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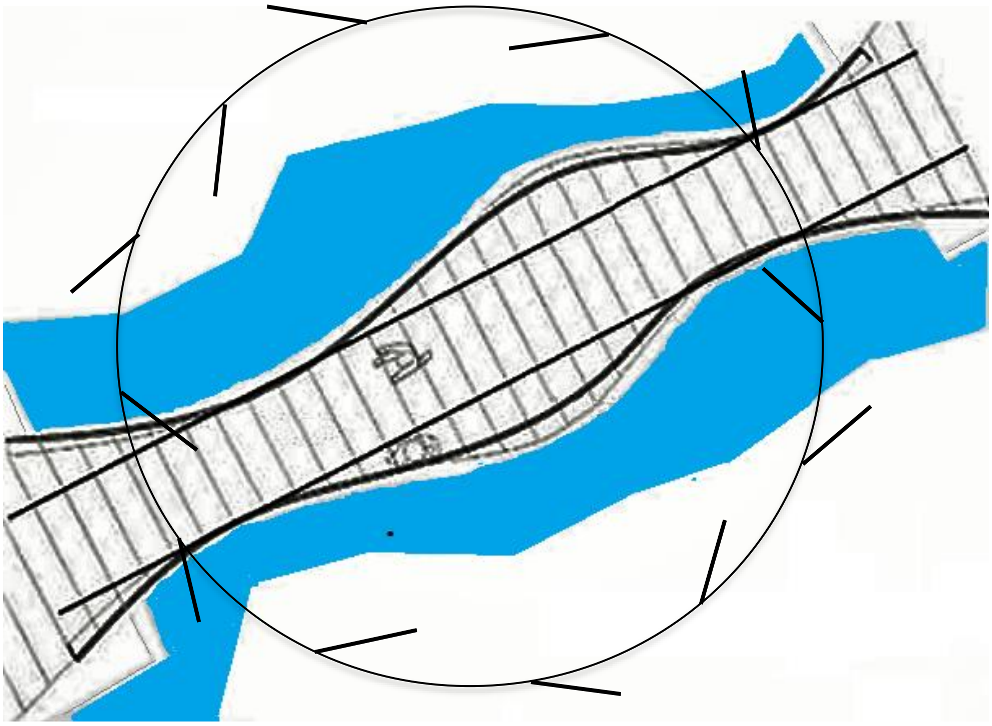

Life cycle cost analysis of FRP pedestrian bridges

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

Ivan Patljak

Department of Architecture and Civil Engineering
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Master's Thesis ACEX30-18-89
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Cover:
Sketch of the Neptuni pedestrian bridge with a life cycle.
Department of Architecture and Civil Engineering.
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ABSTRACT

Modern bridge construction is under development and with sustainability in focus. As part of that progress has the 20th century invention Fibre Reinforced Polymer (FRP) been developed and applied as a structural material in civil engineering. The desirable features are its low weight, high specific strength and stiffness and fast on-site assembly.

This thesis project investigates different pedestrian bridge construction materials and their outcoming life cycle costs. This is done by implementing the life cycle cost analysis method (LCCA) in a case study with five different designs containing four different building materials (concrete, steel, Carbon-FRP and Glass-FRP). Much revolves around studying the different materials, gathering information on costs, defining bridges life cycle and making Excel sheets. Large part of the LCCA is limited to the frame of the FALCON project and a specific bridge in the city of Malmö (Sweden).

LCCA results indicate that agency cost of the concrete & steel solution is 15 % less than the Glass-FRP composite solution. Future estimated maintenance cost for the concrete and the concrete & steel solution is higher than maintenance cost for an FRP composite solution. The Carbon-FRP bridge solution was most expensive amongst the FRP composite solutions. Its cost is approximately 50 % more than the cost of the cheapest Glass-FRP bridge solution.

Key words: Life cycle cost, LCC, bridge, pedestrian bridge, fibre reinforced polymer, FRP, concrete, steel

Livscykelkostnadsanalys av FRP gång- och cykelbroar

Examensarbete inom mastersprogrammet Konstruktion och byggteknik

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SAMMANFATTNING

Modern brobyggnad är under utveckling med hållbarhet i fokus. Som en del av denna utveckling har 19-talets uppfinning fiberförstärkt polymer (FRP) utvecklats och applicerats som ett strukturellt material inom samhällsbyggnad. De önskvärda dragen är dess låga vikt, höga specifik styrka och styvhet samt snabb montering på plats.

I detta avhandlingsprojekt undersöks olika byggnadsmaterial av gångcykelbroar och deras kommande livscykelkostnader. Detta görs genom att implementera livscykelkostnadsanalys-metoden (LCCA) i en fallstudie med fem olika fall som består av fyra olika byggmaterial (betong, stål, kol-FRP och glas-FRP). Mycket handlar om att studera olika material, samla information om kostnader, definiera en bros livscykel och skapa Excel-ark. Stor del av LCCA är begränsad till ramen för FALCON-projektet och en specifik bro i Malmö (Sverige).

LCCA-resultatet indikerar att direkta kostnader för betong & stål-lösningen är 15% mindre än Glass-FRP kompositlösningen. Framtida uppskattad underhållskostnad för betong och betong & stål designlösningen är högre än underhållskostnaden för FRP-kompositlösningen. Kol-FRP designlösningen var dyrast bland de tre FRP designlösningarna. Kostnaden för den är cirka 50% mer än kostnaden för den billigaste Glass-FRP designlösningen.

Nyckelord: Livscykelkostnad, LCC, bro, fotgängarbro, fiberförstärkt polymer, FRP, betong, stål

Contents

Preface

This thesis was written at the Department of Civil and Environmental Engineering, division of Structural Engineering, at Chalmers University of Technology. Major part of the thesis was conducted during the months of 2017.

I would like to thank my supervisors Alann André and Erik Marklund at Swerea SICOMP, Erik Olsson at ELU and my examiner Reza Haghani Dogaheh at Chalmers University for all their patience and support.

Also, a big thanks to the project consultants for shearing their knowledge and experience. Thank you, Ralph Dougan and Charlotta Bjerkborn at GVV, and Abbas Khayyami at the City of Malmö.

Notations

1 Introduction

1.1 Background

As cities are growing in population and expanding in area, so are their infrastructural system rearranged. New paths are constructed, while old ones are upgraded or rebuilt. An essential part of these paths are bridges. A bridge can be seen as that which gives a path its continuity over troublesome obstacles. An ingenuity that have help mankind reach and spread resources, over millennia.

"Mankind's conquer of space."

New technology and materials are constantly emerging and intertwining with the current, while fulfilling human needs. In modern days, terms such as sustainable thinking, economical competition and innovation are all highlighted. And in all of that, awareness has been averted to human material housekeeping and new material development together with implantation of present materials into new fields.

Modern bridge construction is not different. Fibre reinforced polymer (FRP) materials have been used in several industries since the beginning of the 20th century and over the last 50 years has it been developed and applied as a structural material in civil engineering. The desirable features are its low weight, high specific strength and stiffness. It also brings possibility for off-site manufacturing and fast on-site assembly.

The subject is still researched, to see if FRP is a valid modern bridge construction material and if it can be regarded as a sustainability contributing material. There is also need for further development in construction standards and in other guidelines.

Chalmers is part of a recently started project called FALCON. The projects goal is to create opportunities for Swedish industries to enter the FRP bridge market (FALCON, 2015). In order to compare FRP solutions with traditional material (concrete and steel) solutions, a life cycle cost analysis has been considered within the workplan of the FALCON project.

Life cycle cost analysis (abbreviated to LCCA) is used as a cost assessment tool/method in early product manufacturing stages, to get an overall assessment of the total life cycle cost. In bridge projects is it often applied around the tendering phase or even earlier.

1.2 Aim and Objectives of the project

The overall aim is to conduct a cost comparison and present the findings. The comparison is conducted from a life cycle perspective on a bridge with alternative designs. The bridges are designed with different construction materials. More specifically, an LCCA case study is to be done on five different designs with four different building materials (concrete, steel, Carbon-FRP and Glass-FRP). To accomplish the aim, two main objectives are set:

- Preform an LCC analysis case study of the Neptuni-bridge in Malmö by looking at five different concepts.
- Develop further LCC understanding for FRP bridges.

1.3 Methodology

The project started with an initial study on the LCCA method and on FRP as bridge construction material. Furthermore, studies were also conducted on pedestrian bridge design and on traditional bridge construction materials (such as concrete and steel). Goal with the initial study was partly to get deep understanding on thesis subject and to get an insight on different approaches regarding LCCA.

The next step was to decide on what to include and exclude in the LCCA. It was done by examining all bridge design solutions and by defining the bridge life cycle. The input data for the LCCA was gathered from literature, available databases and by consulting with experts in each respective area. The LCCA and case study was preformed over time as more and more data were obtained. The analysis was done in MS Excel by creating work sheets and also by using an already assembled Excel program, ETSI Bridge LCC, (ETSI, 2013). The tool ETSI Bridge LCC was used in the initial part of the project with the intent to create a *work base* for the forthcoming analysis. The final part of the project consisted of collecting output data and going through results.

1.4 Scope and Limitations

The limits are set around the FALCON project, Neptuni-bridge project and the available design solutions of it. It should be noted that the results and conclusion in this project are bound to its assumptions and limitations. A broad view on the concerning subjects should be acquired before any "general" conclusions are drawn from the findings in this thesis (recommended).

Costs and activities considered in this project are only those concerning the construction of the bridge *superstructure*. The service life of the bridge designs is set to 100 years for all cases in the case-study.

In a bridge LCCA there is usually cost categories called Agency, User and Society costs. These will be explained further in the report. But, this LCCA will only treat the category what is called 'Agency costs'. This is done partly because the analysed subject is a pedestrian bridge. Traffic data that is used when calculating User cost is not treated in the same way on a pedestrian bridge (no passenger cars etc.) compared to a road bridge with ADT data (with passenger cars etc.), hence the User cost category is disregarded in the LCCA. Society and Environmental cost are not treated in the thesis as the timeframe doesn't allow for a rigorous analysis of these aspects. An LCA should be conducted to *better* cover the Society and Environmental aspects.

Construction, maintenance, and end-of-life costs estimations and activities are based on data from available drawings, consultation with engineers and researchers, extracted data from available databases and on data found in previously conducted projects and thesis. Simplifications and assumptions were made to get best possible or acceptable comparable results between the different cases. The time it takes to construct or erect the bridges (the different design solutions) at the construction site was not compared in the case study.

2 Fibre Reinforced Polymers (FRP)

Fibre Reinforced Polymers (FRP) are polymers (e.g. epoxy, vinyl ester, etc.) that are reinforced with fibres (e.g. glass, carbon, aramid, etc.). The need to reinforce the polymers is due to their low stiffness for most structural applications (Nystrom, 2003). FRP have been developed and researched in military, aviation and space applications and have since the beginning of 1980's developed to be used in bridge construction.

FRP is a composite material with anisotropic mechanical properties. It is made anisotropic during manufacturing by arranging the fibres in multiple directions, thus making FRP composites strong where strength and stiffness are needed. FRP composites have been around for a while now and have brought change to a lot of industries (e.g. aerospace, marine, electrical, transportation). And these industries have over the years gained experience and reviled FRPs' different benefits and disadvantages (Nystrom, 2003).

Table 2-1 General FRP benefits and disadvantages.

Advantages	*Drawbacks*
• *Light weight* • *High strength to weight ratio* • *Corrosion resistance* • *Maintenance reduction* • *Weather resistance* • *Long term durability* • *Faster construction time* • *Reduced installation costs*	• *High initial cost* • *High amount of carbon emissions* • *Uncertain durability (bridges)* • *Lack of ductility* • *Susceptibility to fire.* • *Few construction standards*

There are some negative aspects reported when considering FRP as a construction building material (Potyrała, 2011). The initial costs for a bridge project are usually high in contrast to concrete bridges and there is a lack of knowledge in terms of long-term experience with FRP bridges. There are some environmental costs reported as well. For instance, production of FRP materials generates a high unit amount of carbon emissions when compared with steel and concrete and some FPR products have high energy consumption during production, see figure 2-1 (Mara, 2014).

Impacts from the oil industry are to be considered as the polymer resin used in FRP manufacturing processes is a by-product from the oil industry (Mara, 2014). In addition, some of the adhesive used during FRP manufacturing processes are harmful to the human body (if used unwisely).

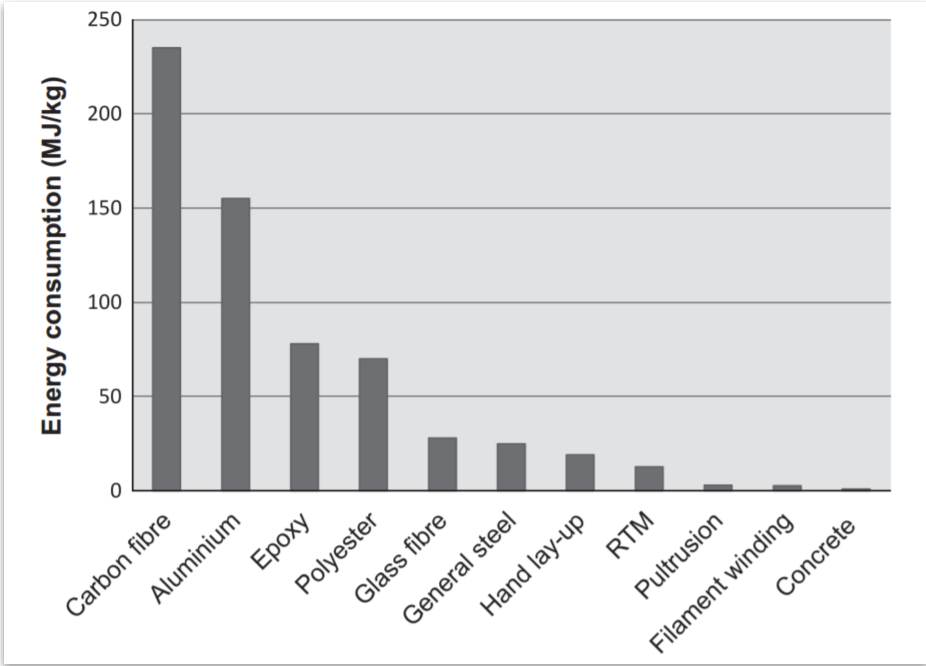


Figure 2-1 Energy consumption during manufacturing (Mara, 2014).

2.1 Fibres and matrices

FRP composites gain their strength from different bas components. The content in most of FRP products are usually a combination of a fibre material and a matrix material. The polymer matrices main purpose is to bind the fibres together and to distribute the stresses between the fibres. Matrices can in general be divided in two categories, organic and inorganic. An inorganic matric can for instance be cement, which is used as a binder in concrete. In FRP context, is it mostly about the inorganic thermoplastic and thermoset polymer matric, which is also called resin.

The thermoplastic polymer resin is a solid at room temperature. During FRP manufacturing processes is it heated to a liquid state and then mixed with the selected fibres. The other polymer resin, thermoset, is a liquid at room temperature and requires a catalytic chemical reaction to shift from a liquid to a solid. It should be noted that the chemical reaction is irreversible, and thus making it difficult to reshape or recycle the resin.

The fibres in an FRP composites can be regarded as the composite materials reinforcement. The usual fibre types are glass, carbon, or aramid fibre and they all have their own characteristic mechanical properties. Fibres can be categorized as man-made or natural fibres. Glass, carbon and aramid fibres are some of the man-made fibres that are used today. Natural fibres can be extracted from plants, wood and animal products (André, 2006). Table 3.1 shows mechanical properties of fibres that are most commonly used when manufacturing materials for the construction industry.

Tabell 2-1 Typical mechanical properties of some fibres and polymers (Potyrała, 2011)

Material	E-modulus [GPa]	Tensile strength [MPa]	Ultimate strain [%]
Glass fibre E - glass, S - glass	69 - 86	2400 - 3700	3.5 - 5.4
Carbon fibre High Modulus (HM), Ultra HM, High Strength (HS)	260 - 450	3500 - 5200	0.78 - 1.93
Aramid fibre Kevlar 49, Kevlar 29	83 - 125	2750 - 2760	2.2 - 3.3
Polyester	2.5 - 4.0	45 - 90	
Epoxy	3.5 - 7.0	90 - 110	
Nylon	1.03 - 2.76	48 - 83	

Glass fibres are manufactured by drawing molten glass through platinum bushings and has been used over 60 years in combination with polyester, vinyl ester and epoxy resin in various industrial fields for FRP applications. Amongst carbon, glass and aramid fibres, is glass fibres the cheapest. Carbon fibres can be manufactured by pyrolysis and aramid fibres by extrusion processes. A known and characteristic aspect of carbon fibre is its very high elastic modulus that can be higher than 450 GPa. Aramid fibres have high impact resistance and both aramid and carbon fibres have low density *(*Sonnenschein, *2004).* It is not uncommon to mix several fibre types into one composite material, to get each of their qualities.

2.2 Mechanics of FRP materials

Mechanical properties of an FRP composite material are governed by, the properties of the fibre and resin used, the ratio between fibre and resin, and the orientation of the fibres in the composite. The fibres in a composite material can alone handle tensile load very well, but they will need help from the resin to handle compressive load. The fibres would buckle if there wasn't for the resin to keep them straight (figure 2-2). The longitudinal black lines in figure 2-2 are fibres, while the surrounding white colour is resin that "holds" fibres together. The resin also distributes and resist shear loading, this resistance depends on the resin's mechanical properties and the adhesive quality between resin and fibres.

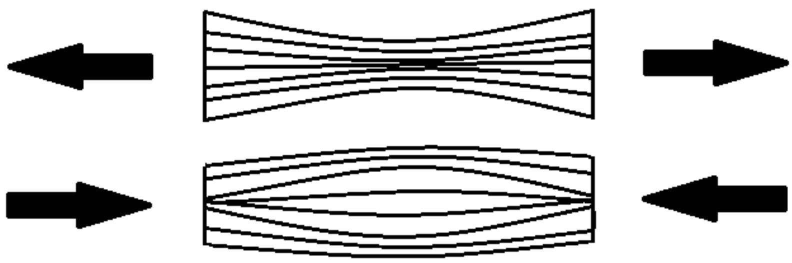


Figure 2-2 Simple illustration of tension and compression behaviour in an FRP composite materials (redrawn by author).

It is quite clear that, the higher fibre volume fraction in the composite material there is, the higher will the mechanical properties of it be. But there is a limit, there needs to be an enough amount of resin in the composition to bind the fibres together and to distribute the loading stresses effectively.

The Young's modulus in table 2-2 describes a materials relationship between mechanical stress and deformation, Young's modulus of an FRP composite depends on the fibre volume fraction and the Young's modulus of the fibre and matrices. The E-modulus in longitudinal direction is calculated by function 2-1 and show how the fibre volume fraction affects the Young's modulus (Andre, 2006).

$$E_L = E_f V_f + E_m(1 - V_f) \tag{2-1}$$

E_L Composite longitudinal modulus of elasticity.
E_m Matrix modulus of elasticity.
E_f Fibre modulus of elasticity.
V_f Fibre volume fraction

2.3 Manufacturing of FRP composite

There are several FRP composites manufacturing processes available at today's date. They have been adapted and developed for different purposes over the last 80 years. Also, due to the late environmental awareness there have been a lot of efforts and energy put in to eco-design (Euro, 2009). Though it remains to be seen how it will influence the FRP manufacturing processes.

Mixing fibres with resin is involved in all FRP manufacturing processes. But what distinguishes them are usually aspects like cost, if they are manual or automated, material options, level of simplicity, working environment, quality, resin and fibre mixture, pressure and temperature. Some typically used production methods,

- Hand Lay-up,
- Spray Lay-up,
- Vacuum Bagging,
- Filament Winding,
- Pultrusion,
- Resin Transfer Moulding,
- Infusion,
- Prepreg with or without Autoclave.

Hand layup and pultrusion are manufacturing processes that are mostly used in the construction industry. To give a simple analogy to concrete and steel, hand layup can be thought of as in-situ concrete construction. It is a manual method where its composite materials are delivered to the building site and assembled. The fibres and resin are assembled together and left to cure for a time. It can also as pre-fab concrete be produced at a factory. While pultrusion could be thought of as steel beam manufacturing. The FRP beams are fabricated in factories and delivered to building sites, for further assembly.

Hand layup

Resin Transfer Moulding (RTM)

RTM is a semi-automated process and as the name suggests is it a method where the resin is injected or transferred in to a mould filled with fibres (a dry preform). The mould consists of two tool halves, a male and a female. The tools can be temperature regulated and a desired thickness is acquired by pressing them together *(Murphy, 2013)*. Figure 3.1 shows how wind turbine blades are manufactured using the RTM method (Attaf, 2012).

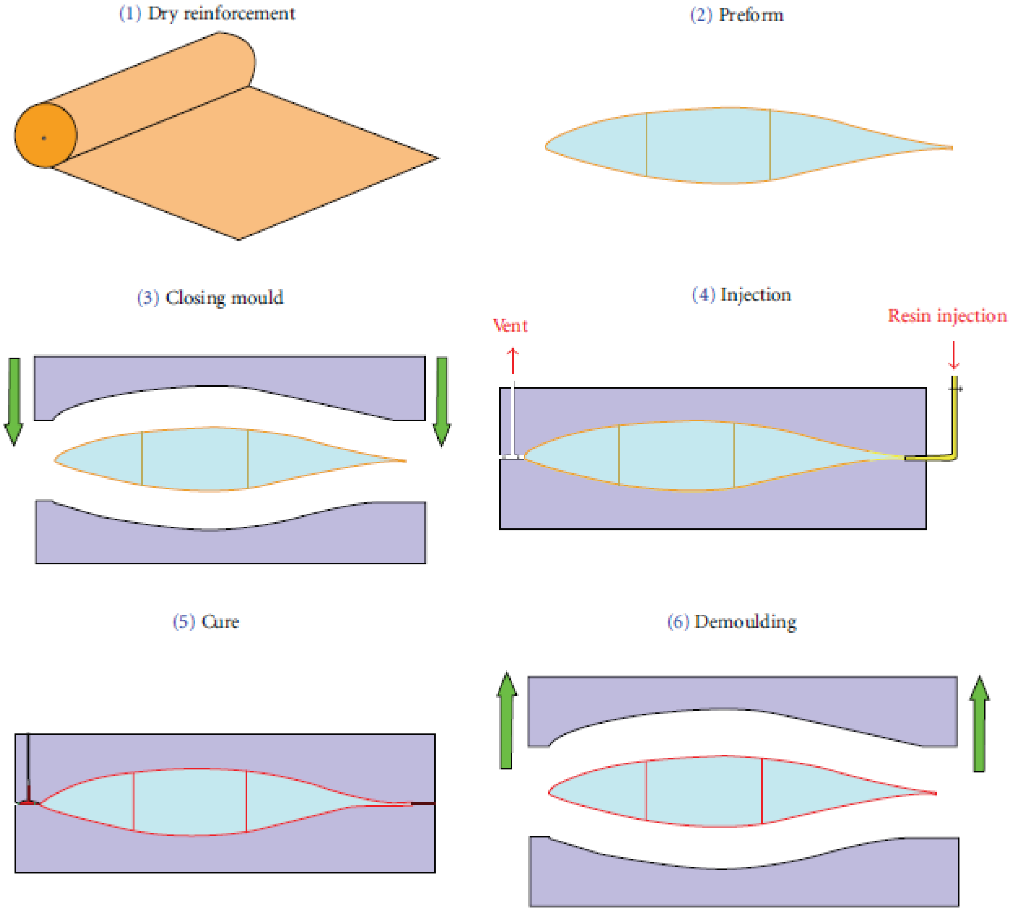


Figure 2-3 Wind turbine blades, RTM manufacturing procedure (Attaf, 2012).

