Durability of construction solutions with fiber-reinforced polymers (FRP) in pedestrian bridges

Beständighet för konstruktionslösningar med fiberarmerade plastkompositer (FRP) i gång- och cykelbroar

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Subject area: FRP composites
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An inventory of studies in the subject area

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En inventering av studier i ämnesområdet

Bachelor thesis – Construction engineering 180 HEC

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Preface

This bachelor thesis of 15 Higher Education Credits was carried out in cooperation with Malmö streets and parks department and Malmö University as part of the program for construction engineering. We would like to express our gratitude to the external tutor Abbas Khayyami at Malmö streets and parks department and the tutor at Malmö University Anders Peterson for their help and guidance.

David Bengtsson

Tommy Magnusson

Malmö, Sweden, May 2016
Abstract

This bachelor thesis was written in cooperation with Malmö Streets and Parks Department to collect information on fiber-reinforced polymer (FRP) composites. In today’s building industry, FRP composites provide an interesting alternative to conventional building materials because of their superior material properties. FRPs are suggested to be a sustainable solution meeting the future requirements in infrastructure and especially bridge design. The use of FRP composites in pedestrian bridge applications have not previously been utilized in Sweden and thus the material is relatively unknown to the building industry.

The aim of this study was primarily to examine the performance in terms of durability of FRP pedestrian bridges subjected to the effects of the surrounding environment by conducting a literature review. The main part of this study was to evaluate different types of degradation to assess the potential weaknesses of FRP composites during in-service use in pedestrian bridges. The connections between the different members and components in FRP bridges were also studied and their impact on the overall durability of the construction was evaluated.

The results from this study provided an overview of the durability characteristics of FRP composites subjected to different types of degradation. From this overview it was concluded that degradation by moisture absorption, high and/or cyclic temperature, and UV-radiation had the most significant impact on the material properties in FRP composites. This study also concludes that the effects of synergism between the different types of degradation need to be considered since FRP composites are subjected to many types of degradations in natural environments. Because of the effects of synergism, the individual effects of the different types of degradations can be difficult to evaluate. Due to lack of information, the impact on overall durability in pedestrian bridges from the connections between components in the superstructure could not be fully evaluated. However, it was found that connections should be avoided if possible due to vibrations, fatigue, and thermal expansions that may cause higher stress levels in the connection points.

The results of this study aims to provide guidance when designing FRP composite pedestrian bridges.

Keywords: Fiber-Reinforced Polymer, FRP, Durability, Environmental impact, Weathering, Composites in civil engineering

Cover: All-composite port bridge in Holland

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1 Photo by Abbas Khayyami (2014-05-17)
Sammanfattning

Arbetet har genomförts i samarbete med Malmö Gatukontor med målet att samla in information om fiberförstärkta plastkompositer (fiber-reinforced polymer; FRP). FRP-kompositer kan vara ett intressant alternativ till konventionella byggnadsmaterial på grund av sina goda materialegenskaper. FRP har inte använts i gångbroar i Sverige tidigare och materialet är därför relativt okänt för byggbranschen.

Studiens syfte var att undersöka och dokumentera beständigheten för FRP-gångbroar som påverkas av den omgivande miljön. Arbetet har genomförts som en litteraturstudie. Huvuddelen av studien fokuserade på att utvärdera olika nedbrytningsprocesser för att kunna bedöma potentiella svagheter hos FRP kompositer i gångbroar. Kopplingspunkter mellan olika delar i FRP broar har också studerats och dess inverkan på den totala beständigheten av konstruktionen har evaluerats.

Studien ger en överblick av hur beständigheidsparametrar för FRP-kompositer påverkas av olika typer av nedbrytning. Från denna överblick värderades nedbrytning genom fuktabsorption, höga och/eller cykliska temperaturer och UV-strålning som de faktorer som mest påverkar materialegenskaperna för FRP-kompositer. Studien konstaterar även att effekten av samverkan mellan olika nedbrytningsprocesser måste beaktas då materialet utsätts för flera olika angrepp i naturliga miljöer. Denna synergi gör att det är svårt att värdera effekten av varje enskilt angrepp. På grund av brist på information kunde inte kopplingspunkterna mellan komponenter i överbyggnadskonstruktionen i gångbroar fullständigt utvärderas, med avseende på dess påverkan på den totala beständigheten. Studien kunde dock konstatera att kopplingspunkter bör undvikas om det är möjligt, då vibrationer, utmattning och termisk expansion kan orsaka högre spänningsnivåer i kopplingspunkterna.

Resultaten från studien syftar till att ge vägledande information vid projektering av gångbroar med FRP-kompositer.
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1 Introduction

1.1 Background

The Swedish parliament has decided that one of the focus areas of the environmental policy should be on good management of natural resources as part of the generation goals (Naturvårdsverket, 2012). Today's building industry accounts for 40% of the total use of material resources in the society, where infrastructural projects accounts for a large portion (Offerman, 2014). In bridge engineering, constructions are expected to last 50-100 years. During service these bridges requires maintenance or refurbishing to remain operational, aspects which can prove costly (Heshmati, 2015; Niroumand, 2009). In order to build sustainable structures, it is important to not only look at the initial cost and environmental impact at manufacture, but also consider the entire life cycle of the construction, thus making the material selection very important (Sweden Green Building Council, 2015; Naturvårdsverket, 2012).

To allow for better and more sustainable solutions it can be of interest to turn to new technologies since conventional materials (steel, wood, and reinforced concrete) have difficulties to meet today's requirements for durability (Mara, et al., 2014). The application of FRP (Fiber Reinforced Polymer) composites in bridge construction is a new technique used mainly in the United States of America but also other parts of the world (Potyrala, 2011). Bridge designs with FRP composites promises high durability performance combined with minimum maintenance and wear (Gururaja & Hari Rao, 2012; Mara, et al., 2014; Niroumand, 2009).

FRP composites have been used in various building projects ranging from strengthening existing structures to full size bridges (Niroumand, 2009; Zaman, et al., 2013). A commonly used FRP bridge design is the so-called hybrid construction where FRP composites are used along with conventional building materials. Another design is the all-composite bridge where the entire superstructure is constructed using FRP composites (Figure 1) (Gururaja & Hari Rao, 2012; Potyrala, 2011). These types of designs are based on the concept of utilizing the favorable properties of FRP composites. High strength-to-weight ratio and superior durability in comparison with conventional building materials will allow engineers to design less complicated and more sustainable constructions (Niroumand, 2009; Zaman, et al., 2013).
FRP composites are relatively new and unknown building materials. Difficulties like high material costs, lack of design standards, and uncertainties regarding material properties have to be overcome in the future to make FRP composites a more viable option in areas such as civil engineering (Niroumand, 2009). Since the design is usually carried out by the manufacturer, the building industry has to rely on their information and methods (Potyrala, 2011; Murphy, 2013). Thus, it is of great importance that studies continues regarding performance of FRP composites (Hollaway, 2010). In order to provide designers and manufactures with important information regarding durability of FRP composites it is necessary to collect and assess previous research and test data (Potyrala, 2011; Masuelli, 2013). It is not only necessary to understand the advantages with composites, comprehension about the materials shortcomings are vital to enable improved designs (Hollaway, 2010). A dangerous myth regarding FRP composites is statements of its invulnerability, unaffected by surrounding environments (Zaman, et al., 2013). Previous reports also suggest further studies regarding the impacts of connection points in FRP bridges (Friberg & Olsson, 2014).

1.2 Aim and objective

This study aims to provide an overview of the durability characteristics of FRP composites used in pedestrian bridge applications. Different types of degradation will be evaluated to present the strengths and weaknesses of FRP composites subjected to the surrounding environment. To provide a better picture, the durability characteristics will be put into perspective in hybrid- and all-composite bridges to display the overall durability of these types of bridge designs. The objective of this study is to answer the following questions:

- How do FRP composites perform under different types of degradation and how do individual components in the material affect the durability characteristics?
- Which types of degradations has the largest impact on the performance of FRP composites and how can designers prevent or minimize the effects?
- How do connection points affect the overall durability of FRP pedestrian bridges?

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Figure 1: All-composite pedestrian bridge in Holland².

² Photo by Abbas Khayyami (2014-05-17)
1.3 Method

The study was conducted as a literature study where the information was collected from research/investigation reports and scientific articles that have been written in the subject area. A literature study was chosen on the bases that no FRP bridges exist in Sweden, which renders practical assessment impossible and because the largest amount of information originates from scientific literature or laboratory testing. Trials of bridge decks are currently being conducted on Universitetsbron in Malmö (Sweden) and both hybrid and all-composite FRP solutions are in the near future planned to be built.

The first and second part of this thesis introduces the reader to FRP materials in civil engineering and the application in pedestrian bridge design. The third and main part of this thesis describes the durability of FRP pedestrian bridges and evaluates pervious research.

The authors have had continuous contact with Abbas Khayyami, project manager at Malmö Streets and Parks Department, who provided information and answers in the subject area since access to information about FRP composites is limited in Sweden.

