CHALMERS
UNIVERSITY OF TECHNOLOGY

Pedestrian bridges of different materials

Comparison in terms of life cycle cost and life cycle assessment

Master’s Thesis in the Master’s Programme Structural Engineering and Building Technology

DIMITRA DIMOPOULOU
NINA KHOSHKHOO

Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Master’s Thesis 2015:148

MASTER'S THESIS 2015:148

Pedestrian bridges of different materials

Comparison in terms of life cycle cost and life cycle assessment

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

DIMITRA DIMOPOULOU

NINA KHOSHKHOO

Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2015

Pedestrian bridges of different materials
Comparison in terms of life cycle cost and life cycle assessment
Master's Thesis in the Master's Programme Structural Engineering and Building Technology

DIMITRA DIMOPOULOU

NINA KHOSHKHOO

Examensarbete 2015:148/ Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2015

Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Pictures (BaTMan 2015) and drawings from the three bridges used for the life cycle cost (LCC) and the life cycle assessment (LCA) analyses.

Chalmers Reproservice / Department of Civil and Environmetal Engineering.
Göteborg, Sweden, 2015

Pedestrian bridges of different materials
Comparison in terms of life cycle cost and life cycle assessment

Master's thesis in the Master's Programme Structural Engineering and Building Technology

DIMITRA DIMOPOULOU
NINA KHOSHKHOO
Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

ABSTRACT

The need for more pedestrian bridges has increased over the years. The trend of producing sustainable solutions leads to the investigation of the structures in terms of the financial and environmental impacts. The purpose of this thesis was to determine the most cost and environmental efficient material for bridge construction.

To achieve this, three bridges, two exciting bridges and one designed bridge, were selected and evaluated from a life cycle perspective. The requirements for bridge selection were to have free span with a length of approximately 19 meters. The materials that had been chosen to be compared were timber, steel and fibre reinforced polymer (FRP). Timber and steel bridge were selected while the FRP bridge was designed according to the same dimensions as the timber and steel bridges.

Life cycle assessment (LCA) and life cycle cost (LCC) analyses were performed for the three bridges. LCC and LCA are two analytical tools which provide reliable estimations of the environmental and economic impacts during the life cycle of a structure. In LCC, the present value method was used, with regards to the recommendations from Swedish companies and authorities. LCA was performed using program Bridge LCA. This program provides a holistic view of the different emissions that can be emitted from a structure.

Evaluating the results of different bridges provided reasonable information for the optimum solution. According to the outcomes of the analyses, the choice of the material can be decisive in the design of a bridge. The results showed that the main impacts in a pedestrian bridge derived from the initial phase, both for the LCA and LCC. Although the initial costs from the three bridges were similar, the most financial efficient material was timber in a life cycle perspective. In addition, timber was found to be the material with less effect to the environment.

Key words: life cycle assessment, LCA, life cycle cost, LCC, pedestrian bridge, fiber reinforced polymer, steel, timber

Livscykelkostnadsanalys och livscykelanalys för broar byggda av olika material

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

DIMITRA DIMOPOULOU
NINA KHOSHKHOO
Institutionen för bygg- och miljöteknik
Avdelningen för Konstruktionsteknik
Chalmers tekniska högskola

SAMMANFATTNING

Behovet av flera gång- och cykelbroar har ökat kraftigt under de senaste åren. Trenden att producera hållbara lösningar leder till granskning av konstruktioner för att värdera de ekonomiska och miljömässiga konsekvenserna. Målet med studien var att fastställa det mest kostnads-och miljöeffektiva materialet i brobyggandet.

För att uppnå detta har tre broar valts ut att utvärderas ur ett livscykelperspektiv. Ett av de viktiga kraven för att välja broarna var att de skulle vara fritt upplagda med en längd av cirka 19 meter. De valda materialen som skulle jämföras var trä, stål och fiberarmerade polymerer (FRP). FRP är ett nytt konstruktionsmaterial och har en begränsad användning i Sverige. Därför har FRPbron dimensioneras utifrån de erforderliga måtten från de befintliga stål- och träbron medan.

En livscykelanalys (LCA) och Livscykelkostnadsanalys (LCC) har genomförts för att uppnå resultat. LCC och LCA är två analysverktyg som värderar de miljömässiga och ekonomiska konsekvenserna under livscykeln av en produkt. I LCC analysen har nuvärdesmetoden använts med hänsyn till rekommendationer från svenska företag och myndigheter. LCA har utförs med hjälp av programmet BridgeLCA. Detta program har använts eftersom det ger en helhetsbild av de olika utsläpp som kan avges från en konstruktion.

Utvärderandet av resultaten producerade rimligt material för den optimala lösningen. Enligt resultaten av analyserna kan valet av materialet vara avgörande vid utformningen av en bro. Resultaten visar att de viktigaste effekterna för en gång- och cykelbro både enligt LCA och LCC orsakas från material produktion fasen. Fastän de initiala kostnaderna från de tre broarna var liknande så var det mest ekonomiska och miljöeffektiva materialet trä. Dessutom visade det sig trä vara det material med minst effekt på miljön.

Nyckelord: livscykelanalys, LCA, livscykelkostnad, LCC, gång och cykelbro,
fiberarmerade polymerer, stål, trä

Contents

Preface

This thesis was carried out at the Department of Structural Engineering at Chalmers University of Technology from January to June 2015.

We would like to thank our supervisor and examiner Professor Robert Kliger for his help and support during performing of this thesis. Moreover, we would like to thank assistant professor Reza Haghani Dogaheh and doctoral student Valbona Mara at Department of Structural Engineering at Chalmers University of Technology for their support during the performance of the analyses.

In addition, we would like to thank Anna Pousette from SP, Technical Research Institute of Sweden, Fredrik Olsson from Swedish Transportation Administration and Erik Johansson from Moelven Töreboda AB for their cooperation during applying the analyses. At the end we would like also to thank KnislingeVerken AB, Martinsons Träbroar and Swedish Transportation Administration for their support and help with the difficulties in our project.

Göteborg June 2015

Dimitra Dimopoulou

Nina Khoshkhoo

List of abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BaTMan	Bridge and Tunnel Management system
EN	European Standard
EOL	End Of Life
EP	Eutrophication Potential
ET	Ectoxicity
ETSI	Bridge lifecycle optimisation (Finnish: *Elinkaareltaan tarkoituksenmukainen silta*)
FD	Fossil Depletion
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
GWP	Global Warming Potential
HTC	Human Toxicity Cancer
HTNC	Human Toxicity Non Cancer
IARC	International Agency for Research on Cancer
ISO	International Organization for Standardisation
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
OR&M	Operation, Repair and Maintenance
PV	Present Value
SETAC	Society of Environmental Toxicology and Chemistry
SP	Technical Research Institute of Sweden
VOC	Volatile Organic Compound

Notations

Upper case letters

C_n	sum of all the costs in year n
L	loaded length
$L_{servicelife}$	service life length
$Lcc_{acquisition}$	cost of designing and construction procedure
Lcc_{agency}	agency costs
Lcc_{su}	support costs during the life cycle
Q_{flk}	horizontal forces from service vehicle
Q_{serv}	vertical force from service vehicle

Lower case letters

f_y	yield strength
f_u	tensile strength
n	year in which the costs appear
r	discount rate
q_{fk}	vertical uniformly distributed load or crowded load

1 Introduction

1.1 Background

Over the last few years the construction of roads, motorways and railways has been increased rapidly, something which results in need of more pedestrian bridges (Andreas 2013). In Sweden, a country with many rivers and lakes, pedestrian bridges are needed in order to connect two distinct areas. The main materials that are using for the construction of pedestrian bridges are reinforced concrete and steel. However, during the last 10 years with the development of technology the use of timber has increased.

Recently, the construction agencies of pedestrian bridges are preferring timber because it is a renewable resource. Timber is a material which can construct more environmentally friendly and economic bridges compared to other materials, without any delay in manufacturing or loss of durability (Crocetti et al. 2011). Many improvements were noticed in the design, construction and preservative treatment of timber bridges, something which contributes to the increase of timber usage.

Moreover, fibre reinforced polymer (FRP) is a new material that becomes more and more interesting for bridge construction. FRP has a potential resistance to environmental conditions, low maintenance cost and good ability to be moulded into various shapes (Jin et al. 2010). Even if the use of FRP in pedestrian and road bridges is not widely spread, it is a promising material for future bridge structures. However, combinations of these materials have been developed all over the world.

The variations of the costs between the different materials are substantial among the different phases of a bridge's life cycle. In Sweden, the costs for many of these phases such as maintenance, reconstruction and repair, are covered by authorities (Nilsson 2011). Hence, a more detail research was needed in order to define a more efficient approach for bridge construction and reduce the costs. In order to compare the different materials, a life cycle cost (LCC) and life cycle assessment (LCA) analysis was performed.

LCC is a tool to define the most effective option based on costs during the whole life of a structure. To perform a comprehensive life cycle analysis boundaries should be defined in order to include all the phases of bridge life (Mohammed 2013).

Bridges have important effects on the natural environment. To assess the environmental impacts of the materials, a LCA analysis was a useful method. LCA is a technique which considers different stages of a product's life. A LCA analysis will present an accurate estimation of the quantities and timing of environmental impacts (Heijungs & Guinee B. 2015). As a result, it will provide information for identifying the benefits of changes in the construction of a bridge or its operation.

Some of the aspects that should be considered in the analyses in this project were the structural materials needed for manufacturing, the construction time and cost, the maintenance and the environmental effects (Mara et al. 2014). The financial and environmental impacts are varied according to the different type of materials; hence, the investigation should begin from an initial stage. The comparison should be able to answer which solution is the most efficient for a pedestrian bridge according to these aspects.

1.2 Aim and objectives

The aim of this thesis was to provide a comparison of costs and environmental effects from a life cycle perspective for bridges made of different materials, namely, steel, timber and FRP. The comparison of the three bridges was achieved with the performance of LCA and LCC analyses. Based on these results the most cost and environmental efficient material for the construction of pedestrian bridges was determined.

In order to accomplish the aim of this thesis two objectives were defined:

- Examine and evaluate the structural behaviour of bridges made from different material. This was achieved by investigating the behaviour and the recommendations for each material.
- Investigate the outcome of the three different bridges with regard to costs and environmental impact.

1.3 Method

The initial step of this project is a literature study considering bridges of different materials. The study should include material properties and the type of bridges. Moreover, a literature study of existing models for LCC and LCA analyses should be done in order to be able to compare the environmental and financial impacts of the bridges to approve their suitability.

The next step in the project is to define the three bridges. The bridges should be consisting of different materials suitable for the investigation. The objective is to compare three different bridges built of timber, steel and FRP. The data that is needed will be retrieved from literature studies, existing databases and by consulting experienced professionals. More specific, this thesis considers a steel beam, a timber slab and a FRP box girder bridge.

In this thesis, the timber and steel bridge were selected from Swedish transportation administration’s national database BaTMan (Bridge and Tunnel Management system) while the FRP bridge was designed similarly to timber bridge and steel bridge. Beside information about existing bridges, this database contains data about drawings and maintenance activities.

Finally, LCC and LCA analyses should be performed and compared. Usually, LCC and LCA analysis is performed with the use of relevant software. In this thesis, both analyses were performed using Microsoft Excel. Furthermore, for the LCC an Excel file was created, while for LCA an existing Excel file (BridgeLCA) was used. Both analyses should be considered from the initial stage of bridge construction. This includes information from the raw material extraction and material production down to the demolition of the bridge. The cost and the way of production of a bridge differ according to the type and the material. An investigation, which will include the steps before the materials arrive to the site, will provide more accurate results and information in LCC and LCA analyses.

1.4 Limitations

The main limitations for the study were related to the assumptions that were considered in the begging and during the performance of the analyses. Several limitations were made during the bridge selection. It was decided that the bridges should be simply designed with roughly the same dimensions. In this case study, the timber and steel bridge were selected based on the required criteria. Therefore, the bridges were chosen to be simply supported with a span of roughly 20 meters. The FRP bridge was designed according to the dimensions of the timber bridge and steel bridge. The calculations were made using a Mathcad file and are provided in Appendix B.

Environmental data were needed for all the materials that were used to construct the bridges. The majority of these data were obtained from consultations with professionals and studying of previous investigations. Both of the selected bridges were located in Sweden. Hence, it was reasonable to consider Swedish conditions for the environmental data. According to these parameters, several estimations were considered for reliable results.

2 Life Cycle Assessment and Life Cycle Cost analysis

To achieve the financial and environmental impacts of the bridges, several analyses were performed from a life cycle perspective in this thesis. LCC and LCA were two methods that can be used for this purpose. In order to perform an accurate and reliable LCA and LCC analysis, all the phases of the product's life cycle should be considered (Zimoch 2012).

In this thesis, the life cycle of a structure were divided in four phases, see Figure 2.1. The first phase of the life cycle begins with the extraction of raw materials by harvesting the trees or mining minerals. In the manufacturing stage, the raw materials were formed to the final product. This stage requires high-energy consumption. Furthermore, the transportation should be considered both from the acquisition area to industry and from the construction site to the disposal field. In this thesis, the case study was to compare the costs and the environmental impacts from the bridge based on the different materials. Therefore, the distance between manufacture to bridge location and from there to the disposal field will be assumed to be the same for all the bridges. In this thesis, all the costs and the impacts to the environment that were considered to be the same were neglected. However, the costs and environmental impacts from transportation will be included in the analyses in order to obtain the effects of this phase.

The second phase of the product's life cycle considers consumers using, reusing and maintenance of the product. Moreover, energy requirements and consumption should be included in this phase. An important aspect during the lifetime of the product is the proper maintenance. This stage includes the repair of the possible damages or renovation of flawed parts.

When the product's life has come to its end the demolition phase starts. This stage requires high energy consumption since large equipment or excavation material uses to demolish the structure. During the waste management phase the different materials are separated based on their composition. Some of the materials are recycled and some other are decomposed (SAIC 2006).

The costs and environmental impacts of all the different stages should be considered. Since these parameters vary depending on the material and its properties, they will be significant variations between the different bridges.

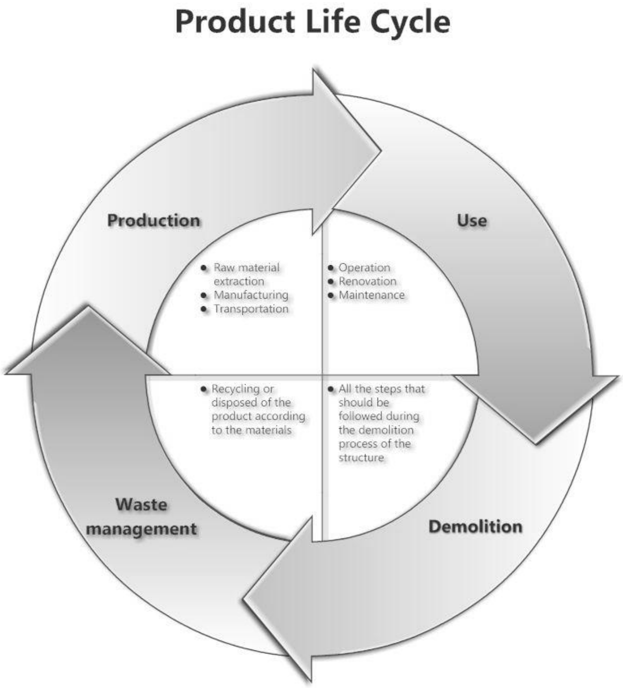


Figure 2.1 The different phases of product's life cycle

2.1 Life cycle assessment

Society has become concerned about the problem of reduction of natural resources and environmental issues. Many companies are investigating techniques or providing methods to minimize their effects to the nature and improve their environmental performance. Hence, life cycle assessment (LCA) is an appropriate and valuable tool to use since it considers the product's entire lifetime (SAIC 2006).

LCA is an analytical method which provides a comprehensive approach for assessing the environmental impact of a construction material, product and service throughout its entire life time.

By including all environmental impacts throughout a product's lifetime, the LCA provides a more accurate description of the environmental consequences of the product and the choice of the process. Therefore, in LCA study it is important to begin the analysis with the extraction of the raw material to create a product and ending it by recycling or disposing it. All processes that are including are the production of energy used to create and manufacturing the product, transportation, repair and maintenance should be considered (SAIC 2006). In this thesis, LCA analyses was helped to choose the most environmental efficient material between three bridge alternatives and identify the major environmental impacts caused by products, processes or services.

The life cycle assessment was first developed during 1960's and 1970's (Russell et al. 2005). The Coca Cola Company was the first to test this method. Therefore, current methods of LCA have their foundation in an internal study that researchers initiated for the Coca Cola Company. This research helped deciding which container had the least effect on the environment and resources.

An attempt to develop LCA in an international approach was from the Society of Environmental Toxicology and Chemistry (SETAC) and International Organization for Standardisation (ISO) in 1990 (Russell et al. 2005). Through the last years, the concern for LCA analysis has been increased. A number of researches and models have been developed in bridge industry. However, these models have not been widely used in construction industry but instead focused on energy requirements. (Hammervold et al. 2013). Therefore, evaluation of these models in practice is required.

In order to perform a LCA, the process for standardised LCA will be followed. The standardised LCA is consisting of four components: goal and scope definition, inventory analysis, impact assessment and interpretation, see Figure 2.2. The phases follow ISO 14040 (SAIC 2006) standards.

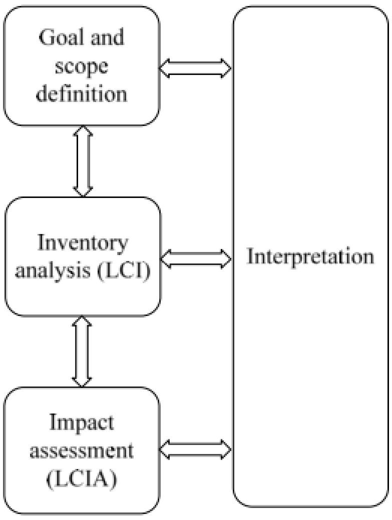


Figure 2.2 The four phases of life cycle assessment as defined in ISO 14040 (SAIC 2006)

2.1.1 Goal and scope definition

The first phase of the LCA defines the goal and scope of the study. The purpose and the method should be clearly defined in order to ensure that the reliability of the analysis will be obtained. Moreover, the type of information that is needed should be defined in order to determine the need of time and resources (SAIC 2006). The definition of the goal should be able to determine field study, the intended audience and the reason for carrying out the study. The scope should include several technical details. This contains the function of a product system (functional unit), system boundaries, assumptions and limitations which will be used, the methodology that will be followed and finally the selected impact categories (Mara 2014).

Moreover, it is important to state the different approaches of LCA. The approaches are separated in two categories based on phases of a product's life cycle that are included (Zimoch 2012). The first is the cradle-to-grave approach which includes the stages from the raw material extraction to the demolition of the structure. The second is the cradle-to-gate approach, which includes the stages from the raw material acquisition to the manufacturing of the product (Zimoch 2012). In this thesis, the cradle-to-grave approach was used to obtain the analysis.

2.1.2 Inventory analysis

The life cycle inventory phase of a LCA evaluates the emissions of the entire life cycle of a product, process or activity. This could be a process of quantifying energy and raw material, atmospheric and waterborne emissions and solid wastes (SAIC 2006). In the LCA analysis, is better to include all these different stages of product's process, in order to obtain more reliable and accurate results. The main task in this phase is to create a model based on the requirements and definitions from the previous step (Baumann, Tillman 2004). Therefore, it is important to choose suitable data, which will be correlated to goal and scope definitions. In this stage, the environmental impact from the product should be defined. In order to collect the data to create the analysis a Microsoft Excel file BridgeLCA can be used (von Bechtolsheim 1989). BridgeLCA is a tool for calculating life cycle environmental impacts of a bridge in which includes eight impact categories; five environmental and three ecotoxicity categories (Salokangas 2013). This software produces detailed analysis with coarse estimations, which covers the entire life cycle of a structure.

BridgeLCA consider production of the bridge material and components, construction, transportation, operation, repair and maintenance (OR&M) and the end-of-life (EOL) of the bridge which includes demolition, waste disposal and material recycling (Salokangas 2013).

2.1.3 Life Cycle Impact Assessment

The third phase is life cycle impact assessment (LCIA). The task in this stage is to describe and evaluate the results from the inventory analysis. More specific, the aim of this stage is to convert the outcomes of the previous analysis into more environmentally relevant information (Zimoch 2012). The performance of LCA analysis will identify the emissions and will find a linkage between the environmental impacts of the product to the ecological and human health. Therefore, it is important to be aware of the impacts and their consequence. For instance, released gasses such as carbon dioxide and methane hasten climate change and will affects human health and natural environment.

The selected impact categories were terrestrial acidification (AP), fossil depletion (FD) freshwater eutrophication (EP), climate change (GWP) and ozone depletion (ODP). The category ozone depletion describes the decreased stratospheric ozone concentrations which damaging human health and ecosystem. Freshwater eutrophication correspond to the increased nitrogen and phosphorus concentration in water which damaging the ecosystem quality. The climate change category, also known as global warming potential, leads to changes in precipitation, sea level and will end the coral reefs, forests and crops. The category fossil depletion defines the decreased non-renewable minerals and fossil fuels which damaging the natural resources. Emissions of terrestrial acidification are the increased acidity in water and soil system which damaging the ecosystem quality.

Based on the result from the inventory analyses, the emissions are classified to the relevant environmental impacts, see Figure 2.3. For example, greenhouse gases;

carbon dioxide, methane, and nitrous oxide, are included in the global warming impact category (GWP) (Lippiatt 2015). In the characterisation, all relevant flows are summarised into a unit. For instance, greenhouse gases are all connected to global warming potential and are expressed in one common unit (Mara 2014). In the normalisation process the impacts are put in relation to a reference value for the entire impact of a region, country or per person (Lippiatt 2015, Mara 2014). In the final stage, weighting, the importance of an environmental impact is rated for the overall environmental performance (Guangli 2012). This stage is important when performing an overall comparison between different options (García 2011).

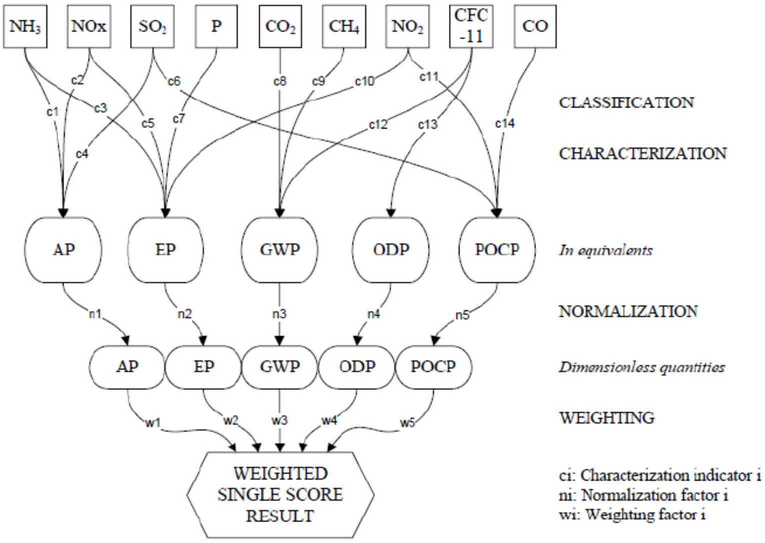


Figure 2.3 Example of LCIA (Hammervold et al. 2013)

2.1.4 Interpretation

The last phase of the LCA is the interpretation of the results from the life cycle inventory and life cycle impact assessment according to the requirements of the study. The results, which were retrieved from the previous phases, were analysed, identified and evaluated in order to ensure their accuracy. This phase is very important in LCA since it includes conclusions and recommendations, which can be used in order to provide relevant comparisons.

Moreover, the outcomes can be used for decision making or public acquisition, with the awareness of that the LCA is based on estimations and assumptions and not actual numbers (Hammervold et al. 2013).

2.1.5 Conclusions of LCA

LCA is a valuable tool which produces a reliable estimation of the impacts from a product to the environment. The aim of this thesis was to compare three LCA analyses. In order to select all the required data several limitations and estimations was considered. These estimations and limitations are provided more detailed in Chapter 5.