RTM method is usually used when moulding parts as truck panels, boat hulls and wind turbine blades. The FRP part size is limited to the size of manageable moulds. The mould system should be constructed in such a way that it can withstand the pressure from the injected resin. This is usually done by having heavy mould halves. Data on production volume stats values between 100 – 10 000 units/year (AZO, 2013).

Infusion

Vacuum infusion is an open mould process, unlike RTM (closed mould). It follows the same principle as RTM, by having a mould prepared with fibre reinforcement and then have the resin injected. Here are the fibres placed in the open mould, sealed and covered with a vacuum bag. After these preparations, the resin is sucked via vacuum pumps in to the vacuum bag and distributed evenly around the fibres. *(Murphy, 2013)*.

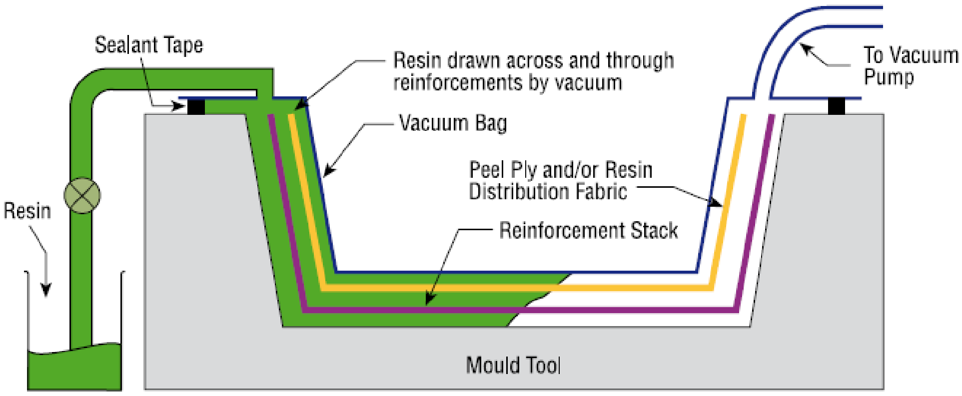


Figure 2-4 Infusion production process (Gurit, 2017).

It is currently used when moulding marine and infrastructure parts. An aspect that distinguish it from the ordinary RTM method is that it allows for production of larger parts. The method is considered low volume product process.

The devlopers of one of the bridge design solutions in this cases study uses infusion in their manufacturing processes. It is a company called FibreCore that is based in Roterdam, Netherlands, and they manufacture structures for architeture and infrastructure.

Amongs its variaty of applications, is infusion used when moulding sandwich composite (Frisk, 2016). A sandwich composite consists of a core material inbetween two skin layers. The core is there to separete the skin layers and provide shear resitance in bending, while the skin layers take compression and tension. It also incresesse the bending stiffness by incessing the moment of inerita (Andre, 2017).

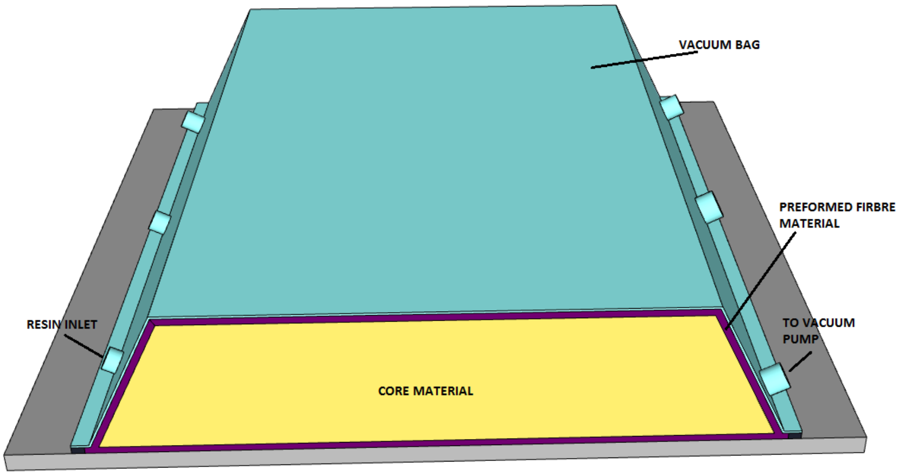


Figure 2-5 A simplyfied illustation of an sandwich composite moulding procedure (reproduced by author).

Prepreg in autoclave

There is a little different variant of the pressure bag manufacturing process available. In this method a mould is prepared with pre-impregnated fibres and fabrics. The material is then sealed with a pressure bag and placed inside an autoclave. An autoclave is a pressure and temperature-controlled chamber. The vacuum in the pressure bag is regulated via hoses inside the autoclave. By using an autoclave, the pressure is evenly distributed over the mould and it also produces high grade FRP composite material (Gurit, 2017). The method can be applied on various products and element sizes. The autoclave size varies from a couple of cubic meters to quite large volumes (e.g. approx. 9 meters in diameter and 30 meters long). This is considered a costly method (mostly due to pre-impregnation and autocalve), and a low production volume process.

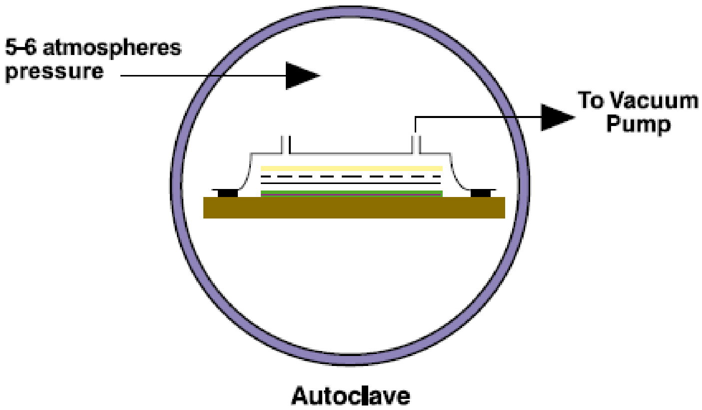


Figure 2-6 Illustration of a mould inside an autoclave (Gurit, 2017).

Prepreg in autoclave process was used for the manufacturing of a recently erected bridge in Sweden (2017). The material used in the bridge was manufactured by Marstrom Composite. The bridge was projected and installed by Composite Design and Kompositbroar. It is considered the first carbon fibre composite bridge in Sweden (Marstrom, 2017).

Figure 2-7 Carbon fibre composite bridge (Marstrom, 2017).

Pultrusion

Pultrusion is an automated FRP production process where fibre strands are pulled through a few processing stations. Figure 3.5 is an illustration of the process in general. First part of the procedure consists of a bath where the fibres are soaked in a resin and additive solution. Then after the fibres have been impregnated with resin are they pulled through a heated die. There is the element (end-product) formed and cured. At the end of the production line is the element measured and cut into desirable lengths *(Murphy, 2013)*.

The process is used in manufacturing of FRP reinforcing bars, strengthening strips and elements with various cross-sections. There is a big variation of profiles available on the market.

- Open cross-section e.g. plate or wide-flange profile.
- Closed cross-section e.g. hollow tube.
- Multicellular cross-section e.g. panel with internal webs.

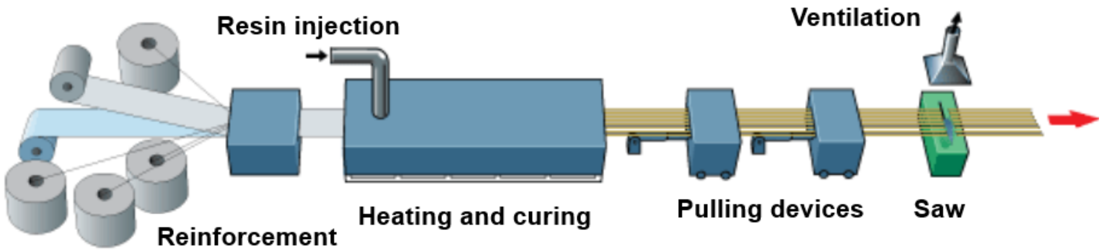


Figure 2-8 Pultrusion process method (Fiberline, 2017).

Pultrusion is considered as a high production volume manufacturing process. It is at present time mostly applied in industries where there is a need of straight profiles. In infrastructure is it used parts like bridge decks and standard profile beams (I, U and T-profiles). It is considered very energy consuming compared to other FRP production methods, mainly because it's fully automated and uses heating in the process.

Pultrusion was used in the manufacturing of the beams and deck in the West Mill bridge, UK (erected 2002). Both glass and carbon fibre were used during the in the bridge. Fiberline pultruded the GFRP box beam, and the CFRP was added by resin infusion at SICOMP at a later stage (SICOMP, 2018). The bridge was part of the ESSET EU research project with participants such as Fiberline Composites A/S, Swerea Sicomp AB, Skanska AB and Munchel (WSP).

Figure 2-9 Glass and carbon fibre composite bridge (Fiberline, 2017).

2.4 End of life and Recycling

Regarding the end-of-life stage of FRP products and materials in general. There is “general” intent to minimize loss of material and environmental pollution. This can be partly done by waste management. The plan or strategy to accomplish this is to manage used material in the following order (Mara, 2014),

I. Waste prevention or reduction.
II. Re-use.
III. Material recycling.
IV. Energy recovery.
V. Landfill/disposal.

There are recommendations from the European composites industry association (EuCIA) that GFRP are to be co-processed (*material recycling*) in cement kilns. The GFRP material is to be re-sized, mixed with other waste material and burnt in a kiln. The outcome from this procedure is energy and feedstock for the cement clinker (Composites UK, 2016).

The FRP waste material (GRFP and CRFP) can also be regrind, processed if needed and then reused in FRP manufacturing processes. Some setbacks here are that the regrind material doesn’t regain its full mechanical strength (i.e. loss of mechanical strength). And, it’s still not economically viable compared to “virgin” material (Composites UK, 2016).

It is prognosed that the global use of composites will increase by approx. 10 percent in the coming two years. And as it stands now, there are some options available for FRP waste management, but more needs to be done (Composites UK, 2016).

Figure 2-10 The final products from a fibre separation process, fibres to the right and polymers to the left. (Rapid, 2017).

A structural FRP material that is at its end-of-life stage and can’t fulfil its intended functionality anymore, can for instance be regrind for further use. There is a company called Rapid Granulator AB that has developed a process chain that separate fibres from FRP materials. The final fibre products can be seen in figure 2-10.

3 Bridge design

3.1 Bridges

There is a complexity in modern bridge design as they are in today's society built, designed and affected by a large group of people. It is an interaction between owner, different architects, engineers of various disciplines (infrastructural, geotechnical, material specialized), students and researchers, universities and state agencies and the society in general. They all interact and work on aspects such as aesthetics, functionality, safety, construction, erection, economics and local politics.

A bridge is designed in such a way that it should be able to withstand loads and deflections that could occur during its construction and service life cycle. The bridge should also perform well and have good durability. To carry out this task, 0 And implements theories such as the limit state theory in their calculations.

The structure is designed not to exceed certain predefined limit states. There are two categories of these predefined limit states in Eurocode, ultimate limit state (ULS) and service limit state (SLS). Limit states that are regarded in the ULS category revolves around the possibility of a whole structural collapse or dangerously large deformations. While in the SLS category are limits stated that regard the possibilities of disruptions in the use of the bridge. Depending on what the bridge is intended for, such disruptions could emerge from deformations, damage to the bridge and vibrations.

Tabell 3-1 Ultimate and Service limit state (Chatterjee, 2003)

<u>ULS - Collapse of whole structure</u> *Concerns*: Loss of static equilibrium and load bearing capacity. Overall instability. *Consequence*: Leading to large deformations and/or collapse.	<u>SLS - Disruption of normal use</u> *Concerns*: Excessive deformation, local damage and vibration. *Consequence*: Leading to discomfort. Affecting appearance, use, durability, functional use and drainage. Damage to non-structural parts.

To ensure a good safety margin in structural design calculations, so called safety factors are applied. They are developed through probability theory and statistics.

A bridge is in short and by definition a structure that provides passage over an obstacle without closing the path beneath (Vasani, 2003). A bridge is usually composed of a superstructure and a substructure, figure 3-1. The superstructure can be constructed in several ways. There is the slab bridge design, it is usually used over shorter spans and constructed with reinforced concrete. Use of girders is another structural system, the idea is to span the girders over obstacle and have some form of a deck resting on them.

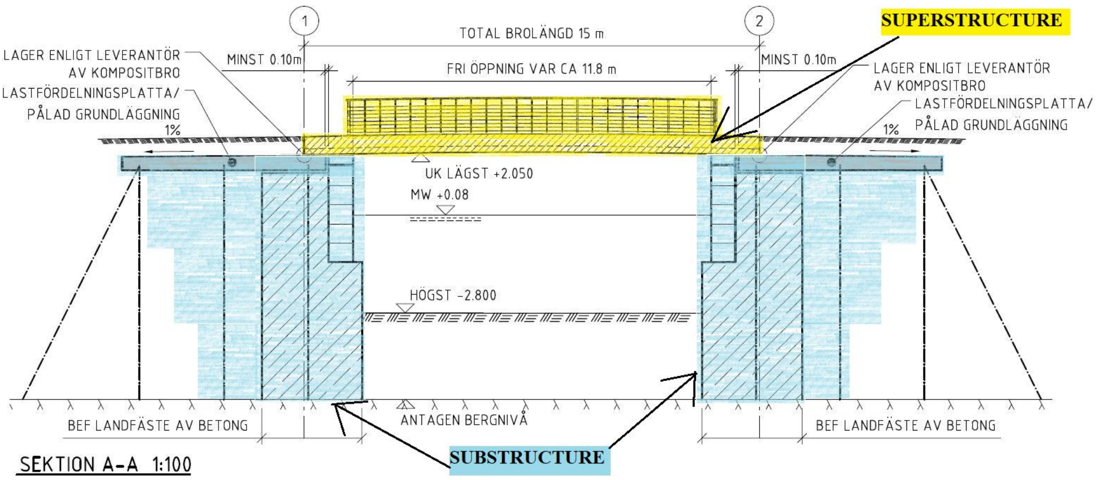


Figure 3-1 *Superstructure and Substructure (Original design-drawing by Malmö City, modified by author).*

A design that usually focuses on material efficiency is the truss bridge design. The thing with this structure type is that it should be constructed in such a way that the load is only distributed by compression and tension. This can produce interesting structural systems that can pick one’s curiosity (force distribution, how is the load distributed throughout the system?). Even more interesting and beautiful bridges (by taste) are produced when arches and cables come into play. The forces from the traffic in arch design are transferred to the supports or abutments through an arch. Vast spans are covered by combining trusses, arches and cables.

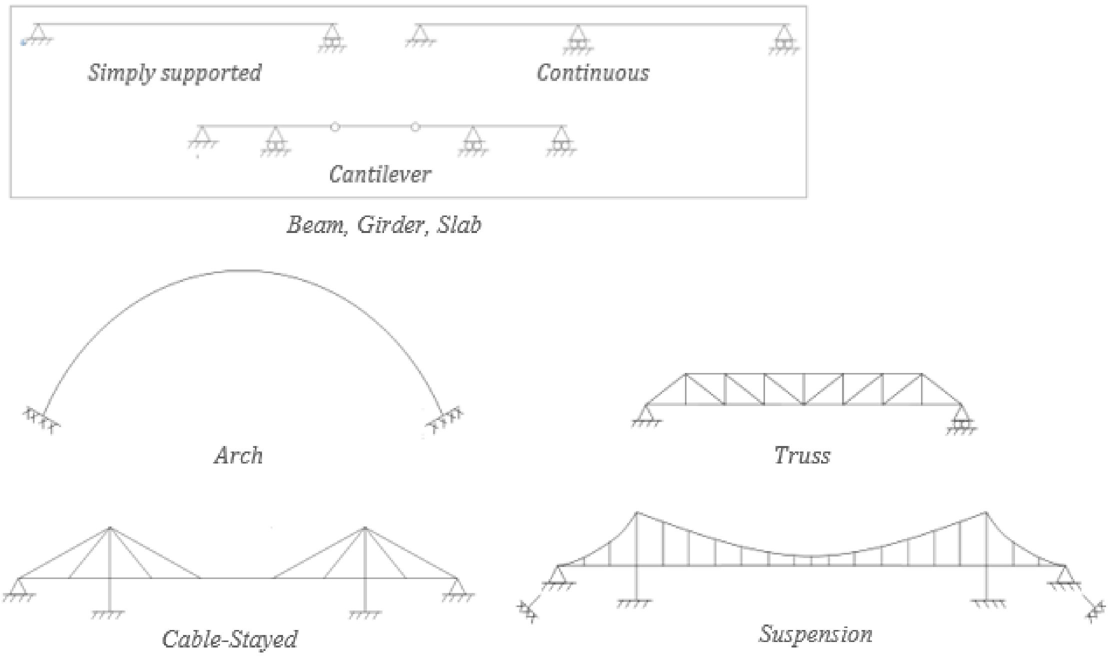


Figure 3-2 *Bridges, structural types.*

Most of the mentioned designs, somehow usually rest on some form of a bridge seat. The bridge seat together with abutments, supports, piers, wing walls, foundation, etc. are categorized as parts of the substructure.

The load from the structure itself, the wind and the traffic on the bridge is evenly distributed by elements of the superstructure. The forces then flow throughout the superstructure down to the substructure, often via bearings. There is a variation in bridge design where bearings are used and not used. The forces from the loads are finally collected into the foundations that are part of substructure and dispersed into the ground.

Bridges are categorized by many factors. Making the list short, bridges can be categorized by type of traffic loads, structure and material. The types that are often categorized by type of traffic loads are bridges built for vehicles, trains or for pedestrians. There are of course combinations of the three types. This report mostly handles simply supported slab bridges, superstructures and pedestrian bridges.

The list below shows a brief overview of a pedestrian bridge life cycle and how it can be organized.

I. Design and planning
II. Tendering
III. Construction
IV. Operation and Maintenance
V. End-Of-Life

The different tasks in the list speak for themselves and what is done at each individual one, no deeper description will be given. But for the sake of this project and its subject, some overview description on designing a pedestrian bridge superstructure, is of interest.

To define the bridge project and design it, both on a preliminary and on a detailed level, some key information is needed. Such data can be categorized by the following list (fib, 2000),

⇒ Geotechnical data about the site and obstacles.
⇒ Technical data about the site.
⇒ Technical data about the obstacle to be crossed.
⇒ Technical data about the new bridge.
⇒ Environmental data.
⇒ Political and economic aspects.

The design and calculation of pedestrian bridge's superstructure procedure would probably begin by defining and stating the general conditions at the specific building site. The conditions are usually governed by the sites shape and form, and by those conditions is a bridge geometry extruded. The site governs aspects as the length of the superstructure span, its thickness, how many internal supports and the foundation design (depending on the soil type). Some other general conditions are, load, environment conditions, building materials and building standards (e.g. relevant parts from Eurocode, national standards or other guidelines).
Further on is some extensive work done by analysing and sizing the structural elements. For instance, checking stresses in structural elements, sizing the concrete slab or beam and its reinforcement, deciding heights and thicknesses of steel girders or the thickness of some FRP box beams.

As humans are very sensitive to vibrations in bridges are vibration analyses often highly prioritised and can be crucial in design. Some other analyses that are usually done, are on vibrations, deformation and long-term effects analysis. This can be analysed with help of various computer programs. Much is dependent on what building material is used and on the situation.

Going back to the categories of bridges and expanding the list further. The following are categories that are often used (in combination) to describe a certain bridge.

<u>Flexibility of the superstructure</u>
The flexibility of the bridge superstructure in this context refers to if it is a movable bridge or not. A movable bridge can be further categorized as a bascule, a swing or a lift bridge (etc.).

<u>Span</u>
When categorizing bridges after span types, is it usually done in the way if they are regarded as simply supported, continuously supported or as a cantilever supported bridge. The load bearing element in a simply supported configurations is supported at each end with a set of degrees of freedom. In a continuously supported configuration rests element over one or more intermediate supports. And in a cantilever supported configuration are the elements fixed in one end and free at the other.

Spans can also be categorized by their length. A culvert (a short bridge) is less than 6 meters, minor and major bridges are less and more than 30 meters respectively. Long-span bridges are regarded as 120 meters or more.

<u>Structural type</u>
As mentioned before, bridges can be built in different ways structurally. The types are defined as slab, girder, truss, arch, suspension and cable stayed bridges. The structural type is in correlation to how the forces are distributed and is much dependent on situation at the site and how engineers want to handle loads. This is probably what gives the bridge its character.

<u>Traffic type</u>
Is related to how much load and what load frequency the bridge should be designed to handle. Usually there is a distinction done between pedestrian, vehicle and train bridges or a combination of the three.

<u>Position of deck</u>
Another aspect that maybe many don’t think of, is where the traveling surface is placed in relation to the load bearing structure. The distinction is done by the following manner.

- Traveling surface is in line with or placed over the top of the load bearing structure,
- Traveling surface is in line with or placed under the bottom of the load bearing structure,
- Traveling surface is placed in some manner through the load bearing structure (between top and bottom).

Construction material

It comes quite naturally to distinguish bridges by their building materials and thus making it common way of categorizing bridges, by stating the building material. There are several bridge building materials available today. To mention some, timber, reinforced or pre/post-stressed concrete, steel, iron, stone and FRP composites. A bridge can be built in one material, but that is not always the case. There can be several different materials in one bridge project. However, some complication may come up when multi-material is chosen.

A tricky part could be to get connections between different materials (by design) correctly assembled or sufficiently centred (e.g. theory versus real life execution). Also, to design in such a way that the materials work chemically well together, e.g. that the materials don't deteriorate. A solution (not the only) to some issues could be the current prefabrication method, to construct the bridge in a closed and controlled environment, e.g. a factory. There, an entire bridge could be assembled, loaded on a transporter and shipped of the bridge site for installation.

