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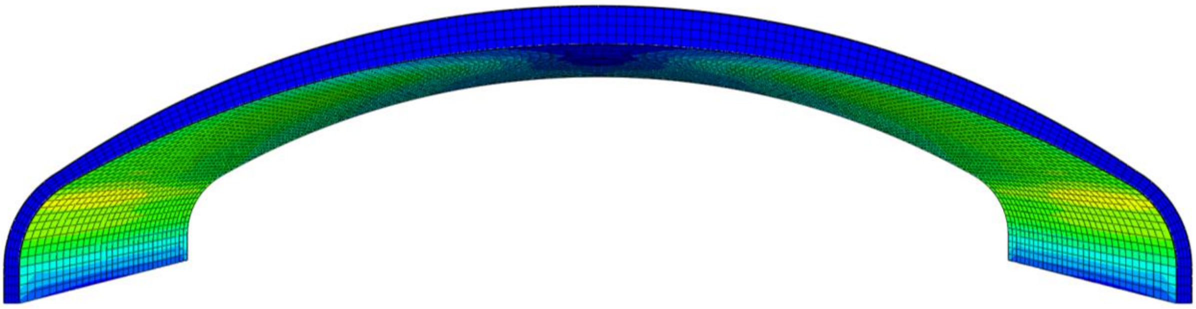

Application of FRP Materials for Construction of Culvert Road Bridges

Manufacturing and life-cycle cost analysis

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Cover:
Finite element model of an FRP culvert manufactured using vacuum infusion method.

Contents

Summary

This report presents the results of a research project, BBT2014-003, funded by Swedish Traffic administration (Trafikverket) titled “Application of FRP materials for Construction of Culvert Road Bridges - Manufacturing and life-cycle cost analysis”. This project is a complement and continuation of a previous project BBT2013-006 titled ”Preliminary study on application of FRP materials in Culvert Road Bridges, with emphasis on mechanical behavior and life-cycle cost analysis”. While the first project addressed the feasibility of using FRP composites as a construction material in culvert bridge structures with respect to limit state design, the current project aims to investigate the possibilities for manufacturing of FRP culvert structures and viability of such structures from LCC perspective.

The results of the previous study indicated that the strength of used FRP materials was sufficient in ULS and the deflection in the mid-span would most probably become the governing issue in the design (if there are requirement on deflection control).

Regarding the manufacturing of the culverts, among existing techniques for manufacturing FRP elements, pultrusion, filament winding, and VARTM are identified to be feasible and investigated further in this report.

Considering LCC analysis, it is shown that the investigated case study bridge, the FRP alternative, compared with traditional steel alternative, can be more cost-efficient along all life-cycle phases, including investment, operation and maintenance and disposal.

Göteborg, January 2016

Reza Haghani
Jincheng Yang

Preface

The work in this project was carried out at division of Structural Engineering, Steel and Timber Structures research group at Chalmers University of Technology in collaboration with DIAB. We appreciate the help from FRP experts Carl Johan Lindholm and Håkan Johansson for their advice on manufacturing and cost calculation of FRP culverts studied in this report.

Authors also appreciate the help from Lone Kaalund from Fiberline composites for her help regarding manufacturing and pricing of pultruded FRP segments.

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Notations

Notations in design and modeling of FRP culverts

Roman Letters

$[A]_{3*3}$	Extensional stiffness matrix for the FRP sandwich
$[B]_{3*3}$	Coupling stiffness matrix for the FRP sandwich
$[D]_{3*3}$	Bending stiffness matrix for the FRP sandwich
$[Q]_{3*3}$	Stiffness matrix for one FRP lamina
$[QQ]_{3*3}$	Stiffness matrix for the FRP lamina with fiber direction considered
d	Thickness of the core layer
E_{11}	Elastic modulus of FRP material in the longitudinal direction
E_{22}	Elastic modulus of FRP material in the transversal direction
EA	The equivalent membrane elastic constants
$E_{d.11.SLS}$	Design value of elastic modulus of FRP material in the longitudinal direction for SLS analysis
$E_{d.11.ULS}$	Design value of elastic modulus of FRP material in the longitudinal direction for ULS analysis
$E_{d.22.SLS}$	Design value of elastic modulus of FRP material in the transverse direction for SLS analysis
$E_{d.22.ULS}$	Design value of elastic modulus of FRP material in the transverse direction for ULS analysis
E_f	Characteristic value of elastic modulus of fiber
EI	The equivalent bending elastic constants
$EI_{k.FRP}$	Characteristic bending stiffness of the designed FRP sandwich in the span direction
$EI_{k.steel}$	Characteristic bending stiffness of the steel culvert in the span direction
$E_{k.11}$	Characteristic value of elastic modulus of FRP material in the longitudinal direction
$E_{k.22}$	Characteristic value of elastic modulus of FRP material in the transverse direction
E_m	Characteristic value of elastic modulus of resin matrix
G_{12}	In-plane shear modulus of FRP material
$G_{d.12.SLS}$	Design value of the in-plane shear modulus of FRP material for SLS analysis
$G_{d.12.ULS}$	Design value of the in-plane shear modulus of FRP material for ULS analysis
$G_{d.23.SLS}$	Design value of the rolling shear modulus of FRP material for SLS analysis
$G_{d.23.ULS}$	Design value of the rolling shear modulus of FRP material for ULS

analysis

G_f	Characteristic value of shear modulus of fiber
$G_{k.12}$	Characteristic in-plane shear modulus of FRP material
G_{k23}	Characteristic rolling shear modulus of FRP material
G_m	characteristic value of shear modulus of resin matrix,
no	Number of plies used for the FRP laminate face
t	Thickness of one FRP ply
t_{face}	Thickness of FRP laminate as the face of a sandwich panel
v	Fiber fraction in volume
w	Fiber fraction in weight

Greek Letters

ε_{mid}	Midplane strains
θ_i	Fiber orientation angle of the i^{th} FRP ply
κ_{mid}	Midplane curvature
υ_f	Poisson ratio of fiber
υ_m	Poisson ratio of resin matrix
υ_{ij}	Poisson ratio of FRP material (the ratio of strain in direction *j* to the applied strain in direction *i*)
$\gamma_{M.SLS}$	Partial factor for FRP material for SLS analysis
$\gamma_{M.ULS}$	Partial factor for FRP material for ULS analysis
γ_{M1}	Partial factor for FRP material considering derivation of properties
γ_{M2}	Partial factor for FRP material considering method of manufacturing
$\gamma_{M3.SLS}$	Partial factor for FRP material considering loading conditions for SLS calculation
$\gamma_{M3.ULS}$	Partial factor for FRP material considering loading conditions for ULS calculation
ρ_f	Density of fiber
ρ_m	Density of matrix

1 Introduction

1.1 Aim and objectives

The culvert structure buried by the backfill soil is the main load bearing member of a culvert bridge. Since most of culvert structures are assembled using corrugated steel plates, the fatigue and corrosion issues are among the most important challenges during the service life of such bridges. Measures required during the life-cycle of steel culvert bridges result in high maintenance cost paid by agencies.

Fiber reinforced polymer (FRP) composite materials are a promising alternative to the traditional steel plates currently used in the culvert bridge structures, mainly due to their high resistance to fatigue and corrosion. In the first preliminary feasibility study performed on the subject of using FRP materials for construction of culvert bridges [1], it was shown that the high strength and the excellent fatigue resistance of GFRP sandwich structure resulted in satisfying structural performance of the studied culvert. As a complementary study, this report aims to investigate the manufacturability and economic feasibility of FRP culvert bridges.

To meet the aim of the project, two objectives are determined to be achieved: 1) to put forward concepts for structural systems for FRP culvert structures and practical manufacturing techniques and examine them through a proper case study, and 2) to carry out a cost analysis for steel and FRP alternatives based on the life-cycle cost (LCC) analysis and sensitivity analyses.

1.2 Methodology

Objective 1: Practical proposals for manufacturing FRP culvert structures

A literature review on FRP composite modeling method is performed first. The FRP manufacturing techniques with focus on manufacturing of structural elements (summarized in Chapter 2). In order to manufacture an FRP culvert structure, the assembly issues are also essential and should be investigated. In Chapter 3, the connections of FRP composite elements is discussed. Based on the study performed on manufacturing and assembly techniques, practical proposals for building FRP culverts using feasible methods are put forward in Chapter 4.

In Chapter 5 an existing steel culvert bridge in Sweden is chosen for a case study. Based on the FRP construction proposals, three alternatives of FRP culvert structures are developed.

The cross-sectional geometry is designed by hand-calculation methods [1], and verified by finite element (FE) modeling in Abaqus (6.13), regarding the stress in ULS and the deflection in SLS.

Objective 2: Economic evaluation of FRP culvert bridge alternatives by LCC analysis and Sensitivity analysis

An LCC analysis is carried out on the selected steel culvert bridge and the FRP alternative in Chapter 6. The alternative with more cost-benefits is highlighted by the LCC results. Based on the LCC results, a sensitivity analysis is further studied to investigate the impact of parameters on the conclusion of LCC analysis.

2 FRP composite manufacturing methods

There exist a number of FRP manufacturing methods that can be used for culvert application. A review of widely used FRP molding methods is helpful for putting forward a practical manufacturing proposal for the FRP culvert. In this section, a summary of promising techniques for the FRP products will be discussed. In order to be applicable for the culvert structures, the following criteria are considered in choosing the proper methods:

- The method can produce FRP composite products for structural use with sufficient strength.
- The method can produce FRP composite in large-size.

2.1 Pultrusion

Pultrusion is an automated continuous manufacturing process. It is economical and widely used for high-volume production of FRP components with constant cross-section, for example, I-beams, solid rods, hollow tubes and flat sheets. Continuous fibers, provided as a combination of roving and mats, pass a resin bath with catalyst blended for impregnation. Then the saturated fibers go with surface veils thought a performer which set the required composite section and take the excessive resin away. A steel die with elevated temperature is used for the curing process. The cured composite is cut into designed length by a saw at the end. Figure 2.1 shows the general pultrusion manufacturing process. Considering the equipment and tooling costs, prefabricating composite parts made by pultrusion and ordering from suppliers is an efficient alternative compared to on-site manufacturing alternatives.

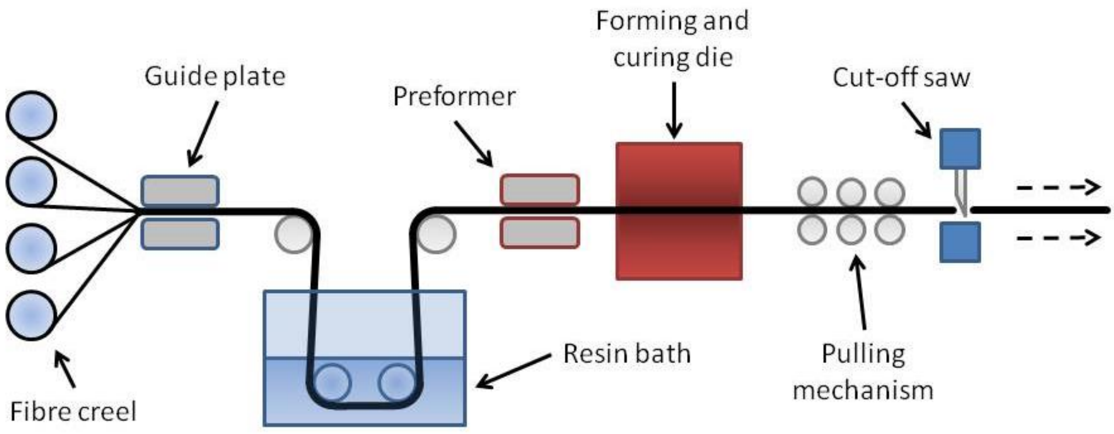


Figure 2.1 FRP composite manufacturing process of pultrusion [2]

Material options [3]**:**

Fiber: Any

Resin: Polyester, vinylester, epoxy, and phenolic

Core: Not used in general

Advantages

Besides the favorable features as the FRP composite, the pultrusion technique gives the following benefits [4], [5]:

- High volume production and customized product length. Pultrusion method in principle sets no limit for the production volume of FRP composite with constant cross-section, which makes it an economic solution to produce FRP members with large size in length dimension.
- Fast production due to highly automatic process. Once the equipment is set up, the manufacturing process would run continuously with little intervention.
- Product quality consistency. Excellent resin dispersion, resin-content control, and fiber alignment can be obtained in pultrusion process.
- High fiber content. Fibers in the pultruded composite are well aligned with a compact, high fiber content. The fiber weight fraction of composite by pultrusion can reach 85 percent with continuous fiber along longitudinal direction.
- High strength-to-weight ratio. Excellent mechanical properties of pultruded FRP members in terms of strength to weight ratio can be achieved.
- Pre-fabrication. Considering the equipment and tooling costs during manufacturing process, prefabricating and ordering from suppliers is more economic than other manual manufacturing methods.

Limitations

- Limited to products with constant cross-section. Pultrusion has difficulty to produce composite with non-prismatic cross section.
- Thin-walled composite parts. It's a challenge to achieve good properties in section with small thickness.
- The continuous reinforcing fibers in pultruded FRP members are mainly placed in longitudinal direction, which results in substantial difference of strength and stiffness

between longitudinal and transvers directions. For higher mechanical properties in non-pultrusion-directions, multiaxial fiber fabrics can be applied.

2.2 Filament winding

This process is generally used for hollow components with circular section, such as pipes and tanks. In filament winding process continuous impregnated fibers are wounded on a rotating mandrel according to the design pattern, and cure either at room temperature or elevated temperature in an oven. In the wet winding method, the fibers go through a resin bath and pick up the low-viscosity resin (see Figure **2**.**2**). In the dry winding method, the fiber is impregnated with resin prior to winding process. When sufficient layers have been applied, the FRP composite is cured on the mandrel, which will be removed after the curing process.

