University of Southern Queensland

Faculty of Engineering and Surveying

Durability of Hybrid Concrete-FRP Bridge Decks

A dissertation submitted by

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Abstract

Conventional bridge building materials, like timber and steel, have problems that can limit their expected service life. These problems include termite and fungi attack for timber, and corrosion for steel. These problems do not affect the hybrid concrete–composite bridge produced by Wagners Composite Fibre Technologies. However, the use of composite materials in the infrastructure industry is relatively new. Their wide acceptance by the industry is therefore tributary on assessing their long-term durability.

The aim of this project is to determine if there are any durability related concerns with the hybrid concrete-composite Bridge produced by WCFT. The durability investigation was carried out at Wagner Composite Fibre Technologies, and it dealt mainly with the durability of the adhesive joints used in the construction of the hybrid bridge. Indeed, adhesive joints were identified as the primary area of durability concerns within the FRP Bridge. After subjecting small coupons to a range of environments no considerable change in shear strength was observed. Due to the short time allocated to conducting this durability investigation, the findings were complemented with a literature review.

This investigation highlighted a number a key aspects that should be observed in future investigations; these include:

- having a long environmental exposure time, for example over 1 year
- have many samples
- investigate only one or two environmental conditions
- have specifically dedicated resources
- use an accurate method to measure weight variations

The literature review also resulted in no alarming results. Some researchers have observed considerable changes in strength after exposure. These were the results of extreme environments that the bridge would be unlikely to be exposed to.

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Table of Nomenclature

FRP = Fibre Reinforced Polymers

WCFT = Wagner Fibre Composite Technologies

FCDD = Fibre Composite Design and Development

ASTM = American Society for Testing Materials

S_H = Shear Strength, N/m^2

P_B = Maximum Load, N

b = Width of Specimen, mm

d = Thickness of Specimen, mm

Chapter 1

Introduction

1.1 Current State of Civil Infrastructure

The Institute of Engineers Australia estimates that over $40 billion will be required for upgrades and maintenance of Australian bridges [1]. Approximately 60% of the 10,000 timber road bridges in Australia were built before the 1940's. Only 100 –150 bridges are replaced each year. This infrastructure problem is even worse for the concrete bridges in the USA, Europe and Japan. This problem is due to the de-icing salts used in these countries [1].

Currently bridges are constructed using timber, steel and concrete. These conventional materials however have individual problems. These problems can lead to a reduced life span or make them unfeasible in certain situations.

Most of the timber bridges in Australia only carry local traffic, usually over a small local creek. These bridges are relatively small and usually single span. In this situation timber is the ideal material. However the availability of suitable timber is becoming increasingly harder to locate as a result of stricter anti-logging legislation.

Termite attack is another problem with timber materials. To prevent termite attack the timber is chemically treated. If these chemicals leach into the environment more damage to the environment will be done. [2]. White rot is another problem with timber bridges. Figure 1.1 shows degradation caused by white rot. The figure shows where the fungus has degraded the timber bridge.

Figure 1.1: White Rot Degradation of Frank Creek Bridge, Wide Bay District (Source: [3])

Concrete is another conventional material commonly used in bridge construction, however concrete is very heavy. The cost of transporting precast concrete can be significant. As most bridges are small and situated in remote areas it may not be feasible to pay the high transport cost.

Another problem with concrete is that the steel reinforcement used corrode. When moisture has easy access to the reinforcing steel corrosion will occur, this will reduce the strength of the steel. The access of moisture is dependant on the moisture in the environment and the protection of the steel.

Although concrete has these problems it cannot be discarded completely as a building material. It is very durable and has a low cost. Concrete is also very effective at carrying compressive forces.

Steel also has some durability issues when used as a building material in civil infrastructure. The major problem is the low corrosion resistance of some steels. During routine maintenance, paint may be applied to prevent corrosion. This to, can leach into the environment and cause damage [2]. This routine maintenance may not be done by a council because of personnel and budgetary restrictions. Steel is also relatively expensive.

Fibre reinforced polymers (FRP) do not have any of these problems: be it corrosion or rotting. This makes them a suitable material to replace these conventional materials. They also have a number of advantages that make them perfect for use in various industries.

The main advantage of FRP material is its strength to weight ratio, this can be up to five times that of steel. The fatigue strength of FRP material is better than steels [4]. FRP has a very good resistance to corrosion and chemical attack. They also have a very high resistants to termite attack [2]. Composites also have better noise and vibration properties than metal [4].

The main disadvantage of composite materials is the higher initial cost. However this can be lowered by combing FRP material and concrete to construct the bridges. Hybrid concrete-FRP bridges also have no constant maintenance costs that a bridge constructed of conventional materials requires.

Unlike conventional materials, designs including FRP materials are conducted without the use of design handbooks. Regarding other disadvantages, composite also absorb moisture, which can affect the strength and dimensions of the material.

Although the initial cost of a concrete-FRP bridge may be high, the low maintenance cost may offset this higher cost. The low maintenance cost however depends on the durability being assessed and proven. As FRP materials have a relative short history, the long-term durability is not yet fully proven.

Two Australian companies, Wagner Composite Fibre Technologies (WCFT) and Fibre Composite Design and Development (FCDD), have already completed the technical prototyping of the hybrid concrete-FRP bridge. Also, the first FRP bridge deck installed in the road network in Australia has also been completed. This bridge was installed near Grafton, New South Wales in February 2003 [1]. This bridge can be seen in Figure 1.2.

Figure 1.2: 1st FRP Bridge in the Australian Public Road Network (Source: [2])

As WCFT has a good understanding of the design and construction of hybrid concrete-FRP bridges further investigation in this area is not required. However durability is not as well understood. Therefore this project will attempt to determine if there are any major durability concerns with the construction of the hybrid concrete-FRP bridge produced by WCFT.

WCFT is a Toowoomba based company that was started in 2001 when they saw an opportunity to develop materials that would be used in a range of applications. The main projects being conducted utilizing FRP materials are bridges, beams, power pole cross arms and lightweight semi trailers.

1.2 Fibre Reinforced Polymer Material Durability

Durability testing of FRP materials are currently being conducted to evaluate the long-term reliability of the material. There are a number of factors that affect the durability of FRP material; these include moisture, temperature and exposure time.

To determine the durability of FRP materials, previous studies will be reviewed. Tests will also be conducted at Wagners on the area of the hybrid concrete-FRP deemed to be susceptible to durability concerns.

1.3 Durability Evaluation

To determine the durability of the hybrid concrete-FRP bridge, it will be investigated as several sections. These individual sections will be investigated separately. These sections include the concrete, the FRP material and the adhesive joints.

To test these different areas, accelerated methods are to be used. These accelerated methods mimic the actual environment the bridge may encounter during its service life. For instance, it will experience cycles of dry and wet conditions, high and low temperatures, and UV light. However, the most deleterious environment is moisture ingress into the fibre/resin matrix. To test for this particular environment, samples of FRP are immersed in solutions like deionised water, and salt water.

Freeze thaw cycling is another method of evaluating the durability of the different areas of the bridge. Evaluation of freeze thaw durability is not a major concern in Australia, however in snow prone areas like Canada, Russia and parts of the United States of America it is important. As WCFT has already constructed and installed a bridge in such an area, which can be seen in Figure 1.3, freeze thaw testing is important.

Figure 1.3: Wagner Composite Technologies Bridge Installed in Erie County, New York, United States of America (Source: [2])

1.4 Limitations of Current Investigations

It is important to realise that the durability of FRP materials is not yet properly assessed. It is also important to realise that the information gained from this investigation will also be limited. The main limiting factor is the time allocated for the completion of this dissertation. This dissertation is to be completed over one year, which a very short time for conducting durability tests. As a result, the test samples will be subjected to the environments for only a few months.

In addition, accelerated testing is carried out in extreme conditions. These environments may cause damage that is unlikely to occur during the service life of the FRP material.

Once the limitation of the investigation is realised, the information that will be gained needs to be examined for a purpose. In this case the investigation will focus on the first years of use of the FRP bridge.

1.5 Project Aim

This project aims to determine if there is any major durability related concerns with the construction of a hybrid concrete-FRP bridge and determine if they are applicable to the bridge deck produced by Wagner Composite Fibre Technologies.

1.6 Dissertation Overview

Chapter 1: Introduction
This chapter shows the problems with conventional bridge building materials and how FRP materials are a likely substitute for these materials. Durability evaluation and testing is also discussed. It also indicates the limitations of the investigations.

Chapter 2: Fibre Reinforced Polymers

This chapter discusses the manufacturing processes, fibre types and resins that are used by FRP manufacturers like Wagners Composite Fibre Technologies.

Chapter 3: Wagners Bridge Deck

In this chapter the set up of the bridge deck produced by WCFT is discussed. The material produced by WCFT is also discussed.

Chapter 4: Durability of Composite Fibre Material and Concrete

This chapter involves a discussion about the durability of the different materials used in the construction of the bridge; this includes FRP, concrete and stainless steel.

Chapter 5: Durability of Adhesive Joints

This chapter details the pervious studies conducted on joints between FRP and FRP as well as the joint between concrete and FRP.

Chapter 6: Test Sample Manufacture and Environmental Conditions

In this chapter the methods of accelerated testing used in durability tests is discussed. The effects of these tests are also discussed.

Chapter 7: Moisture Absorption and Shear Test Results

The durability investigations conducted at Wagners Composite Fibre Technologies are detailed in this chapter. This testing will examine the durability of the adhesive joint between FRP materials.

Chapter 8: Conclusion and Recommendations

This chapter will conclude the literature review and present testing and give some recommendations as to further investigations that should be completed.

Chapter 2

Fibre Reinforced Polymers

2.1 Introduction

Fibre reinforced polymers (FRP) are a combination of two materials: fibres and a polymer matrix, resin is the most common matrix. The fibres and polymer matrix have different functions. The fibres carry 70% to 90% of the structural load and ensure the structure has stiffness and strength. The polymer matrix provides the shape and rigidity of the material as it binds the fibres together [3].

There are three main types of fibre: carbon, glass and aramid, each of these fibres have slightly different characteristics and uses. Carbon fibres are used in high performance areas because of their high strength and high stiffness. However carbon fibres are rarely used because of their high cost. Aramid fibres are mainly used in ballistics because of their high-energy absorption. They are rarely used in infrastructure because of their inability to bond to resins. Glass fibres are the most common because of their relatively low cost and high flexibility [5]. As Wagners Composite Fibre Technologies (WCFT) only uses glass fibres, this will be the focus of the investigated

The second part of FRP materials is the resin. The three main types of resin used in civil infrastructure are epoxy, vinylester and polyester. Epoxy is the most common resin and is used in many different applications from pultrusion to bonding material. Vinylester and polyester are not quite as versatile as epoxy, but they are much cheaper which makes them a more viable resin.

FRP materials have a number of advantages over conventional materials. The main advantage of FRP material are their high strength to weight ratio, this can be up to five times that of steel. Furthermore FRP do not corrode and are resistant to termite attack. This gives them advantages over steel and timber as these features means that there are low life cycle costs. FRP also have low thermal and electrical conductivity. There is also excellent flexibility in design of FRP bridges [2].

WCFT is a Toowoomba company that specialises in the production of FRP material. They have constructed and installed hybrid concrete-FRP bridges in Grafton, Darwin, Blackbutt and in the United States of America. WCFT have also been developing FRP cross arms for power poles, railway sleepers and a lightweight flattop semi-trailer [2].

FRP materials have been used in aerospace, marine, transport and leisure industries. Nowadays FRP materials are finding their way into civil infrastructure and now are the second major user [4]. In Australia, the first hybrid concrete-FRP bridge on a public road was installed in February 2003 near Grafton, New South Wales. WCFT and Fibre Composite Design and Development (FCDD) developed this bridge. It was then constructed and installed by WCFT. The installation of the bridge took only four days [6].

2.2 Glass Fibres

Glass fibres are account for about 90% of the fibres used in the composite industry. This is because of their low relative cost. They have been used in car bodies, boat hulls and in sporting applications like fishing poles [7]. Glass fibres are sold in two ways, in a woven fabric or as a continuos fibre on a roll. WCFT uses only glass fibres thus this will be the focus of this investigation. This section is only a brief introduction of glass fibres not a detailed investigation.

Glass fibres are a combination of silica, bionic acid, limestone and several other products like clay and fluorspar. To create the glass, all the materials are melted in a high refectory furnace and then put into a fibre-drawing furnace. This molten glass is then fed through small openings of 1-3 mm and then through another aperture with a diameter of 3-20 μm [8]. This produces a continuos glass fibre.

By adding different chemicals, glass fibres with different characteristics can be produced. These include A, E, C, S-2 and R glass. These different compositions have varying advantages, these can be seen in Table 2.1.

Table 2.1: Glass Fibre Range and Advantages (Source: [7])

Glass Type	Advantages
E	High Electrical Insulation
A	Good Chemical Resistance
C	Excellent Chemical Resistance
S-2	Higher Tensile Strength
R	Good Alkali Resistance

Glass fibres are commonly used because of their low specific gravity and their good insulating properties. Glass fibres are also relatively inexpensive [7].

2.3 Resin

Resins form the second part of the FRP material. A resin matrix is formed around the fibres through impregnation by one of several different manufacturing processes. Once the resin has cured the final product is produced.

In the composite industry there are three main types of resins. These are epoxy, vinylester and polyester. WCFT use epoxy and vinylester to produce their different products. This section is only a brief introduction of resins not a detailed investigation.

Vinylester and polyester are thermoset resins, typically cheaper than epoxy. A comparison of vinylester, polyester and epoxy is shown in Table 2.2.

Table 2.2: Mechanical Properties of Epoxy Polyester and Vinylester (Source: [5])

	Density (kg/m^3)	Tensile Modulus (Gpa)	Tensile Strength (Mpa)	Compressive Strength (Mpa)	Flexural Modulus (Gpa)	Flexural Strength (Mpa)	Approximate Cost (AUD$/kg)
Epoxy	1000-1300	2.4-6	55-100	90-115	2.9	95-125	10-12
Vinylester	1000-1200	3.2-3.6	70-90	105-125	2.8-3.4	100-145	6-8
Polyester	1100-1460	2.8-3.4	40-80	100-120	2.5-3.2	80-100	3-4

2.3.1 Epoxy

Epoxy is the most common resin because it can be used in many different ways and applications. It is a thermoset resin, this means once the resin has cured it cannot be remelted and reformed. Thermoset resins are brittle, but they have a better fibre penetration.

The main advantage of epoxy is its excellent mechanical properties and its excellent adhesion. Epoxy is also safe while it is curing, as there are no volatile by products released. However these properties mean that epoxy is one of the most expensive resins. There is also a longer curing time compared to other resins. By changing the chemicals involved in the manufacture of epoxy, these characteristics can be changed or improved.

Epoxies are made of two parts, a catalyst and a hardener. By mixing these two parts together a curing reaction occurs. Changing the hardener can alter the cure rates of the epoxy.

There are three forms of epoxy: liquid, semi solid and solid. These different forms allow epoxy to be used in many different applications. A liquid epoxy can be used in the pultrusion, filament winding and lay-up manufacturing processes. When the epoxy is solid it can be used to bond materials together.

2.3.2 Vinylester

Vinylester resin is a combination of epoxy and acrylic resins and has similar curing properties to epoxy. It was developed for use in corrosive environments. The other major advantage of vinylester is that it has better mechanical properties than most unsaturated polyesters [4]. This property means that they are being increasingly used in civil infrastructure.

These improved properties mean that the cost of vinylester is more than the polyester. Vinylester resin is also sensitive to UV radiation. However this damage can be minimised with the use of a UV resistant coating. [9]

2.3.3 Polyester

Unsaturated polyesters are a very common type of resin, they account for 75% of the total resins used. They are however best known for their use in textiles and clothing. Polyesters can be used in a variety of manufacturing processes and have been used to produce boats, truck components and furniture [10].

Polyester resins are a combination of reactive polymers and reactive monomers. To induce curing a catalyst is required. When polyester is curing nothing is released which makes it very safe. There are many different types of polyester, each with their own advantages. These include low shrinkage, weather resistant, chemical resistant and general purpose. [11]

2.4 Production Methods

The production of FRP material can be accomplished through many different processes. The most common of these processes are pultrusion, lay-up, filament winding and die moulding. The processes used at WCFT are pultrusion and lay-up. In this section, a basic introduction of these two processes is discussed.

2.4.1 Pultrusion

Pultrusion is an automated process that produces a continuous product of constant cross sectional shape. The fibres used in this process can be rovings, filament mats and fabrics. Figure 2.1 shows the layout of a pultrusion machine.

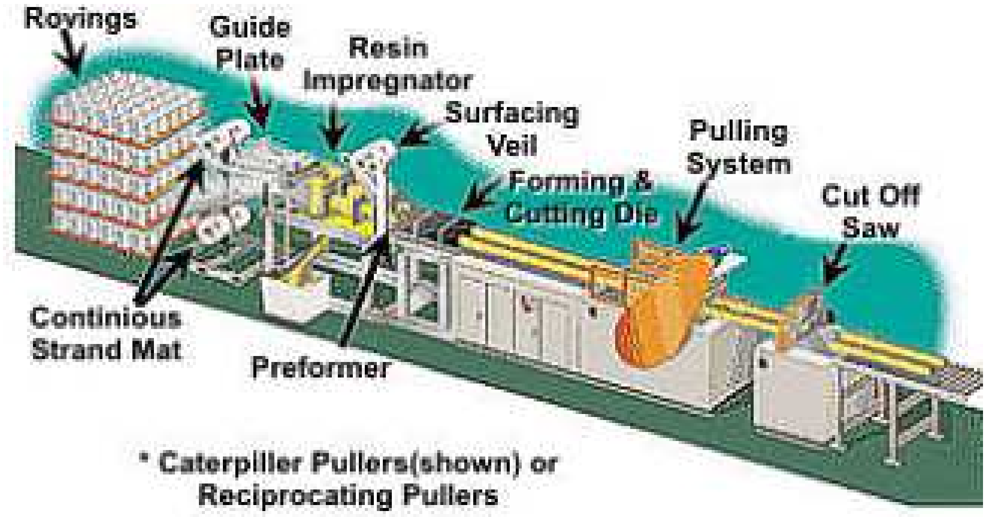

Figure 2.1: Pultrusion Machine (Source: [2])

This figure shows that the glass fibres are kept in rovings, stored in a rack. These glass fibres are pulled through a resin impregnator, this is where the fibres are 'wet out' by the resin. This wet material then passes through a forming and curing die. The curing die heats the wet material to a temperature over 100^{o}C in order to cure the resin.

Throughout this process a set of pullers are used to keep the material moving at a constant rate. When the required length of material has been produced a cut off saw located at the end of the machine cuts the material. This process can produce a range of shapes. Figure 2.2 shows some of these shapes.

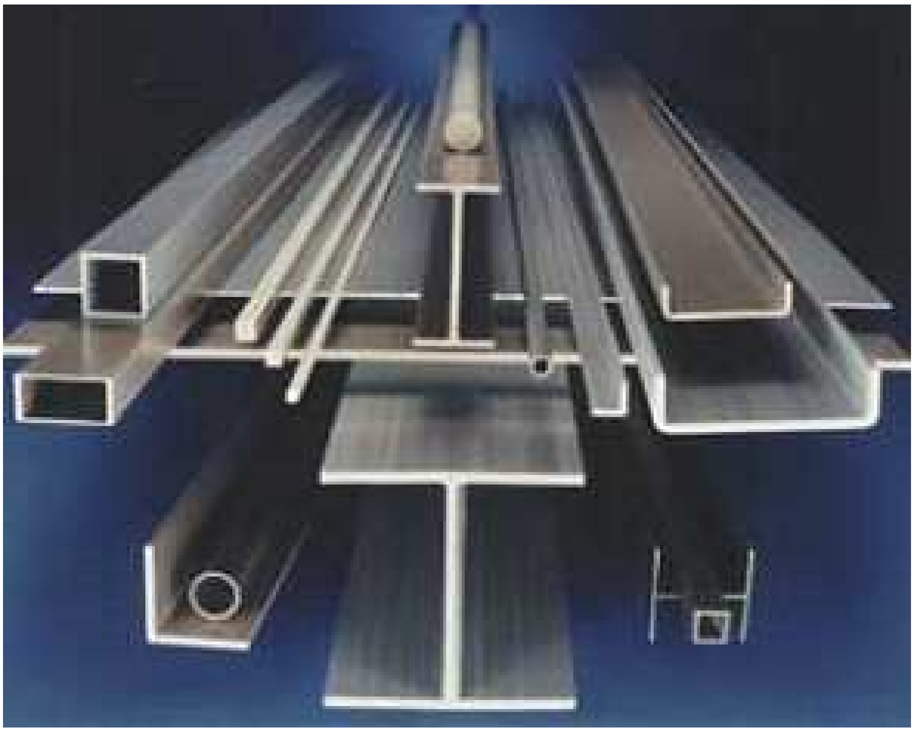

Figure 2.2: Typical Pultruded Shapes (Source: [12])

This process produces material with a fibre volume of about 60%. Pultrusion can produce products with very high strengths and can generally be performed at a low cost. This process also produces a low material scrap rate, as the control of the process is very good.