3.2 Pedestrian bridges

What distinguishes a pedestrian bridge or a footbridge from a vehicle bridge is usually its width and lighter structure. This part of the study tries to find some defining key aspects that only concern footbridges. For instance, how they are perceived, geometrical dimensions, materials, loads, placements, reasons why they are built and how they are erected.

Modern footbridges have become more than a path over an obstacle. As they still fulfil their fundamental task, they have become a space that intrigues and brings joy or simply a place to rest at. Footbridges were built aesthetically pleasant and intriguing in the past, it just that it is becoming more common today.

It could be argued that in recent history (since early 19th century) there have been a lot of focus and energy put on producing cost-effective (serial) structures. And that in turn has led to less space for aesthetics in these structures, like bridges for instance.

The fact that people have a more mental and physical interaction with footbridges contra vehicle-bridges and that footbridges aren't exposed to the same level of loads and infrastructural demands as vehicle-bridges, drives and allows engineers and architects to spend more time, funds, focus on aesthetics and the feel of the bridge together with its surroundings.

Some general guidelines (from construction codes) concerning functionality of footbridges states that a footbridge should not be much smaller than 2 meters in width, that the sloping gradient should be around 6 percent, that the wear surface should have sufficient slip resistance and that the rails should be placed at approximately 1.2 meters above the walking surface.

These guidelines/construction rules are maybe more directed towards urban situations, which include bicycles and wheelchairs. One of the longest footbridges is not much wider than half a meter (The Charles Kuonen Suspension Bridge, in the Swiss Alps) and other footbridge are wide enough to have room for various social activities.

The *"best"* positioning for a footbridge in a certain area is difficult to "standardise", as there a several factors to weight in. The bridge should serve the concerning area in the most optimal way. Though this requires an amount of balancing done between, most effective crossing spot for users in the area, the level of constructional difficulty in the terrain (mountains, open landscape, rivers, complex urban cities, valleys, etc.), size of the budget, level of impact on environment and ecosystems.

The direct effect of footbridges (often) being lighter and smaller would suggest that there is less time, material, machinery, manpower, etc. needed during erection. But the overall erection procedure doesn't differ so much between footbridge and other type of bridges. Bridges in general are either constructed in-situ, off site, prefabricated or in combination of all.

In-situ construction often leads to scaffolding and stationary falsework. The general idea is to build a temporary structure that transfers load from the formwork down to the ground. The structure usually consists of frames or towers that are adapted to the terrain and is often made of steel beams and bars. This method is considered as expensive and is commonly not used over water or other complex obstacles. Mostly because of unreasonable amount of time and material used to construct a sufficiently stable structure over these obstacles.

An 'off site' construction entails that the bridge or parts of it is somehow constructed off site and then transported to site and installed into position (e.g. right next to the bridge crossing or far away – for instance it can be manufactured in Netherlands and be mounted in Sweden). In erection methods like cantilever construction, incremental launching and launching girders is the bridge assembled step by step, either by prefabricated modules or in-situ. In the cantilever construction method is the bridge build gradually outwards from each support until the whole superstructure is connected. The incremental launching method can roughly be described that the bridge pushed out over the supports (if any) from one end to the other. Parts of a bridge can be prefabricated far of site and transported to the location for assembly or optionally can a bridge be completely manufacture at a factory and then shipped of.

Structural objects are evidently constructed to fulfil a human need. Why specifically a footbridge is constructed, could be that as cities expand, new crossings emerge. It could be that an existing crossing with one wider bridge is converted in to two bridges, a footbridge and a vehicle bridge. A vehicle bridge is usually uncomfortable for pedestrians, so a footbridge is build nearby. Newly found opportunities (new technology and materials, financially) that allow for a bridge construction at a location where it was not possible before.

Loads that are considered during design of a footbridge are, pedestrian induced loading, self-weight of structural elements, wind loads and temperature loads. Pedestrian load varies in pedestrian density and speed depending on the bridge location. This loading is treated as vertical loading, dynamic loading (vibrations, fatigue strains) and vertical loading on railings. A key structural criterion that a footbridge should uphold is the comfort criteria. Much due to that vibration can lead to discomfort and induce nausea in people.

3.3 Concrete

Concrete, a building material, composed by a mixture of aggregates, binder (and water). Aggregates is an umbrella name for crushed (or not) rock minerals of different types and sizes, such as sand, gravel, crushed stone, slag, reused concrete or synthetic. Aggregates is what gives concrete it's major compressive strength. The binder that sets, hardens and adheres, is known as cement. There is a distinction done between hydraulic and non-hydraulic cement. The distinction is based on how the cement sets and becomes adhesive, i.e. if it reacts with water or carbon dioxide.

Concrete as a building material have sufficient compressive strength and very low tensile strength. Values extracted from Eurocode EN-1992 states that high strength concrete class has a mean compressive strength of 98.0 MPa and a mean tensile strength of 5.0 MPa. Note the quite large span between the compressive strength and tensile strength, which is quite characteristic for concrete.

The word concrete comes from Latin word concretus, which means compact or condensed. Historically has it been found that humans used this practise (mixing rocks with some form of binder) thousands of years ago. It's been used in different structures, where bridges were some amongst them.

Building a bridge before reinforced-concrete was invented, required often that the concrete structure had to have an arch like form. So that the load would spread evenly through the arc and the forces would mainly act in compression. It was difficult to construct a long concrete slab bridge with a homogenous cross-section longitudinally. Mostly since the loads on the homogenous slab will produce compression and tensile forces throughout the cross-section (flexural loading), as the shape is no longer an arch. Even though concrete has the potential of ultra-high compressive strength, it will still flex and crack duo to its relative low tensile strength. Leading to that the bridge slab will evidently break down, without using most of its compressive strength.

Around the year 1849 did Joseph Monier invent reinforced concrete and the first reinforced concrete bridge was built at Castle of Chazelet in 1875. It is a 16.5-meter-long and 4.0 meters wide footbridge.

The reinforcing steel bars helps to balance out the forces across the cross section. The bars are place at the bottom of a beam (under flexural loading) where tensile forces usually would appear in a simple supported set-up. The reinforcing bars absorbs the tensile forces and allows the beam to utilize its compressive strength capacity. The reinforcing bars are designed so that they yield nearly before concrete reaches its compressive strength peak. This is good from at least two (much related to safety) points of view. Firstly, by reinforcing with steel, the concrete becomes a much less brittle composite material. And Secondly, by creating a margin between cracking of the lower parts of a beam and its ultimate compressive strength, the composite material will allow people to visually see the cracks. These two attributes give people in contact with the structural object time to act (repair, evacuate, etc.) before it collapses.

A clear improvement from plain concrete to reinforced concrete is that it has the potential to, with less material quantity and fewer supports, reach much larger spans.

Concrete in general (reinforced or not) has the good quality of being very adaptive, it can work as a building material in various environmental situations. With the right recipe of ingredients (aggregates, cement, water, additives) can it be used on land, sea or at warm and cold climates.

Other construction elements beside reinforced concrete elements are pre- and post-stressed concrete elements. They were developed nearly before and under the second world war. These are structural elements that are stressed induced by tensioned steel cables or wires. This creates internal stresses or a “buffer” of compressive strength that the element has available to utilize when externally loaded. The terms pre- and post- refers to if stress is applied to the wires before or after the concrete element have cured.

Concrete is a well-used building material in infrastructure. For instance, concrete bridges cover approximately two thirds of all Swedish bridges. It is used in subparts of other material type defined bridges, e.g. in bridge foundation, supports or decks.

3.4 Steel

This thesis will describe construction steel briefly. Further study on iron metallurgy and metallurgy in general, steel properties, steel manufacturing processes and other iron manipulations is recommended, as it gives deeper understanding (e.g. study-literature, thesis on subject, etc.)

Another greatly used and highly appreciated building material is construction steel. It is a material with relatively high compressive and tensile strength and high specific strength (strength divided by density). Which is good as the material is quite heavy compared to other construction materials, its density is roughly about 7800 kg/m^3 (depending on alloy material) (EN 1991-1-1). While for instance concrete have a density around 2400 kg/m^3 (depending on w/c, aggregates, etc.) (EN 1991-1-1) and a carbon fibre epoxy can have a density roughly around 1600 kg/m^3 (depending on the fibre amount) (Gurit, 2017).

Steel is a form of processed iron (alloy), e.g. iron with approximately 2% or less carbon content. There are also alloying materials (copper, silicon, nickel, etc.) included and some unwanted materials that cannot be removed (sulphur, phosphorus).

Steel has been produced in centuries (weapons, jewellery, tools, etc.) and over this time have extensive manufacturing methods with multiple process been developed. The core material, iron, for steel production is harvested from various sorts of ore (magnetite, hematite, goethite, etc). Steel is also produced with already existing steel products (e.g. steel recycling). Steel has a relatively healthy life cycle that starts at the raw ore (or recycled steel), processed, used and recycled (again). The construction steel products that come at end of the manufacturing line are usually different beam profiles, plates or bars. The production line can be extended even further, by adding for instance prefabrication of bridges or other civil structural building-parts.

Historically has iron or steel been used in bridge building some hundred years ago. For instance, have long spanning bridges been built in China of iron chains at the beginning of 1700. The design is quite straightforward, long linked chains or eye-bars crossing spanning over the obstacle with some form of walking deck integrated with the chains. Furthermore, one of the first major all iron bridge was built sometimes around the third quarter of the 18^{th} century. It is called Ironbridge and is built of cast iron (carbon content higher than 2%). Steel was first used in major bridge construction approximately a 100 years later.

Steel products that are used in bridge construction today are usually products such as structural steel, steel cables and reinforcing steel. The key parameters and properties (other than its yield strength) that are highlighted in structural steel are low production cost, its ductility, weldability, notch toughness and weather resistance.

Steel ductility and notch toughness can be tested in a so called Charpy test. It is conducted using a device with a pendulum that falls freely and breaks a test specimen, thus giving sufficient information to calculate the fracture energy. Weldability is dependent on the amount of carbon and the composition of other alloy materials. Less carbon gives higher weldability. This leads to a balancing between strength and weldability, as more carbon gives steel a higher strength.

Steel is just like other building materials affected by the weather, either by sun, rain and winter. Though some steel compositions are (more or less) affected by environmental aspects. One way of make steel more corrosions resistant is by having some extra thickness (sacrificial thickness) that is reactive to the surrounding air. The occurring reaction will after time create a protective film on the steel surface that separates the moist from the steel and ends the corrosion.

Some available construction steel on the market have a tensile strength somewhere between 215 MPa and 570 MPa, to give an idea of magnitude and span. These values are approximate and taken from strength tables (EN 1993-1-1). Tables and charts are usually based on tests performed on various steel products, tables state the minimum strength values from tests. A safety procedure, done to lower the probability of failure.

3.5 FRP

FRP is in relation to concrete and steel quite a new building material. It is applied in construction as reinforcement of concrete, strengthening of structural members and as structural elements and has often been used as a bridge deck replacement material. These decks a mostly fabricated with the pultrusion manufacturing method and made of glass fibres and thermosetting polymers. But there are as well decks that are manufactured by hand layup, mould and VARTM procedures.

The subject is still under research and development and some of the present concerns regarding FRP as a bridge construction material are, the lack of standardization, there are some issue regarding well-functioning connection systems (Mara, 2014) and there is research that investigated if it is a valid sustainable material.

The qualities that often speaks for and drives FRP forward to become a valid building material is its high stiffness and specific strength, together with high fatigue and deterioration resistance. One of its setbacks and a reason why it is not greatly used in bridge construction is its high initial cost.

FRP structural element will, as steel and concrete, behave differently accordingly to the configuration of its constituent materials (fibres, etc.). The FRP element configuration settings are adjusted by type, quantity and direction of the fibres. As other construction materials are dependent on the structural elements cross-sectional geometry and manufacturing method and behave differently depending on other structural interacting materials.

4 Bridge life cycle cost

During the early stages in the production of a bridge a question usually emerges. What construction material to use? Choosing the best material for the situation at hand can be challenging or it could be difficult to identify (at first sight) which material is most economically favourable. Mostly, because there are several construction materials available on the market at present time and they all have their pros and cons.

Thus, by doing a life cycle cost analysis, a good strategy to “tackle” this question is established. This strategy helps to map the various costs that emerge during a bridges entire life cycle and match them with the material pros and cons. It also stimulates the conductor of the analysis to search for all the detailed (or hidden) costs, including aspects other than material costs. Aspects that could be, if missed, “troublesome” later in the bridge life cycle.

4.1 Life cycle of a pedestrian bridge

A typical life cycle of a bridge can be divided in four stages, a production, a usage, a demolition and an end-of-life stage (Dimopoulou, 2015). The production stage contains a lot of activities. Here is the cement for the concrete heated in cement kilns, iron ore melted and shaped to steel beams (or recycled), wood is cut to timber in sawmills and fibres are mixed with resin in the FRP manufacturing processes. Here is the bridge also designed and planed and then constructed. A more organised way of describing the stage could be, manufacturing, transport and installation.

After the production stage when the bridge is correctly constructed and is operational. Follows the next stage, the usage stage. This is the stage that covers most of a bridge’s life, that can span over a hundred years. Meaning, a lot can happen to it and on it.

Then after many years, at its end-of-life stage is the bridge presumably demolished. Here is the bridge dismantled and its different parts handled in various ways. Some parts of the bridge could still be in a good shape and reused in the construction of a new bridge or other structures. Often is the material used in some energy recovery process, material recovery process (steel) or disposed of at a landfill (Mara, 2013).

4.2 The LCCA method

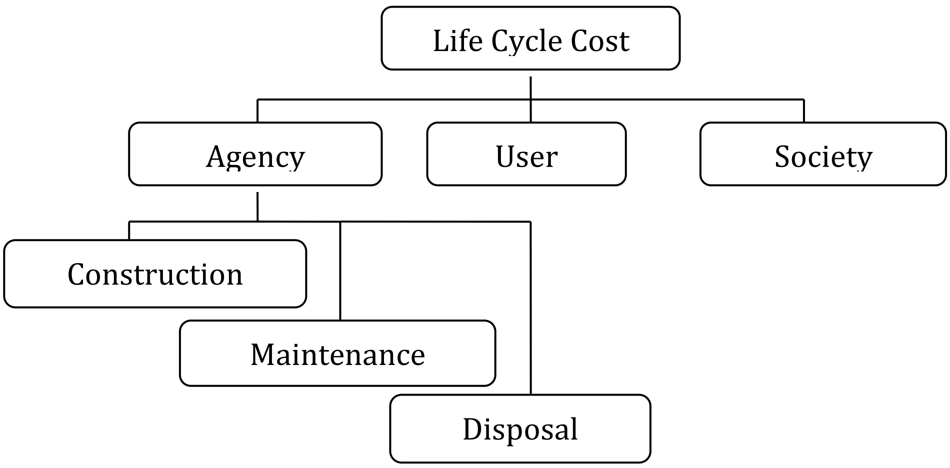


Figure 4-1 Cost categorization in a bridge LCC analysis (ETSI, 2013), edited by author.

A life cycle cost analysis (LCCA) has been proven to be a good way to assess present and future cost of a product. In the current study, the LCCA will be focusing on a pedestrian bridge in Malmö. In practise when conducting an analysis on a bridge, is a life cycle cost analysis divided into three main categories, namely agency cost, user cost and society cost. The description of the LCCA method in this chapter will mainly focus on agency cost, due to the pre-sets in the limits of this project.

A common approach when conduction a LCCA, that is usually used in practice. The steps are the following, establish design alternatives, determine activity timing, estimate costs, compute life cycle costs and analyse the results (Sagemo, 2012).

An LCC analysis usually starts by collecting data on the bridge, identifying all the parameters of interest and creating boundaries. Much of it is a straight forward procedure, though a challenging part could be to assume reasonable maintenance activities when comparing different building materials. The next step is to obtain and estimate costs and time intervals, for the considered parameters/activities. This is mostly founded on data from agencies, consultants and manufactures that are involved. The assumptions and simplifications of costs and time intervals usually depends on how detailed the available and included data is. After all the information have be assembled, can the analysis be carried out and the results analysed. Proposal wise can tables and various of graphs be created and studied.

There are some available LCCA tools, Excel-workbooks or other developed techniques to use when conducting a LCCA. In a project called ETSI was an Excel based tool developed (ETSI, 2003). It is called Bridge-Stand-alone-LCC and was used in the initial stage in this project. It allows the user to enter parameters such as bridge dimensions, materials used, maintenance activity costs, etc. The tool then accumulates all the agency, user and end of life costs and presents the results in an ‘present value’ form.

4.3 Present value

The life span of a bridge can stretch up to 120 years. That gives rise for considerations in a LCCA regarding future value of currency and its correlation with present currency value. Present value method is often used in LCCA to assemble all the future approximated costs to a single present value.

A known method to assess value of currency over time is the Net Present Value (NPV) method. It is tuned by using a discount rate that varies depending on who is conducting the LCC analysis. Public sectors tend to use a lower rate somewhere between 2% - 5%, while the public sector usually favours a high rate that varies between 2-15% (Langdon, 2007). There are two variations of discount rate, ‘real’ discount rate and ‘nominal’ discount rate. The difference between the two is that an estimation of future inflation is considered in the ‘nominal’ discount rate and not in the ‘real’ (Sagemo, 2012). The Swedish Transport department is recommending at present date a discount rate of 3.5% (Trafikverket, 2017).

The Net Present Value is calculated in the following manner (Safi, 2012),

$$NPV = \sum_{n=0}^{L} \frac{C_n}{(1+r)^n} \quad (4.1)$$

NPV - Life-cycle cost expressed as a present value.
n - Year considered.
C_n - Sum of all cash flows in year n.
r - Discount rate.
L - Service life-span.

As an example, assume that a maintenance, rehabilitation and repair (MR&R) activity occur on a bridge ever 20 years and costs 15 000 SEK each time. Assume as well, a 3.5 % discount rate, that the life span of the bridge is 80 years and that the disposal of the bridge will cost 100 000 SEK. Then a present value can be calculated in the following manner:

$$MR\&R\ Activity\ 1\ at\ year\ 20{:}\ NPV_1 = \frac{15\,000_{20}}{(1+0{,}035)^{20}} = 7\,538\ SEK$$

$$MR\&R\ Activity\ 2\ at\ year\ 40{:}\ NPV_2 = \frac{15\,000_{40}}{(1+0{,}035)^{40}} = 3\,789\ SEK$$

$$MR\&R\ Activity\ 3\ at\ year\ 60{:}\ NPV_3 = \frac{15\,000_{60}}{(1+0{,}035)^{60}} = 1\,904\ SEK$$

$$Demolition\ Activity\ 4\ at\ year\ 80{:}\ NPV_4 = \frac{100\,000_{80}}{(1+0{,}035)^{80}} = 6\,379\ SEK$$

$$Sum\ of\ NPV = 19\,610\ \approx 20\,000\ SEK$$

This can be interpretation as if 20 000 SEK are reserved today, then with a 3.5 % discount rate they can grow over time and cover the future coming bridge activities. 7 538 SEK of the 20 000 SEK will grow and cover the first activity that will come after 20 years, 3 789 SEK for the next and so on.

Tabell 4-1 A representation of the example on NPV calculations.

Present Value [SEK]	Year			
	20	40	60	80
	Activity cost [SEK]			
7 538	→ 15 000			
3 789	→	15 000		
1 904	→	→	15 000	
6 379	→	→	→	100 000

Having different bridge concepts and materials in an LCC analysis leads to different life spans. That makes the NPV method insufficient as the method is lifespan dependent, thus leading to incomparable analysis. The Equivalent Annual Cost (EAC) method can then be used to make a reasonable comparison between two bridge concepts with unequal life-span. It allows for calculation of a yearly cost of owning and operating the bridge, representing the entire bridge life span. Formulated in the following manner (Sati, 2012),

$$EAC = NPV \times A_{t,r} \quad (4.2)$$

$$A_{t,r} = r/\big(1-(1+r)\big)^{-L} \quad (4.3)$$

EAC - Equivalent annuity cost.
$A_{t,r}$ - Annuity factor.

4.4 Agency

Costs that fall under the category 'agency cost' is a sum of construction costs, end-of-life (disposal) costs and cost that emerge from maintenance activities. In the construction subcategory (see figure 4-1) lies in general all cost related to the materials used to construct the bridge, costs for transportation of materials to the building site and for costs for installing the bridge. The bridge construction approach is connected is Construction costs as well. For instance, a prefabricated approach with structural parts delivered to the building site and mounted into place using a crane could give different cost compared to an in-situ construction approach or compared to a mixed approach. Some other variables that effect the Construction costs and again the construction approach is, the bridge geometry and the accessibility to the construction site. Which suggest that the detail level of a LCCA and how accurate its results are depends on the considered complexity level of the bridge construction process together with the detail level of its entire life.

Maintenance and reparation activities are presumably going to occur over the entire bridge life span. Which means that a lot of estimation of future activities and their costs are going to be needed. The planning and cost estimation of these actions are usually built on the knowledge gained from past and presently constructed bridge objects. Much of this information, on maintenance and repair related cost, gathered and stored in digital databases. One such (online) database is the Bridge and Tunnel Management (BaTMan) database (BaTMan, 2017). The values in table 4-2 is an extract from the BaTMan data base, from 2016.

Tabell 4-2 An extract from BaTMan, in 2016.

Activity	Unit Price	
Bridge deck concrete reparations (0-30 mm)	3 000	SEK/m^2
Main or cross beam patch painting	2 500	SEK/m^2
Main or cross beam repainting	2 000	SEK/m^2
Edge beam impregnation	500	SEK/m^2
Edge beam concrete reparation (0-30 mm)	4 200	SEK/m^2
Edge beam replacement	13 000	SEK/m
Insolation removal	700	SEK/m^2
Insolation completion	1 700	SEK/m^2
Insolation replacement	3 300	SEK/m^2
Surfacing adjustment	700	SEK/m^2
Surfacing replacement	1 000	SEK/m^2
Bearings repainting	9 100	SEK/m^2
Bridge seat concrete reparation	6 000	SEK/m^2

BaTMan is an online based bridge and tunnel management system developed by the Swedish transport administration. It was released in 2004 and has been a helpful tool to agencies, consultants and planers since its release (Trafikverket, 2017). The system contains structural information of bridges, their status and cost approximations on maintenance and repair activities. It can be used when conducting a LCCA to organizing needed bridge maintenance and repair actions (Safi, 2012).

The end of life subcategory contains estimations on what it would cost to demolish the bridge and to take care of its (waste) material. It requires an estimation on when the bridge will be in such a deteriorated state that it loses its ability to fulfil its designated function and a plan needs to be establish of the disassembling procedure. For instance, what to with the (waste) materials (concrete, steel, timber, FRP, etc) are they to be recycled or reused in some way or placed into landfills.