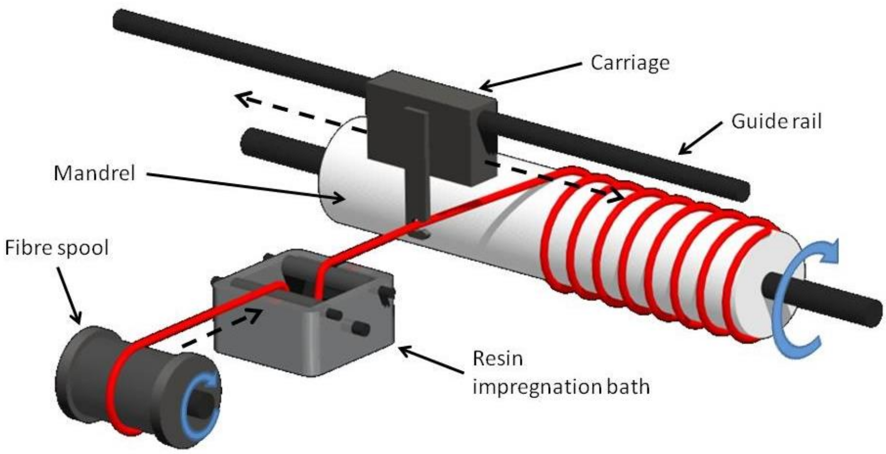


Figure 2.2 FRP composite manufacturing process of filament winding [2]

Material options [3]**:**

Fiber: Any. Continuous fibers from a creel, but not woven or stitched in a fabric form.

Resin: Any, e.g. polyester, vinylester, epoxy, and phenolic

Core: Any

The filament winding method has some advantages and limitations than other forming techniques:

Advantages of filament winding [6]

- High control of fiber placement and orientation. The computer-controlled winding machine provides good control of fiber pattern (from part to part and from layer to layer), which guarantees the design mechanical properties of the FRP products.

- Fitting cylindrical and spherical products. The expanding technology enables the winding machine to make complex shapes, such as wind turbine blades and helicopter tail booms. When it comes to culvert structure, filament winding for culverts with circular, ellipse, and pipe-arch profiles can be investigated. The span of these culvert bridges is usually design less than 10 meters.
- Additional strength from hoop effect. As a result of winding process with continuous fiber the hoop effect is favorable in terms of structural performance.
- Eliminating assembly work. Assembly of segments is usually labor- and time-consuming, which counts substantial proportion of the investment costs of projects. The filament winding method is an economical alternative than other FRP molding methods.

Limitations of filament winding

- Difficulty in winding reverse curvature in concave shapes. It's also a challenge for filament winding method to produce FRP culverts with bottom-open arch profile or box culvert.
- Poor external surface finishing. Coating layer is necessary to be applied if aesthetic value to be satisfied.
- Fiber cannot be placed along the length direction of the products.
- Mandrel costs can be high when the products have large size.

Both thermoplastic and thermosetting resin can be used in filament winding method, which results in great difference in terms of manufacturing process and FRP products. More details are discussed respectively.

2.2.1 Thermoplastic filament winding

During the process of thermoplastic filament winding, fibers are continuously fed and impregnated with molten thermoplastic resin and wound on a mandrel. As a focused subject for future study, the filament winding method with thermoplastic resin includes the following characteristics [7]–[10]:

Advantages

- Possible to make thick-wall composite. For instance, tanks and containers withstand high pressure.
- One-step in situ consolidation (on-line consolidation) during winding process. It helps speed up the production.

- Low thermal residual stresses

Limitations

- Relatively high cost of fiber impregnation process
- Creep behavior of thermoplastics matrix. Therefore, *it is unfavorable to be used for FRP culvert structures*, in terms of mechanical performance.

2.2.2 Thermosetting filament winding

Most of the thermosetting resins are usable for filament winding [11], such as widely used unsaturated polyester and epoxy with higher mechanical properties [12]. The wet winding method is widely used in commercial applications with polyester and epoxy resin.

Advantages

- Curing at ambient temperature is possible [13], for instance, by adding hardeners into epoxy resin.
- Relatively lower material cost. Raw continuous fiber and resin can be used in wet winding at a lower cost than woven fabrics or prepreg. Besides, the cost of mandrel is usually less than the dies or molds used in other forming methods, such as resin transfer molding (RTM) and compression molding.

Limitations

- Void content of most wet-wound FRP composites are normally in the range of 3 to 6 percent. It is of concern when the FRP member is under compression, bending or shear unless special precautions are taken.
- Low control of resin content. To guarantee the resin content some important parameters during wet winding process need to be noticed [6]:
    - Resin viscosity should be 2 Pa.s or lower
    - Interface pressure at the mandrel surface
    - Tension during winding process
    - Number of winding layers

2.3 Vacuum bagging

Vacuum bagging was developed as an extension of traditional wet lay-up method where the laid-up fibers are impregnated by hand with the consolidation rollers. In vacuum bagging, an improved impregnation and consolidation is achieved by covering the wet laid-up fabrics with a plastic film and sealing them on the tooling plate. A vacuum pump extracts the air and thus generates up to one atmosphere of pressure on the laminate for consolidation.

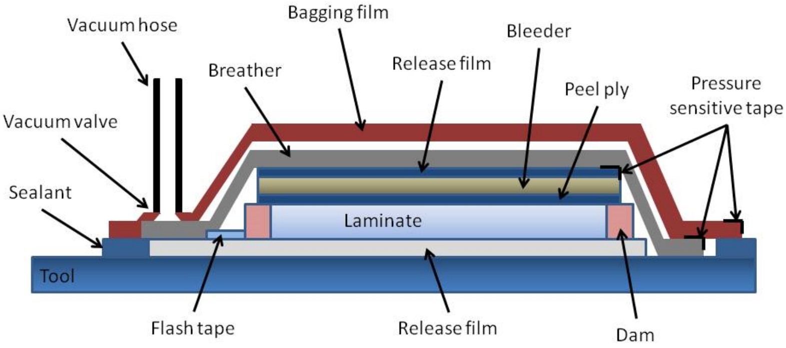


Figure 2.3 FRP composite manufacturing process of vacuum bagging [2]

Material options [3]**:**

Fiber: Usually fiber fabrics. The consolidation pressure allows the wet-out of a variety of heavy fabrics.

Resin: Usually epoxy, and phenolic. Polyester and vinylester may have problems due to excessive extraction of styrene from the resin by the vacuum pump.

Core: Any

Advantages

As an upgrade of conventional wet lay-up process, the vacuum bagging has the following benefits:

- Higher fiber content and lower void content can be achieved compared with conventional wet-lay-up techniques.
- Better resin infusion through the structural fibers and fiber impregnation with the help of vacuum environment.
- Suitable for manufacturing large-size components with a sandwich cross-section.
- Healthier due to the reduced emission of volatiles during cure.

Disadvantages

- Increased cost of labor and disposable bagging materials
- Higher requirement of operators' skill to guarantee the product quality

2.4 Resin transfer molding (RTM)

RTM belongs to a class of processes called liquid composite molding. Thermosetting resins are usually used as matrix material due to their low viscosity (typically 0.1-0.5 Pa.s)[14]. Dry fiber fabrics are stacked up and placed in the first mold. These fabrics usually fit better on the mold. A second mold half is then clamped over, which follows the shape of the first mold. Low-viscosity resin from reservoir is pumped into the space between the moulds, penetrating and filling the space between fibers. Air in the molds is displaced and vented out. Once the fabrics are fully wet, the resin inlets are closed and the curing process starts. Both the injection and cure process can be done in either elevated temperature or ambient temperature. The main steps are shown in Figure 2.4.

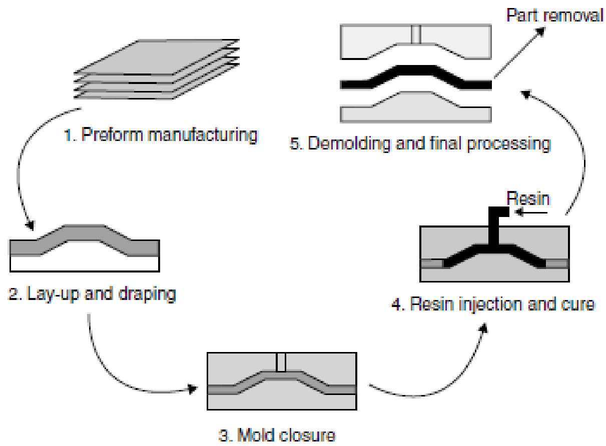


Figure 2.4 FRP composite manufacturing process of RTM [14]

Material options [3]**:**

Fiber: Any. Stitched fiber fabrics work well since the gaps allow easy resin infusion.

Resin: Usually polyester, vinylester, epoxy and phenolic.

Core: For some foam materials, the risk of crushing exists if pressure is applied by the molds. For honeycomb, it is not feasible if the celled are not sealed.

Advantages

- Near net shape composite parts with good surface finishing on both sides.
- Close dimension tolerances due to the compaction from upper and lower rigid molds with gel-coated surfaces
- Complex shapes with ribs, channels and tapered thickness can be produced.
- High fiber content. The compaction pressure gives a higher fiber volume fraction (60-70%) compared with traditional hand lay-up and vacuum bag molding.
- Fast produce cycle due to the positive pressure applied during the resin injection process
- The evolving of modern RTM make it possible to make load-bearing composite structures.

- Healthy and safe due to enclosure of resin.

Limitations

- High tooling cost due to matched molds.
- Limitation of product dimension due to the limited span of typical milling machines, compared to vacuum bag molding.
- Inconsistency in reproducibility. There exists difference due to fiber preforms, stacking, and placement in the mold cavity.

2.5 Vacuum assisted resin transfer molding (VARTM)

The VARTM, as a developed method of RTM technique, was originally developed for manufacturing high-quality and large-size composite parts[15]. Different from RTM, in VARTM process only one-side rigid mold is needed (see Figure **2.5**). The dry fiber stack is covered by a peel ply and a knitted type of non-structural fabric[3], which acts as a porous medium layer in the following resin injection process. This resin injection technique is also referred as Vacuum Infusion. After the lay-up of fiber preform, the mold is sealed with a flexible bag. Vacuum condition is created by pumping the air out from fiber lay-up on the mold. It utilizes the pressure difference between vacuum in the bag and atmosphere outside to obtain the compaction on fibers preform and the distribution of resin.

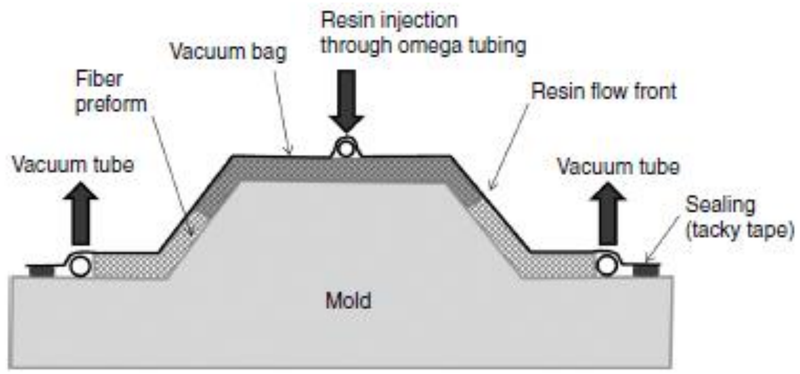


Figure 2.5 FRP composite manufacturing process of VARTM [15]

Material options [3]**:**

Fiber: Any conventional fabrics, e.g. stitched fiber fabrics.

Resin: Usually polyester, vinylester and epoxy.

Core: For honeycomb, it is not feasible if the cells are not sealed.

Advantages

- Lower mold tooling cost compared with RTM.
- Large-size composite parts with complex shape can be made.
- High fiber volume fraction and low void content.
- Easy to remove dry spot with air entrapped. Due to the use of transparent vacuum bag, the dry spots occurring during resin infusion are visible to be removed by inserting vacuum needle.
- Low volatile organic compounds emission due to a closed-mold process compared with traditional hand lay-up method.
- It is feasible to produce sandwich structure with inserted core in one operation.

Limitations

- Low recycling of molding tools. For each individual process, flow distribution medium layer, peel ply, sealing tape may not be reused.
- High risk of air leakage to be concerned during forming process. It is highly related to workman's skill and environment conditions. Frequent inspection for the air leakage is necessary.
- Risk of un-impregnated areas.

2.6 Compression Resin Transfer Molding (CRTM)

Compression resin transfer molding, as another variant of composite forming process RTM, has advantages of near-net-shape and dimension control in RTM and a reduced resin infusion time that obtained in VBM by using a flow distribution medium layer. Different from RTM, the upper mold is not lowered and closed to form a cavity of finial part geometry. After the measured amount of resin is injected to the mold, the upper mold will close completely and apply compression, pushing the resin and fiber in order to reach the designed thickness. As a result, the resin filling process combines the injection and compression driven flow, see Figure 2.6.

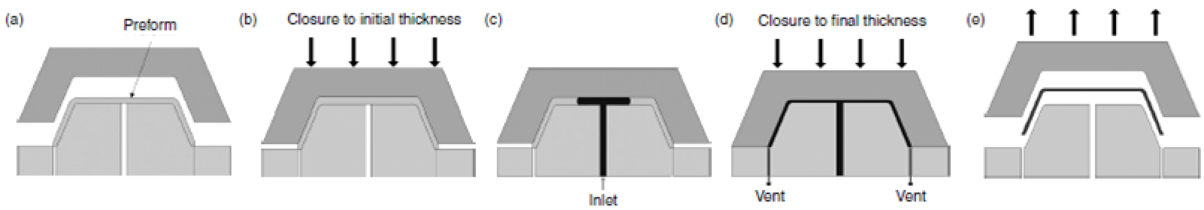


Figure 2.6 FRP composite manufacturing process of CRTM [16]

Advantages

Besides the similar advantages of RTM, for instance composite parts with good surface finishing and high fiber volume content, CRTM also yields the following benefits:

- Suitable for producing high-quality composite parts with high fiber content.
- Relatively shorter cycle time and faster production rate. Due to the mold clamping force, significant reduction of mold filling time is obtained in CRTM compared to RTM.
- Reduced void content in the composite parts compared to RTM.

Limitations

- High costs of molding tools. It makes CRTM less competitive to RTM or VARTM when manufacturing composite parts with complex shape, large size, or different required geometry.