2.4.2 Lay-up

The lay-up method is the most common process of manufacturing FRP material. It is however very labour intensive. This process can produce material with many different shapes and cross-sections. The problem with this process however, is that it produces a low fibre content in the fibre material. The average is about 40%. A lower fibre volume results in a material with lower strength and stiffness.

In this manufacturing process, dry glass roving and resin are combined using hand rollers. The orientation of the glass rovings that can be used in the lay-up process varies. Typical orientations include unidirectional fibres, and a combination of unidirectional and 45^{o} rovings. FRP material can be designed to have adequate shear strength by varying the orientation of the fibres. The manufacturing process is the same for all the glass orientations. Figure 2.3 shows the fibre orientation of a triaxial fibre. As a comparison biaxial fabric only has 0^{o} and 45^{o} fibres.

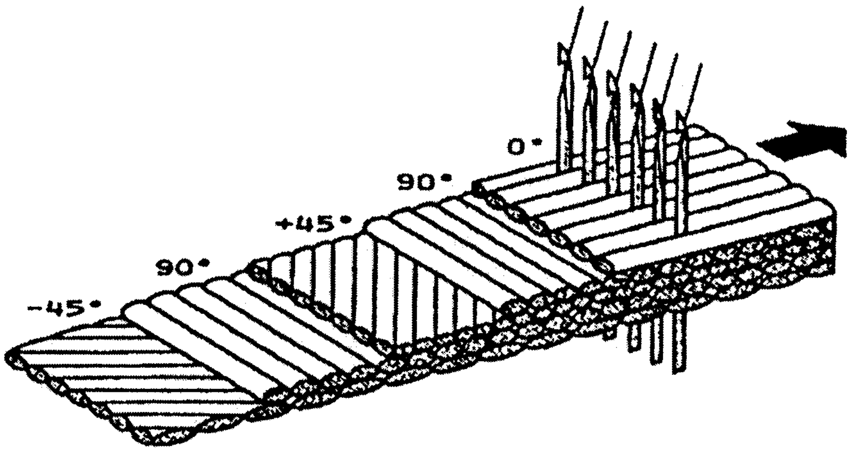

Figure 2.3: Fibre Orientation for a Triaxial Fabric (Source: [13])

During the lay-up process, a layer of the resin is applied to a non-stick surface to ensure to material will be completely covered by the resin. The first layer of glass is applied to the resin and rollers are used to push the resin through the fibres to ensure there is a complete ‘wet out’ of the fibres.

More resin and layers of glass fibre are applied until the required numbers of layers or thickness is obtained. This needs to be done fairly quickly to prevent the resin curing, resulting in large air bubbles being trapped in the material. This process can be seen in Figure 2.4.

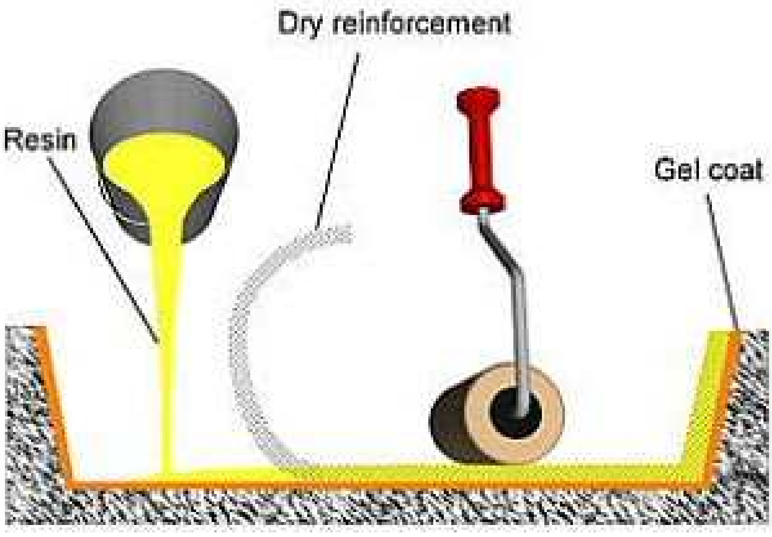

Figure 2.4: Lay-up (Source: [14])

Lay-up is a simple manufacturing process that requires minimal equipment. The final product of the material can also be changed easily and does not need to be uniform. However there can be problems with the quality of the final product and some health issues may exist with some of the resins used.

2.5 Major Applications of Composite Fibres

FRP materials are used in many different engineering applications. These range from military and aerospace to the marine industry. Figure 2.5 shows the breakdown of the FRP market in the United States of America. This figure shows that the majority of FRP materials are used in the transport industry.

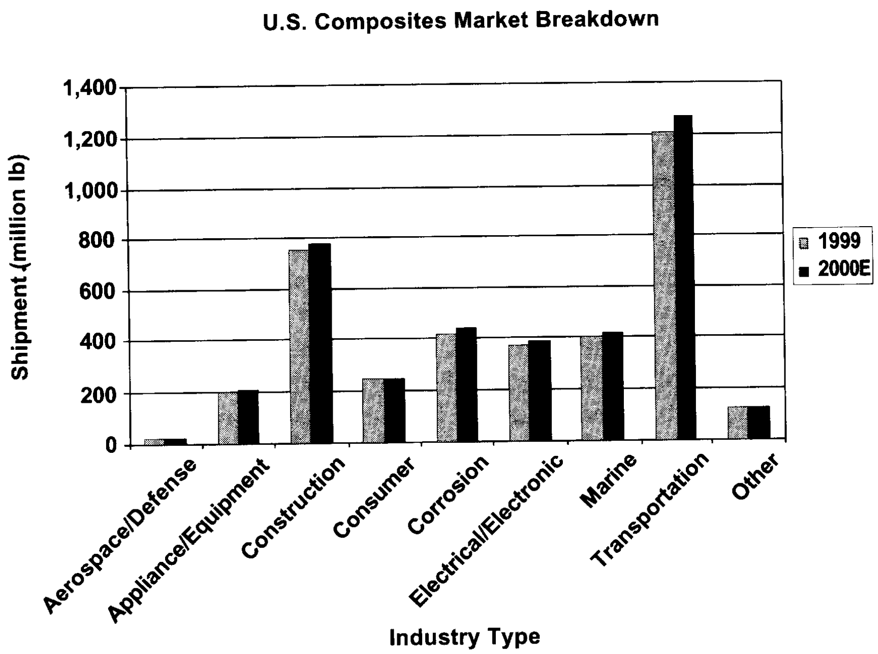

Figure 2.5: Market of Composite Shipments in 1999 and the Expected Shipment in 2000 (Source: [4])

Table 2.3 shows a range of industries and the applications in which FRP materials are used. It used in these industries because of they are lightweight, corrosion resistant and flexible in design.

Table 2.3: Common Applications of FRP Materials (Source: [4])

Industry	**Common Applications**
Aerospace	Rudders, spoilers, doors etc in planes
Construction	Bridges, formwork and trusses
Automotive	Roof panel, bumper bar and radiator support
Marine	Hulls and decks
Sporting	Bike frames, tennis racquets and hockey sticks

Chapter 3

The Wagner Bridge Deck and FRP Material

3.1 Introduction

To determine the durability of the hybrid concrete-FRP bridge constructed by WCFT, it is important to understand the bridges basic design. The design of the hybrid concrete-FRP bridge was performed in collaboration between FCDD and WCFT. This design has been used on the bridge near Grafton, NSW and for all the other bridges produced by WCFT.

The bridge is made of different sections whose durability will need to be investigated separately. Most importantly, the bridges already constructed, have not been in service long enough to assess their durability directly from onsite observations. Therefore, it will be necessary to rely on previous studies dealing with the durability of FRP bridges in general, and FRP materials in particular, to gain an understanding of the long-term behaviour of these bridges.

The materials used in the construction of the bridge will also be detailed in this section. This is important as variations in the manufacture of the material may have large effects on the durability of the bridge.

3.2 Basic Design

The initial design of the concrete–FRP bridge is a product of the collaboration between several companies and the University of Southern Queensland. The companies involved where WCFT, Huntsman Composites, Main Roads Queensland, Connell Wagner and the New South Wales Road and Traffic Authority.

Professor Gerard Van Erp et al. [1] presents the design of the hybrid bridge and the initial test results in a paper entitled: "An Australian approach to fibre composite bridges", which can be accessed at www.fcdd.com.au. The basic design approach done by Professor Gerard Van Erp is presented in this section.

The hybrid concrete–FRP bridge deck design is based on reinforced concrete fundamentals. To understand the design philosophy, first consider a reinforced concrete beam as shown on Figure 3.1. This beam uses steel reinforcement in the tension side, this is because concrete is poor in tension but strong in compression.

Concrete beams designed in this manner have two main disadvantages, the first being that 75 – 80% of the beams weight is not directly contributing to the strength of the beam [1]. The second disadvantage is that during service the reinforcing steel may corrode if the beam is placed in a moist environment and is not properly protected.

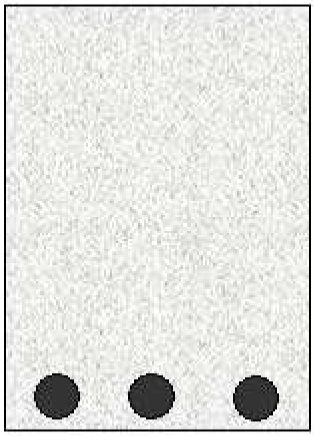

Figure 3.1: Concrete Beam

Based on the design of the concrete beam, and the aforementioned disadvantages, one may be tempted to redraw the section, and eliminate all the extra concrete that is not participating in the load carrying ability of the beam. This is shown in Figure 3.2. This design would eliminate about 75 % of the total weight [1].

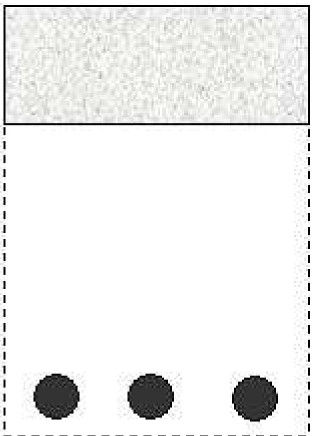

Figure 3.2: Effective Section of a Concrete Beam

This idea inspired the design of the hybrid concrete-FRP beam, where the unnecessary concrete was simply replaced by FRP, which is much lighter and capable of carrying tensile forces. The FRP replaces the steel reinforcement, which are vulnerable to corrosion. The effective section of the FRP beam is shown in Figure 3.3. This figure can be compared to the beam shown in Figure 3.2 to see the simple change that was made [1].

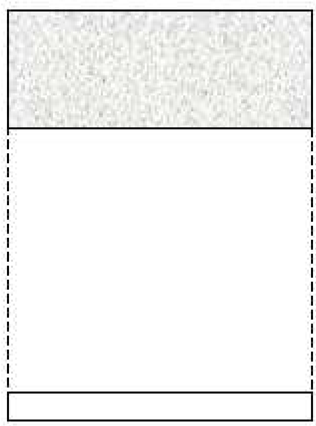

Figure 3.3: FRP Flange Replaces the Steel Reinforcement

Since concrete is a very good material in compression, it is utilised in the hybrid beam to carry the compressive forces that develop in the section above the neutral axis. In addition, this concrete also provides the bridge with a vehicular traffic surface that the public will view positively.

As shown in Figure 3.4, two webs are used to separate the compression and tension sections of the beam. These webs replace ineffective concrete in a normal reinforced concrete beam. By replacing the concrete, the weight of the beam is reduced by about 66% [1].

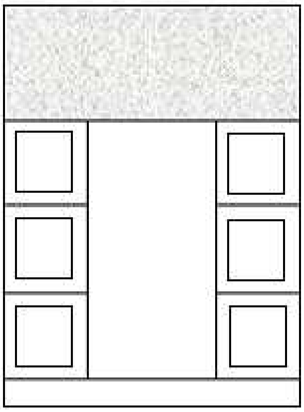

Figure 3.4: Complete Hybrid Concrete-FRP Bridge Section

To construct the bridge deck, several of these beams are manufactured, and joined together as shown on Figures 3.5 and 3.6.

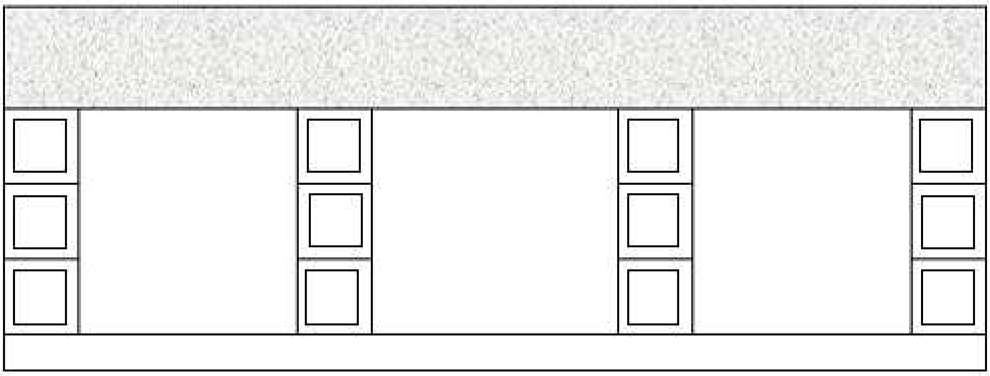

Figure 3.5: Bridge Deck Produced Using FRP and Concrete

Figure 3.6: Picture of a Hybrid Concrete-FRP Bridge Deck Produced by WCFT

To guard against the corrosion of negative moment reinforcement, the concrete contains stainless steel reinforcement. This stainless steel, which has the same mechanical properties as normal steel, is suitable for long term service as it is less susceptible to corrosion. Having reinforcement in the concrete will also help prevent any cracks from appearing in the surface during installation and the life of the bridge.

This new design has several advantages over existing bridges. This design can be tailored for any particular site. In addition, the materials are used efficiently and economically. The risk of corrosion is greatly reduced, since the bridge uses corrosion resistant materials: FRP, concrete and stainless steel. The low weight of the bridge means that the transportation cost is greatly reduced as fewer trucks are required.

3.3 Materials Used in Construction

There are several different types of materials used to construct the bridge section. Wagners produce most of the materials using a high level of quality control.

High strength concrete with a 28-day strength of about 60 Mpa, produced by Wagner's concrete division, is used in the compression zone of the bridge. The final strength of the concrete is determined by compression tests carried out at the Wagner Concrete Laboratory.

The laminates used for the webs are produced through pultrusion. The cross section is a 100 x 100 x 5 square hollow section made from glass fibres and vinylester resin. This material is used to make the webs. The fibre weight of this material is 78%; this was found through a burn-off test.

WCFT also produce a pultruded plate of size 300 millimetres wide by 6 millimetres thick, which contains 79% of fibres by weight. The tension flange is made from plate material glued together.

3.4 Areas for Durability Issues

To successfully assess the durability of the bridge, it is necessary to identify all the possible areas of concern. Based on the results of this preliminary investigation, testing of coupons will be carried out where deemed appropriate. However, for issues requiring longer periods of time, use will be made of existing studies published in the literature. As per Figure 3.4, a number of areas of concern can be identified as:

- The adhesive joint between the concrete and the composite fibre material
- The adhesive joint between the web material
- The web material

- The adhesive joint between the web and flange material
- The composite fibre flange material
- The concrete
- The stainless steel reinforcement

These areas are highlighted on Figure 3.7. Investigating these areas separately will make it possible to identify the most vulnerable ones.

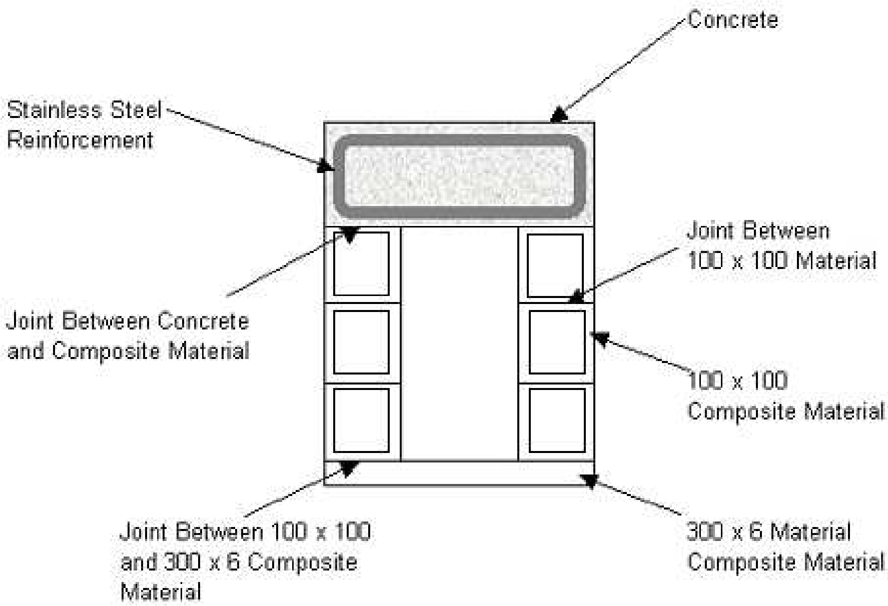

Figure 3.7: Areas for Durability Investigation

3.5 Preliminary Investigation

Based on a preliminary literature investigation it appears that the major area of concern is the adhesive joint. Both Castro et al [15] and Beevers [16] identified adhesive joints as an area of uncertain durability. The adhesive joints used in their investigations were slightly different than that used in the hybrid concrete-FRP bridge. For this reason a durability investigation was undertaken to examine the adhesive joints used in the WCFT Bridge. This investigation and the results gained are given in chapters 6 and 7.

The next area of concern is the FRP material its self. As reported in [9] FRP can suffer damage from the moisture, temperature, ultraviolet light, creep and fatigue. All these aspects of the environment will be subjected to FRP material while it is in service. However the damage from some of these aspects can be reduced using specific techniques during the construction of the FRP material: for example using a UV resistant coating. For the other environmental aspects, durability investigations must be carried out. As there is limited time to conduct this research, the durability of the FRP material and the other areas of durability concern, shown on Figure 3.7, will be determined using previous investigations. The results from this investigation are detailed in chapters 4 and 5.

Chapter 4

Durability of FRP Material and Concrete

4.1 Introduction

This chapter has been divided into four sections. These sections will investigate the previous durability studies conducted on pultruded and lay-up FRP material, concrete and stainless steel rods. Pultruded and lay-up FRP materials are considered different as the manufacturing process and the resin content may affect the durability of the materials.

In this part of the investigation, tests conducted on material similar to that produced by WCFT are considered. For this reason, only glass fibres were investigated. The majority of the published work concerns vinylester, this is the main resin that is used in the production of the WCFT FRP material.

To test for the durability of the material, a range of environments were investigated. This should give a good indication the effect these environments have on the materials. The mechanical tests also vary, although the main type of test is the short beam shear test and the tensile test.

In order to compare the results from all of the tests, they will be reported as a percentage of strength retained. This has been calculated by the following equation:

$$\% \, Strength \, \mathrm{Re}tained = \frac{Final \; Strength - Initial \; Strength \; x \quad 100}{Initial \, Strength}$$

4.2 Lay-up FRP Material Durability

Lay-up material is the main type of FRP produced. However, there is a limited use of this type of material in the WCFT Bridge. Nonetheless, it is important to examine this material as it may be applied to the bridge in future and give an indication of the durability of the FRP material itself.

When this process is carried properly, the fibre volume of lay-up FRP material can be similar to that of pultruded material. However the fibre volume can be as low as 30% [17]. It is important to realise that this reduced fibre content may affect the long-term durability of the material.

Wu et al. [18] investigated the effect of moisture on lay-up FRP materials. After 12 months of immersion, the tensile strength and short beam shear results were very similar despite the differences in the immersion solutions used. Table 4.1 shows the results from these tests.

Table 4.1: Reduction in Strength of Fibre Composite Material after 12 Months of Immersion (Data Source: [18])

	Tensile Strength	Short Beam Shear
Environmental Condition	% Reduction in Strength	% Reduction in Strength
Deionised Water	11.29	19.3
Seawater	13.50	15.6
Synthetic seawater	12.95	15.4

Zhang et al. [17] conducted similar tests to Wu et al., however they resulted in slightly worse results. After 11 months in saltwater the samples lost 25.5% tensile strength. This may be a result of a lower fibre volume in these samples. Thermal cycling was also conducted on the lay-up material. After 120 cycles from 100^{o}C to 15^{o}C the strength of the samples reduced by only 11%. Natural weathering was also conducted, after 11 months only a 6% strength reduction was recorded.

Karbhari et al. [19] used freeze thaw cycling to examine the FRP material. These experiments also showed the effect of different thawing solutions. The results of the tests conducted are shown in Figure 4.1 and 4.2. These figures show the change in strength when the samples were tested in tension and compression.