1.4 Limitations

The study only included pedestrian bridges in natural environments. The study was conducted as an inventory of previous studies, research, and surveys where FRP composites in bridge applications was evaluated based on durability characteristics. This study will only include the most commonly used fibers and polymer resins in civil engineering applications. No measuring or testing was conducted. The study was limited to technical facts and testing results in the subject area for durability during the constructions lifetime or via laboratory testing, which only included natural aging. This study did not include environmental impacts, calculations, nor evaluations of manufacturing processes or substructure constructions. No comprehensive cost comparison was performed.
2 Components and properties of FRP Composites

Fiber-Reinforced Polymer (FRP) is a collective term for fiber-reinforced plastic composite materials. FRP composites have a structural buildup composing of two main parts, fiber reinforcement and a polymer resin. The polymer resin is part of what is called the polymer matrix. There are three main types of fiber reinforcements in FRP composites that are commonly used for engineering purposes: glass, carbon, and aramid fibers (Masuelli, 2013; Correia, 2013). The type of fiber-reinforcement used in the composite is what define the name, i.e. Glass Fiber-Reinforced Polymer (GFRP), Carbon Fiber-Reinforced Polymer (CFRP), and Aramid Fiber-Reinforced Polymer (AFRP). Containing the fiber reinforcement is a polymer used as a binder, which is the body of the composite. Different types of polymers, mainly epoxy, polyester, and vinyl ester thermosetting plastics are used as binders (Friberg & Olsson, 2014; Mara, 2014; Potyrala, 2011). Other constituents (additives) can be added during the production to further enhance specific properties. Depending on the area of use the fibers, polymer, and other additives are selected to meet the engineering requirements such as strength, weight, and durability (Potyrala, 2011; Masuelli, 2013).

In civil engineering purposes FRPs has demonstrated favorable properties when compared to conventional materials like steel and reinforced concrete, and has been characterized as a high performance material (Masuelli, 2013; Correia, 2013). FRP composites show high potential in infrastructural purposes because of favorable properties, such as high-strength, structural stiffness, resistance towards aggressive environments, and having minimum requirements for maintenance and an overall more sustainable construction (Correia, 2013; Potyrala, 2011). The strength, stiffness and resistance towards aggressive environments are dependent on the bonding between polymer matrix and fiber reinforcement (Sethi, 2015).

2.1 Fiber-reinforcement

The mechanical properties of the composite are mainly provided by the fiber-reinforcement in the material, which can vary depending on the fiber type (Table 1). The fibers provide the load carrying capability and stiffness of the structure as well as thermal resistance of the material (Potyrala, 2011; Masuelli, 2013). To enable these properties a composite needs to contain a considerable amount of fiber reinforcements, which can be up to 70 % of the composite volume (Budinski & Budinski, 2005). The mechanical properties can vary depending on the orientation of the fibers, which can be arranged to maximize for instance the stiffness of the structure in a desired direction (Potyrala, 2011; Masuelli, 2013).

Table 1: Properties of different fibers (Potyrala, 2011; Niroumand, 2009).

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Glass fibers</th>
<th>Aramid fibers</th>
<th>Carbon fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>2500 - 2600</td>
<td>1440</td>
<td>1800 - 2100</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>1,72 - 2,53</td>
<td>2,27</td>
<td>1,31 - 2,48</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>72 - 87</td>
<td>83 - 124</td>
<td>230 - 620</td>
</tr>
<tr>
<td>Cost (compared to other fibers)</td>
<td>Low</td>
<td>Average / high</td>
<td>High</td>
</tr>
</tbody>
</table>
2.1.1 Arrangement of the fibers

FRP composites are usually anisotropic materials, which means that it has different material properties in different directions. The alignment of the fibers causes this anisotropy. When the fibers are aligned in one direction only, the composite is called unidirectional and has different properties along the fibers’ direction than any other direction. If the fibers are aligned in two perpendicular directions the material is orthotropic. The properties in both directions may not be the same, since this is depending on the volume of the fibers in each direction (Gowayed, 2013).

This is what have made composite materials what they are today; the ability to design for anisotropy (Gowayed, 2013). Thus the properties of the FRP material can be tailored as desired by changing the quantity and direction of the fibers (Moy, 2013).

2.1.2 Glass fiber

Glass fiber (Figure 2) is the most widely used fiber material in civil engineering applications, because of the lower costs compared to carbon- and aramid fibers (Potyrala, 2011; Masuelli, 2013). Although carbon fiber has the most favorable properties regarding strength and stiffness, glass fiber has significantly better material properties than conventional materials, which make it a better choice in infrastructure construction. Glass fiber can be split in four categories, S-glass, E-glass, T-glass, and C-glass, which all has varying properties and can be used in different situations. S-glass has a higher strength than its counterparts, hence the high tensile strength values of glass fibers (Table 1), E-glass is an electrical insulation material, T-glass has thermal resisting properties, and C-glass is resistant towards chemical attacks (Potyrala, 2011; Niroumand, 2009). However, only S-glass and E-glass is used for civil engineering purposes, where E-glass provides the lowest manufacturing costs, which make it the more favorable of the two. Compared with other fiber materials, glass fiber has certain drawbacks, which limits its use (Masuelli, 2013; Potyrala, 2011). Glass fiber is sensitive to moisture and alkaline attacks, which can result in a buildup of micro cracks and lowering the overall strength of the structure. Another disadvantage is the lower E-modulus that generally results in larger deflections than other fiber materials; this combined with a low resistance towards fatigue can create a problem when dynamic loads are occurring (Potyrala, 2011; Niroumand, 2009).

Figure 2: Plate of glass fiber-reinforced polymer (GFRP).
2.1.3 Carbon fiber

Compared to other fiber composites, especially glass fiber composites, carbon fiber composite (Figure 3) is the best preforming material regarding mechanical and durability properties (Potyrala, 2011). There are two main types of carbon fiber used, high-strength and high-stiffness, which can be used depending on the requirements (Potyrala, 2011). Unlike glass fiber, carbon fiber has higher resistance towards fatigue and higher elastic modulus making the material stronger and less prone to deflection under long-term and dynamic loads on the structure (Niroumand, 2009). Regarding durability, carbon fiber has, in theory, better properties for withstanding the effects from surrounding environments and increases the structures lifetime compared to other fibers; however, more field-testing is needed to determine this fact. Carbon fiber-reinforced polymer is not a material without its downsides; the largest problem is the complex manufacturing process of carbon fiber resulting in a higher cost than other fiber materials (Potyrala, 2011; Masuelli, 2013; Niroumand, 2009). Another problem is the carbon fiber’s inability to withstand mechanical impacts, which might occur in civil engineering applications such as a bridge construction. However, these drawbacks should not exclude carbon fiber from being used where higher requirements of strength and stiffness are needed. In addition, carbon fiber has a lower density than other fiber materials, which is preferable when a more lightweight construction is needed (Potyrala, 2011).

![Figure 3: Section of carbon fiber-reinforced polymer (CFRP).](image)
2.1.4 Aramid fiber

Like carbon fiber, aramid fiber has advantageous material properties like high tensile strength, lightweight, and high elastic modulus in comparison to glass fiber. Unlike carbon fiber, aramid fiber has a lower production cost and better resistance towards mechanical impacts (Potyrala, 2011; Niroumand, 2009). Aramid can be used in constructions where the demands for resistance towards saltwater environments and dynamic loads are needed. In addition, aramid fibers open the possibility for lightweight constructions due to their low density (Potyrala, 2011; Masuelli, 2013).

In comparison to carbon fiber, aramid fiber has certain disadvantages, which limits its use in civil engineering applications. Aramid fibers have low material properties for withstanding compression and UV-radiation (Potyrala, 2011; Friberg & Olsson, 2014). Aramid fiber is a more expensive option than glass fiber, however the material costs are lower than that of carbon fiber (Friberg & Olsson, 2014). Another downside is the ability to withstand creep under long-term loads. Due to these widespread drawbacks and their difficulty to manage, aramid fibers are less commonly used in civil engineering (Potyrala, 2011).

2.2 Polymer resin

Depending on the requirements, two different types of resin, thermosets and thermoplastic, is applied to contain the fiber reinforcement, often called the resin in FRP composite (Masuelli, 2013; Potyrala, 2011). The polymer resin also provides rigidity to the structure member, helps the composite to transfer the forces to the fiber-reinforcements, and protects the fibers from the surrounding environment, significantly influencing the durability of the composite (Potyrala, 2011). Numerous binders can be used when manufacturing FRP composites and they all have different properties, which enable FRP composites to be applied in various applications, not restricted to civil engineering. However, for construction purposes only a limited number of binders are used. These binders are epoxy and polyester thermosetting plastic, and vinyl ester (Table 2), which all belong to the category thermosetting polymers (Murphy, 2013; Potyrala, 2011). Thermoplastics are used for other purposes and are not common in civil engineering applications. The main reasons being thermoplastics ability to creep under long-term loads and its sensitivity towards thermal cycles. However, thermosetting polymers are more complex to manufacture and thus more expensive than thermoplastics and they are not recyclable. No matter which polymer is chosen the problem remains of the low resistance towards UV-radiation, which can result in deterioration of the surface in FRP composites (Potyrala, 2011).

<table>
<thead>
<tr>
<th>Polymer type</th>
<th>Epoxy</th>
<th>Polyester</th>
<th>Vinyl ester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1200-1300</td>
<td>1200-1300</td>
<td>1120-1160</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>60-80</td>
<td>20-70</td>
<td>68-82</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>2,0-4,0</td>
<td>2,0-3,0</td>
<td>3,5</td>
</tr>
<tr>
<td>Cost (compared to other polymers)</td>
<td>High</td>
<td>Low</td>
<td>Average / Low</td>
</tr>
</tbody>
</table>

Table 2: Properties of different polymer (Correia, 2013; Friberg & Olsson, 2014).
2.2.1 Epoxy

Epoxies belong to the category thermosetting polymer and are used because of their high-strength and thermal resistance compared to other polymers, it is also a nonflammable polymer (Friberg & Olsson, 2014). It is not the most commonly used binder in FRP composites but it is preferred in constructions where requirements of strength and stiffness are high and is often combined with carbon fiber-reinforcements to maximize the mechanical properties (Potyrala, 2011). In addition, epoxy polymers are less prone to shrinking during manufacturing and therefore have less residual stress than other polymers. The drawback of epoxy polymers is the high costs compared to other polymers, therefore limiting their use in civil engineering (Friberg & Olsson, 2014).