2.7 Prepreg-autoclave

Prepreg refers to the fiber materials that are pre-impregnated by the manufactures with pre-catalyzed resin. At room temperature, the catalyst is latent which gives the prepreg longer useful life. It is usually stored as frozen for a prolong shelf life. In the composite forming process, the prepregs are laid up on a mold surface, covered with bleeder and breather, and sealed with a vacuum bag, and heated to typically 120-180 Celsius degree[3], [17]. It results in the melting and reflow of resin in the prepreg, and then curing in the end. The autoclave creates an enclosed space and can provide a high pressure up to 5 atmospheres acting on the laminate. Curing in autoclave is the most widely used method of producing high-quality laminates in the aerospace industry[18].

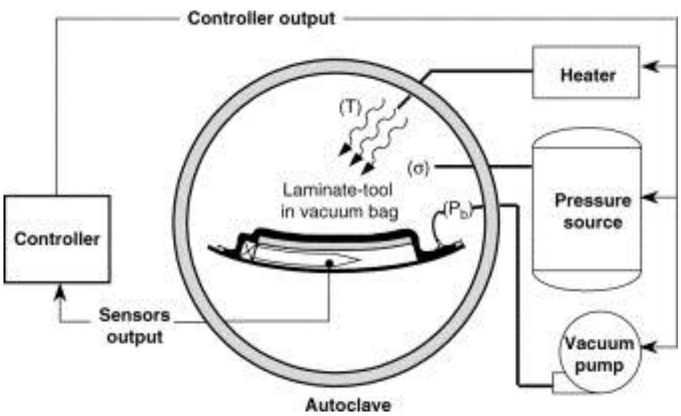


Figure 2.7 Typical autoclave processing system[17]

Material options[3]**:**

Fiber: Any.

Resin: Usually polyester, epoxy, phenolic, and high temperature resins such as polyimides, cyanate, esters and bismaleimides.

Core: Limited to special types of foam material due to the elevated temperature and pressure in the autoclave.

Advantages:

- Due to the use of prepreg, good control of resin content and high fiber content can be achieved.
- Mechanical and thermal performance of resin chemistries can be optimized due to good control of temperature and pressure in the autoclave process.
- Healthy to work with and the process is potential for automation and labor saving.

Disadvantages:

- Relatively higher material cost due to the use of prepregs
- High manufacturing cost and size limitation of products due to the expensive autoclave equipment.
- For thicker laminates, the prepregs need to be warmed during lay-up process in order to remove the air between plies.

2.8 Prepreg-out of autoclave

For FRP products with a fiber volume fraction from 50% to 60%, a very high pressure is not necessarily needed in the forming process. Instead of using the high-cost autoclave, the vacuum bagging can be applied to provide required pressure as an economic solution[17], see Figure 2.**8**. Therefore, the out-of-autoclave method is a combination use of prepregs and vacuum bagging technique that introduced in section 2.3. In the out-of- autoclave process, the used type of prepregs can be cured at a lower temperature from 60 to 120 Celsius degree, namely the low-temperature-curing prepregs. Heating to the curing temperature can be achieved by simple hot-air circulated ovens[3].

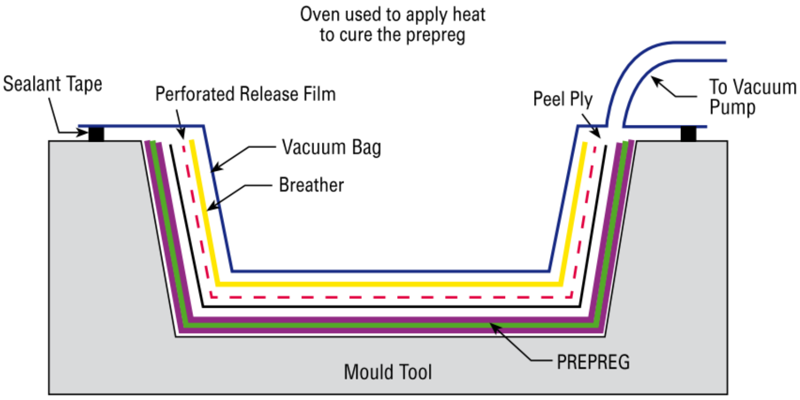


Figure 2.8 Out of autoclave process by vacuum bagging[3]

Material options [3]**:**

Fiber: Any. The same fiber used in conventional prepregs.

Resin: Only epoxy in general.

Core: Any. Special care is needed for standard PVC foam.

Advantages:

Besides the benefits of using prepregs, the out of autoclave method has the following improvements compared with the autoclave process:

- Reduced tooling cost
- Composites with large-size can be produced.
- Conventional foam core materials can be used due to reduced pressure.
- Lower energy cost than autoclave process

Disadvantages:

- Material cost is still higher than the process using non-preimpregnated fabrics.

3 Joining and assembly in culvert bridge structures

3.1 Challenges for execution of joints in steel culvert structures

Galvanized steel plates with corrugated shape is the most prevalent material used in metallic culvert bridges. The corrugated steel plates are assembled by bolt fasteners into culvert structures with different profiles, ranging from circular and ellipse types to bottom-open arch and box shapes. An important performance aspect of steel culvert bridges is the behavior of mechanical fasteners in joints which is a critical issue attracting special concerns in design of such structures. The main issues involved in bolted joints are discussed below.

- Costs of labor and material. The assembly process using bolted connections is usually conducted in situ. The required installation time, intensive labor, and fasteners contribute in increasing life-cycle cost.
- Mechanical performance. The effect of stress concentration in joints yields higher risk of failure. Previous analyses on mechanical behavior of steel culverts show that fatigue failure in critical sections such as bolted joints could be governing in steel culvert structures [1]. As a result, the full utilization of material is limited.
- Influence on the durability of culvert bridges. Water passage under the structure is a rather common condition in culverts. As a result, the corrosion is a problem which cannot be eliminated in steel culvert bridges. The joints are more vulnerable to moisture diffusion and water penetration, and normally corrosion initiates at these locations. To guarantee the structural performance during service life, annual inspection and regular maintenance are necessary, which increases the agency costs of steel culvert structures.

3.2 Assembly of FRP composite elements

Compared to connection of steel plates, assembly of FRP composite elements have more choices, including using conventional mechanical fasteners, adhesive bonding and hybrid joints. The hybrid joint refers to a combination of adhesive bonding and mechanical joining to obtain the benefits from both techniques.

One of the highlighted advantages of composite products is that it is possible to produce integral structures in large-size aiming at reducing the assembly work involved. In terms of economic efficiency, reduced assembly work is of a great concern in the design and execution of FRP culverts. A previous study shows that the assembly costs can reach as high as 50 percent of the total delivered cost of FRP composites due to the intensive labor and complex operational process [5].

3.2.1 Joining composite elements using mechanical fasteners

The process of mechanical joining of composites includes the following steps in general:

- Construction of frame work
- Placement of the FRP segments in right position
- Drilling holes and installation of fasteners
- Sealing with a surface coating if necessary

Although failure modes of mechanical joints in composites are similar to those in the conventional metallic structures, more considerations are required since composite materials are relatively brittle and due to less ductility compared to metals, less redistribution of local stress concentrations is expected. Important issues relative to the use of mechanical joints in composites are discussed below.

3.2.1.1 *Stress and heat generated damage during trimming and drilling*

Since composite products are made of fibers and relatively weak and brittle matrix material, there is a high risk of damage in composite during trimming and drilling process, compared to most of metals. Possible damage includes delamination, cracking, fiber pullout, matrix chipping and heat damage. For instance, a reduction of joint efficiency occurs in mechanically fastened joints, due to the notch sensitivity of relatively brittle composite material [19].

3.2.1.2 *Stress concentration around holes in composite laminate*

Stress concentration in mechanical joints causes great reduction of utilization ratio of materials. It shows that in general only 20-50 percent of the laminate ultimate tensile strength is developed in mechanical joints [5], [19].

3.2.1.3 *Acceptable failure mode*

The favorable failure mode of mechanical joints should be considered as bearing failure, rather than shear out or rupture of the FRP element, in order to prevent catastrophic failure.

3.2.1.4 *Prevent potential corrosion*

For composites made of carbon fibers, aluminum and steel fasteners cannot be used due to risk of galvanic corrosion. Instead, titanium is usually chosen as fastener material [5]. A good sealing over fasteners is also necessary to prevent water penetration through joints and introducing corrosion.

3.2.2 Joining composite elements using adhesive bonding

3.2.2.1 *Introduction of adhesive bonding*

Adhesive bonding is another widely used method to assemble composites. For composite structures with thin sections, joints bonded by adhesive is preferred than using mechanical fastening since the bearing stress in the bolted joints would be unacceptably high.

In general, there are two different ways to conduct adhesive bonding in composite structures—secondary bonding and co-curing. In secondary bonding process, cured composite parts are adhesively bonded to each other, core materials, or metallic pieces. Co-curing is a process in which uncured composite sheets are cured and bonded to other materials at the same time during the cure cycle.

Both of these two methods can be used to build, for instance, a composite sandwich structure with foam core inserted between FRP sheets. Prefabricated cured FRP sheets can be bonded to core material on-site with proper adhesives in the secondary bonding process. Otherwise, the foam core can be piled with impregnated fiber lay-up, and then co-cured in the workshop to realize bonding strength for assembly.

In this section, the main focus is put on secondary bonding process. Details of co-curing method are investigated and discussed in details in Section 3.3.4 in which the manufacturing method of sandwich structures is explained.

3.2.2.2 *Joint design*

An important principle in the design of adhesively bonded joints is that the failure of joint should not occur in the bonding interface. Only the failure in adhesive or adherent materials is acceptable. In order to achieve satisfactory load-bearing capacity, the design of a structural adhesive joint requires understanding about the load transfer mechanism and mechanical behavior of the constituents. Since adhesively bonded joints are strong in shear and weak in peeling, loading in tension, cleavage and peeling should be avoided in a proper design (see Figure **3.1**). However, in joints experiencing bending in practice, the peeling forces cannot be avoided. In this case, it is preferred to use a ductile adhesive with higher peeling resistance, instead of a brittle adhesive characterized with higher strength and modulus of elasticity.

Figure 3.1 Critical loading configurations to be avoid in adhesive joint design (Left: tension; Middle: Cleavage; Right: Peel) [18]

Typical joint designs includes lap joint, tapered lap joint, strap joint, scarf joint and step lap joint for thick composite (applicable only in co-curing process). Configurations are shown in Figure 3.2.

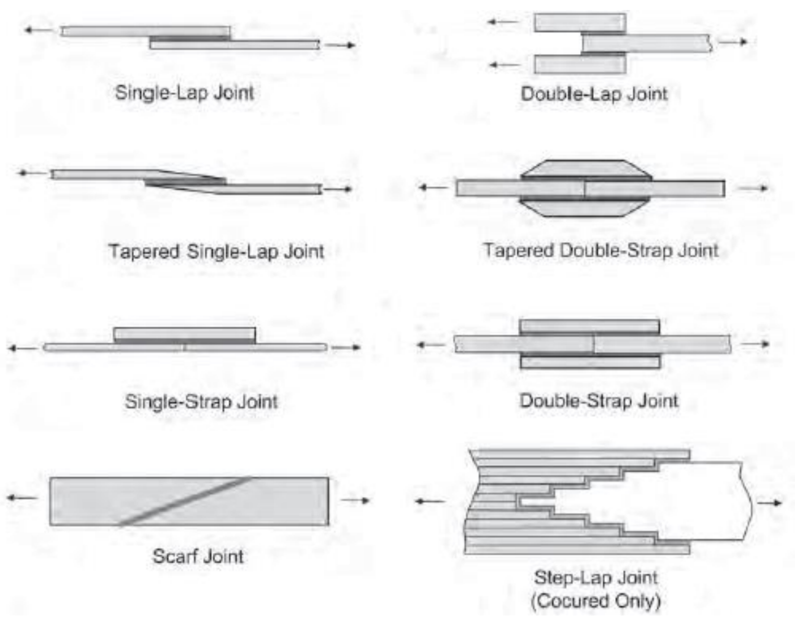


Figure 3.2 Typical configurations of adhesively bonded joints [18]

3.2.2.3 *Bonding procedure*

The process of adhesive bonding includes the following steps in general [5], [18]:

- Collection of all the parts to be bonded and placed as a kit
- Verification of the fit to bond line tolerances
- Surface preparation of the composite parts
- Application of the adhesive
- Mating the parts and adhesive with force and/or heat application
- Inspection of bonded joints

More details and consideration about surface treatment and application of adhesive materials are discussed in the following section 3.2.2.4 and section 3.2.2.5.

3.2.2.4 *Surface preparation*

Demonstrated by extensive field experience, the durability and long-term performance of adhesive bonding depends on the surface preparation work before adhesive application[3].

(a) Surface treatment technique

One of the most widely used methods for surface treatment is the use of peel ply. The peel ply, usually a closely woven nylon or polyester cloth, is applied as the outer layer of the composite in the manufacturing process. During surface treatment, this outer layer is peeled away to create a clean surface on the composite with enough roughness. An additional step of abrasion by light grit blasting (about 20 psig) is encouraged [18]. It can remove the fractured resin left by peeling process, and increase contact area of the bonding surface. Thus, peeling off the ply should be performed with care to prevent damage of the reinforcing fibers.

If the composite parts to be bonded are not produced with a peel ply, a proper solvent is used for pre-cleaning to remove the organic contaminants. Light abrasion by dry wipe on the surface is followed to obtain roughness. It is worth to mention that the steps conducted in reverse sequence is not acceptable.

As a summary, the principles of surface treatment process are:

- Surface cleanliness before abrasion to remove smear contamination
- Careful abrasion process to avoid fiber damage or interlaminar cracks
- Removal of residue after surface abrasion
- Bonding after surface preparation as soon as possible

(b) Moisture control before bonding

During the preparation work, the moisture absorption in the composite laminates is a critical issue to be considered, especially for the bonding process conducted in situ. Moisture absorbed into the laminate can diffuse to the bonding interface during curing at elevated temperature, which can influence the curing reaction and create voids in the adhesive bond line. Therefore, the storage of composites and moisture control deserves special attention to guarantee the quality of adhesive bonded joints.

3.2.2.5 *Adhesive materials*

According to different chemistry of resins, structural adhesives can be categorized into thermosets and thermoplastics in general. Common thermosetting adhesives include epoxies, phenolics, and thermosetting polyurethanes, while typical thermoplastic adhesives are acrylics and thermoplastic polyurethanes.