2.2 Life cycle cost

Aspects such as competitions between industrial sectors, expensive products or systems and budget limitations were the most important reasons for using a method such as life cycle cost (LCC). LCC is an analytical tool which allows defining the most cost efficient option during the whole life of a structure. This method includes the cost of the manufacturing, operation, annual maintenance, transportation and disposal cost of the product (B.S 1989). LCC can be considered as a part of life cycle analysis and is strongly connected with the life cycle assessment method (Zimoch 2012). Since they combine cost and environmental effects, the connection of these two methods is very important for producing more accurate results. The life cycle cost analysis can be used in the decision making process in order to specify the most efficient solution. In decision phase, LCC analysis helps to select the proper materials and choose the most suitable production method (Zimoch 2012). Moreover, the availability of reliable cost data is very important to apply this method (Langdon 2007). However, several simplifications were needed since there were many parameters that were included. Thus, the LCC analysis should be used carefully in the decision making process.

To be able to create a comparative analyses it should be ensured that all the alternatives have similar parameters and that the analyses include the costs of all the different phases of the structure's life (Mohammed 2013). In order to include all the different stages boundaries should be defined. These boundaries should consider the costs from the extraction of raw materials, product manufacture, transportation, construction, operation, repair, maintenance and final disposal.

To calculate the total cost of the bridge, the costs from each phase were needed to be calculated separately. The analysis should combine the costs in relation to the time in order to count the total cost throughout the life cycle of the structure. The common method to calculate the life cycle cost is to discount them to a specific time, normally the present value. The discounted costs can be calculated according to the Equation (2.1).

$$PV = \sum_{n=0}^{L_{servicelife}} \frac{C_n}{(1+r)^n} \tag{2.1}$$

where

PV is the present value of the life cycle cost

$L_{servicelife}$ is the service life

n is the year which the costs appear

C_n is the sum of all the costs in year n

r is the discount rate, interest rate in %

The choice of the discount rate is an important aspect in the LCC analysis. The choice is based on assumptions related to future advantages. Hence, a smaller value for the discount rate means a higher consideration for future impacts. The public authorities tend to use smaller values for discount rates compare to private agencies (Langdon 2007).

The costs of different phases can be classified in three categories based on their derivation which is depended on the case study and the manner of use of the parameters. The categories can be divided in agency costs, user costs and society costs (Mohammed 2013), see Figure 2.4. The LCC analyses in this master thesis will mostly focus on agency costs. This category includes the costs of material, construction, maintenance and disposal. The other categories consider costs related to aesthetic and cultural values as well as costs from environmental impacts and traffic accidents. Since the case study in this thesis was regarding the pedestrian bridges these categories was be neglected.

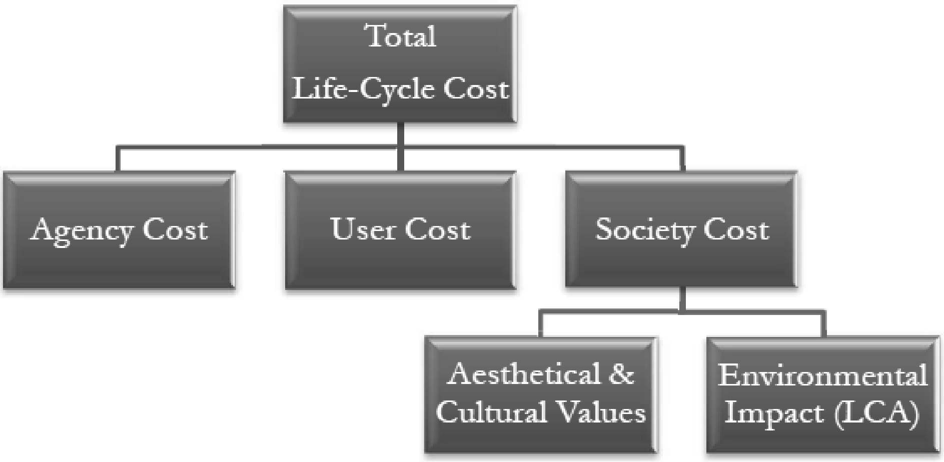


Figure 2.4 Life cycle cost for a bridge (Mohammed 2013)

2.2.1 Agency cost

Agency costs can be considered all the direct costs obtained from the initial stage of material acquisition to the replacement or disposal (Zimoch 2012; Mara 2014). Some of the parameters that were included were the costs of raw material extraction, manufacturing costs, labour work and transportation. Agency costs can be categorized according to the Equation 2.2 (Hammervold et al. 2009).

$$Lcc_{agency} = Lcc_{acquisition} + Lcc_{su} \tag{2.2}$$

where

$Lcc_{acquisition}$ is the cost of designing and construction procedure

Lcc_{su} is the support costs during the life cycle of the bridge and includes maintenance, reconstruction and replacement

The inspection in structures varies according to the country (Murphy 2013). The common types of inspection in Sweden are four; yearly, general, main and special inspection (Murphy 2013). Yearly inspection is a short-term inspection which mostly ensures that the maintenance activities have been applied properly. The general inspection usually is performed every three years in order to verify that the bridge elements have no structural damages. Moreover, it can be ensured that the damages from the previous inspection have been repaired. The main inspection examines the operation of the entire structure and is performed every six years. The last type is the special inspection which will be performed only when it is required (Murphy 2013). Many of the costs in this category were difficult to define. The worth of operation or maintenance in a long-life construction can be counted with estimations. The parameters that influence the structure are many and for several of them the existing data are not sufficient (Hammervold et al. 2009).

2.2.2 User cost

The category user cost contains the indirect costs which affect the citizens. User costs can be divided in two separate kinds; long-term and work-zone user costs (Mohammed 2013). The first type includes the costs from permanent components of the bridge. The second type includes costs due to traffic delay, vehicle operation or material transportation. This thesis was regarding pedestrian bridges and therefore the user costs were neglected.

2.2.3 Society cost

This category includes costs related to aesthetic and cultural values as well as costs from environmental impacts and traffic accidents. These are costs which affect the society during the life of the structure (Mohammed 2013). In this case study, the risk of an accident to occur was assumed to be the same for all bridges. Therefore, these costs was neglected (Mara 2014).

Society cost was very important since the costs which effect the environment were included. These effects are environmental issues produced from the structure as for example from energy consumption and emissions.

Environmental impacts and costs of the bridge vary according to the different methods for maintenance, repair or disposal. The effects to the environment were considered in the LCA analyses and therefore the society costs were omitted in LCC.

2.2.4 Conclusion of LCC

LCC is an analytical tool which allows defining the most financial efficient option during the life of a structure. In this thesis, LCC was used in order to define the most cost efficient material between timber, steel and FRP for a pedestrian bridge. Therefore, three different analyses were performed, one for each material.

As it was mentioned before, to be able to create a comparative analysis it should be ensured that all the alternatives have similar parameters and that the analyses include the costs of all the different phases of the structure’s life cycle (Mohammed 2013). In order to simplify the analysis and to obtain the effects based on different materials the parameters that were assumed to be the same in all cases were neglected. The required data was retrieved from previous analyses and from consulting experienced professionals. It was important to specify the different aspects that are needed for each bridge since the requirements are relevant to different materials. For example, the maintenance activities and the disposal are different depending on the construction material that has been used. To calculate the total cost of the bridge the costs from each phase were needed to be calculated separately.

3 General types of pedestrian bridges

The type of the bridges varies depending on the construction type, the purpose of the construction and the material. Almost all the different types can be used for the construction of a pedestrian bridge (Vasani, Bhumika n.d.). More specific, the bridges can be categorized according to:

- The flexibility of superstructure (fixed or movable bridges)
- The position of deck (deck, through or semi through bridges)
- The internal span (simple, continuous or cantilever bridges)
- The type of the structure (slab, beam, girder, truss, arch, suspension or cable stayed)
- The construction materials

These are the basic parameters in order to define the type of a bridge (Vasani & Bhumika 2003).

The most common types of pedestrian bridges according to the form of the superstructure are listed and explained further in this chapter. The types of bridges that were considered in this thesis were made of steel beams, a timber slab and a FRP box girder bridge.

3.1.1 Beam and slab bridges

The most common types of bridge in Sweden are beams and slab bridges, shown in Figure 3.1. These types of bridges are inexpensive and easy to build (Kramer 2004).

The superstructure of slab bridges is wide compared to the height of the slab and has the ability to divide loading in a very broad areas (Ahonen, Jurigova 2012). The beam bridges, also known as girder bridges, have a simple structure with horizontal beam supported by piers. The top surface of the beam is compressed while the bottom edge is under tension. To strengthen this type of bridge a truss system or piles in distance could be chosen. In spite of the reinforcing trusses, the length of the bridge is limited due to the trusses and bridges weight. This kind of bridges is both strong and economical (Kramer 2004).

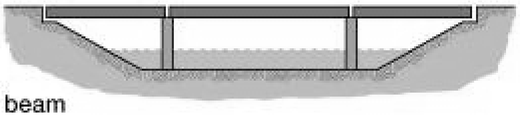


Figure 3.1 Beam and slab bridge (Billington P. 2015)

3.1.2 Arch bridges

The arch bridges carry the load along the curve of the arch down to the ground where it can be fixed or hinged at both its ends (Beek, Ages 2008), see Figure 3.2. Arch bridges are the oldest type of bridges and they usually were made of stone or brick. The material stone as well as steel and concrete, works well in compression. In contrast, timber is an anisotropic material and its strength properties perpendicular to the gain are relatively weak (Bridge 2009). Today, these bridges are often built of concrete or steel.

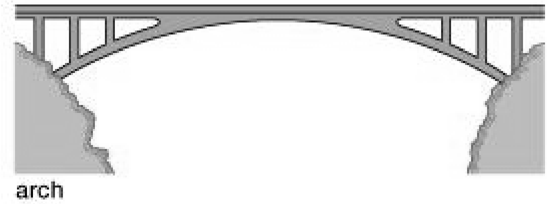


Figure 3.2 Arch bridge (Billington P. 2015)

3.1.3 Suspension bridges

Suspension bridges suspend the deck from two tall towers by high tensile cables, see Figure 3.3. The cables transfer the weight from the roadway as compression to the towers and they dissipate it directly to anchor blocks, usually a huge concrete box or solid rock. The very first suspension bridges were made of rope and wood. Today, the cables are made of many steel wires bound tightly together and are strong under tension.

These lightweight, high and strong bridges can have long spans and are capable of resisting heavy forces. However, this type of bridge is the most expensive to build (Myerscough, Hons 2013).

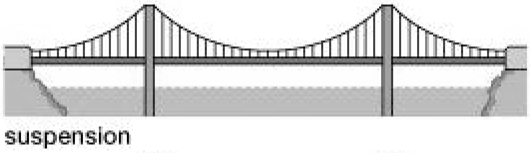


Figure 3.3 Suspension bridge (Billington P. 2015)

3.1.4 Cable-stayed bridges

Cable-stayed bridges may look similar to suspension bridges since they both have towers that carry the load by cables and transfer it to the ground. The differences between these bridges are the way the cables are connected to the towers (Vasani & Bhumika 2003), see Figure 3.4. In cable-stayed bridges the load is carried alone by each cable that is fixed to the towers and transfers directly to the ground. Therefore, there is no need for massive anchor blocks. These kinds of bridges are stable in the wind and are less expensive to build (Juvani 2012).

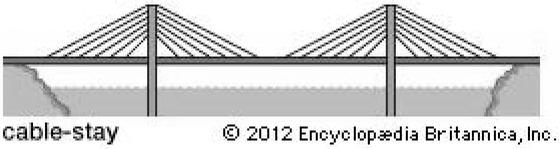


Figure 3.4 Cable-stayed bridge (Billington P. 2015)

4 Design guidelines for pedestrian bridges

The construction of pedestrian bridges has been increased during the last years. Footbridges have been built in diverse locations in order to facilitate the access to different areas. The bridges should fulfil all the requirements for safety and durability as well as functional requirements, statics and dynamics (CEN 1990). For the design of each bridge the basic assumptions should be combined with recommendations from the specific Eurocodes based on the materials (Crocetti et al. 2011). The specific Eurocode for timber is EN 1995, while for steel EN 1993. Moreover, part two is regarding bridges. Since FRP is a new material there is no specific Eurocode related to this material. Hence, for the design of a FRP bridge the general recommendations were followed (Clarke 1996). In the following chapters the assumptions and the requirements for each bridge are provided more detailed.

4.1 Common geometric requirements

To fulfil comfort requirements regarding pedestrian bridges relevant principals should be considered. The width of a footbridge is one of the first decisions to be made. The footbridges used only by pedestrians should have a minimum deck width between 1.5 and 3 meters. The footbridges that are used of both pedestrians and cyclists should have a minimum deck width between 2 and 3 meters (Béton 2005). Moreover, the inclination requirements are depended on the location of the footbridge. The maximum inclination for bridges used by pedestrians is between 5 and 12%. The maximum inclination for bridges used by both pedestrians and cyclists is between 3 and 8%. Additionally, for wheelchair users the maximum acceptable slope is 8% over a length of 5 meters. Moreover, a clearance distance between 2.5 and 3 meters is appropriate for footbridges (Béton 2005).

4.2 Actions on footbridges

Footbridges are subjected to many different loads. Forces acting on pedestrian bridges may be separated in vertical and horizontal loads.

According to EN 1991-2, the vertical loads acting on a pedestrian bridge are divided in two different types; uniformly distributed and vehicle. Uniformly distributed loads are corresponded to loads from people and crowds, while the service vehicle loads are corresponded to emergency vehicle (Crocetti et al. 2011). Service vehicle are affecting the bridge in the vertical and horizontal direction. These loads are variable and should be considered as short-term loads.

Furthermore, the effects from different densities, self-weight of the bridge, snow and wind loads, thermal actions, actions during construction, accidental actions and traffic loads are included (Crocetti et al. 2011). However, the snow loads should be included in the cases with bridge with roof; otherwise it is assumed to have the snow removed and therefore was not considered in the calculations. The self-weight of a bridge was considers as a permanent load and was related to the strength class of the material that was used according to EN 1991-1-1, *Actions on structures*.

Another important aspect was the static and aesthetic demands on railings since they transfer loads from the deck to the substructure (Vasani & Bhumika 2003). The most common materials for railings are wood and steel. There are limitations and requirements for the height and dimensions of the different parts of railings. These requirements should also correspond to load and safety requirements. More specific, for pedestrian bridges there are recommendations for the distance between the bars and the different parts (Pagliarin 2012).

4.2.1 Load combinations

The vertical and horizontal forces should consider groups of loads and are shown in Table 4.1. The load combination should include either uniformly distributed load or service vehicle load, according to EN 1991-2, *Actions on structure*.

Table 4.1 Definition of groups of loads (EN 1991-2, Actions on structure)

Load type		Vertical forces		Horizontal forces
Load system		Uniformly distributed	Service vehicle	
Groups of loads	Group 1	q_{fk}[1]	0	Q_{flk}[3]
	Group 2	0	Q_{serv}[2]	Q_{flk}

[1] Uniformly distributed load or crowded load

[2] Service vehicle load

[3] Horizontal force due to vehicle and uniformly distributed load

4.2.2 Vertical loads

According to EN 1991-2, *Action on footbridges*, the characteristic vertical loads contain:

- Uniformly distributed load or crowded load, q_{fk}
- The load representing service vehicle load, Q_{serv}

Crowded load

The self-weight of the bridge and the crowd of people are the main vertical loads. The characteristic value for uniformly distributed load, the pedestrian induced load on the bridge, according to EN 1991-2, is equal to Equation (4.1) or calculated by using Equation (4.2).

$$q_{fk} = 5\frac{kN}{m^2} \tag{4.1}$$

$$q_{fk} = 2 + \frac{120}{L+30}\frac{kN}{m^2} \tag{4.2}$$

where

L is the loaded length in meters

Vehicle load
For footbridges, the load for service vehicle or emergency vehicle was specified according to EN 1991-2. Service vehicle may be a vehicle for maintenance, emergencies such as fire truck or ambulance. For these situations the load model that was used consist of a two axle loads of 80 kN and 40 kN. The distances between the two axle loads are 3 and 1.3 meters for the vehicle and both of these distances are measured from wheel centre to wheel centre. The recommendation for square contact areas at the coating level is 0.2 meters according to the Figure 4.1.

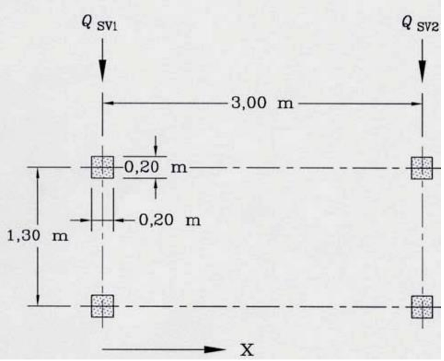


Figure 4.1 Vehicle load (EN 1991-2- Actions on structures)

where
x is the bridge axis direction
Q_{sv1} = 80 kN
Q_{sv2} = 40 kN

4.2.3 Horizontal loads

According to EN 1991-2, *Actions on footbridges*, the characteristic horizontal loads contain:

- Horizontal force due to vehicle and uniformly distributed load Q_{flk},
- Railing load
- Wind load

Vehicle load
The horizontal traffic load Q_{flk} should be taken into account acting along the bridge deck axis. This characteristic horizontal load should be the maximum value of 10% of the uniformly distributed load or 60% of the vehicle load.

Railing
According to the EN 1991, *Action on structures*, the forces that horizontally are transferred to the bridge deck by pedestrian railings should be taken into account. Railings are used to protect people from falling off the bridge. A line force of $1.0kN/m$ acting as variable load, horizontally or vertically, on top of the parapets of the pedestrian bridge should be considered. The height of the railings varies and is between 1.0 and 1.15 meters. For footbridges designed to carry cycle traffic the required height increases to 1.20 meters. For the safety of children, the railing posts should be designed to prevent children slipping between posts. Therefore, the maximum distance of 15 centimetres between filling posts should be considered

(Béton 2005). In this thesis, the horizontal loads from railings were neglected during calculation and designing of the FRP bridge due to lack of time.

Wind

Footbridges are affected of wind actions. Hence, a detailed analysis of wind loads is required especially in countries in which wind is a particular problem. Normally, a footbridge could be regarded as static considering wind if the natural frequency is less than 5 Hz, the height of the structure is less than 15 meters and the bridge has a slenderness ratio less than 4. In addition, the wind load does not cause significant deformations and damaging swings for bridges with beams or slabs with a span over 40 meters.

4.3 Footbridge dynamics

In recent history, dynamic effects have caused structural failure in footbridges. Therefore, the dynamic properties corresponding to vertical, horizontal and torsional vibrations should be evaluated. These dynamic properties, which could be caused from pedestrians and wind, should be considered in order to fulfil the comfort criteria. Another important property to consider was structural stiffness, mass and damping.

According to EN 1991-2, *Actions on structures*, if the fundamental frequency of the deck is less than 5 Hz for vertical vibrations and less than 2.5 Hz for horizontal and torsional vibrations, the verifications of vibration for comfort criteria should be performed. Moreover, the maximum acceptable acceleration should not exceed $0.7m/s^2$ in vertical and $0.2m/s^2$ in horizontal direction, respectively.

The frequency range from pedestrians is roughly between 1 and 3 Hz in vertical direction and between 0.5 and 1.5 Hz in horizontal direction.

The type of pedestrian traffic density has a great influence on initial state of design. Footbridges in the cities are not subject to the same dynamic loading as bridges outside cities. Another important dynamic property, with respect to wind, is the natural frequency and damping properties. Damping behaviour of the bridge will appears after building the bridge and depends on many parameters such as materials, surfacing, bearing conditions and railings and the crowd on the bridge.

By increasing traffic density on the bridge the walking velocity reduces, see Figure 4.2. Each pedestrian has to correct his walking velocity to the movement of the mass. Hence, if the pedestrian density increases each pedestrian will not be able to walk on his own step frequency and walking velocity. At a pedestrian density of $0.5 pers/m^2$ the first restrictions appears and the passing would become more difficult. When a pedestrian density reach $0.6 pers/m^2$ the freedom of movement become extremely limited (Béton 2005).

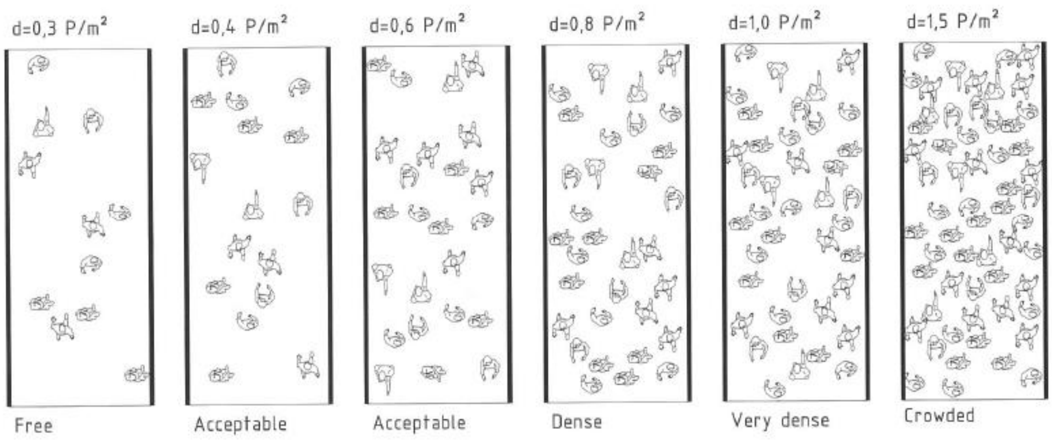


Figure 4.2 Different types of pedestrian densities (Béton 2005)

4.4 Requirements and conclusions

In conclusion, the bridges that have been selected in this thesis, should be able to fulfil all the requirements for safety and durability, as well as functional requirements, statics and dynamics (CEN 1990). In this thesis, the criteria that were followed in the design phase are based on Eurocodes produced after the 1990.

Moreover, the specific requirements related to each material should be combined with the basic assumptions for the design of pedestrian bridges (Crocetti et al. 2011). The specific Eurocode for timber is EN 1995, while for steel EN 1993. Since FRP is a new material and there is no specific Eurocode related to this material, the general recommendations were followed (Clarke 1996). More specific, one of the requirements for all three bridge were to have approximately 3 meters in width. Therefore, the comfort requirements related to the deck width were fulfilled.

5 Different materials for bridge construction

In the 19th century, the first material used for railroad bridge construction was timber (Kramer 2004). Soon after, the improvement of steel technology it ended the dominance of wood bridges. However, the low cost and easy working characteristics of wood did not eliminate it as material option for construction of bridges after all. The main materials for bridge construction in 20th century became steel and concrete. However, timber has been used for construction of bridges of short span (Kramer 2004). In order to be able to design and construct safe and durable structures, the basic requirements and recommendations were developed over the years. Earlier in this chapter, the general suggestions for pedestrian bridges were mentioned. In addition, the recommendations for each material, according to EN 1995-2 and EN 1993-2, are explained further in this chapter.

5.1.1 Timber

The use of timber in bridge construction has been increasing during the last few years since timber is a light material with high load capacity compared to its weight. Timber as material has high strength, low conduction of heat and ability to vary in form. Moreover, timber is cheap, environmentally friendly and easy to work with. However, these anisotropic material have likewise many different defects such as moisture-dependent properties that may result in swelling and shrinkage and are sensitive to rot and insects (Crocetti et al. 2011).

Sweden is one of the countries with large amount of sawn timber. Most forests in Sweden are planted with a rotation time of approximately 80 years (Barklund 2009). After harvesting the trees, logs are taken to sawmill in order to cut the saw logs into timber. Finally, the ground will replanted with new plants after harvesting (Barklund 2009). For an illustrative picture of the product and timber process see Figure 5.1.