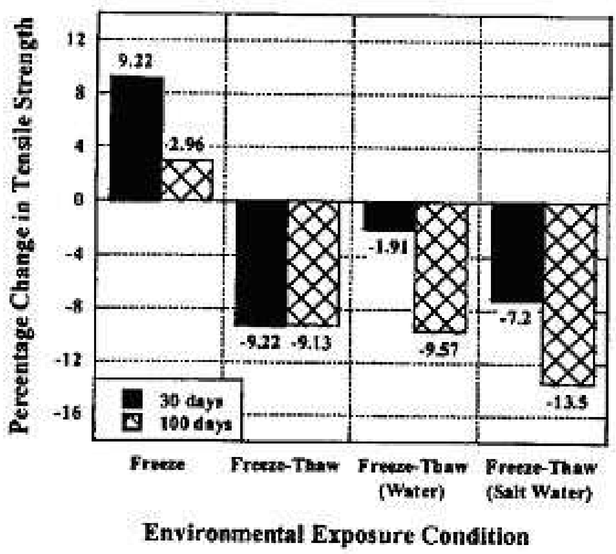

Figure 4.1: Change in Tensile Strength After 100 Days Exposure (Source: [19])

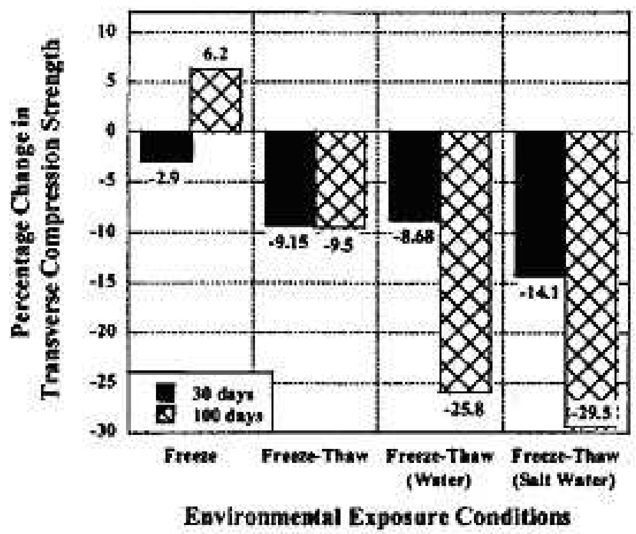

Figure 4.2: Effect of Environmental Exposure on Compressive Strength (Source: [19])

Both figures show that considerable damage has been done during the first 30 days of exposure. They also show that the damage to the samples is increased when the thawing cycle is conducted within a solution.

Karbhari et al. [20] also conducted tests on samples with different fibre orientation in a range of different environments for a period of 57 weeks. Table 4.2 shows the results from the tension and short beam shear tests.

Table 4.2: Percent Reduction in Mechanical Properties after 57 Weeks Immersion (Data Source: [20])

			0^o Orientation			90^o Orientation		
Fabric Orientation	Exposure	Layers	Tensile Strength	Tensile Modulus	Short Beam Shear	Tensile Strength	Tensile Modulus	Short Beam Shear
Unidirectional	Water at 23C	2	47%	12%		20%	2%	
		4	62%	13%	13%	14%	8%	53%
	Water at 60C	2	64%	12%		47%	7%	
		4	47%	6%	24%	15%	13%	54%
	PH 10 Buffer	2	23%	4%		22%	12%	
		4	27%	18%	15%	25%	7%	31%
Biaxial	Water at 23C	2	27%	19%		12%	10%	
		4	16%	5%	8%	21%	7%	5%
	Water at 60C	2	68%	23%		56%	21%	
		4	60%	26%	16%	64%	14%	5%
	PH 10 Buffer	2	24%	28%		10%	19%	
		4	1%	11%	14%	4%	8%	0%
Triaxial	Water at 23C	2	14%	23%		18%	12%	
		4	15%	4%	13%	8%	4%	8%
	Water at 60C	2	57%	20%		61%	29%	
		4	55%	7%	34%	41%	7%	21%
	PH 10 Buffer	2	4%	31%		15%	6%	
		4	13%	-4%	27%	9%	11%	17%

These results show that over 57 weeks the effect of the water at room temperature has a greater effect on the tensile strength than the solution with a pH of 10. Most of the results show that the thicker the samples are the greater the resistance to degradation.

4.3 Pultruded FRP Material Durability

The main type of pultrusion is unidirectional pultrusion. This menas that the fibres are orientated in the same direction. This type of material is used in the tensile flange of the WCFT bridge. The fibre volume for this process is about 60% [21]. Since this is greater than the fibre volume for lay-up material the durability of pultruded material should be better. By having a higher fibre volume, the pultruded material should absorb less moisture. This should limit the damage that can be induced by the moisture.

Liao et al. [22] found that after 164 days of immersion in deionised water, the pultruded samples lost 5% flexural strength when the samples were orientated at 0^o for testing. They also found that after 380 days of immersion, the samples lost 30% tensile strength. However, the samples that these tests were conducted on had a fibre volume of 34%. This is well below the average fibre volume for pultruded material. Chopped fibre strand mats where also used in the production of this material. As a result of this, the samples absorbed 0.64% moisture after 164 days, this is also higher than the average.

Chu et al. [21] conducted tests on pultruded material at a range of elevated temperatures. He determined that the samples tested by a short beam shear test reduced by 50%. This was after being exposed to 80^oC deionised water for 75 weeks. He also found a 46% when an alkali solution was used. By conducting tests at elevated temperature a prediction of the strength retention can be determined. Figure 4.3 and 4.4 where developed from these experiments.

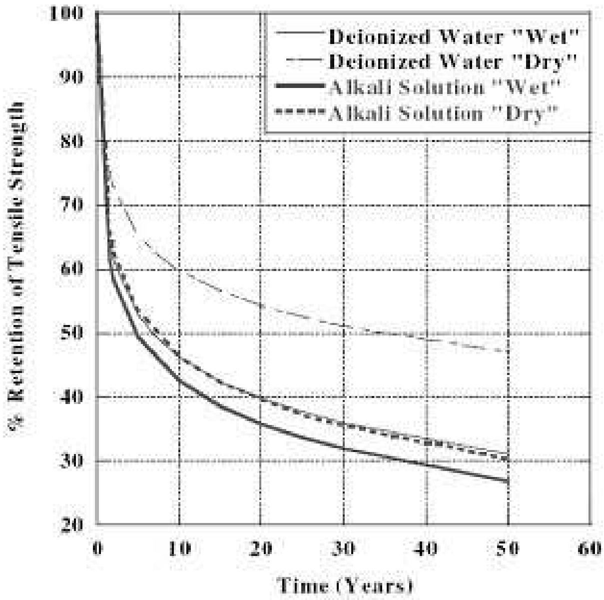

Figure 4.3: Prediction of Tensile Strength (Source: [21])

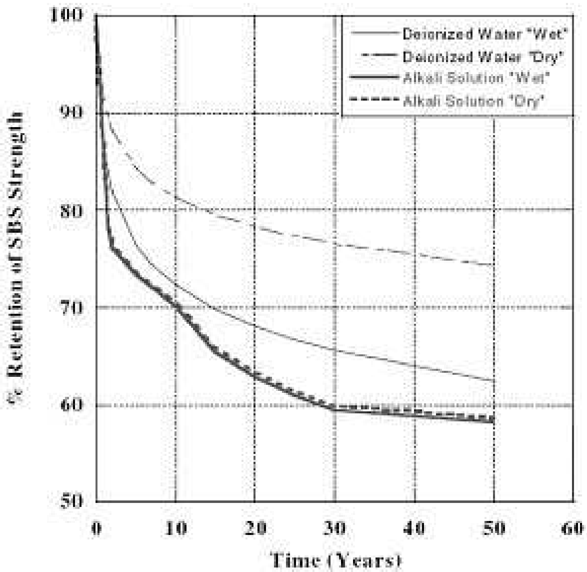

Figure 4.4: Prediction of Short Beam Shear Strength (Source: [21])

These graphs show that the strength retention during the life of the FRP material is dependant on its application, for example tension or bending. Chu also determined that there was limited strength that can be recovered after the samples were subjected to these harsh environments.

Chu's results are similar to the tests conducted by Nishizaki et al. [23]. Their tests were conducted at different humidity levels and immersion times. Figure 4.5 shows the test results determined from Nishizaki's investigations.

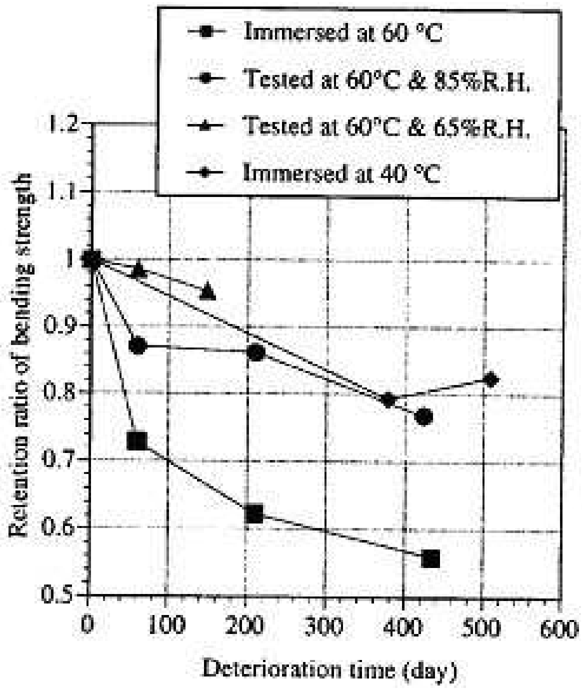

Figure 4.5: Retention of Bending Strength (Source: [23])

Nishizaki hypothesises that the strength reduction is caused by the separation of the fibres and resin when the samples are exposed to 60°C water. These temperatures may not be achieved in the actual environment and this degradation may not occur.

Gentry [24] conducted tests on pultruded vinylester/E-glass plate with a thickness of 6.25 millimetres and a fibre volume of 22%. This is very similar to the material produced by WCFT although the fibre volume is much lower. Figure 4.6 shows the results from tensile tests after the material was exposed to several environments.

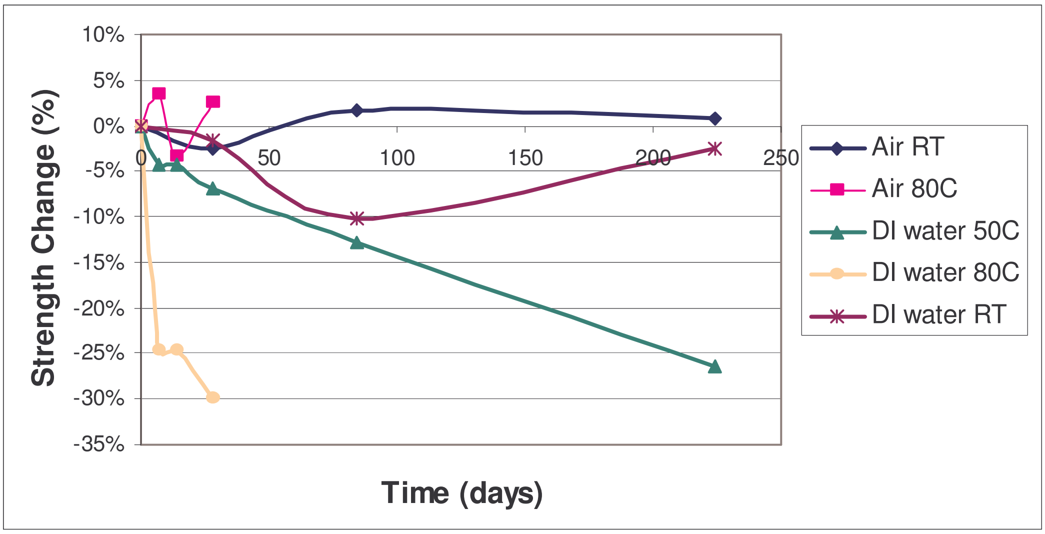

Figure 4.6: Percent Tensile Strength Retention of Vinylester/E-glass Composite Bars Subjected to Varying Environments (Data Source: [24])

The results for the samples exposed to deionised water at room temperature are unusual. After a decrease of about 10% after 84 days the samples regain some strength so that only 3% strength is lost. The authors have not indicated a reason for this behaviour.

FRP bars used as reinforcement were also investigated. This particular type of material is not used in the WCFT bridge but the control of the fibre volume is similar to the pultrusion material produced by WCFT.

Sen et al. [25] conducted tests on bars in a solution with a pH of 13.5. These samples also had an applied stress. The combination of these two accelerated factors increased the degradation. The results of the tests were alarming since a sample exposed to 6 months with 25% ultimate load applied retained only 8% tensile strength while the other 5 samples failed within 173 days. When there was no load applied the samples lost 60% tensile strength after only 3 months.

Tannous et al. [26] investigated FRP bars subjected with a range of different environments. The strength reductions from these experiments are shown in Table 4.3. Two types of resins where used in the production of these bars vinylester and polyester. These results are much better than the results determined by Sen.

Table 4.3: Percentage Strength Reduction in FRP Rebars After 6 Months Exposure (Data Source [26])

		Vinylester		Polyester	
	Environment	**10 mm dia**	**19.5 mm dia**	**10 mm dia**	**19.5 mm dia**
Water T=25C		3%	3%	6%	5%
Hydrated Cement	T=25C pH=12	13%	11%	25%	19%
	T=60C pH=12	20%	12%	29%	20%
HCl	pH=3	4%	4%	7%	6%
Salt water	NaCl 3.5%	6%	5%	11%	8%
	NaCl+$CaCl_2$ 7%	23%	6%	27%	12%
	NaCl+$MgCl_2$ 7%	24%	8%	29%	11%
UV	31.7x10-6 J/sec/cm^2	-	-	1%	-

This table indicates that the hydrated cement solution has the greatest effect on the bars. In three of the samples the effect of the higher temperature is minimal. The effect of the water and the acidic solution are very similar. It can also be seen that the polyester has a greater degradation in these environments. The UV exposure conducted on the polyester bar has a minimal effect on the strength.

Gentry [24] also conducted tests on polyester FRP bars. The results are shown on Figure 4.7. These results are not as severe as the results found in the tests conducted by Sen [25], they are however similar to the results by Tannous [26]. It should be noted however that the environments used by Gentry are not as severe as those in the other two investigations but the exposure time for these tests are longer.

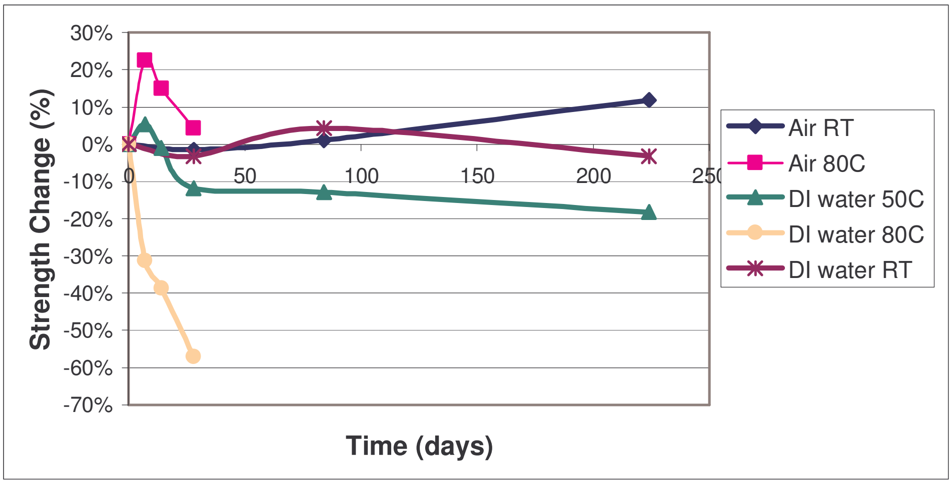

Figure 4.7: Percent Flexural Strength Retention of Polyester/E-glass Composite Bars Subjected to Varying Environments (Data Source: [24])

Sao et al. [27] conducted tests on FRP material with transverse rovings. They conducted tests on the flange of a FRP sheet pile. As the fibre volume for the flange is similar to the material produced by Wagner's the results from this material are relevant and displayed on Figure 4.8.

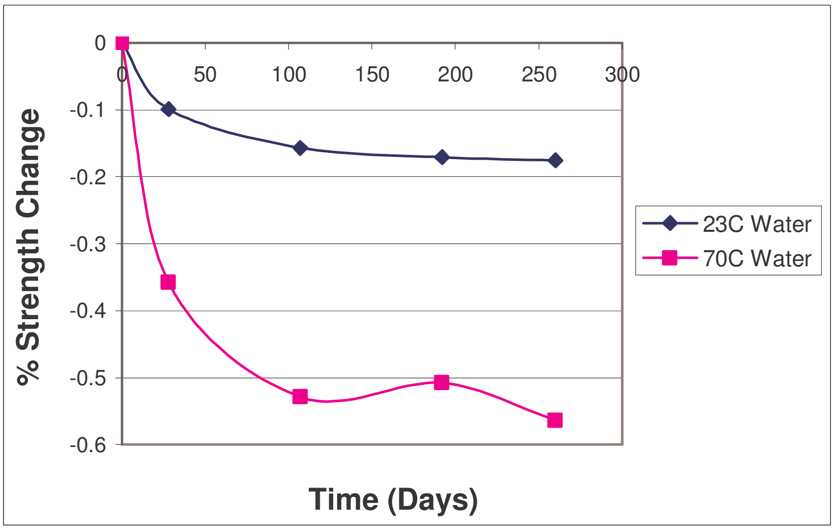

Figure 4.8: Percent Tensile Strength Retention in FRP material with Transverse Fibres Tested in Tension (Data Source: [27])

Sao also conducted freeze thaw tests on the same FRP material. After 564 cycles the samples retained only 53% strength [27]. Prior to the freeze thaw cycling the samples were immersed in 70^{o}C for 192 days, this is where the majority of the damage was done. The freeze thaw cycling only caused 5% damage to the samples.

4.4 Concrete Durability

Concrete is used in the FRP bridge as the compression member of the structure and therefore its durability needs to be investigated. The concrete division at Wagners produces the concrete used by WCFT. Compression samples are taken each time to ensure high a quality of the concrete is used.

Concrete can be attacked by seawater by either chemical or physical actions, the intensity of these is dependant on the location of the concrete relative to the sea. The dissolved salts in the seawater are the cause of these chemical attacks.

Salt weathering can occur when the bridge is in direct contact with seawater and from air-borne salts. When the water evaporates, some of the dissolved salts can remain in the form of crystals. Re-hydration and growth of the crystals occur by the repeated wetting of the concrete. An expansive force is then exerted on the concrete. Salt weathering can occur for several millimetres in the concrete [28]. The aggregate selected may also be subjected to damage. A dense and low absorption aggregate should be selected. The type of cement used is not as critical.

De-icing salts can also cause salt weathering to occur on concrete bridges. De-icing salts are used in snow prone areas to remove the snow from bridges. This practice can also cause scaling of the concretes surface and corrosion to occur to the reinforcement. However, scaling can be reduced by the use of air entrainment in the concrete [28]. A high resistance to scaling is also shown in high strength concrete.

Figure 4.9 shows the effect of the temperature on wet concrete. A range of temperatures were used to moist-cure the concrete for 28 days. The specimens were then moist-cured at 23^{o}C for the remaining time. This figure indicates that the curing temperature has a long-term effect on the strength of the concrete as it takes longer for the samples to reach the 28-day strength.

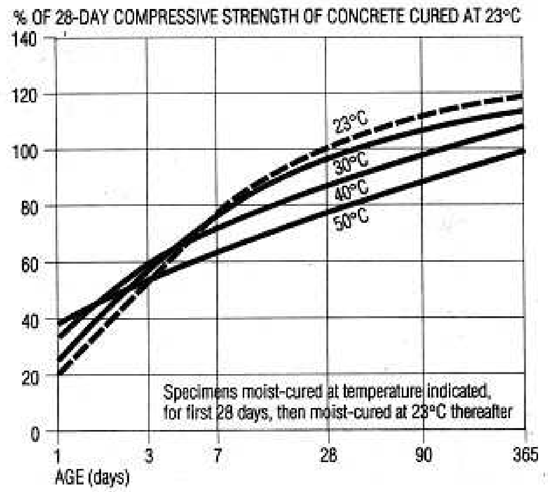

Figure 4.9: Effect of Curing Temperatures on the Compressive Strength of Concrete (Source: [29])

Freeze thaw resistance of concrete is an important feature for the hybrid concrete-FRP bridge produced by WCFT as they have already installed a bridge in a snow prone area. Mohamed et al. [30] conducted investigations on concrete subjected to freeze thaw conditions at the Green Mount Dam, Colorado, United States of America. Table 4.4 shows the results from compressive tests conducted on concrete cores taken from the dam wall. The cement type shows the variations in chemical and physical characteristics of the cement used, these are standard groups set by the American Society for Testing Materials (ASTM).

Table 4.4: Percent Strength Increase of Concrete Cylinders (Data Source: [30])

Cement Type	Concrete Number	2 Year Exposure	53 Year Exposure
1	16	21 %	58 %
1	16B	28 %	55 %
1	18	28 %	55 %
2	21	55 %	61 %
3	31	15 %	-36 %
3	34	17 %	8 %
3	34B	21 %	45 %
4	42	106 %	102 %
4	42B	87 %	117 %
4	43A	70 %	71 %
5	51	55 %	53 %

The results show that most of the concrete samples increased in strength after 2 and 53 years of exposure. Only sample 31 reduced in strength after the 53 years of service. It was observed in this sample that soluble salts migrated from within the wall and crystallised on the outer surface and the strength reduction was caused by disintegration of the internal structure.