(a) Characteristics of commonly used adhesives

In terms of mechanical behavior, adhesives can be either brittle or ductile. In general, thermosetting adhesives are brittle with higher strength and modulus compared with thermoplastic adhesives (Figure **3.3**). Thermosetting adhesives are stiffer and have better creep resistance, while thermoplastic adhesives are preferred for joints experiencing bending and peel loading [20]. In practice, a mixture with additives are commonly used to modify the adhesive in order to obtain a better mechanical performance. For instance, for the bonding of thin composites under bending or flexure, toughening agent is added to epoxy-based (thermosetting) adhesive to enhance its peel resistance. Besides the required mechanical properties, the selection of suitable adhesive material also needs to consider its compatibility with adherents.

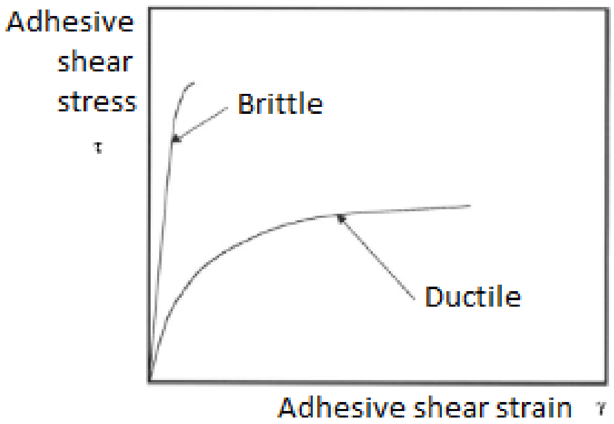


Figure 3.3 Stress-strain behavior for brittle and ductile adhesives [5]

(b) Epoxy-based adhesives [3], [5], [18]

Epoxy-based adhesives are the most widely used materials for bonding and repairing of aircraft structures, due to the excellent adhesion, relatively high strength, low shrinkage, and good chemical resistance. Even though limitations of epoxy adhesives exist—brittleness, moisture absorption, and long cure time, epoxy-based adhesives have good flexibility to modify the performance parameters, such as density, viscosity, toughness, pot-life, cure time and temperate. An epoxy resin system is usually modified by a range of additives, including accelerators, viscosity modifiers, fillers, flexibilizers and toughening agents.

Three types of epoxy-based adhesives are discussed in the follow sections, including (1) one-part epoxy adhesives curing at elevated temperature, (2) two-part epoxy adhesives curing at room temperature, and (3) Epoxy film adhesives.

One-part epoxy adhesives curing at elevated temperature

Details of one-part epoxy resin system are:

- Cure temperature and time. Typically cured at an elevated temperature from 120 °C to 180 °C in 20 to 60 minutes
- Shelf/storage life. 15-30 days for catalyzer-mixed system, while up to 6 months for a non-catalyzed system.

Two-part epoxy adhesives curing at room temperature

When curing at room temperature is desired, for instance bonding in-situ, two-part epoxy adhesives can be used. The two-part systems require a mixture of Part A (the resin and filler portion) with Part B (curing agent portion) in a predetermined ratio. In order to guarantee the cured properties, mixing in precise proportion is required. After mixture, curing agent from Part B generates exothermic heat for the curing cycle. As a result, the amount to be mixed is determined and limited by the adhesive pot time. Pot time refers to the period from the time mixing of two parts to the time when adhesive losses workability with an increased viscosity.

Two-part epoxy adhesives are available in form of liquid with low-viscosity and thick paste. They are frequently used in aircraft structures. Low-viscosity version can be injected into cracked bond lines or delaminations, while thick pastes are suitable for the bonding requiring flow control.

Typical cure time at room temperature are 5 to 7 days. In most cases, 70-75 percent of the ultimate cure can be achieved within 24 hours.

Epoxy film adhesives

Adhesive films can be used in processes such as secondary bonding, core-bonding and co-curing with prepregs. Technical details are:

- Supplied in film form or roll
- Storage under refrigerated conditions (20°C) with a shelf/storage life as long as 20 to 30 days
- Cure temperature from 120 °C to 180 °C

3.2.3 Fastened-bonded joints

A combination of mechanical fasteners with adhesive bonding may be used due to the following concerns [20]:

- Manufacturing requirement. For instance, the fasteners provide clamping pressure required during the bonding and curing of the adhesive.

- Performance requirement. Adhesive bonding is designed to satisfy the requirements in serviceability limit state, while mechanical fastening to satisfy the ultimate limit state conditions.
- Enhanced security. Fasteners are used to prevent the growth of damage or cracks in bond line, for instance, under peel loading during service life.

The principle of fastened-boned joints is that either the fastener or adhesive bond is assumed to carry the load. In the joints applied with structural adhesive, the adhesive bonding provides stiffer load transfer path, and carries almost all the load until its failure. So, the fastened-bonded joints should follow the design procedures of adhesive bonding. When the elastomeric adhesives and sealants are applied, the load should be assumed to be taken by fasteners, and the joint should be designed like a mechanically fastened joint.

3.2.4 Comparison of three types of composite joining methods

In general, thin composite structures with well-defined load paths are good candidates for adhesive bonding, while thicker structures with complex load paths are suitable to be assembled by mechanical fastening. The main characteristics of assembly methods discussed are summarized in **Error! Reference source not found.** for design considerations.

Table 3.1 A summary of characteristics of three types of composite connection [5], [20]

	Benefits	**Limitations**
Mechanical fastening	• Relatively mature technique, utilization of metal-work tools and technique • Easier inspection of joint quality • Little surface preparation work required •	• Stress concentration in bolted joints • Strength degradation due to notched effects • Heat damage during drilling • Intensive labor • Potential corrosion of fasteners contacting carbon fiber in composites
Adhesive bonding	• Uniform stress distribution • Reduced joint weight than mechanically fastened joints • Smooth external surfaces • Stiffening effects in bonded joints	• Hard for disassembly or non-destructive inspection • concern for adhesive application-storage on-site, pot life and curing time • Durability of adhesive properties in the bonded joints due to potential degradation
Fastened-bonded	• Higher safety	• Higher cost and weight

3.3 Manufacturing of FRP sandwich structure

3.3.1 Introduction of FRP sandwich structure

When it comes to the manufacturing and assembly of composites, the FRP sandwich structure is worthy to be investigated as an alternative of cross-section design to the corrugated steel plates used in conventional steel culvert bridges. The FRP sandwich panels are built by an inside core material bonded to outer FRP laminate sheets, namely FRP faces or FRP skins. Light-weight foam, honeycomb, balsa wood are commonly used as core materials.

(a) Structural performance

The sandwich structure is widely used in aerospace, automobiles, and commercial industries due to the excellent strength-to-weight ratio and high stiffness [18], [21]. Figure 3.4 shows how a sandwich structure behaves under loading. By increasing the thickness of core layer between the FRP skins, the bending stiffness increases significantly with little increase of self-weight. Figure 3.5 demonstrates the structural efficiency of a sandwich cross-section.

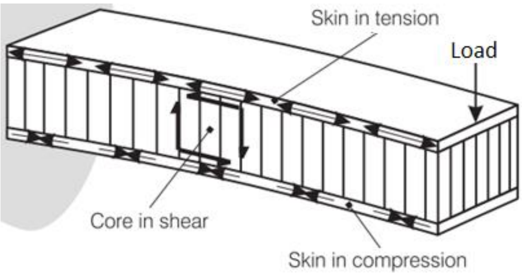


Figure 3.4 Sandwich panel under loading [22]

Properties	Solid material	Core thickness t	Core thickness 3t
	t	2t	4t
Stiffness	1.0	7.0	37.0
Flexural strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Figure 3.5 Structural efficiency of a sandwich cross-section [22]

(b) Selection of proper core material

The selection of core material is a great topic in sandwich design. Honeycomb, foam and Balsa wood are commonly used core materials for structural use in the sandwich structures. Table 3.2 gives an overview of these three types of core material.

Table 3.2 Comparison of light-weight structural core materials—honeycomb, balsa, and foam [23]

Property	**Honeycomb**	**Balsa**	**Foam**
Density (typical), kg/m^3	Expanded: 32–192 Corrugated: 160–880	96–288	32–288
Moisture resistance	Excellent	Fair	Excellent
Chemical resistance	Fair to excellent	Fair to very good	Fair to very good
Flammability resistance	Excellent	Poor	Fair to excellent
High-temperature resistance	Adhesive bonded: to 177 °C Braze welded: between 370 and 815 °C depending on material	To at least 95 °C	Typically to 80 °C; mechanical properties decrease significantly at higher temperatures
Strength and stiffness	Excellent	Excellent	Fair
Energy absorption and crush strength	Constant crush strength value	Not used for energy absorption	Increasing stress with increasing strain
Impact resistance	Fair to excellent	Very good	Fair to poor
Fatigue strength	Good to excellent	Very good	Fair to poor
Abrasion resistance	Good integrity	Fair	Friable
Acoustic attenuation	Yes	Yes	Yes
Formability	Various cell configurations for different shapes	Must cut (e.g. scoring), or use joined strips	Requires molds or scoring
Cost	Inexpensive (Craft paper) to very expensive (Carbon)	Moderate	Very inexpensive (Polystyrene) to expensive (Polymethacrylimide)

Regarding the service condition of culvert bridges with water passage, the wood-based core material, for instance Balsa, is not a good choice due to the high risk of moisture damage and rot during the service life. The choice between honeycomb and foam material would influence the properties of the sandwich products, but also results in different tooling and operational details in the manufacturing process. Commonly used foam and honeycomb materials are investigated in section 3.3.2 and section 3.3.3 respectively.

3.3.2 Foam core

The commercial application of foam cores is due to the balance between their cost and performance. Compared with honeycomb, foam materials give an easier bonding process, for instance, when manufacturing a sandwich panel. Bonding methods that are applicable to foam materials includes:

- Secondary bonding by adhesive in the form of liquid, past or adhesive film
- Co-curing with FRP laminates in processes such as vacuum Bagging, RTM and VARTM as described in section 2.

The common thickness of foam products from suppliers ranges from 5 mm to 50 mm. In general, the thermoplastic foam has better formability, while thermosetting foam obtains better mechanical properties. Properties of commonly used foam materials in mode details are [3], [5]:

Polystyrene (PS) foam

- Light weight (40 kg/m^3) and relatively low cost
- Foam with closed cell and can be thermoformed
- Rather weak mechanical properties, not suitable as structural core
- Incompatible with polyester resin system due to the risk of being dissolved
- Used for wet or low temperature lay-ups

Polyurethane (PU) foam

- Low to high density
- Foam with closed cell and can be thermoformed
- Available as thermosetting and thermoplastic
- Moderate mechanical properties
- Widely used in sandwich panel for thermal insulation. Feasible for adhesive bonding or co-curing process to produce sandwich panels with flat or curved geometry
- Good acoustic absorption
- Introduce risk of degradation in resin-core interface

Polyvinyl chloride (PVC) foam

- One of the most widely used core materials in high performance sandwich structures
- Low to high density
- Available as thermosetting (crosslinked) and thermoplastic (uncrosslinked)

    - Thermoplastic PVC: tougher, higher peel loading resistance, thermoformable for curved geometries
    - Thermosetting PVC: brittle, higher mechanical properties, less susceptible to creeping, better heat resistance
- Commercial PVC foams are strictly a chemical hybrid of PVC and polyurethane. They provide a balanced combination of static and dynamic properties
- Good resistance to water absorption
- Heat stabilization treatment can be applied to improve dimensional stability and resistance to elevated temperature

Polymethyl methacrylamide (acrylic) foam

- Light cross-linked (thermosetting) foams with closed-cell
- Excellent mechanical properties and good heat and solvent resistance
- Relatively higher cost and suitable for aerospace application such as helicopter rotor blades and aircraft flaps

Based on the analysis of four different types of foam materials, commercial PVC foam, for instance Divinycell H from supplier DIAB, is suitable to be used in the FRP sandwich segments and then assembled to form culvert structures due to the following advantages:

- Reach a balance of material cost and mechanical properties.
- Satisfy the requirement for curvature conformability due to the profile of culvert structure. Curvature can be achieved by treating the foam in two ways—thermoforming and grooving. Thermoplastic foam materials can be reshaped by thermoforming method—heating to soften, clamping to required shape and cooling to set the geometry. Conformability can also be obtained by additional finish processes of core products, such as grooving for different curvature surface. PVC foam core with single cut along the longitudinal direction of culvert structure is a proper choice, see Figure **3.6**. Compared with thermoforming method, grooved core materials yield more adhesive resin absorption due to the increased surface after cuts. The weight of bonded sandwich structure increases in the end, while the costs of clamping tools and heat applied in the thermoforming method can be saved.

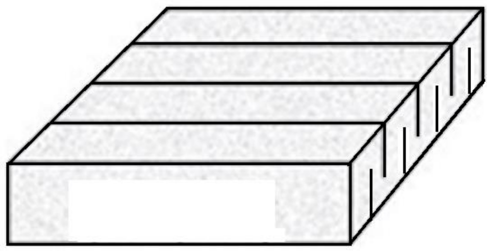


Figure 3.6 Single cut format of foam core for curvature conformability used in culvert structure[23]

3.3.3 Honeycomb core

Honeycomb cores are available in different materials for structural use. Commonly used honeycomb materials to be investigated in this section includes aluminum honeycomb, Nomex honeycomb, and thermoplastic honeycombs. As a potential alternative to the foam core to construct FRP sandwich products, the following aspects need to be considered to choose a proper type of honeycomb:

Limited bonding area

Due to the configuration of honeycomb product, the area of bonding interface is small. Therefore, it is important to use high-performance resin system such as epoxies to guarantee the sufficient bonding strength to the skins. The cells of honeycomb can also be filled with rigid foam to create larger area for bonding if necessary. It also helps to increase the mechanical properties of core.

Material cost

Nomex honeycomb is fabricated from a kind of paper based on Kevlar^{TM}. Although it has high mechanical properties and good durability, the high material cost undermines its competence as a core material for the purpose of FRP culvert bridges, see Figure **3.7**. If applied to culvert structure, its advantage of excellent fire resistance is not fully utilized. Therefore, the Nomex honeycomb is not a good choice in terms of economic efficiency.