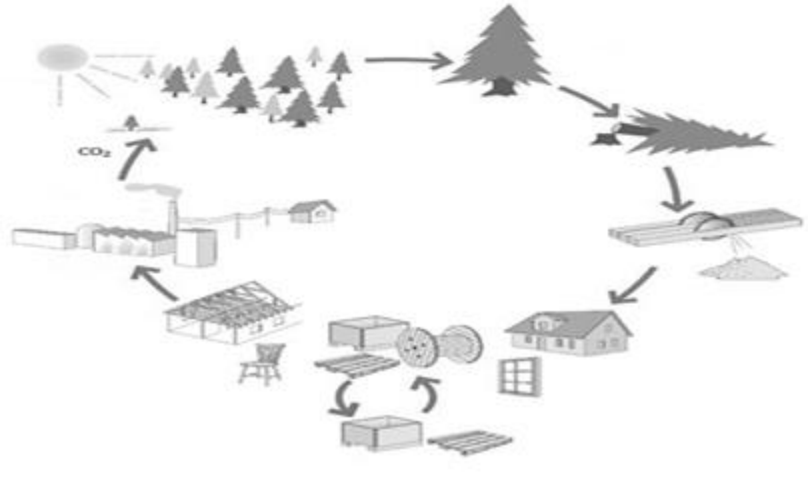


Figure 5.1 Life cycle of timber (Bergkvist & Fröbel 2013)

Through the last years several developments have been achieved in timber industry. An important development is the different types of glue that can be used to bonding together glue laminated beams. The most well-known adhesive for timber is Phenol-Resorcinol-Formaldehyde (PRF) glue. However, a new adhesive known as Melamine-Urea-Formaldehyde glued (MUF), is used nowadays for timber elements. According to different tests, the emissions of acetaldehyde are relatively high from the elements that have been glued with PRF compared to the MUF-glued elements (Funch 2002). Acetaldehyde is an organic chemical combination, which is widely produced in industry. Acetaldehyde has been included as a Group 1 carcinogen according to the International Agency for Research on Cancer (IARC). Therefore, the development of new adhesives is crucial. Moreover, this new adhesive is quite important strengthens the sustainability of timber as a construction material.

It is important that the design and construction of a timber bridge ensure the stability and durability of the structure. In order to achieve this, the main recommendations and principles for the design and construction should be followed. The relevant Eurocode for timber bridges is EN 1995-2. According to EN 1995-2, *Design of timber structures*, structural parts of the bridge should be designed in order to fulfil the requirements for safety, serviceability and durability. In this part, the basic requirements from EN 1990 and the principles of limit state design from EN 1995-1-1 should be followed. Moreover, in order to compute the loads relevant parts from EN 1991 should be used.

Timber elements, likewise other traditional material such as steel and concrete, are usually subjected to bending, shear stresses, torsion and tension/compression combined stresses. Design checks for pedestrian bridges should be performed with respect to moment capacity, shear capacity, vibrations and deflections which controlled against the strength. According to EN 1995-1-1, the tension strength perpendicular to the grain is roughly equal to the half of the shear strength for rolling shear in solid wood.

Durability of the structure is an important aspect in the design phase of the bridge. In order to reduce the effect of direct weathering by precipitation or solar radiation on structural timber members several constructional preservation measures can be used. Additionally, timber with preservatives against biological attacks can be sufficient. Timber structures are sensitive to moisture problems and the risk of high moisture content is higher in the parts near to the ground. This risk can be minimized by covering the ground with course gravel or similar and by increasing the distance limitations from the ground. Moreover, moisture changes in combination with external loads increase the deformation in a structure. Eurocode provides recommendations for the value of this deformation. In order to compute it many aspects such as the creep behaviour of structure members should be taken into account.

One of the main advantages of timber is that it is a sustainable material. Timber, after it is removed from the structure, can be recycled and re-used. In demolition phase, timber waste is sorted and shredded into woodchip. During the shredding process, other materials such as steel nails and bolts are removed. Afterwards, the recycled woodchip is used as a raw material to produce particleboard and manufacture of compost (Australian Government: DSEWPaC 2011).

5.1.2 Steel

Steel is a material made of iron and carbon. In construction, the different alloys that are allowed to be used are identified from the national standards (Worldsteel 2011). Steel is extensively used in structures since it is easy to manufacture. It could easily be drilled, welded and assembled into the desired shapes. However, steel is relatively more expensive to manufacture compared to other materials and it tends to rust easily in exposed to the environment. This material has high tensile resistance although the resistance against compression forces is small. The different stages of steel eco cycle can be shown in Figure 5.2.

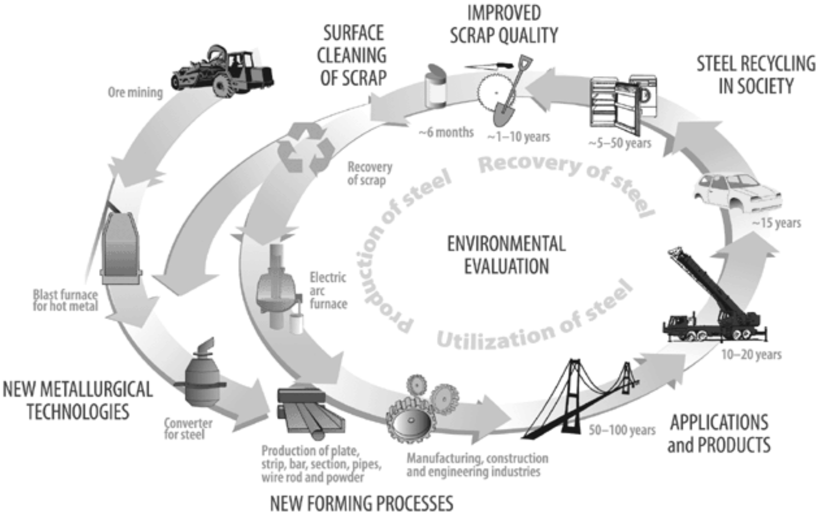


Figure 5.2 The steel eco cycle (Stirling 1993)

In steel bridges, the protection concept that should be considered during the design process should follow the recommendations from EN 1993-2, *Design of steel structures*. EN 1993-2 is the second part of EN 1993, *Design of steel structures*, and includes the standards for safety, serviceability and durability for steel bridges.

The design rules that should be followed were retrieved from the basic design principles of EN 1993-1-1, EN 1990, *Basis of design* and EN 1991, *Actions on structures*. These parts include recommendations about the distances and the dimensions of steel components in order to fulfil the safety requirements. EN 1993-1-1 includes principles in order to ensure that the steel members will provide sufficient resistance in tension, compression bending moment and shear forces. Moreover, Eurocode provides recommendations and requirements for several combinations of forces and moments in the structure.

In the design of steel component a minimum ductility is required. In order to succeed a desirable value for ductility several limitations should be considered. The first limitation is that the value of ratio f_u / f_y should be equal or higher than 1.10.

Another important aspect is the deflections of the different components. The limitations for vertical and horizontal deflections are provided from the general recommendations in EN 1990-Annex A1.4. This part also refers to the dynamic effects in the structure and provides the acceptable values of discomfort for users.

Moreover, for the construction of a durable steel structure, all the members should be designed in such a way to diminish the damage or to be protected from deformations, deterioration, fatigue problems and accidental actions that may occur. In addition, it is needed to ensure that the plastic deformations caused by the railings will not damage the structure. This is important since the railings of a bridge are connected with other structural parts.

Moreover, if a part of a bridge is damaged from accidental actions it is needed to ensure that the remaining structure will be able to sustain the loads. The effects of fatigue and corrosion should be considered according to the principles from EN 1993-1-9 and EN 1993-1-10.

The majority of the recommendations and principles differ in relation to the different cases. This includes the different components that may have been used and the different ways to construct a steel bridge.

Steel is a sustainable material. In the end of construction's life, steel can be removed and recycled in order to be reused. However, even if the amount of the material that is recycled is plenty, the required demands in order to use recycled steel in manufacture phase are not fulfilled. Therefore, over 50% of the steel is needed to be made from primary sources. In the demolition phase, steel has beneficial effects both in LCA and LCC analyses (Worldsteel 2011). The demolition phase for steel is beneficial because the entire material is recyclable. In addition, the recycled steel will reduce the total cost since the entire material can be used in another structure.

5.1.3 FRP

Recently, a new material has become more and more popular in bridge industry. Fibre Reinforced Polymer (FRP) is a composite material which has characteristics such as high strength capacity, potential resistance to environmental conditions, low maintenance cost and good ability to be moulded into various shapes (Fukuyama 1999). FRP is a mixture of at least two materials with different mechanical properties. However, the combination of these materials will improve and provide superior properties compared to the constituent materials individually. An important characteristic in these combinations is that the initial components are separate. (Fukuyama 1999). This means that the fibres can easily be distinguished from the polymer.

Pedestrian bridges constructed with FRP have many advantages compare to bridges which have been constructed with traditional materials. Several of the advantages that FRP bridges could provide are the short construction time, resistance to corrosion, aesthetical appearance and good fatigue and seismic performance (Jin et al. 2010).
Different types of FRP are categorized based on the material that has been used for the fibres. For this purpose, glass, carbon or aramid can be used. Moreover, the construction materials that can be used as matrix are polyester, epoxy or phenol. Fibres mostly consist of glass and matrix of polyester (Storck & Sagemo 2013). In this thesis, the FRP bridge was a box GFRP glass fibre reinforced polymer girder bridge with an ASSET deck produced by Danish company, Fiberline Composites (Engdahl, Rousstia 2012). ASSET deck is a FRP truss action which is consists of two diagonal plates. This FRP plates are created by the pultrusion process.

More specific, the ASSET deck is supported on a top plate of GFRP and two GFRP composite girders. The polymer of the FRP composite was epoxy (Murphy 2013).

The developments and improvements in FRP provide new techniques and methods which increase the performance of this material. The high performance of FRP bridges, combined with the use of the standard characteristics can fulfil a majority of the requirements from clients (Fukuyama 1999). Since the strength capacity of this material is relatively high, the bearing capacity of the bridge is not the main control parameter in bridge construction. Even if the FRP is a competitive material, it is considered as a material with low bending stiffness compare to the majority of traditional materials. The design of an FRP bridge was performed according to the basic limitations and recommendations for pedestrian bridges provided in Eurocode (Fukuyama 1999).

In FRP structures, several fundamental requirements should be considered in the design process. The structure should be able to fulfil the basic requirements and to sustain the different actions and impacts that may occur during its life time. Moreover, it will be reasonable to design a structure which will be able to endure damages from unexpected actions or situations (Clarke 1996).

In order to minimize the risk of damages there were several recommendations that should be followed. The selection process of the structural form that will be used should be based on the risks that have been considered in their respective cases and on its ability to sustain the actions while a structural member has been removed or damaged.

In the demolition phase, there are several options for FRP elements. The optimal choice is to reduce the waste or to reuse this material. Since the elements were constructed for specific cases it is not possible to reuse them in the manufacturing or construction phase. However, several methods have been developed in order to recycle FRP waste. These methods ensure that the whole amount of the material will be recycled.

6 Case study of three different bridges

In order to create comparable results several criteria and requirements should be fulfilled for all of the bridges. In the design phase of pedestrian bridges, the criteria that were followed are based on Eurocodes produced after the 1990. Moreover, the specific requirements for all three bridge were a span length of 19 meters, approximately 3 meters in width and an 80 year life span. An overview of the three bridges and parameters are given in Table 6.1. Two existing bridges made of timber and steel, were selected from the database BaTMan. The FRP Bridge was designed based on the dimensions of steel and timber bridge in order to provide comparable results. The calculations of the FRP bridge were performed using Mathcad file and are provided in Appendix B. A detailed description of each bridge is explained further in Chapter 6.1.1, 6.1.2 and 6.1.3.

Table 6.1 Key parameters for the bridges

	Timber bridge	Steel bridge	FRP bridge
Type	Slab bridge	Beam bridge	FRP box girder
Span length	19 meters	19 meters	19 meters
Construction length	20 meters	19 meters	19 meters
Height of the deck [m]	0.69	0.36	1.28
Bridge width	3.01 meters	2.90 meters	2.90 meters
Service life class	80 years	80 years	80 years
Built	2014	2009	2015[1]

[1] FRP bridge was designed with using a Mathcad file.

6.1.1 The timber slab bridge

The pedestrian timber bridge was constructed in 2014 by Martinsons Träbroar and was delivered to the site, in Skellefteå, Sweden see Figure 6.1.

Figure 6.1 The timber bridge (BaTMan 2015)

Martinsons AB, which is a sawmill company, usually prefabricate bridges in the factory and transport them to different locations in Sweden. The chosen bridge, which was 19 meters long and 3.014 meters wide, was a slab timber bridge and had a simply supported span. The bridge was consisted of 13 glued laminated timber beams with height of 630 millimetres each. Glulam beams were in transversal direction by pre-tensioned steel tendon with a diameter of 20 millimetre to create a deck. The bridge's parapet was made of spruce. Furthermore, the railings and panel cover were made of spruce. The superstructure had a safety class of three, a climate class of two and a lifespan of 80 year. See Appendix A for more information regarding cross sections and drawings of the bridge. Several rough estimations were made since the detail descriptions and drawings were the only available data for analysing the amount of material for steel and timber bridge. The estimations were regarding the quantities of construction materials, connections such as screws and bolts as well as cross beams and bracings.

The calculated quantity of the material that was used to construct the timber bridge is shown in Table 6.2. These calculation is shown in Appendix E.

The loads that the consultant of the timber bridge were included in the design of the timber bridge were the self-weight loads of the bridge itself, the vehicle loads which correspond to two vertical loads of 40 kN and 20 kN and horizontal loads from the vehicle load, imposed load also known as crowded load and the wind load.

Table 6.2 Quantities calculated for timber bridge

Material	**Quantity [m^3]**	**Density [kg/m^3]**
Glulam beams	35.19	430
Tension rods	0.04	7 850
Pressure impregnated timber	0.76	500
Sawn timber	4.88	430
Sum	**40.88**	

6.1.2 The steel beam bridge

The pedestrian steel bridge, which was built in 2009, was a simply supported beam bridge and was located in Ludvika, Sweden, see Figure 6.2. The bridge was prefabricated by manufacturing and assembling company KnislingeVerken in Knislinge. The steel bridge has a span of 19 meters with a width of 2.9 meter. The deck of the bridge contains of 20 I-beams with height of 200 millimetres and seven I-beams with height of 240 millimetres. Two simply supported truss beams carry the deck on seven cross I-beams. Moreover, the top flanges of the truss beams act as railings. This static system has beneficial impacts to the bridge since the amount of required steel minimized. See Appendix A for more information regarding cross section and drawings of the bridge.

The loads that the consultant of the steel bridge were included in the design of the steel bridge were the self-weight loads of the bridge itself, the vehicle loads which correspond to two vertical loads of 40 kN and 20 kN and horizontal loads from the vehicle load, imposed load also known as crowded load and the wind load.

Figure 6.2 The steel bridge (BaTMan 2015b)

Several rough estimations were made since the detail descriptions and drawings were the only available data for analysing the amount of material for steel and timber bridge. The estimations were regarding the quantities of construction materials, connections such as screws and bolts as well as cross beams and bracings. The calculations were approximately the same as the amount material that the manufacturing and the assembling company had stated. The calculated quantity of the material used to construct the timber bridge is shown in Table 6.3.

Table 6.3 Quantities calculated for steel bridge

Material	**Quantity [kg]**	**Density [kg/m^3]**
Beams Railings Screw, bolts[1]	12 000	7 850[1]
Sum	**12 000**	

[1] (Engdahl & Rousstia 2012)

6.1.3 The FRP box girder bridge

In order to get results that were more accurate the FRP Bridge was designed to be comparable with the steel and timber bridge, see Figure 6.3. These calculations are provided in Appendix B. The FRP bridge was assumed to be constructed in Sweden, Gothenburg and was designed to have a deck width of 2.9 meter with a span of 19 meters. See Appendix B for more information regarding cross section and drawings of the bridge. The FRP bridge was contained of an FRP ASSET deck which was supported on a glass fibre reinforced polymer (GFRP) top plate and two GFRP composite girders. The polymer of the FRP composite was epoxy. For the production of the ASSET deck the standard dimensions from the Danish company, Fiberline Composites were used (Engdahl, Rousstia 2012). According to the calculations the ASSET deck had a height of 225 millimetres and weight of $0.93 kN/m^2$, see Figure 6.4. In order to be capable to understand the structural system of this bridge, it is important to mention that the box girders are simply supported with ASSET deck in full interaction.

The loads that were included in the design of the FRP bridge were the self-weight loads of the bridge itself, including the FRP deck and girders, the vehicle loads which correspond to two vertical loads of 40 kN and 20 kN and horizontal loads from the vehicle load, imposed load also known as crowded load and the wind load. The criteria such as ultimate limit state, service limit state and dynamic were checked and were approved, see Appendix B.

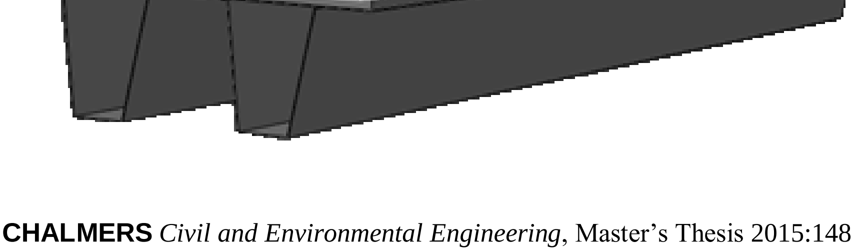


Figure 6.3 The FRP box girders bridge

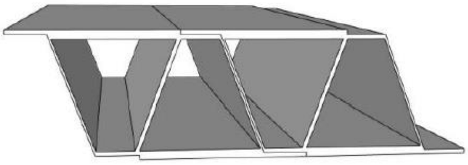


Figure 6.4 Cross-section of the ASSET bridge deck (Engdahl & Rousstia 2012)

Figure 6.5 illustrate the GFRP girder. It is an open-shaped FRP beam (Poneta 2011). Moreover, the type of fibers that was considered in the design of the girders was E-glass. The connection of different parts was assumed to be performed with epoxy resin. Since the required checks for stiffness were fulfilled, there was no need of incorporating carbon fiber cables to stiffness the GFRP girders.

Figure 6.5 FRP girder (Poneta 2011)

The calculated material quantity used to construct the FRP bridge is shown in Table 6.4 Quantity calculated for GFRP and appendix E. The material quantities were calculated by studying the cross section of the chosen bridge. Density of ASSET DECK was retrieved from experienced professionals consulting.

Table 6.4 Quantity calculated for GFRP bridge

Material	**Quantity [m^3]**	**Density [kg/m^3]**
Girders	0.92	1 800[1]
Top plate	0.56	1 800
Asset deck	12.83	94.33
Epoxy	0.18	1 200[2]
Sum	**14.32**	

[1] (Uddin 2013)

[2] (Kaw 1997)

7 Life cycle cost and life cycle assessment

7.1 LCA

In order to be able to provide results of the impacts released from the bridges to the environment, three LCA analyses were made. Moreover, assumptions and input values for each life cycle phase are explained further in this chapter. These assumptions affect the results significantly and therefore should be considered carefully. Consulting experts and researchers were helping to provide the results. All the material and input quantities for timber and steel bridge were calculated from the available detail descriptions and the drawings were provided from Swedish Transport Administration and BaTMan. The FRP bridge was designed using a Mathcad file that was provided in previous research report, see Appendix B (Friberg 2014).

The LCA analyses were performed with the use of the excel file BridgeLCA which were created as a part of ETSI project (Salokangas 2013). The ETSI project was a result of a cooperation agreement between Nordic National Road Administrations and dealt with the bridge life cycle optimization from the cradle to the grave. BridgeLCA is structured with an input sheet where the users can manually add the material amount that has been used, maintained and recycled. Furthermore, there were other sheets such as Ecoinvent sheet and energy sheet where values can be added manually.

BridgeLCA contains emission and energy use coefficient values for construction materials such as timber and steel. Since BridgeLCA tool unfortunately had a very limited opportunity for including non-specified materials such as FRP, more data was needed to examine the impacts from the FRP bridge. Therefore, the two important aspects that were important to consider were emission coefficient values in the Ecoinvent sheet and energy use coefficient values in the energy sheet. The value for emission coefficient were taken from previous research report where the values were obtained through the software OpenLCA and the Ecoinvent database to use it further as input in BridgeLCA, see *Table 7.1* (Storck & Sagemo 2013). The values for energy use coefficient ertr not included in BridgeLCA and were calculated separately due to the lack of information. The values are explained further in this chapter.

Moreover, this thesis was regarding three pedestrian bridges and therefore the entire traffic effects were neglected in the LCA analyses.

Table 7.1 Emission vectors for FRP (Storck & Sagemo 2013)

Impact category	Unit	FRP
GWP	kg CO_2 eq	3.62
ODP	kg CFC-11 eq	3.40×10^{-7}
EP	kg p eq	1.16×10^{-3}
AP	kg SO_2 eq	1.49×10^{-2}
FD	kg oil eq	1.21
ET	CTUe	1.52
HTC	CTUh	1.68×10^{-7}
HTNC	CTUh	7.21×10^{-7}

7.1.1 Material production phase

Several rough estimations were made since the detail descriptions and drawings were the only available data for analysing the amount of material for steel and timber bridge. The estimations were regarding the quantities of construction materials, connections such as screws and bolts as well as cross beams and bracings.

All elements for the construction of the bridges were decided to be prefabricated. The bridges were assumed to be fully assembled in a factory before transport to the construction site. However, several treatments were already performed to the bridges in the factory such as painting of the railings and beams. These initial treatments were included in the LCA analyses as well as the yearly maintenance activities.

The material amount that was calculated for the bridges is presented in Table 7.2. The calculations provided in Appendix E. The timber bridge contains tension rods, bolts and screws which were calculated separately. The amount of asphalt was assumed to be same for all the bridges and therefore was neglected in the analyses.

Table 7.2 Total weight and height of the bridges

Material production	Timber	Steel	FRP
Total weight of the bridge [ton]	18	12	12
Height of the deck [m]	0,69	0,36	1.28

The prefabricated steel bridge was built in the manufacturing and assembly company KnislingeVerken AB which is located in Knislinge, Sweden. The timber bridge was built and manufactured by Martinsons Träbroar AB, a timber industry and manufacturing company, and transported from their factory to the construction site. Since there are no composite manufacturing companies in Sweden the only company that could transport the prefabricated FRP at time would be Fibercore Company in Rotterdam, Holland. But since the effects from different materials were more interesting to investigate in this case study, the transportation was assumed to be same for all the bridges.

7.1.2 Energy consumptions

As mentioned before, the energy coefficient values were calculated separately and were not considered in BridgeLCA due to the lack of information. The calculated embodied energy consumption only comprised the energy consumed during the production phase. The values were calculated using embodied energy coefficient for different materials according to Table 7.3 (Hammond, Jones 2008).

Table 7.3 Embodied energy of different materials used in bridge construction (Hammond & Jones 2008)

Material	Embodied energy consumption [MJ/kg]
Steel	24.40
Timber	8.50
GFRP	67.20
Epoxy resin	139.30

7.1.3 Construction phase

The construction phase and its energy consumption were neglected in the analyses due to lack of information regarding equipment that was used during manufacturing of the bridge. The foundation and blasting were assumed to be same for all bridges and therefore were not included in LCA analyses.

7.1.4 Operation and maintenance phase

Bridges should be maintained continuously to give the bridge a longer service life. For the maintenance activities, the sawmill company Martinsons Träbroar AB is recommending cleaning and washing the coloured surface and if the timber surface absorbs the water the surface should be repainted. However, the bridge railings should be repainted after eight years. The bridges coating should be maintained with interval of 20 year. Furthermore, different aspects such as climate, type of paint, dimensions of the elements and previous treatments is determine how often they should be performed.

Some assumptions were made in order to consider the operation activities in the results. The values for steel and timber bridge and the entire life cycle maintenance is specified further in this sub chapter.

According to BridgeLCA, in order to perform the LCA analysis for operation activities the quantities of material should be specified and calculated. The maintenance activities are specified in the BridgeLCA as for instance the amount paint for repainting or the amount of material for replacing the overlay. Moreover, repair and maintenance due to accidents or other unexpected actions were not included in the analyses.