Agency costs in this LCCA are accumulated in the following manner (equation 4.4). The capital 'C' stands for costs and the sub-notation (n) in C_n denotes the respective category.

$$C_{agency} = C_{constriction} + C_{remidal} + C_{end\ of\ life} \qquad (4.4)$$

4.5 Other costs

As mentioned previously, bridges need maintenance during their entire life. Some of these maintaining activities could be, removing salt and gravel that was used during winter seasons, prolong life span and slow down (or stop) deterioration by repainting different structural parts, or restoring the bridge deck (edge-beams, overlays, etc). And most of these activities will create disturbance and delays in the traffic passing over or under the bridge. Which then leads to increased expenses for the bridge users.

User cost are usually considered when conduction LCCA on road and rail bridges and disregarded for pedestrian bridges. They are an estimation on the cost of increased user travel time. These estimations depend on how the maintenance activities are proceeded (e.g. is the bridge completely closed or are parts of it open for traffic). And that in turn determines other aspects to consider. Such as, if it's a car or truck traffic (e.g. traffic density, type of cargo and value of the time elapsed), length of detour and the additional time contra normal conditions, how "clogged" is the pathway (e.g. stopping and slowing, delay time). Useful data and information for assessing user cost in a LCCA can be acquired from administration agencies or from conducted researches. User cost can be implemented into a LCCA by the following manner (Safi 2012),

$$C_{user} = C_{delay} + C_{vehical\ operating} \qquad (4.5)$$

A more detailed calculation and further information on how user cost is implemented in LCCA can be found in the reports from a research project called ETSI (ETSI, 2013).

Costs from social and environmental impacts are some other often considered aspects in LCCA. This is a rather broad cost category where social aspect such as accidents, fatalities and health care cost are estimated. Cost estimations on safety establishments both for workers and residents. Economical aspects such as disturbances to the ongoing business or commercial activities. Noise (vibrations) and dust emissions that emerges during construction or maintenance activities. These are all viewed from a social welfare perspective and cost assessed into the LCCA.

The bridge construction and maintenance activities affect the environmental as well. Cost assessments that could be considered into a LCCA are for instance cost concerning green gas emissions and other pollutions. Here is where LCCA and LCA starts to complement each other. Life-cycle assessment (LCA) is a framework for assessing a products impact onto the environment thought out its entire life (Mara, 2014).

4.6 LCCA tool

The LCC analysis is done with the help of ETSI Bridge LCC tool, an Excel-workbook program that was developed by the ETSI project team. The program allows the user to enter input data concerning general agency costs (Construction, MR&R and end-of-life costs) and user costs. The excel program processes the input data and then prints the results in the form of tables and graphs. The ETSI project was a collaboration between Nordic road authorities, universities and companies with the goal to develop methodology and tools for analysing the life cycle of bridges (ETSI, 2012). The project was conducted between 2006 and 2013.

The workbook's interface is designed for steel and concrete, but the algorithms for cost calculations and currency conversion works well with other construction materials as well. Much due to the fact that Microsoft Excel is good platform for such studies (e.g. new Excel-sheets can be built on the current ones and extended the tool).

5 Neptuni-bridge

The LCCA and case study in this project is conducted on a pedestrian bridge in Malmö that is currently under construction and is estimated to be completed in summer 2019. The bridge is called Neptuni-bridge and is part of a bigger project that is currently transforming an industrial zone in a central part of Malmö to an area with a high environmental profile and place for education, research, housing, culture, recreation and other social activities (Malmö, 2017). The new crossing (same site, new bridges) will consist of five independent bridges. The bridge that is considered in this LCCA is the pedestrian bridge circled in black, in figure 5-1.

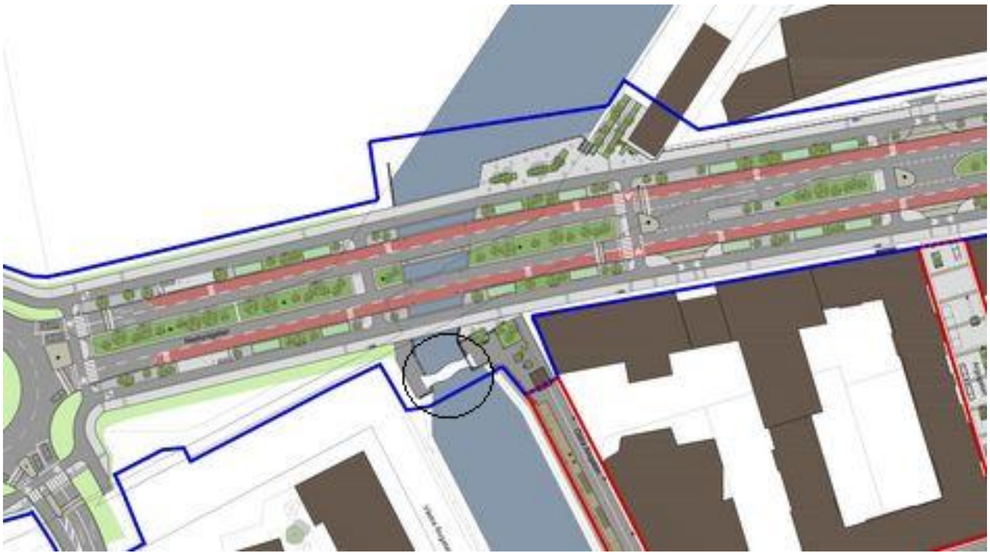


Figure 5-1 A section from the Malmö City project situation plan. The New Neptuni-bridge's (Malmö, 2017).

The Neptuni-bridge will be constructed with FRP material and have a wave curved shape. It will be an important link in the area as it helps stretching a current boardwalk even further.

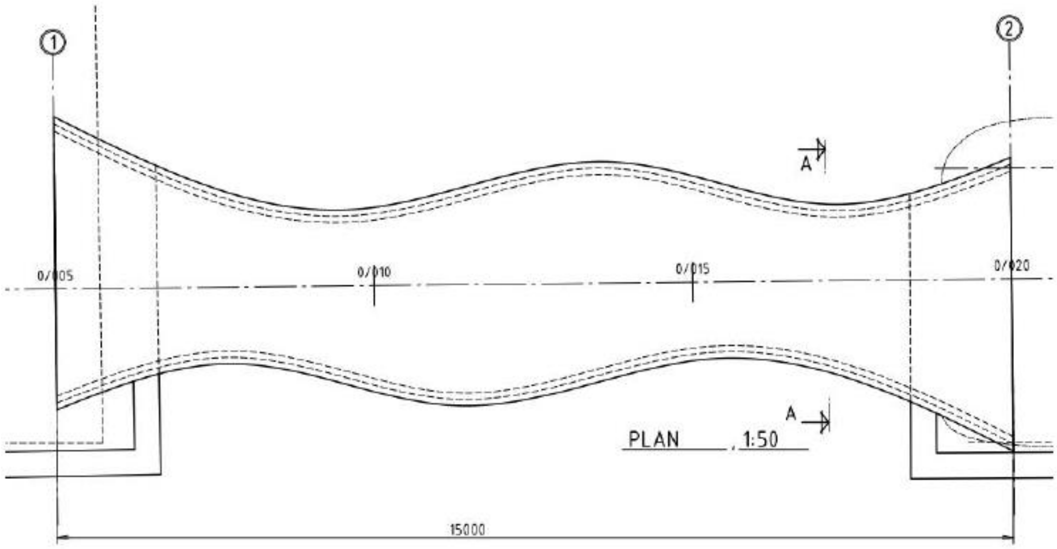


Figure 5-2 A plan view of the new Neptuni pedestrian bridge (Centerlöf & Holmberg).

5.1 Case study

The general case states that the bridge has a curvaceous varying width. Loads considered on the bridge are pedestrians and bicycle traffic, service vehicles, weather conditions and the bridges own self-weight. The case study will examine what the cost turn-out will be if different materials are used for the superstructure (the deck). The cases that are evaluated are, a pure concrete solution, a steel/concrete solution and three different FRP solutions.

Tabell 5-1 The considered cases (solutions) used in the study.

Case	**I**	**II**	**III**	**VI**	**V**
Bridge type	Concrete slab	Concrete deck & steel girders	GFRP box beam	CFRP slab	GFRP slab
Designer/ Manufacturer	Centerlöf & Holmberg	Centerlöf & Holmberg	Diab, Podcomp, Velox	Marstrom Composite, Composite Design	FiberCore Europe

<u>*General design constraints and values:*</u>

- *The effective bridge width and length, 2.5 m respectively 15 m.*
- *The area of the bridge is approx. 48 square meters.*
- *Characteristic traffic load (pedestrian, bicycle) is 5.0 kN/m^2. That gives two load cases in ULS (due to safety variables). One at 1.3 kN/m and the other at 3.0 kN/m. The load is distributed over the bridges width (5.0 m / 2.4 m)*
- *The service-vehicle axial point loads are 40 kN at the front and 80 kN at the back.*
- *It has a ULS safety class 3, by Eurocode standards.*
- *The exposure class is set to XD3/XF4 (marine environment), by Eurocode standards.*
- *The bridge is allowed to deflect a maximum of 37 mm (L/400) in the downwards direction, by Eurocode standards.*

5.2 Case one - A Concrete slab

The first bridge design solutions the bridge superstructure is a concrete slab. The design drawings are composed by the engineers at Centerlöf & Holmberg. It is designed for a service life of 100 years. The slab structure is made of concrete class C35/45 with a cover thickness of 55 mm. The walking surface is of asphalt (PGJA) and is approximately 65 mm thick. The total thickness of the slab is 565 mm. The reinforcement quality is of class B500b with a total reinforcement weight of approximate 100 kg per cubic meter. The entire bridge superstructure weighs roughly 70 tons with a total volume of approx. 27 cubic meters.

<u>*Case specific design loads:*</u>

- *Load due to concrete slab self-weight is approximately 44,7 kN/m (ULS factors excluded).*
- *Dynamic loading: The bridge's first natural frequency is around 2.7 Hz.*

<u>*Case specific deformations:*</u>

- *The bridge is estimated to deflect downwards appro. 6 mm and upwards approx. 88 mm.*
- *Pedestrian comfort criteria (Perception of vibration): The bridge vertical acceleration is approximately 1.2 m/s^2. Which is acceptable since it is below 1.5 m/s^2.*

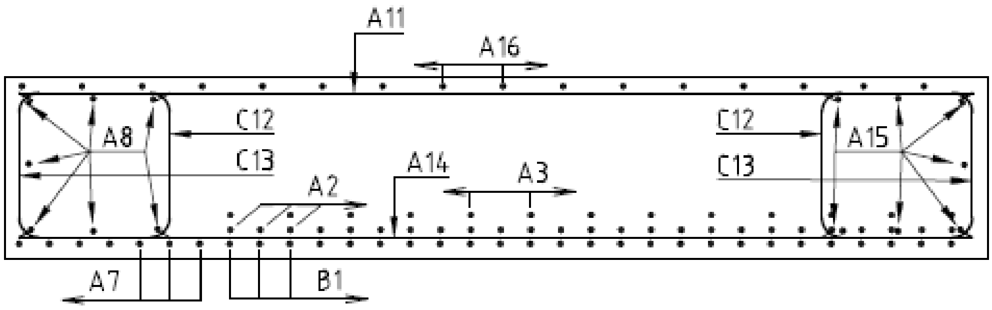


Figure 5-3 The cross-section of solution one at mid-span, designed by Centerlöf & Holmberg.

The planed erection method is an in-situ construction with scaffolding and piling. The piling seems manageable and costly reasonable, as the drawings show that it is approximately 2 meters from the waterbed to solid rock.

5.3 Case two - Composite, Concrete Deck on Steel Girders

Case two is a concrete deck and steel girder solution. The two longitudinal steel girders (main girders) span from side to side and are stabilised with three cross-beams (two at the ends, one in the middle). The concrete deck is bolted to the girders and is almost half as thick as the slab in case 1. The steel girders are roughly 330 mm high and 300 mm wide and weigh together approx. 3900 kg. The concrete deck together with the PGJA covering surface is 265 mm thick and weighs approximately 33.5 tones.

Case specific design loads:

- *Load due to concrete slab self-weight is approximately 22,3 kN/m and due to steel self-weight approximately 2.6 kN/m (ULS factors excluded).*
- *Dynamic loading. The eigenfrequency of the bridge is 3.4 Hz.*

Case specific deformations:

- *The bridge is estimated to deflect downwards approximately 6.5 mm.*
- *Pedestrian comfort criteria: The vertical acceleration is below 1.5 m/s^2*

The planed erection method for this case is a form and off/in-site construction with craning. The concrete slab is to be prefabricated in a factory and joined with the steel girder structure. The whole superstructure is then transported to the bridge site and craned in to position. Some falsework and scaffolding may be needed to ease the installation job. The prefabrication cost is assumed and estimated here. The assumption is that the concrete deck costs the same as case one, except the cost for the scaffolding, i.e. same cost per unit is applied, except the scaffolding.

(An alternative: The overlay/paving can be applied after the superstructure have been placed in position. The steel girders together with the concrete slab would weigh less then, but this would lead to more time spent and in-situ costs.)

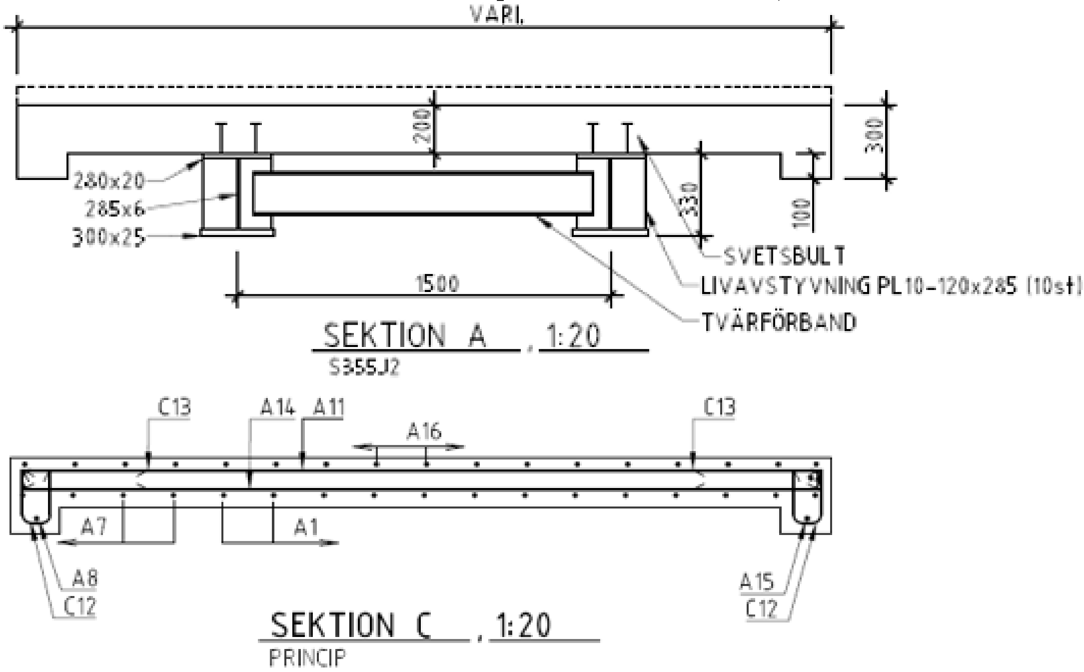


Figure 5-4 Two sections from solution two, designed by Centerlöf & Holmberg.

5.4 Case three - GFRP box beam

The first FRP concept is a glass fibre reinforce polymer (GFRP) box beam solution designed and developed by DIAB, Podcomp and VELOX. The deck has a surface overlay that is made of polymeric concrete which is placed on top of a protective layer made of GFRP. The decks main structural load bearing element is a box beam in the centre of the cross-section (figure 5-5). The box beam is made of a thin (10 to 20 mm) GRFP material and the prepreg process is used in the manufacturing of the GFRP material in this case. The box is beam is also filled and surrounded with a low-density thermoplastic foam. The cap layer (approx. 5 mm) envelopes both the foam and box beam and is made of GFRP material and painted with a polyurethane paint (Swerea, 2017). The overall weight of the deck (superstructure) is approx. 9.5 ton.

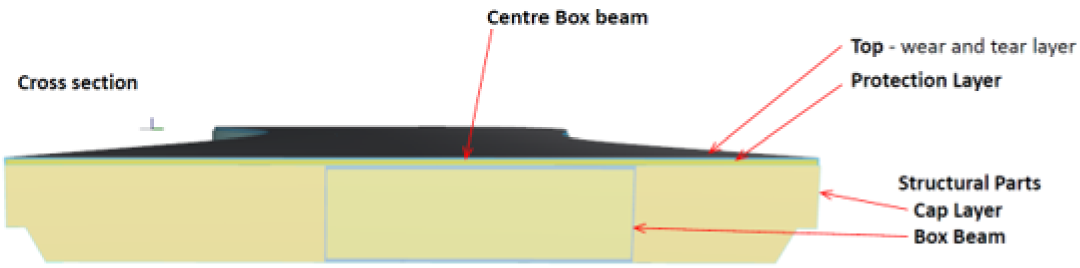


Figure 5-5 A cross-section of the case three solution (Diab, 2017).

The erection method is a type of of-site construction and craning and will be the same for all the FRP solutions. The entire superstructure is to be pre-fabricated at a manufacturer and transported to the construction site. The superstructure will then be lifted by carne and installed into position. The crane type and size will be adapted to the weight of the different FRP solutions, as they vary somewhere between 5 to 10 tons. There will presumably (with high security thinking) be no need for assisting framework or scaffolding.

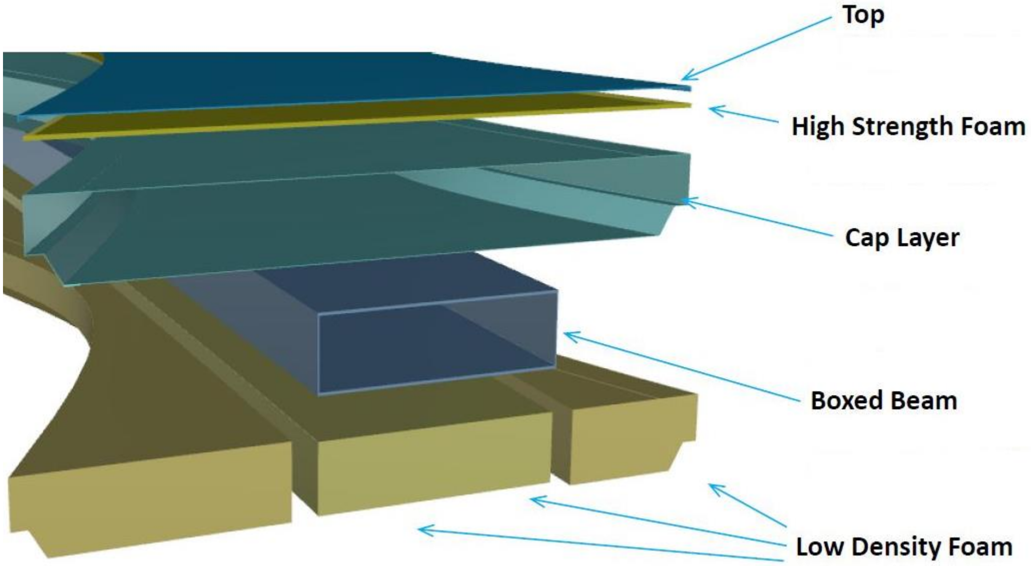


Figure 5-6 A blow-up view of the case three solution (Diab, 2017).

5.5 Case four - CFRP beams

The next bridge design is composed of longitudinal beams made out of carbon fibre. It is developed by the FRP manufacture and design companies Marstrom Composite and Composite design. The superstructure consists of several beams that are glued together. The deck superstructure is approximately 35 mm thick and the weighs approximately half of what the GRFP solution (case 3) weighs, i.e. approx. 5 ton. The walk surface is made out of a thin carbon FRP layer. An approximation on the manufacturing costs and its activities can be seen in table 5-1.

Tabell 5-1 Superstructure cost, case four (by Marstrom Composite).

Superstructure cost	
	Cost [SEK]
Carbon fibre glue consumption Siporex	720 000
Siporex and glue	120 000
Edge element laminate	68 000
Top laminate injected	70 000
Colour surface	65 000
Construction Time	820 000
Construction	80 000
Total	1 943 000

5.6 Case five - GRFP slab

The final case is the actual design solution for the Neptuni-bridge. The bridge is manufactured by FiberCore Europe in the Netherlands. It is to be shipped from the Netherlands to Sweden and installed in Malmö. The bridge is designed with the patented InfraCore technology.

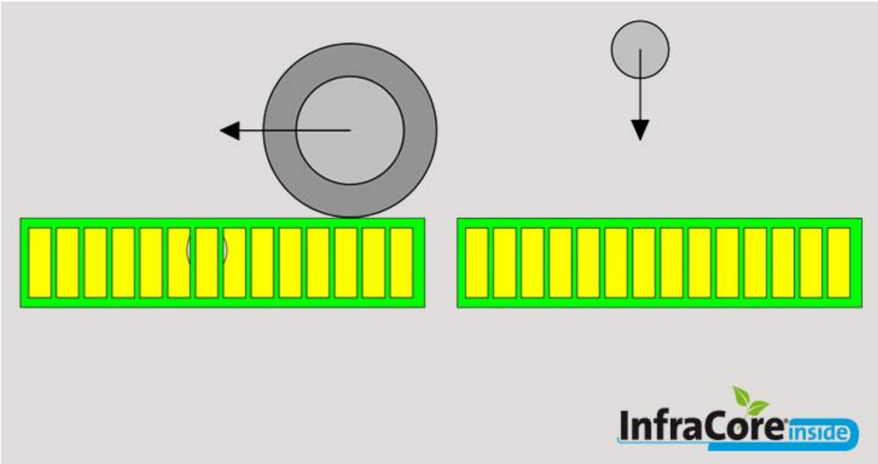


Figure 5-7 Element cross-section illustration, InfraCore technology (FibreCore Europe, 2017).

FibreCore Europe has good video describing the technology on their homepage. But briefly, it is a form of sandwich-element multi-beam plates structure. With the intention of combining the good properties from both worlds, without the drawbacks (FiberCore Europe, 2017). Vacuum infusion process is used to manufacture the superstructure and the FRP layers contain fibres placed in multiple directions.

The shape of the slab superstructure can be found in figures 5-1 and 5-5 and its thickness is approximately 600 mm. The superstructure weights approximately same as the case three solution, i.e. roughly around 10 ton.

6 Life cycle cost analysis

The purpose of this analysis is to investigate life cycle cost of the planned Neptuni-bridge and with Neptuni-bridge as a basis, compare alternative designs (e.g. different materials). In the task of comparing the different bridge designs, it became quite early clear that common cost in-between the concepts were irrelevant and thus omitted (i.e. they did not produce any contrast).