2.2.2 Polyester thermosetting plastic

Polyester based polymers are the most widely used polymer in civil engineering applications (Potyrala, 2011). This is due to the overall preferable properties and resistance towards the surrounding environment. The three main polyester based polymers used are vinyl ester, orthopolyester, and isopolyester (Potyrala, 2011).

Orthopolyester is used because of its low cost, durability, and overall good mechanical properties. Isopolyester provides better flexibility, better resistance towards corrosion, and temperature fluctuation (Friberg & Olsson, 2014; Potyrala, 2011). Both of these polymers have the disadvantage of low impact resistance (Potyrala, 2011). Uncertainties remains regarding durability of polyester based resins, with the exception of vinyl ester, in moist and chemical environments. Generally, they are not recommended in infrastructure applications (Hollaway, 2010).

Vinyl ester is the preferred polymer in the polyester based category and the most widely used, usually combined with glass fibers, because of the better impact and thermal resistance. All polyester based polymers have the disadvantage of being flammable (Potyrala, 2011). Vinyl ester also displays satisfactory resistance towards moist environments, a strong advantage in infrastructure applications (Hollaway, 2010).

2.3 Other constituents in composites

In the matrix there are components such as polymer resin, filler, and additives (Potyrala, 2011; Murphy, 2013). The resin has previously been explained in section 2.2. The other main component in the polymer matrix is the filler. The filler has no major function in the composite other than filling up the volume of the material, but sometimes special fillers are used to protect the polymer matrix from UV-radiation (Mara, 2014; Chlosta, 2012). Since binders and fibers are relatively expensive materials, manufacturers and designers does not want to use more than is needed, thus fillers are used to give composites their volume (Potyrala, 2011).

To enhance the performance of a composite, certain additives can be added during manufacturing. There are two types of additives, process and function related additives, however process related additives are specifically added to make manufacturing more efficient and will not be included in this study (Potyrala, 2011). Function related additives vary depending on the requirements, most common are resistance towards corrosion and fire. Other additives like color pigments can be added and are not function related but gives FRP constructions a certain esthetic appeal (color or form) (Potyrala, 2011; Friberg & Olsson, 2014; Murphy, 2013).
Another way of protecting the fibers and binder in the composite is coating, better known as gel-coating. Coating means that a surface treatment is applied and is usually for protecting the FRP composite against fire (Friberg & Olsson, 2014). However, it can also protect against the impact from surrounding environment (Chlostá, 2012; Friberg & Olsson, 2014; Hollaway, 2010). The degradation from moisture absorption and UV-radiation can be reduced by the application of gel-coating (Chlostá, 2012; Hollaway, 2010). However, coatings on FRP composites may need maintenance to preserve their protective function (Chlostá, 2012).

2.4 FRP composites in civil engineering applications

As previously mentioned this study focuses on the applications in civil engineering and specifically pedestrian bridges.

2.4.1 Advantages with FRP composites

The main advantages that FRP composite materials offer compared to conventional materials (steel, reinforced concrete, and wood) in infrastructure constructions are listed below (Potyrala, 2011; Hastak, et al., 2004; Niroumand, 2009).

- FRP composites have lower density than conventional materials, even if FRPs are used only in the bridge deck, the total weight of the structure can still be significantly reduced. Because of lower weight, FRP constructions require less complicated or extensive framework/supporting structure, which also includes the foundation supporting the bridge. In addition to lower weight, FRP composites have better mechanical properties that allows for stronger constructions.
- The FRP components in bridges are prefabricated and assembled or installed on site. This makes the building process short and easy, and leads to lower working costs. Due to the fast assembly on site, costs for maintaining the building site can be significantly reduced.
- Compared to conventional building materials, FRPs are less affected by the surrounding environment therefore giving FRP composites better durability properties. The components in FRPs can be chosen depending on the requirements to provide the best solution for a given situation. In addition, special treatments can be applied during manufacturing to further improve the durability properties of the composite.
- Constructions with FRP composites are predicted to have a long service life, because of superior durability properties. However, this is just a prediction and has yet to be proven considering that the material has only been used in civil engineering applications in the past three decades.
- In addition to a long service life, FRP composite constructions require little to no maintenance, depending on the construction, which significantly lowers the operational costs. Furthermore, FRP composites have higher tolerance towards material fatigue, which also lowers the requirements of maintenance or reconstruction. This suggest that in a long-term perspective, FRP composites could be a cost saving and a sustainable alternative to conventional materials.
2.4.2 Disadvantages with FRP composites

FRP composites are not materials without their disadvantages. The main disadvantages in infrastructure constructions are listed below (Potyrala, 2011; Hastak, et al., 2004).

- The major problem with FRP composites is the material and production costs. This makes construction projects with FRP composites expensive and it can sometimes be difficult to justify higher initial costs.
- Another significant problem is the lack of general knowledge of FRP constructions in the construction industry. Combined with no material design codes (e.g. Eurocode) or standards, FRP composites are often overlooked or not considered in civil engineering constructions.
- Some of the FRP composites, such as glass fiber-reinforced polymer (GFRP), have low elastic modulus and are therefore prone to larger deflection under heavier loads. This can cause damages to other components in the construction.
- There are still uncertainties regarding the long-term effects of the surrounding environments on FRP composites. This is a problem when predicting service life, the need for maintenance, and durability of the construction.
- All types of composites are sensitive to fire; some are even flammable, in comparison to most conventional materials.
- FRP composites are sensitive to UV-radiation, which can cause deterioration of the composite and consequently affects the mechanical properties.
3 FRP in pedestrian bridges

When constructing bridges, many aspects are put into consideration as mentioned earlier. Structural properties, esthetics, costs, and long-term durability are all connected to find a suitable solution.

3.1 Design solutions

FRP composites in bridge constructions are increasingly considered because of recent developments. There are several methods of FRP bridge construction but they can be split in two main categories, hybrid and all-composite constructions (Potyrala, 2011). The most commonly used is the hybrid concept, which usually consists of a bridge deck made of FRP composites and a supporting structure made with conventional materials (Mara, et al., 2014). The all-composite concept uses FRP composites for the entire superstructure of the bridge with the exception of substructure (the foundation/anchorage in both ends of the structure) (Chlosta, 2012; Potyrala, 2011).

3.1.1 Hybrid FRP composite bridges

In hybrid constructions, the bridge deck is made with FRP composites and the supporting structure is designed with conventional materials like steel or concrete. Usually the bridge deck is constructed in panel units (Figure 4), which are delivered directly from the manufacturer. This allows for a swift on site assembly (Hollaway, 2010). The panels are held in place via adhesive (usually an epoxy) or mechanical bolts (Potyrala, 2011). The panel-to-panel concept is the most commonly used in infrastructure projects of today and comes with a variety of profiles. The panel units are produced using a method called pultrusion (Mara, 2014).

Figure 4: Example of a GFRP panel cross-section with top-surface paving.
FRP bridge decks’ high strength-to-weight ratio is a significant advantage. The weight of a FRP deck is only 10-20% of a structurally equivalent reinforced concrete deck (Reeve, 2010; Hollaway, 2010). This advantage has led to a method of replacing old existing bridge decks in need of maintenance with new and superior FRP bridge decks. The main reason is that the supporting structure does not need a rebuilding or strengthening to carry the weight of the FRP deck, and can often be used in same state as before making the overall reconstruction of the bridge less comprehensive (Mara, 2014). The low weight of the FRP decks allows for a less demanding supporting structure (Figure 5) (Reeve, 2010; Mara, 2014; Hollaway, 2010).

However, by using FRP composites in the hybrid concept the favorable properties of the material may not be fully utilized due to the limitations of the conventional materials used in the supporting structure (Potyrala, 2011). The hybrid concept is based on traditional design methods using steel or reinforced concrete in the supporting structure, where the durability problem remains such as sensitivity towards corrosion resulting in a limited lifetime of the construction (Potyrala, 2011). However, hybrid FRP bridges offer significant advantages in comparison with conventional bridges in terms of weight, strength, and the overall durability is significantly better (Potyrala, 2011; Mara, 2014). An important note is that the bridge deck will absorb most of the damage caused by the surrounding environment, weathering effects, mechanical damage and chemical attack, thereby the improved durability with FRP bridge decks (Hollaway, 2010).

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3 Photo by Abbas Khayyami (2014-05-15)
3.1.2 All-FRP composite bridges

The all-composite bridge concept fully utilize the material properties by constructing the bridge superstructure i.e. deck and supporting system throughout the span of the bridge, of FRP composites (Potyrala, 2011; Hollaway, 2010). This concept is often used in pedestrian bridges and can, depending on the span of the bridge, be constructed as a single unit lifted into place during assembly (Figure 6). For a longer bridge span, the superstructure can be constructed in smaller units (Figure 7) (Rizkalla & Dawood, 2015). However, from a design standpoint it is preferred to construct all-composite bridges as a single unit or with as few units as possible to minimize the local weak spots (Potyrala, 2011).