From these investigations the authors concluded with that air entrainment helps the concretes resistance to freeze and thaw, however distress may be caused by the freeze thaw action depending on the severity and frequency of the cycling. The authors also state that an air entrainment of 2-6% increases the concretes resistance to freeze thaw damage [30].

4.5 Stainless Steel Durability

Stainless steel is used in the hybrid concrete-FRP bridge to reduce any possible cracks from appearing in the concrete. It is used because of its ability to resist corrosion better than regular steel. This is a result of the large amount of chromium in the steel [31]. There are many different types of stainless steel, and it is important that the correct grade be chosen for the particular situation.

Gonenc [32] conducted durability tests on two types of stainless steel bars. The environment the bars were subjected to was hot water. This environment is used to test the steel under the most intense environment. A comparison of the two bars used is shown in Table 4.5.

Table 4.5: Comparison of Two Stainless Steel Bars Used in Experiments (Data Source: [32])

	Bar 1	Bar 2
Manufacturer	Cada Stainless & Alloys	HP Alloys
Type	T-316	Nitronic 50
Tensile Strength (MPa)	1379	1193

The specimens used in this experiment were exposed to water at range of temperatures from 44^{o}C to 80^{o}C for a period of up to 224 days. The solution used was 5% salt water. Once the exposure was complete the strength reductions were tested through flexural, tension and short beam shear tests. Through these tests the flexural yield strength, tensile strength and the shear yield strength were obtained, these are showed in the following graphs.

Figure 4.10 and 4.11 shows the changes in the flexural yield strength of the two samples. When the two graphs are compared a number of similarities are obvious. The first observation is that the environment has caused an increase in the flexural yield strength. Both set of the samples peaked after 112 days of exposure, but only stainless steel sample 2 showed a decrease of all temperature samples. The 68^{o}C from sample 1 exhibited slightly different behaviour than the other temperatures. The author did not give a reason for this behaviour.

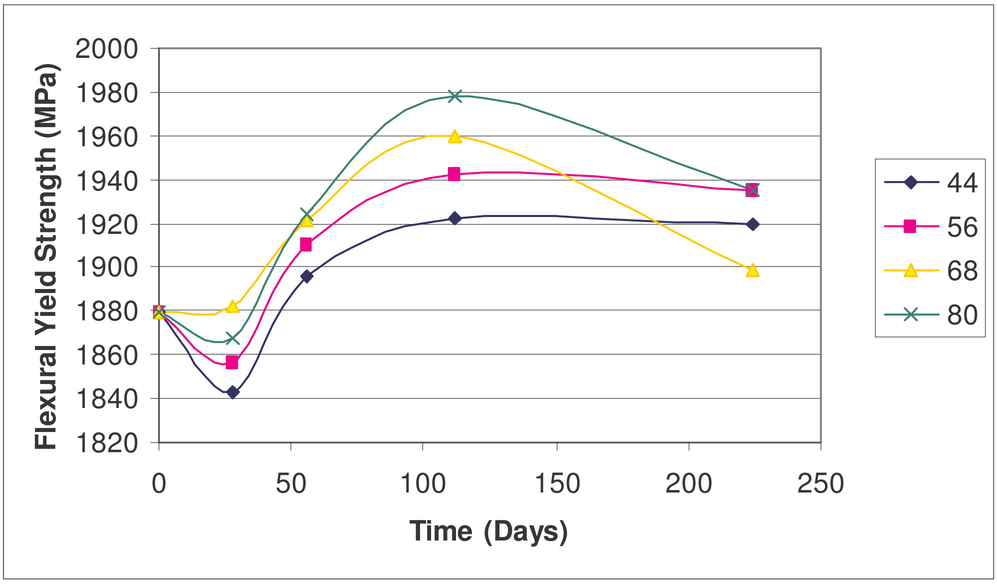

Figure 4.10: Flexural Yield Strength Changes at Different Temperature for Stainless Steel Sample 1 (Data Source: [32])

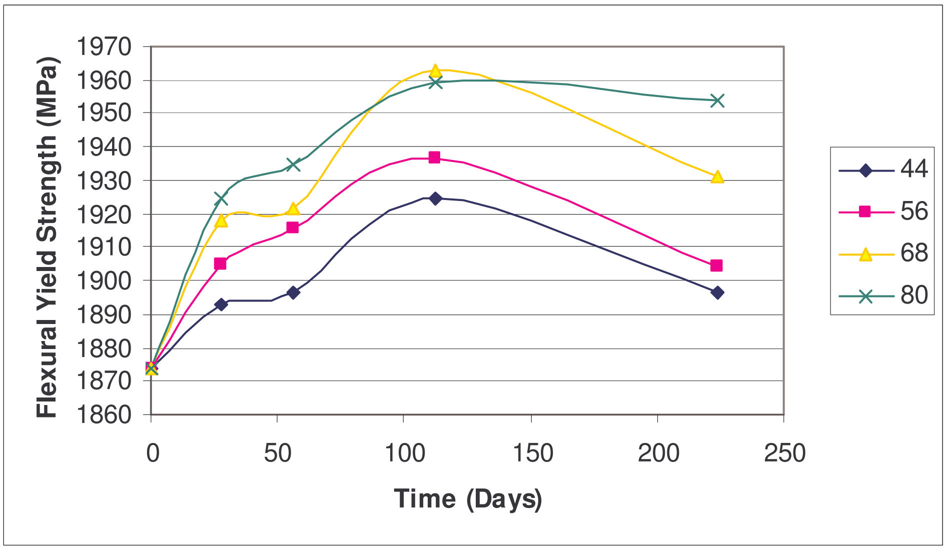

Figure 4.11: Flexural Yield Strength Changes at Different Temperature for Stainless Steel Sample 2 (Data Source: [32])

Figures 4.12 and 4.13 shows the test results from the short beam shear tests. Once again the two samples showed similar behaviour for all temperatures. Unlike the flexural tests, the shear yield strength did not decrease at the end of the test period.

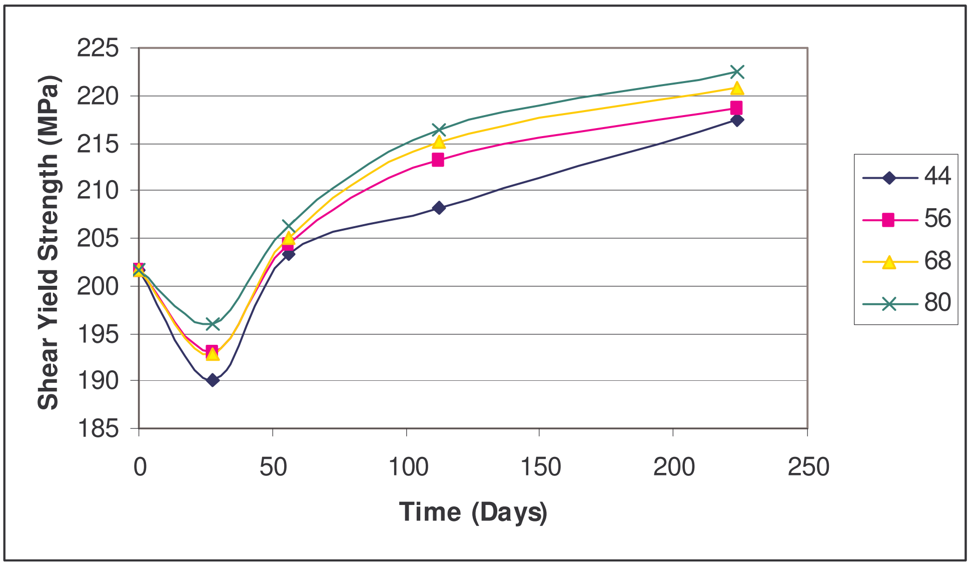

Figure 4.12: Shear Yield Strength Changes at Different Temperature for Stainless Steel Sample 1 (Data Source: [32])

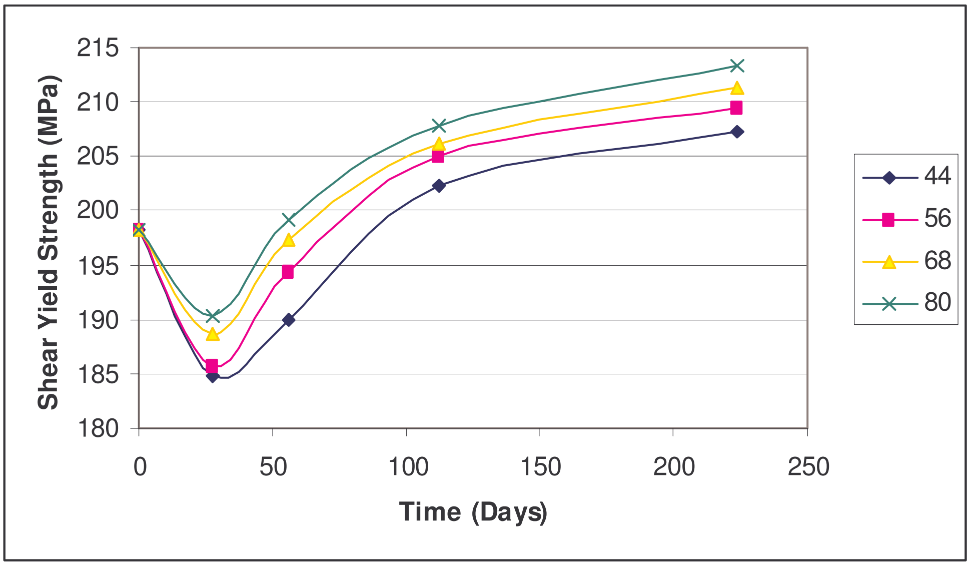

Figure 4.13: Shear Yield Strength Changes at Different Temperature for Stainless Steel Sample 2 (Data Source: [32])

Figures 4.14 and 4.15 show the tensile tests conducted on the two samples at two different temperatures. The results of these tests are very different and showed no similarities between the two samples. There are little similarities between the individual test samples unlike the bending and flexural tests.

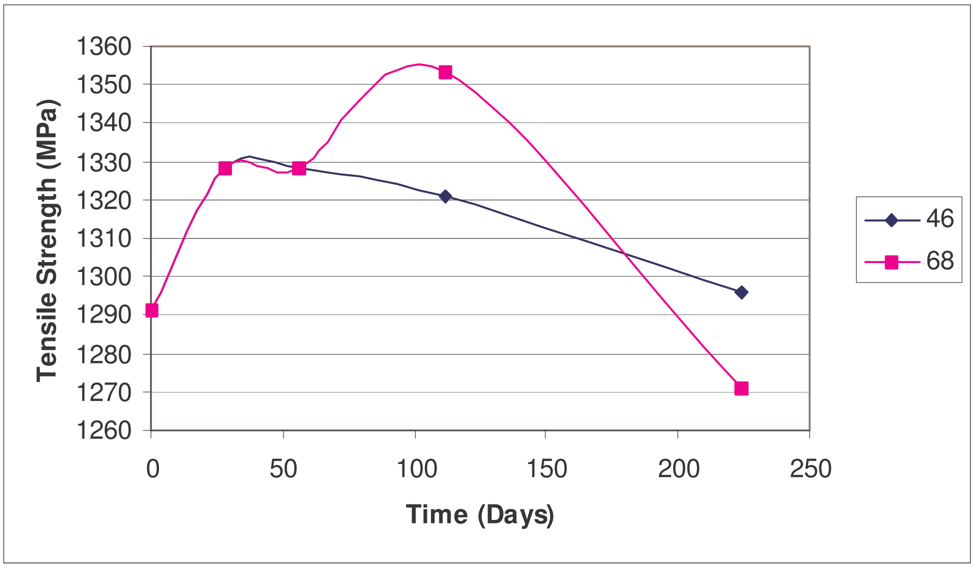

Figure 4.14: Tensile Strength Changes at Different Temperatures for Stainless Steel Sample 1 (Data Source: [32])

In Figure 4.15, the 56 day test for the 68^{o}C samples are lower than the other test results. The author does not give any explanation for this behaviour.

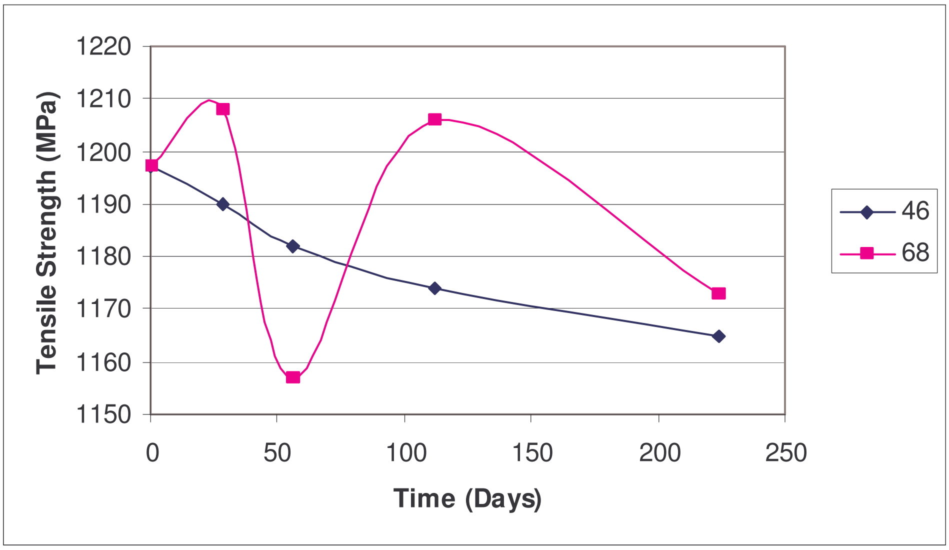

Figure 4.15: Tensile Strength Changes at Different Temperatures for Stainless Steel Sample 2 (Data Source: [32])

This investigation shows that stainless steel has a good resistance to this harsh environment. The flexural and bending test showed an increase in strength over the test period but the tension tests showed unusual behaviour.

Chapter 5

Durability of Adhesive Joints

5.1 Introduction

This chapter covers the durability of the different applications of adhesive joints; namely: concrete to FRP joint, FRP to FRP joint and steel to steel or FRP joint. Since joints are the prime area of concern in durability, they have been given particular attention in durability studies [33-38]. Different types of environments and mechanical tests were used to gain a fairly good indication of the joints final characteristics.

The change in the mechanical properties is reported as follows:

$$\%\, Strength\, Retained = \frac{Final\ Strength - Initial\ Strength\ x\ \ 100}{Initial\ Strength}$$

By using this equation all of the different tests can be compared more easily.

5.2 Concrete to FRP Adhesive Joint

The adhesive joint between the concrete and FRP is used in many different ways. The most common is when the FRP is used as an external reinforcement for beams and columns. It is also used to repair a damaged section in a structure, like a single beam in a bridge. This can be done instead of replacing the entire structure. [33]

Green et al [33] conducted test on the concrete to FRP adhesive joint subjected to freeze thaw cycling. The cycling was done once a day from -18^{o}C in a freezer to $+15^{o}$C. The thaw cycle was done in water. To subject the joint to shear stresses the beam was tested in four point bending.

Three types of beams were tested; these included a plain concrete beam, reinforced beam and beams with external glass fibre reinforcement. The adhesive used to glue the FRP to the concrete was an epoxy. The results of the tests are shown in Figure 5.1.

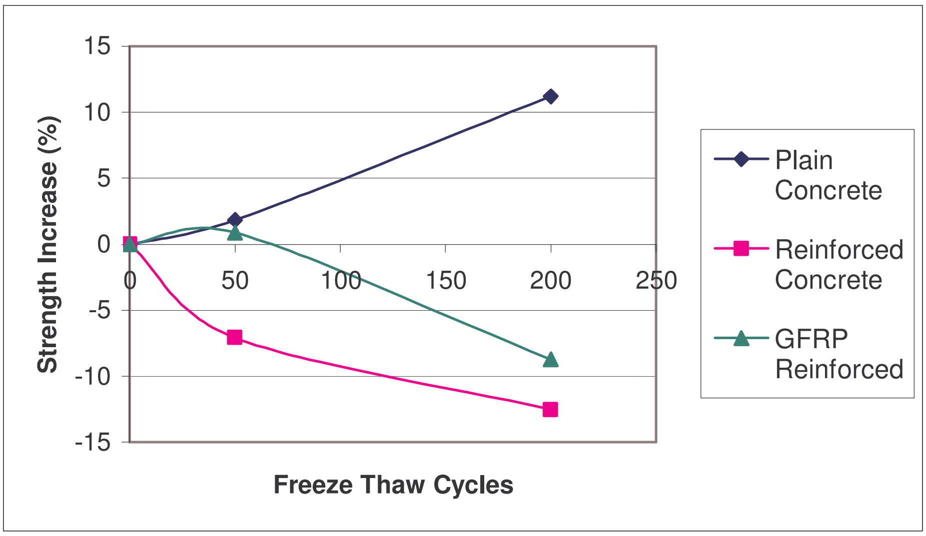

Figure 5.1: Strength Changes in Concrete Samples Subjected to Freeze Thaw Cycling (Data Source: [33])

The effect of the freeze-thaw cycling caused a strength reduction in the beam with the FRP reinforcement. The authors hypothesise that this decrease could have occurred within the FRP material itself. Findings from Green [34] support this hypothesis.

Karbhari et al [35] also conducted tests on beams externally strengthened by FRP material. The FRP material was produced using the lay-up method, this was done directly onto the concrete beams. Two types of epoxy were used, one from the Tonen Corporation and one from Epon.

The samples were subjected to several different environments; these include freeze thaw cycling, water, salt water and freezing. This was done over a period of 60 days. The mechanical test used in this experiment was also a four point bending test. The results of the tests are shown in Figures 5.2 and 5.3.

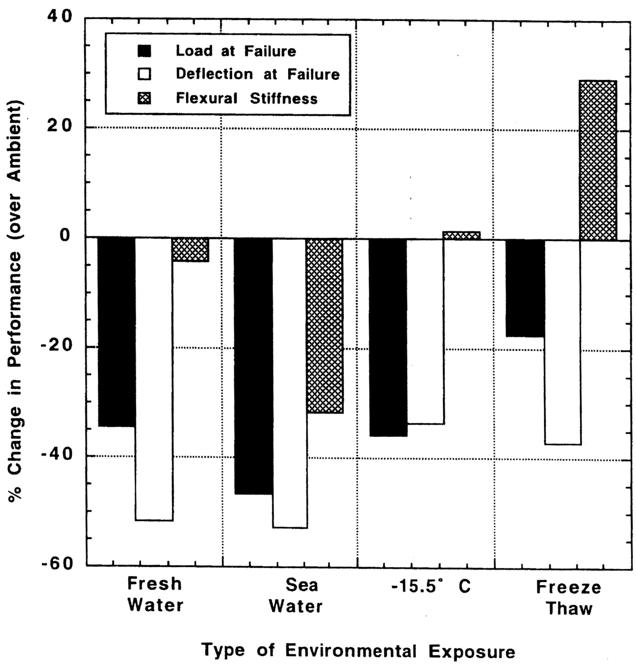

Figure 5.2: Strength Changes in Samples Exposed to Different Environments with Tonen Epoxy (Source: [35])

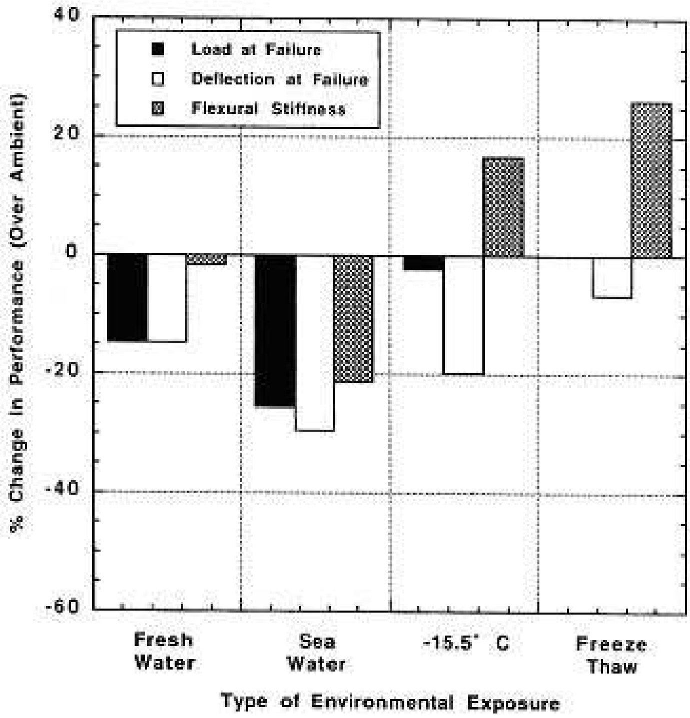

Figure 5.3: Strength Changes in Samples Exposed to Different Environments with Epon Epoxy (Source: [35])

By comparing the two figures, it can be seen that the type of epoxy affects the results. Under all of the environmental conditions the Tonen epoxy showed the greater degradation. This indicates that the durability of the adhesive joint between concrete and FRP is dependant on the adhesive used.

Lyons et al. [36] conducted bond tests using a modified double cantilever beam test. The samples were first subjected to a range of hot and wet environments.

To conduct these tests the FRP material is produced through lay-up directly onto a masonry substrate. One edge of the FRP materials is pulled up and the strain energy release rate (G) is calculated through a function of crack length, and load P. This is shown in Figure 5.4. The test was designed to analyse the bond between the FRP and concrete.