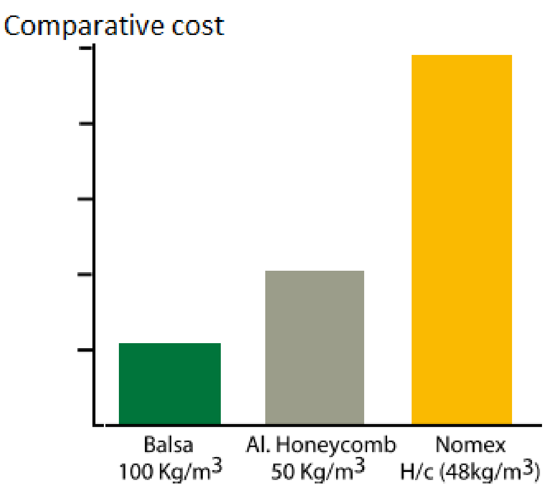


Figure 3.7 Comparative price of three types of honeycomb core (Al.--aluminum)

Therefore, polypropylene (PP) honeycomb as a member of the thermoplastic honeycomb group can be an alternative of core material due to the following advantages:

- Capable to be thermoformed for a curvature shape
- Low material cost
- Good resistance to water and chemicals

However, the main limitation of the thermoplastic honeycomb is the poor mechanical properties. In the loaded sandwich structure, the core material is designed to take shear stress, while the shear strength of PP honeycomb ranges from 0.3 to 0.8 MPa. If the PP honeycomb is to be used in FRP culverts, the shear stress in the core material should be checked in the design.

3.3.4 Manufacturing methods of FRP sandwich structure

As briefly introduced in section 3.2.2.1, the conventional manufacturing method for composite sandwich structures is secondary bonding—adhesive material applied to prepared cores and composite faces, and then bonding into an integrity. This process generally includes serval steps, which increases the operational complexity and labor cost. Co-curing method, as an alternative bonding technique coupled with low-cost manufacturing foaming methods, is an idea solution to construct sandwich panels for reduced cost and cycle time [24].

For the foam core, the bonding operation is easy to handle due to sufficient area of bonding interface and its closed-cell. The consideration usually includes:

- The absorption of resin material in the foam with lower density
- Chemical compatibility with other components. For instance, the Gurit PVC product is compatible with epoxy but may suffer from styrene attack with some polyesters and vinylesters [23].
- The risk of foam crush during consolidation. During the co-cure process, compression and/or temperature applied should be considered, instead of using the same parameters during composite face manufacturing, since core materials are weak in both strength and stiffness compare to face materials. For instance, the pressure applied for co-curing ranges approximately from 275 kPa to 345 kPa, which is much lower than the normal compression (690 kPa) used for laminate manufacturing [18].
- The maximum operational temperature of foam material during cure

However, when the procedure comes to honeycomb cores, challenge appear due to the open-cell configuration of the honeycomb. The main task is to prevent resin from entering the hollow cells during the manufacturing process and ensure sufficient bonding between core material and FRP skins.

The available commercial solutions to construct a honeycomb sandwich by co-curing can be generally divided into two different ways depending on the skin material and composite forming technique used.

3.3.4.1 *Manufacturing based on VARTM method*

Details of VARTM method are introduced in section 2.5. In the process, the dry fiber fabrics are laid-up on the core material in the mold, impregnated in the vacuum assisted resin infusion and cured. The bonding to core material realized in the same cycle. To prevent resin flowing to the cell, the solution includes filling the hollow cells and sealing the core with surface veils. Plascore Inc. provides the thermoplastic honeycomb cores covered with barrier films for using in VARTM [25]. Utilizing this surfacing film, the open cell structure is sealed, thereby allowing the flow of resin during infusion to remain at the bond line with minimal penetration into the honeycomb core [26].

3.3.4.2 *Manufacturing based on prepregs used with vacuum bagging method*

The technique of using prepregs coupling with vacuum bagging method is introduced in the former section 2.8, namely as Prepreg-out of autoclave. In the curing process, the elevated temperature would allow the resin in prepregs reflow and consolidate, which creates fillets in the bonding interface and avoid the problem of low-viscosity resin flowing into the hollow cell. Company Hexcel uses prepregs stacks on the honeycomb to construct sandwich. With the help of vacuum bagging, it is feasible to produce honeycomb sandwich with curved profile [22]. Another advantage is that large-size sandwich parts can also be produced by using the adhesive that can be cured at room temperature. See Figure **3.8**8.

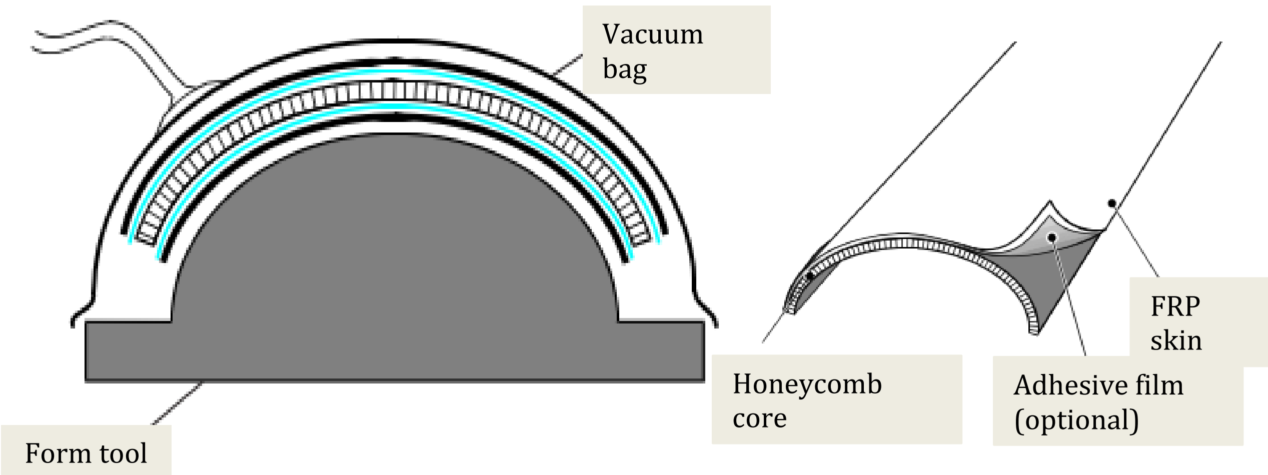


Figure 3.8 Construction of curved sandwich part by prepregs and vacuum bagging [22]

4 Proposals for manufacturing of FRP culverts

Based on the review of composite forming and assembly techniques, practical proposals for constructing FRP culvert structures are investigated and presented in this section. The main criteria accounted for in developing manufacturing concepts for FRP culverts were as followings:

- Ability to produce structural FRP composite elements with good load bearing capacity
- Possibility to produce large-scale FRP composite parts to minimize assembly work

4.1 Proposal 1: Production of FRP segments using pultrusion technique

Most commonly FRP members produced by pultrusion are I-beams and bridge deck panels. When it comes to culvert structures, FRP segments (see Figure **4.1**) produced with a certain curvature could be used. These segments can be transported to construction site, and assembled into a circular or semi-circular profile on site as illustrated in Figure 4.1.

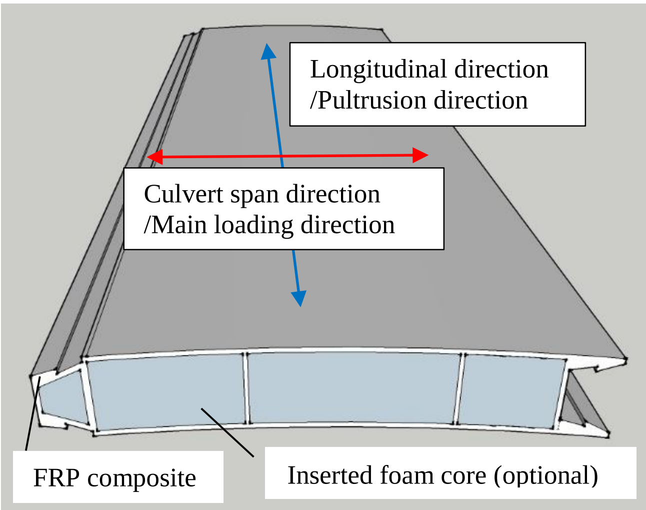


Figure 4.1 FRP segments produced by pultrusion method with a certain curvature to form a circular or semi-circular section

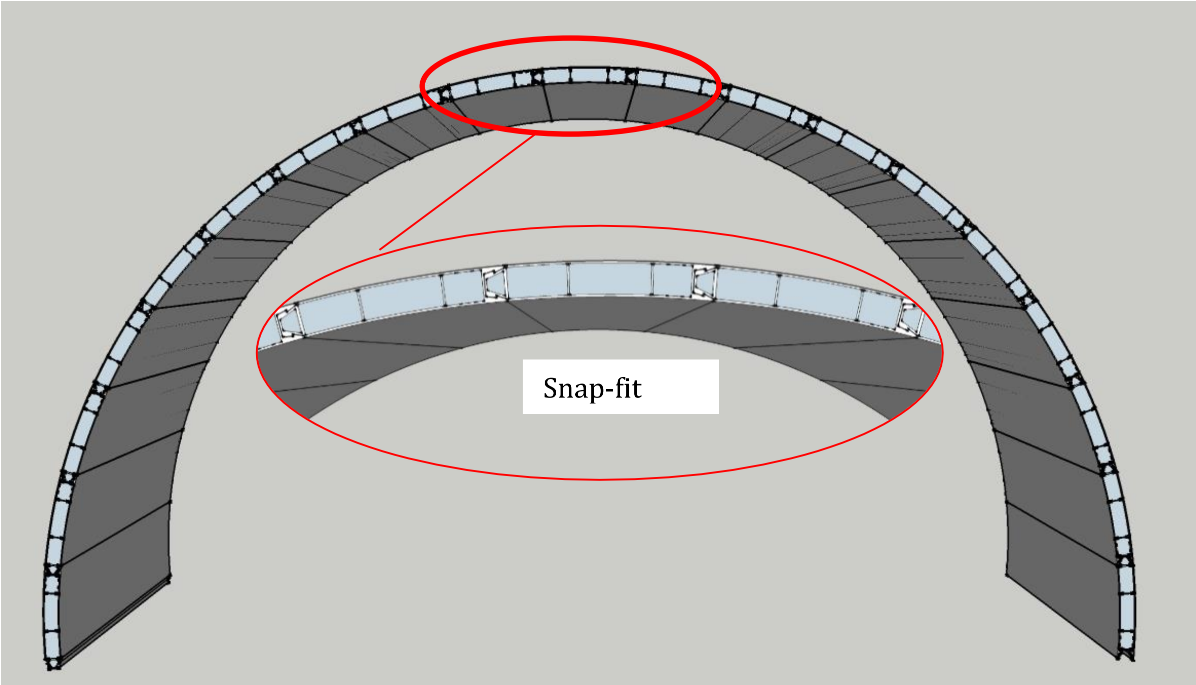


Figure 4.2 FRP segments assembled into a semi-circular profile by snap-fit joints

4.1.1 Manufacturing of FRP segments by pultrusion

The FRP pultruded segments can be prefabricated in workshop and delivered on-site. Considering the pultrusion forming method, the following details need to be considered.

- Placement of fiber direction. In most of pultruded members, major fibers are placed along the pultrusion (longitudinal) direction. So, FRP products formed by pultrusion method usually have higher mechanical properties in the longitudinal direction, for instance the FRP I-beam designed for bending along length direction. When it comes to culvert structure, the main load path is perpendicular to the longitudinal direction of FRP members (see Figure **4.1**). It means that fibers perpendicular to the pultrusion direction becomes favorable instead. As a result, multiaxial fiber fabrics should be used instead of continuous straight fibers from creel.
- Foam core inserted. For members in the critical sections, rigid foam materials can be inserted and filled in the hollow space to obtain better structural performance, if necessary.

4.1.2 Design of snap-fit joints

The joint design of pultruded members aims to meet the requirements: 1) fast assembly with minimum labor force, 2) minimizing the use of adhesive bonding and/or fasteners for assembly, and 3) sufficient loading capacity of compressive force and bending moment. The idea of snap-fit joints is put forward to satisfy the requirements above. The illustration of some designs of snap-fit joint are shown in Figure 4.3.

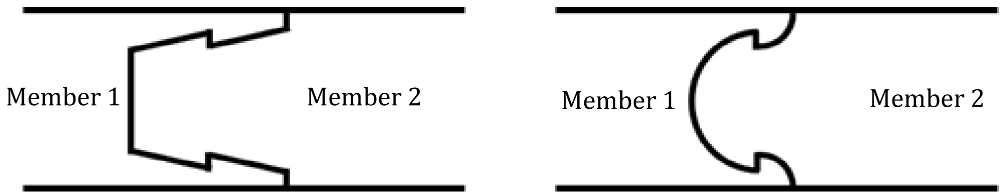


Figure 4.3 Illustrations of snap-fit joint design of pultruded members

4.1.3 Benefits and limitations

Besides the benefits of pultrusion technique, this proposal allows additional advantages such as:

- The mature production line of suppliers can be taken advantage of, for instance, company Fiberline Composite that produces FRP bridge decks
- Ready delivery to the construction site since the cross-section of pultruded members is not large regarding the transportation by trucks.
- Reduced assembly costs, due to snap-fit joints.

This production proposal is suitable to make culverts with circular or semi-circular cross section. It is also possible for elliptical cross sections, arch-pipe culverts and box culverts, but the manufacturing cost would increase as varying cross-sections needs new design for production dies. This is certainly the most important drawback of pultrusion technique for this purpose.

4.2 Proposal 2: Production of FRP culverts using filament winding

The second proposal for construction of FRP culverts is to use a sandwich with circular or semi-circular cross section produced using filament winding method, see Figure **4.4**. The essential steps involved in this proposal are: 1) manufacturing of the FRP laminate as the inner face of sandwich by filament winding, 2) bonding the core material on the wound FRP layer, and 3) winding the outer FRP face of the sandwich culvert, see Figure **4.5**.