![Figure 6: All-composite pedestrian bridge in Holland](image)

![Figure 7: All-composite port bridge in Holland](image)

4 Photo by Abbas Khayyami (2014-05-17)
5 Photo by Abbas Khayyami (2014-05-17)
A preferred structural profile of all-composite bridges is the so-called sandwich elements. These consist of a honeycomb core (Figure 8) or cell structure (Figure 9) enclosed by external panels, much equivalent the structural buildup of cardboard (Qiao & Davalos, 2013), and are constructed in the same mold using VARTM (Vacuum Assisted Resin Transfer Molding) or hand lay-up methods (Mara, 2014). The volume inside the honeycombs can be filled with foam, which provides thermal insulation to the structure (Hollaway, 2010). The advantages of sandwich elements are that they can be used to design entire superstructures of smaller bridges in a single unit, thereby reducing the weight of the bridge significantly (Rizkalla & Dawood, 2015). Other types of sections can be used in all-composite bridges and the designs can vary between different manufacturers and depending on the requirements.

Figure 8: Principle sketch of a honeycomb core structure.

Figure 9: Cellular sandwich element section with top-surface paving.
3.2 Connections

FRP composites display brittle behavior combined with anisotropic properties, which often leads to problems regarding the design of connections between members and components in the superstructure (Potyrala, 2011). The connections help the superstructure maintain stiffness and stability. Improper connection designs can lead to structural failure of the construction (Liu, 2007). Similar to the bridge superstructure, the connections are subjected to weathering, mechanical stress, and chemical attack during the bridge’s service lifetime. If these factors are not considered during the design phase, the overall durability and time to failure can be severely affected (Liu, 2007). Connections in FRP bridges should therefore be avoided if possible. The two main types of connections used in FRP composite bridges are adhesive- and mechanical connection (Potyrala, 2011).

3.2.1 Adhesive connections

Adhesive connection is the newer type of connection in FRP bridges that has been developed in tandem with the bridge concepts. Unlike mechanical connections, adhesive connections utilize similar properties as the FRP members and a general guideline is to use an adhesive with similar properties as the polymer binder used in the composite (Majumdar, 2008). The most common adhesives in bridge constructions are epoxy based; these are also common in the matrix of the FRP composite (Potyrala, 2011). The configuration of these connections can be different but in general, overlapping joints between panel members (Figure 10) are preferred due to the ability to transfer the stress over a larger cross section, resulting in lower stress levels and higher load carrying capability. Adhesives can also be used when connecting the bridge panel deck to the supporting structure (Potyrala, 2011).

Figure 10: Adhesive connection between panels.

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6 Photo by Abbas Khayyami (2014-05-15)
Typical advantages of adhesive connections in comparison with mechanical connections are the ability to transfer and distribute internal loads at the connection point, thereby making them less susceptible to fatigue and internal vibrations in the structure. The ability to withstand dynamic loads, thermal expansion, and weathering are better than bolted joints (Liu, 2007; Potyrala, 2011; Majumdar, 2008). However, the durability towards moisture, UV-radiation, and chemical attacks remains a problem that needs to be considered when using adhesive connections (Potyrala, 2011). The thermal properties that adhesive connections have compared to bolted joints only apply in the northern hemisphere where the climate is colder (Rizkalla & Dawood, 2015). When adhesive connections are used to attach the FRP bridge deck to supporting girders the difference in elastic moduli needs to be considered (Hollaway, 2010).

3.2.2 Mechanical connections

Mechanical connections are designed using traditional methods and utilizes the mechanical properties of steel or other alloys. The connections in FRP bridges usually consists of a series of bolts, placed around the superstructure attaching the bridge deck to the supporting structure (Figure 11) (Friberg & Olsson, 2014; Potyrala, 2011). The advantages of mechanical connection in relation to adhesive connections are the ease of assembly and easy access for inspections. Additionally, guidelines regarding the design of bolted joints from manufacturers of FRP bridges are easy to obtain (Potyrala, 2011).

![Figure 11: Principle sketch of a mechanical connection between steel girder and FRP deck panel.](image)

However, a significant disadvantage with these connections are the difference in thermal expansion between FRP composites and steel or other alloys. When members constructed with FRP expand due to increased temperature, the mechanical connections prevent deflection, which causes internal stresses around the area of the connection, ultimately leading to cracking and mechanical failure (Friberg & Olsson, 2014; Hollaway, 2010). This problem can be prevented if the connections are designed with the ability to expand. In comparison to adhesive connections, steel bolt connections suffer from limited durability when exposed weathering and acid environments (Potyrala, 2011). Some bridge projects have used mechanical bolts made with FRP composite to overcome this problem, but this concept is still in a developing stage (Rizkalla & Dawood, 2015).
4 Durability of composites in bridge applications

Durability of a material is commonly defined as its ability to “resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a specified period of time under specified environmental conditions” (Karbhari, 2003, p. 7).

The long-term durability effects of composites are identified usually in terms of physical, chemical, and mechanical aging and their combinations, which depends primarily on temperature, pH level, creep/relaxation, UV radiation, and externally induced thermo-mechanical stress fluctuations. These effects are further accelerated in the presence of water or salt solutions because of their expansion under freezing. In terms of the parameters mentioned above, fluid absorption in and out of composites during freeze-thaw cycles has the highest impact on durability (Liang & Hota, 2013). Deterioration of FRP composites are generally not caused by a single type of degradation but rather by synergism between several degradation processes, an aspect that needs to be considered (Helbling, et al., 2006; Zaman, et al., 2013).

In civil engineering applications, one of the main reasons for choosing FRP composites is the superior durability compared to conventional materials (Heshmati, et al., 2015). Although FRP composites have been implemented in bridge constructions around the world for several years, one of the main concerns still is the insufficient understanding of the durability performance under natural weathering (Wu & Yan, 2013; Potyrala, 2011). The durability data that the industry has today originates from accelerated environmental tests, which are conducted in laboratories (Sethi, 2015).

The polymer matrix has the highest influence on the overall durability of the composite (Hollaway, 2010; Zaman, et al., 2013). When subjected to the surrounding environment, the different types of degradation affect the polymer matrix and causes alterations in its chemical composition or micro cracks. The interface between polymer matrix and fibers are affected because of this, which ultimately leads to debonding between these components. Strength and stiffness are lost (Hollaway, 2010).

Several studies have concluded that the durability of composites originates from the same source as the mechanical properties, i.e. the bonding between polymer matrix and fiber reinforcement. The degradation mechanisms attack these bonds and thereby reduce the mechanical properties (Sethi, 2015). Polymer matrix deterioration mainly affects the composite’s stiffness and the fiber interface. Deterioration of the fibers mainly affects the strength of the FRP composite (Hollaway, 2010). When designing a construction with FRP composites it is important to focus on the durability of the bonds and choose the polymer resin and fibers depending on the situation (Sethi, 2015).

4.1 Weathering effects

4.1.1 Moisture effects

Environments with high quantities of moisture or relative humidity are one of the factors that are most damaging to FRP composites, some studies suggests that it is the most damaging (Sethi, 2015; Santhosh, et al., 2011). Degradation of FRP composites can often be traced to the moisture absorption rates of the material (Heshmati, 2015). The absorption of moisture can be placed in two categories but have similar impacts on the material properties. These categories are absorption from direct contact with water and in humid conditions (Zaman, et al., 2013; Friberg & Olsson, 2014). The absorption of moisture affects the individual properties of the
polymer matrix and fibers, which alternates the overall properties of the composite. Thermal properties, mechanical behavior, and chemical composition are affected because of moisture absorption. Thermal and mechanical alterations are reversible meaning that properties will be restored when water and humidity levels diminishes. However, alterations in the chemical composition are permanent (Heshmati, 2015). As well as influencing individual constituents in composites, moisture affects the interface between polymer matrix and fiber-reinforcement, which may cause debonding due to cracking in the polymer matrix (Heshmati, 2015). The absorption of moisture in FRP composites is dependent on the polymer matrix, fiber types, and cross section design. Other factors like temperature, PH-value, and salinity in the surrounding environment also influence the absorption rate and deterioration (Hoffard & Malvar, 2005; Hollaway, 2010). Concerns about the impact of moisture on FRP composites are especially raised in marine areas, since moisture in combination with salt creates a damaging environment (Hoffard & Malvar, 2005).

4.1.1.1 Moisture effect on composite constituents

Since epoxy, vinyl ester, and polyester are the most common in civil engineering applications, these materials have been extensively tested in laboratories under harsh conditions (Heshmati, 2015; Hoffard & Malvar, 2005). The effects on the polymer matrix caused by moisture absorption are volume expansion and reduced stiffness (Kalia, et al., 2009). These effects have a direct impact on the mechanical properties of the composite, reducing tensile strength (Heshmati, 2015). Laboratory testing concludes that the different polymers display various absorption rates and properties in moist environments (Heshmati, 2015). Vinyl ester displays the best durability towards moisture due to low absorption rate. Epoxy polymers do not share the same resistance to moisture as vinyl esters, but both are considered suitable in moist environments. Performance of polyester during moist conditions remains uncertain, previous studies display different results. In general, polyester resins are not recommended for application in such environments (Santhosh, et al., 2011; Wu & Yan, 2013; Friberg & Olsson, 2014). A protective solution that has been developed is gel-coating. Gel-coating is applied to the surface of the FRP composite and provides protection against moisture absorption as well as preventing the top surface or the polymer matrix from cracking (Hollaway, 2010; Santhosh, et al., 2011).

