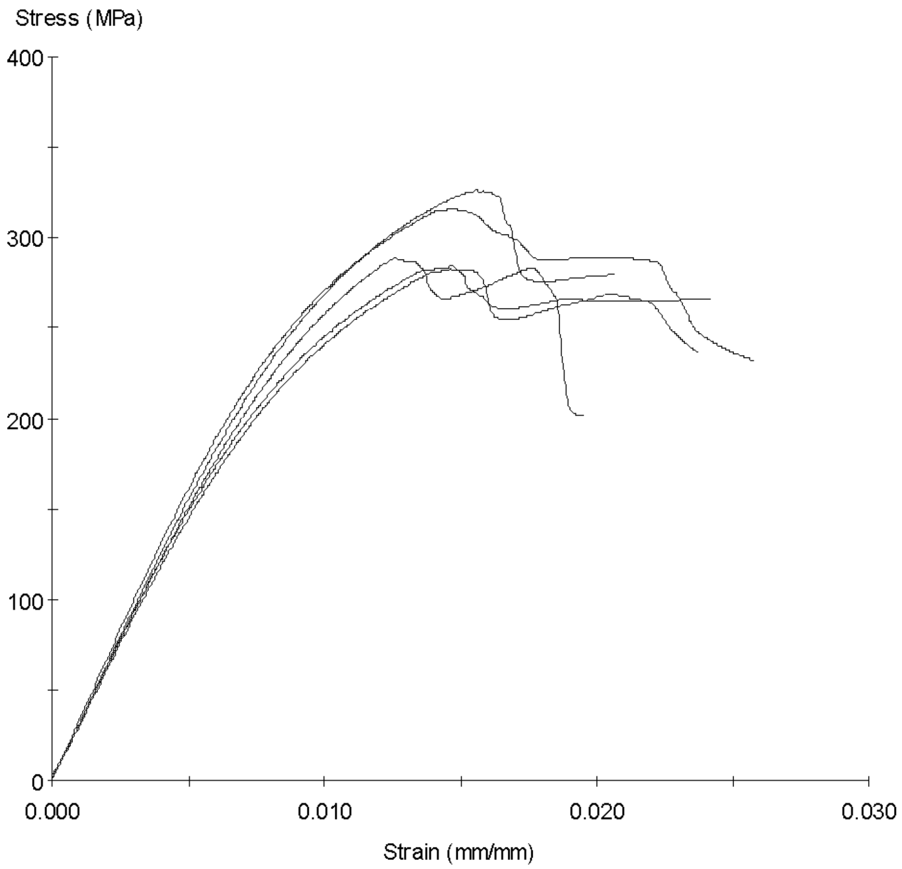

Figure B - 7: Stress vs. Strain plot for samples at 105°C.