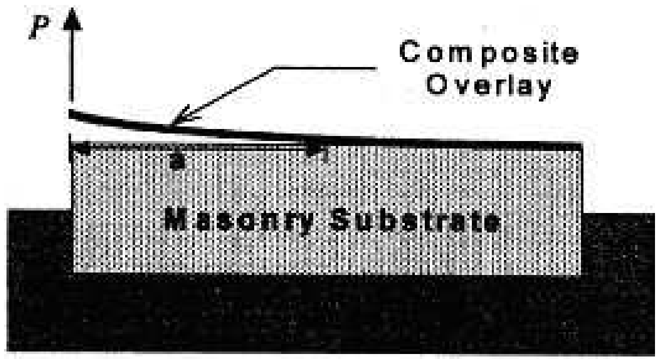

Figure 5.4: Modified Double Cantilever Beam Test (Source: [36])

Table 5.1 shows the results from the tests. The samples were either in hot air (dry) or at a humidity of 95% (wet).

Table 5.1 Strain Energy Release Rates at 60mm Crack Length for Samples Subjected to Different Environment (Source: [36])

23°C Dry		60°C Dry		60°C Wet		100°C Dry		100°C Wet	
Time (Days)	G_{60} (J/m^2)	Time (Days)	G_{60} (J/m^2)	Time (Days)	G_{60} (J/m^2)	Time (Days)	G_{60} (J/m^2)	Time (Days)	G_{60} (J/m^2)
3	749	2	857	2	344	8	552	3	323
5	910	2	685	2	377	14	845	6	289
14	714	5	614	5	801	26	925	14	630
14	943	5	790	5	610	36	716	23	318
24	930	10	754	10	645	36	895	30	683
51	940	20	1119	20	1034	40	642	40	400
53	721	21	621	21	1035	40	717	40	557
55	1274	40	925	40	642	40	504		
55	467	41	764	40	520				
112	673								
126	725								
126	897								
163	400								

The results show that there is no correlation between exposure time and the energy release rate. There was also no statistical variance in the 60^{o}C wet, 60^{o}C dry and 100^{o}C dry results.

After the test was conducted the failure surface was examined. As the temperature increased the failures changed from within the FRP material to the bond between the FRP and the concrete.

5.3 FRP to FRP Adhesive Joint

This type of adhesive joint requires a detailed investigation as it is used in many different places in the bridge cross section. It is used in the manufacture of the compression flange, joining the 100 x 100 material together to form the webs and joining the webs and tension flange together.

Castro et al. [15] examined the epoxy bond between two pieces of graphite fibre reinforced polymer material. Even though this examination was done with graphite, the focus of the investigation was the adhesive joint. Two different environments were used in this investigation; moisture immersion and freeze thaw cycling. The mechanical test used after the environmental exposure was the lap shear test. The lap shear test was used because it will test the strength of the adhesive joint rather than the graphite material. Fatigue loading was also conducted on the freeze thaw samples

The moisture immersion tests were conducted in water at room temperature. The samples were tested once they stoped absorbing moisture; the time this took was not reported. The lap shear test showed an increase of 23% shear strength [15].

The freeze thaw samples were subjected to 1000, 30 minute cycles. Periodic testing showed that there was a 16% gain in shear strength after 800 cycles. The shear strength steadily decreased after this point. The authors hypothesised that this could be a result of the adhesive increasing in toughness with the exposure to small amount of moisture.

Fatigue testing was also conducted on some samples. The samples used were first subjected to 1000 cycles of freezing thawing. The fatigue testing was conducted at: R = 0.1, 10 Hz. When the results were compared to the control samples there was no appreciable difference [15]. This could be a result of the low fatigue load used.

5.4 Steel Adhesive Joints

The adhesive joint between steel plates was also investigated. This will give a good indication of the degradation in the adhesive, as degradation should not occur in the steel members during the short time period.

Beevers [16] conducted an investigation on an aircraft with steel adhesive joints that was constructed in 1963 and had been in service for 30 years. He also found lab samples from 1963. These two sets of samples were compared to samples made using adhesives used on the newer BAe 146 aircraft. These samples were tested using a lap shear test. The samples were then exposed to 24 weeks of immersion in 40^{o}C water. The results are shown in Table 5.2.

Table 5.2: Test Results From Aircraft Samples (Data Source: [16])

Test Method	1963 Comet	1963 Lab samples	BAe 146 Aircraft
Lap shear strengths (kN) (MPa)	11.36 36.4	12.56 40.2	12.52 40.1
40C water immersion for 24 weeks (% Shear Strength retention)	71%	74%	78%

The lap shear test results are very similar. The results show a decrease of 10.5% between the samples from the plane in service compared to the lab samples. This is quite a low reduction after being in service for 30 years.

The decrease in tensile strength is comparatively large for the samples immersed in 40^{o}C for 24 weeks. However there is little difference between samples that have been in service to samples that have been sitting in a laboratory.

Bowditch [37] published results from several different tests, two are of particular interest. The first was conducted on epoxy bonded aluminium. These samples were exposed a to high temperature environment. One environment had 5% humidity and the other had 100% humidity. The reductions in shear strength of these samples are shown in Figure 5.5.

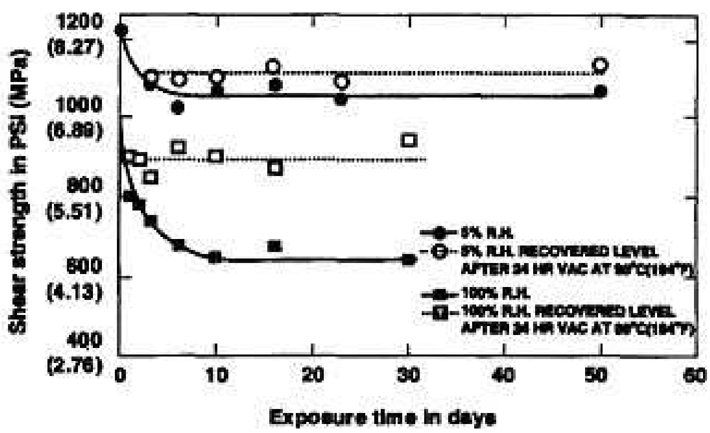

Figure 5.5: Two Humidity Levels at 90°C For Epoxy Bonded Aluminium (Source: [37])

This figure shows that the samples at 100% humidity decreased in strength the most. It also shows that the degradation will stop once it reaches a certain stage. Some samples were dried for 24 hours before they were tested. The results from these samples indicate that most of the damage done can be reversed.

Bowditch [37] also reported an investigation that was conducted over a period of eight years. The samples were subjected to a seawater environment for this period of time, and then tested using the tensile butt joint test. The results of the tests are shown in Figure 5.6. This shows that the samples gained strength during the exposure time.

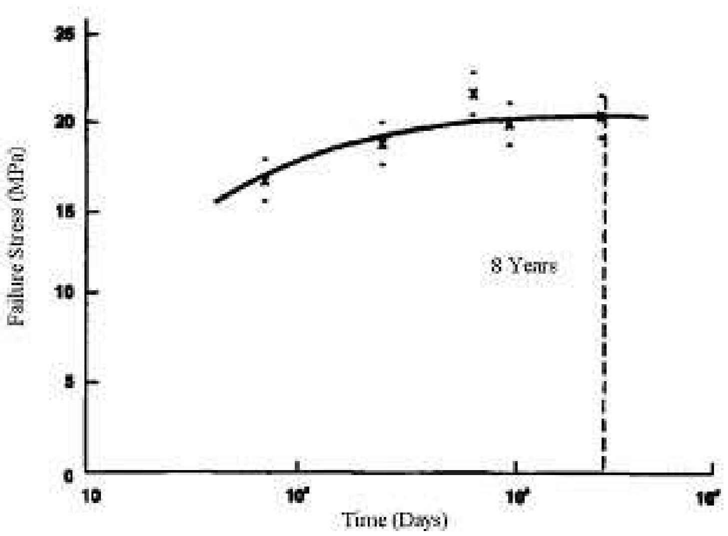

Figure 5.6: Effect of Sea Water on Epoxy Bonded Butt Joints (Source: [37])

Karbhari et al. [38] investigated the joint between FRP material and steel. A range of environments were used, these included water, freeze thaw cycling and hot water. Two types of glass fibre was also investigated, E and T. Epoxy was used in this investigation as the adhesive.

The mechanical test used in this investigation was the wedge test. This test was chosen because of its sensitivity to environmental attack on the bond and is a more reliable test than the lap shear or peel tests. After 2 weeks of initial exposure, a wedge was inserted into the adhesive joint and the samples were returned to the environment for a further 7 days. This is shown in Figure 5.7. The final crack length was measured and is shown in Figure 5.8 and 5.9.

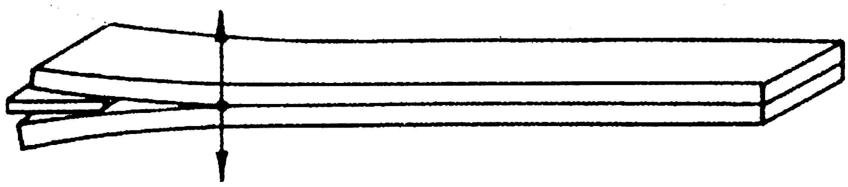

Figure 5.7: Wedge Test (Source: [16])

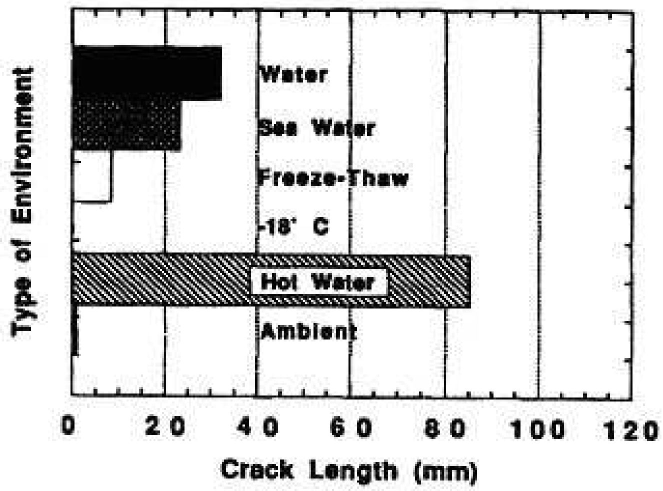

Figure 5.8: Crack Length of Samples with E-Glass After 7 Days of Exposure (Source: [38])

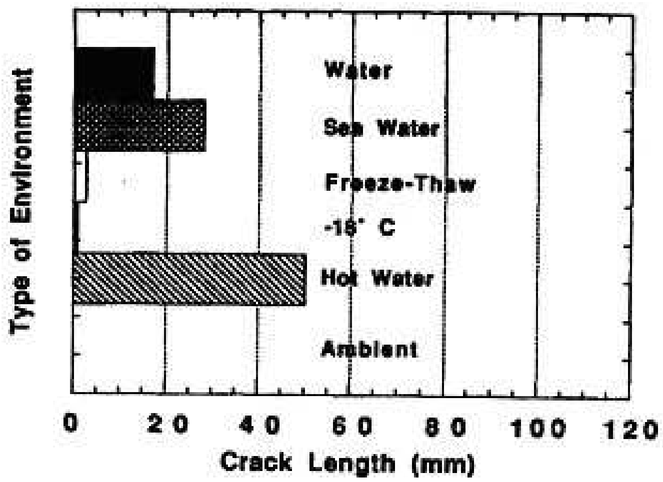

Figure 5.9: Crack Length of Samples with T-Glass After 7 Days of Exposure (Source: [38])

The results indicate that the effect of the environment depends on the type of fibre used. However the hot water has the greatest effect and the $-18^{o}C$ has the least effect on the samples. The effect of the deionised is similar to the effect of the seawater environment.

Chapter 6

Test Sample Manufacture and Environmental Conditions

6.1 Introduction

In 2001 Wagners Composite Fibres Technology (WCFT) was established to provide a new technology for the construction industry using FRP materials. In the relative short existence of the centre, WCFT has already commercialised FRP bridges, cross arms for power poles, and currently working on a new lightweight semi-trailer. However, since FRP materials are relatively new as construction materials without any “experience of use”, naturally there are concerns about their long-term durability. To address these concerns, WCFT has embarked on a project to investigate the durability of these materials.

WCFT uses the pultrusion process to produce FRP sections such as unidirectional laminates and RHS. To construct a bridge deck, as described in the third chapter, many of the pultruded elements are joined together to produce a beam section.

The beam sections are then joined together to produce a bridge deck. Unlike steel sections, FRP sections cannot be welded or riveted. Therefore, they have to be bonded using adhesive joints. These adhesive joints constitute the major area of durability concerns. There are limited numbers of studies conducted on adhesive joints. Therefore this short term testing will contribute to this knowledge.

To conduct the durability tests on the adhesive joints, approximately 300 samples were manufactured using a range of configurations and adhesives. This was done to analyse all of the adhesive joints on the FRP bridge. The samples were constructed in large sheets, and then cut to a size of 200 mm by 50 mm.

To test for durability, a range of environmental conditions are simulated. The environments include distilled and saltwater immersion, freeze thaw cycling and temperature cycling. These conditions were chosen because they would best mimic the environments that the bridges are likely to be exposed to during their service life.

6.2 Test Sample Manufacture

As these samples need to resemble adhesive joints used in the hybrid concrete-FRP bridge, the same sample manufacturing process used was the same as the process used for constructing the bridge. To do this, large sections of adhesively bonded FRP plates were produced then cut to the appropriate sizes. To construct the sample 300 mm x 6 mm unidirectional pultruded FRP sheets were utilised. Before gluing the material together, the FRP plates were sanded and made dust free using a rag and acetone. Sanding and cleaning the FRP material will ensure that good adhesion is achieved. This process is also used when constructing a bridge.

There are two main adhesives used in the construction of the Wagner FRP bridge: epoxy and vinylester. Samples were produced using both of these resins. The majority of the samples produced were three layers thick. A sample is shown in Figure 6.1. This configuration is similar to that used in the bottom flange in the bridge produced by WCFT. Some samples were also produced with eight layers. This will increase the area affected by the environment.

Figure 6.1: Durability Test Sample

To glue the FRP together, a large table was prepared and greaseproof paper was laid out to ensure the final product did not stick to the table. Once the FRP sheets had been sanded and cleaned, the first plate was placed on the table. The adhesive was then applied to the sheet, and a second FRP plate is applied. The process is then repeated until the required number of layers has been glued. The fibres are orientated in the same direction, this is similar to the bottom flange of the beams used in the bridge. Pressure is applied to the glued FRP materials by clamps and weights to ensure a good bond between the samples. Once the adhesive in the large sections has dried the clamps and weights are removed. The excessive glue that is squeezed out by the pressure is removed. The large section of FRP is then cut into samples of 200 millimetres long by 50 millimetres wide. This is done with a diamond bladed drop saw.

When the samples are cut, two different fibre orientations were produced. This was performed in order to investigate the effect of fibre orientation. The fibres are either longitudinal or transverse. The different orientations are shown in Figure 6.2 and 6.3.

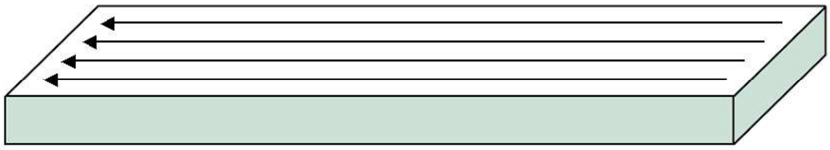

Figure 6.2: Longitudinal Orientation of Fibres

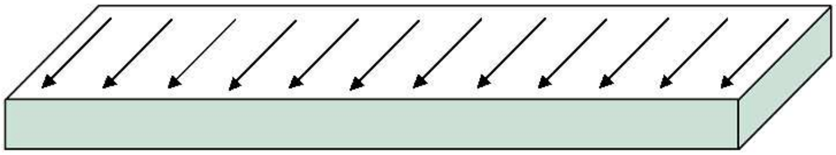

Figure 6.3: Transverse Orientation of Fibres

The effect of edge protection on the durability of the adhesive joint was also examined. The edge protection applied to the samples was a thin layer of epoxy. This was applied only to the cut edges. This protection was used to mimic a sample taken from the middle of the bridge were moisture would be absorbed through the surface, not the edges.

6.3 Environmental Exposure Conditions

Different environments are chosen to mimic the range of possible conditions that the FRP bridge could be subjected to in its service life. These environments are either constant immersion or cycles of dry air/immersion. Deionised and salt water are used as constant immersion environments. These environments will mimic the effect of moisture on the samples. Hot cold cycling and freeze thaw cycling are used to further investigate the effect of cycling on the samples. To determine the degradation caused by the different environments the initial strength of the samples needs to be determined. This will be achieved by having some samples in a controlled environment to minimise any degradation.

Throughout the exposures the samples were kept in racks, which eliminates the possibility of the samples touching each other. This will allow moisture to gain access to the samples on all sides, and increase moisture ingress. Figure 6.4 shows a rack with a single sample. A single rack can hold up to 20 samples.

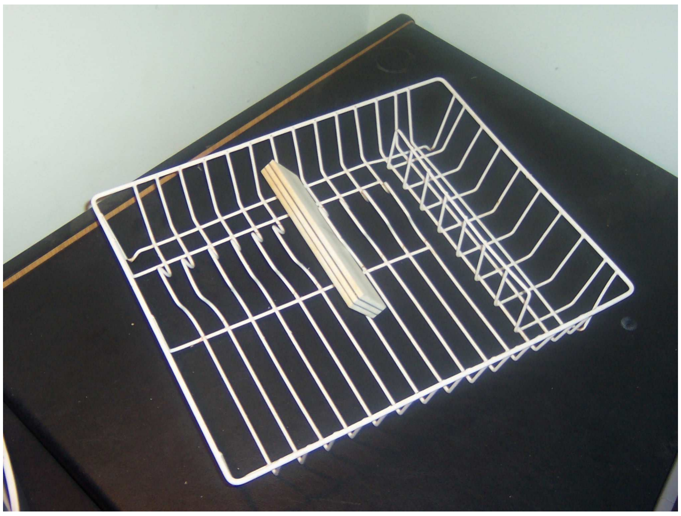

Figure 6.4: Test Sample in a Rack Used to Assist Environment Exposure

6.3.1 Immersion Environments

By immersing the samples in water, the effect of moisture on the samples can be examined. Deionised and salt water are used as the immersion liquids. This immersion was conducted over a period of 22 weeks. During this period weight measurements were taken to determine the amount of moisture the samples absorbed. Deionised water is used to ensure there were no chemicals in the water that could adversely affect the samples and give an incorrect indication of the samples absorption and degradation. The salt water solution is made with 35 grams of salt per litre of deionised water.

6.3.1.1 Effect of Immersion in Deionised Water

Immersion of samples in deionised water is a very easy experiment to conduct. The samples are simply immersed in the solution. Special care should be taken to ensure that the samples are not in contact with each other. If this occurs, the weight gain results will not be correct, as it will take slightly longer for the samples to gain full saturation.

As reported in the literature [9], moisture is mainly absorbed by diffusion through the resin. It can also permeate through microcracks and voids along an imperfect surface. This can results in two effects, weight gain and reduction of strength in the FRP material. Once the moisture has been absorbed into the FRP, it can cause some damage at the microscopic level such swelling, plasticisation and leaching. The moisture in the resin can act as a plasticiser, which results in a loss of strength. Moisture uptake causes the samples to swell, which results in debonding of the fibre resin interface and cracking. Hydrolysis of the resin causes some microscopic particles to leach out. Some of the absorbed moisture may be removed simply by drying the samples.

6.3.1.2 Effect of Immersion in Salt Water

The process of salt water immersion is very similar to that described for the deionised water. However to make the solution salty a designated amount of salt

(Sodium Chloride, NaCl) is added before the samples are immersed. This amount is generally about 3.5% salt by weight.

Salt water is used in durability tests to mimic two different environments. The first is a marine environment were the FRP could be in contact with seawater. The second is to mimic de-icing salts used in snow prone areas, $MgCI_2$ and $CaCI_2$ salts are used to mimic these environments.

The moisture, not the salt, causes most of the degradation of the FRP material immersed in salt water. The salt may however increase the cracks in the FRP material and allow more moisture to be absorbed.

6.3.2 Freeze Thaw Cycling

Freeze thaw cycling is done to mimic a real environment that FRP material may be subject to during service. This would occur over a long period, and range from a sever frost or light snow to the peak daytime temperature. In many parts of the world, structures undergo a large number of freeze thaw cycles, over 100 cycles is not unusual. When this is mimicked in the laboratory it is done on a much smaller time frame.

To conduct freeze thaw cycling the guidelines given by ASTM C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing [40], are generally used. The method consists of two procedures. Procedure A states that the samples are surrounded by water during both the freeze and thaw stages while for procedure B the samples are surrounded by air during the freeze stage and water during the thaw stage. WCFT used procedure B for this durability investigation.

Before cycling the samples are usually immersed in water until they have stoped gaining weight. This is where the samples sustain most of the damage. If the freezing time is long enough, the moisture within the samples may freeze and expand. This causes larger cracks to form in the FRP material, which would allow more moisture to be absorbed and hence more damage would be caused. The effect of the freeze thaw cycling is not completely understood because of the differences in test methods reported in the literature.