The properties of the fibers have lower effect on durability than the polymer matrix regarding moisture impact since they are isolated within the composite (Hollaway, 2010; Heshmati, 2015). However, moisture absorbed in the polymer matrix will ultimately affect the fibers, sometimes causing chemical reactions and altering the fiber surface (Heshmati, 2015). Carbon fiber displays the lowest absorption rate of the three main fiber types and best resistance towards moisture due to a stable chemical structure (Heshmati, 2015; Kalia, et al., 2009). Because of the high-strength characteristics of carbon fibers, minor limitations in strength and stiffness do not have a significant influence on the composite (Zaman, et al., 2013). Glass fibers tend to react with water, which alters the surface of the fibers. In contrast to carbon fibers, glass fibers are sensitive towards moisture absorption due to lower strength characteristics and therefore reductions in strength and stiffness has a more significant impact (Zaman, et al., 2013; Heshmati, 2015; Hollaway, 2010). The surface area of glass fibers is larger in comparison to other fibers, which makes them more sensitive (Hollaway, 2010). In combination with high and low PH-value that creates a moist acid or alkali environments, the mechanical properties of glass fibers can be limited (Zaman, et al., 2013). Aramid fibers have a high absorption rate and are sensitive to alteration of the fiber surface, which results in that they are generally not recommended in moist environments (Heshmati, 2015). However, aramid fibers are resistant towards chloride attacks but the problem remains regarding wet and dry cycles (Ceronia, et al., 2006).
4.1.1.2 Cyclic humidity and hygrothermal impact

Under natural conditions where the levels of moisture are not consistent, composites are subjected to what is known as cyclic humidity. The moisture level in the material during this period does not remain constant, which leads to internal changes in volume. This may lead to the buildup of micro cracks caused by internal stresses (Zaman, et al., 2013).

When moisture and high temperature coexist in an environment, constructions are subjected to what is called hygrothermal exposure (Zaman, et al., 2013). Elevated temperature leads to increased absorption rate of FRP composites. This interaction can result in a more rapid deterioration of the tensile strength in composites (Zaman, et al., 2013; Silva, et al., 2014; Sethi, 2015). The moisture impact on the polymer matrix and fibers was presented earlier in this section. However, the impact of high temperatures, beside increased moisture absorption, is increased thermal expansions. This results in a higher internal stress between the constituents in the composite, reduces the time before cracking in the polymer matrix and ultimately time to failure (Sethi, 2015). When tested in a simulated extreme environment, carbon fiber had better material properties after exposure than glass fiber (aramid fibers were not included). Although a reduction in strength, carbon fiber did show high tensile strength after testing (Zaman, et al., 2013). Hygrothermal degradation is the most damaging factor where moisture is included and should be carefully considered in the design phase (Zaman, et al., 2013; Silva, et al., 2014).

4.1.2 Corrosion

Compared to steel and reinforced concrete, FRP composites in bridge applications have a superior resistance towards corrosion (Potyrala, 2011; Niroumand, 2009; Murphy, 2013). However, FRP composites are susceptible to corrosion from some of the degradation mechanisms. Corrosion degradation of FRP composites can be divided in two main categories: physical corrosion and chemical corrosion (Hollaway, 2010).

The physical corrosion is caused by the impact from surrounding environment and affects the polymer matrix (Hollaway, 2010). The degradation that occurs is caused by weathering effects, which means that no chemical attacks are included, leaving the chemical structure of the composites intact (Friberg & Olsson, 2014; Hollaway, 2010).

The chemical corrosion is caused by substances like acids, alkalis, and chlorides that the composites are exposed to. These attacks, unlike physical corrosion, alter the internal bonds between the molecules in the polymer matrix. The results are reduction in stiffness and the buildup of micro cracks in the polymer matrix (Hollaway, 2010). In combination with moisture, the chemical substances enhance the potential to deteriorate composites (Hollaway, 2010; Zaman, et al., 2013).

FRP composites are not, unlike metals, susceptible to electrochemical corrosion, which is a significant advantage. However, if carbon fibers are exposed to direct contact with alloys they will corrode under a process called galvanic corrosion. This is due to the fact that carbon is non-metal (Friberg & Olsson, 2014).
4.1.2.1 Stress corrosion

A phenomenon that has been observed in FRP composites is stress corrosion. This type of corrosive degradation is caused by many factors such as internal stress, impact from surrounding environment, polymer/fiber properties, and time. This often occurs in acid or alkali environments (Sharma, et al., 2007; Chlosta, 2012). The characteristics of stress corrosion are the mechanical failure of the material when stress levels are below the maximum capacity (Chlosta, 2012).

The properties of the resin in the polymer matrix have a significant impact on the resistance towards stress corrosion in composites. The polymer resin prevents the chemical substances from reaching the fibers and maintains stiffness in the material. Epoxy shows the best resistance towards stress corrosion followed by vinyl ester. Polyester is considered the most vulnerable resin towards this type of degradation. The fiber properties are also important where carbon fiber has the best resistance whereas aramid and glass fibers are susceptible (Chlosta, 2012).

4.1.3 UV-radiation

UV-radiation (ultraviolet radiation) is a type of high energetic radiation, which originates from sunlight and is a concern in civil engineering applications with composites. In the UV-light spectrum the wavelength between 280-315nm (nanometer) is known to be the most damaging. All polymer resins used in civil engineering applications are susceptible to UV-radiation (Hollaway, 2010; Zaman, et al., 2013). The internal covalent bonds in the polymer matrix have detachment energies within the interval of 290-400nm (Chlosta, 2012).

The UV-radiation is strong enough to cause cleaving of the covalent bonds in the polymer matrix (Hollaway, 2010; Zaman, et al., 2013). This effect is known as photolysis, which is a process of disrupting the molecular bonds by the absorption of energy. Photolysis produces free particles in the polymer matrix, which can react with other mediums. In natural environments, oxygen is always present and reacts with the free particles. This process is called photo-oxidation and follows because of photolysis in natural environments. Photo-oxidation results in both physical and chemical alterations in the polymer matrix (Zaman, et al., 2013). The physical alterations affect the appetences of the of FRP composites, the usual consequence is discoloration of the material. Chemical alterations affect the internal bonds causing disruptions and severing between the molecules in the polymer matrix (Hollaway, 2010; Zaman, et al., 2013). The effects of photo-oxidation lead to embrittlement and micro cracking in the polymer matrix. UV-radiation only affects the top surface of the material, which makes thicker FRP sections less vulnerable than thinner sections (Chlosta, 2012; Friberg & Olsson, 2014). However, the most damaging effect caused by UV-radiation is the ability to combine with other types of degradation processes. Absorption of moisture in areas previously affected by UV-radiation is considered one of the most damaging processes (Chlosta, 2012).

Tests conducted with simultaneous UV- and moisture exposure revealed that the strength of carbon fiber is less affected under these conditions than other fibers. Glass fiber is more affected than carbon fiber but less affected than aramid fibers. The highest reduction in strength was observed in aramid fibers (Friberg & Olsson, 2014). It is difficult to trace the effects on FRP composites from UV-radiation alone due to the interaction between different types of degradation. Factors that tend to increase degradation are high temperatures, thermal cycles, and moisture absorption (Friberg & Olsson, 2014).

The problem with UV-radiation have been recognized, which has led to the application of UV-resistant fillers (also known as UV-stabilizers) in the polymer matrix. These types of fillers are used to absorb the damaging energy from the UV-rays and prevent polymer resin deterioration.
(Chlosta, 2012; Hollaway, 2010). Other protection methods have also been implemented such as gel-coating the surface of composites. This protects the surface of the material from the effects of direct exposure but does not prevent the energy from UV-radiation to reach the polymer matrix. These types of coatings may require maintenance to ensure its protective function. Sufficient UV-protections methods for FRP composites still need to be developed since coating is the only way to create a reasonable protection (Chlosta, 2012).

4.1.4 Temperature

FRP composites are typically subjected to -30 to +60 Celsius in natural environments. The temperature depends upon geographical zone, season, and time of day (Zaman, et al., 2013). FRP composites exposed to elevated temperatures during a longer period have displayed signs of degradation and even failure. The effects of temperatures on FRP composites can be split in two categories: short-term and long-term exposure (Zaman, et al., 2013; Hollaway, 2010). Short-term is best described as a physical effect where the material properties will be recovered when the temperature returns to normal levels. These conditions are known as reversible effects. Long-term exposure is generally represented by chemical alterations, which have irreversible effects on the material properties. This effect is better known as aging of composites (Hollaway, 2010). These effects are the result of high temperatures in and around the material/construction. Sunlight can have an influence on the temperature in the material due to the energy in UV-radiation (Chlosta, 2012; Zaman, et al., 2013). Another type of degradation caused by temperature is thermal cycles caused by variation in temperature during shorter periods of time (Chlosta, 2012; Zaman, et al., 2013).