Amongst the commonly used LCC analysis categorises agency, user and society costs, only agency cost is considered in this project. Most costs that are included in the user category are absent here as this project deals with pedestrian bridge, thus user costs can be omitted. The society and environmental cost are omitted, simply because there is not enough time to investigate that as well. This LCC analysis will only regard the life cycle of the Neptuni-bridge *superstructure.*

Tabell 6-1 General input data for the LCC analysis

Life span	100 years
Discount Rate	3.5 %
Length	15 m
Width	3.2 m
Area	48 m^2

6.1 Construction

The construction costs that are used in this analysis are estimated with the help of consultants that have expertise in bridge construction and as well from FRP manufacturers DIAB and Marstrom Composite. The cost estimations included such aspects as installation, transportation and manufacturing.

Tabell 6-2 Construction cost input data that are used in the LCC analysis.

Moment	Unit Price	
Scaffolding and Falsework	4 000	SEK/m^2
Formwork on scaffolding and falsework	1 800	SEK/m^2
Only Formwork	700	SEK/m^2
Concrete	2 500	SEK/m^3
Reinforcement	17 000	SEK/ton
Structural steel elements	60 000	SEK/ton
Surfacing	-	-
Surfacing & insulation	1 000	SEK/m^2
Bearings	10 000	SEK/pcs
FRP	-	-

6.2 Maintenance and repair

The maintenance and repair costs are estimated with the help of data stored in BaTMan, consultants with expertise in bridge maintenance and on data from previous works (projects, thesis). Anticipating future maintenance activities and costs for FRP is difficult as FRP is relatively new in bridge construction context, compared to already established construction materials. Leading to the assumption of only surface replacement activity for all three cases. Concrete and steel have been used many years and thus making it little bit easier to anticipate activities, thou not entirely easy as these bridges are constantly improved. MR&R costs for each case used in the analysis are presented in table 6-3.

Tabell 6-3 Overview of MR&R cost input data used in the analysis.

Case	Part	Activity	Interval [yr.]	Unit Price	
One - Concrete slab	Insulation	Repair	30	1 700	SEK/m^2
	Surfacing	Replace	30	1 000	SEK/m^2
	Edge beam	Impregnation	25	500	SEK/m
Two - Composite Steel & Concrete	Insulation	Repair	30	1 700	SEK/m^2
	Surfacing	Replace	30	1 000	SEK/m^2
	Edge beam	Impregnation	25	500	SEK/m
	Steel girders and beams	Repaint	30	1 700	SEK/m^2
	Bearings	Repaint	30	9 100	SEK/pcs
Three - GFRP box beam	Surfacing	Replace	30	1 000	SEK/m^2
Four - CFRP slab	Surfacing	Replace	30	1 000	SEK/m^2
Five - GFRP slab	Surfacing	Replace	30	1 000	SEK/m^2

There was a recent research on deterioration rates in bridges conducted in USA (Hurt, 2016). The results of the collected data show that a change from a condition of no deterioration to a condition somewhere in-between minor and serious deterioration in steel abutment bearings took approx. 45 years. It took 59 years for elastomeric abutment bearings to reach the same deterioration level. Results for superstructure elements such as slab or steel plate girders showed 47 and 60 years respectively to undergo the same deterioration span.

6.3 End-of-life and demolition

The assumption is that the concrete in case one will be dismounted onto some sort of a vessel (boat, raft, etc) and then disposed of. The steel in case two generates a profit (e.g. recycling) and is relatively simple to dissemble. The FRP bridges will presumably be craned on to some sort of transportation (land) vehicle and shipped of to a recycling plant. End of life and demolition cost are based on feedback from consultants and on previous project data.

Tabell 6-4 Overview of End-of-life and demolition cost used in the analysis.

Case	Activity	Quantity	Unit cost	
One - Concrete slab	Disposal of concrete	58 ton	500	SEK/ton
	Vessel	-	75 000	SEK
Two - Composite Steel & Concrete	Disposal of concrete	14 m^3	500	SEK/ton
	Vessel	-	75 000	SEK
	Disposal of steel	-	12 500	SEK
Three - GFRP box beam	Craning	-	10 000	SEK
	Disposal of FRP	10 ton	1 000	SEK/ton
Four - CFRP slab	Craning	-	10 000	SEK
	Disposal of FRP	5 ton	1 000	SEK/ton
Five - GFRP slab	Craning	-	10 000	SEK
	Disposal of FRP		1 000	SEK/ton

The cost estimation regarding the disposal of FRP in this case study is generalized for all the FRP cases. Meaning that there is an end-of-life cost variation depending on the FRP material composition. The cost estimation is built on a previous doctoral project work done by Valbona Mara (Mara, 2014). The project deals with aspects such as bridge decks of fibre reinforced polymer and sustainability. Note that the price is bound to the case-study preformed in that project. The price has a reference to Fibreline Composite Sweden

6.4 LCCA results

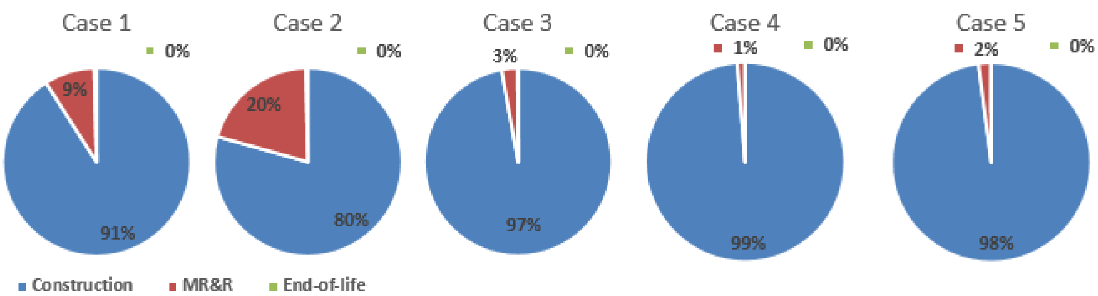


Figure 6-1 LCC results in percent of present value.

The result of the LCC analysis is presented in figure 6-1. All life costs are converted to present value except for construction cost (e.g. initial cost). The blue part in figure 6-1 is the construction cost and covers major part of the life cycle cost in every case. Maintenance costs (red) in the first two cases (concrete & steel) covers a notably large portion of their respective life, compared with the three FRP cases. Case two has the largest MR&R cost, mostly due to the need of steel repainting. The end of life cost (green) can be disregarded here as they almost reach zero percent.

Tabell 6-5 LCC by category. Note that the costs in column three are not discounted.

Case	Category	Net Present Value [SEK]
One - Concrete slab	Construction	769 000
	MR&R	73 000
	End-of-life	3 400
	Total cost	845 400
Two - Composite Steel & Concrete	Construction	595 000
	MR&R	152 000
	End-of-life	2 600
	Total cost	749 000
Three - GFRP box beam	Construction	920 000
	MR&R	26 000
	End-of-life	700
	Total cost	946 700
Four - CFRP slab	Construction	2 069 000
	MR&R	26 000
	End-of-life	500
	Total cost	2 095 500
Five - GFRP slab	Construction	1 275 000
	MR&R	26 000
	End-of-life	700
	Total cost	1 301 700

Table 6-5 shows that FRP case four has the largest initial costs, making it the most expensive alternative. The case with concrete and steel girder composite has the lowest initial cost and case one (concrete slab) has the lowest total costs overall. Amongst the three FRP cases is number three the cheapest one in this study.

Figure 6-2 considers only the maintenance costs in the LCCA and show that the FRP designs have substantial lower maintenance costs. In addition to the *surface replacement* activity that exist in almost all cases, activities such as *insulation repair*, *edge beam impregnation* and *repaint of steel surfaces* increase the costs for cases one and two. Note that the costs in figure 6-2 are not converted to present value.

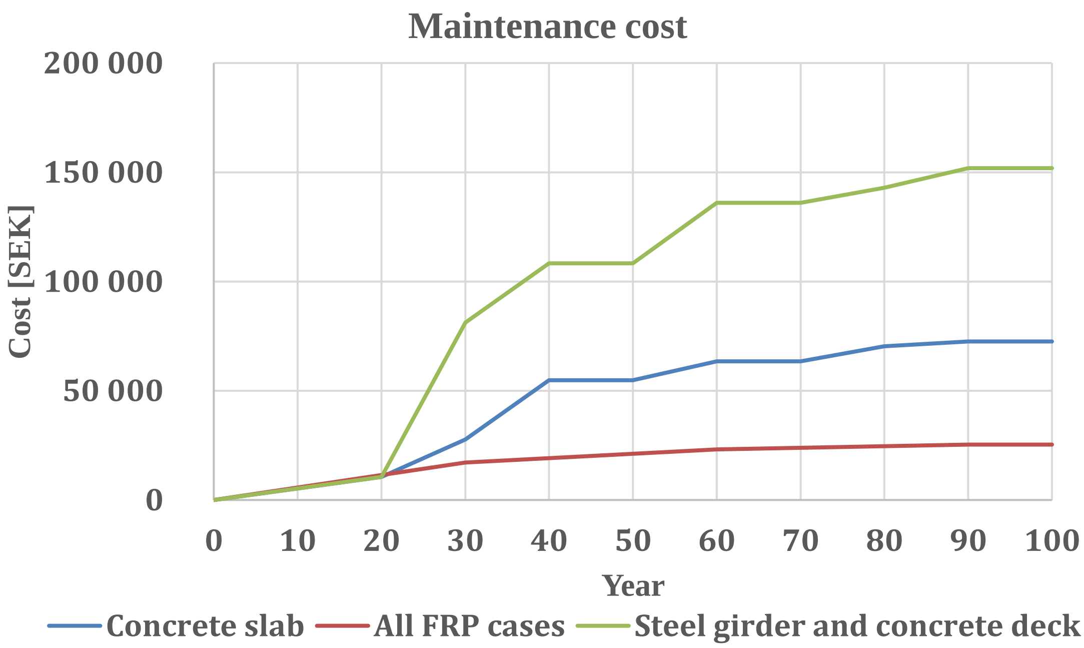


Figure 6-2 Graph over life cycle maintenance costs.

6.5 Sensitivity analyses

A sensitivity analyses is done to see how much some key parameters in the LCCA affects the resulting costs. The analysed parameters are discount rate, cost of the FRP material, edge beam impregnation period and alternative maintenance activate, edge beam replacement.

The discount rate has a high effect on the present value cost and will therefore be investigated. The costs effects of a discount rate between 2 % and 6 % will be examined. Another interesting parameter in the LCCA is the cost of glass and carbon fibre used to manufacture FRP bridge elements. The market of carbon fibre is in particular difficult to predict (Andre, 2018). So, a part of the sensitivity analysis will to investigate the costs effect of a 40 % drop and a 25 % raise in FRP material cost. It is also interesting to see how the edge beam impregnation frequency affects the total maintenance cost. The investigated frequency is every 20 years and every 30 years. And finally, as there are other options of edge beam maintenance, it is interesting to compare edge beam impregnation and edge beam replacement.

Discount rate

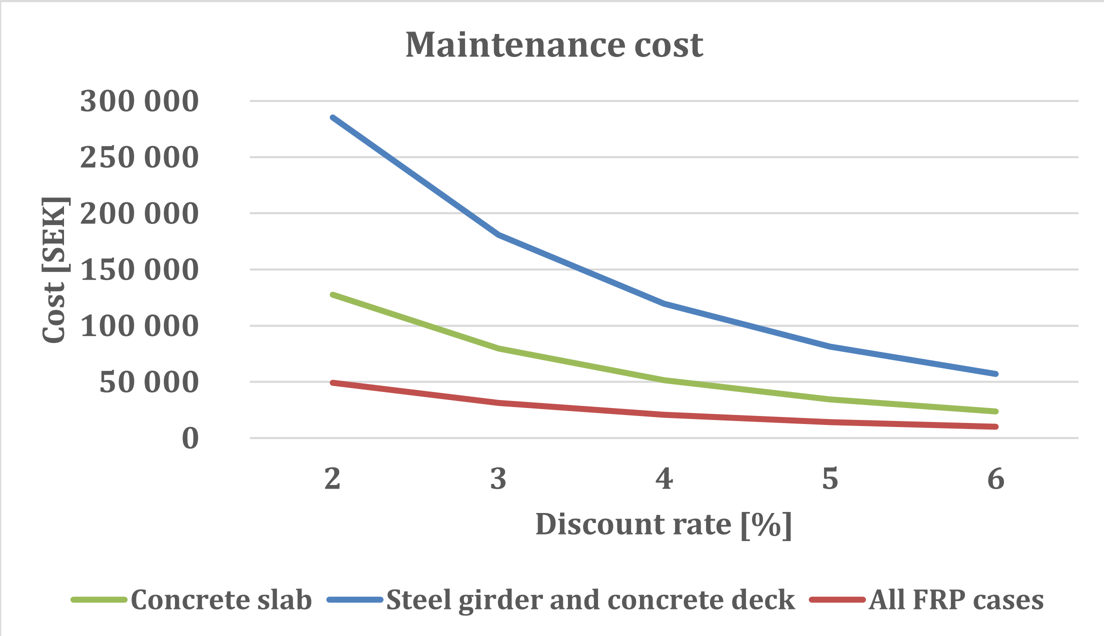


Figure 1 Graph of the maintenance cost with variating discount rate, between 2% and 6%.

The discount rate as expected has a large impact on the future cost. It has the most dramatic affect (exponential) below approximately 5 %. Above 5% discount rate has less influence on the maintenance costs.

Cost of FRP manufacturing

The manufacturing cost of case three's (GFRP box beam) superstructure is approximated to 800 000 SEK. A price drop by 40 % would lead to a cost of 480 000 SEK and a rise by 25 % in price, would lead to 1 000 000 SEK. Concluding that a cost estimation with 40% drop and a 25 % rise gives a manufacturing cost interval, 480 000 SEK to 1 000 000 SEK.

But the 800 000 SEK that are estimated for cost of manufacturing the case three superstructure includes such aspects as material cost, construction cost, cost for the time spent during the (labour, etc) and cost for other manufacturing expenses. A rough assumption (by the author) of the material costs, is approximately 300 000 SEK. Lowering that cost by 40 % leads to 180 000 SEK and a total manufacturing cost of 680 000 SEK. Razing that cost by 25 % gives a cost of 375 000 SEK and total manufacturing cost of 875 000 SEK. Meaning that a drop by 40 % and a raise by 25 % in material cost would give the interval of 680 000 SEK to 875 000 SEK, for the total manufacturing cost. Note again that this is a rough estimation done by the author. Some derivation of how this is estimated can be found in the appendix.

The total manufacturing cost for the superstructure is estimated to 1 943 000 SEK for case four (CFRP beams). Lowering and razing that cost as previously (40 % drop, 25 % rise) gives the following manufacture cost-interval, 1 165 800 SEK to 2 428 750 SEK. Note that in this case there is data available on costs for individual parts in the manufacturing process, table 6-1, by the manufacturer (Marstrom Composite).

Tabell 6-1 Superstructure cost, case four (by Marstrom Composite).

Superstructure cost	
	Cost [SEK]
Carbon fibre glue consumption Siporex	720 000
Siporex and glue	120 000
Edge element laminate	68 000
Top laminate injected	70 000
Colour walk-surface	65 000
Construction Time	820 000
Construction	80 000
Total	1 943 000

Considering and manipulating only the material costs, 1 043 000 SEK, from table 6-1 in the same way as before (40 % drop, 25 % rise). This results in the following interval, for the total manufacturing cost, 1 525 800 SEK to 2 203 750 SEK.

Due to data limitation at the time of the study, only an approximation on the cost of the complete bridge are included in the LCCA for case five (including railing and lighting). The total agency cost is 1 300 000 SEK.

There is an approximation on the railing cost done by the manufacturer of case four. The approximated cost is somewhere between 100 000 SEK and 150 000 SEK. Subtracting the middle value of that interval, 125 000 SEK, from the total cost, 1 300 000 SEK, yields the resulting approximated manufacturing cost is 1 175 000 SEK for case five.

Manipulating the value 1 175 000 SEK in an identical manner as done for other case (40% drop, 25% rise), it yields a cost interval between 705 000 SEK and 1 468 750 SEK.

There was no data on material costs at the time of the study, thus an assumption was done for case five. It can be deduced that the material costs cover approximately 54 % of the total costs for case four and that the assumed material cost for case three covers approximately 37.5 %. The assumption is that the materials cost of case five is 40 % of its manufacturing cost. This all results in the approximated material cost of 470 000 SEK for case five. Manipulating 470 000 SEK in an identical manner as done for other case (40% drop, 25% rise) yields a cost interval between 987 000 SEK and 1 292 500 SEK.

Edge beam impregnation frequency

Changing the Edge beam impregnation frequency from every 20 years to every 30 years showed that the total maintenance cost is less if the frequency is set to every 30 years, as it can be seen in figure 6-3.

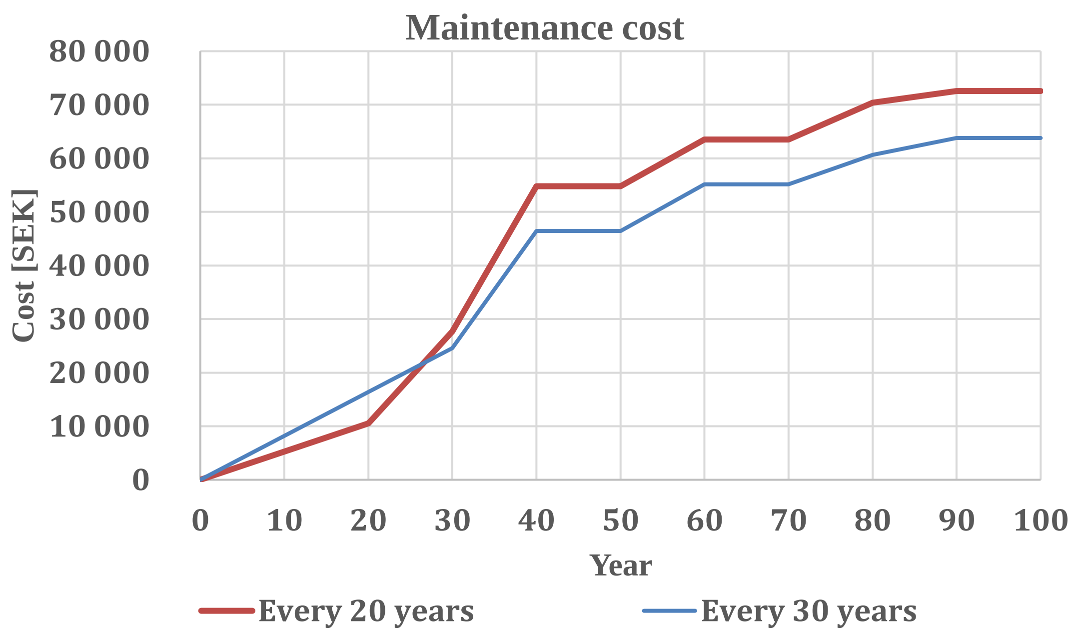


Figure 6-3 Shift in edge beam impregnation frequency.

<u>Alternative Edge beam maintenance</u>

Figure 6-4 shows that the total maintenance cost would be higher if edge beam replacement was chosen instead of impregnation.

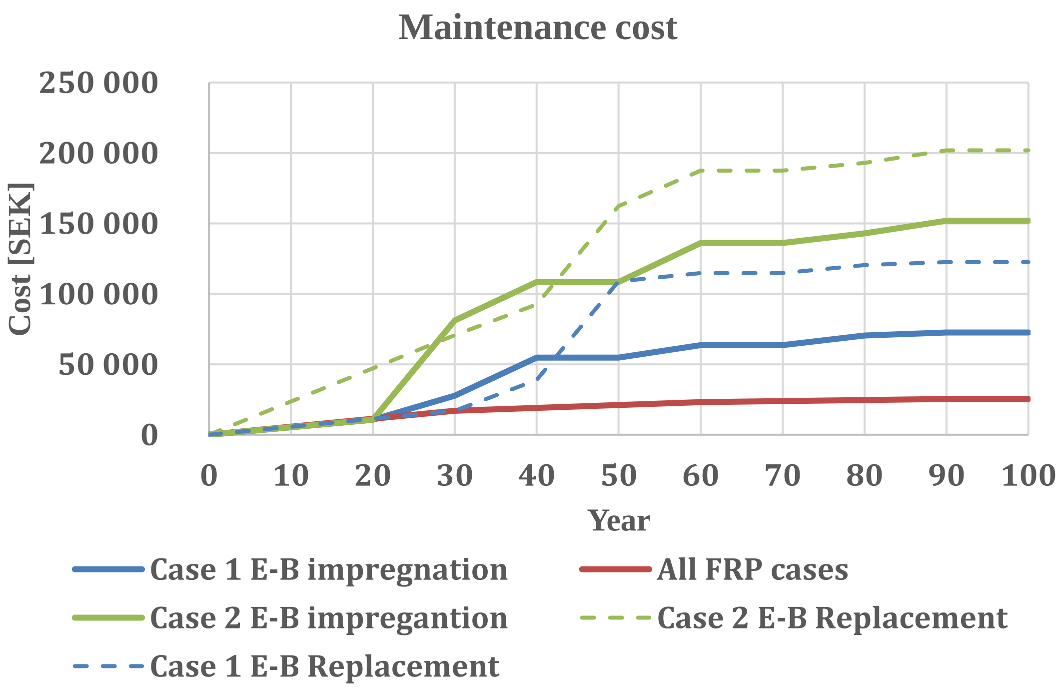


Figure 6-4 Edge beam impregnation and replacement, E-B is short for Edge Beam.

7 Conclusions and Discussion

It can be concluded that the LCC analysis was successful in the sense that it produced results with sufficiently good level of cost transparency, which allowed for a cost comparison.

Results from the LCC analysis in chapter 6 shows that the steel & concrete design solution (case 2) has the lowest total life cycle cost and that it has the highest maintenance cost in comparison to all the other cases This is because of its low construction cost and due to that steel needs a continuous restoration of its protective layer (i.e. repainting), which rises the maintenance cost.

Maintenance of the edge beams in the concrete design solution (case 1) and the concrete deck on steel girders design solution (case 2) is done by impregnation. It was a decision between impregnation or replacing the edge beams after approximately half its life span. Professionals in the subject state that a modern well designed and well-constructed pedestrian bridge is not in a need of edge beam replacement and that preventing measures such as impregnation together with standard maintenance (cleaning, washing, etc) are enough for the bridge to function during its entire service life. This is the main reason why impregnation was selected as a maintenance active for both concrete design (case 1) and the concrete deck on steel girders design (case 2). The assumption is that by impregnating the bridge every 20 years, will be enough to counteract deterioration sufficiently and that there will be no need for replacing the edge beams (During & Malaga, 2014).

Cost of replacing edge beams at age 50 was estimated to approximately 70 000 SEK (NPV) while impregnation edge beams costs approximately 20 000 SEK (NPV). Thus, making impregnation maintenance a cheaper option amongst these two options. Though, no cost was taken inconsideration in any form for possible environmental (marine) impacts from the impregnation procedure.