In Australia there is limited need to test for freeze thaw cycling. However, for this investigation it is important to study the effects of freeze thaw cycling because WCFT has installed a bridge in to Eire County, New York, United States of America. Figure 6.5 shows this bridge during the snow season.

Figure 6.5: WCFT Bridge Deck in Eire County, USA (Source: [2])

6.4 Other Durability Tests

There are many other types of durability tests that can be conducted. The most common of these tests are high temperatures and ultraviolet light. These environments are usually combined with another durability test to either accelerate the effect or expose the samples to real environmental conditions.

6.4.1 High Temperature

High temperatures are used to accelerate the environmental conditions. This is either done is water or air, at temperatures over 40^{o}C. It should be noted that post-curing of the FRP may occur at elevated temperature. This could give unexpected results. Previous studies have shown that as the temperature increases, the effect on the strength of the material increases due partly to the post-curing phenomena. This is shown by Gentry et al [24] and Gonenc [32].

Damage to samples may occur through differences in thermal expansion coefficients. FRP has a similar thermal expansion coefficient to concrete. However, the adhesives expansion coefficient can be very different from that of the FRP. This would cause debonding of the samples during the environmental conditioning.

Two different high temperature cycling regimes will be used in the current tests. The first high temperature cycling will be performed between 60^{o}C and room temperature. The second temperature range was between 60^{o}C and –5^{o}C. For both environments, the cycling was performed every three hours.

6.4.2 Ultraviolet Radiation

Ultraviolet radiation is used in tests to expose the samples to an environment very similar to Australian conditions. The radiation can be used alone or with a routine spray similar to rain. Using ultraviolet radiation will determine the strength degradation and the change in colour of the FRP during its service life.

In previous studies ultraviolet radiation has been shown to minor effects on FRP [26]. This effect only occurs to a small depth below the surface. This will however be detrimental to the FRP material as the radiation will crack the resin and allow moisture to ingress.

For the current investigation this type of conditioning will not be performed. However as Wagners use vinylester, UV testing is important, as vinylester is susceptible to degradation [8].

6.5 Summary of Environments

Table 6.1 shows the summary of the conditions and sample orientations used in the durability testing. The table also shows the cycling schedule and temperatures used.

Table 6.1: Summary of Environmental Conditions Used in Durability Tests

Environmental Condition	**Fibre Orientation**	**Side protection**	**Condition/Cycling Schedule**
Benchmark Samples	Longitudinal Transverse	Unprotected	No conditioning, stored at room temperature
H20 Immersion	Longitudinal Transverse	Unprotected & Protected	Immersed in distilled H20 continuously
Salt/H20 Immersion	Longitudinal Transverse	Protected	Immersed in distilled H20/ 3.5 % NACL solution continuously
Freeze Thaw Cycling	Longitudinal Transverse	Unprotected & Protected	1) 3 hours distilled H20 2) 3 hours -10 ^{o} C 3) Repeat*
High Temperature Cycling	Longitudinal Transverse	Unprotected & Protected	1) 3 hours Room Temperature 2) 3 hours approx. 60 ^{o} C 3) Repeat**
High / Low Temperature Cycling	Longitudinal Transverse	Unprotected & Protected	1) 3 hours Room Temperature 2) 3 hours approx. 60 ^{o}C 3) 3 hours Room Temperature 4) 3 hours -10 ^{o} C 5) Repeat***

*Cycling was stoped overnight and samples were kept in freezer or water

** Samples were left at room temperature overnight

*** Samples were left in freezer overnight

Chapter 7

Moisture Absorption and Shear Test Results

7.1 Introduction

Moisture absorption is an important consideration when evaluating the durability of FRP materials. For this reason routine weight measurements were taken at the start of the immersion period. The shape of the graph drawn from these measurements will help determine if there has been any damage due to environmental degradation [9, 39].

Once the samples have been exposed to the environments, a mechanical test was used to determine the effect on the samples. The mechanical test chosen for this durability evaluation was a short beam shear or the three point bending test. This will directly test the strength of the adhesive layer between the FRP materials.

As this was only a one-year project the environmental exposure was relatively short. This means that only short-term evaluations will be able to be made with the data.

7.2 Moisture Absorption Results

Moisture absorption results can indicate what is occurring within the FRP material. Such behaviour can be seen in Figure 7.1.

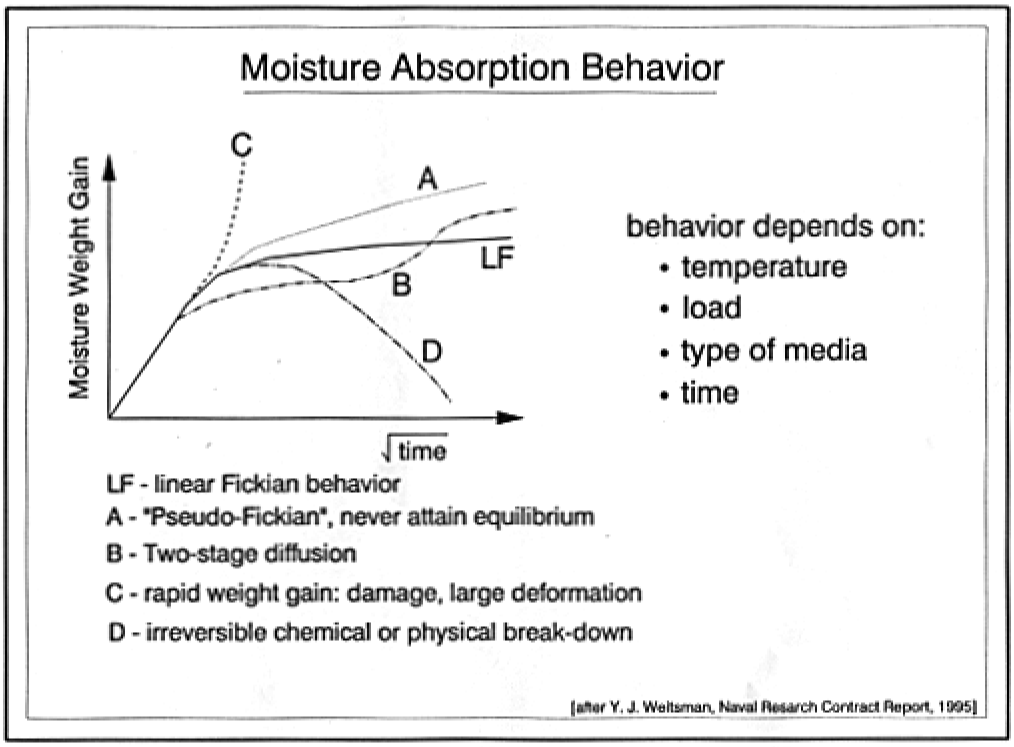

Figure 7.1: Moisture Absorption Behaviour of FRP Material (Source: [9, 39])

The LF curve is the most common moisture absorption pattern. This is characterised by Fickian behaviour, where there is a rapid initial increase in weight followed by equilibrium. This behaviour can be described analytically. Curve A shows the pseudo-Fickian behaviour, this indicates that the samples never reach equilibrium. The two-stage diffusion behaviour is shown as curve B. FRP material showing this behaviour appears to reach equilibrium before a further increase in weight. This second increase may be caused by a change in environmental conditions like temperature, relative humidity or applied load. [9, 39]

The two adverse curves are C and D. These indicate that the absorbed moisture has caused damage to the FRP material. Curve C shows the samples have rapidly increased in weight, which may be caused by resin cracking or fibre/matrix debonding. The behaviour shown by curve D has resulted from chemical action or physical breakdown, allowing a leaching process within the FRP material.

Absorption tests were conducted on epoxy and vinylester glued samples. Routine weight measurements were taken on a scale that reads to 0.1 grams in order to determine the amount of moisture that was absorbed. Before measuring the samples, a clean rag was used to remove any surface moisture, as this would affect the accuracy of the measurements.

Figure 7.2 and 7.3 shows the amount of moisture absorbed by the different samples. The epoxy samples have shown a much larger increase in weight, however the weight gain is still linear, which indicates a Fickian diffusion process. The vinylester sample results in Figure 7.3 have shown some equilibrium.

The results shown in Figure 7.2 shows that the epoxy samples with 7 layers absorbed much more moisture than the samples with three layers. This was expected because there is more FRP and resin which will absorb the moisture.

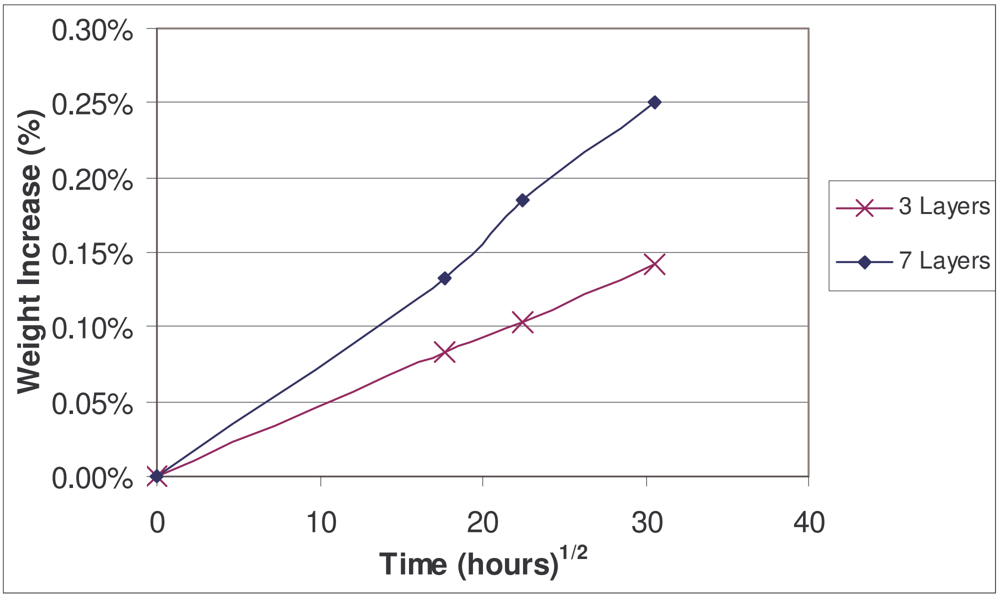

Figure 7.2: Weight Gain of the 3 and 7 Epoxy Samples

The vinylester samples did not gain as much weight as the epoxy samples but they have shown some equilibrium. This can be seen for the saltwater samples in Figure 7.3. The samples immersed in deionised water with protected edges have not shown any equilibrium. No direct information on the effect of the water absorbed by these samples can be drawn as the weight measurements were stopped too early.

The samples that had unprotected edges, and were immersed in deionised water, have shown some possible leaching. This was an unexpected result. This leaching may have been caused by the cut edges as this behaviour has not occurred in the samples with protected edges. As the vinylester samples absorbed very little moisture, the weight scales or method of weighing may not be accurate enough to confirm that the FRP material is leaching. However, to complete a good moisture absorption test, longer immersion times are required, which is not feasible within the time frame allocated to this project.

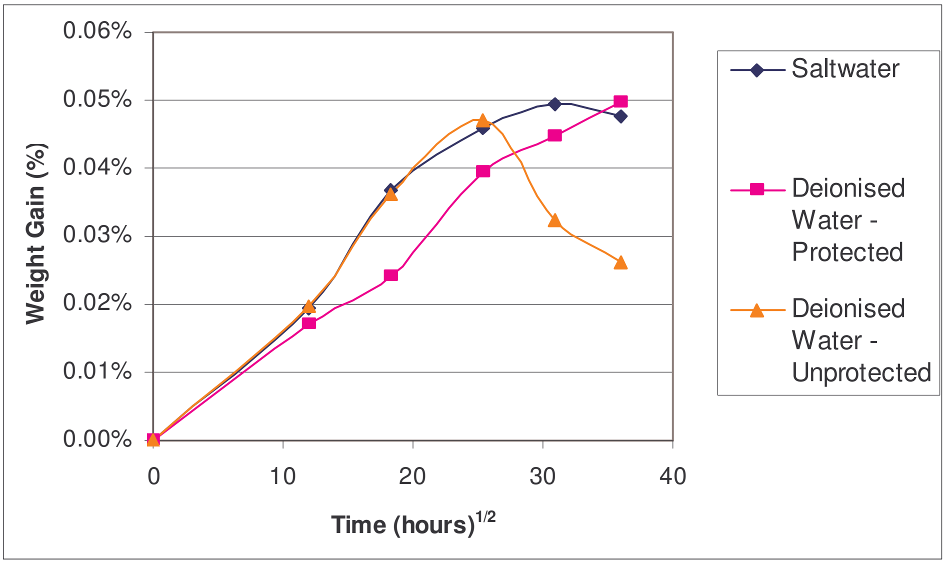

Figure 7.3 Weight Gain of the Vinylester Samples from Saltwater and Deionised Water

7.3 Test Method

The samples were mechanically tested after exposure to the environment conditions. Short beam shear test was chosen since it will test the shear strength of the adhesive bond between the FRP laminates. The set-up for these tests is shown in Figure 7.5 and 7.6.

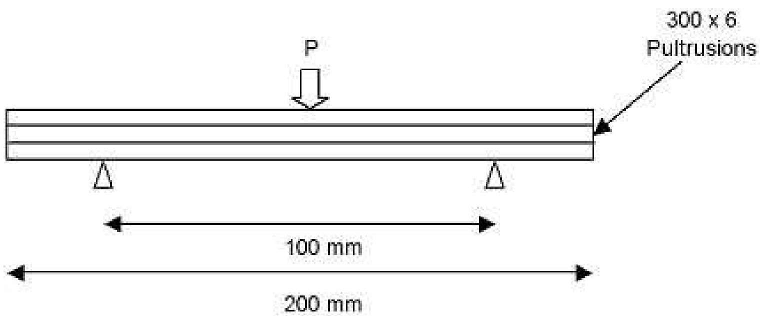

Figure 7.4: Distances for Short Beam Shear Test

A jig was made to help test the samples. This is shown in Figure 7.6. This jig will ensure that the support spacing and load position will remain constant throughout the time that the tests are conducted.

Figure 7.5: Sample Set-up in Test Jig and Machine

7.4 Test Results and Analysis

From the shear tests the maximum load is determined. The apparent shear strength is then calculated using the equation given in ASTM D2344, Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fibre Composite by Short-Beam Method [41]. The equation given in this standard is:

$$S_H = \frac{0.75P_B}{bd}$$

S_H = Shear Strength, N/m^2

P_B = Maximum Load, N

b = Width of Specimen, mm

d = Thickness of Specimen, mm

The results have been shown in different sections depending on the environment the samples were exposed to. The first column in all the graphs is the initial strength of the manufactured samples. The standard deviation of the samples and the number of samples tested are also shown on the graphs. The complete results from the shear tests are given in Appendix B.

7.4.1 Deionised Samples

Figure 7.6 to 7.19 shows the apparent shear strength of the specimens immersed in deionised water. Figure 7.6 shows a steady increase in the apparent shear strength during the 22 week exposure.

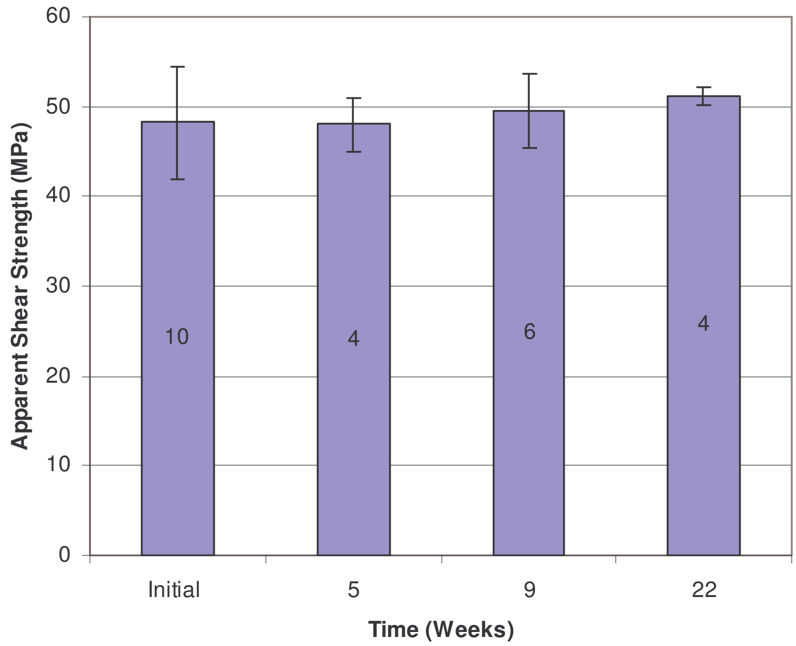

Figure 7.6: Apparent Shear of Samples Immersed in Deionised Water, Longitudinal Fibres and Protected Edges

Figure 7.7 shows the samples with unprotected edges. The apparent shear strength of the adhesive joint increases after 5 weeks of immersion. However the shear strength for the 9 and 22 week samples are very similar to the initial shear strength. This shows that very little damage has been caused by immersion in deionised water.

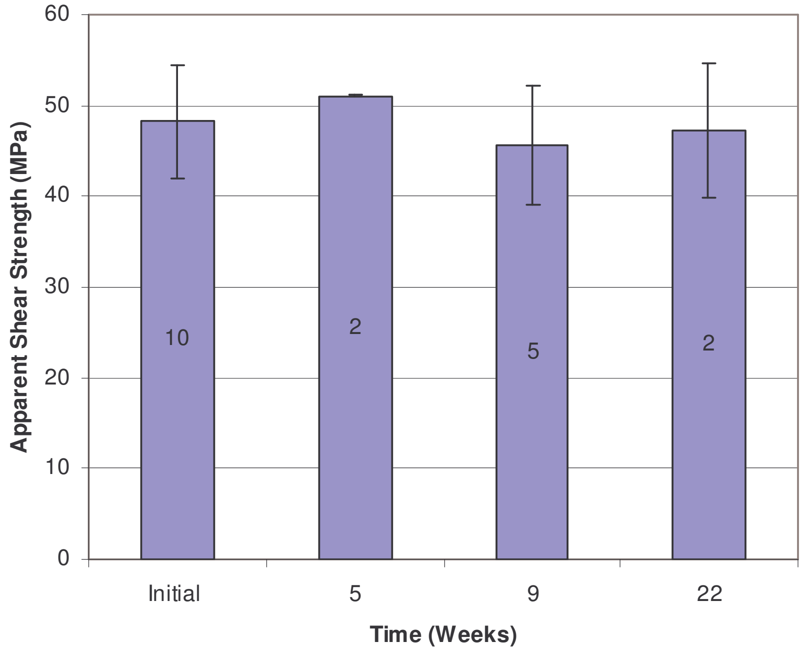

Figure 7.7: Apparent Shear of Samples Immersed in Deionised Water, Longitudinal Fibres and Unprotected Edges

The results from the transverse samples are shown in Figure 7.8 and 7.9. After an increase in shear strength of the adhesive joint after 5 weeks, the strength decreases for the 9 and 22 week samples. However the variation in the results from the samples with unprotected edges is more pronounced.

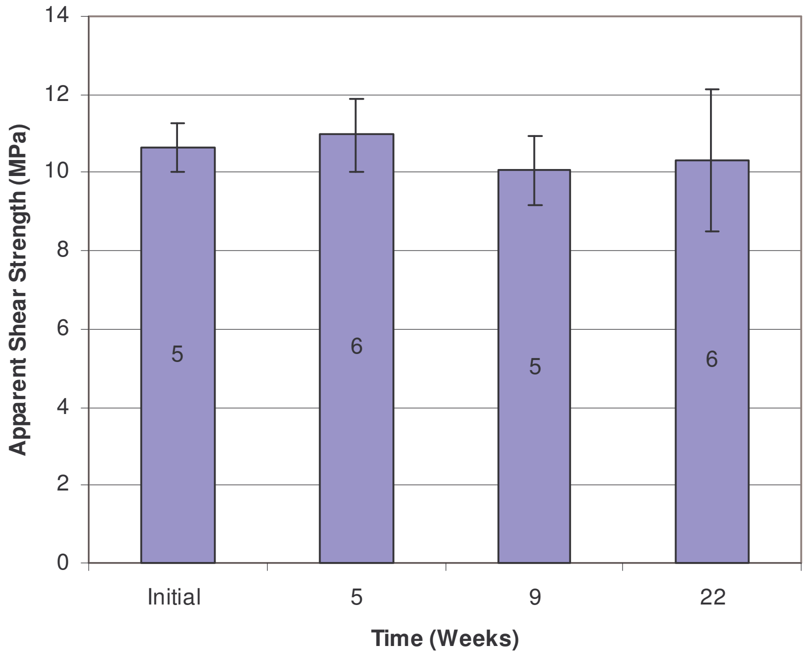

Figure 7.8: Apparent Shear of Samples Immersed in Deionised Water, Transverse Fibres and Protected Edges

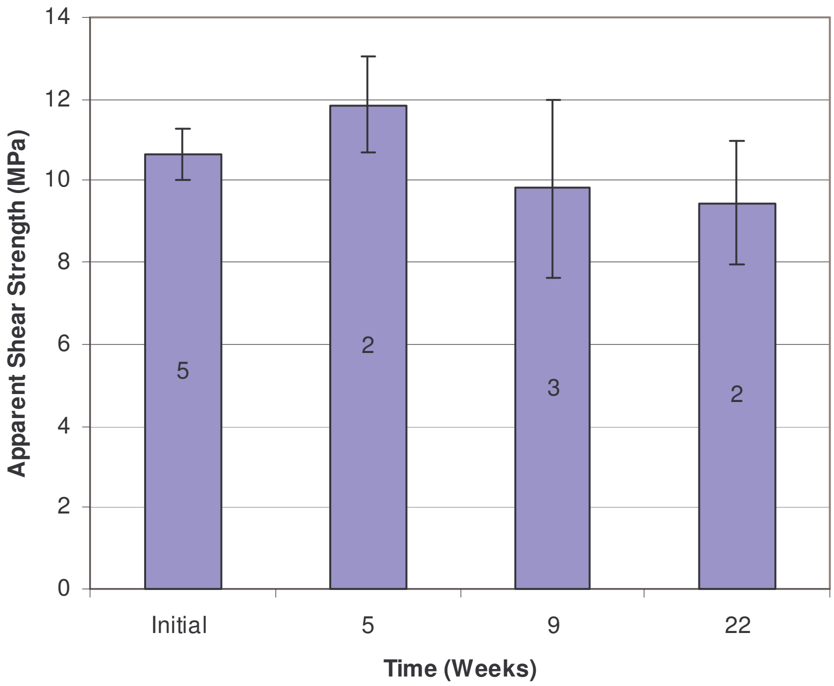

Figure 7.9: Apparent Shear of Samples Immersed in Deionised Water, Transverse Fibres and Unprotected Edges

7.4.2 Saltwater Samples

The shear strength of the adhesive joint of the samples immersed in saltwater are shown in Figure 7.10 and 7.11. Both of these graphs show that the samples slowly increased in shear strength during the 22 week test period. This is similar to what occurred to the protected edge samples immersed in deionised water shown in Figure 7.6.