4.1.4.1 Elevated temperatures

As previously mentioned, the effects of elevated temperatures can be temporary or permanent, depending on the circumstances of exposure. The exposure to elevated temperatures during natural environments mostly causes short-term effects but during warmer periods, long-term effects are a possibility. During long-term exposure, energy is incorporated into the polymer matrix. This energy contributes to chemical reactions between the polymer molecules and free oxygen. The internal bonding in the polymer matrix will display signs of cracking, leaving the composite vulnerable to other types of degradation (Zaman, et al., 2013). The usual effects of elevated temperatures are softening of the material as well as reduction of strength (Chlosta, 2012; Friberg & Olsson, 2014). High temperatures also influence the absorption rate of moisture and causes internal stress in the material. Since moisture absorption is considered one of the most damaging aspects on FRP composites, the increased absorption rates caused by temperature effects needs to be considered during the design phase (Chlosta, 2012; Zaman, et al., 2013).

FRP composites’ sensitivity towards high temperatures originates from the close vicinity to the glass transition temperature of thermosetting polymer resins. The glass transition temperature for epoxy, vinyl ester, and polyester used in civil engineering is typically between 100 and 170 °C. Epoxy typically displays the highest glass transition temperature (130-170 °C) followed by vinyl ester (100-120 °C). The glass transition temperature of polyester is usually 100 °C but can be slightly lower (Hoffard & Malvar, 2005). Once this temperature is achieved, the polymer resin will become soft and very flexible ultimately losing its stiffness (Hollaway, 2010; Hoffard & Malvar, 2005). During normal environments, no matter the geographical zone, it is highly unlikely that these temperatures can be generated in bridge applications (Hoffard & Malvar, 2005). However, a general rule is that FRP composites never should be subjected to temperatures that exceed 30 °C below glass transition temperature (Chlosta, 2012).
Another important aspect is the thermal expansion properties of FRP composites. In comparison to conventional materials, FRP composites show higher thermal deflections during elevated temperature, due to the poor thermal properties of the polymer matrix. In itself, this may not harm or affect the composite but may affect the overall construction where other materials are used, creating higher stress levels. Connections points between FRP composite members and the connections themselves needs to be designed with this in mind, otherwise the structure may suffer or even fail in these locations (Hollaway, 2010).

4.1.4.2 Thermal cycles and Freeze-thaw effects

Due to shifting temperatures under natural environments, FRP composites are subjected to a type of degradation called thermal cycles. Thermal cycles are caused by the effects of heating and cooling of the material. The effects of thermal cycles are shifting stress levels within the composite that can cause buildup of cracks in the polymer matrix (Zaman, et al., 2013). FRP composites have good thermal conductivity, which means that composites have good thermal insulation. This means that the buildup of cracks is usually confined to the top surface of the composites (Hollaway, 2010; Zaman, et al., 2013). The resistance towards these effects is significantly influenced by the polymer matrix. The properties of the polymer resin that influences the thermal characteristics of composites are thermal conductivity, thermal expansion properties, and glass transition temperature (Hollaway, 2010). This type of degradation can be far more severe if the surrounding environment contains high levels of moisture (Chlosta, 2012).

Another type of effect caused by thermal cycles is the phenomenon of freeze-thaw. This type of degradation is caused by cyclic freezing and thawing of the composite during a sustained period of time (Chlosta, 2012; Zaman, et al., 2013). Freeze-thaw cycles can have deleterious effects on the composite, especially on the polymer matrix (Li, et al., 2011). Due to different elastic moduli and properties between polymer resin and fibers, the expansions and stress levels in the composite will cause cracking in the polymer matrix, which leads to deterioration of the polymer matrix and fibers (Chlosta, 2012). Freeze-thaw is one of the most damaging types of degradation, in combination with moisture and salt it is considered the most damaging (Liang & Hota, 2013). The results from various accelerated laboratory tests are however somewhat divided. A study carried out by Wu, et al (2011) concluded that a GFRP bridge deck subjected to freeze-thaw cycling between -17.8 °C and 4.4 °C alone, conditioned in dry air, distilled water, and salt water exhibited minor or no change in flexural strength (Wu, et al., 2006). Li et al. (2011) concluded in their study that BFRP (basalt fiber-reinforced polymer) and GFRP displayed no degradation of the tensile properties when exposed to freeze-thaw cycling. CFRP did however showed a 16 % reduction in tensile strength and 18 % in the elastic modulus (Li, et al., 2011).

4.2 Mechanical performance

4.2.1 Vibrations

A concern in pedestrian bridges is the vertical dynamic loads caused by people walking, running, maintenance vehicles, and bicycles, this combined with horizontal wind force, also known as side motion, creates vibrations leading to increasing stress in the structure (AASTHO, 2008). Vibrations in pedestrian bridges can often lead to unacceptable behavior during their service life, with high motions and discomfort for the users (Chlosta, 2012). The main issue with vibrations in FRP pedestrian bridges is primarily depending on the low weight of the bridge deck and/or superstructure. The lower density of composites combined with an overall lighter construction is more prone to smaller movements causing vibrations throughout the
structure. These vibrations can affect weak points such as connections between bridge deck and supporting structure, increasing the stress levels that ultimately can lead to mechanical failure (AASTHO, 2008; Chlosta, 2012). Another important factor that can influence the occurrence of vibrations is the stiffness of the FRP composite due to the material elastic modulus. Higher stiffness means less prone to movement and ultimately less vibrations in the structure (AASTHO, 2008). As mentioned in sections 2.1 and 2.2, the different FRP composites have different mechanical properties for stiffness and strength, this should be considered when selecting a combination of fiber and polymer if vibrations are a significant problem.

The problem with vibrations in the structure is heavily dependent on the design and shape of the bridge, i.e. the span in relation to width of the cross section (AASTHO, 2008; Chlosta, 2012). A bridge with a longer span and narrower cross section are more likely to experience problems with vibrations than a bridge with a shorter span and wider cross section (AASTHO, 2008). For pedestrian bridges with activities typically varying from walking, running, and jumping, the frequencies of these vibrations is within the interval of 2.0 - 8.0 Hertz. Experience in bridge design conclude that the most damaging frequencies are in the interval of 1.6 - 2.4 Hertz, depending on shape and mechanical properties. This has resulted in the general guideline of avoiding frequencies below 5.0 Hertz in bridges exposed to live loads (AASTHO, 2008).

The combination of the vertical variable loads and horizontal wind forces can create a vibration that matches the resonance frequency in the structure. This can have a devastating effect on the stress levels and accelerates the time to failure in connections between bridge deck and supporting structure in hybrid bridge solutions. To counter this amplification, the design guidelines recommend stiffening guardrails and/or dampers (usually rubber strips or plates) placed between deck and girders in every connection point (AASTHO, 2008). However, vibrations in pedestrian bridges are difficult to calculate and predict (Chlosta, 2012).

4.2.2 Fatigue

FRP composites are construction materials that have shown excellent resistance towards fatigue under moderate cyclic loads (Niroumand, 2009). For that reason, the fatigue behavior of FRP materials used in civil engineering constructions are not considered in the design phase (Potyrala, 2011; AASTHO, 2008). Pedestrian bridges that do not experience heavy cyclic loads are often assumed to have no fatigue limitations in their service lifetime (Potyrala, 2011).

The effect of fatigue on materials is the degradation of the mechanical properties (Friberg & Olsson, 2014). The strength and stiffness of the structure are ultimately affected resulting in a softening of the material over time (Potyrala, 2011). Cyclic loads are the causing factor behind the fatigue degradation and can occur from varying surrounding factors, examples of these are traffic loads, wind forces, and temperature expansions (Friberg & Olsson, 2014). The effects of fatigue may vary depending on the dead load/ dynamic load ratio (Chlosta, 2012). According to guidelines for pedestrian bridges constructed with FRP composites, the overall cyclic loads from pedestrians are not significant in relation to cyclic loads from heavy vehicles in traffic bridges. The impact of horizontal cyclic forces from high wind speeds are also neglected (AASTHO, 2008).

Fatigue causes debonding between fibers and polymer and the buildup of micro cracks in the polymer matrix (Potyrala, 2011). The great resistance towards fatigue originates from the properties of the polymer matrix and its capability to withstand cracking. Many studies have concluded that polymer resins in the matrix have different properties regarding fatigue resistance and results can differ depending on the loading rates and cycles. In general, the best preforming polymer binder used in civil engineering are epoxy, maintaining a higher strength after testing than other polymers (Friberg & Olsson, 2014). The fiber-reinforcement also play
an important part in fatigue resistance, FRP composites depend on the fiber/matrix interface, orientation of the fibers, and fiber volume ratio for maintaining strength, and stiffness. Carbon fiber displays the best properties in resistance towards fatigue due to its higher elastic modulus (Friberg & Olsson, 2014). The other fibers, glass and aramide, display good resistance towards fatigue (Friberg & Olsson, 2014). In general, FRP composites show little or no signs of fatigue after testing and can display as much as ten times higher resistance towards fatigue than steel (Potyrala, 2011). An important note is that the fatigue resistance of FRP composites can be affected if other factors such as moist absorption and high temperature are considered (Friberg & Olsson, 2014).

The fatigue phenomenon has the tendency to become localized in certain points where stress levels are at their highest during loading cycles (Engdhal & Roussita, 2012; Mara, 2014). This is often the case for connections between bridge decks and other components in the superstructure that are subjected to higher stress levels and may determine the overall resistance towards fatigue in the bridge construction (Potyrala, 2011). A general guideline that previous studies have advocated is that the connection points between deck and supporting structure should be designed stronger than the other structure that they are supporting (Majumdar, 2008). The bridge deck and the connections should be designed to withstand two million load cycles when subjected to the designed service load (Mara, 2014).