The values for maintenance activities were chosen accurately by contributing with professional in operation, repair and maintenance at Swedish Transport Administration and Technical Research Institute of Sweden (SP). For instance, in the maintenance phase, the timber and the steel bridge was repainted with the same amount of paint that they were painted with at the first time the bridges were built. The interval of the maintenance activities is shown in Table 7.4.

Table 7.4 Performance of operation and maintenance activities

Operation and maintenance	Timber	Steel	FRP
Use phase	Repainting of railings every 8 years, repainting of panels every 15 years and replacement of overlay every 20 year	Repainting of the bridge every 30 year, replacement of overlay every 30 year	5% of the total material amount used to construct the bridge

7.1.5 End of life phase

The last phase contains the demolition work, see Table 7.5. Several assumptions were made during applying the analyses regarding recycling and recovering of the different materials. These assumptions were made accurately by contributing with professional at Swedish Transport Administration and Technical Research Institute of Sweden (SP). For instance, in the

All the assumptions are mentioned further in this sub-chapter.

All construction steel elements were assumed to be scraped and transported to the recovery company. For the timber bridge, 80% of the construction timber were assumed to be recycled and 20% were taking to a landfill site. For the FRP bridge, the entire materials were assumed to be taken to the composite recycling company Zajons Zerkleinerung in Melbeck in Germany.

Table 7.5 Assumptions regarding demolition phase

End of life	Timber	Steel	FRP
Disposal	20% of total timber volume to landfill and 80% of total timber volume to material recovery	All material to material recovery	All material to energy recovery

7.1.6 Transportation

One of the aspects that affect the environment by transport activities is the weight of the transportation vehicle and the goods. Lighter goods lead to less fuel consumption (DG TREN 1994). However, the weight of the bridges was different and therefore the environmental effect of each bridge was different as well. According to a brief research the weight of the material that a construction truck can transport is approximately 30 tonnes (Hussein, Shaswar 2011). Since the weight of all the bridges was below 30 tonnes only one truck was needed.

All the bridges were supposed to be in same conditions and therefore the FRP bridge was assumed to be built in Gothenburg, Sweden. The distances between the manufacturing to the construction site and from there to the disposal location was decided to be 100 kilometres for all the bridges and phases. Table 7.6 shows the chosen manufacturing and disposal factories for each material. The transportation from gate to site, operation and maintenance and demolition were included in the BridgeLCA.

Table 7.6 Manufacturing and disposal factories related to different bridges

Transportation	Steel	Timber	FRP
Manufacturing company	KnislingeVerken AB	Martinsons Träbroar AB	Fibercore company in Rotterdam[1]
Use phase	100 km by truck	100 km by truck	100 km by truck
End of life	Skrotcentralen in Uppsala		Zajons Zerkleinerung in Melbeck[2]

[1] Rotterdam to Gothenburg is assumed as 100 km in the analysis

[2] Gothenburg to Melbeck is assumed as 100 km in the analysis

7.2 LCC

In order to define the most cost efficient material for a pedestrian bridge, three life cycle cost analyses were performed according to the methodology which was analysed in Chapter 2. Therefore, the costs were categorized in agency, users and society costs.

The three bridges have a service life of 80 years and a discount rate of 3.5% according to the recommendation from Swedish Transport Administration. To provide more comparable results between the different bridges several assumptions were made before the calculations of the costs. The assumptions were made based on the aim of the thesis. Since the aim of the thesis was to provide comparable analyses of the three bridges and not to find the total cost of the bridge life cycle the common costs were omitted. The assumptions for LCC analysis were the following:

- The costs that were considered to be the same for the three bridges were costs from asphalt deck, construction and from planning and designing phase.
- The environmental effects were considered in LCA analysis. Hence, the costs from environmental impacts were not included.
- The distances between the manufacturing to the construction site and from there to the disposal location were assumed to be the same in all bridges.

In this thesis both user and society costs were neglected from LCC analysis. User costs comprises the indirect costs which affect the society (Mohammed 2013) and include costs due to traffic delay and vehicle operation. Society costs include costs from environmental impacts and accidents. This category provides information about the impacts of the structures and of different activities during the life of the bridge that affect the environment. However, according to the assumptions that were taken into account in this analysis, the environmental effects were considered in the life cycle assessment analysis.

Moreover, the costs from accident should be considered. The term accident costs include both the costs from accidents that could occur during the construction of the bridge and from the accidents during the operation phase. The influence of accident costs was negligible in the total LCC analysis since the possibility for an accident to occur was small. Therefore, the accident costs were not included in the calculations.

Usually, a life cycle cost analysis is performed with the help of different software. However, in this thesis the calculations were computed using Microsoft Excel.

7.2.1 Agency costs

As it was mentioned before, agency costs can be considered all the direct costs obtained from the initial stage of material acquisition to the replacement or disposal. Table 7.8 provides the price per unit of the agency costs in the initial phase. This category includes material and construction costs. These values were taken from previous investigations and by consulting experts about the requirements and the costs that the transportation companies in Sweden were using. The initial costs for timber and steel bridge were assumed to be 700,000 SEK. This estimation was made with the help of professionals in the Martinsons for the timber and KnislingeVerken AB for the steel bridge. However, in order to obtain a holistic view of the cost distribution in the initial phase the costs from raw material are also provided in Table 7.8.

In order to calculate the costs from the transportation of the structural elements several assumptions had to be made. According to our research the volume of the material that a construction truck can transport is approximately 30 tones (Hussein, Shaswar 2011). Therefore, for the calculation of the transportation costs it was assumed that only one truck will be needed in all cases. Therefore, the distances were roughly estimated to be the same for all bridges. However, in order to observe the impacts in costs and to provide more accurate results, transportation costs were included in the LCC analysis. The distances that were considered in the analysis were the distances between manufacture and construction site and from there to the disposal field. According to the construction companies the cost for transportation is approximately 1,200 SEK/h. Furthermore, both the distances from manufacturing to construction site and from there to disposal field, were assumed to be 100 kilometres. Although transportation is a part of the initial phase the costs were included separately in the analysis. As a result, the effects from this part to the final cost will be clearer.

Table 7.7 Transportation costs

	Unit [min]	Cost [SEK/unit]
Transport to construction	60	1200
Transport to disposal	60	1200

Table 7.8 Agency costs in the initial phase

	Unit	**Cost [SEK/unit]**
Man hour[3]	h	500
Insulation and surfacing[2]	m^2	1 160
Timber Bridge		
Base Paint	litre	106
Glulam	m^3	4 313
Installation of struts[3]	N°	29
Moisture indicator[1]	N°	2 000
Paint	litre	100
Pressure impregnated	m^3	2 352
Sawn timber	m^3	2 445
Steel rods[3]	N°	1 000
Steel Bridge		
Steel[2]	tonne	24 500
FRP Bridge		
FRP Asset deck[2]	m^2	6 338
GFRP girders[4]	m^2	3 962

[1] Anna Pousette, SP Technical Research Institute of Sweden
[2] Ochsendorf et al. 2011
[3] Erik Johansson, Moelven Töreboda AB E-mail 2015-05-11
[4] Yang & Kalabuchova 2014

In the timber bridge, different species of wood were used during the construction. Sawn timber and glulam was used in different parts of the bridge. Therefore, in order to produce more accurate results the costs from each type were included separately. These values were retrieved from the prices that Swedish companies recommended and by consulting professionals in timber bridges. Based on the recommendations from the professionals, the costs were found from Swedish companies and were adjusted. Moreover, the same procedure was followed in order to determine the cost and the type of the paint that was used for the bridge. The cost of steel rods was calculated based on the recommendations from Erik Johansson of Moelven Töreboda AB. This includes both the costs of the material and the installation of struts. However, as it was mentioned before, the total cost for the timber and steel bridge in the initial phase was assumed to be 700,000 SEK.

The costs for the different components of the FRP bridge was found from previous investigations and according to the recommendations of the experts on this kind of bridges. The material that was used in this bridge was Glass Fiber Reinforced Polymer (GFRP) and the type of the fiber was E-glass. Since this bridge was designed, the costs for the raw materials and the installation calculated approximately, based on previous investigations. The final cost for GFRP girders includes the cost of E-glass fibers, epoxy resin, material of the core, moulds for laminas, labour work or man hour and other costs. Table 7.9 provides the costs calculated per square meter. The cost for a man working per hour for the construction of FRP is different than the cost of the man working per hour for the maintenance activities.

The cost of epoxy resin in FRP bridge, was assumed to be 100 SEK/litre (Friberg 2014). Epoxy was used in order to connect the top plate with the girders. According to the calculations the initial cost for FRP bridge is 825,211 SEK.

Table 7.9 Costs of GFRP girders

	Unit	Cost [SEK/unit]
E-glass fiber[1]	m^2	106
Epoxy resin[1]	m^2	476
Core material[1]	m^2	100
Moulds of laminans[1]	m^2	2 000
Man hour[1]	m^2	650
Other cost[1]	m^2	600
Total cost of GFRP girders	m^2	3 962

[1] (Yang & Kalabuchova 2014)

Since the case study was focused to achieve the consequences of a bridge construction, the taxes were neglected from the final cost. More specific, the taxes for the products in Sweden are approximately 25%.
The estimation of the construction costs is difficult since the prices of the products and labour work varies between the different countries and methods (Murphy 2013).
Additionally, the costs from the operation and maintenance of the bridge should be included in the analysis. The activities in maintenance can be categorized based on two factors; inspection and repair (Friberg 2014). The inspection costs were assumed to be independent of the bridge material and therefore were neglected.

The second factor which influences maintenance activities was the repairing process. These activities differ according to the material that was used for the construction of the bridge. The maintenance activities that were considered in LCC are provided in Table 7.10. The activities are listed in the table based on the specific requirements for each bridge.

The maintenance activities for the timber bridge were calculated according to the recommendations of Anna Pousette, SP, Technical Research Institute of Sweden. The maintenance for the impregnated panels and beams was included in the cost for repairing the bearings of the bridge. Furthermore, the cost for repainting panels and railings was calculated by considering both the men work and the cost of the paint.

To define the maintenance activities in steel bridge the recommendations from Fredrik Olsson, Swedish Transportation Administration were followed. The costs for repainting of the bridge and for replacing the overlay were estimated approximately.

The maintenance activities for the FRP bridge were basically assumptions made according to the suggestions from professionals. Based on these recommendations the activities that were considered for the FRP bridge except from the general maintenance activities were the repair of the Asset deck and the GFRP girders. In order to provide reliable results only 2.5% percentage of the total elements assumed to be replaced.

Several values were calculated according to the required time for each activity. In these cases, the cost per hour was assumed to be the cost for the labour work or man hour.

Table 7.10 Maintenance and repair activities

Activity	**Performed every years**	**Unit**	**Time [h]**	**Cost [SEK/unit]**
Timber				
Inspection of bearings[1]	40	h	4	500
Cleaning of bridge[1]	2	h	3	500
Moisture indicators[1]	7	h	4	500
Painting of panel[1]	15	h	20	500
Prestressing of rods[3]	20	h	29	500
Repainting of railing[1]	8	h	20	500
Replacement of overlay[1]	20	h	20	500
Steel				
Cleaning of bridge[2]	1	h	2	500
Repainting of bridge[2]	40		-	200 000
Replacement of overlay[2]	20		-	20 000
Washing of bride[2]	5	h	2	500
FRP				
Cleaning of bridge	2	h	3	500
Replacement of overlay	20	h	20	500
Repair FRP Asset deck	40		-	2.5% of initial FRP
Repair GFRP girders	40		-	2.5% of initial GFRP

[1] Anna Pousette, SP Technical Research Institute of Sweden

[2] Fredrik Olsson, Swedish Transportation Administration

[3] Erik Johansson, Moelven Töreboda AB E-mail 2015-05-11

The disposal of the structural elements depends on the bridge material. According to the material that was used in the construction the elements can be recycled or disposed to a landfill site. (Mara 2014) Disposal costs for each material can be retrieved from the Table 7.11. Since steel can be recycled the value in this table is negative. Timber and FRP are recyclable materials; however, the procedure of disposal was provided an extra cost to the construction company. Therefore, the values for the demolition of the timber and FRP bridges could not be considered to be negatives. Furthermore, the required working hours for the demolition of the bridges were included to the disposal costs. The working hours for the disposal of the timber and the FRP bridge were estimated to be 56 h (approximately 7 days) and for the steel bridge 32 h (approximately 4 days).

Table 7.11 Costs from demolition phase

	Unit	Cost [SEK/unit]
Demolition[1]	h	500
Timber[1]	tonne	1 000
Steel[2]	tonne	-500
FRP[2]	tonne	1 100

[1] Anna Pousette, SP Technical Research Institute of Sweden

[2] Ochsendorf et al. 2011

7.2.2 Sensitivity analysis

In order to perform a life cycle analysis all the required data should be defined in an initial stage. As a result of uncertainties and lack of information, several assumptions should be taken into account. It is important to establish the risks and uncertainties early in the analysis to ensure the reliability of the results. In this case a sensitivity analysis can be used in order to observe the affects from an uncertainty by changing this parameter. In this method, the value of an uncertain parameter will change either by increasing or decreasing (Langdon 2007).

Most parameters that were investigated in sensitivity analysis were parameters which include traffic volume, speed of vehicles and hourly costs for the delay caused by these aspects. However, this thesis investigates pedestrian bridges and therefore the parameters that were examined were only the discount rate and the price of the FRP.

Discount rate

The discount rate in sensitivity analysis varies between 0% and 8%. This value changes according to the recommendations of each country. The discount rate was taken as 3.5% based on the recommendation of previous investigations and Swedish parameters.

Price of FRP material

The use of FRP as a construction material is increasing which could result to decreasing its price. Therefore, the sensitivity analysis was investigating reductions in the price of the FRP. More specific, the reductions between 0% and 50% of the present value were considered. In the FRP bridge different prices were assumed for the ASSET deck and the girders. The value for FRP ASSET deck was calculated to 6,338 SEK/m^2 while for the GFRP girders it was calculated to 3,962 SEK/m^2. The values can also be seen in Table 7.8.

8 RESULTS

In order to compare the three bridges from the environmental and financial aspects LCA and LCC analyses were performed based on the description in Chapter 5, 6 and 7. The analyses are provided in Appendix C and D respectively. Moreover, the calculation regarding designing of the FRP bridge can be seen in the Appendix B. The designed FRP bridge consists of two GFRP girders and an asset deck. The deck was required a height of one meter to resist the loads according to the calculation.

8.1 LCA

The purpose of LCA analysis was to calculate and compare the emissions released from the three bridges made of different materials. Based on the assumptions and the recommendations for each material the emissions from the bridges were calculated for all the different phases of the bridge life cycle. The procedure can be found in Appendix C. The LCA analyses were performed with the use of the excel file BridgeLCA which were created as a part of ETSI project (Salokangas 2013). BridgeLCA was structured with an input sheet where the material amount that was used, maintained and recycled were manually added in the Excel file and produced the results in terms of emissions which were seen in the diagrams, see Figures 8.1 – 8.4. The input data were calculated and measured from the drawings that were extracted from BaTMAN and the maintenance activities and its performing intervals and demolitions activities were retrieved by consulting experts at SP and Swedish Transportation Administration. The choice of the precise values and the procedure of the LCA analysis were explained in previous Chapter 7.1.

LCA analysis was performed for each bridge, timber, steel and FRP. The emissions that were considered in the LCA analyses were sulphur dioxide, carbon dioxide, nitrogen dioxide, methane, carbon monoxide. These emissions were classified into different categories of environmental impacts. Figure 8.1 shows the results of normalized which consider person equivalent, the unit impact potential per person per year, for each impact category and bridge. As shown in Figure 8.1 and Figure 8.2, the timber bridge had the lowest environmental impact, nearly half the environmental impact from the steel bridge, and the FRP bridge caused the largest environmental impact.

The largest potential environmental impact for each bridge was fresh water eutrophication. Freshwater eutrophication correspond to the increased nitrogen and phosphorus concentration in water which damaging the ecosystem quality (Smith et al. 2006). In addition, fossil depletion and terrestrial acidification had also large potential environmental impact. Further, detailed results are presented in Appendix C.

Table 8.1 Emissions from the different bridges

	Timber [PE]	**Steel [PE]**	**FRP [PE]**
Climate change	1,70	2,57	4,32
Ozone depletion	0,05	0,04	0,20
Terrestrial acidification	3,06	2,80	5,85
Freshwater eutrophication	15,17	38,51	36,49
Fossil depletion	4,39	5,76	9,80
Sum	24,37	49,69	56,65

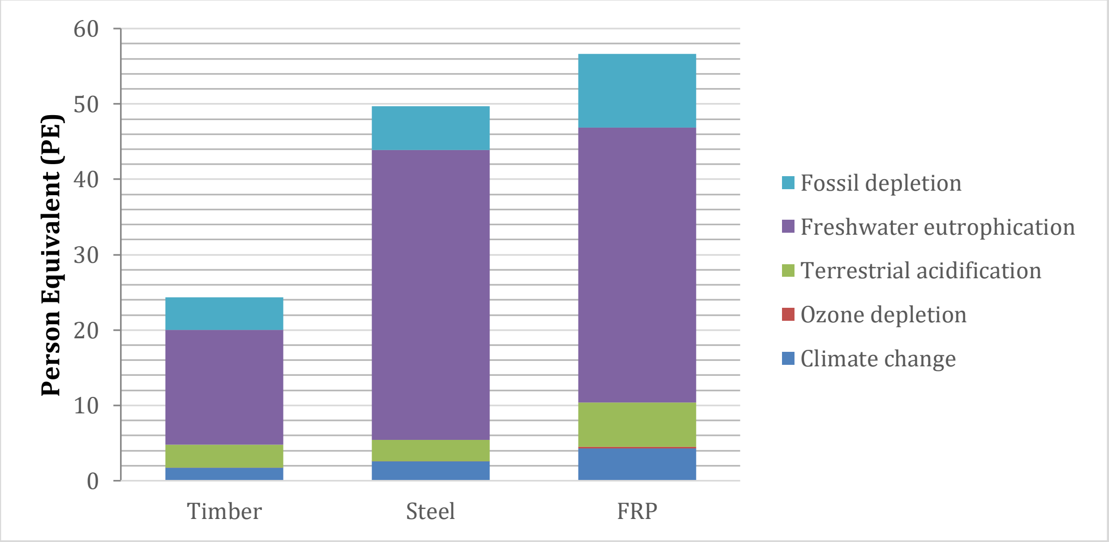


Figure 8.1 Emissions from different bridges

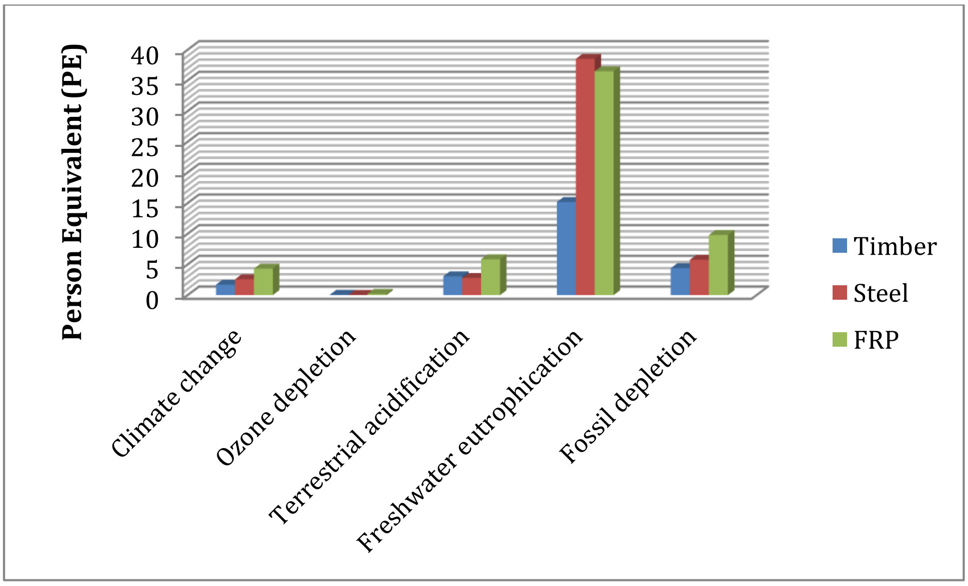


Figure 8.2 Emissions from different bridges

In Figure 8.3, LCIA results for each environmental impact indicator are shown. As illustrated in Figure 8.3, the material production phase dominated in all three bridges. Analysing the results, the operation and maintenance activities such as painting the timber and steel bridges affected climate change, terrestrial acidification and fossil depletion. For all the bridges, the main material of the superstructure itself caused the largest environmental impacts, see Figure 8.2 and Figure 8.3. The transportations mostly affected the ozone depletion. The epoxy in the FRP bridge mostly affected terrestrial acidification, fossil depletion and global warming potential.

Table 8.2 LCIA results

	Timber	Steel	FRP
Material Production	81,6	116,7	239,9
OR&M	4,6	8,3	2,7
Sum	86,2	125,0	242,6

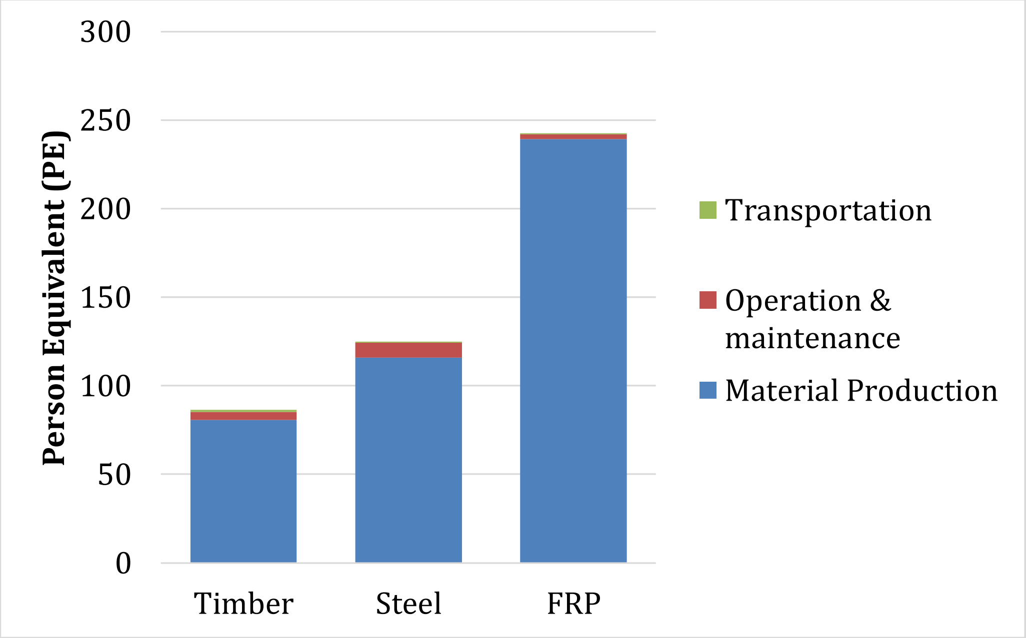


Figure 8.3 LCIA results

The illustrated result in Figure 8.4 shows the energy consumption of different bridges during the material production phase. The energy consumed for the timber bridge was the lowest while for the FRP was the highest. Furthermore, steel bridge required higher energy consumption than timber bridge but lower than FRP bridge.