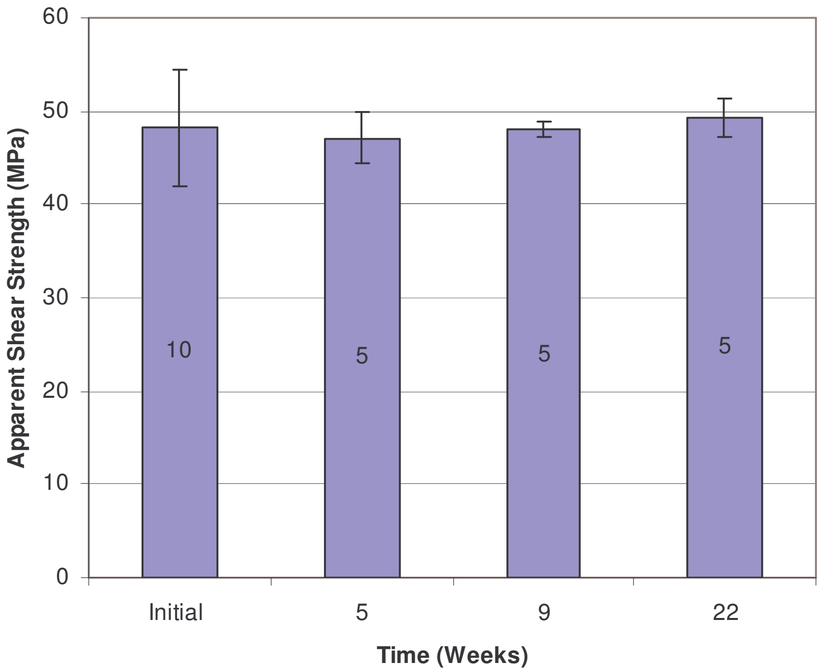

Figure 7.10: Apparent Shear of Samples Immersed in Saltwater, Longitudinal Fibres and Protected Edges

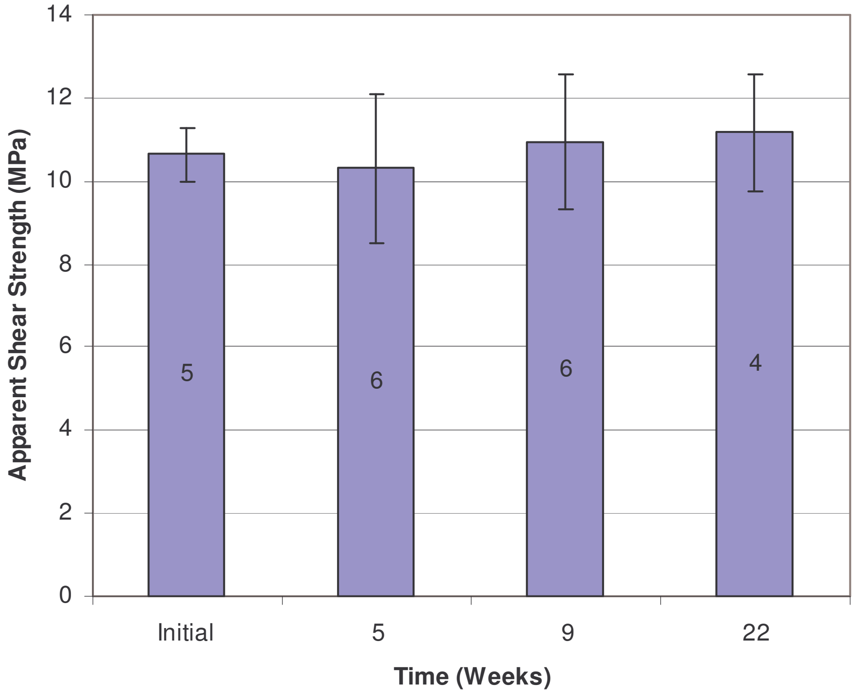

Figure 7.11: Apparent Shear of Samples Immersed in Saltwater, Transverse Fibres and Protected Edges

7.4.3 Freeze Thaw Cycling

The results from the freeze thaw cycling are shown in Figure 7.12 to 7.15. The behaviour for the unprotected and protected samples is similar irrespective of the fibre orientation. For the protected edge samples, there is decrease in the shear strength of the adhesive joint after 4 weeks of cycling. This is followed by an increase in shear strength to be similar to the initial strength. However for the unprotected edge samples there is an increase in strength after 4 weeks, the strength after 9 weeks is then similar to the initial shear strength.

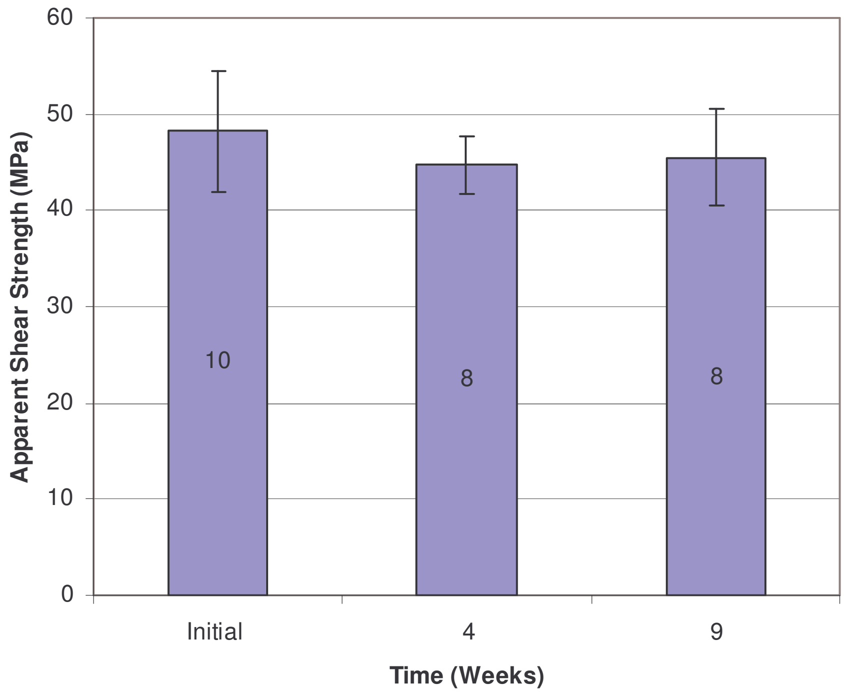

Figure 7.12: Apparent Shear of Samples Subjected to Freeze Thaw Cycling, Longitudinal Fibres and Protected Edges

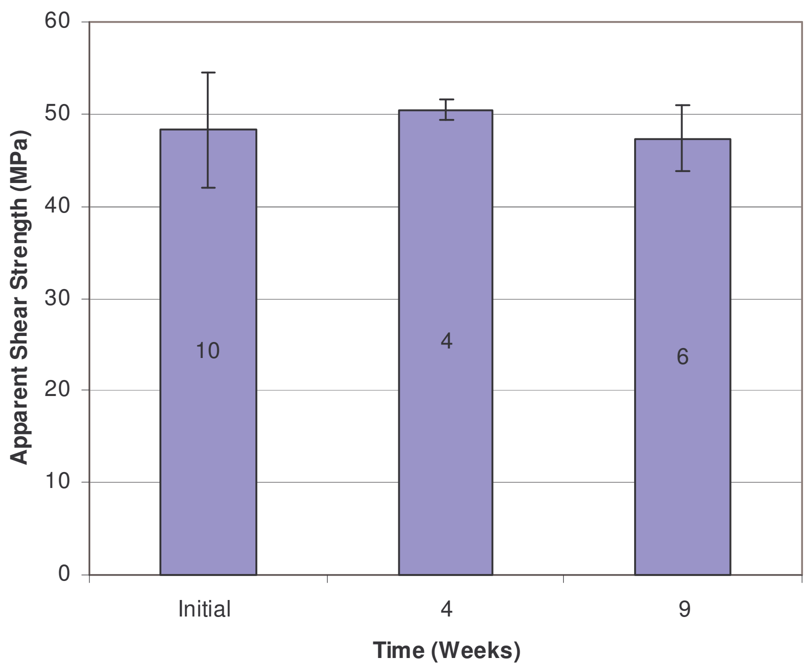

Figure 7.13: Apparent Shear of Samples Subjected to Freeze Thaw Cycling, Longitudinal Fibres and Unprotected Edges

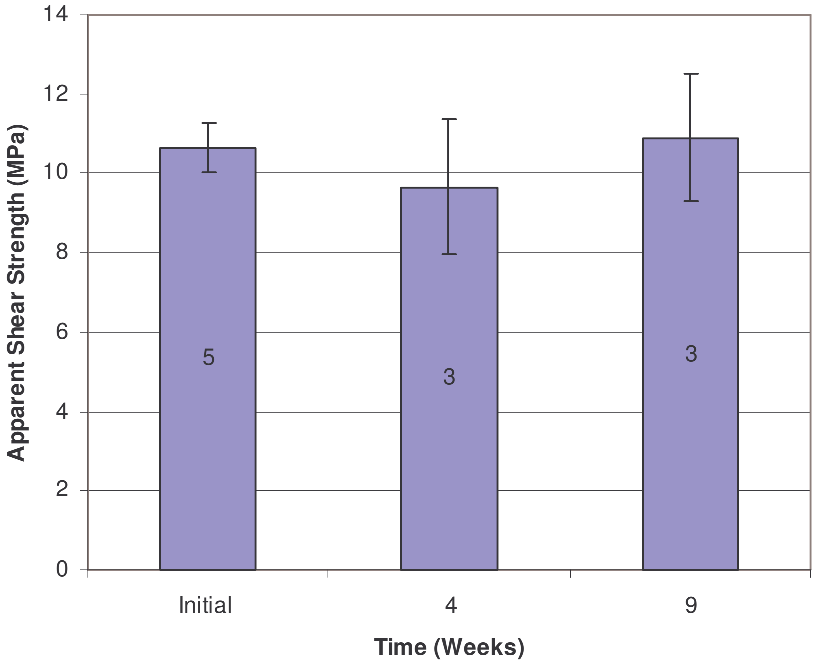

Figure 7.14: Apparent Shear of Samples Subjected to Freeze Thaw Cycling, Transverse Fibres and Protected Edges

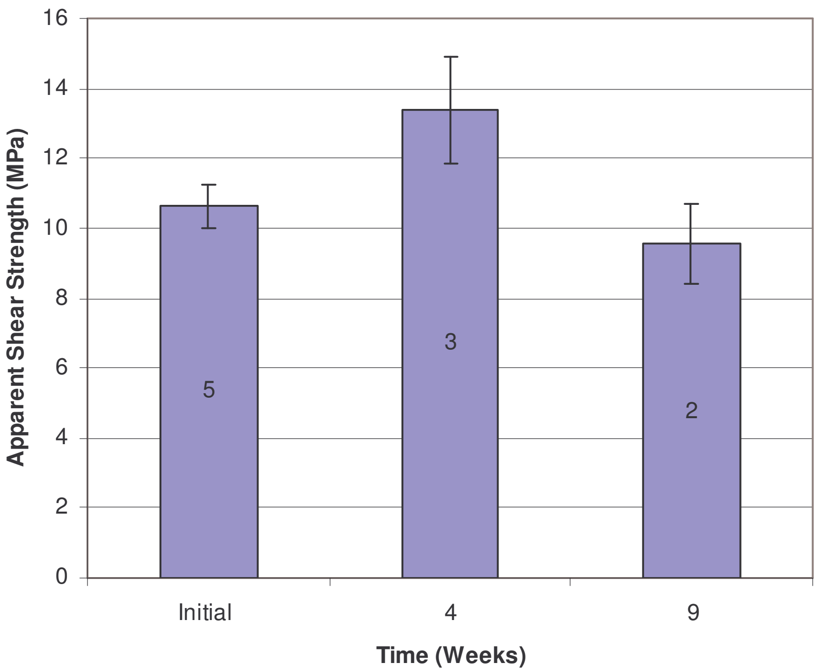

Figure 7.15: Apparent Shear of Samples Subjected to Freeze Thaw Cycling, Transverse Fibres and Unprotected Edges

7.4.3 Thermal Cycling

The thermal cycling samples were separated into two sections depending on the temperatures used. The first section shows the samples cycled from room temperature to 60°C and the second set shows the samples cycled from –5°C to 60°C.

<u>7.4.3.1 Room Temperature to 60°C Samples</u>

The affect of this thermal cycling regime produces a clear behaviour pattern for the longitudinal samples, as seen in Figure 7.16. This small increase in shear strength over the first 9 weeks of cycling can be explained by the post curing effect of the FRP. However after 13 weeks the samples have lost much of this shear strength and is slightly lower than the initial shear strength.

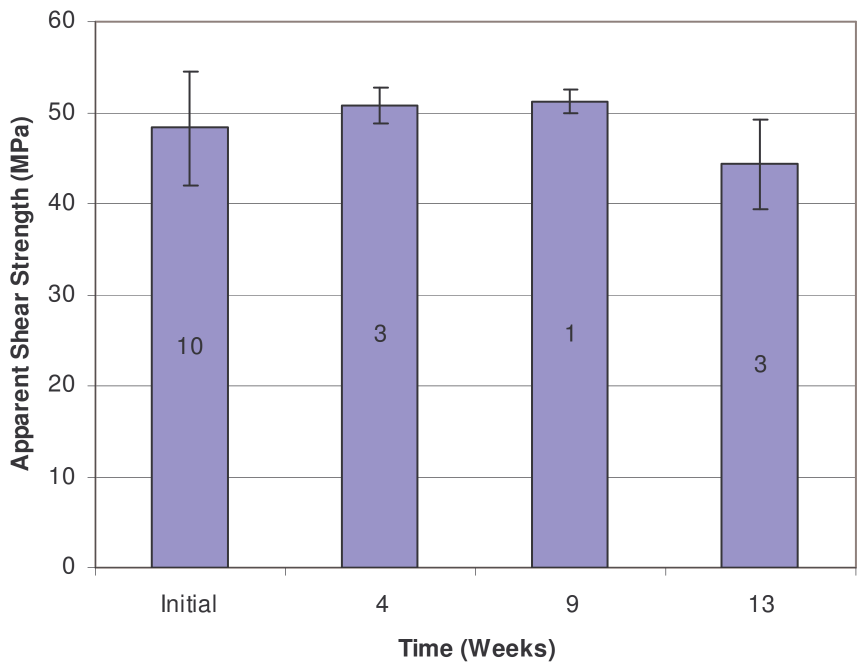

Figure 7.16: Apparent Shear of Samples Subjected to Thermal Cycling From Room Temperature to 60°C, Longitudinal Fibres and Unprotected Edges

The post curing effect does not seem to occur with the transverse fibre samples, as Figure 7.17 shows. This thermal cycling has actually caused a decrease in shear strength of the adhesive joint. The decrease is only small after 9 weeks of cycling but a large decrease in shear strength is observed after 13 weeks of cycling. This decrease after 13 weeks is similar to the behaviour of the longitudinal fibre samples.

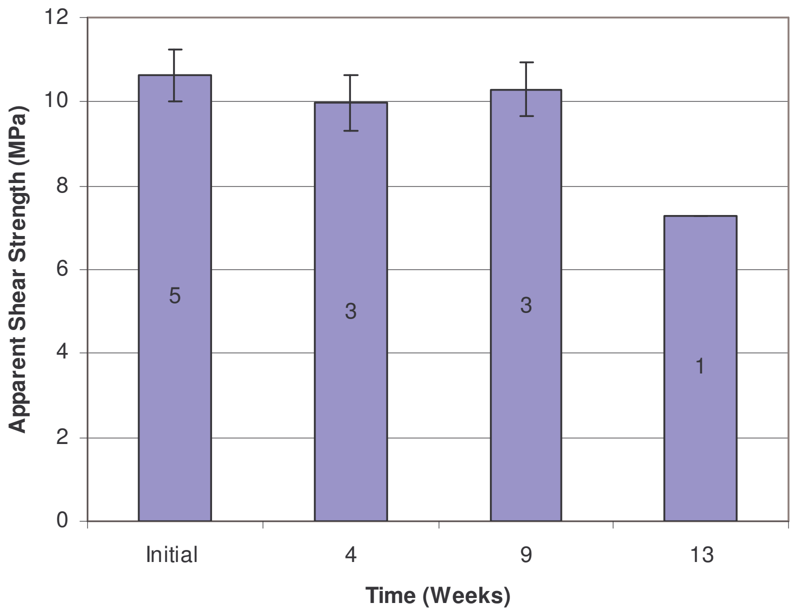

Figure 7.17: Apparent Shear of Samples Subjected to Thermal Cycling From Room Temperature to 60°C, Transverse Fibres and Unprotected Edges

7.4.3.2 -10°C to 60°C Samples

The samples cycled from -10°C to 60°C exhibit similar behaviour irrespective of the fibre orientation as can be seen in Figure 7.18 and 7.19. Both sample sets show the adhesive joint shear strength has decreased during the cycling period. After about 10 weeks of cycling it was observed that the samples had broken apart at the adhesive joint. This indicates that either the environments were two extreme or the cycling time was to short. It would be highly unlikely that a bridge would undergo an environment quite as extreme as this.

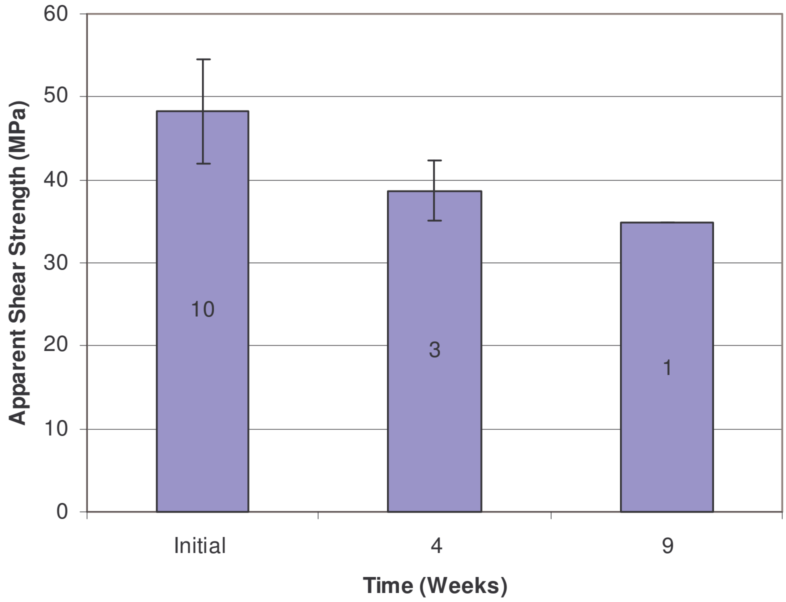

Figure 7.18: Apparent Shear of Samples Subjected to Thermal Cycling From -10°C to 60°C, Longitudinal Fibres and Unprotected Edges

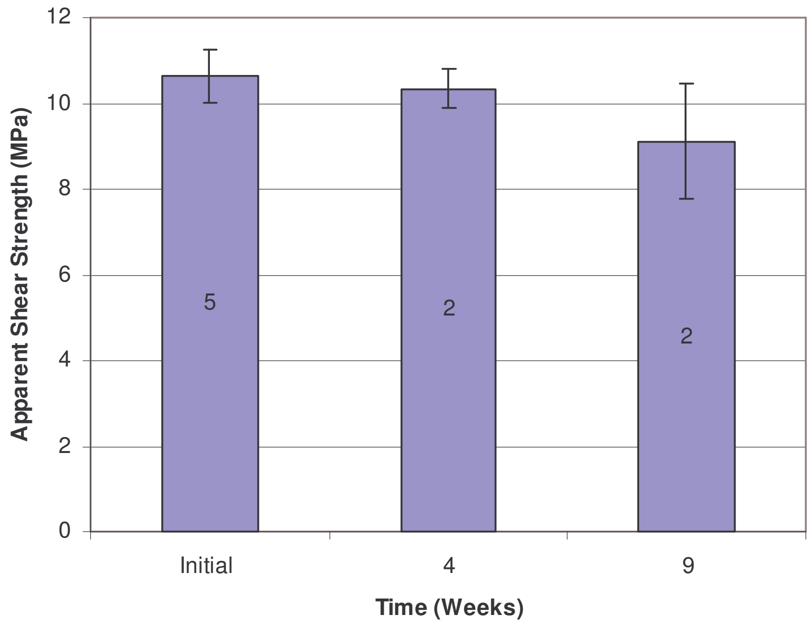

Figure 7.19: Apparent Shear of Samples Subjected to Thermal Cycling From -10°C to 60°C, Transverse Fibres and Unprotected Edges

7.5 Conclusion

From these test results a number of conclusions can be drawn. It was observed that the edge protection that was applied to the samples affected not only the absorption results but also the shear test results.