4.2.3 Creep

In bridge designs with conventional materials as well as in other civil engineering applications, the creep phenomenon is often considered in structural elements (Ascione, et al., 2012). In-service bridge elements are affected by permanent dead loads, which cause deflection. The deflections in construction elements are split in two categories, instant and time dependent deflections. The elastic deflections occur as the dead loads are added, i.e. the weight of the construction added during assembly/production (Burström, 2006). The time dependent deflection is known as creep (Burström, 2006). Creep is caused by the internal stress in the material generated by the long-term dead loads of the construction. The creep phenomenon strives for lower internal stress by higher deflections (Ascione, et al., 2012; Burström, 2006). Other surrounding factors, especially temperature, can have an effect on FRP composite’s creep behavior and may need to be considered during the design phase (Friberg & Olsson, 2014). The most significant impact on the creep behavior of FRP composites is the orientations of fibers and its relation to the load direction. If the stress caused by the direction of the dead load cannot be obtained within the fibers, the stress level in the polymer matrix will increase and ultimately cause higher deflections due to creep (Friberg & Olsson, 2014). This is because of the polymer matrix’s impact on creep durability since it provides the stiffness of the material (Friberg & Olsson, 2014).

When creep occurs in FRP composites the buildup of creep raptures can be observed. This is because of the higher deflections, ultimately reaching the material’s maximum strain. The appearance of creep raptures however, is mostly influenced by other types of degradations that affect the fiber reinforcements. This is particularly true in damaging environments where alkali- or acid attack is present, this reduces the strength of the fibers during degradation (Friberg & Olsson, 2014). Creep rupture in FRP composites is dependent on the polymer matrix and fiber properties, stress levels, and effects from surrounding environments (Ascione, et al., 2012; Friberg & Olsson, 2014).

In general, creep behavior of FRP composites is not considered during the design phase. This is because of the strength in FRP composites, which only causes small deflections during the constructions service lifetime (Hollaway, 2010). Regarding the fiber types, glass, aramide, and carbon, they exhibit satisfactory creep durability. Carbon fiber is chemically stable with strong
mechanical properties, which results in very little creep during the service lifetime of the construction. In contrast, glass fibers are sensitive to alkali and acid attacks. In combination with lower strength compared to other fibers, GFRP composites are the most likely to have low creep resistance. Aramid fibers have the same drawback as glass fibers regarding alkali and acid attack sensitivity. However, aramid fibers have better mechanical properties than glass fibers, which results in a better resistance towards creep (Friberg & Olsson, 2014). The influence of the polymer matrix on FRP composites creep behavior depends on the chosen resin. Epoxy displays good resistance towards chemicals in combination with good mechanical properties making it resistant towards creep. Vinyl ester in general displays positive all-around properties as described in section 2.2.2 and has satisfactory resistance towards creep. The least suitable polymer resin regarding creep behavior is polyester. Polyester is susceptible towards acid attacks and moisture absorption, which limits the strength in the FRP composites (Friberg & Olsson, 2014).

The creep behavior of FRP composites is not fully understood. Previous studies conducted in the area have only tested the FRP composites in laboratory environments and does not include the impact from surrounding environments and long-term effects. To understand the creep phenomenon, laboratory research and field-testing needs to be integrated (Ascione, et al., 2012).

4.3 Chemical resistance

Besides weathering and other natural degradation, FRP composites in bridge applications can be subjected to chemical attack from the surrounding environment (Zaman, et al., 2013; Hollaway, 2010). Constructions can be subjected to acid and/or alkali environments, this degradation process is called chemical corrosion (Hollaway, 2010). In general, all polymers and fibers have a good chemical composition and will not degrade because of acid or alkali attacks. However, high concentrations of chemical substances can cause degradation of FRP composites, deteriorating the material properties (Reichhold, 2009; Friberg & Olsson, 2014; Hollaway, 2010). Another important factor that needs to be considered during the design phase is the interaction between chemicals and other types of degradation, mainly moisture and temperature (Helbling, et al., 2006).

4.3.1 Acids attack

Acid attacks on FRP constructions can originate from different sources like acid rain, marine environments, or from the soil below the construction (Reichhold, 2009; Sharma, et al., 2007). The typical process of an acid attack on FRP composites is via transportation in fluids or moisture (Sharma, et al., 2007). Acids cause a reaction with the polymer matrix and/or fibers, which alters the chemical composition and ultimately affect the mechanical properties of the material (Reichhold, 2009; Sharma, et al., 2007). These alterations cause debonding of the polymer matrix and fiber interface, which limits the strength and stiffness of the material (Sharma, et al., 2007). Chemical attacks in combination with moisture and high temperatures on FRP composites as mentioned in section 4.1.1 results in irreversible alterations of the material properties. The extent of damage to FRP composites suffered from acid attacks mainly depends on the possibility to interact with moisture in the surrounding environment (Sharma, et al., 2007). A common failure due to acid attack is stress corrosion (further explained in section 4.1.2.1) when the internal strength of the material is reduced via acid degradation under sustained internal stress (Sharma, et al., 2007). In acid and moist environments, fillers in FRP composites are not recommended because they make the material more permeable and able to absorb the damaging substances easier (Reichhold, 2009; Zaman, et al., 2013).
In civil engineering, all polymer matrices are considered to have sufficient resistance towards acid attacks. However, the commonly used polymer resins are sensitive to high concentrations of nitric and sulfuric acids (Reichhold, 2009; Zaman, et al., 2013; Hollaway, 2010). The most chemically stable resin is epoxy, which have better properties to withstand chemical attacks. However, epoxy is still susceptible to moisture absorption, which can transport acids into the material (Sharma, et al., 2007; Reichhold, 2009). Vinyl ester and polyester display satisfactory resistance towards chemical attack. If problems with high acid concentrations and temperatures do occur it is recommended to choose a more durable resin like epoxy (Reichhold, 2009).

Acid attacks also affect the connections between components in FRP bridges. Adhesive connections are usually designed with epoxy-based adhesives, which means that they have good chemical durability (Reichhold, 2009; Sethi, 2015). In contrast, mechanical connections are susceptible to acid environments due to the design with steel or other alloys. The presence of moisture will further accelerate the corrosion rate of these connections (Reichhold, 2009).

4.3.2 Alkali attack

Like acid attacks, alkali attacks affect the polymer matrix and fibers, and alter their internal chemical composition, which affect the mechanical properties and deteriorate the material (Hollaway, 2010). The degradation from alkali environments ultimately affects the internal bonds between polymer matrix and fibers due to the buildup of micro cracks in the polymer matrix (Hollaway, 2010; Zaman, et al., 2013). Like acid attacks, the effects of alkali attacks can increase due to higher temperature and internal stress in the composite. This can lead to stress corrosion as explained in section 4.1.2.1 (Ceronia, et al., 2006). Some of the common alkali substances are sodium, calcium, and ammonium hydroxides (Reichhold, 2009).

The best preforming fiber are carbon due to low absorption of moisture and chemically stable nature (Ceronia, et al., 2006; Hollaway, 2010). Aramid fibers display satisfactory resistance towards alkali attacks. However, in combination with the absorption of moisture, alkali substances can have a damaging effect on aramid fibers and deteriorate the interface with the polymer matrix by altering the surface area of the fibers (Ceronia, et al., 2006). Glass fibers are susceptible to moisture absorption and in combination with alkali substances can deteriorate the mechanical properties. The reduction in strength is higher in glass compared to other fibers exposed to alkali environments (Ceronia, et al., 2006).

The resin in the polymer matrix is sensitive to high concentrations of alkali substances in the surrounding environment (Hollaway, 2010; Zaman, et al., 2013). The resistance depends on the chemical stability and permeability of the polymer resin (Zaman, et al., 2013). Because of this, epoxy and vinyl ester resins are suitable in alkali environments. Vinyl ester resins display the best resistance in alkali environments due to low absorption rates and epoxy resins have a stable chemical structure (Ceronia, et al., 2006). Polyester is sensitive to alkali attacks due to a less stable chemical structure than other polymer resins and is therefore not recommended in these environments (Friberg & Olsson, 2014).

In general, FRP composites are not significantly affected by moderate concentrations of alkali substances in the surrounding environment (Ceronia, et al., 2006). When field-testing was conducted, FRP composites did not show significant degradation of the mechanical properties as a result of alkali attacks. The problem with alkali attacks mainly relates to concrete constructions where FRP composites rods are used as reinforcement where concentration levels are high enough to cause degradation (Hollaway, 2010).
5 Analysis

FRP composites show excellent durability properties in civil engineering applications. In comparison to conventional materials, FRP composites do not display significant signs of aging, failure or deterioration under normal service environments in bridge applications. This is however somewhat ambiguous since the oldest FRP bridges are only about 30 years old.

The main constituents in FRP composites, polymer resin and fibers, have different properties regarding durability. The constituent that has the main influence on durability of the composite is the polymer matrix. The matrix protects the fiber reinforcement and provides rigidity to the material. When FRP composites are subjected to degradation the interface between polymer matrix and fiber reinforcements are affected. The usual effect is debonding due to cracking in the polymer matrix. Because of this, composites are permanently damaged ultimately losing strength and stiffness. Therefore it is of utmost importance to choose the most fitting polymer for the circumstance from a durability perspective.