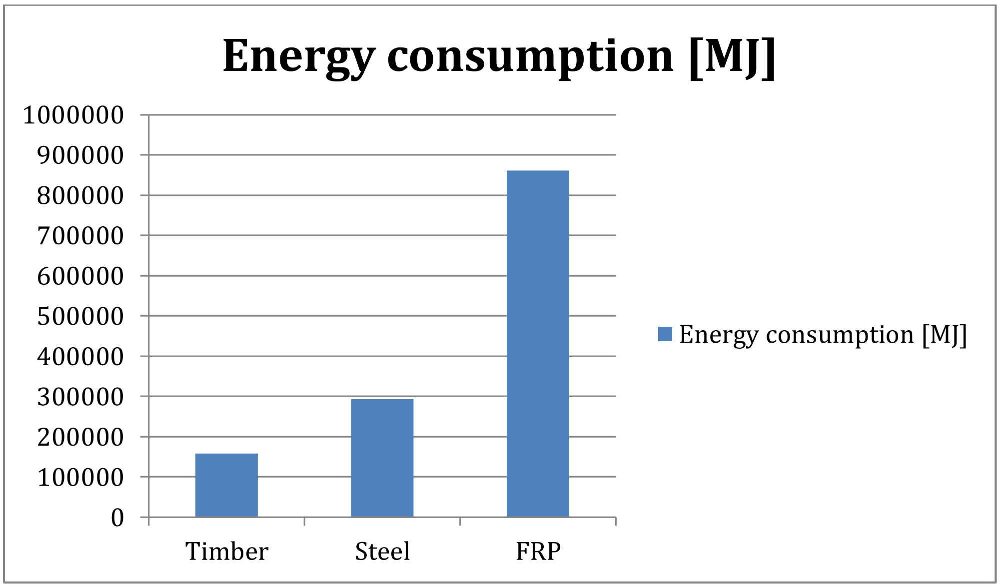


Figure 8.4 The energy consumption for different bridges

8.2 LCC

The purpose of LCC analysis was to calculate and compare the total costs for three bridges made of different materials. Based on the assumptions and the recommendations for each material the costs of the bridges were calculated for all the different phases of the bridge life cycle. The procedure can be found in Appendix D. The choice of the values and the procedure of the LCC analysis are explained in Chapter 5.2.

LCC analysis was performed for each bridge, timber, steel and FRP. In all cases, the main contribution to the costs was derived from the initial phase. This phase includes the costs from the material extraction and manufacturing. As it can be seen from the Table 8.3 the initial costs are quite similar in all bridges. More specifically, timber and steel bridges have the same initial cost, while the cost for FRP bridge is relatively high.

Furthermore, maintenance phase has important influence on the total costs. Transportation and demolition costs have also been added to the analysis. However, the contribution from these costs was trivial in the total amount. It is important to mention that the total costs for the different phases were calculated according to the present value method. The common method to calculate the life cycle cost is to discount them to a specific time, normally the present value. These values are explained further in Chapter 2.2.

Table 8.3 Life cycle analysis for different bridges

	Timber bridge [SEK]	**Steel bridge [SEK]**	**FRP bridge [SEK]**
Initial	700 000	700 000	825 211
Transportation	1 277	1 277	1 277
Maintenance and repair	94 612	99 760	31 869
End-of-life	2 880	638	2 654
Total costs	798 769	801 675	861 011

Figure 8.5 presents the total costs from the three bridges. Overall, timber the bridge has the lowest total cost followed by steel and FRP bridge. Initial costs have the main influence in the total cost in all cases. More specific, the initial cost for timber and steel bridge was 700,000 SEK, while for FRP it reaches 825,211 SEK (already stated in table- mention it here.

The costs from maintenance and repair activities in the FRP bridge were less than half compared to the relevant cost for timber and steel case. However, the influence from initial phase was greater and as a result the total cost in timber bridge was lower.
The costs from transportation and disposal were essentially inferior compared to the other phases.

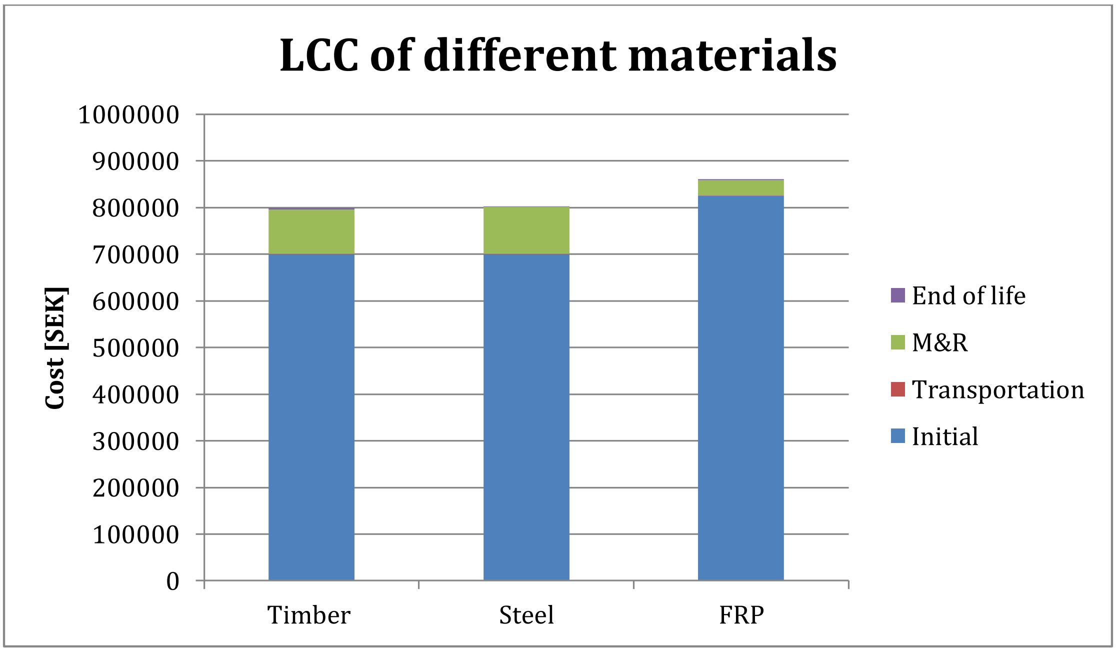


Figure 8.5 Total life cycle cost of different bridges

The figures in Appendix D, provide detailed information about the cost distribution of the three alternatives. In all bridges, the contribution of transportation and demolition costs to the final cost is negligible. Therefore, these two values are not included in the charts. However, the different costs from transportation and end of life phase can be seen more detailed in the Appendix D.
The initial cost for the timber bridge covers 88% of the total cost, while maintenance and repair covers 12%. The initial costs for the steel bridge cover the 88% of the total

amount, while the maintenance and repair (M&R) activities the 12% of the total cost. The initial costs in FRP bridge cover the 96% of the total amount, while the maintenance and repair activities cover the 4%.

According to the diagrams, the bridge material amount occupies the main part of the costs in the life cycle of the structure followed by the maintenance and repair activities. As it can be seen from the figures, the costs in timber and steel alternatives were similar in all the different phases. In all cases, transportation and demolition cost were significantly lower compared to costs of other phases and they have small influence in the total amount.

8.2.1 Sensitivity analysis

In Chapter 7.2.2, the procedure and the different parameters were described in order to perform the sensitivity analysis. The different parameters that should be considered were the discount rate and the price of the FRP material.

8.2.1.1 Discount rate

The effects from the discount rate were examined in sensitivity analysis with a variation between 0% and 8%, see Figure 8.6. In total, the costs from the three bridges tend to decrease with higher values of discount rate. Costs vary slightly for the different percent of discount rate in the FRP bridge. On the other hand, the difference between the total amount in the timber and steel bridge is higher. The breaking point for all the bridges was around 1%. The prices after that point have small variations. It is important to mention that for a discount rate between 0 and 1% for the steel and the timber bridge the total costs were higher than for FRP. An explanation for this change is the higher cost of the maintenance activities in these two alternatives. Discount rate affect the price of maintenance activities as it was used for the calculation of the future values. Since the FRP bridge has significantly low maintenance cost, the other two bridges will be more expensive for costs closer to the present value. Moreover, with a discount rate of 5% or higher, the maintenance cost of steel bridge decreases significantly. As a result the total cost of timber bridge was slightly higher than of steel bridge, but still lower than FRP.

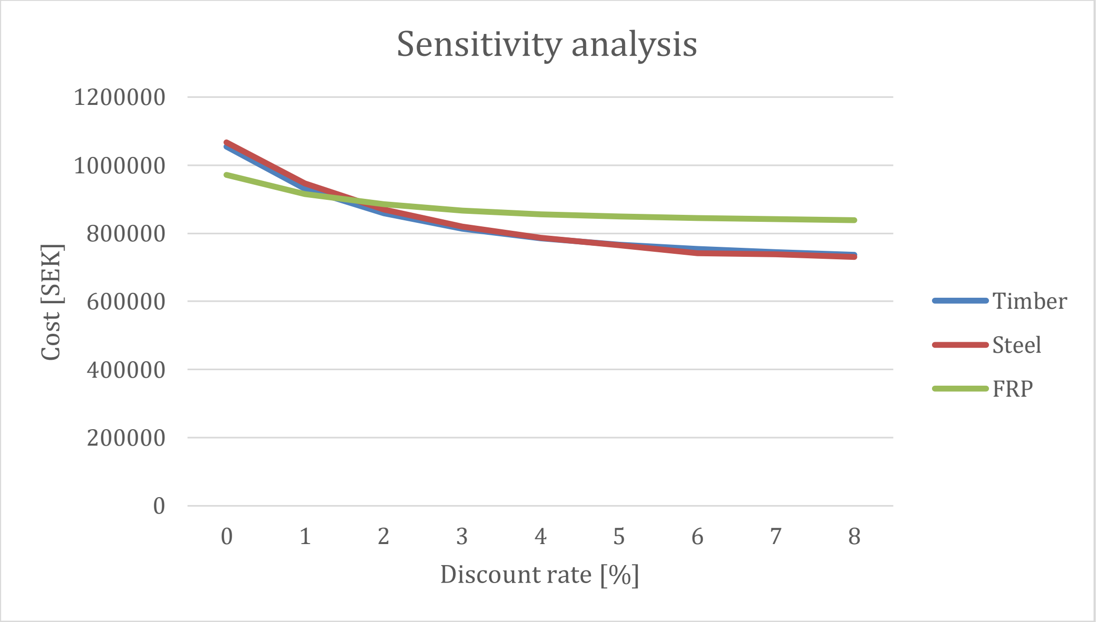


Figure 8.6 Sensitivity analysis of discount rate

8.2.1.2 Price of FRP

Figure 8.7 illustrate the changes in total costs based on different prices for the FRP material. The diagram provides information about the changes in the price of the FRP bridge compare to the other two alternatives. The lines which represent the total costs from timber and steel bridge have no changes since the cost of FRP has no influence on them. According to the diagram, with a reduction in the price between 10% and 50% the total amount of this alternative decreases significantly. As a result of the price reduction, the total cost of FRP bridge became lower than in the other cases. It is important to mention that in the analysis both the price for the ASSET deck and GFRP girders were assumed to decrease. The explanation of the significant difference in the results is that the main costs of the FRP bridge derived from the initial phase.

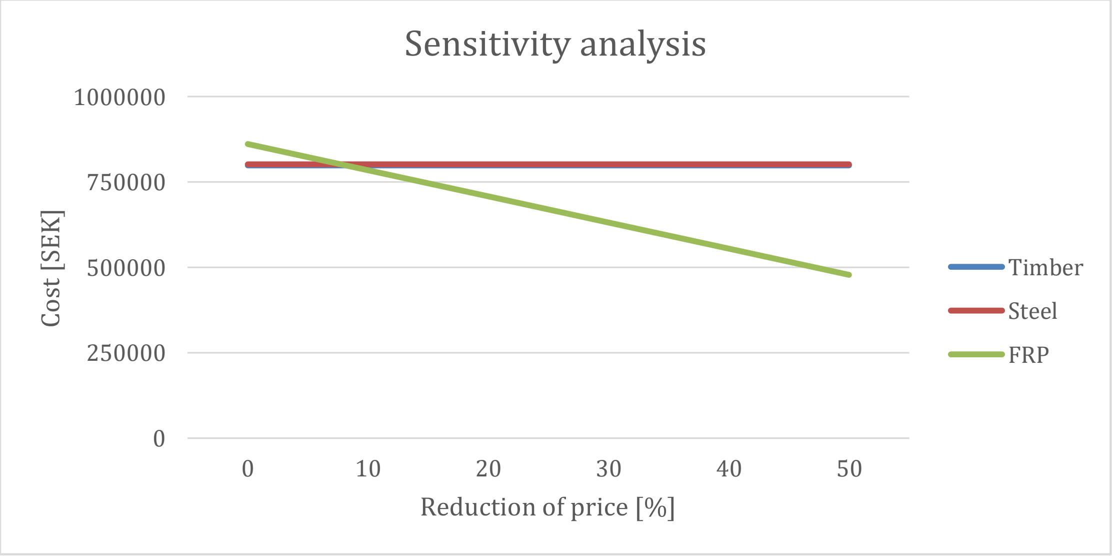


Figure 8.7 Sensitivity analysis of FRP price

9 Discussion and conclusion

The aim of this thesis was to compare three bridges made of different materials, from a financial and environmental perspective. The comparisons performed based on the results from LCC and LCA analyses.

In order to perform analyses, several parameters were assumed to be the same for all the bridge cases. One such parameter was the asphalt deck. Nevertheless, since the case study was pedestrian bridges the asphalt deck in the FRP material might be needless.

Regarding transportation, the distances between the industry and the construction site and from there to the disposal field were considered the same for all the alternatives. This assumption was made in order to neglect the differences based on the bridge's location. Therefore, the results were not limited regard to the location that the bridges were placed. However, transportation phase was included in both analyses since it was considered that has notable influence in the life cycle of a bridge.

In conclusion, timber and steel are preferable materials for the construction of a pedestrian bridge. Previous investigations regarding road bridges showed that FRP was a promising material in bridge industry (Yang & Kalabuchova 2014). However, based on the results from these analyses, the use of FRP regarding pedestrian bridges needs further developments.

9.1 Life cycle assessment analysis

The conclusion of the LCA analyses were that timber can be considered as the most environmental efficient material for the construction of a pedestrian bridge. Analysing the results, freshwater eutrophication was the largest environmental impact in all the three bridges. This type of impact refers to the excessive growth of aquatic plants or algal blooms due to the high level of nutrients, nitrogen and phosphorous, in freshwater.

In addition, fossil depletion and terrestrial acidification had large potential environmental impact. The impact fossil depletion refers to the consumption of fossil fuels. Terrestrial acidification, which is the emission of nitrogen and sulphur, contribute to corrosion and effect ecosystems. Transportation had high influence on ozone depletion. Increasing of the ultraviolet radiation is the consequence of the impact ozone depletion. Furthermore, painting had a large influence on the environment. Painting and repainting used in material production and maintenance phase had the highest impact on global warming, terrestrial acidification and fossil depletion. This is because paint contains high quantities of volatile organic compounds.

According to the results, the highest amount of emissions were released from the main load bearing material and structure such as construction steel, glue laminated wood, FRP, reinforcement and parapets. The results showed that the material production phase had the largest environmental impacts in all the bridge types but particularly in the FRP bridge case. The specific environmental impacts of FRP were emissions of volatile organic compounds (VOC), energy consumptions and toxicity. Also the use of crude oil to derive fundamental materials of a composite, fiber and matrix, is doubtful when it comes to sustainability of FRP composites. On the other hand, composite material is considered as environmental friendly with respect to its weight.

The light weight of FRP reduces consequent harmful exhaust emissions and save fuel in transportation.

Impregnation treatment, prestressing of tension rods and painting are several maintenance activities for timber bridges. When it comes to steel surface treatment such as corrosion protection has environmental effects as well. In comparison with the steel and timber bridges the FRP bridge requires less regular maintenance operations and therefore has small potential environmental impacts from the maintenance phase. For instance, the FRP bridge does not need painting and has sufficient resistance to corrosion. The environmental impact of energy consumption is different depending on the way the energy was extracted. Using sustainable energy extraction methods, such as wind power and hydropower, will have less effect on environment. However, it should be mentioned that the energy consumption during the construction phase was included in the analyses and could have been affected the result. Unfortunately there was limited access to information regarding the energy consumption of equipment during construction and manufacturing phase. Therefore, only the energy consumption during the material production was calculated for all the three bridges.

In cases where the bridge is located above a road and the traffic should be closed in order to install the bridge the results will have significant changes. In that case, the energy consumption of the FRP bridge might be less compared to the other alternatives since the installation of a FRP bridge requires less energy and time. As it showed in the results the energy consumed for manufacturing the steel was higher than timber. However, FRP had the highest energy consumption.
Due to the lack of input information and values regarding the construction phase the impact caused from this stage was neglected.

The transportation of the material and the end of life activities were of minor importance and had not considerable effect on the results. However, the weight of the materials varied and therefore the fuel consumption during transportation was different as well.

The impacts such as human toxicity and ecotoxicity were not included in this thesis. Since there was no normalization results for these type of impacts in the BridgeLCA due to the fact that the issues are still correlating with doubt in the LCA analyses. Therefore, it is important to keep this in mind when analysing the results.

In the end of life phase several assumptions were made in order to calculate the impacts from this phase. However, as it can be seen in the results this phase was not included in the diagrams. It is because the recycled material will only have benefits to the next bridge system. Therefore, the benefits of the recycled material, from the previous bridges that were recycled, are already considered in the material production phase. Therefore, BridgeLCA avoid double counting of this value. Furthermore, only the transportation of the material to the recycling facility was included. It is important to mention that the impacts from the demolition work were not included.

In order to minimize the environmental impacts different design options can be effective. The choice of sustainable materials already in the initial stage will have significant variations on environmental impacts. The LCA analyses can be used for comparative purposes in order to support decisions of material and maintenance activities. Every selected input into BridgeLCA contributes to different impact indicators. Therefore, the results can be used to identify the most important impacts and minimize it.

9.2 Life cycle cost analysis

In these life cycle cost analyses of pedestrian bridges, users and society costs were neglected. Agency costs included all the different parameters that affect the costs during the life cycle of a pedestrian bridge. According to the results, initial and maintenance costs have the main influence in the analysis. Both of these categories, initial costs and maintenance activities on the bridge, were depended on the selected material. Therefore, the choice of the material can be decisive in the examination of the cost during the life cycle of a bridge.

Considering the results from the demolition of the three bridges, the contribution of this phase in the total cost was negligible. It is important to mention that the costs in this phase were predictions based on the present values. In this thesis, the discount rate was assumed to be 3.5% according to the recommendations of the Trafikverket for infrastructure projects (Storck & Sagemo 2013). Perhaps with a lower discount rate the contribution of disposal costs will be higher since the value will be similar to the present value.

Moreover, results show that transportation cost has small influence in the total cost of the bridge. It is important to mention that in the analysis the distances between the different locations were assumed to be same for all bridges. This assumption was made in order to obtain the impacts based on the different materials since the difference between the locations could probably affect the total costs of the bridges. However, the main contribution in total costs became from the material costs and therefore, the transportation will not produce significant changes.

Furthermore, the costs from planning and designing phase were neglected since they were assumed to be similar in all cases. Nevertheless, FRP is a new construction material and the costs for designing an FRP bridge might be different compared with the designing costs for a timber or a steel bridge. It should be mentioned that the costs, that were the same for all the cases, were omitted. This provides the differences of the total costs based on the material of the structure. If the neglected costs would were added in the analysis, the difference between the costs would be lower or higher, depending on the different parts of the analysis.

The result from the sensitivity analysis shows that the changes in the discount rate have important effect in the total cost for all the different materials. In all cases, the total costs tend to decrease for higher values of discount rate. Discount rate is used for the calculation of the present value. Therefore, smaller values of discount rate during the service life of the bridge will produce results that are more equal to the present values. However, maintenance and disposal costs were estimations and therefore higher values of discount rate will postpone costs to future values. In the case of the FRP bridge, the main costs were related with the initial phase and therefore a lower discount rate will affect FRP beneficially compared to the other alternatives.

Moreover, the possibility of decreasing the price of the FRP material was investigated in the sensitivity analysis. The price of this material was expected to be lower in the future since the use of FRP is increasing. The results demonstrate that even a reduction of 10% will be enough to provide a significant decrease in the total cost of the FRP bridge. Furthermore, since the cost from the maintenance activities in FRP bridge, with a reduction in the price, was only 4%, FRP will be a profitable option for the construction of a pedestrian bridge.

The conclusion of the LCC analysis was that timber can be considered as the most cost efficient material for the construction of a pedestrian bridge with the span of about 20 metres. It is important to mention that the conclusions of this analysis were valid for these specific situations. Therefore, the results of these analyses cannot be directly applied to another investigation. However, sensitivity analysis provides reliable estimations for the results for further investigations.

Finally, the assumptions that were considered during the performance of the analysis, should be taken into account in order to use the results in the decision making process.

10 Recommendations for future studies

During the performance of the analyses several aspects were observed which need to be further investigated. An interesting investigation could be to include the designing and production phase in the analyses. Designing phase will be interesting to investigate since the FRP is a new construction material and therefore the knowledge about the designing of a FRP pedestrian bridge is limited compared to the steel and timber. This phase will not affect the LCA analysis but will probably have a great impact in the LCC analysis. Production phase will affect both LCA and LCC analyses by including the energy consumption and the production costs relatively.

Another interesting subject for further examination is the impacts from transportation. As it was mentioned before, the distances between the different areas is assumed to be the same in all the alternatives. By including the actual distances, the variation based on the bridge location will be considered in the results.

It is important to mention that the results from LCC and LCA analyses would be different for different types of bridges or different dimensions. It would be interesting to obtain the environmental and financial effects from bridges made of the same material but with different construction type or with different dimensions than in this thesis.

11 References

Ahonen, T. & Jurigova, M., 2012. Slab Bridges.

Andreas, K., 2013. *Pedestrian Bridges*,

Australian Government: DSEWPaC, 2011. Construction and Demolition Waste Guide - Recycling and Re-Use Across the Supply Chain.

B.S, D., 1989. *Life Cycle Costing: Techniques, Models and Applications*, Ontario: Routledge. Available at: http://books.google.se/books?id=eP4Sq3KUBkYC&lpg=PA29&hl=sv&pg=PA29#v=onepage&q&f=false.

Barklund, Å., 2009. The Swedish Forestry Model. , pp.1–16.

BaTMan, 2015a. Bro över kraftverkstub intill väg 247 V Enbacken på GC-väg. *BaTMan*, 1(1), pp.1–12.

BaTMan, 2015b. GC bro över Bjurån Sammanställning - Konstruktion. *BaTMan*, 1(1), pp.1–10.

Baumann, H. & Tillman, A.-M., 2004. *The Hitch Hiker's Guide to LCA*,

von Bechtolsheim, S.P. & von Bechtolsheim, S.P., 1989. The software package. *TUGboat*, 10(March), pp.25–27.

Beek, V. & Ages, M., 2008. Design of arch bridges.

Bergkvist, P. & Fröbel, J., 2013. Att välja trä.

Béton, fib F. internationale du, 2005. *Guidelines for the desing of footbridges*, International Federation for Structural Concrete.

Billington P., D., 2015. Bridge Engineering. Available at: http://global.britannica.com/technology/bridge-engineering/Live-load-and-dead-load#toc72040 [Accessed May 20, 2015].

Bridge, A., 2009. Fi Ve Bridge Types Fi Ve Bridge Types.

CEN, 1990. S TA N DA R D S Hitta rätt produkt och ett leveranssätt som passar dig Find the right product and the type of delivery that suits you. *Euro code SS-EN-1990*.

Clarke, J.L., 1996. *Structural Design of Polymer Composites*,

Crocetti, R. et al., 2011. *Design of timber structures*,

DG TREN, D.-G. for E. and T., 1994. *Transport and the Environment*,

Engdahl, K. & Rousstia, K.D., 2012. Upgrading of an old steel bridge using FRP composite deck.

Friberg, E., 2014. Application of fibre reinforced polymer materials in road bridges – General requirements and design considerations.

Fukuyama, H., 1999. *FRP Composites in Japan*,

Funch, L.W., 2002. Determination of emissions from solid wood elements. *Wood Technology*, (May).

García, S.M.L., 2011. *Life Cycle Assessment of Railway Bridges- Developing a LCA tool for evaluating Railway Bridges*,

Guangli, D., 2012. Towards Sustainable Construction : Life Cycle Assessment of Railway.

Hammervold, J., Reenaas, M. & Brattebø, H., 2013. Environmental Life Cycle Assessment of Bridges. *Bridge Engineering*, 18(x), pp.153–161.