The samples with their fibres orientated longitudinally were affected more than the transverse samples. As the fibres would have carried the load for the longitudinal samples, the thermal cycling may have affected the glass fibres and/or the fibre/matrix bond.

The samples that were thermally cycled may have been subjected to a temperature greater than 60^{o}C. As there are limited facilities at WCFT, the oven was shared between many research and development projects being conducted at the time of this investigation. This sharing may have resulted in the oven temperature being changed and not returned to the 60^{o}C temperature. Therefore the samples may have been subjected to temperatures over 80^{o}C, this temperature would affect the FRP material in a way that would not occur in service.

The results derived from this investigation are limited for several reasons. The main reason is the limited time given to conduct this project. There is also too few samples to gain a reliable indication of the environmental effects, although over 300 samples were produced to many environmental conditions were mimicked. As indicated above there is limited resources available at Wagners to conduct a thorough durability investigation. Therefore to conduct a durability investigation the following aspects of the investigation are important:

- Long environmental exposure time, for example over 1 year
- More samples for each test time
- Less environmental conditions
- Specifically dedicated resources
- Accurate method to measure weight increase

These recommended aspects may mean that particular types of durability investigations would not be advised for private companies like WCFT. However some environmental conditions, like moisture immersion, would be recommended because it requires very little resources after immersion has commenced.

Chapter 8

Conclusion and Recommendations

8.1 Conclusions

This project was conducted to determine if there is any major durability related concerns with the construction of a hybrid concrete-FRP bridge deck and determine if they are applicable to the bridge deck produced by Wagner Composite Fibre Technologies.

This was done by:

- Investigating FRP material and the construction of the hybrid-FRP bridge produced by WCFT
- Determine the most susceptible area of the bridge to durability problems
- Conduct tests and analyse the results on this area using various accelerated environments

- Analyse previous durability investigations relating to the construction of the concrete-FRP bridge to determine if there is any other areas of durability concern

By analysing FRP material and the construction of the hybrid-FRP bridge helped identify a range of areas that could be have a durability concern. Investigating the design fundamentals of the bridge and the material produced by WCFT helped do this.

From the initial analysis it was determined that investigations on the adhesive joints used in the bridge was the area most susceptible to durability problems. This investigation yielded some unusual and surprising results. The moisture absorption test yielded the most unexpected result, with a possible leaching problem with the FRP material revealed. Due to the limited time given for this investigation, the leaching observed in the vinylester samples may not be correct.

The shear test indicated that no damage was sustained by the samples due to the different environments used. However due to the short time allocated to conduct this project, only a short environmental exposure times was used. Therefore the environmental conditions may not have enough time to affect the adhesive joint.

From the investigation conducted at WCFT a number of recommendations can be made about future durability investigations. To conduct a thorough durability investigation, it is recommended the following aspects be considered:

- Having a long environmental exposure time, for example over 1 year
- Have many samples for each test period
- Investigate one or two environmental conditions
- Have specifically dedicated resources
- Create an accurate method to measure weight increase

By investigating the other areas of the hybrid concrete-FRP bridge any other durability concerns would be highlighted. The only area that showed a possible durability problem was the adhesive joint between concrete and FRP. The literature however, is not entirely related to the bridge produced by WCFT. The reason for this is the construction of the test specimens used in the literature is not the same as that used in the concrete-FRP bridge. Therefore, durability tests may need to be conducted on the adhesive joint used by WCFT. The literature also highlighted that the durability of the adhesive joint between concrete and FRP is dependant on the adhesive used [35].

8.2 Recommendations for Further Study

This investigation has identified a possible leaching problem with the FRP material produced by WCFT. However because of the possible errors in the weight scales and weighting process this cannot be confirmed. Therefore it is recommended that a longer immersion test be conducted on the FRP material, this does not necessarily need to be mechanically tested. This longer study will need to be more precise and consistent throughout the exposure period.

It is also recommended that a longer study be completed on the adhesive joints. This does not need to involve as many environments used in this study but needs to be done over a longer period of time. The type of mechanical test may also be changed, for example a single or double lap shear test.

A long-term investigation could also be conducted on the prototype bridge. This bridge is still in service at the Wagner quarry located at Wellcamp Downs, Toowoomba. Yearly inspections should be conducted to identify any signs of fatiguing or degradation. A large investigation on this bridge should only be conducted after 10-20 years of service.

Chapter 9

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Appendix A

Project Specifications

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project

PROJECT SPECIFICATION

FOR: **MARK PRASSER**

TOPIC: THE DURABILITY OF HYBRID CONCRETE-FRP BRIDGE DECKS

SUPERVISOR: Dr Amar Khennane

PROJECT AIM: This project aims to determine if there are any major durability related concerns with the construction of a hybrid concrete-FRP bridge deck and determine if they are applicable to the bridge deck produced by Wagner Composite Fibre Technologies

SPONSERSHIP: Wagner Composite Fibre Technologies

PROGRAMME: **Issue B 1st August 2005**

1. Investigate the bridge decks and fibre composite material produced by Wagner Composite Fibre Technologies.

2. Research the durability studies done that relate to the different components of the Wagner bridge decks.

3. Determine what components require further investigation based on the reviewed literature.

4. Decide on test method and sample configuration that will test the gap in literature

5. Analyse test data and determine if there is a durability problem

As time permits:

6. Analyse current bridges in service to determine any deterioration

AGREED:____________________ (Student) ____________________ (Supervisors)

__/__/________ __/__/______

Appendix B

Shear Test Results

Initial Unconditioned Samples **Longitudinal**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
50	46.8	17.7	46.78	41.3
51	43.6	17.8	43.62	37.7
56	61.7	17.7	61.69	53.5
78	51.8	17.6	51.79	45.1
80E	55.5	17.6	55.47	48.5
80W	59.49	17.2	59.49	53.0
82	66.32	17.0	66.32	59.8
227	52.4	17.9	52.35	44.9
229	64.92	18.2	64.92	54.7
247	55.4	17.4	55.36	49.0
251	50.2	18.0	50.21	42.9
280	58.4	18.5	58.38	48.5

Average Max Load	55.53
Average Shear	48.25
Standard Deviation	6.28
Coefficient of Variance	13%
Number of Tests	10

Initial Unconditioned Samples **Transverse**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
30	48.0	17.7	11.72	10.3
158	48.8	18.3	13.92	11.7
198	48.85	18.3	11.91	10.0
209	49.0	18.1	12.46	10.5
29	48.8	18.3	12.62	10.6

Average Max Load	12.53
Average Shear	10.64
Standard Deviation	0.63
Coefficient of Variance	6%
Number of Tests	5

Immersion In Deionised Water - 5 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
33	49.65	17.85	55.43	46.9
36	49.3	18	52.88	44.7
49	48.75	17.8	60.01	51.9
249	49.8	17.95	57.92	48.6

Average Max Load	56.56
Average Shear	48.02
Standard Deviation	3.02
Coefficient of Variance	6%
Number of Tests	4

2 tests deleted because of incorrect test method

Immersion In Deionised Water - 9 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
34	49.3	17.7	59.26	50.9
35	49.4	17.95	62.96	53.3
37	49.8	17.75	56.83	48.2
254	49.45	18.35	55.13	45.6
255	49.6	18.9	68.29	54.6
261	50	17.8	53.01	44.7

Average Max Load	59.25
Average Shear	49.55
Standard Deviation	4.07
Coefficient of Variance	8%
Number of Tests	6

Immersion In Deionised Water - 22 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
38	49.3	17.7	60.91	52.4
55	49.75	17.95	60.88	51.1
256	49.45	17.95	60.99	51.5
257	49.45	18.15	59.54	49.8

Average Max Load	60.58
Average Shear	51.19
Standard Deviation	1.09
Coefficient of Variance	2%
Number of Tests	4

2 tests deleted because of incorrect test method

Immersion In Deionised Water - 5 Weeks Longitudinal Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
58	48.9	17.6	58.53	51.0
237	48.9	17.8	59.33	51.1

Average Max Load	58.93
Average Shear	51.06
Standard Deviation	0.08
Coefficient of Variance	0%
Number of Tests	2

1 tests deleted because of incorrect test method

Immersion In Deionised Water - 9 Weeks Longitudinal Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
57	48.7	17.7	59.54	51.8
60	49.5	17.55	57.45	49.6
125	48	18.5	45.62	38.5
238	48.95	17.8	44.74	38.5
248	48.9	17.95	58.45	49.9

Average Max Load	53.16
Average Shear	45.68
Standard Deviation	6.59
Coefficient of Variance	14%
Number of Tests	5

Immersion In Deionised Water - 22 Weeks Longitudinal Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
59	48.8	17.75	60.67	52.5
65e	49.2	17.95	49.48	42.0

Average Max Load	55.08
Average Shear	47.28
Standard Deviation	7.43
Coefficient of Variance	16%
Number of Tests	2

Immersion In Deionised Water - 5 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
1	49.7	18.1	12.81	10.7
4	49.5	18	13.32	11.2
6	49.6	17.8	15.01	12.8
141	50.35	18.75	12.81	10.2
156	49.8	18.5	12.66	10.3
161	50.8	18.65	13.53	10.7

Average Max Load	13.36
Average Shear	10.97
Standard Deviation	0.94
Coefficient of Variance	9%
Number of Tests	6

Immersion In Deionised Water - 9 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
2	50.2	17.9	11.51	9.6
8	49.7	17.9	13.49	11.4
166	49.9	19	12.01	9.5
171	49.7	18.9	11.62	9.3
176	50.35	18.8	13.31	10.5

Average Max Load	12.39
Average Shear	10.06
Standard Deviation	0.88
Coefficient of Variance	9%
Number of Tests	5

Immersion In Deionised Water - 22 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
5	50.8	18.65	9.38	7.4
141	49.7	18.1	12.71	10.6
146	50.15	18.75	11.51	9.2
151	49.6	17.8	12.4	10.5
186	49.5	17.95	13.85	11.7
291	49.85	18.5	15.3	12.4

Average Max Load	12.53
Average Shear	10.31
Standard Deviation	1.80
Coefficient of Variance	17%
Number of Tests	6

Immersion In Deionised Water - 5 Weeks Transverse Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
199	48.9	18.25	13.14	11.0
213	48.9	18.2	15.05	12.7

Average Max Load	14.10
Average Shear	11.86
Standard Deviation	1.16
Coefficient of Variance	10%
Number of Tests	2

Immersion In Deionised Water - 9 Weeks Transverse Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
194	48.8	18.2	8.78	7.4
204	48.95	18.15	13.82	11.7
290	50	18.2	12.6	10.4

Average Max Load	11.73
Average Shear	9.82
Standard Deviation	2.18
Coefficient of Variance	22%
Number of Tests	3

Immersion In Deionised Water - 22 Weeks Transverse Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
299	49.5	17.95	12.47	10.5
304	49.3	18.15	10.01	8.4

Average Max Load	11.24
Average Shear	9.46
Standard Deviation	1.51
Coefficient of Variance	16%
Number of Tests	2

Immersion In Saltwater - 5 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
40	49.5	17.8	56.88	48.4
42	49.75	18	58.46	49.0
54	49.5	17.8	58.76	50.0
223	50.2	18	53.34	44.3
226	50.75	18.1	53.92	44.0

Average Max Load	56.27
Average Shear	47.14
Standard Deviation	2.79
Coefficient of Variance	6%
Number of Tests	5

1 tests deleted because of incorrect test method

Immersion In Saltwater - 9 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
39	49.2	17.9	55.23	47.0
44	49.8	17.7	57.97	49.3
53	49.4	17.85	56.32	47.9
221	50.15	18.75	59.94	47.8
225	50.75	18	58.6	48.1

Average Max Load	57.61
Average Shear	48.04
Standard Deviation	0.83
Coefficient of Variance	2%
Number of Tests	5

Immersion In Saltwater - 22 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
41	50.25	18.2	56.76	46.5
43	49.4	17.95	60.23	50.9
52	49.75	17.8	60.7	51.3
222	49.8	17.7	56.52	47.9
279	50.1	18.5	61.79	50.0

Average Max Load	59.20
Average Shear	49.34
Standard Deviation	2.06
Coefficient of Variance	4%
Number of Tests	5

1 tests deleted because of incorrect test method

Immersion In Saltwater - 5 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
5	50.8	18.65	9.38	7.4
141	49.7	18.1	12.71	10.6
146	50.15	18.75	11.51	9.2
151	49.6	17.8	12.4	10.5
186	49.5	17.95	13.85	11.7
291	49.85	18.5	15.3	12.4

Average Max Load	12.53
Average Shear	10.31
Standard Deviation	1.80
Coefficient of Variance	17%
Number of Tests	6

Immersion In Saltwater - 9 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
10	48.95	17.9	14.38	12.3
14	49.6	17.8	12.51	10.6
15	49.8	17.9	14.7	12.4
201	50.8	18.65	12.87	10.2
206	50.55	18.6	10.34	8.2
216	50.6	18.9	15.28	12.0

Average Max Load	13.35
Average Shear	10.95
Standard Deviation	1.61
Coefficient of Variance	15%
Number of Tests	6

Immersion In Saltwater - 22 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
16	49.75	18.15	12.99	10.8
32	49.5	17.75	15.35	13.1
196	50.2	18.5	12.04	9.7
214	50.1	18.25	13.5	11.1

Average Max Load	13.47
Average Shear	11.17
Standard Deviation	1.41
Coefficient of Variance	13%
Number of Tests	4

Freeze Thaw Cycling - 4 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
20	49.20	18.2	51	42.7
21	49.50	18.15	57.5	48.0
22	49.85	17.9	58.5	49.2
241	50.35	18.55	53	42.6
246	50.50	18.65	57	45.4
253	49.90	18.55	57.26	46.4
266	50.40	18.45	52	41.9
269	49.40	18.65	51	41.5

Average Max Load	54.66
Average Shear	44.71
Standard Deviation	2.94
Coefficient of Variance	7%
Number of Tests	8

Freeze Thaw Cycling - 9 Weeks **Longitudinal** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
230	50.20	18.7	60.6	48.5
217	50.40	18.5	57.16	46.1
236	50.30	18.2	47.01	38.5
28	49.40	18.1	61.24	51.4
281	49.02	18.5	52.63	43.6
234	50.15	18.6	47.64	38.3
27	49.60	18.1	60.33	50.4
26	49.60	18.0	55.83	46.9

Average Max Load	55.31
Average Shear	45.47
Standard Deviation	4.99
Coefficient of Variance	11%
Number of Tests	8

Freeze Thaw Cycling - 4 Weeks **Longitudinal** **Unprotected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
68e	48.90	17.45	56	49.2
71w	49.00	17.65	59	51.2
68w	48.90	17.45	56.5	49.7
77w	48.92	17.55	59	51.5

Average Max Load	57.63
Average Shear	50.40
Standard Deviation	1.13
Coefficient of Variance	2%
Number of Tests	4

2 tests deleted because of incorrect test method

Freeze Thaw Cycling - 9 Weeks **Longitudinal** **Unprotected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
71	48.90	17.4	56.43	49.9
267	48.80	18.4	52.89	44.3
74E	48.80	17.4	58.12	51.5
74W	48.93	17.5	56.46	49.5
413	49.60	18.0	55.42	46.7
265	49.25	18.2	50.24	42.2

Average Max Load	54.93
Average Shear	47.33
Standard Deviation	3.60
Coefficient of Variance	8%
Number of Tests	6

1 tests deleted because of incorrect test method

Freeze Thaw Cycling - 4 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
148	49.90	18.55	13.5	10.9
149	49.90	18.2	12.5	10.3
159	50.00	18.45	9.5	7.7

Average Max Load	11.83
Average Shear	9.66
Standard Deviation	1.71
Coefficient of Variance	18%
Number of Tests	3

Freeze Thaw Cycling - 9 Weeks **Transverse** **Protected**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
143	49.75	18.7	15.73	12.7
139	50.20	19.0	12.42	9.8
138	50.05	18.8	12.79	10.2

Average Max Load	13.65
Average Shear	10.90
Standard Deviation	1.59
Coefficient of Variance	15%
Number of Tests	3

Freeze Thaw Cycling - 4 Weeks Transverse Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
184	48.90	18.7	17	13.9
189	48.90	18.2	13.84	11.7
292	50.10	18.2	17.7	14.6

Average Max Load	16.18
Average Shear	13.39
Standard Deviation	1.53
Coefficient of Variance	11%
Number of Tests	3

Freeze Thaw Cycling - 9 Weeks Transverse Unprotected

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
169	48.90	18.2	12.31	10.4
174	48.95	18.2	10.38	8.7

Average Max Load	11.35
Average Shear	9.56
Standard Deviation	1.16
Coefficient of Variance	12%
Number of Tests	2

Thermal Cycling - 4 Weeks **Longitudinal** **Unprotected**
Min temp. **20C** **Max temp.** **60C**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
75	49.20	17.9	60.01	51.1
81	49.80	17.7	57.04	48.5
135	49.40	17.85	61.71	52.5

Average Max Load	59.59
Average Shear	50.71
Standard Deviation	2.01
Coefficient of Variance	4%
Number of Tests	3

Thermal Cycling - 9 Weeks **Longitudinal** **Unprotected**
Min temp. **20C** **Max temp.** **60C**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
72	48.85	17.55	60.01	52.5
73	48.8	17.5	57.04	50.1
132	49.05	18.45	61.71	51.1

Average Max Load	59.59
Average Shear	51.24
Standard Deviation	1.21
Coefficient of Variance	2%
Number of Tests	3

Thermal Cycling - 4 Weeks **Transverse** **Unprotected**

Min temp. 20C Max temp. 60C

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
208	48.95	17.9	11.1	9.5
193	49.6	17.8	12.6	10.7
295	49.8	17.9	11.52	9.7

Average Max Load	11.74
Average Shear	9.97
Standard Deviation	0.65
Coefficient of Variance	6%
Number of Tests	3

Thermal Cycling - 9 Weeks **Transverse** **Unprotected**

Min temp. 20C Max temp. 60C

Sample Number	Width (mm)	Thickness (mm)	Max Load, P(kN)	Max Shear Strength (MPa)
31	48.8	17.6	12.6	11.0
61	48.5	17.6	11.52	10.1
64	48.5	17.6	11.1	9.8

Average Max Load	11.74
Average Shear	10.29
Standard Deviation	0.64
Coefficient of Variance	6%
Number of Tests	3

Thermal Cycling - 4 Weeks **Longitudinal** **Unprotected**

Min temp. **-5C** **Max temp.** **60C**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
124	49.2	17.9	44.27	37.7
123	49.8	17.7	41.92	35.7
67	49.4	17.85	50.15	42.7

Average Max Load	45.45
Average Shear	38.67
Standard Deviation	3.59
Coefficient of Variance	9%
Number of Tests	3

Thermal Cycling - 9 Weeks **Longitudinal** **Unprotected**

Min temp. **-5C** **Max temp.** **60C**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
274	48.75	18.5	41.96	34.9

Average Max Load	41.96
Average Shear	34.89
Standard Deviation	-
Coefficient of Variance	-
Number of Tests	1

Other samples failed before tests could be done

Thermal Cycling - 4 Weeks **Transverse** **Unprotected**

Min temp. **-5C** **Max temp.** **60C**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
63	49.6	17.8	12.56	10.7
173	48.95	17.9	11.7	10.0

Average Max Load	12.13
Average Shear	10.34
Standard Deviation	0.46
Coefficient of Variance	4%
Number of Tests	2

Thermal Cycling - 9 Weeks **Transverse** **Unprotected**

Min temp. **-5C** **Max temp.** **60C**

Sample Number	Width (mm)	Thickness (mm)	Max Load, P (kN)	Max Shear Strength (MPa)
62	48.85	17.65	11.56	10.1
178	48.8	18.4	9.81	8.2

Average Max Load	10.69
Average Shear	9.12
Standard Deviation	1.32
Coefficient of Variance	14%
Number of Tests	2