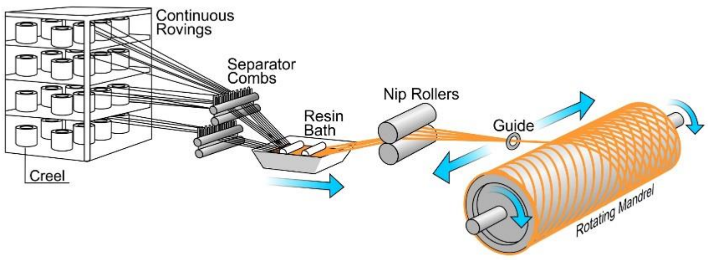


Figure 4.4 Forming a FRP layer on rotating mandrel by filament winding method

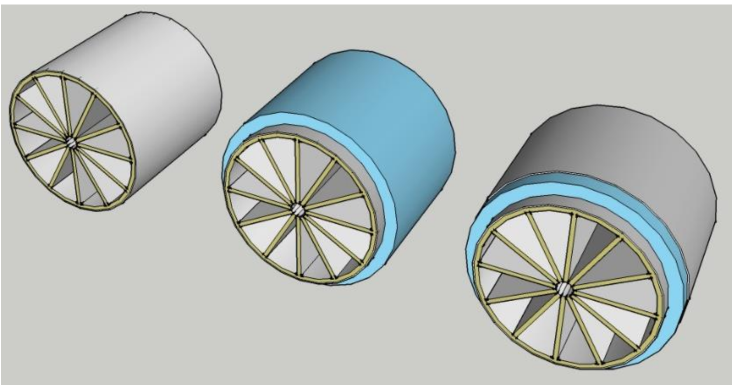


Figure 4.5 Essential steps of proposal 2 (Left: winding the inner FRP layer on the rotating mandrel; Middle: glue the foam core layer on the inner FRP face; Right: winding the outer FRP face on the mandrel)

In filament winding method, the culvert structure, for instance circular type, can be produced as an integrity after demolding. As a result, it avoids assembly work and saves costs, while the delivery and transportation process sets limitations on the supplier. In terms of culvert dimensions, the manufacturing process of filament winding can be conducted either in workshop or on site.

4.2.1 Filament winding in workshop

For normal transportation, the maximum allowable dimension for truck delivery in Sweden is 2.55 m × 4.5 m × 24.0 m (width × height × length) [27], [28]. Additional measures are required for larger sizes, see Table 4.1. For culverts within these dimensions, the prefabrication can be performed at factory, and then delivery to site and assembly process.

Table 4.1 Measures of transportation (According to DIAB, 2015)

Maximum width for delivery [Unit: meter]	**Measures**
less than 2.5	Normal delivery
2.5 – 3.1	Special marks (Bred Last) needed on the truck
3.1 – 3.5	One car following behind the truck
3.5 – 4.5	Two cars following the truck with one in front and one behind
Over 4.5	Special permission is required; Depending on the route condition

4.2.2 Filament winding on site

For culverts with large dimensions which cannot be delivered by truck, the winding process can be carried out on the construction site. As discussed in section 2.2.2, wet-winding method is an economical choice in the filament winding process. Filament winding equipment can produce wound tube with large diameter up to 25 meters [29].

Figure 4.6 On-site filament winding of FRP tube with large diameter [29]

Advantages and limitations of filament winding

The characteristics of filament winding proposal are discussed below:

- Reduced joints. FRP elements product by filament winding is an integrity after demolding with no joints. The joint design has to be considered only in the case that the required culvert length exceeds the maximum length that can be produced by the supplier.
- FRP culverts prefabricated by filament winding are preferable than those wounded on site. Filament winding on site gives great challenge to the quality control, which is critical to the culvert as the main load bearing structure. The challenge comes from complex steps on site, curing conditions, and resin distribution.
    - Long manufacturing process on-site. The main steps include 1) winding of inner FRP layer, 2) curing of inner FRP layer, 3) bonding the core material on the cured FRP layer, 4) winding and curing the outer FRP layer, and 5) demolding from the mandrel.
    - Resin distribution during winding process. In the vertical filament winding process, the resin with low viscosity would flow under gravity, which causes the uneven distribution of resin content from top to bottom.
    - Curing process of winding on site set the requirements of ambient temperature and relative humidity. If winding process is conducted on site, temperature and humidity depends on the climate, which yields less control and more uncertainty of the product quality in the end.
- Limitation of culvert geometry. Culvert structures with symmetric cross-sections are preferred, such as circular and ellipse type. This proposal is not suitable for the box culvert.
- Only applicable on circular or semi-circular cross sections
- This method is very cost effective in two span culvert bridges as one circular or semi-circular section can be cut into two halves to create the bridge

- This manufacturing method produces elements of high efficiency as the fibers are exactly aligned with regard to the loading direction. Therefore, compared to the pultrusion technique, filament winding will produce more efficient sections in terms of stiffness and strength.

4.3 Proposal 3: Production of FRP culverts using vacuum infusion method

The general idea of Proposal 3 is first to build FRP sandwich segments and then bond the segments to form a culvert structure on construction site. In section 3.3 the potential methods to construct FRP sandwich panels suitable to be used for manufacturing culvert structures were investigated. It was mentioned that manufacturing sandwich members by co-curing process with help of VARTM method is a promising method. The proposal developed from this procedure, is referred to as vacuum infusion, and is described in the following.

4.3.1 Construction of FRP sandwich panels using vacuum infusion process

The main steps of the process are:

- Set up the mold, clean and prepare it with release agent.
- Lay up the fiber reinforcement and core material. Core materials, in forms of foam and honeycomb can be used.
- Build the vacuum bag, plan the resin infusion path with inlet and outlet.
- Install the vacuum pump, catalyze the resin and prepare for the infusion process.
    - If the foam core is used, an innovative infusion method from company DIAB, namely Core Infusion Technique, can be applied for lower labor cost and shorter mold cycle time [30]. The foam core material is processed with special grooves and penetrating holes, which can also act as the resin distribution medium during the infusion process. As a result, the conventional resin distribution mat can be eliminated [31].
    - In case of honeycomb core, the cells should be sealed for resin infusion as mentioned in section 3.3.4.1. For example, the PP honeycomb from Plascore Inc. sealed by barrier film on the surface is suitable to be used in the VARTM process.
- Impregnation, co-curing and demolding.

To obtain a better quality control, the construction process is suggested to be carried out in workshop. Vacuum assisted resin infusion is not the only way to prefabricate these sandwich segments. Application of prepregs with the vacuum bagging method can be a practical alternative, which is introduced in details in section 3.3.4.2.

4.3.2 Bonding of segments to form a culvert structure on site

Conventional adhesive bonding process discussed in Section 3.2.2 can be applied to assemble the prefabricated FRP sandwich segments into a culvert structure on site. Adhesives in paste form or film adhesive can be used for bonding. It is economical to use the epoxy based adhesive, which can be cured at room temperature. More details about two-part epoxy adhesive can be find in Section 3.2.2.5. It is also possible to use on-site vacuum injection for bonding of the segments which takes place after the montage of segments in the right position. Vacuum injection can result in better bond quality as the risk for un-bonded areas and defects along the adhesive bond line, such as air bubbles will be minimized.

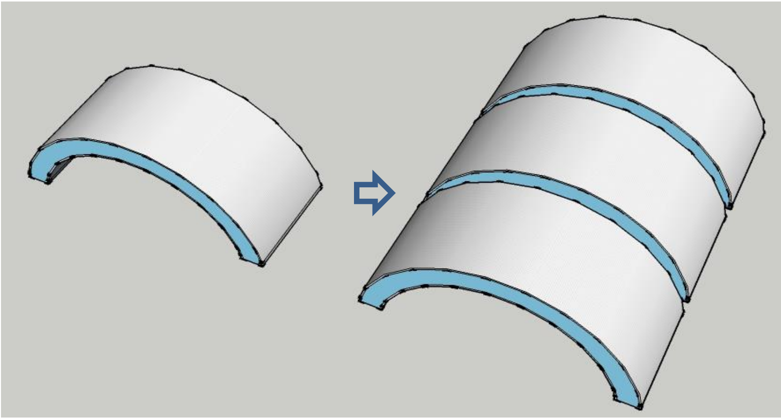


Figure 4.7 Left: Prefabricated FRP sandwich segment; Right: bonding the segments into a culvert structure

The details of the joints in sandwich segments are shown in Figure 4.8.

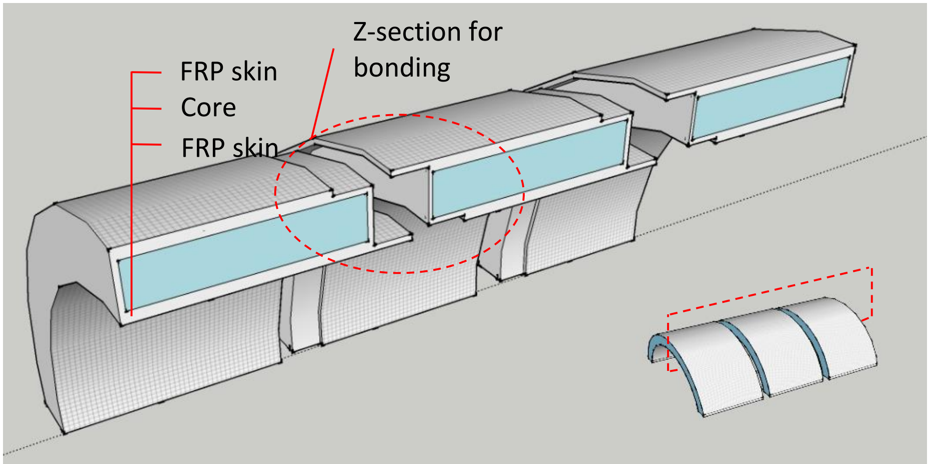


Figure 4.8 Joint design of FRP sandwich segments for adhesive bonding

4.4 Summary of the proposals for manufacturing of FRP culverts

The discussed manufacturing proposals are summarized in Table **4.2**, which includes the manufacturing and assembly method.

Table 4.2 Manufacturing and assembly method of FRP culvert proposals

Order	Description	Manufacturing method	Assembly method
Proposal 1	FRP culvert by pultrusion	Pultrusion	Snap-fit joints
Proposal 2	FRP culvert by filament winding	Filament winding	Adhesive bonding
Proposal 3	FRP culvert by vacuum infusion	VARTM	Adhesive bonding

5 FRP culvert alternatives for existing steel culvert bridges

5.1 Overview of existing culvert bridges in Sweden

In Sweden, totally, 4785 culvert bridges are registered in the Swedish bridge and tunnel management system (BaTMan). Among all types of bridges, steel culvert bridges is one of the most common types, as shown in Figure **5.1**.

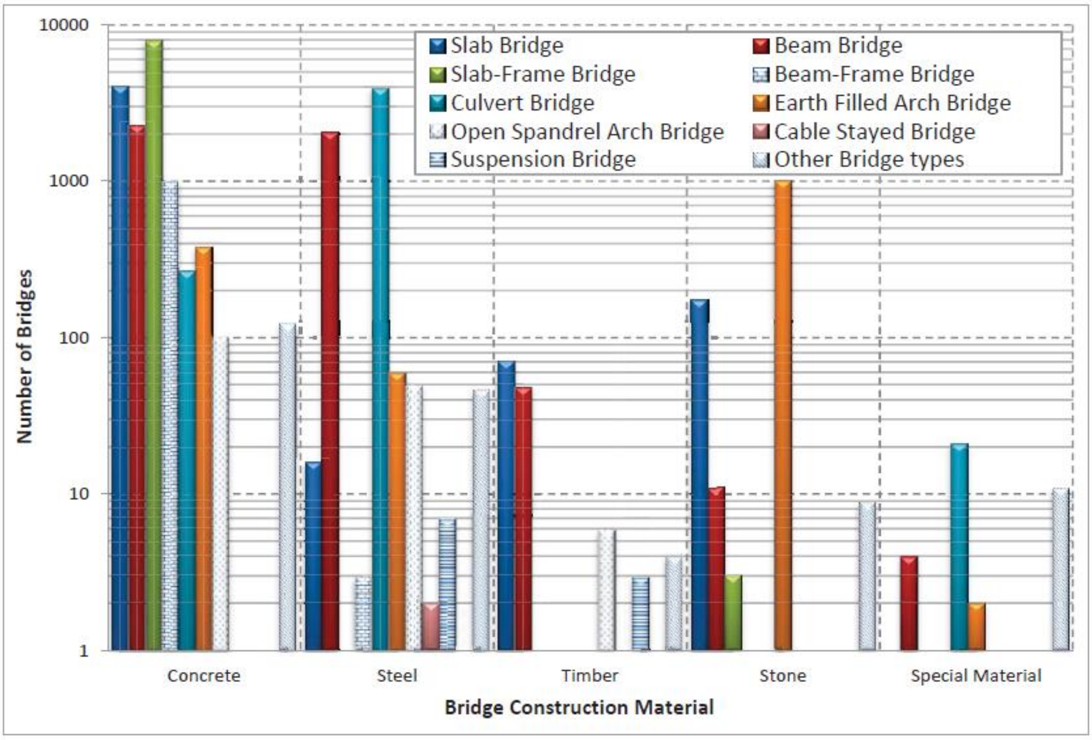


Figure 5.1 Statistics on different type of bridges in Sweden [32]

Statistical data regarding culvert bridges listed in the Table 5.1 provides an overview of culverts in Sweden with respect to span and construction material. It shows that about 95 percent of the culvert bridges have a span less than 5 meters, and the steel culvert has been used in almost 93 percent of the culvert bridges. More details of the most commonly used steel culvert regarding profiles and spans are shown in Table 5.2.

Table 5.1 Statistic number of culvert bridges in Sweden, regarding span dimension and construction material

Culvert bridge stock in Sweden (data provided by BaTMan's helpdesk, on July 9th 2015)							
Span [m]					**Material**		
< 2	2-5	5-10	10-20	> 20	Steel	Concrete	Other
101	4462	204	17	1	4387	367	31
			In total	4785		In total	4785

Table 5.2 Normal distribution of the span length of steel culvert bridges [33]

	Profile	Number	Average Span [m]	Standard Deviation	95% have shorter span than
Steel culvert bridge	Arch-pipe	1104	4.2	3	10.2
	Circular	814	3.2	2.3	7.8
	Vertical ellipse	788	3.6	2.0	7.5

In terms of traffic, the bridges are classified as railway bridges, road bridges and pedestrian bridges. Usually, normal traffic or water would go thought the culvert bridges.