The results show that the maintenance cost for all FRP design solutions where lower than the maintenance cost for the two traditional construction materials (concrete and steel). This is due to the future maintenance approximate, that the FRP design solutions will only need surface layer replacement. The maintenance cost for the FRP design solutions is this LCC study is approximately 80 % less than for the two traditional materials (concrete, steel).

GFRP box beam design solution (case 3) is the cheapest among the three FRP design solutions and is 100 000 SEK more expensive than the concrete slab design (case 1) and 200 000 SEK more expensive than the concrete deck on steel girders design (case 2). This is because the GFRP box beam design solution and two other FRP design solutions have higher construction costs compared to the two traditional construction materials.

The most expensive design solution from the LCC analysis is the CFRP slab design solution (case 4) and it costs twice of what the GFRP box beam design solution (case 3) costs. This reflects the current fibre prices on the market, that carbon fibres are more expensive then glass fibres.

It can be seen from the perceptual results of LCC for each case that the end of life costs is less than 1 percent. The concrete slab design solution (case 1) had the highest disposal cost and the FRP designs had the lowest. These costs were particularly difficult to assess and estimate as this is far in the future and FRP waste management is still under development.

The end of life cost assessments is built on today's costs and by today's procedures. Current work on sustainability and on reducing pollution, would suggest that material waste management and material recycling will become more cost and management effective in the future, 80 or 100 years from now. Meaning, that the end of life assessment in the LCCA is probably overpriced.

Biggest uncertainties in the LCCA revolved mainly around the estimations of future maintenance activities and end of life procedures. FRP bridges haven't been around as long as concrete and steel bridges. Meaning, that there is a more available data on maintenance when dealing with concrete and steel bridges, but a shortage in data on maintenance of FRP bridges.

8 Recommendations for future studies

Here follow some ideas on future studies that emerged throughout the project and from discussion with consultants.

It could be interesting to investigate what kind of LCCA is of interest at different stages in a bridge production process. To investigate what sort of information and how much information is available at a specific time in the bridge production process. By finding out what is interesting for the decision maker in a bridge production process and what information is available at the time of interest, LCCA's with different level of detail depth could be established. Maybe two or three different LCCA detail level categories. It could help to reduce the work time for the LCCA conductor or make it easier to carry out the LCCA if there is a situational flow chart available.

Regarding the LCCA in this project and its limits, a suggestion for further studies could be to investigate the social and environmental aspects. To see how they affect the total life cycle costs. And an LCA could be interesting to conduct to see how the LCCA and LCA complement each other.

The following idea is more aimed towards vehicle-bridges. It could be interesting to conduct a study or an investigation on how future traffic development will affect bridge maintenance activities and costs. Investigate if cars deteriorate bridges less or not by becoming lighter in the future.

9 References

Sagemo A., Storck L. (2013): *Comparative study of bridge concepts based on life-cycle cost analysis and lifecycle assessment*. Department of Civil and Environmental Engineering. Chalmers University of Technology.

Safi, M., Sundquist, H., Karoumi, R. & Racutanu, G. (2012): *Integration of life-cycle cost analysis with bridge management systems*. Division of Structural Engineering and Bridges, KTH Royal Institute of Technology.

Safi, M. A. E.-F. (2012): *LCC Applications for Bridges and Integration with BMS*. Department of Civil and Architectural Engineering, KTH Royal Institute of Technology.

ETSI (2013): *ETSI Project; Bridge Life Cycle Optimisation; Stage 3*. Available at: http://folkbro.com/wordpress/wp-content/uploads/2015/07/ETSI_Stage3.pdf

Nystrom H., Watkins S., Nanni A., Murray S (2003): *Financial Viability of Fiber Reinforced Polymer (FRP) Bridges*, Vol. 19, No. 01.

Domone P., Illston J. (2010): *Construction Materials*. Spon Press, New York, 305-364 pp.

Gurit Manufacturers. (2017): *Guide to composites* [Online]. Available at: http://www.gurit.com/-/media/Gurit/Datasheets/guide-to-compositesv5webpdf.ashx [Accessed 2017-03-31]

Bosman J. (2015): *FRP road bridges as a concrete alternative*. Faculty of engineering technology, University of Twente.

Friberg E., OLSSON J. (2014): *Application of fibre reinforced polymer materials in road bridges – General requirements and design considerations*. Department of Civil and Environmental Engineering. Division of Structural Engineering. Chalmers university of technology. Göteborg, Sweden 2014

Malaga K., During O. (2014): *Life cycle cost analysis on impregnated bridge edge Beams*. Available at: http://hydrophobe.org/pdf/lisboa/VII_27.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. At: http://dx.doi.org/10.1016/j.conbuildmat.2013.09.036.

Murphy, N. (2013). *Feasibility Analysis of a Fiber Reinforced Polymer Bridge*. Department of Civil and Architectural Engineering, KTH Royal Institute of Technology.

Attaf. B. (2012): *Ecomoulding of Composite Wind Turbine Blades Using Green Manufacturing RTM Process*. Available at: https://www.hindawi.com/journals/isrn/2012/734328/

André A. (2006): *Fibres for strengthening of timber structures*. Department of Civil and Environmental Engineering, Luleå University of Technology.

Dimopoulou D., Khoshkhoo N. (2015): *Pedestrian bridges of different materials.* Department of Civil and Environmental Engineering. Division of Structural Engineering. Chalmers university of technology. Gothenburg, Sweden 2015.

Potyrala P. B. (2011): *Use of Fibre Reinforced Polymer Composites in Bridge Construction*. Enginyeria de la Construcció, Universitat Politécnica de Catalunya.

BaTMan. (2017): *Managementsystemet BaTMan.* avalible at: https://batman.trafikverket.se/externportal

Yang J., Kalabuchova L. (2014): *Application of FRP materials in Culvert Road Bridges A feasibility study with focus on mechanical behaviour and lifecycle cost analysis*. Department of Civil and Environmental Engineering. Division of Structural Engineering. Chalmers university of technology. Göteborg, Sweden 2014.

FALCON. (2015): *Future lightweight composite infrastructure.* Available at: https://www.chalmers.se/en/projects/Pages/FALCONQ-LQttviktslQsningar-i-fiberkomposit-fQr-framtidens.aspx

Sonnenschein R., Gajdosova K., Holly I. (2016): *FRP Composites and their Using in the Construction of Bridges*. Department of Concrete Structures and Bridges, Slovak University of Technology. Vol 161, pp 477-482.

Tromp L., De Boer A. (): *Developments in Dutch FRP design guidance for FRP in infrastructure.*

Clarke J. L. (1996): *Structural Design of Polymer Composites EUROCOMP Design Code and Handbook*. The European structural polymeric composites group. Sir William Halcrow and partners ltd, London, UK.

Ecodesign. (2009): *Directive 2009/125/EC of the European parliament and of the council*. Official Journal of the European Union.

Rapid. (2017): *Products and separation systems.* Available at: http://rapidgranulator.com/

Frisk N. (2016): *Manufacturing of Lightweight Sandwich Composites with Bio-Based PU Foam Core and Cellulose Fiber Network Skin*. Department of Engineering Sciences and Mathematics, Luleå University of Technology.

Marstrom. (2017): Available at: https://www.marstrom.com/en/news/item/108-first-composite-bridge-in-sweden

Domone P., Illston J. (2010): *Construction materials: their nature and behaviour / edited by Peter Domone and John Illston*. Milton Park, Abingdon, Oxon; New York: Spon Press, 2010.

Bank C. L. (2006): *Composites for construction: structural design with FRP materials / Lawrence C. Bank*. Hoboken, N.J.: John Wiley & Sons, c2006.

Baus U. (2008): *Footbridges: construction, design, history / Ursula Baus, Mike Schlaich; with photographs by Wilfried Dechau*. Basel: Birkhäuser, cop. 2008.

Chatterjee S. (2003): *The design of modern steel bridges***.** Oxford: Blackwell, 2003.

FIB. (2000): *Guidance for good bridge design: guide to good practice.* Prepared by FIB Task Group 1.2 Bridges. Lausanne: Fédération Internationale du béton (FIB), 2000.

Composites UK., Job S., Leeke G., Mativenga P. T., Oliveux G., Pickering S., Shuaib A. (2016): *Composite recycling: Where are we now*. Composites UK, July 2016.

Mara V. (2014): *Fibre reinforced polymer bridge decks: sustainability and a novel panel-level connection.* Department of Civil and Environmental Engineering, Chalmers University of Technology, 2014.

Trafikverket. (2017): *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 6.1. Kapitel 5 Kalkylprinciper och generella kalkylvärden*. Available at: https://www.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-6.1/05_generella_principer_o_varden_a61.pdf

Hassoun M. N. (2002): *Structural concrete: theory and design.* Upper Saddle River, N.J.: Prentice Hall, cop. 2002.

O'Connor C. (2000): *Bridge loads: an international perspective / Colin O'Connor and Peter A. Shaw.* London: Spon Press, 2000.

Detail. (2013): *Pedestrian bridges: ramps, walkways, structures.* Institut für Internationale Architektur-Dokumentation GmbH & Co. Kg, Munich. Ed. Detail, 2013.

Vasani, P.P.C., Bhumika, B.M. (2003): *Different Types of Bridges and Its Suitability*. Applied Mechanics Department, L. D. College of Engineering, Ahmedabad.

Bakis C. E., Lawrence C. Bank, F., Brown V. L., Cosenza E., Davalos J. F., Lesko J. J., Machida A., Rizkalla S. H., Triantafillou T. C. (2002): *Fiber-Reinforced Polymer Composites for Construction—State-of-the-Art Review.* American Society of Civil Engineers. Journal of Composites for Construction Vol. 6, Issue 2 (May 2002)

Langdon D. (2007): *Life cycle costing (LCC) as a contribution to sustainable construction: a common methodology - Final Report.* Davis Langdon Management Consulting. European Commission.

FibreCore Europe. (2017): *InfraCore technology.* Available at: https://www.fibercore-europe.com/infracore-technologie/

Steel construction. (2017): *Bridge design*. Available at: https://www.steelconstruction.info/Bridges.

Encyclopædia Britannica. (2017): *Bridge design*. Available at: https://www.britannica.com/technology/bridge-engineering.

Malmö. (2017): *The Neptuni Bridge.* Available at: https://malmo.se/Stadsplanering--trafik/Vagarbeten-ombyggnationer--avstangningar/Nyheter-vagarbeten-och-avstangningar/2016-10-21-Neptunigatan-och-Citadellsvagen.html

APPENDICES

Case 1

Developers: Centerlöf & Holmberg (CoH)

Production costs		
	Unit price	
Formwork	1 800	SEK/m²
Concrete	2 500	SEK/m³
Reinforcement	17 000	SEK/ton
Surfacing & Insulation	1 000	SEK/m²
Scaffolding & framework	4 000	SEK/m²

Construction cost						
	formwork [m²]	concrete [m³]	reinforcement [ton]	steel [ton]	surfacing & insulation [m²]	Cost [SEK]
Bridge deck	48	24	2,3			521 160
Edge beam						-
Overlay					48	48 000
Other*						199 206
					Total cost:	769 000

*Associated costs, such as small machinery, sheds, containers, electricity, etc.

Maintenance and Repair						
Activity	Interval [yr]	Unit cost [SEK/unit]	Quantities	Cost each time [SEK]	Cost [SEK]	Total present cost [SEK]
Change edge beam [m]	51	13 000	30	-	-	-
Impregnation edge beam [m]	20,5	700	30	21 000	84 000	19 863
Change Insulation [m²]	40	1 800	48	86 400	172 800	27 334
Change Surfacing [m²]	30	1 000	48	48 000	144 000	25 365
				Total cost:	400 800	72 562

Case 1

Developers: Centerlöf & Holmberg (CoH)

Demolition cost				
	Unit cost [SEK/unit]	Quantity	Cost [SEK]	Present Value [SEK]
Concrete [ton]	500	57,6	28 800	923
Raft			75 000	2 405
		Total cost:	103 800	3 400

Life cycle cost	
	Present value [SEK]
Construction cost	769 000
MR&R cost	72 562
End-of-life cost	3 400
Total:	844 962

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
(Answer concerning craning) Lifting or not is always an issue ... The lift itself costs about 40 - 60 000 SEK a little depending on the lease. Form can be done regardless of the same cost, space shortage can be a phenomenon just for Neptune. Scaffolding/framework/piling (Pålbrygga) costs about 4,000 SEK/m^2 since it adds a relatively simple shape to it to get to the right height. Formulation is probably most likely in m^3 for those who can, but one must be careful when low heights are like on Neptuni-bridge. Low scaffolding can be relatively expensive as there are not a lot of standard products to use.

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
(Discussion revolving what to include in constructions costs) When calculating costs, the direct costs of materials, work, machinery and subcontractors (e.g. handrails, throws (smide) and barriers (tätskikt)) are first to be addressed. Then you have to look at the costs and make an estimate of it. Associated costs (kringkostnader) are such as small machines, storage facilities, containers, etc. It's a bit more work and you need more detailed information. It's also works great to guess a little bit. I know what 1 m^2 formwork costs, a ton of reinforcement etc and can make a pretty *(next page)*

roughly hewn calculation that hits quite close.

I note that there are reinforcement amounts below 100kg/m^3 which I have not been with since the happy 90's.
I would suggest that the actual quantities end up in the range of 150-180 kg/m^3.

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
(Cost estimations) 1 - Formwork, pile bridge 4 000 SEK/m^2 with formwork 1 800 SEK / m^2, other formwork consider 6 – 800 SEK/m^2 2 - Concrete, consider about 2 500 SEK/m^2 3 - Reinforcement, consider 17 000 SEK/ton 4 - Steel, more uncertain but around 60 SEK/kg painted and clear is not unreasonable 5 - Insulation, consider including surface layer with 1000 SEK/m^2 6 - Surface layer, bearings and expansion joints. Bearings cost in the order of 10 000 SEK/piece transition structures 10 000 SEK/m (needed?) And get it installed and clear (as well as removed in terms of shape and position). Included in the above. Add about 30-40% to get it all.

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
(Cost estimations) Roughing and disposing of concrete costs about 500 SEK/m^3. What is going to increase the cost here is partly that it is a small volume and that it is water below. Raving down on raft is then preferable, which gives an addition of about 75 000 SEK for establishing raft. The steel costs no big money because the demolition of it is relatively simple and the scrap generates an income, I would guess today it costs in the order of 10 000 - 15 000 SEK to get rid of the scrap ..

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
(Discussion concerning abutment construction) One of the problems here is that you have to drive a certain number of piles into the ground according to the norm, which means that the abutment will be oversized, regardless of whether the load is 25 tonnes or 5. Erik can pick up the number according to the standard versus what would be needed. In this case, the front piles to be drilled through an existing concrete structure are quite expensive at an estimated 50 k SEK, the others cost maybe 20 k SEK or so.

Case 2
Developers: Centerlöf & Holmberg (CoH)

Production cost		
	Unit price	
Formwork	700	SEK/m^2
Concrete	2 500	SEK/m^3
Reinforcement	17 000	SEK/ton
Steel	60 000	SEK/ton
Surfacing & Insulation	1 000	SEK/m^2

Geometry data		
Painted area	49,026 m^2	
Main beam mass (volume*density)	0,45114	3,541449 ton
Cross beam mass	49,7	0,0497 ton
Total main and cross beam mass		3,591149 ton
Bridge mass	37,32 ton	
Bridge mass – surface layer	30,27 ton	
	Vol.	mass
Reinforcement mass	0,1470065	1,154001025 ton

Construction cost						
	formwork [m^2]	concrete [m^3]	reinforcement [ton]	steel [ton]	surfacing & insulation [m^2]	Cost [SEK]
Main beams				3,9		234 000
Cross beams						-
Bridge deck	48	13,365	1,269401128			88 592
Edge beam						-
Bearing						40 000
Overlay					48	48 000
Crane						40 000
Other*						143 707
					Total cost:	594 300

Case 2

Developers: Centerlöf & Holmberg (CoH)

Maintenance and Repair						
Activity	Interval [yr]	Unit cost [SEK/unit]	Quantities	Cost each time	Cost	Total present cost
Change edge beam [m]	50	13 000	30	-	-	0
Impregnation edge beam [m]	20,5	700	30	21 000	84 000	19 863
Repainting steel surfaces [m^2]	30	1 700	66,9	113 730	341 190	60 099
Change Insulation [m^2]	40	1 800	48	86 400	172 800	27 334
Change Surfacing [m^2]	30	1 000	48	48 000	144 000	25 365
Repaint Bearings	30	9 100	4	36 400	109 200	19 235
Change Bearings [pcs]	51	10 000	4	-	-	0
				Total cost:	851 190	151 896

Demolition cost				
	Unit cost	Quantity	Cost [SEK]	Present Value [SEK]
Concrete [m^3]	500	14	7 000	224
Raft [pcs]			75 000	2 405
Steel [ton]	- 500	3,66	- 1 830	- 60
		Total cost:	80 170	2 569

Life cycle cost	
	Present value [SEK]
Construction cost	594 300
MR&R cost	151 896
End-of-life cost	2 569
Total:	748 765

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
1) Yes, it works fine to lift if the weight is no more than about 35 tons, which means a crane-cost of about 25 000 - 30 000 SEK provided that the crane can be placed next to the abutment.

Case 3

Developers: Diab, Podcomp, Velox

Initial material cost estimation (not regarded in LCCA results)					
Material	Weight [kg]	Unit price [SEK/kg] Interval values [min - max]		Price [SEK] Interval values [min - max]	
Glass Fibre	4744	11,5	23,0	54 556	109 112,0
Polyester	2828	20,1	20,1	56 914	56 913,5
PET Foam	2147	60,0	60,0	128 820	128 820,0
Polyurethane	70	27,0	72,0	1 890	5 040,0
Total	9718			242 180	299 885,5
Currency transformation: 1 USD = 9 SEK and 1 GBP = 11.5 SEK (E - glass price form GURIT sheet) (Divinycell H foam price from previous master thesis work) (polyester price from: http://oa.upm.es/14340/2/Documentacion/13_Presupuesto/Polyester%20Resin%20Price%20List.pdf) (polyurethane price approximated from: https://www.alibaba.com/showroom/polyurethane-paint.html)					

Construction cost					
	Area	Thickness	Volume	Density	Weight
	m2	mm	m3	kg/m3	kg
Top Surface Layer	47,4	3	0,14	1 500	210,0
Top FRP	47,4	7	0,33	1 850	610,5
High Strength Core - PN250	47,4	30	1,42	250	355,0
Cap Layer	111	5	0,56	1 850	1 036,0
Boxed Beam- T/B	51,9	16	0,83	1 850	1 535,5
Boxed Beam- Sides	15,3	5	0,08	1 850	148,0
Inner Foam - PN115	47,4	100	4,74	115	545,1
Inner Foam - Recoboard	47,4	420	19,91	150	2 986,5
Polyester for core bonding (app.)					189,6
Polurethane Paint	64	1	0,06	1100	66,0
Total					7 682,2
Margin for overlaps etc. (also used for cost calculation)			1,25		9 602,75
From DIAB					9 598
Approx. Structural cost Approx. Installation Cost (2 400 SEK/m^2)					800 000 SEK 120 000 SEK

Case 3

Developers: Diab, Podcomp, Velox

Maintenance and Repair						
Activity	Interval [yr]	Unit cost [SEK/unit]	Quantities	Cost each time [SEK]	Cost [SEK]	Total present cost [SEK]
Change Surfacing [m^2]	30	1 000	48	48 000	192 000	25 365
				Total cost:	192 000	25 365

Demolition cost				
	Unit cost [SEK/ton]	Quantity	Cost [SEK]	Present Value [SEK]
Recycling FRP	1 000	10	10 000	321
Crane	-	-	10 000	321
		Total cost:	20 000	700

Life cycle cost	
	Present value [SEK]
Construction cost	920 000
MR&R cost	25 365
End-of-life cost	700
Total:	946 065

Mail correspondence with Ralph Dougan at GVV (translated from SWE!)
An answer concerning transportation and craning. 2) Boat is probably completely excluded, it usually gets both expensive and not in time. What I can see is the bridge no wider than 4.5 m which is no problem to transport by road. The cost of this option should not amount to more than 10 000 SEK, as stated above. (*clarification last sentence, it's about craning*)

Case 4
Developers: Marstrom Composite, Composite Design

Superstructure cost	
	Cost [SEK]
Carbon fiber glue consumption siporex	720 000
Siporex and glue	120 000
Edge element laminate	68 000
Top laminate injected	70 000
Colour surface	65 000
Construction Time	820 000
Construction	80 000
Total	1 943 000

Other cost
Railing 100 000 SEK - 150 000 SEK Transport + Installation 100 000 SEK
Half the weight of fiberglass options

Demolition cost				
	Unit cost [SEK/unit]	Quantity	Cost [SEK]	Present Value [SEK]
Recycling FRP [ton]	1 000	5	5 000	160
Crane	-	-	10 000	321
		Total cost:	15 000	500

Life cycle cost	
	Present value [SEK]
Construction cost	2 043 000
MR&R cost	-
End-of-life cost	500
Total:	2 043 500

Case 5
Developers: FibreCore Europe

Construction cost
The investment cost is approximated in the following manner: 1 300 000 SEK + 100 000 SEK = 1 400 000 SEK (source: Malmö City, Abbas Khayyami). Minus the railing which is approximated to 125 000 SEK in case 4 (source: Marstrom Composite). This gives the total investment cost of 1 400 000 SEK – 125 000 SEK = 1 275 000 SEK.

Maintenance and Repair						
Activity	Interval [yr]	Unit cost [SEK/unit]	Quantities	Cost each time [SEK]	Cost [SEK]	Total present cost [SEK]
Change Surfacing [m^2]	30	1 000	48	48 000	192 000	25 365
				Total cost:	192 000	25 365

Demolition cost				
	Unit cost [SEK/unit]	Quantity	Cost [SEK]	Present Value [SEK]
Recycling FRP [ton]	1 000	10	10 000	321
Crane	-	-	10 000	321
		Total cost:	20 000	700

Life cycle cost	
	Present value [SEK]
Construction cost	1 275 000
MR&R cost	25 365
End-of-life cost	700
Total:	1 301 065

Mail correspondence with Abbas Khayyami at Malmö City (translated from SWE!)
FRP source complete incl. railing and lighting costs about 1.3 million SEK. Transport and assistance with installation on site approx. 100 000 kr.

Mail correspondence with Abbas Khayyami at Malmö City (translated from SWE!)
Annual supervision, do not know, hope no vandalization occurs. Superficial inspection, do not know, hope no vandalization occurs. Main inspection - performed every 6 years, General Inspection performed every 3 years. Cleaning of bridge surface, do not know, should not be required, check with FiberCore Europe or experts in marine painting systems. Cleaning of drainage system, is not in this project, possibly outside, check the actions. Impregnation of edge beam, is not present in this project.