The three polymer resins studied display different durability characteristics depending on the type of degradation. Epoxy based resins have the most stable chemical structure and low absorption rate. This provides good durability characteristics towards chemical attacks, corrosion, temperature effects, and moisture. Vinyl ester resins have satisfactory performance during every type of degradation and is generally the most preferred polymer. The low absorption rate of vinyl ester makes it suitable in marine environments. Regarding polyester resins, uncertainties remain, since previous research displays different results. In general, polyester is considered the most susceptible to degradation of the polymer resins used in civil engineering, in some aspects they should be avoided in demanding environments. Despite having overall good durability properties, all polymers are susceptible to UV-radiation.

Even though the fiber-reinforcement typically occupies the largest part of the composite’s volume, its influence on durability is less significant. Aramid and glass fibers do not share the same resistance and chemical stability as carbon fibers towards the surrounding environment. However, they display overall good durability characteristics. A downside with aramid fibers are the varying durability properties, which can possibly be difficult to manage in civil engineering applications. In addition to chemical stability, carbon fibers have low absorption rate and better thermal resistance. Glass fibers have good all-round durability properties with the exception of thermal and alkali resistance. Another up-and-coming type of fiber of which the properties resemble glass fiber is basalt fiber. However, this fiber type is yet not as researched as other fibers.

To protect FRP composites from degradation, fillers, additives, and surface treatments can be applied. Fillers are mainly used to create the volume of the composite but can also be added to protect the polymer matrix from UV-radiation via absorbing the damaging energy. In moist environments, fillers can be a drawback and increases the moisture absorption rate of the polymer matrix. Surface treatments like gel-coating is applied to provide protection against UV-radiation as well as the absorption of moisture. The drawback of gel-coating is that it may require maintenance to preserve the protective function.

The effects from the surrounding environment can be divided in to three categories, weathering, mechanical, and chemical effects. FRP composites exhibit good durability towards mechanical effects and chemical attacks in pedestrian bridge application. The effects from vibrations, fatigue, and creep are often neglected because of the strength and stiffness in composites as well as light-weight and smaller service loads of FRP pedestrian bridges. In natural environments, the effects of chemical attacks are not significant since high concentrations are
needed to deteriorate composites. The most significant deterioration of FRP composites are related to weathering effects, in particular moisture absorption, UV-radiation, and elevated or shifting temperatures. Freeze-thaw in combination with moisture or saltwater are considered the most damaging. If these aspects are not handled appropriately during the design phase, the composite may deteriorate. Another important aspect that needs to be considered is the synergy between certain degradation processes, which can accelerate the degradation of the material. Previous studies conclude that a significant problem with estimation of long-term durability is the lack of knowledge of these synergies (Helbling, et al., 2006).

The problem with verification of FRP composite’s durability is connected to the tests and evaluation of the material. To assess the long-term performance, composites are subjected to accelerated testing in laboratory environments, with various results. These tests often showed significant reductions in strength and stiffness, for example the study conducted by Li et al. (2011) about freeze-thaw resistance. Some of these tests subjected FRP composites to extreme environments, which can be debated if they represent normal service environments for pedestrian bridges. There is however an all-composite GFRP bridge in Aberfeldy, Scotland, that was constructed in 1992 in cooperation with the University of Dundee. Since then it has been subjected to continuous surveys and research, which concluded that the bridge shows few signs of deterioration (Stratford, 2012). This suggests that the material performs well in in-service use but it is questionable if it is too early to tell, nevertheless it shows great promise. Surveys like those performed on Aberfeldy footbridge should be implemented on other FRP bridges, to evaluate long-term performance. Difficulties still remains with verifying the long-term performance of FRP composites and should be further researched.

The connections in FRP bridges can affect the overall durability of the construction. A general guideline is to avoid connections if possible or otherwise reduce the amount. If the connections are neglected during the design phase the overall durability of the construction may be dictated by the connections. This mainly applies to mechanical durability and in particular to fatigue and vibrations since the effects tends to be localized in these weak points. Little research has been conducted regarding the durability of connection in FRP bridges. However, the durability of mechanical connections can be questioned due to their design with conventional materials like steel or other alloys. This may cause problems during thermal expansions due to the difference in elastic moduli between the materials. In addition, maintenance may be required during the constructions service life. The adhesive connections are typically designed with epoxy based adhesives with the potential of durability properties equal to the polymer matrix using epoxy based resins. However, little is known about the durability of these types of connections and further research regarding the durability of these connections is needed.

Arguments can be raised regarding the design with FRP composites in pedestrian bridges. FRP composites are often chosen because of their excellent durability along with other favorable properties like low-weight and high-strength. If aspects like moisture absorption, high and/or cyclic temperature, and UV-radiation is neglected during the design phase the construction may not utilize the full potential of FRP composites. This involves design of connections as well. Previous studies also conclude that improper designs of the connection points may affect the overall durability of the construction (Potyraila, 2011; Liu, 2007). This mainly applies to hybrid FRP bridges since the bridge deck needs to be attached to the rest of the superstructure. All-composite bridges can be designed as a single section thereby minimizing the risks of the connections.
6 Discussion

This study was performed as a literature review of previous research and studies. The collected information originates from scientific reports and articles, previous thesis, and design guidelines regarding FRP composites in civil engineering applications. The information was selected upon the basis of being up to date and studies older than the year 2000 was excluded. In this study, no possibilities for field-testing or evaluation was possible since no FRP bridges currently exists in Sweden. The literature used in this study can be debated considering how accurately the researches describe the actual environments FRP pedestrian bridges are subjected to during service. Since no guidelines or standards exist, this study aims to present an unbiased viewpoint on the durability of FRP composites and not to rely on manufacturers information, which otherwise is the largest source of information.

In this study, the influence of natural effects on composites and how to manage them was investigated. The durability of constructions also includes accidents and vandalism. Effects such as fire and mechanical impacts can be of great importance in some applications, but was considered a low risk scenario in pedestrian bridges and therefore not included in this study. Vandalism is by its nature hard to predict but should be kept in mind in bridge design. If the composite show signs of damage, reparation is eminent. Reparation techniques were not a part of this study but can be an interesting area for further studies.

This study did not consider any economic aspects nor the manufacturing process, both factors that may speak against the material. FRP composites are often more expensive than conventional materials, at least the initial costs, and since no long-term data of their durability is available it may be difficult to justify the higher investments. The technique is, however, constantly developing which may lower the prices in the long run, making it an even more competitive alternative. The manufacturing process does not only affect prices it can have an influence on durability, but was not a part of this study.

It is worth noting that this study focused on durability characteristics of FRP pedestrian bridges. FRP composites have also been used in other applications in the construction industry. Other areas of use are reinforcement bars in concrete, load-carrying beams, and external facing in buildings (Moy, 2013; Lau, 2013). However, as mentioned in chapter 4, FRP composites are often chosen because of the superior durability characteristics, an aspect that may not be as relevant in buildings, with the exception of external components. Despite favorable properties in comparison to conventional materials, FRP composites suffers from poor fire resistance, a factor that may cause problems in building design. In building projects, FRP composites could be used in areas where low weight or high strength is desired, interesting attributes when clients, for example, want to add floors to an existing building. In addition, the high strength-to-weight ratio may bring new possibilities to produce extraordinary geometric forms. FRP composites have been implemented as external cladding in buildings projects for about forty years (Moy, 2013), taking advantage of the durability properties of composites. In the future we may experience an increased use of composites in building cladding. Continuous developments may result in more extensive use of FRP composites in building projects in the future.

With the implementation of standards and design codes (e.g. Eurocode) FRP composites may gain widespread acceptance in the construction industry, thus open up the possibility for extensive use, for instance in bridge applications.
7 Conclusion

This study concluded that FRP composites perform well under different types of degradation and the polymer matrix that has the biggest influence on durability. FRP’s two major components, fiber and resin, have varying properties, which influence the overall properties of the composite. This study concludes that the best combination of fiber and resin, from a durability perspective, is carbon fiber and epoxy resin. In bridge applications, the effects of mechanically and chemically related degradation are not significant. The largest impacts on FRP composites are the effects of weathering.

According to this study the biggest threats to the overall durability is moisture absorption, high and/or cyclic temperature, and UV-radiation. Protection methods such as UV-fillers and gel-coating can be applied to minimize the influence of these types of degradation with the exception of temperature related degradation. In moist environments, fillers are considered a drawback since they increase the absorption rate of composites. The application of gel-coating is considered the best option to protect composites from moisture and UV-radiation. If necessary, designers can chose the composition of the material according to the situation. In moist environments, vinyl ester resins display the highest resistance. Regarding UV-radiation, all polymer resins are susceptible. This study could not determine an effective protection method against temperature related degradations. Regarding elevated temperatures, epoxy and vinyl ester displays the best resistance with epoxy generally having the highest glass transition temperature.

Due to limited information regarding the effects of the connections on overall durability in pedestrian bridges, this study could not determine a sufficient answer. Although previous research has brought to light that connection points in bridges have to be considered in the overall design, otherwise they might limit the durability of the construction. Adhesive connections are susceptible to moisture, UV-radiation, and temperature related degradation much like FRP composites. The limitations with mechanical connections are the designs with steel or other alloys, making them susceptible to corrosion. This concerns the hybrid concept since connections are required to attach the bridge deck to the rest of the superstructure. All-composite bridges can be prefabricated in full-size sections and thereby minimizing the number of connections.

In conclusion, fiber-reinforced polymer composites can be described as a highly degradation resistant material, it is however important to keep in mind the environmental conditions that affects the construction. Composites are not without their weaknesses, but protection methods are available as well as the option of selecting the constituents in the composite to adapt the material accordingly to the situation.
References