The existing knowledge about culvert bridges in Sweden helps to select a proper culvert bridge for further studies. A culvert bridge with the following characteristics is determined to be chosen:

- A culvert bridge with a span larger than 10 meters. As shown in Table 5.1, most of the bridges have spans shorter than 5 meters. Large-span culvert bridges attract great interest from construction and research points of view due to existing design limitations and challenges. In the design of steel culvert bridges, the fatigue issue is highlighted by experienced engineers and limiting the application of steel culverts with large spans, which was also demonstrated in a previous study carried out by authors [1]. It is worth to investigate whether FRP culvert alternatives are able to display better mechanical performance than steel culverts when challenging large-spans are selected.
- A road bridge with water passage below the culvert. The construction of road bridges can block the traffic during the demolition and rebuilding phase. As a result, the impact on traffic and associated user costs account for more consideration. Service condition with water passage under the bridge is worse than a road with normal traffic, which lends the steel culvert to higher risk of corrosion during service life. Since FRP materials have better corrosion resistance than steel, the worse environment helps better justification for FRP culvert alternatives.

5.2 The case study bridge

An old bridge over Siktån at Rörbäcksnäs in Sweden was replaced by a box culvert bridge, see Figure 5.2, in 2008. This bridge is selected for a case study, which aims to investigate whether it would have been more economical to replace the old bridge with an FRP culvert rather than with a steel box culvert.

Figure 5.2 Box culvert bridge over Siktån at Rörbäcksnäs (Picture from BaTMan, bridge number 20-1335-1)

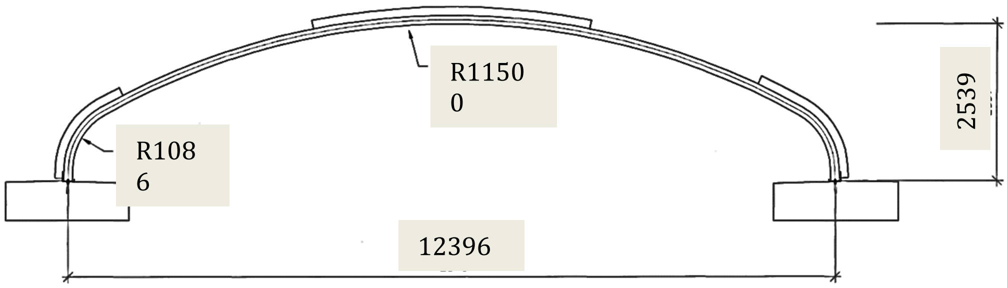


Figure 5.3 Dimension of steel culvert structure with box profile (Unit: mm)

The selected culvert bridge carries road traffic with water passage below. The box-shape steel culvert (Figure 5.3) is the load bearing structure with a span of 12.4 meters. Extra reinforcement layers are added to the crown and two corner sections as illustrated in Figure 5.3. Important information of this case study bridge is listed in Table 5.3.

Table 5.3 General information of selected steel culvert bridge over Siktån 20-1335-1 (data obtained from BaTMan)

Design service life	year	80
Culvert span	m	12.4
Culvert width	m	10
Culvert rise (height)	m	2.5
Total bridge length	m	27
Effective bridge width	m	6.9
ADT[1] vehicle on bridge	vehicle/per day	136
ADT truck on bridge	truck/per day	10
Allowed maximum speed	km/h	50

[1] ADT: average daily traffic (the data was recorded in 2004)

5.3 Design of FRP culvert alternatives

As mentioned in the introduction, the old bridge over Siktån was replaced by a steel culvert bridge. In this section, the design of FRP culvert as an alternative to the steel culvert is put forward based on the manufacturing proposals discussed in section 4. The design of each FRP alternative mainly focuses on the material selection and geometry of cross-section, which are critical input data to calculate the investment cost of FRP structure in the Section 4.

5.3.1 Selection of FRP materials

Mechanical properties are of great importance when choosing FRP materials, in order to achieve good structural performance during the service life. Selection of FRP materials basically includes choosing the resin as matrix material and fiber as reinforcement. The selected resin and fiber materials would be applied to all FRP culvert concepts to be discussed.

5.3.1.1 *Resin material*

Resin materials can be generally categorized into two families, thermosetting and thermoplastic. Considering structural requirements for mechanical properties, thermosetting resins are preferred to thermoplastic ones. Among different thermosetting resins, polyesters, vinylesters, and epoxies are most widely used. In general epoxy has relatively higher price than the other two resin materials, while it provides better mechanical properties and compatibility with other components involved, such as fibers and adhesives. In terms of balancing cost to performance, epoxy resin is chosen for matrix material of FRP composite. Mechanical properties of epoxy used in the design calculation is listed in Table 5.4.

Table 5.4 Mechanical properties of epoxy as matrix material (characteristic value) [34]

Mechanical properties	**Young's modulus**	**Shear modulus**	**Poisson's ratio**
Epoxy	E_m [GPa]	G_m [GPa]	ν_m
	3.2	1.2	0.36

5.3.1.2 *Fiber reinforcement*

Glass fibers are prevalent in commercial use among fiber reinforcement materials due to their satisfying properties and relatively lower cost. E-glass fibers from the glass fiber family are preferred as reinforcing fibers for FRP culvert structures. Basalt and carbon fibers can be used together with E-glass fiber if additional properties are needed. Fiber material can be applied to composite in different forms, such as chopped fiber, continuous fiber, and fiber fabrics. The type of fibers to be used would be stated in the description of each FRP culvert alternative design. Mechanical properties of E-glass fiber used in the design calculation is listed in Table **5.4**.

Table 5.5 Mechanical properties of E-glass fiber as reinforcement (characteristic value) [34]

Mechanical properties	**Young's modulus**	**Shear modulus**	**Poisson's ratio**
E-glass fiber	E_f [GPa]	G_f [GPa]	ν_f
	70	30	0.22

5.3.2 Design of FRP culvert based on alternative 1 using pultrusion method

The first FRP culvert design is based on the first manufacturing proposal using pultrusion method that discussed in section 4.1. In order to achieve a span of 12.4 meter, two semi-circular culvert structures are designed to be placed in parallel as an alternative to the steel box culvert (Figure 5.4). Each semi-circular culvert is assembled by FRP pultruded members, and has a radius of 2.8 meter (Figure 5.5).

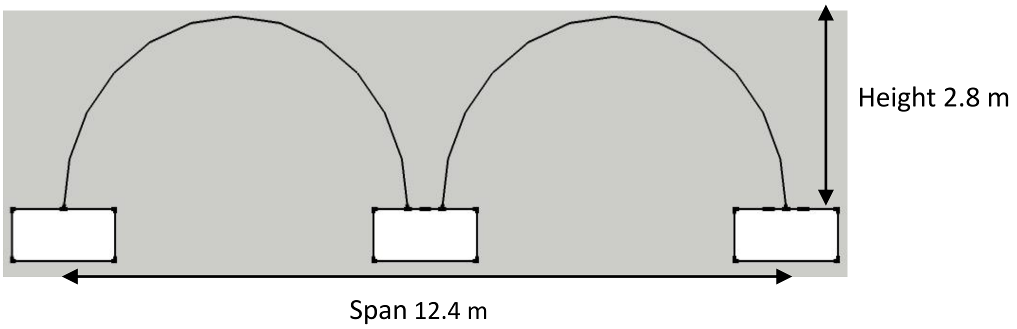


Figure 5.4 FRP alternative 1: two semi-circular culvert structures placed in parallel

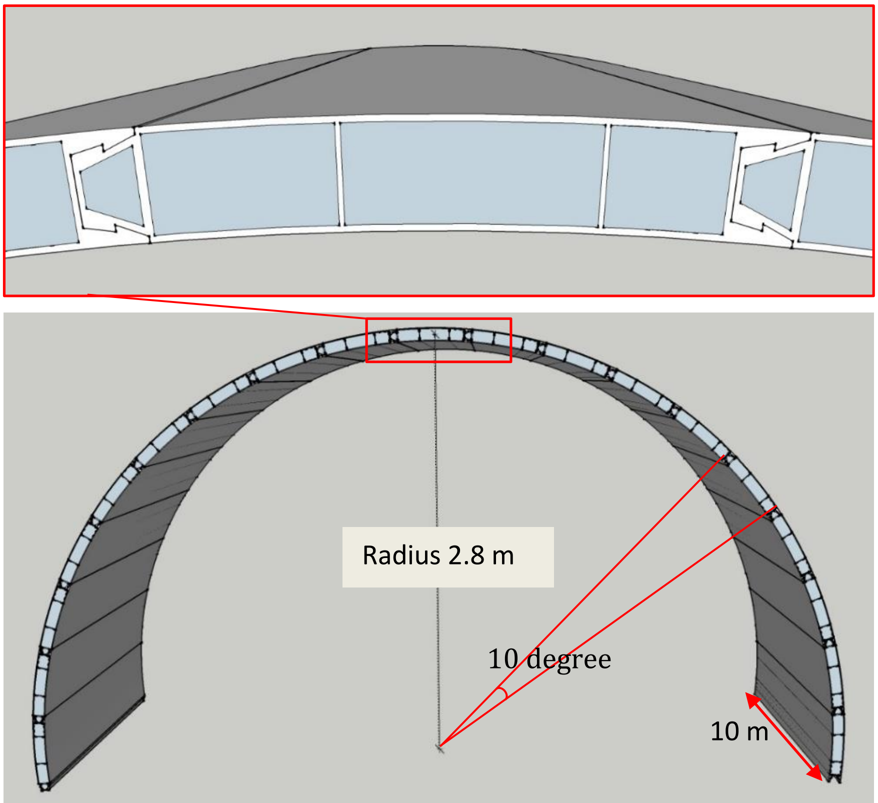


Figure 5.5 Semi-circular FRP culvert assembled by 18 pultruded segments with snap-fit joints

36 FRP segments, in total, are required to build two semi-circular culvert structures. Design details of uniform FRP members are shown in Figure 5.6 and Table 5.6. The design of cross-sectional geometry is presented in Appendix A-1.

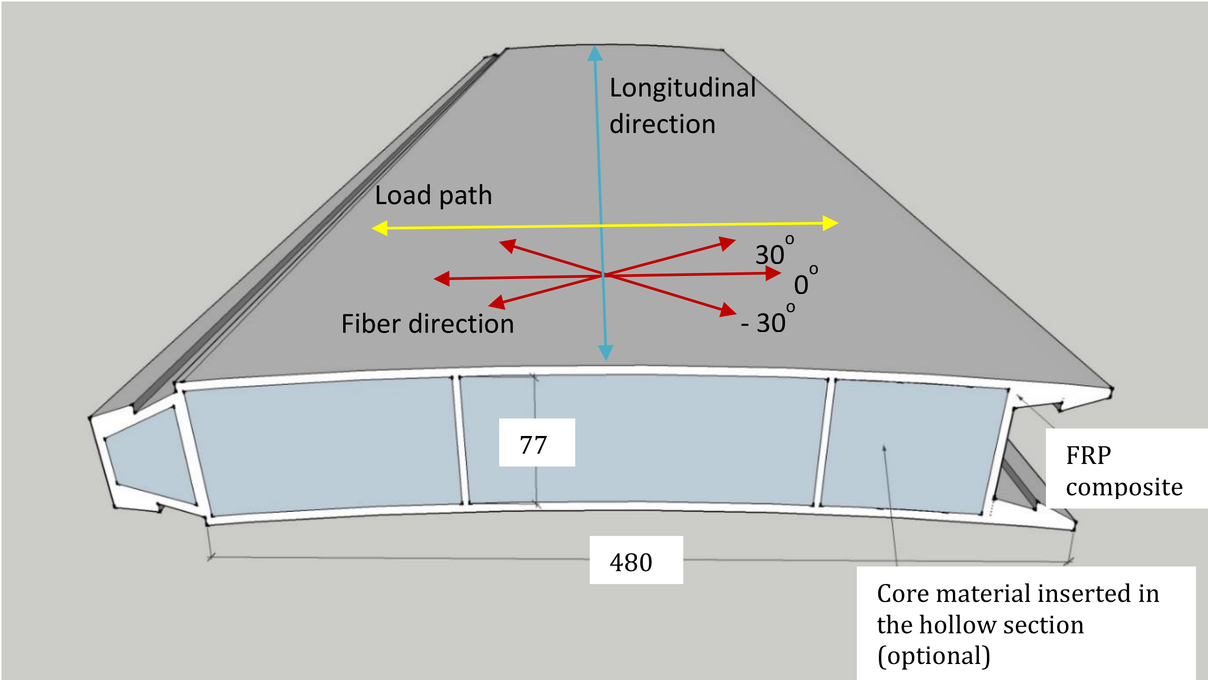


Figure 5.6 Geometry of the FRP pultruded segment with uniform cross-section

Table 5.6 Design summary of the FRP pultruded segments with uniform cross-section

Solid part (skins)	Hollow part
- FRP composite	- Insert structural form core (optional)
• Thickness of FRP laminate: 6 mm in general • Fiber: E-glass; fiber fabric with tri-axial: -30 degree, 0 degree, 30 degree • Resin: Epoxy • Fiber volume fraction: 65% • Cross-sectional area: 9950 mm^2 • FRP volume (one segment): about 0.1 m^3	• Thickness of core: 77 mm • Cross-sectional area: 33742 mm^2 • Core volume (one member): 0.34 m^3

5.3.3 Design of FRP culvert based on alternative 2 using filament winding

The second alternative is based on using filament winding method which is described in Section 4.2. The idea is to 1) prefabricate four FRP tubes by filament winding in the workshop, 2) delivery to construction site, 3) execution of backfill soil (see Figure 5.7). Each FRP tube has a diameter of 2.8 meter. The FRP tube has a sandwich structure with FRP skins on two faces and foam core in between, see Figure 5.8. The design summary of FRP tubes is summarized in Table 5.7. The design calculations can be found in Appendix A-1.