Case 5

Developers: FibreCore Europe

Mail correspondence with Abbas Khayyami at Malmö City (translated from SWE!)
Maintenance of rails, should not be required in about 20-25 years if vandalization does not occur. Maintenance of storage pallet, not in this project, check the documents. Maintenance of expansion joints, do not exist in this project, check the documents. Refilling and restoration of erosion protection, do not exist in this project, check the documents. Repainting, should not be needed in about 20-25 years if vandalization does not occur.

Mail correspondence with Abbas Khayyami at Malmö City (translated from SWE!)
(Answer concerning vehicles) Spontaneously, I think it is about 500 service vehicles, 12 ton per year.

Mail correspondence concerning assumptions in the project

Mail correspondence with Charlotta Bjerkborn at GVV (translated from SWE!)
(Answers concerning MR&R assumptions: 1. I have assumed that inspections of the bridge will be independent of materials and not considered it in the analysis. 2. I'm unsure but supposing cleaning (washing, salt removal) is the same for all materials. 3. Regarding the rails. How would the maintenance of the attachment look if an option has a bolt and the other is 'glued'. 4. What is your thoughts on concrete footbridge in a marine environment. What would it need for maintenance during its 120 years. E.g. Edge beam and deck repair or replacement.) 1. In principle, yes. There are no inspection procedures for this material, but the supplier must establish a maintenance plan that will define, inter alia, how inspection is to be performed (as for wooden bridges). I have discussed this with Ed Hoogstad at FiberCore and Fredrik Wettermark on Composite Design and dare to assume that inspection times need not be different from time to time than for steel and concrete bridges. 2. Basically, yes, if we compare bridges located on the same road type. However, the design of the bridge affects this. If we take a bridge with steel superstructure, the main body is usually not routinely washed (I can say, sometimes, that this should be done, especially if you have bridge bridges and the like). 3. The rack is washed and it should be remembered that a handrail that can not be washed with a normal wash rig from a car must be hand washed (with high pressure wash, not with bucket and sponge ...)! There may also be a need to wash the rail fasteners, even if there is no edge beam, because the steel, though stainless, is still sensitive. I suspect that the laundry will have to be done by hand. A glued attachment is probably easier to wash and collects less dirt. The smoother attachment, the better and if you screw a sheet to something else, it always comes in moisture and dirt in practice. The railing must be screwed! TDOK 2016: 0204 Requirements Bridging, G.). 1.6.6: "A railing that is placed on a construction of concrete, steel, aluminum or wood must be attached to the underlying structure using screws". Now, FRP is not included in the list because there is not something that exists under TRV, but the principle had probably been the same. However, one can assume that a console or the like is glued to the main rack, which can then be attached to the screws so that the rack is not attached directly to the main rack. The idea is that when a railing is taken, the railing will go out of position, rather than in the screws, and therefore the replacement will be limited to installing a new bucket in existing screws, rather than welding. 4. This has to be a clean guess because they are very different, and it will also be a very long answer: First of all, you must distinguish between state-controlled / remedial maintenance, correcting an error or performing an improvement, and time-controlled maintenance, such as washing, etc. I suppose you mean state-controlled with your question. *(Next page)*

Mail correspondence concerning assumptions in the project

Most of the maintenance had probably touched the substructure - either it is in the water and then the abrasion in the waterline is something that may be a problem or it will cross a possible salty road and that's the problem. Here, however, we speak superstructure, I guess, and it's really a separate question. Most bridges we change the edge beam on suffer from a thin-layered concrete layer (often thinner than it would have been at that time, ie a construction defect). Reinforced concrete was still a fairly new material and the long-term consequences of the design had not yet been seen. It was not until the 80's that it was not a good idea to have chlorides as additives! The concrete we use today is frost resistant and we use on bridges a very thick covering concrete layer. We wash what is salted and we do not put coatings as it can grow in. We impregnate concrete parts that are exposed to salt.

GC bridges all over concrete in concrete are not very common today. I looked at the bridges that are part of Blekinge and Kalmar County and I found one that was built after the bridge-norm 88 started to apply (when it became tougher frost resistance rules, after that they start to resemble today's bridges), bridge 10-540- 1st It was built in 1995 and thus more than 20 years old. The inspection points that exist there are partly settlements behind the bridge end, partly a construction defect and partly cracks in edge beams and beams. None of these errors are due to wear and tear of normal use.

A pedestrian bridge needs seldom to be updated due to a changed traffic situation (as we today change rails and then also have to change an otherwise working sidebar). The rack may also need to be painted or similar, and the lighting may need to be replaced - but there is no difference to another bridge, as does ground and surface float and also milling of the wear bearing.

However, the sealant ages and needs to be replaced and the sealant will not be enough for FRP bridges. How old they become is also a difficult issue - some clients have a strategy where they change the density when they have reached a certain age, others wait until there are indications that it is necessary (i.e. leakage). Some people change when they are 50 years old, others when they are 25 years old. It may be due to such things as if the bridge has drainage and the like - as soon as you have a joint in the sealant, there is a greater risk of problems. It also depends on the coating; A protective layer of PGJA gives longer life to the sealant.

That this is a GC bridge makes it harder to find action. The measures I have taken on the superstructure of the GC bridge have affected either the impact, surface protection of rails or any type of remodeling. If, on a today's newly built GC bridge of concrete, it is necessary to change the edge beam during the life of the bronze, because it is "worn out" without structural defects or malfunctions (including poor maintenance; they must sweep away sand on the bridge), so I'm really surprised.

If the bridge runs over a busy road, especially someone who is trafficked by heavy traffic, there is a risk of accidental injury. In this case, you should include this in all materials, as the cost of correcting the damage may severely differ. If the bridge crosses the protected road, including the highway (and rail!), The shutdown will be very expensive. An impacted steel structure is usually addressed faster than the corresponding concrete structure, for example.

Mail correspondence concerning assumptions in the project

Mail correspondence with Charlotta Bjerkborn at GVV (translated from SWE!)
(Answers concerning MR&R assumptions and selected activities) Insulation and wear layers sound reasonable, I think. The wear layer will be applied regardless of material, the sealant is applied to FRP bridges, assuming they have some type of acrylate coating or the like (as in Klaffbron). The washing is done simultaneously for a "normal" edge beam with a "normal" railing. Now, however, I realized that on your pedestrian bridge you can not drive the cleaning truck. There you can hand wash. I talked to the colleague who handles the city of Gothenburg's bridges and he said that the price depends on how long the bridge is etc. A guess is 50 SEK/m and then we have adopted a 20 m long bridge. I'll hear a few other colleagues and see if I get other bids. For a GC bridge, laundry of railing and sidebar etc. is done every guessing every other year. However, this is the same regardless of material.

Mail correspondence with Charlotta Bjerkborn at GVV (translated from SWE!)
(Answers concerning railings and case 2 maintenance activities) Because the bridge-type looks like it does, the railings plays less role. One could say, however, that the design of the rail fastening is important, but it is too much of a detailed question (see below, below). Yes, steel parts, including layers, will probably need to be re-painted once or twice. It's hard to say the number of years, but 40 years you'll be able to get out of the system, I think. It depends a bit on how the steel structure is designed; I see a bit of the cross section of the drawing, but not really enough. A screw-jointed construction may need more maintenance than a (well-executed) welded construction - easy corrosion around the screw, etc. Even the connection between steel and concrete may be difficult, even if you like to make collaborative constructions in this way, I am doubtful. I see that they have designed both concrete structures with a recessed edge beam. I think there is a risk of a major maintenance requirement because you have water that will flow over the edge in a much larger amount than if you had a "normal" elevated edge beam, where the surface water is mainly on the coating. I also do not know how the rail fastening looks, but as I say, it affects it. A side fence raises on this construction, where all water, rubbish and leaves, flows over the edge will require more cleaning or it may be a problem. Collections of leaves, dirt etc collect moisture and destroy the concrete.

Mail correspondence concerning assumptions in the project

Mail correspondence with Charlotta Bjerkborn at GVV (translated from SWE!)
Maintenance can be divided into three parts (now it may be repeat): Timed State-controlled Improvement The three groups are part of each other, but broadly speaking, it is correct. Timed: In particular, washing etc and general supervision. It's a huge post on an openable bridge, for example, and a rather small post on a bridge over water that only takes GC traffic. Generally, railing etc will always be washed, even if it is stainless (stainless steel is not an indelible material in any way but has greater resistance to certain things). Coating should be swept etc. Much below this heading can be deepened by a complicated design, which we had noticed if you would have compared, for example, ideal fragments for their respective materials, without appearance requirements, and also across different subways (ie over water, rail, over highway). However, I understand that it would be a bit too much for you to take on. As we have said before, time-consuming maintenance is basically the same. State programs: These are, often, clean repairs. They are often caused by collision damage, construction defects, construction of a different type previously and not having the same traffic load, etc. or the wear of water and ice in underlying waterways. However, we can not expect construction defects or a future different traffic load or the like (what would it be like on a GC bridge, maybe electric bikes that become disproportionately heavy and provide aggressive double tires? That sounds silly, but that's what happened to cars, in principle). Water and ice concern the foundation and we are in a hurry. Had the bridge gone above a road, I would have thought it would be interesting to look at what an impact injury had meant for the different materials. Now, however, a run is not really relevant, there are no larger boats under the bridge. What is meant by this is what we know will need to be addressed and which, in fact, should be included in the time-controlled: Tissue change and remeasurement of steel. I do not know what you have taken for repositioning decisions etc on the FRP bridges, if you have assumed it's the same as for a regular bridge. Seal layers are easily released. Then it's that with re-painting. What I have understood, all the patches of light are affected and you have to surface. Here I have not really received any answers as to how long a surface treatment holds. On our small carbon fibre bridge in Malmö, we have a "sacrificial layer" that the rack is mounted in which does not belong to the main carrier and which can be replaced. However, I have not learned how difficult it is to replace it or how often it has to be done. I have understood that you can make on-site fixings with laminations, but how do you remove a glued construction part without affecting it? *(Next page)*

Mail correspondence concerning assumptions in the project

Improvement: This is what you can call a conversion to something "better". Replacing the edge beam and railing on concrete bridges counted there. It's hard enough for you to expect that you will need to rebuild the bridge.

Mail correspondence with Charlotta Bjerkborn at GVV (translated from SWE!)
(Discussion and thoughts about futuristic possibilities) One possible development: The bridge is 50 years old, so in 2070. For different reasons, it is not trafficked by very much pedestrian/bicycle traffic anymore. However, a new public transport vehicle has been invented. It's like a bus, but it hovers a decimetre above the ground with the help of propellers (I'm not a vehicle designer, as you hear). It does not stress bridges etc with traffic loads. It is likely that it can drive on pedestrian/bicycle bridges that are wide enough (for some reason it may not fly, so it needs bridges). The bridge is, however, a meter too narrow and the railing must be able to hit the propeller bus. You need to broaden the bridge by one meter and you need to change the railings. The railings have a different cc distance on the rail fasteners and the fasteners need to take a bigger load. The width must be made so that the bridge is assembled in the "joint", you cannot have a longitudinal joint. This type of action is often done on concrete bridges. Is it possible to perform on the FRP bridges? We solved it on our carbon-fibre bridge - we had added a beam on each side with new handrails and glued them to the existing one. But how was Fibercore's bridge done? Or the other variants we've talked about in Falcon? This may sound a little strange, but those who built bridges 50 years ago could not imagine today's traffic volumes, the size of some vehicles or that snow and wind loads, as well as sea levels, would change due to climate change. Here is a less futuristic thought: If you need to change the profile of the bridge connecting route, for example - change it simply if you have a typical asphalt coating. As I understand, the FRP bridges usually require a very thin coating due to the heat of the asphalt and you cannot adjust that easily. How do you solve this?

Extracts from the ETSI Bridge LCC tool

Case 1 Concrete slab

(Note that there could be some difference in the numbers here compared with the final tables and graphs. Mostly as the tool was used initially and new tables were created with new information together with information from the tool. As new data was collected though out the project meant that only the final tables and graphs where adapted accordingly, i.e. not the tool.)

Climate zone:		South Sweden
Road salting		Normal salt spreadin
Investment cost according to tender	CUR	1 096 344
Demolition cost in % of investment cost	%	7,9
Calculus period	years	100
Yearly real interest rent	%	3,5
Average daily traffic, ADT		0
Percentage of trucks	%	0
Allowed speed on the bridge	km/h	7
Reduced speed due to repair actions	km/h	7
Hourly cost, car	CUR/h	0
Hourly cost, truck	CUR/h	0
Total bridge length	m	15,0
Length of superstructure	m	15,0
Lengths of edge beams	m	30
Effective bridge width	m	3,2
Total bridge width	m	3,2
Bridge area	m^2	48
Area of surfacing	m^2	48
Painted area (steel beams etc)	m^2	0
Number of railings (parapets)	no.	2
Total length of railings(parapets)	m	30

	Weighting factor	inputted default intervals own factor
Climate zone	0,8	0,0
Average daily traffic, ADT	1,2	0,0
Saltning	1,0	0,0
Construction part subjected to salt action	1,0	0,0
Concrete quality > C30/C37	1,1	1,1
Concrete cover > Standard	1,0	0,0

Extracts from the ETSI Bridge LCC tool

Case 1 Concrete slab

	New construction costs	
	Unit price	
formwork	5 800	CUR/m^2
concrete	2 500	CUR/m^3
steel	0	CUR/ton
reinforcement	17 000	CUR/ton
cables	0	CUR/m
rammed piles	0	CUR/m
parapet	0	CUR/m
insulation	0	CUR/m^2
surfacing	1 000	CUR/m^2

Dotted fields contain the default values evaluated with the help of previously entered data. You have the possibility to input your own values in the fields.

	Quantities for calculation of investment cost							
	formwork [m^2]	concrete[m^3]	reinf. [ton]	steel [ton]	cables [m]	piles [m]	others, total cos	cost
SUBSTRUCTURE								
foundation slab	0	0	0			0		0
pier & column	0	0	0			0		0
front wall	0	0	0					0
wing wall	0	0	0					0
bridge seat	0	0						0
upper front wall								0
backfill							0	0
substructure others								0
SUPERSTRUCTURE								
main beams				0				0
cross beams				0				0
truss								0
arch								0
pylon or tower								0
cables								0
bridge deck	99	24	2,28					672 960
edge beam,	0	0	0					0
superstructure others								0
BRIDGE DETAILS								
bearing							0	0
insulation							0	0
surfacing							48000	48 000
railing or parapet							0	0
expansion joint							0	0
drainage system								0
bridge details others								0
OTHERS								
aesthetics							0	0
other construction costs							288 384	288 384
							Σ Investment cost/CUR	1 009 344

Extracts from the ETSI Bridge LCC tool

Case 2 Steel girders and concrete deck

Climate zone:		South Sweden
Road salting		Normal salt spreadin
Investment cost according to tender	CUR	531 641
Demolition cost in % of investment cost	%	15,4
Calculus period	years	80
Yearly real interest rent	%	3,5
Average daily traffic, ADT		0
Percentage of trucks	%	0
Allowed speed on the bridge	km/h	7
Reduced speed due to repair actions	km/h	7
Hourly cost, car	CUR/h	0
Hourly cost, truck	CUR/h	0
Total bridge length	m	15,0
Length of superstructure	m	15,0
Lengths of edge beams	m	30
Effective bridge width	m	3,2
Total bridge width	m	3,2
Bridge area	m^2	48
Area of surfacing	m^2	48
Painted area (steel beams etc)	m^2	49
Number of railings (parapets)	no.	2
Total length of railings(parapets)	m	30

	New construction costs	
	Unit price	
formwork	700	CUR/m^2
concrete	2 500	CUR/m^3
steel	60 000	CUR/ton
reinforcement	17 000	CUR/ton
cables	0	CUR/m
rammed piles	0	CUR/m
parapet	0	CUR/m
insulation	0	CUR/m^2
surfacing	1 000	CUR/m^2

Extracts from the ETSI Bridge LCC tool

Case 2 Steel girders and concrete deck

Dotted fields contain the default values evaluated with the help of previously entered data. You have the possibility to input your own values in the fields.

	Quantities for calculation of investment cost							
	formwork [m^2]	concrete[m^3]	reinf. [ton]	steel [ton]	cables [m]	piles [m]	others, total cos	cost
SUBSTRUCTURE								
foundation slab	0	0	0			0		0
pier & column	0	0	0			0		0
front wall	0	0	0					0
wing wall	0	0	0					0
bridge seat	0	0						0
upper front wall								0
backfill							0	0
substructure others								0
SUPERSTRUCTURE								
main beams				3,55				213 000
cross beams				0,121				7 260
truss								0
arch								0
pylon or tower								0
cables								0
bridge deck	48	13	1,144					85 548
edge beam,	0	0	0					0
superstructure others								0
BRIDGE DETAILS								
bearing							40000	40 000
insulation							0	0
surfacing							48000	48 000
railing or parapet							0	0
expansion joint							0	0
drainage system								0
bridge details others								0
OTHERS								
aesthetics							0	0
other construction costs							137 833	137 833
							Σ Investment cost/CUR	**531 641**

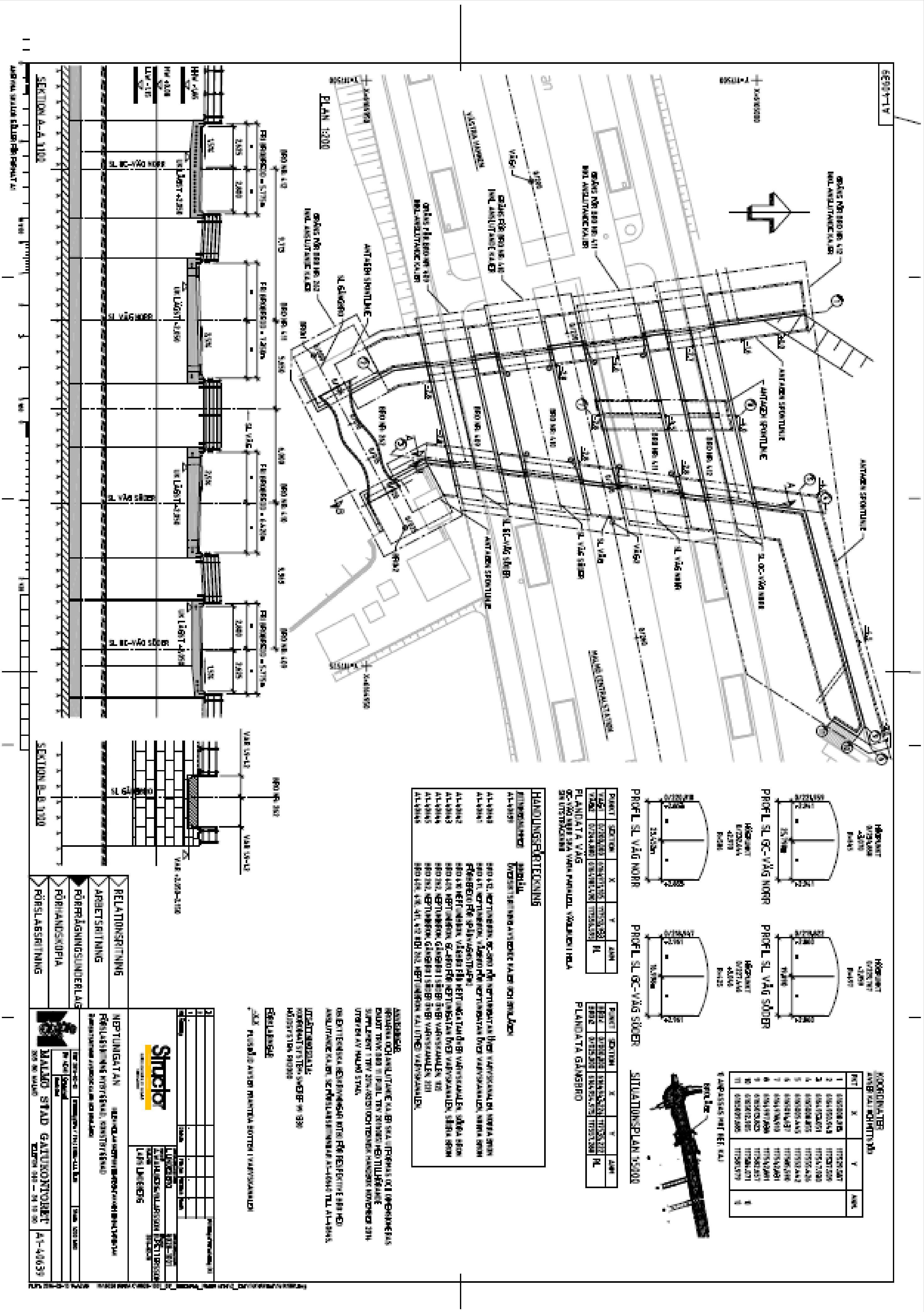
Extracts from the ETSI Bridge LCC tool

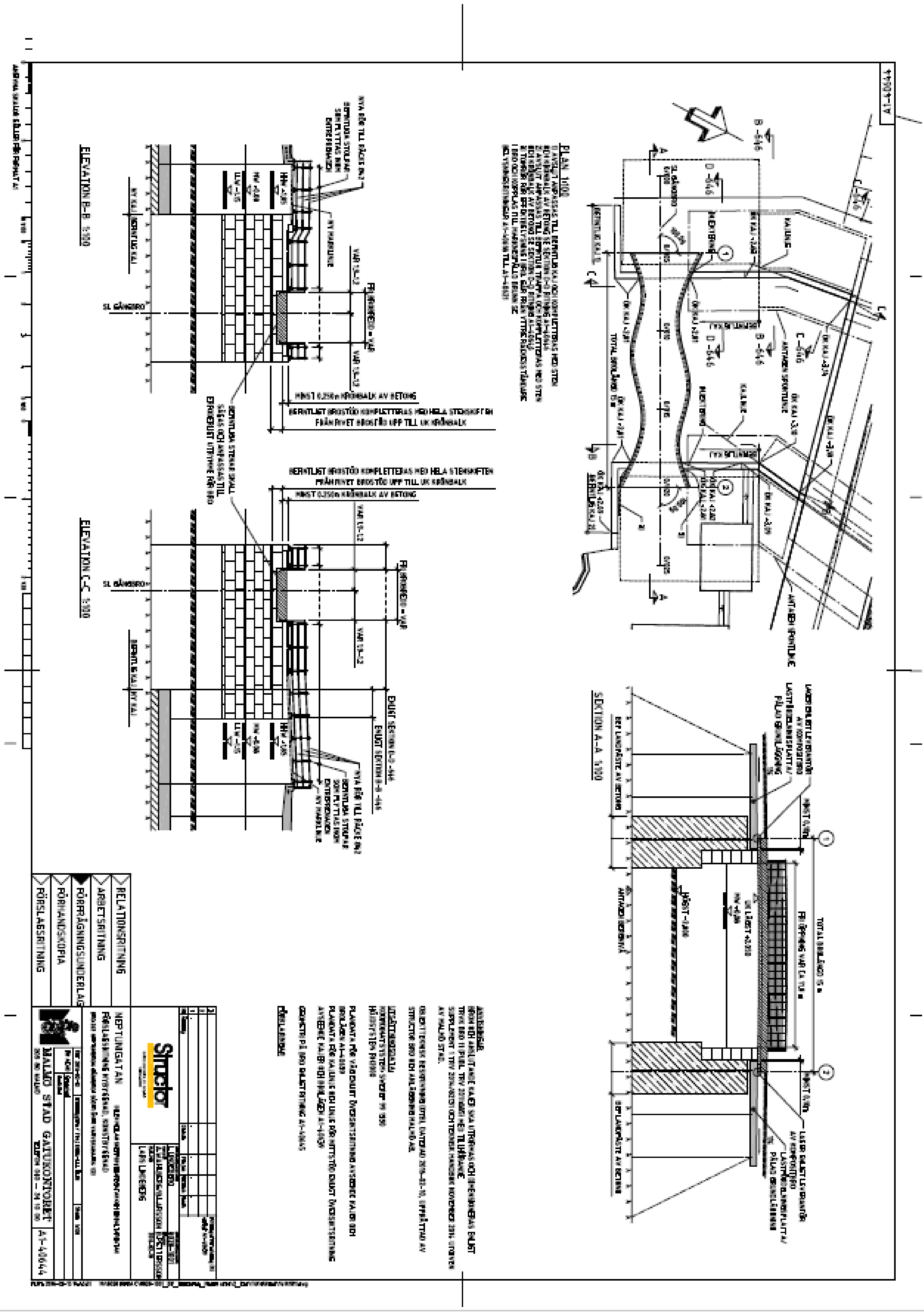
Case 2 Steel girders and concrete deck

Operation and Maintenance cost

dotted fields contain the default values evaluated with the help of previously entered data. You have the possibility to input your own values in the fields.