Hammervold, J., Reenaas, M. & Brattebø, H., 2009. *ETSI PROJECT (Stage 2) Bridge Life Cycle Optimisation. Environmental effects - Life Cycle Assessment of Bridges*,

Hammond, G.P. & Jones, C.I., 2008. Embodied energy and carbon in construction materials. , 161, pp.87–98. Available at: http://dx.doi.org/10.1680/ener.2008.161.2.87.

Heijungs, R. & Guinee B., J., 2015. Curran, Mary Ann. Life Cycle Assessment Handbook : A Guide for Environmentally Sustainable Products. Somerset, NJ, USA: John Wiley & Sons, 2012. ProQuest ebrary. Web. 21 January 2015. Copyright © 2012. John Wiley & Sons. All rights reserved. , (January).

Hussein, S. & Shaswar, H., 2011. Jämförelse mellan en träbro och en betongbro. , (November).

Jin, F., Feng, P. & Ye, L., 2010. Study on Dynamic Characteristics of Light-Weight FRP Footbridge. , pp.27–30.

Juvani, J., 2012. Cable Stayed Bridge. , pp.0–22.

Kaw, A.K., 1997. *Mechanics of composite materials*,

Kramer, G., 2004. *Slab, beam & girder bridges in Oregon*,

Langdon, D., 2007. Life Cycle Costing (LCC) as a contribution to sustainable construction: a common methodology. *Final Report*, (May). Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Life+cycle+costing+(+LCC+)+as+a+contribution+to+sustainable+construction+:+a+common+methodology#0\nhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Life+Cycle+Costing+(+LCC+)+as+a+.

Lippiatt, B.C., 2015. Evaluating Sustainability Using Standard Approaches : , 5(1), pp.1–11.

Mara, V., 2014. Fibre reinforced polymer bridge decks : Sustainability and a novel panel-level connection. Available at: http://publications.lib.chalmers.se/records/fulltext/193310/193310.pdf.

Mara, V., Haghani, R. & Harryson, P., 2014. Bridge decks of fibre reinforced polymer (FRP): A sustainable solution. *Construction and Building Materials*, 50, pp.190–199. Available at: http://dx.doi.org/10.1016/j.conbuildmat.2013.09.036.

Mohammed, S., 2013. *Life-Cycle Costing*.

Murphy, N., 2013. *Feasibility Analysis of a Fiber Reinforced Polymer Bridge*. KTH Royal Institute of Technology.

Myerscough, M. & Hons, M., 2013. Suspension Bridges : past and present.

Nilsson, D.A.N., 2011. Design of short-span bridges with regard to life cycle costs.

Ochsendorf, J. et al., 2011. Methods, Impacts, and Opportunities in the Concrete Building Life Cycle. *Research Report R11-01, Concrete and Sustainability Hub, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology*, (August), p.119. Available at: http://www.greenconcrete.info/downloads/MITBuildingsLCAreport.pdf.

Pagliarin, M., 2012. *Barrier system for stress-laminated road bridge timber decks*.

Poneta, P., 2011. New Industrialised Construction Process for transport infrastructures based on polymer composite components. In *ECTP-EZBA-Eracobuild Conference*. Warsaw, Poland, pp. 1–20.

Russell, a., Ekvall, T. & Baumann, H., 2005. Life cycle assessment - Introduction and overview. *Journal of Cleaner Production*, 13, pp.1207–1210.

SAIC, 2006. Life Cycle Assessment: Principles and Practice. *Vasa*, (May), p.88. Available at: http://medcontent.metapress.com/index/A65RM03P4874243N.pdf.

Salokangas, L., 2013. *ETSI Project. Bridge Life Cycle Optimisation. Stage 3*,

Smith, V.H., Joye, S.B. & Howarth, R.W., 2006. Eutrophication of freshwater and marine ecosystems. *Limnol. Oceanogr.*, 51(1, part 2), pp.351–355.

Stirling, S., 1993. The steel.

Storck, L. & Sagemo, A., 2013. Comparative study of bridge concepts based on life-cycle cost analysis and life- cycle assessment.

Uddin, N., 2013. *Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering, 1st Edition*,

Vasani, P.P.C. & Bhumika, B.M., 2003. *Different Types of Bridges and Its Suitability*,

Worldsteel, 2011. *Methodology report. Life cycle inventory study for steel products*, Available at:

http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:methodology+report+Life+cycle+inventory+study+for+steel+products#6.

Yang, J. & Kalabuchova, L., 2014. *Application of FRP materials in Culvert Road Bridges*.

Zimoch, E., 2012. Life-cycle assessment (LCA) of existing bridges and other structures.

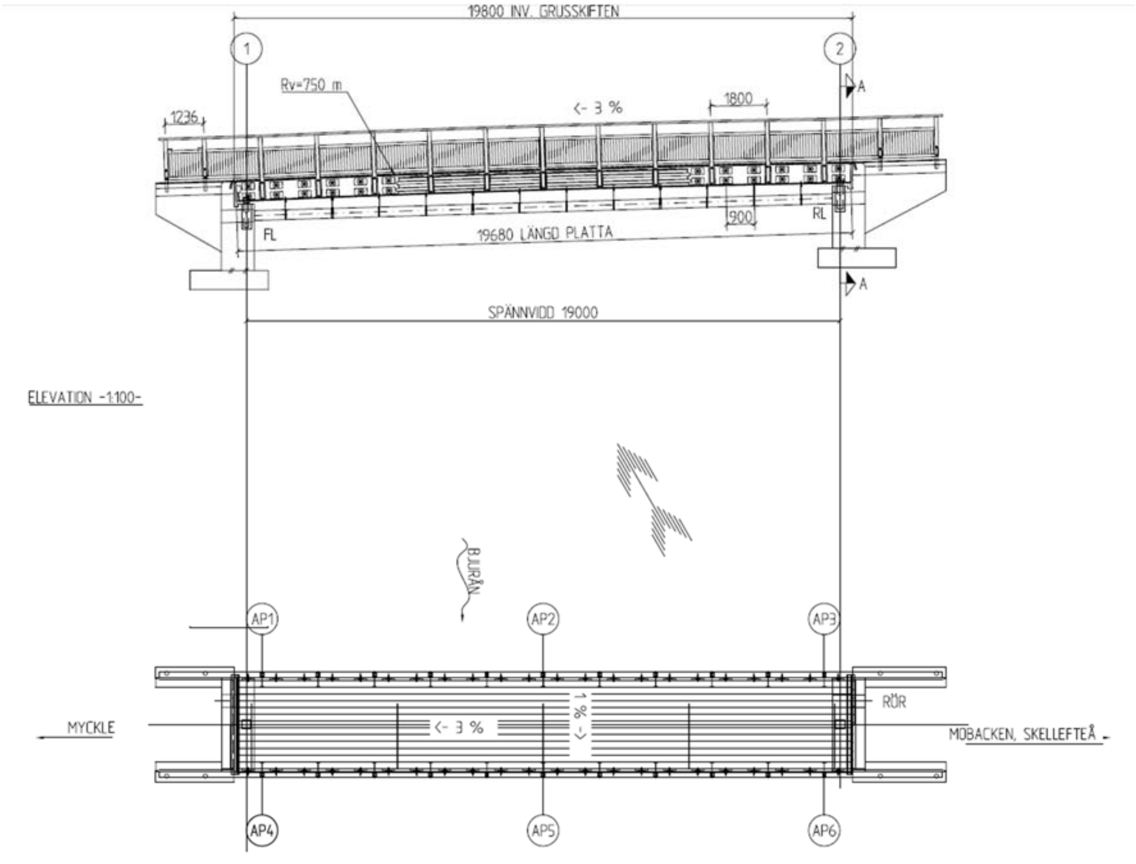
Appendix A – Drawing of timber and steel bridge
Appendix B – Design of the FRP bridge
Appendix C – LCA analyses
Appendix D – LCC analyses
Appendix E – Material amount of bridges

APPENDIX A

Drawing of timber and steel bridge

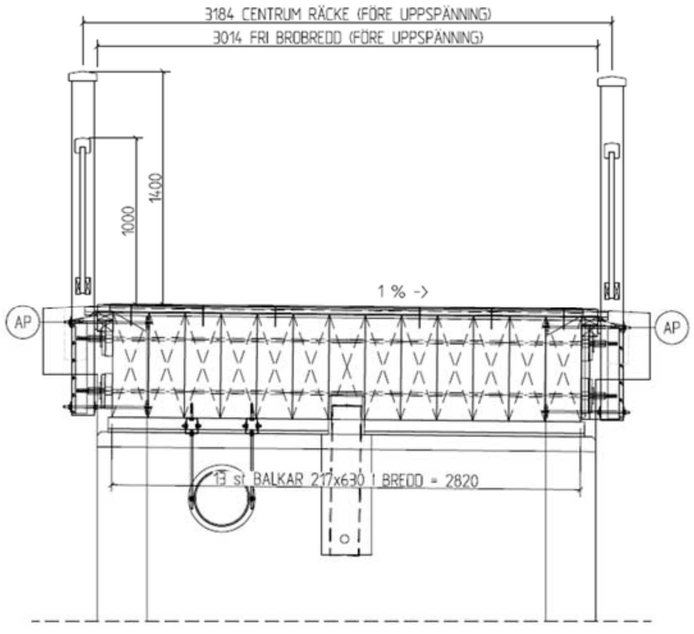
- Timber bridge - Bridge over Bjurån
- Steel bridge - Bridge over Kraftverkstub

Appendix A – Drawing of timber bridge



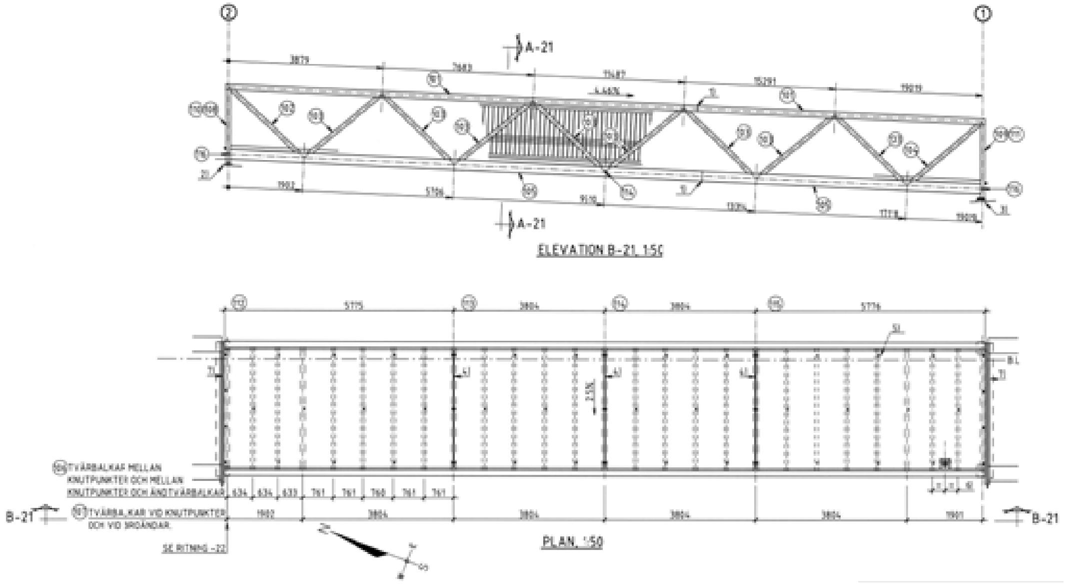
ELEVATION -1:100-

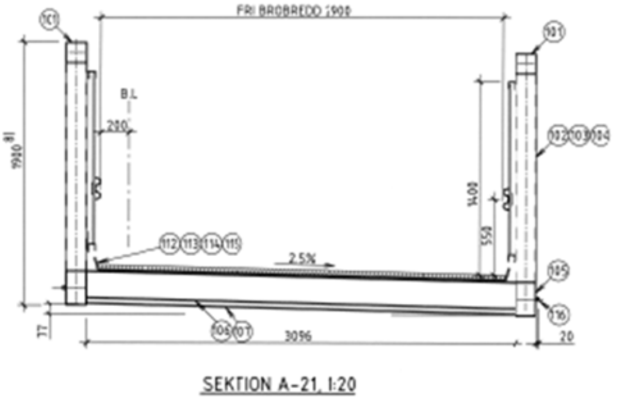
PLAN -1:100-



SEKTION A-A -1:20-

Appendix A – Drawings of steel bridge





APPENDIX B

Design of the FRP bridge

FRP bridge preliminary design
Bridge 5-136-1
Hand Calculation for optimize cross-section
GFRP design

The bridge consists of a FRP deck with an asphalt wearing surface layer. The deck is supported on two GFRP girders. The bridge has lanes and a span of 19m.

Cross-section of FRP Girders

The open shape of the GFRP girders is retrieved from the "Trans-Ind catalogue"

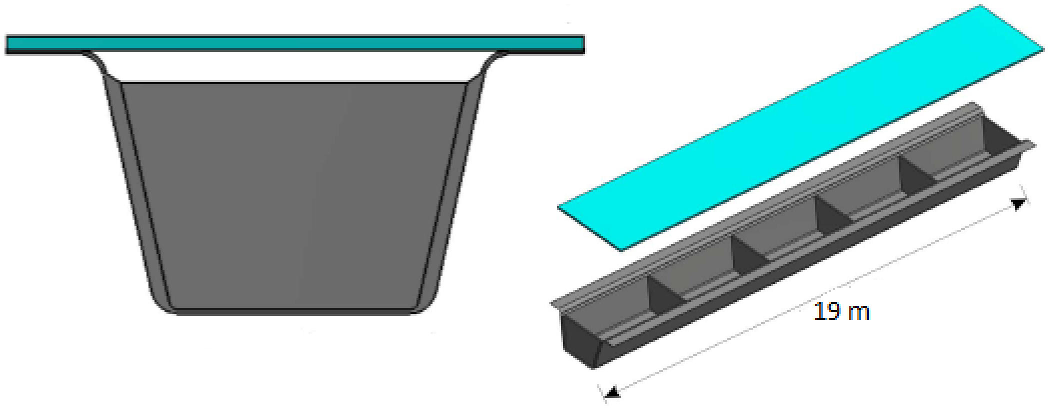


Figure 1. Cross section of the FRP girder

Material parameters:

Both the top flange and the open shape beam of the GFRP bridge girder consists of glass fibre reinforced polymer and the cables from carbon fibres. The polymer of the FRP composite is furthermore epoxy.

$E_{GFRP.girder.0} := 25GPa$	Modulus of elasticity unidirectional fibres with load acting transversally (Applied in span where moment is high)
$E_{GFRP.top.plate.0} := 25GPa$	Modulus of elasticity for unidirectional fibres with load acting transversally (Applied in span where moment is high)
$E_{GFRP.90} := 15GPa$	Modulus of elasticity for bidirectional fibres with load acting transversally (Applied in span where moment is high)
$E_{asset.0} := 23GPa$	Modulus of elasticity for ASSET deck in longitudinal direction
$E_{asset.90} := 18GPa$	Modulus of elasticity for ASSET deck in the transversal direction

$G_{xy} := 4.14\text{GPa}$ Shear modulus of GFRP

$\nu_{23} := 0.237$ Poission ratio of GFRP

Geometry of the bridge:

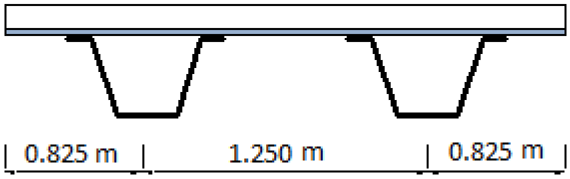


Figure 2. Cross-section of the bridge - position of the girders

Dimensions:

$L_{span} := 19m$ Length of bridge

$w_{deck} := 2.9m$ Width of bridge

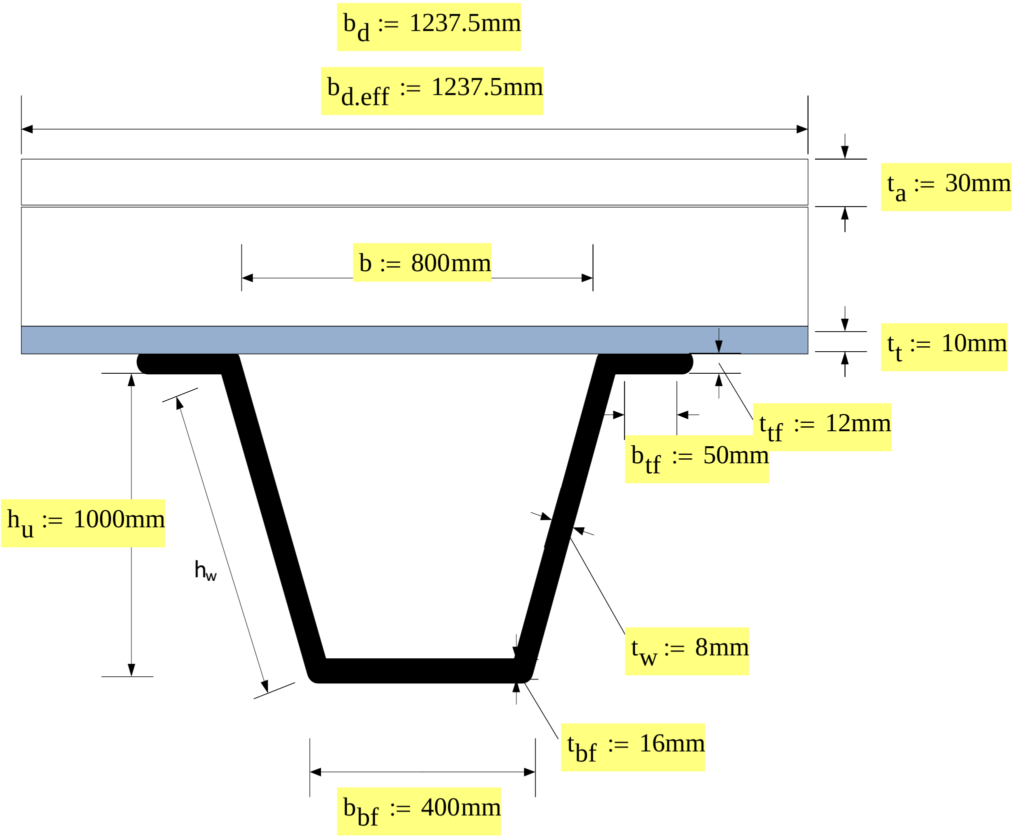


Figure 3. Dimensions of the girder, top plate and ASSET deck

GFRP Girders:

$$\alpha_h := \operatorname{atan}\left(\frac{\frac{b-250\mathrm{mm}}{2}}{h_u}\right) = 15.376\cdot\mathrm{deg}$$

The inclination of the "webs" of the U-shaped beam

$$h_w := \frac{h_u}{\cos(\alpha_h)} = 1.037\,\mathrm{m}$$

Height of the "webs"

ASSET Deck:

$t_{deck} := 0.225\mathrm{m}$

Thickness of the ASSET deck

$t_{f.asset} := 15.5\mathrm{mm}$

Thickness of the flanges of the ASSET deck, can be seen in Figure 4.

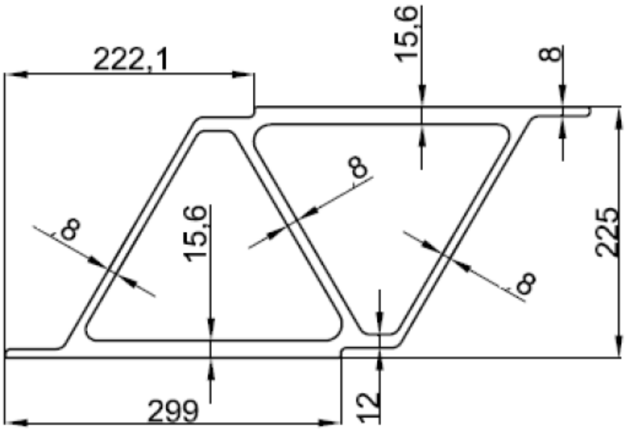


Figure 4. Cross-section of the ASSET deck

Concrete Asphalt Wearing Surface:

$t_{asphalt} := 30\mathrm{mm}$

Thickness of the asphalt layer

$E_{asphalt} := 5\mathrm{GPa}$

Modulus of elasticity of the wearing surface

Total thickness of the cross section of the bridge:

$t_{tot} := t_a + t_{deck} + t_t + t_{tf} + h_u = 1.277\,\mathrm{m}$

Calculation of second moment of area of the FRP girders

Area of the open shaped U beam:

$A_{asphalt} := b_{d.eff} \cdot t_{asphalt} = 0.037\,m^2$

Area of the asphalt layer

$A_{deck.plate} := b_{d.eff} \cdot t_{f.asset} = 0.019\,m^2$

Areas of the flanges fo the ASSET deck

$A_{top.plate} := b_{d.eff} \cdot t_t = 0.012\,m^2$

Area of the GFRP top plate

$A_{beam} := 2 \cdot h_w \cdot t_w + b_{bf} \cdot t_{bf} + 2 \cdot t_{tf} \cdot b_{tf} = 2.419 \times 10^4 \cdot mm^2$

Total area of the one GFRP girder

$A_{tot} := 2 \cdot A_{deck.plate} + A_{top.plate} + A_{beam} + A_{asphalt} = 0.112\,m^2$

Total area of the cross section seen in Figure 3.