Appendix C – Temperature Gradient Data

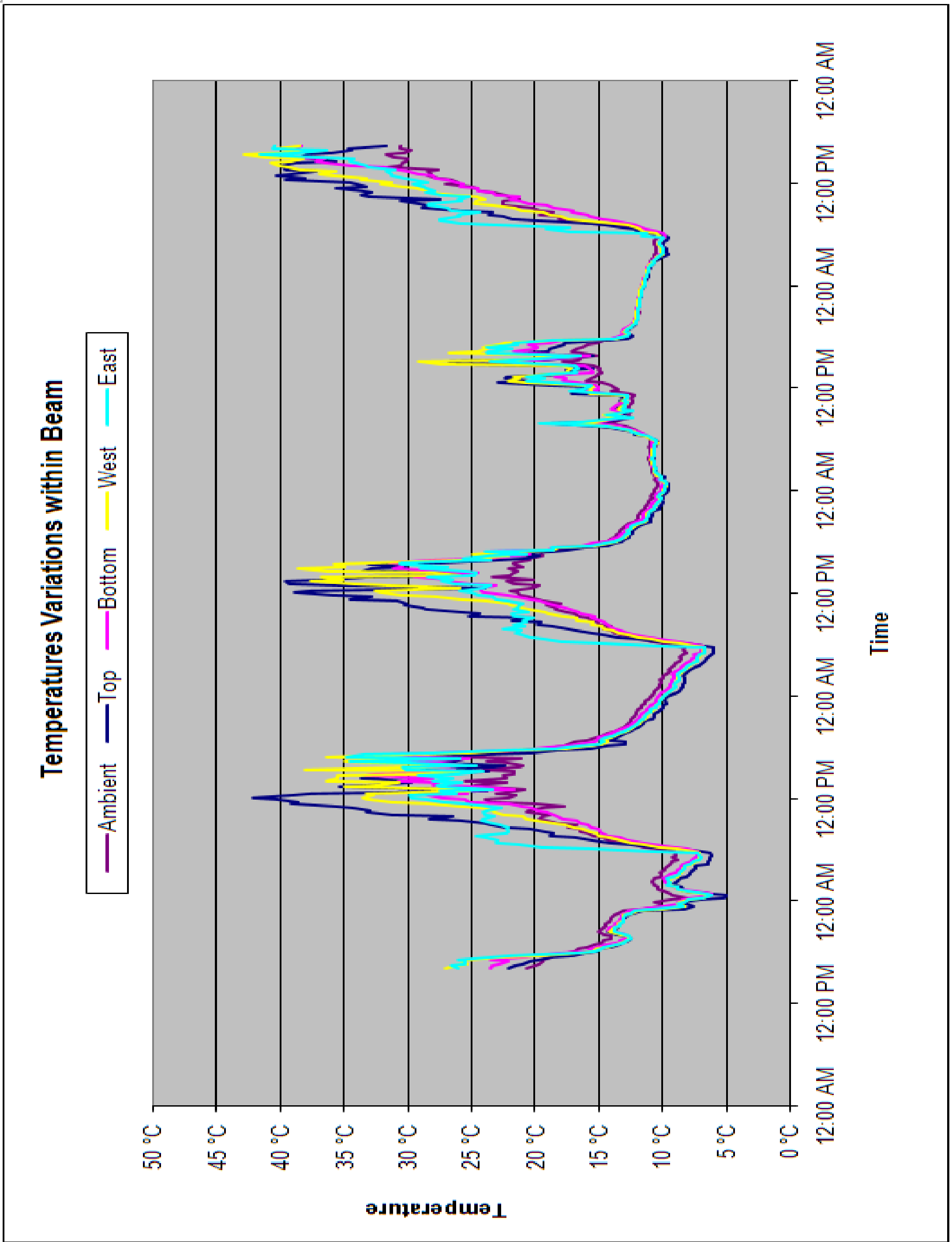

Figure C - 1: Temperature data for bonded pultrusion member over 96 hours.