	MR&R unit cost & quantitie			MR&R interval alt. Single year				Traffic disturbanc		MR&R cost		User cost	
	unit costs		quantities	interval, year	action year	action year	action year	days	length	cost each time	tot cost	cost each time	tot cost
yearly surveillance	0	CUR		0	80	0	0	0,0	0,0	0	0	0	0
superficial inspection		CUR		0	0	0	0	0,5	0,3	0	0	0	0
main inspection	0	CUR		1	0	0	0	0,5	0,3	0	0	0	0
cleaning (removal of salt etc.)		CUR/m²	48	0	0	0	0	0,5	0,2	0	0	0	0
rodding of drainage system		CUR		0	0	0	0	0,0	0,0	0	0	0	0
impregnation of edge beams		CUR/m	30	0	0	0	0	5,0	0,0	0	0	0	0
maintenance of parapets, patch painting		CUR/m	30	0	0	0	0	3,0	0,0	0	0	0	0
maintenance of bridge seat		CUR		0	0	0	0	10,0	1,0	0	0	0	0
maintenance of expansion joints		CUR/m	6	0	0	0	0	4,0	0,0	0	0	0	0
backfilling and restoration of erosion protection		CUR		0	0	0	0	0,0	0,0	0	0	0	0
painting patching	1 700	CUR/m²	49	30	0	0	0	5,0	1,0	83 300	40 252	0	0
dehumidification device, el + maintenance		CUR/a		0	0	0	0	0,0	0,0	0	0	0	0
edge beam rep 0 - 30 mm/m²		CUR	418	0	0	0	0	20,0	0,8	0	0	0	0
change of rubber in expansion joint		CUR	6		13	63	0	5,0	0,1	0	0	0	0
adjustment of wearing course		CUR	48		0	0	0	0,0	0,0	0	0	0	0
bearings minor repair + painting		CUR	8	0	0	0	0	0,0	0,0	0	0	0	0
										Σ present cost	40 252 kr	Σ present cost	0 kr

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ELEVATION C-C 1:100
SECTION A-A 1:100
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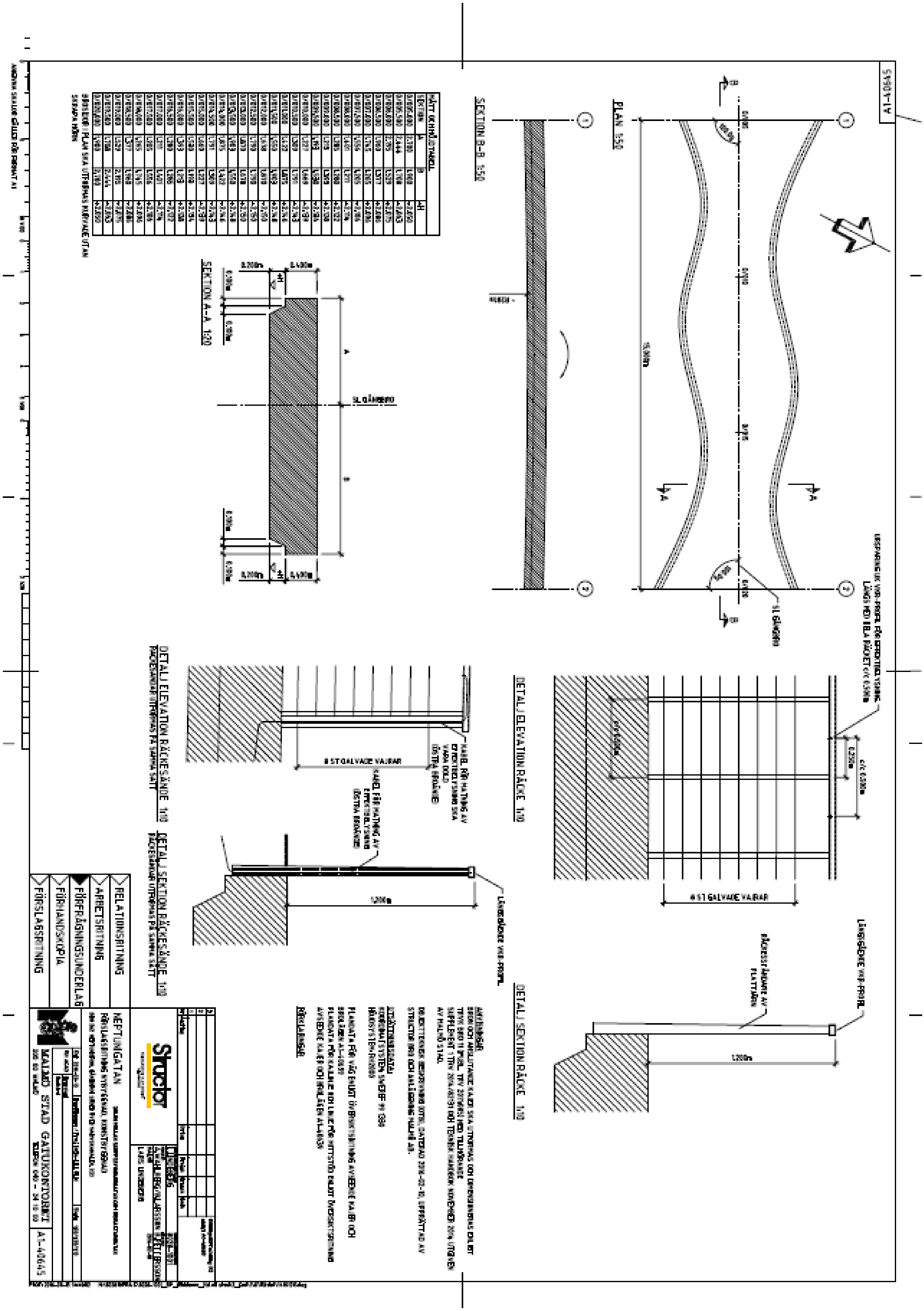
ARBETSRITNING
FÖRFRÅGNINGSUNDERLAG
FÖRHANDSKOPIA
FÖRSLAGSRITNING
NEPTUNIGATAN
MALMÖ STAD GATUKONTORET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DETALJ ELEVATION RÄCKESÄNDE 1:10
DETALJ SEKTION RÄCKESÄNDE 1:10
8 ST GALVADE VAJRAR
1,200m
RELATIONSRITNING
ARBETSRITNING
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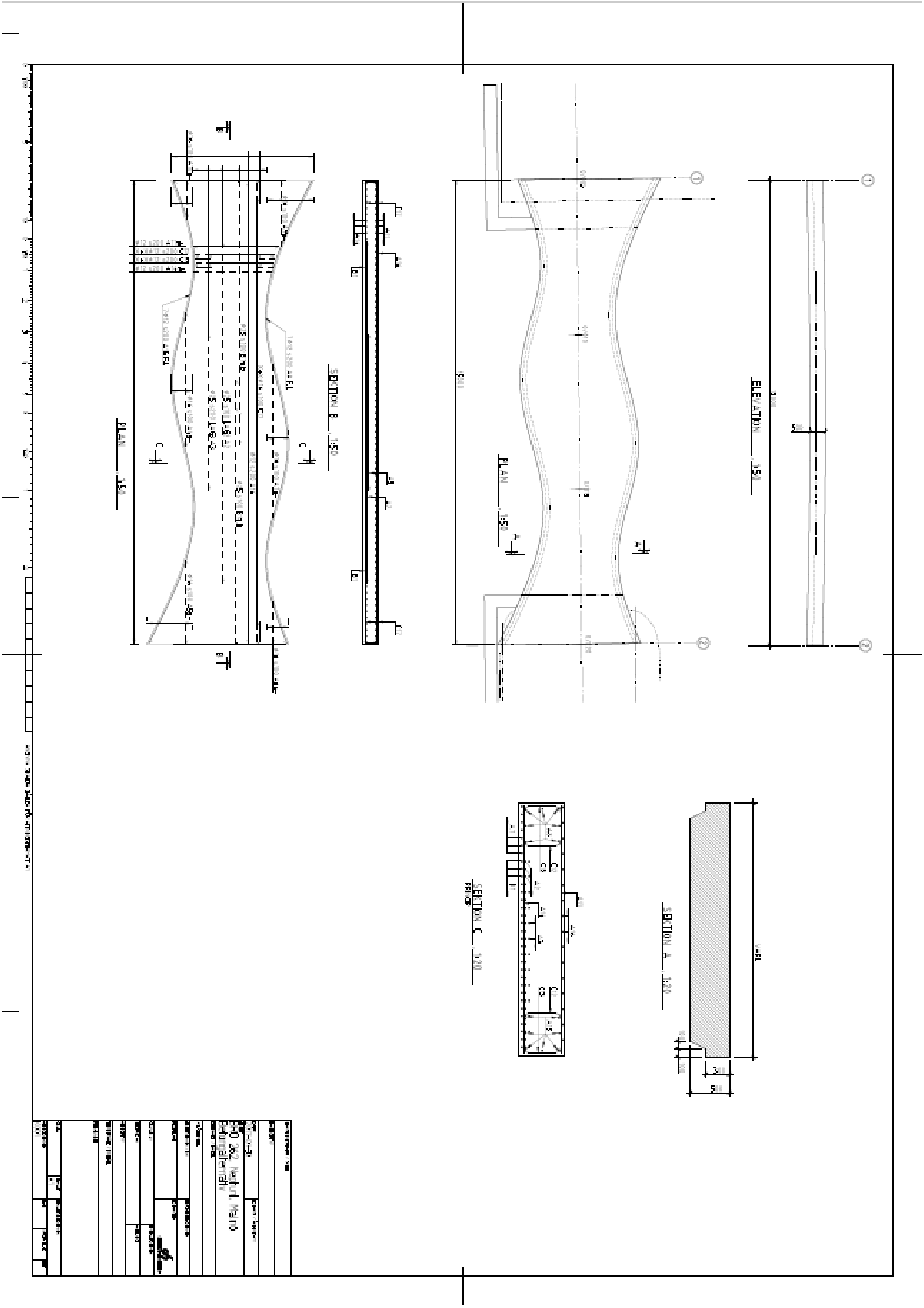
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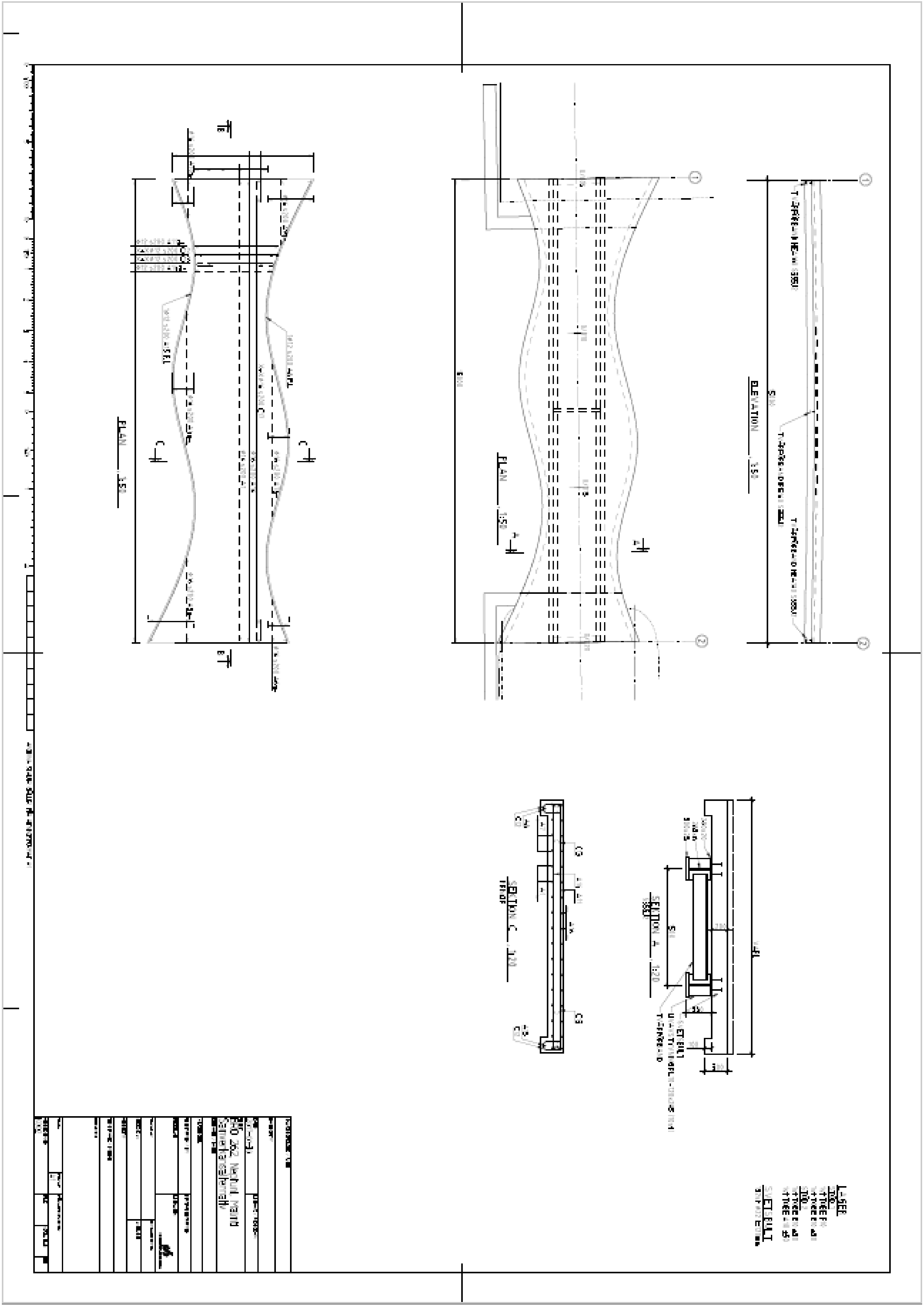
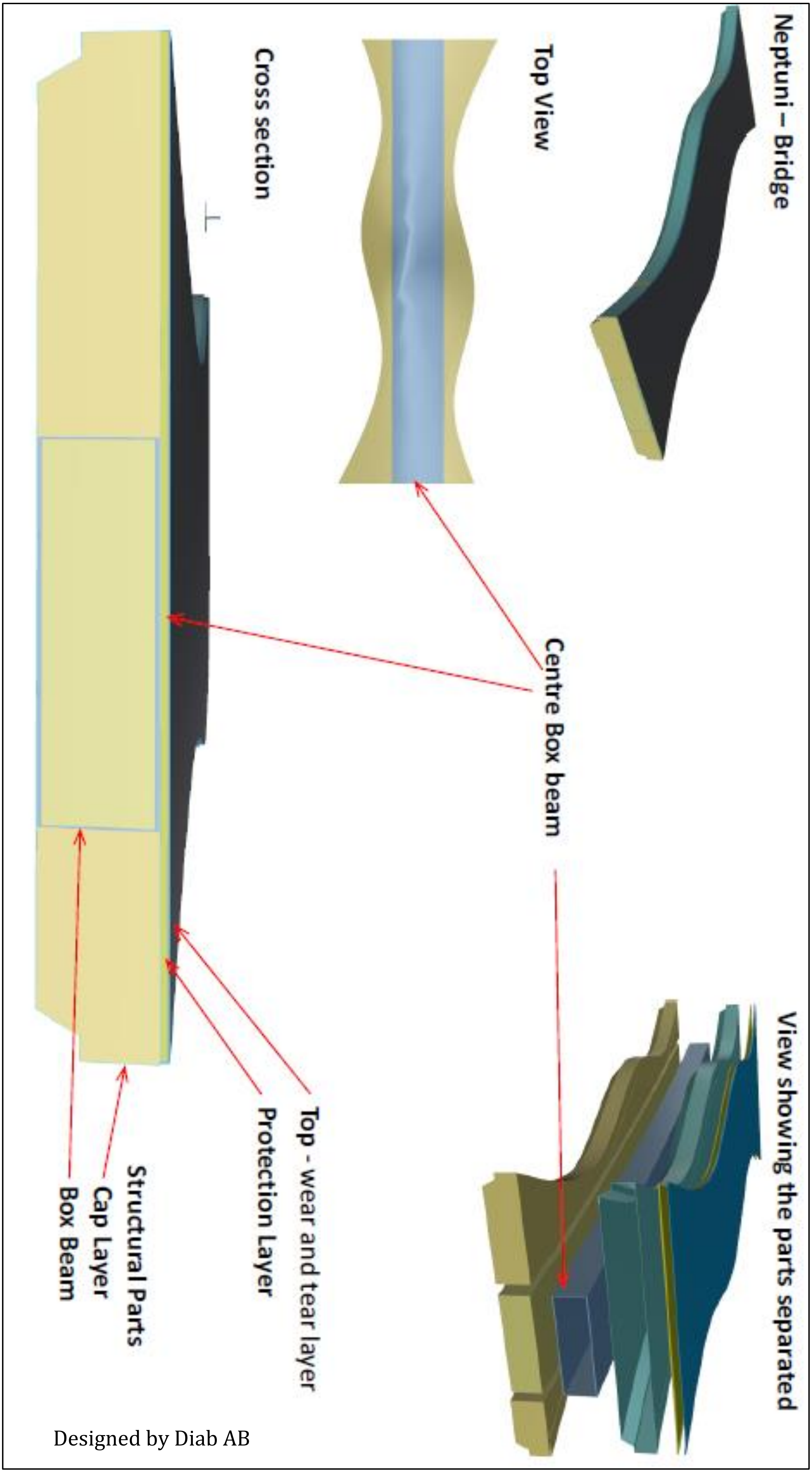
SECTION B 1:50
PLAN 1:50
ELEVATION 1:50
SECTION C 1:20
SECTION A 1:20


PLAN
ELEVATION
SECTION A
SECTION C

Data from BaTMan on pedestrian-bridge maintenance

(It is in Swedish! Åtgärdsår = Year of action, GC-bro = Pedestrian bridge, Kantbalk = Edge beam, Mängd = Quantity, Län = County)

Åtgärdsår	Funktionstyp	Län	Design elements	Aktivitet	Mängd	Enhet
2005	Gc-bro	Dalarnas län	Brobaneplatta Surface treatment	Komplettering	300	m2
2013	Gc-bro	Gävleborgs län	Brobaneplatta	Utbyte	1	st
2015	Gc-bro	Hallands län	Platta ytbehandling	Ommålning	1	st
2011	Gc-bro	Kronobergs län	Kantbalk	Injektering	20	st
2004	Gc-bro	Norrbottens län	Kantbalk	Betongreparation >70-110 mm		
2011	Gc-bro	Skåne län	Kantbalk	Impregnering	40	m
2002	Gc-bro	Södermanlands län	Kantbalk ytbehandling	Impregnering	2	st
2004	Gc-bro	Södermanlands län	Kantbalk	Impregnering	2	st
2007	Gc-bro	Värmlands län	Kantbalk	Betongreparation >30-70 mm	2	m2
2007	Gc-bro	Värmlands län	Kantbalk	Impregnering	64	m
2009	Gc-bro	Värmlands län	Kantbalk	Betongreparation >30-70 mm	2	m2
2009	Gc-bro	Värmlands län	Kantbalk	Impregnering	91	m
2009	Gc-bro	Värmlands län	Kantbalk	Impregnering	132	m
2009	Gc-bro	Värmlands län	Kantbalk kantskoning	Bättringsmålning	91	m
2009	Gc-bro	Värmlands län	Kantbalk räckesinfästning	Betongreparation >30-70 mm	5	st
2015	Gc-bro	Värmlands län	Kantbalk	Impregnering	50,4	m
2000	Gc-bro	Västerbottens län	Kantbalk	Betongreparation >30-70 mm		
2013	Gc-bro	Västerbottens län	Kantbalk	Försegling	1,5	m
2016	Gc-bro	Västerbottens län	Kantbalk räckesinfästning	Betongreparation >30-70 mm	46	st
2008	Gc-bro	Västmanlands län	Brobaneplatta fog	Rensning	2	st
2013	Gc-bro	Västmanlands län	Kantbalk	Utbyte	64	m
2004	Gc-bro	Västra Götalands län	Kantbalk	Impregnering		
2004	Gc-bro	Västra Götalands län	Kantbalk	Impregnering		
2004	Gc-bro	Västra Götalands län	Kantbalk räckesinfästning	Betongreparation >30-70 mm		
2007	Gc-bro	Västra Götalands län	Kantbalk	Impregnering	122	m
2013	Gc-bro	Västra Götalands län	Brobaneplatta	Fräsning	131	m2
2014	Gc-bro	Västra Götalands län	Kantbalk	Impregnering	245	m
2015	Gc-bro	Västra Götalands län	Brobaneplatta fog	Komplettering	3	m
2005	Gc-bro	Örebro län	Kantbalk	Impregnering	84	m2


Neptuni – Bridge
Top View
Cross section
Centre Box beam
View showing the parts separated
Top - wear and tear layer
Protection Layer
Structural Parts
Cap Layer
Box Beam
Designed by Diab AB