$EA_{asphalt} := E_{asphalt} \cdot A_{asphalt}$

$EA_{deck} := E_{asset.90} \cdot A_{deck.plate}$

$EA_{top.plate} := E_{GFRP.top.plate.0} \cdot A_{top.plate}$

$EA_{beam} := E_{GFRP.girder.0} \cdot A_{beam}$

$EA_{tot} := EA_{asphalt} + 2EA_{deck} + EA_{top.plate} + EA_{beam}$

Distance to the center of gravity:

$$z_{tp} := \frac{\begin{aligned} & E_{asphalt} \cdot b_{d.eff} \cdot t_{asphalt} \cdot \frac{t_{asphalt}}{2} + E_{asset.90} \cdot b_{d.eff} \cdot t_{f.asset} \cdot \left(t_{asphalt} + \frac{t_{f.asset}}{2} \right) \dots \\ & + E_{asset.90} \cdot b_{d.eff} \cdot t_{f.asset} \cdot \left(t_{asphalt} + t_{deck} - \frac{t_{f.asset}}{2} \right) \dots \\ & + E_{GFRP.top.plate.0} \cdot t_t \cdot b_{d.eff} \cdot \left(t_{asphalt} + t_{deck} + \frac{t_t}{2} \right) \dots \\ & + E_{GFRP.girder.0} \cdot 2 \cdot b_{tf} \cdot t_{tf} \cdot \left(t_{asphalt} + t_{deck} + t_t + \frac{t_{tf}}{2} \right) \dots \\ & + E_{GFRP.girder.0} \cdot 2 \cdot h_w \cdot t_w \cdot \left(t_{asphalt} + t_{deck} + t_t + t_{tf} + \frac{h_u - t_{bf}}{2} \right) \dots \\ & + E_{GFRP.girder.0} \cdot b_{bf} \cdot t_{bf} \cdot \left(t_{tot} - \frac{t_{bf}}{2} \right) \end{aligned}}{EA_{tot}} = 0.398\,m$$

$n_{asphalt.deck} := \frac{E_{asphalt}}{E_{asset.90}} = 0.278$

$n_{deck.plate} := \frac{E_{asset.90}}{E_{GFRP.top.plate.0}} = 0.72$

$$n_{plate.girder} := \frac{E_{GFRP.top.plate.0}}{E_{GFRP.girder.0}} = 1$$

Moment of Inertia:

Level arms:

$$d_1 := \frac{t_{asphalt}}{2} = 0.015\,m \qquad d_5 := t_{asphalt} + t_{deck} + t_t + \frac{t_{tf}}{2} = 0.271\,m$$

$$d_2 := t_{asphalt} + \frac{t_{f.asset}}{2} = 0.038\,m \qquad d_6 := t_{asphalt} + t_{deck} + t_t + t_{tf} + \frac{h_u - t_{bf}}{2} = 0.769\,m$$

$$d_3 := t_{asphalt} + t_{deck} - \frac{t_{f.asset}}{2} = 0.247\,m \qquad d_7 := t_{tot} - \frac{t_{bf}}{2} = 1.269\,m$$

$$d_4 := t_{asphalt} + t_{deck} + \frac{t_t}{2} = 0.26\,m$$

$$\begin{aligned} I_y := {} & \frac{n_{asphalt.deck} \cdot b_{d.eff} \cdot t_{asphalt}^{3}}{12} + n_{asphalt.deck} \cdot b_{d.eff} \cdot t_{asphalt} \cdot \left(z_{tp} - d_1\right)^2 \ldots = 1.233 \times 10^{10} \cdot mm^4 \\ & + \frac{n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset}^{3}}{12} + n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset} \cdot \left(z_{tp} - d_2\right)^2 \ldots \\ & + \frac{n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset}^{3}}{12} + n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset} \cdot \left(z_{tp} - d_3\right)^2 \ldots \\ & + \frac{n_{deck.plate} \cdot b_{d.eff} \cdot t_t^{3}}{12} + n_{deck.plate} \cdot b_{d.eff} \cdot t_t \cdot \left(z_{tp} - d_4\right)^2 \ldots \\ & + 2 \cdot \left[\frac{b_{tf} \cdot t_{tf}^{3}}{12} + b_{tf} \cdot t_{tf} \cdot \left(z_{tp} - d_5\right)^2\right] \ldots \\ & + 2 \cdot \left[\frac{t_w \cdot h_w}{12} \cdot \left(h_w^{2} \cdot \cos\left(\alpha_h\right)^2 + t_{bf}^{2} \cdot \sin\left(\alpha_h\right)^2\right) + t_w \cdot h_w \cdot \left(d_6 - z_{tp}\right)^2\right] \ldots \\ & + \frac{b_{bf} \cdot t_{bf}^{3}}{12} + b_{bf} \cdot t_{bf} \cdot \left(d_7 - z_{tp}\right)^2 \end{aligned}$$

Section modulus's for the four different locations of the beam to be investigated:

$$W_1 := \frac{I_y}{z_{tp} - t_{asphalt}} = 0.034 \cdot m^3$$

Top of the deck

$$W_2 := \frac{I_y}{z_{tp} - t_{asphalt} - t_{deck} - \frac{t_t}{2}} = 0.09 \cdot m^3$$

In the middle of the deck top flange

$$W_3 := \frac{I_y}{z_{tp} - t_{asphalt} - t_{deck} - t_t} = 0.093 \cdot m^3$$

Top of the U girder

$$W_4 := \frac{I_y}{t_{tot} - z_{tp}} = 0.014 \cdot m^3$$

Bottom flange of the U girder

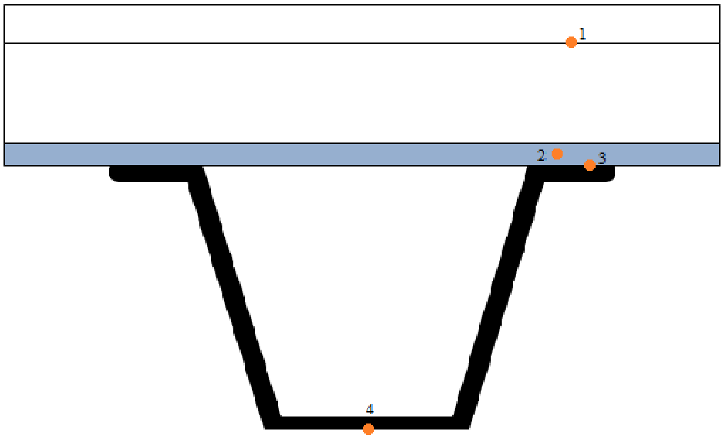


Figure 5. Four different location of the beam

Applied Loads

Input data:

$c_w := 1.3m$ Distance between the wheels

Self-Weight

FRP Deck:

The FRP deck consists of a ASSET deck manufactured by Fiberline Composites in Denmark

$$g_{FRP} := 925 \frac{N}{m^2}$$

The weight of the ASSET bridge deck (Fiberline)

$$\rho_{Asphalt} := 2.097 \cdot 10^3 \frac{kg}{m^3}$$

The design self-weight of the FRP deck for one girder:

$$G_{deck} := b_d \cdot g_{FRP} = 1.145 \cdot \frac{kN}{m}$$

Asphalt Layer - Wearing surface:

$$\gamma_{as} := 26.4 \frac{kN}{m^3} \qquad \rho_{ASSET} := 267 \frac{kg}{m^3}$$

$$G_{asphalt} := b_d \cdot t_{asphalt} \cdot \gamma_{as} = 0.98 \cdot \frac{kN}{m}$$

FRP Girders:

The self-weight of each girder (including the top plate):

$$\rho_{GFRP} := 1800 \frac{kg}{m^3}$$

The density of FRP composites generally lie in the range of 1200 to 1800 kg/m^3

$$G_{girder} := \rho_{GFRP} \cdot g \cdot \left(A_{beam} + A_{top.plate}\right) = 0.646 \cdot \frac{kN}{m}$$

Total self-weight of the FRP bridge structure:

The total self-weight per girder:

$$G_{k.girder} := G_{deck} + G_{girder} + G_{asphalt} = 2.77 \cdot \frac{kN}{m}$$

loads

$$Q_{sv1} := 40kN$$

$$Q_{sv2} := 20kN$$

Crowded load

$$q_{fk.tot} := 2\cdot\frac{kN}{m^2} + \frac{120kN}{\left(L_{span} + 30m\right)m} = 4.449\cdot\frac{kN}{m^2}$$

$$2.5\frac{kN}{m^2} \le q_{fk.tot} \le 5\frac{kN}{m^2}$$ Requirements

$$q_{fk} := q_{fk.tot}\cdot b_d = 5.506\cdot\frac{kN}{m}$$ The total crowded load per girder

Horizontal load

$$Qflk_{unifor} := 0.1\cdot q_{fk}\cdot L_{span} = 10.461\cdot kN$$

$$Qflk_{point} := 0.6\left(Q_{sv1} + Q_{sv2}\right) = 36\cdot kN$$

Wind load

$$q_{bridge} := 1.8\frac{kN}{m^2}$$

$$h_r := 2m$$ Height of railings

$$q_w := q_{bridge}\cdot h_r\cdot L_{span} = 68.4\cdot kN$$

Load combination

$$\gamma_d := 1.0$$ Safety factor

$$\psi_0 := 0.3$$

$$\psi_1 := 0.4$$

Ultimate unite state

Vertical loads

$$q_{d.selfweigth.uls} := \gamma_d\cdot 0.89\cdot 1.35\cdot G_{k.girder} = 3.329\cdot\frac{kN}{m}$$

$$q_{d.crowded.uls} := \gamma_d\cdot 1.5\cdot q_{fk} = 8.258\cdot\frac{kN}{m}$$

$$q_{d.vehicle.uls} := \gamma_d\cdot 1.5\cdot Q_{sv1} = 60\cdot kN$$

$$q_{d.vehicle.uls2} := \gamma_d \cdot 1.5 \cdot Q_{sv2} = 30 \cdot kN$$

Horizontal load

$$q_{d.wind.main.uls} := \gamma_d \cdot 1.5 \cdot q_w = 102.6 \cdot kN$$

$$q_{d.wind.second.uls} := \gamma_d \cdot 1.5 \cdot q_w \cdot \psi_0 = 30.78 \cdot kN$$

$$q_{d.vehicle.uls.horizontal.main} := \gamma_d \cdot 1.5 Qflk_{point} = 54 \cdot kN$$

$$q_{d.vehicle.uls.horizontal.second} := \gamma_d \cdot 1.5 \cdot \psi_0 \cdot Qflk_{point} = 16.2 \cdot kN$$

Service limit state

$$q_{d.selfweigth.sls} := 1.0 \cdot G_{k.girder} = 2.77 \cdot \frac{kN}{m}$$

$$q_{d.crowded.sls.main} := 1.0 \cdot q_{fk} = 5.506 \cdot \frac{kN}{m}$$

$$q_{d.crowded.sls.second} := 1.0 \cdot \psi_1 \cdot q_{fk} = 2.202 \cdot \frac{kN}{m}$$

$$q_{d.vehicle1.sls} := 1.0 \cdot Q_{sv1} = 40 \cdot kN$$

$$q_{d.vehicle2.sls} := 1.0 \cdot Q_{sv2} = 20 \cdot kN$$

Maximum moment & shear considering uniformly distrubuted load

$$M_{d.uniform} := \frac{\left(q_{d.selfweigth.uls} + q_{d.crowded.uls}\right) \cdot L_{span}^2}{8} = 522.86 \cdot kN \cdot m$$

$$V_{d.uniform} := \frac{\left(q_{d.selfweigth.uls} + q_{d.crowded.uls}\right) \cdot L_{span}}{} = 110.076 \cdot kN$$

1st case - Middle

$$R_{A1} := \frac{1}{L_{span}} \cdot \left(\frac{q_{d.selfweigth.uls} \cdot L_{span}^2}{2} + q_{d.vehicle.uls} \cdot 9.5m + q_{d.vehicle.uls2} \cdot 6.5m \right) = 71.884 \cdot kN$$

$$R_{B1} := q_{d.vehicle.uls} + q_{d.vehicle.uls2} + q_{d.selfweigth.uls} \cdot L_{span} - R_{A1} = 81.358 \cdot kN$$

$$M_{d.vehicle} := R_{A1} \cdot 9.5m - q_{d.selfweigth.uls} \cdot 9.5m \cdot \frac{9.5m}{2} = 532.699 \cdot kN \cdot m$$

2nd case - Edge

$$R_{A2} := \frac{1}{L_{span}} \cdot \left(\frac{q_{d.selfweigth.uls} \cdot L_{span}^{2}}{2} + q_{d.vehicle.uls} \cdot L_{span} + q_{d.vehicle.uls2} \cdot 16m \right) = 116.884 \cdot kN$$

$$R_{B2} := q_{d.vehicle.uls} + q_{d.vehicle.uls2} + q_{d.selfweigth.uls} \cdot L_{span} - R_{A2} = 36.358 \cdot kN$$

$$V_{d.vehicle} := \max\left(R_{A2}, R_{B2}\right) = 116.884 \cdot kN$$

$$M_{d.max} := \max\left(M_{d.uniform}, M_{d.vehicle}\right) = 532.699 \cdot kN \cdot m$$

$$V_{d.max} := \max\left(V_{d.uniform}, V_{d.vehicle}\right) = 116.884 \cdot kN$$

Shear force due to wind and axial load

$$F_{t1.d} := q_{d.vehicle.uls.horizontal.main} + q_{d.wind.second.uls} = 84.78 \cdot kN$$

Capacity checks

Partial safety factors for material

Partial safety factors ULS:

$\gamma_{m1} := 1.15$	Derived from material properties from test values
$\gamma_{m2} := 1.2$	Material and production process - Resin Transfer Moulding and fully post cured
$\gamma_{m3} := 2.5$	Long-term loading (traffic load)

$$\gamma_{m.uls} := \gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} = 3.45$$

Partial safety factors SLS:

$\gamma_{m1.sls} := 1.15$	Derived from material properties from test values
$\gamma_{m2.sls} := 1.2$	Material and production process - Resin Transfer Moulding and fully post cured
$\gamma_{m3.sls} := 1$	Short-term loading (traffic load)

$\gamma_{m.sls} := \gamma_{m1.sls} \cdot \gamma_{m2.sls} \cdot \gamma_{m3.sls} = 1.38$

ULS checks:

Bending stresses

$M_{Sd} \leq M_{Rd}$ where $M_{Rd} := \dfrac{W_s \cdot \sigma_{t.k}}{\gamma_m}$ From the book "Structural Design of Polymer Composites" (Clarke 1996)

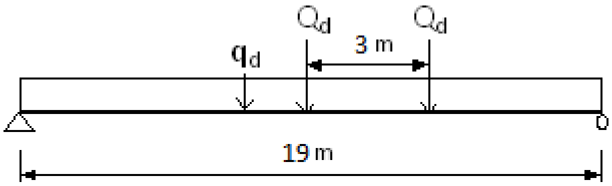


Figure 11. Load condition for ULS bending

The bending stresses are analysed in four different locations of the cross-section, seen in Figure 5.

The design strength of GFRP composite are retrieved from the book "analysis and performance of fiber composites", and are as follows:

<u>Longitudinal direction of the fibres:</u>

$\sigma_{b.ks} := 1062\text{MPa}$ $\sigma_{b.d} := \dfrac{\sigma_{b.ks}}{\gamma_{m.uls}} = 307.826 \cdot \text{MPa}$ Design tensile strength

$\sigma_{c.ks} := 610\text{MPa}$ $\sigma_{c.d} := \dfrac{\sigma_{c.ks}}{\gamma_{m.uls}} = 176.812 \cdot \text{MPa}$ Design compressive strength

<u>Transversal direction of the fibres:</u>

$\sigma_{t.k.t} := 118\text{MPa}$ $\sigma_{t.d.t} := \dfrac{\sigma_{t.k.t}}{\gamma_{m.uls}} = 34.203 \cdot \text{MPa}$ Design tensile strength

$\sigma_{c.k.t} := 31\text{MPa}$ $\sigma_{c.d.t} := \dfrac{\sigma_{c.k.t}}{\gamma_{m.uls}} = 8.986 \cdot \text{MPa}$ Design compressive strength

Design stresses in the four different locations:

$$\sigma_1 := \frac{n_{deck.plate} \cdot M_{d.max}}{W_1} + \frac{F_{t1.d}}{A_{tot}} = 12.19 \cdot MPa$$

$$\sigma_2 := \frac{M_{d.max}}{W_2} + \frac{F_{t1.d}}{A_{tot}} = 6.7 \cdot MPa$$

$$\sigma_3 := \frac{M_{d.max}}{W_3} + \frac{F_{t1.d}}{A_{tot}} = 6.484 \cdot MPa$$

$$\sigma_4 := \frac{M_{d.max}}{W_4} + \frac{F_{t1.d}}{A_{tot}} = 38.747 \cdot MPa$$

Check:

$$check_1 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_1}{\sigma_{b.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

$$check_2 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_2}{\sigma_{c.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

$$check_3 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_3}{\sigma_{b.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

$$check_4 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_4}{\sigma_{b.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

Utilization ratio bending stresses:

$$UR_1 := \frac{\sigma_1}{\sigma_{b.d}} = 0.04 \qquad UR_2 := \frac{\sigma_2}{\sigma_{c.d}} = 0.038 \qquad UR_3 := \frac{\sigma_3}{\sigma_{b.d}} = 0.021 \qquad UR_4 := \frac{\sigma_4}{\sigma_{b.d}} = 0.126$$

Shear

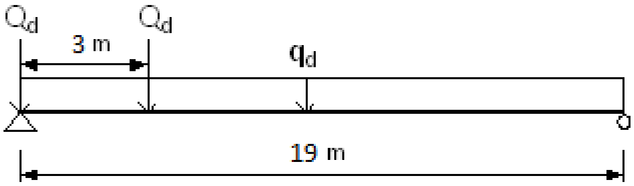


Figure 12. Load condition for ULS shear

$A_{web} := 2t_w \cdot h_w = 1.659 \times 10^4 \cdot mm^2$ Area of the webs

$\tau_{shear} := \dfrac{V_{d.max}}{A_{web}} = 7.044 \cdot MPa$ Shear stress in the webs

$\tau_{xy.k} := 72MPa$ Characteristic shear strength of laminate

$\tau_{xy.d} := \dfrac{\tau_{xy.k}}{\gamma_{m.uls}} = 20.87 \cdot MPa$ Design shear resistance of the section

Utilization shear stress:

$$check_5 := \left| \begin{array}{ll} \text{"OK"} & \text{if } \dfrac{\tau_{shear}}{\tau_{xy.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{array} \right. = \text{"OK"}$$

$$U_{shear} := \frac{\tau_{shear}}{\tau_{xy.d}} = 0.338$$

Utilization between hand calculations and Abaqus:

$\tau_{A.shear} := 11.3MPa$ Shear stress in neutral axis from Abaqus

$U_{conv.shear} := \dfrac{\tau_{shear}}{\tau_{A.shear}} = 0.623$ Same

Bearing capacity of supports:

$S_s := \dfrac{V_{d.max}}{\left(b_{tf} \cdot \sigma_{c.ks}\right)} = 3.832 \cdot mm$ The required width of the support

SLS check:

Deflection

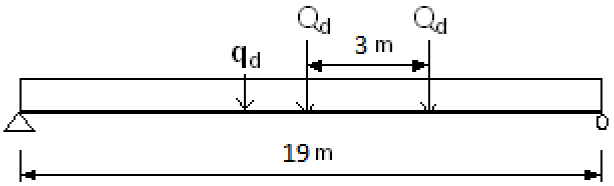
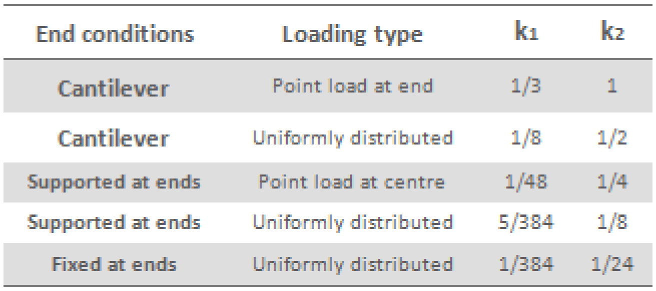


Figure 13.Load condition for SLS

Deflection limit for traffic bridge:

$$\delta_{lim} := \frac{L_{span}}{400} = 47.5 \cdot mm$$



End conditions	Loading type	k₁	k₂
Cantilever	Point load at end	1/3	1
Cantilever	Uniformly distributed	1/8	1/2
Supported at ends	Point load at centre	1/48	1/4
Supported at ends	Uniformly distributed	5/384	1/8
Fixed at ends	Uniformly distributed	1/384	1/24

Table 1. Selection factors k1 (bending) and k2 (shear) according to deflection behaviourof the beam

$$q_{d1.sls} := q_{d.crowded.sls.main} = 5.506 \frac{1}{m} \cdot kN$$

SLS design uniform load

$$Q_{d1.sls} := q_{d.vehicle1.sls} = 40 \cdot kN$$

$$Q_{d2.sls} := q_{d.vehicle2.sls} = 20 \cdot kN$$

SLS design point load

Deflection due to bending:

$$\delta_{bending} := \frac{k_1 \cdot F \cdot L_{span}^{3}}{EI}$$

Equation to calculate deflection from bending (Clarke 1996)

Deflection from uniform load:

$$\delta_{bending.uniform} := \frac{5}{384} \cdot \frac{q_{d1.sls} \cdot L_{span}^{4} \cdot \gamma_{m.sls}}{E_{GFRP.girder.0} \cdot I_y} = 41.821 \cdot mm$$

Deflection from point load:

$$\delta_{1bending.point} := \frac{1}{48} \cdot \frac{Q_{d1.sls} \cdot L_{span}^{3} \cdot \gamma_{m.sls}}{E_{GFRP.girder.0} \cdot I_{y}} = 25.587 \cdot mm$$

Point load in the middle

$$\delta_{2bending.point} := \frac{1}{48} \cdot \frac{Q_{d2.sls} \cdot 6.5m \cdot \left[3 \cdot L_{span}^{2} - 4 \cdot (6.5m)^{2}\right] \cdot \gamma_{m.sls}}{E_{GFRP.girder.0} \cdot I_{y}} = 11.081 \cdot mm$$

$$\delta_{bending.point} := \delta_{1bending.point} + \delta_{2bending.point} = 36.668 \cdot mm$$

Total deflection from bending:

$$\delta_{bending} := \max\left(\delta_{bending.point}, \delta_{bending.uniform}\right) = 41.821 \cdot mm$$

Utilization factor:

$$u_{bending} := \frac{\delta_{bending}}{\delta_{lim}} = 0.88$$

Deflection due to shear:

$$\delta_{shear} := \frac{k_{2} \cdot F_{v} \cdot L_{span}}{A_{v} \cdot G_{xy}}$$

Equation to calculate deflection from shear (Clarke 1996)

$$A_{v} := A_{web} = 0.017\, m^{2}$$

Area of the webs

$$G_{xy} = 4.14 \cdot GPa$$

Shear modulus of the GFRP composite

Deflection from point load:

$$\delta_{1shear.point} := \frac{1}{4} \cdot \frac{\left(Q_{d1.sls} \cdot L_{span}\right)}{A_{v} \cdot G_{xy}} = 2.766 \cdot mm$$

$$\delta_{shear.point} := \delta_{1shear.point} \cdot 2 = 5.531 \cdot mm$$

From 2 point loads

Deflection from uniform load:

$$\delta_{shear.uniform} := \frac{1}{8}\cdot\frac{\left(q_{d1.sls}\cdot L_{span}^{\ 2}\right)}{A_V\cdot G_{xy}} = 3.616\cdot mm$$

Total deflection from shear:

$$\delta_{shear} := \max\left(\delta_{shear.uniform}, \delta_{shear.point}\right) = 5.531\cdot mm$$

Total deflection of the bridge:

$$\delta_{tot} := \delta_{shear} + \delta_{bending} = 47.352\cdot mm$$

$$U_{sls} := \frac{\delta_{tot}}{\delta_{lim}} = 0.997$$

$$check_6 := \left|\begin{array}{l} \text{"OK"} \quad \text{if } \dfrac{\delta_{tot}}{\delta_{lim}} \le 1 \\ \text{"NOT OK"} \quad \text{otherwise} \end{array}\right. = \text{"OK"}$$

Dynamic analysis

$$M_{FRP.girder} := \left[\rho_{GFRP}\cdot\left(A_{beam} + A_{top.plate}\right) + \rho_{Asphalt}\cdot\left(b_d\cdot t_{asphalt}\right) + \rho_{ASSET}\cdot\left(b_d\cdot t_{deck}\right)\right] = 218.0$$

$$f := \frac{\pi}{2L_{span}^{\ 2}}\cdot\sqrt{\frac{E_{GFRP.girder.0}\cdot I_y}{M_{FRP.girder}}} = 5.174\cdot Hz$$

$2.5Hz \le f \le 4.6Hz$ OK

APPENDIX C

LCA analysis

- Emissions from different bridges
- Global warming potential
- Ozone depletion
- Fossil depletion
- Terrestrial acidification
- Freshwater eutrophication

Appendix C – Life Cycle Assessment analysis

Results of the emissions from the three different bridges

Emissions from different bridges	Timber	Steel	FRP
Climate change	1,7040	2,5709	4,32E+00
Ozone depletion	0,0496	0,0405	2,03E-01
Terrestrial acidification	3,0624	2,7995	5,85E+00
Freshwater eutrophication	15,1712	38,5142	3,65E+01
Fossil depletion	4,3867	5,7617	9,80E+00

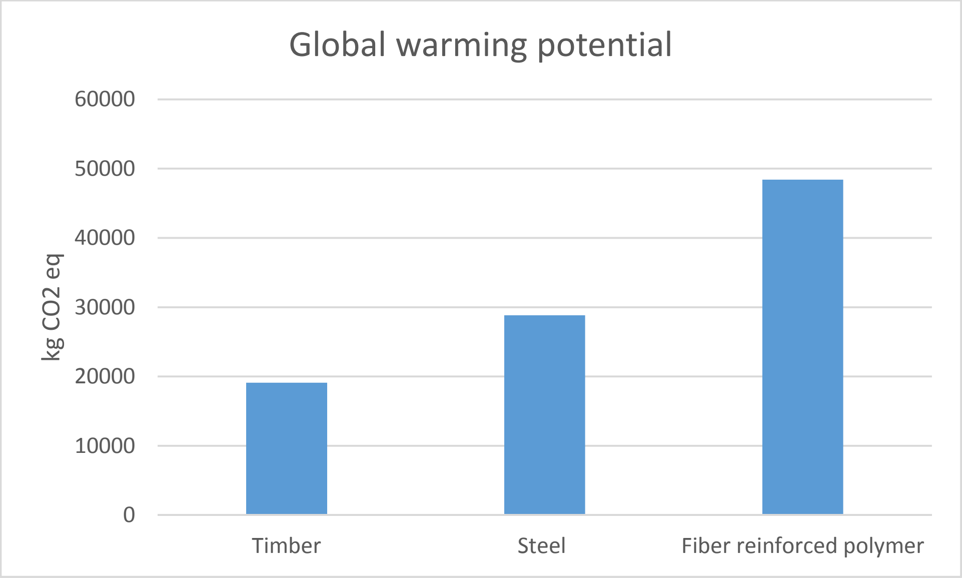
Results of LCA based on the different phases of bridge life cycle