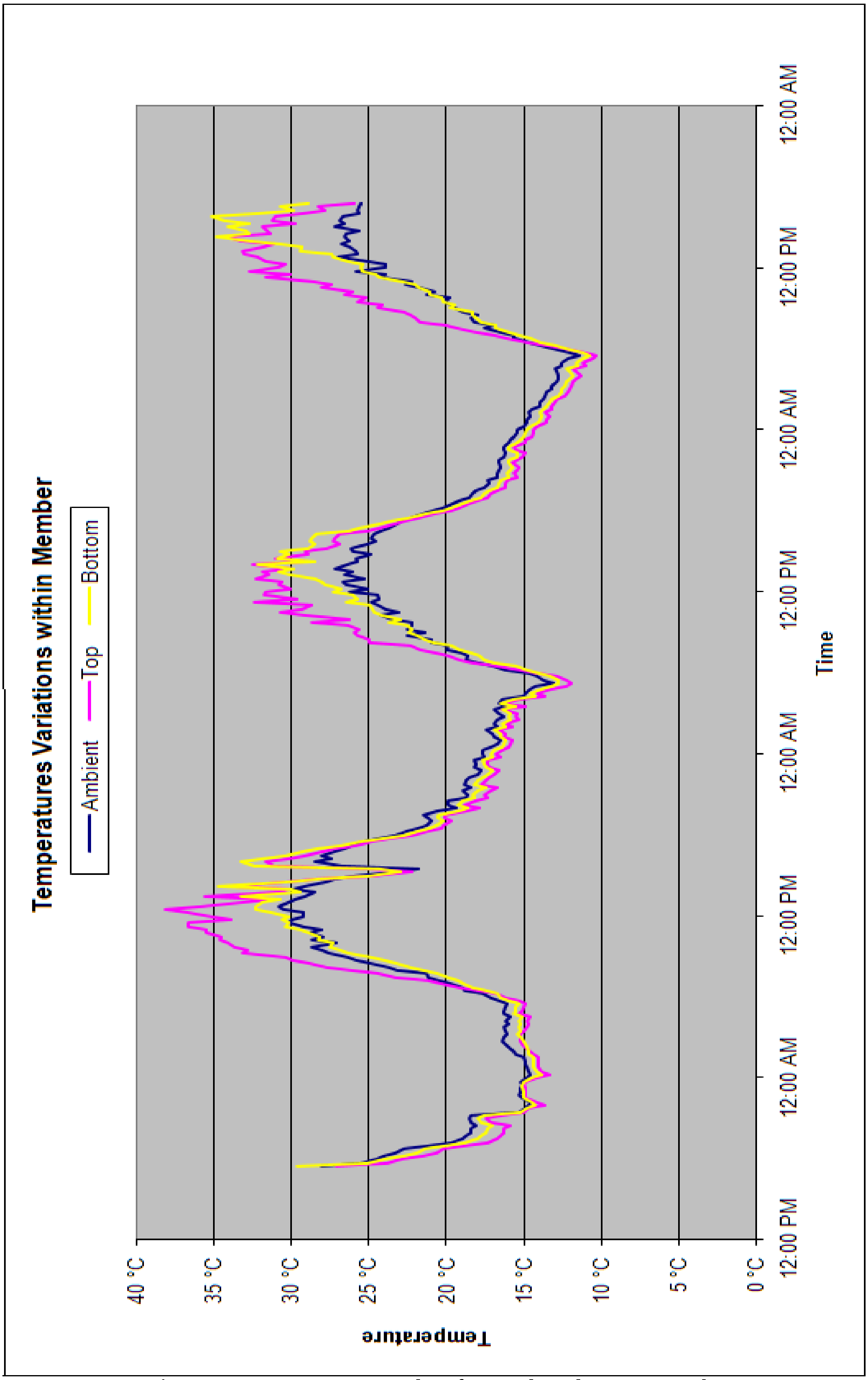

Figure C - 2: Temperature data for single pultrusion member over 72 hours.

Appendix D – Risk Assessment

The following risk assessment recognizes the hazards and risks involved in practical work that is undertaken throughout the duration of this research project. Table D-1 and Table D-2 include the guidelines that are used to determine the risk score of various practical activities.

	Consequences: How severly could it hurt someone?			
Likelihood: How likely could it happen	**Extreme** - death, disablement, >$200k	**Major** - serious bodily injury, $50-$200k	**Moderate** - casualty treatment, $5-$50k	**Minor** - first aid, no lost time, <$5k
Very likely - could happen frequently	**1**	**2**	**3**	**4**
Likely - could happen occasionally	**2**	**3**	**4**	**5**
Unlikely - could happen, but rarely	**3**	**4**	**5**	**6**
Very Unlikely - could happen, but probably never will	**4**	**5**	**6**	**7**

Table D - 1: Criterion for ranking hazards on a scale that considers the likelihood of an incident occurring and the damage that will result.

Score	**Action**
1, 2 or 3	Do something about these risks immediately
4 or 5	Do something about these risks as soon as possible
6 or 7	These risks do not need immediate attention, although precautions should be taken

Table D - 2: The recommended actions to be taken for hazards ranked in table 1.

The following tables are Job Safety Analysis (JSA) tables which indicate the processes that are used in the preparation and testing of materials throughout the course of the project work to ensure and personal injury or equipment damage is avoided.

PROCESS STEPS	POTENTIAL HAZARDS AND RISKS	RISK	HAZARD CONTROLLED MEASURES	NEW RISK
Identify task	Injuries caused by trips and slips	6	Ensure clean and tidy work area	7
Select sanding tools for the job	Injuries caused by trips, slips and manual handling of larger tools	6	Ensure clean and tidy work area	7
Set benches, rollers etc to suit the job	Cut injuries due to sharp bench edges, injuries from moving heavy benches	6	Use correct procedures to move benches, inspect benches for sharp edges	7
Sanding process	Hearing damage, skin, eye and respiratory irritation	5	Safety glasses, steel cap boots, gloves and respirators to be used	7
Clean work area	Injury due to slips and trips	6	Use correct housekeeping and general safety	7

Table D - 3: Sanding Fibre Composite Materials.

PROCESS STEPS	POTENTIAL HAZARDS AND RISKS	RISK	HAZARD CONTROLLED MEASURES	NEW RISK
Preparing to lift materials manually	Injuries caused by trips and slips	5	Ensure clean and tidy work area before working out how to lift	7
Lifting loads	Injuries caused by manual lifting, hands and fingers in pinch points, contact with the load	5	Use of PPE, correct lifting techniques, hand and fingers away from pinch points	7
Repetitive lifting or work	Strains and fatigue	4	Job rotation, regular breaks	6

Table D - 4: Manual Handling.

PROCESS STEPS	POTENTIAL HAZARDS AND RISKS	RISK	HAZARD CONTROLLED MEASURES	NEW RISK
Setting up	Injuries caused by manual handling, pinch points, slips and trips	6	Ensure clean and tidy work area, know the machine setup procedure	7
Using machine	Injuries caused by debris, hands and fingers in pinch points	6	Use guards on machines, protective glasses, keep hands and fingers clear of pinch points	7
Shutting machine down	Injuries due to manual handling, pinch points	6	Use correct shut down procedures, know the machine	7

Table D - 5: Use of MTS Machine and Environmental Chamber.

PROCESS STEPS	POTENTIAL HAZARDS AND RISKS	RISK	HAZARD CONTROLLED MEASURES	NEW RISK
Select correct tool for job	Overworking a tool may cause injury, injury caused by unserviceable tools	5	Use tools of correct size and condition, tag electrical leads, fit guards where necessary	7
Make tool ready for use	Electrocution from power tools or leads. Hand injuries due to adjusting tools	5	Use tools supplied for adjustment	7
Use of tool	Injuries from shavings, sparks, sharp tools. Burns from welders, torches etc	4	Use of PPE, basic training of tools	6
Cleaning and replacing tools	Cuts from sharp filings, irritation from shavings and dust	5	Use of PPE	7

Table D - 6: Power Tool Operation.