LCA results	Timber	Steel	FRP
Material Production	80,5922	116,0199	239,2025
Operation & maintenance	4,6169	8,3039	2,7023
Transportation	1,0308	0,7128	0,7347

Appendix C – Life Cycle Assessment analysis

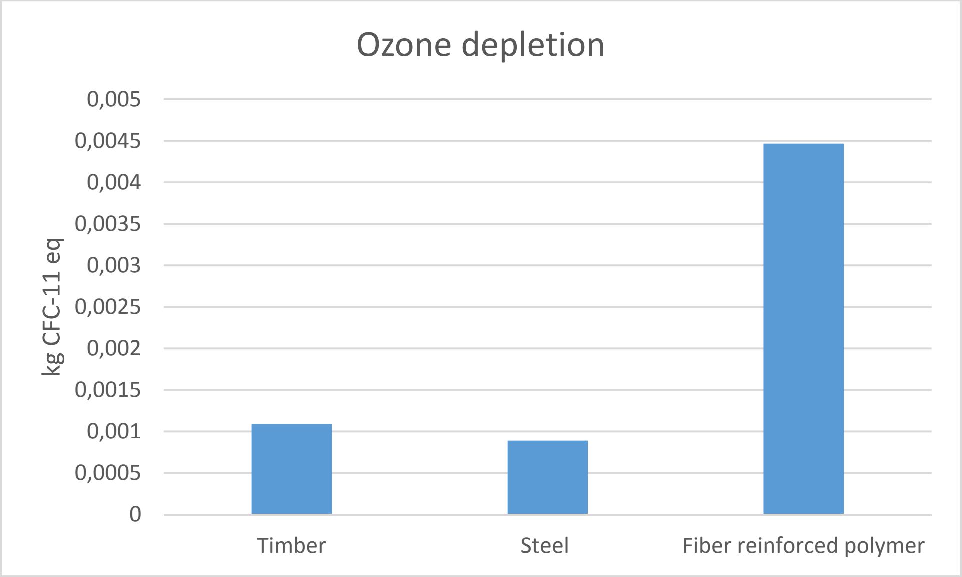
- Global warming potential

Timber	Steel	Fiber reinforced polymer
19110,25	28832,41	48418,92



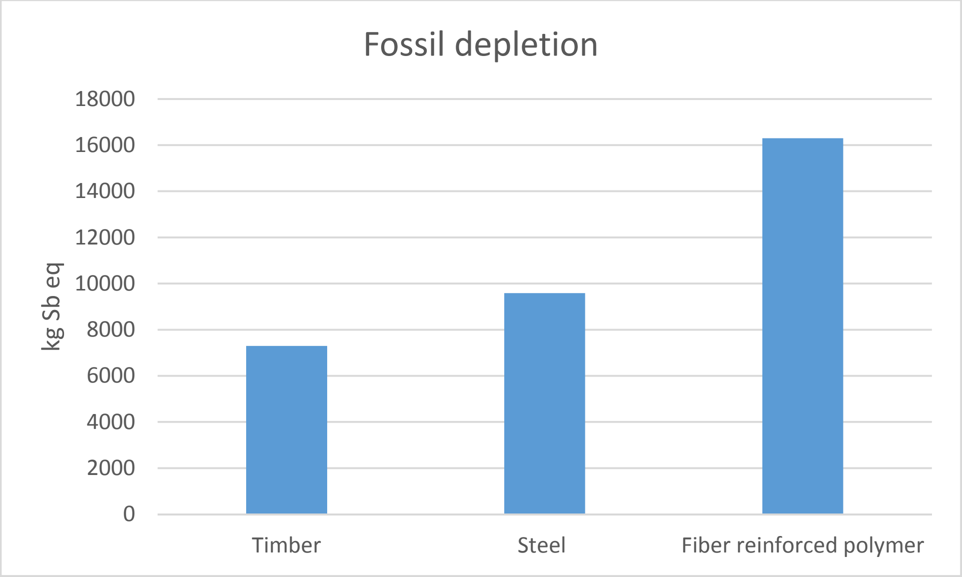
- Ozone depletion

Timber	Steel	Fiber reinforced polymer
0,001091	0,000891	0,004466



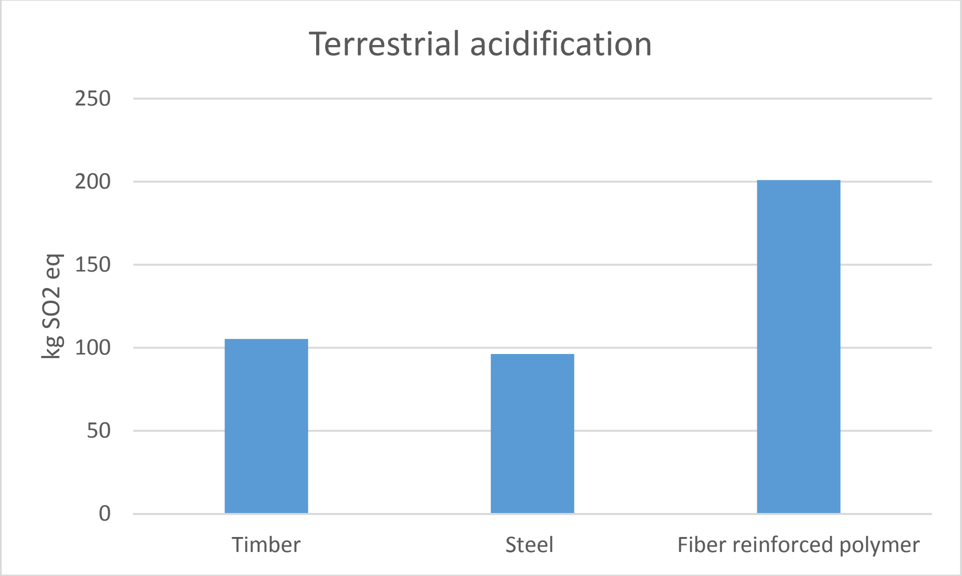
- Fossil depletion

Timber	Steel	Fiber reinforced polymer
7297,88	9585,45	16299,12



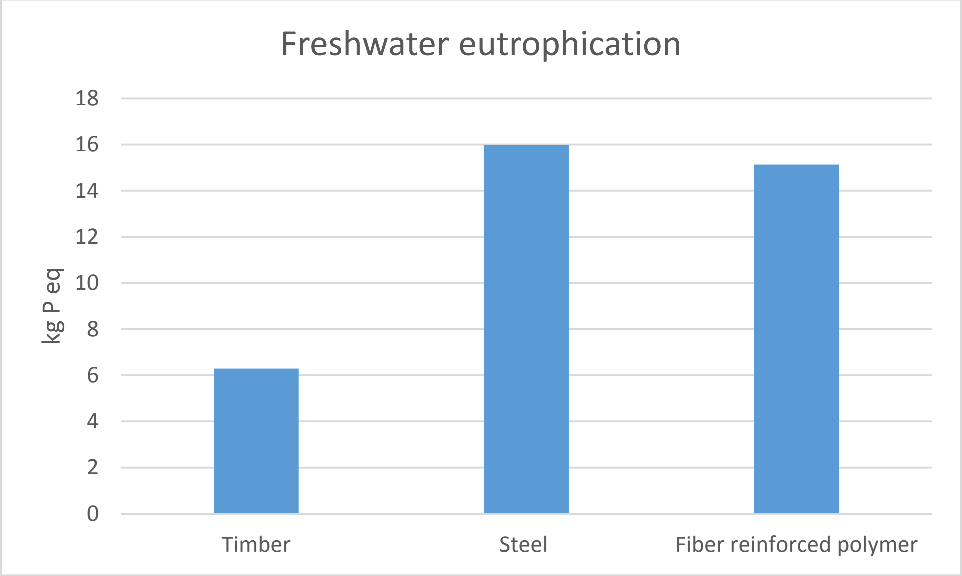
- Terrestrial acidification

Timber	Steel	Fiber reinforced polymer
105,27	96,23	200,93



- Freshwater eutrophication

Timber	Steel	Fiber reinforced polymer
6,29	15,98	15,14



APPENDIX D

LCC analysis

- Timber bridge - Bridge over Bjurån
- Steel bridge - Bridge over Kraftverkstub
- FRP bridge

Appendix D – Life Cycle Cost analysis for timber bridge

General information and input data for timber bridge

Bridge over Bjurån		
	Unit	
Service life	80	years
Discount rate	3,50%	%
Area of railings	69,11	m2
Area of surfacing	60,28	m2
Bridge area	60,28	m2
Bridge length	20	m
Bridge width	3,014	m
Effective bridge width	3,014	m
Span length	19	m

Appendix D – Life Cycle Cost analysis for timber bridge

Initial costs		
	Unit	Cost [SEK/unit]
Base Paint	litre	106,00
Glulam	m3	4312,60[1]
Installation of struts	N°	29,33
Insulation of surfacing	m2	1160,00
Men power	h	500,00
Moisture indicator	N°	2000,00
Paint	litre	100,00
Pressure impregnated	m3	2352,32
Sawn timber	m3	2443,64
Steel rods	N°	1000,00[2]

[1] The costs for timber parts have been calculated based on the prices from Swedish companies without taxes

[2] The cost of steel roads has been calculated based on the recommendations of Erik Johansson

	Insulation of surfacing [m2]	Moisture indicator	Pressure impregnated [m3]	Sawn timber [m3]	Steel rods [m3]	Timber Glulam [m3]	Cost [SEK]
Timber Glulam						35,19	151760,46
Sawn timber				4,88			11924,95
Pressure impregnated			0,759				1785,41
Overlay	60,28						69924,80
Moisture indicator		10					20000,00[1]
Steel rods					22		22645,33
Total cost							278040,95

[1] In the timber bridge moisture indicators have been placed in order to ensure that no moisture damages will occur in the bridge. 10*2000 SEK

Appendix D – Life Cycle Cost analysis for timber bridge

Transportation costs	Time [min]	Cost [SEK]	Total present value [SEK]
Transport to construction	60	1200	
Transport to disposal	60	1200	76,55
Total cost			1276,55

Maintenance and repair	Performed every [yrs]	Unit	Cost [SEK/unit]	Quantity	Cost [SEK]	Total Present value [SEK]
Bearings (rubber)	40	h	500,00	4,00	2000,00	505,15
Cleaning of bridge	2	h	500,00	3,00	1500,00	19620,00
Moisture inspections	7	h	500,00	4,00	2000,00	6826,00
Painting of panel	15	h	500,00	20,00	10300,00	14100,00
Prestressing of rods	20	m3	500,00	29,33	14666,67	12940,00
Replacement of overlay	20	h	500,00	20,00	10000,00	8821,00
Repainting of railing	8	h	500,00	20,00	11000,00	31800,00
Total cost						94612,15

[1] In working hours we add the price of the paint for panel (20*500,00+300,00)

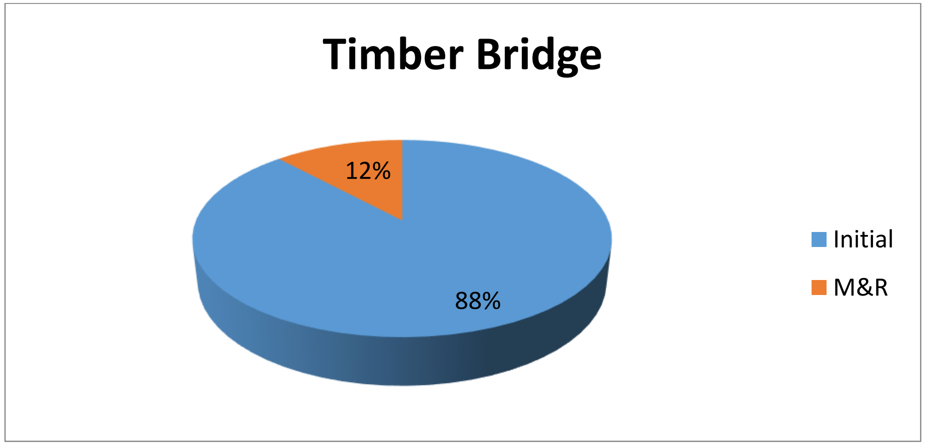
[2] In working hours we add the price of the paint for railings (20*500,00+1000,00)

Appendix D – Life Cycle Cost analysis for timber bridge

Disposal costs					
	Unit	Cost [SEK/unit]	Quantity	Cost [SEK]	Present value [SEK]
Demolition work	h	500,00	56	28000,00	1786,00
Steel	tonne	-500,00	0,911	-455,50	-29,06
Timber	tonne	1000,00	17,6	17600,00	1123,00
Total cost					2879,94

Final cost	
	Cost [SEK]
Initial	700000,00[1]
Transportation	1276,55
Maintenance and repair	94612,15
Disposal	2879,94
Total cost	798768,64

[1] The initial cost assumed to be 700000 SEK



Appendix D – Life Cycle Cost analysis for steel bridge

General information and input data for steel bridge

Bridge over Kraftverkstub		
	Unit	
Service life	80	years
Discount rate	3,50%	%
Bridge length	19,00	m
Bridge width	3,096	m
Span length	19,00	m
Effective bridge width	2,90	m
Bridge area	58,82	m2
Area of surfacing	55,10	m2
Area of railings	27,55	m2

Appendix D – Life Cycle Cost analysis for steel bridge

Initial costs		
	Unit	Cost [SEK/unit]
Steel	tonne	24500,00
Membrane and surfacing	m2	1160,00

	Steel [ton]	Membrane and surfacing [m2]	Cost [SEK]
Total bridge amount	12,00		294000,00
Overlay		55,10	63916,00
Total cost			357916,00

Transportation costs			
	Time [min]	Cost [SEK]	Total present value [SEK]
Transport to construction	60	1200,00	
Transport to disposal	60	1200,00	76,55
Total cost			1276,55

Appendix D – Life Cycle Cost analysis for steel bridge

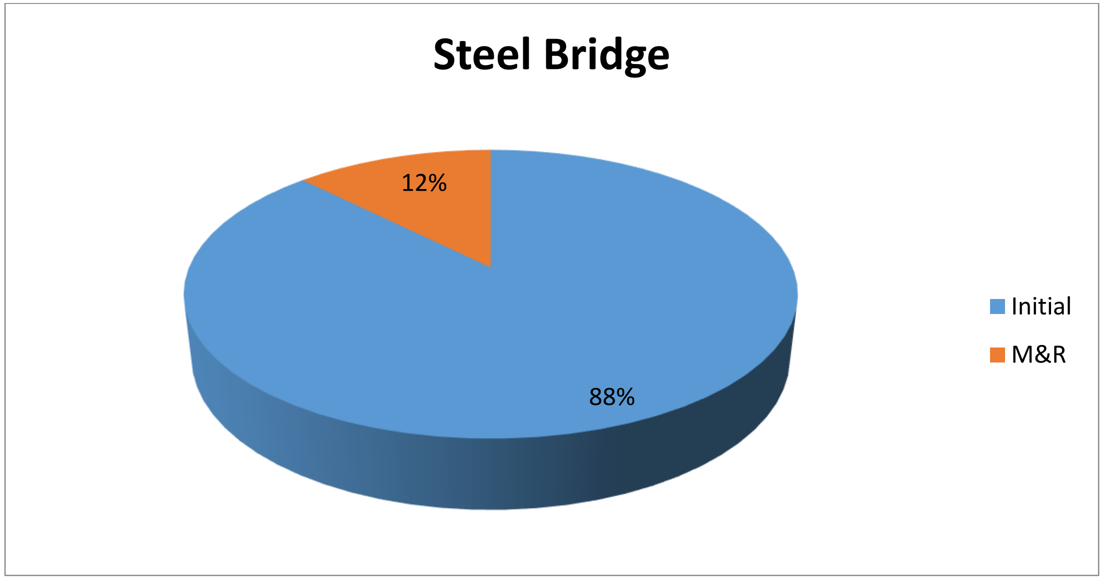
Maintenance and repair						
	Performed every [yrs]	Unit	Cost [SEK/unit]	Quantity	Cost [SEK]	Total present cost [SEK]
Cleaning of bridge	1	h	500,00	2	1000,00	26680,00
Repainting of bridge	40				200000,00	50514,49
Replacement of overlay	20				20000,00	17641,45
Washing the bridge	5	h	500,00	2	1000,00	4924,00
Total cost						99759,95

Disposal costs					
	Unit	Cost [SEK/unit]	Quantity	Cost [SEK]	Present value [SEK]
Demolition work	h	500,00	32	16000,00	1021,00
Steel	tonne	-500,00	12	-6000,00	-382,76
Total cost					638,24

Appendix D – Life Cycle Cost analysis for steel bridge

Final cost	
	Cost [SEK]
Initial	700000,00[1]
Transportation	1276,55
Maintenance and repair	99759,95
Disposal	638,24
Total cost	801674,74

[1] The initial cost assumed to be 700000 SEK



Appendix D – Life Cycle Cost analysis for FRP bridge

General information and input data for FRP bridge

FRP Bridge		
	Unit	
Service life	80	years
Discount rate	3,50%	%
Bridge length	19,00	m
Bridge width	2,90	m
Span length	19,00	m
Effective bridge width	2,90	m
Bridge area	55,10	m2
Area of surfacing	55,10	m2
Area of railings	69,11	m2
Area of top plate	55,10	m2
Area of Asset deck	55,10	m2
Area of GRFP girder	48,91	m2

Appendix D – Life Cycle Cost analysis for FRP bridge

Initial costs		
	Unit	Cost [SEK/unit]
FRP Asset deck	m2	6338,00
GFRP girders	m2	3962,00
Insulation and surfacing	m2	1160,00

	FRP Asset deck [m2]	GRFP girders [m2]	Insulation and surfacing [m2]	Cost [SEK]
FRP Asset deck	55,10			349223,80
GFRP Girders		48,91		193765,57
Top plate		55,10		218306,20
Overlay			55,10	63916,00
Total cost				825211,57

Transportation Costs			
	Time [min]	Cost [SEK]	Total present value [SEK]
Transport to construction	60	1200,00	
Transport to desposal	60	1200,00	76,55
Total cost			1276,55

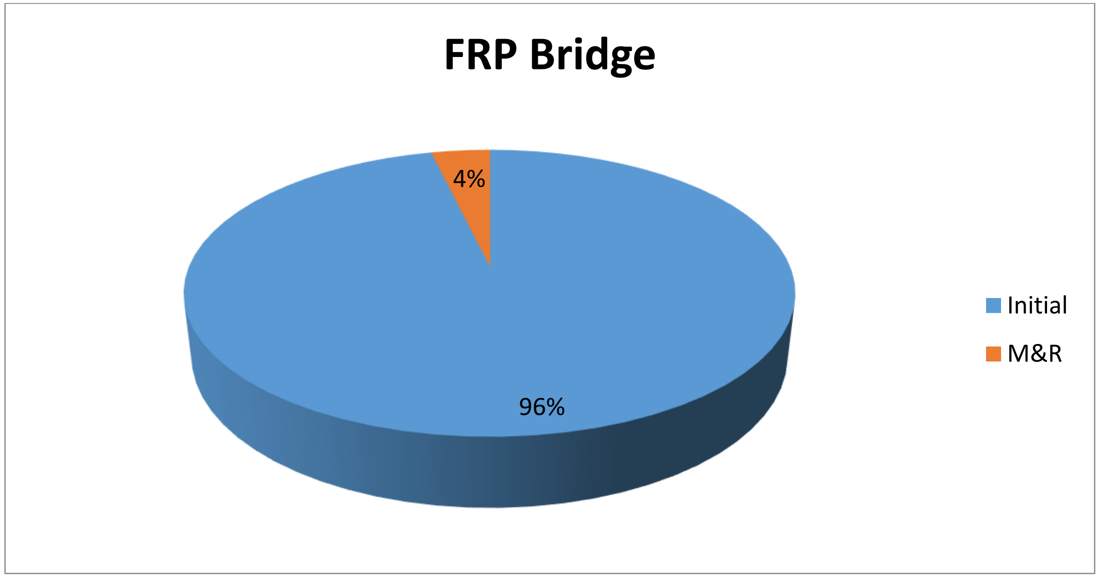
Appendix D – Life Cycle Cost analysis for FRP bridge

Maintenance and repair						
	Performed every [yrs]	Unit	Cost [SEK/unit]	Quantity	Cost [SEK]	Total present cost [SEK]
Cleaning of bridge	2	h	500,00	55,10	1500,00	19620,00
Replacement of overlay	20	h	500,00	55,10	10000,00	8821,0
Repair of FRP Asset deck	40	m2	8730,60	2.5%	8730,60	2205,00
Repair of GRFP girders	40	m2	4844,14	2.5%	4844,14	1223,00
Total cost						31869,00

Disposal costs					
	Unit	Cost [SEK/unit]	Quantity	Cost [SEK]	Present value [SEK]
Demolition work	h	500,00	56,00	28000,00	1786,00
FRP	tonne	1100,00	12,37	13607,00	868,03
Total cost					2654,03

Appendix D – Life Cycle Cost analysis for FRP bridge

Final cost	
	Cost [SEK]
Initial	825211,57
Transportation	1276,55
Maintenance and repair	31869,00
Disposal	2654,03
Total cost	861011,15



APPENDIX E

Material amount of bridges

- Timber bridge
- FRP bridge

Appendix E – Material amount of Timber bridge

- Timber bridge

Rods							
	314	22	2	3184		0,044	345,323
Glulam beams							
	13	217	630	19800		35,189	15131,340
Panel							
	19800	22	2	540		0,470	202,293
Railling							
Newel Cap/Top part	58	170	2	21478		0,424	211,773
Handrail/vertical	115	133	22	2013		0,677	291,262
small horizontal	98	58	4	24636		0,560	240,853
Baluster/Small vertical	28	95	234	880		0,548	235,531
Support beams	22	70	1675	20	8	0,052	25,795
	22	70	4	800	1	0,005	2,464
Support beams	70	70	42	490		0,101	50,421
beams	20	1675	45	70		0,106	52,763
Ground plate (Syll)	4	70	195	1325		0,072	31,108
Coating (Slitplank)	114	45	170	3010		2,625	1128,759

Appendix E – Material amount of Timber bridge

Screw					
24	12,5	8,8	1	1	2,640E-06
2	12,5	8,8	24	1	5,280E-06
17,5	30	3	1	1	1,575E-06
24	12,5	8,8	2	1	5,280E-06
120	88	15	1	1	1,584E-04
6	160	7	1	1	6,720E-06
6	2	10	1	1	1,200E-07
4	125	5	1	1	2,500E-06
13	6,5	18	1	1	1,521E-06
50	50	3,14	10	88	6,908E-03
88	100	100	3,14	20	5,526E-02
60	37	37	3,14	6	1,548E-03
44	120	80	15	1	6,336E-03
8	24	12,5	10	1	2,400E-05
				Sum	**7,026E-02**

Metal sheet				
0,6	75	20	1825	0,00164
0,6	75	4	1000	0,00018
			Sum	**0,00182**

Appendix E – Material amount of FRP Bridge

- FRP Bridge

Top plate										
	2,90	19	0,01		0,55	m3		**Sum**	1,47	m3

Girder										
	0,024	m2	19	m	0,460	m3		**Sum**	0,919	m3

Asset deck	2,90	19	1	55,10	m2
Density	GFRP	1800,00	kg/m3	2646,53	kg
	Asset	94,80	kg/m2	5223,48	kg
				7870,01	kg

Railings			**FRP density**			
	2,50	m3	1800,00	kg/m3	4500,00	kg

Epoxy											
	0,003	19,000	2,900		**Sum**	0,165		kg/m3		**Density**	198,360
	0,003	19,000	0,050	4		0,011		1200,000			13,680
		55,100									212,040
		3,800					0,177	m3			
		58,900									
							Sum	12582,050	kg		