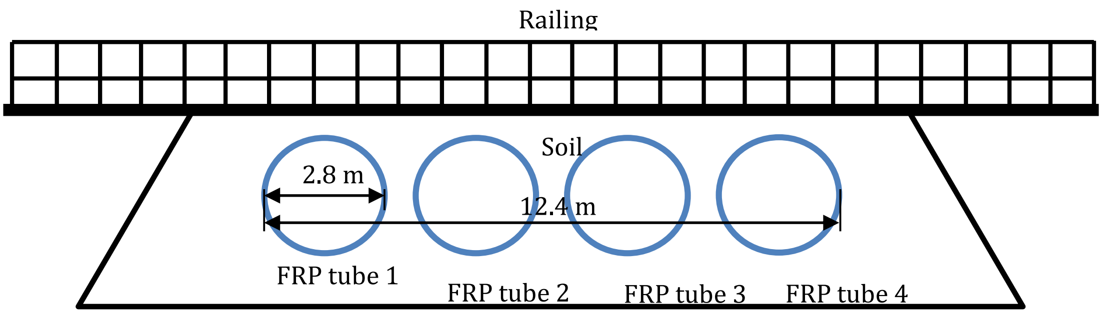


Figure 5.7 FRP tubes placed in parallel and buried by soil

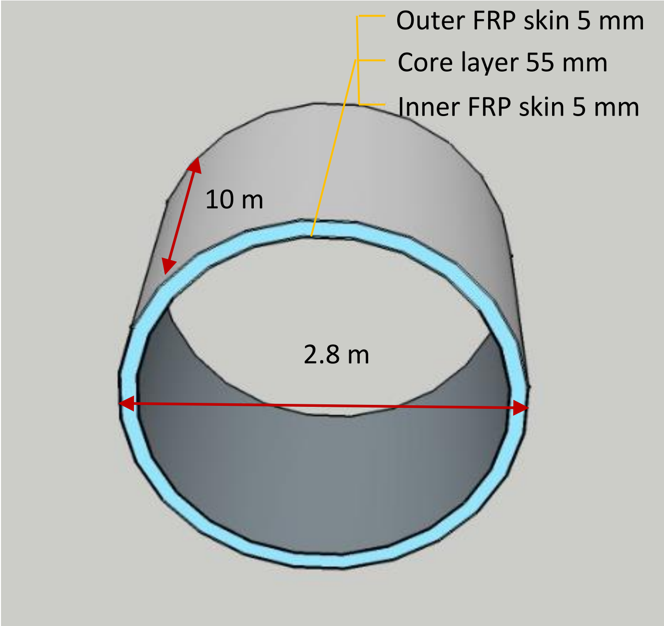


Figure 5.8 FRP tube formed by filament winding method with a sandwich cross-section

Table 5.7 Design results of the FRP tube formed by filament winding method with a sandwich cross-section

FRP laminate - FRP skin on inner and outer side	**Foam core** - Insert structural foam core between FRP skins
• Diameter 2.8 meter • Pipe length: 10 meter • Thickness of FRP layer: 5 mm • Fiber: E-glass, continuous fiber roving • Fiber direction: hoop (circumferential) winding • Matrix: Epoxy • Fiber volume fraction: 55%	• Thickness: 55 mm • Cross-section area: 0.48 m^2 • Volume: 4.8 m^3

5.3.4 Design of FRP culvert based on alternative 3 using vacuum infusion

The third alternative is based on using vacuum infusion as described in Section 4.3. Due to flexibility of this manufacturing technique, the geometry of the FRP culvert can follow that of the steel box culvert, see Figure 5.9. In the crown section, the FRP culvert has an increased thickness in order to obtain higher cross-sectional stiffness. Details of the cross-sectional geometry is shown in Table 5.8. Both PVC foam and PP honeycomb are investigated as core material. Design calculations are included in Appendix A-1.

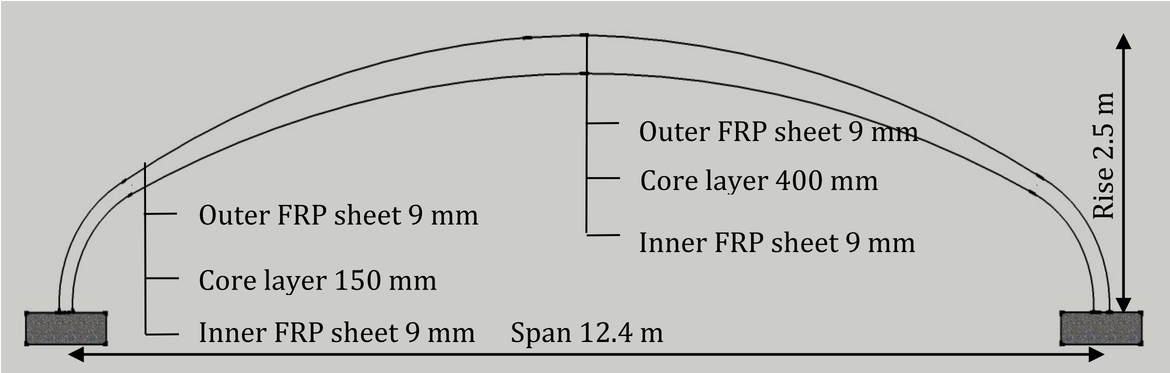


Figure 5.9 Cross-sectional geometry of the FRP culvert using vacuum infusion method

Table 5.8 Design results of the FRP culvert with box profile

FRP laminate	**Core layer**
- FRP skin on the inner and outer face	- Both PVC foam and PP honeycomb are studied as core material
• Thickness 9 mm • Length (along curve) 14.6 m • Fiber: E-glass, unidirectional • Matrix: Epoxy • Fiber volume fraction: 45%	• Initial thickness 150 mm • Increased thickness in crown section 400 mm • Cross-sectional area 4.05 m^2 • Volume 40.5 m^3

6 Life-cycle cost (LCC) analysis of the case study

6.1 LCC analysis

In general, LCC analysis serves as a good support for decision-making during the bridge management processes. For culvert bridge projects in specific, LCC analysis is helpful to investigate the potential saving of the taxpayer's money, since the long-term-cost from maintenance and repair activities of conventional steel culverts forms a significant portion of the total life-cycle cost [33].

The traditional tendering is often based on the lowest bid which is associated with the lowest investment cost of a project. In advanced tendering programs, however, it is not only the cost during investment phase being considered but also the cost during the service life a structure. In this regard, the LCC analysis, is considered as a primary tool to evaluate the whole life cycle costs. Figure 6.1 shows different life-cycle phases of a bridge project in general. The last three phases from the beginning of construction till the end of service life are the main phases investigated in LCC analysis.

Figure 6.1 Life-cycle phases

Different life-cycle phases include different aspects of cost influencing the total LCC. They can be categorized into agency cost, user cost and society cost [33], [35]. LCC categories with more details are shown in Figure 6.2

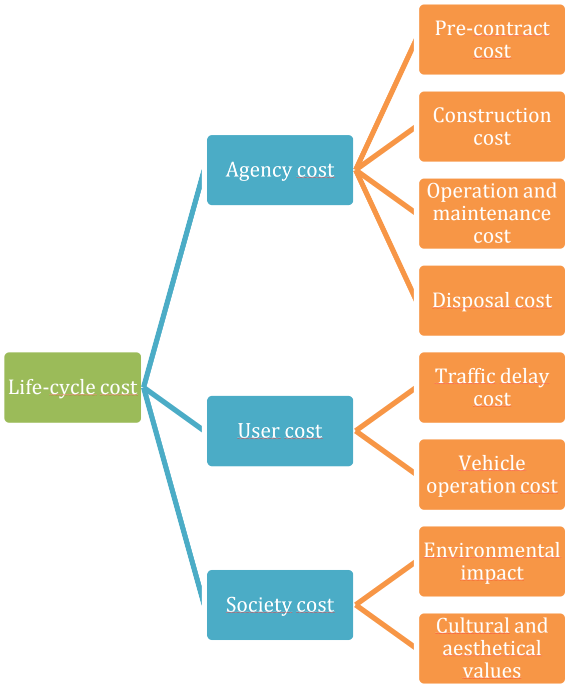


Figure 6.2 Categories of LCC

6.2 Strategy for the LCC analysis of the case study bridge

6.2.1 LCC categories considered in the case study

In Section 5, three FRP culvert alternatives are put forward to compete with the original steel culvert. Among the FRP alternatives, the FRP alternative 3 by vacuum infusion is selected to compare with the steel culvert bridge in the LCC analysis. The main reason for selection of this alternative is that there is no deviation in the shape and geometry of the FRP culvert from the steel one. Even though FRP alternative 3 may not be the cheapest alternative, it preserves the box-profile of the existing steel culvert bridge to full extent with the same span length. In Appendix B-1, the manufacturing cost of FRP culvert structures based on the three proposals is presented. A summary of the cost for each FRP alternative is presented in Table 6.7. In the LCC analysis of the case study, both the agency cost and user cost are considered from investment phase, through operation and maintenance phase, until the end-of-life. The operation and maintenance phase, named O&M in the following sections, counts from the inauguration to the demolition, which includes the activities applied to the bridge for inspection, operation, maintenance, repair, rehabilitation and replacement [33]. The social cost is not considered in this report. The components included in the total LCC of culvert bridges are stated in Figure 6.3.

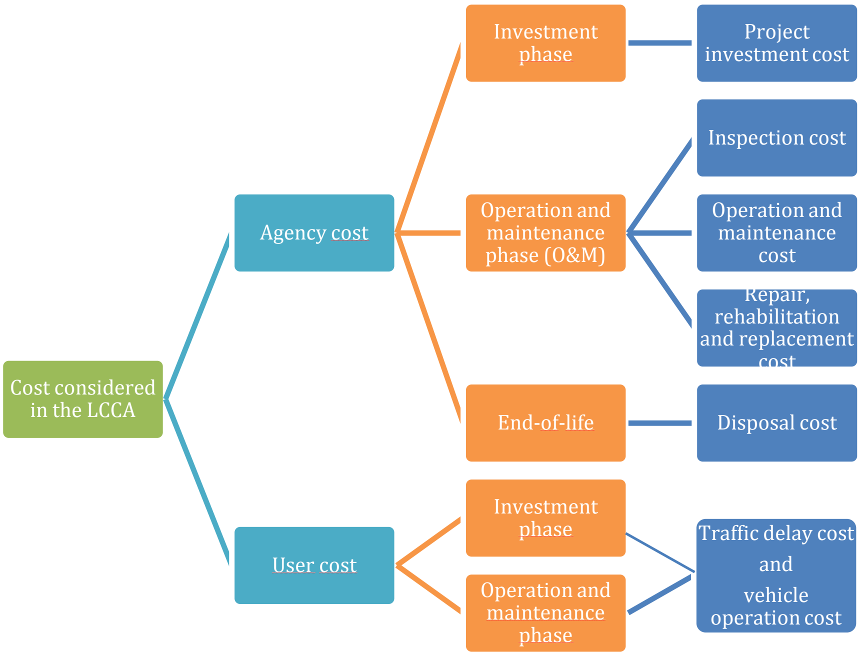


Figure 6.3 Cost taken into consideration in the LCC analysis of case study

6.2.2 Equivalent Annual Cost (EAC) method and Net Present Value (NPV) method

In the LCC analysis, the activity costs happening at different time points would be converted to a value at the same time point. In order to summarize the total costs of a project and make a comparison between different design plans, proper method should be chosen to express the LCC results.

In the LCC analysis, the activity costs happened at different time points would be converted to the value at a same time point. In order to summarize the total costs of a project and make a comparison between different design plans, proper method should be chosen to express the LCC results.

The Net Present Value (NPV) method fits the alternatives with the same life span. The costs occur at different time points during the service life are converted to their value at a common time point and summed up. It is shown in the NPV equation [33]:

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

Where,

NPV The net present value of total cost

n The year considered

L The life-span

r The discount rate

C_n The cash flows in year n

For the alternatives with different service life, the Equivalent Annual Cost (EAC) method can be used as a help tool for decision-making. In finance the EAC is the cost per year to own and operate the bridge over its entire life-span. The EAC is calculated by multiplying the NPV by the annuity factor [33]:

$$EAC = NPV \times A_{t,r} = NPV \times \frac{r}{1-(1+r)^{-L}}$$

Where,

EAC The equivalent annual cost

$A_{t,r}$ The annuity factor

In the case study, the design service life of steel culvert bridge is 80 years, while for the lie span for FRP culvert alternatives is assumed to be 100 years. Furthermore, the life span of FRP alternatives would be one of the factors to be regulated in the following sensitivity study in order to show how the life span of FRP culvert influences its economic-efficiency. Therefore, the EAC method is applied to the cost calculation for the case study.

6.2.3 Annual saving and net saving

When the LCC results of alternatives are expressed in EAC value, the alternative with a lower EAC is more economic. If this alternative is implemented, the cost benefit can be interpreted as annual saving as described in Equation 1:

$$Annual\ saving = EAC_1 - EAC_2 \qquad (1)$$

Where,

EAC_1 The equivalent annual cost of alternative 1

EAC_2 The equivalent annual cost of alternative 2, which is more cost-efficient.

The concept of annual saving can be further developed into net saving (Equation 2) regarding the life-span of the alternative that is chosen to be implemented [33].

$$Net\ saving = (EAC_1 - EAC_2) \times \frac{1-(1+r)^{-L_2}}{r} \tag{2}$$

Where,

EAC_1 The equivalent annual cost of alternative 1

EAC_2 The equivalent annual cost of alternative 2, which is the more cost-efficient alternative

r The discount rate

L_2 Life span of alternative 2, which is more cost-efficient

6.2.4 Time value of cash and discount rate

In the LCC calculation, the time value of cash is delivered by an important factor—discount rate. In Sweden a discount rate of 4% is recommended by Trafikverket [36]. Since the impact of discount rate on the LCC results is rather significant, it is worth to be considered in the sensitivity study.

6.3 Agency cost

6.3.1 Agency cost in the investment phase

6.3.1.1 *Investment cost of existing steel culvert bridge*

During the replacement of the old bridge over Siktån, a steel culvert bridge with box profile was built in 2008. According to the project records registered in BaTMan system, the total investment cost of this steel culvert bridge was 7,448,069 SEK. The box-profile culvert structure was assembled from SuperCor® steel plates from supplier Viacon, at a cost of 596 000 SEK including steel material and labor (Reference: Lars Hansing, Viacon, Jun. 30th 2015).

6.3.1.2 *Investment cost of FRP culvert bridges*

Since the culvert bridges have less structural components and larger amount of earth work, it is better to evaluate the investment cost of FRP culvert alternative based on that of the steel culvert project. The difference of investment costs would come from two aspects:

- Different cost of main load bearing structures-the FRP culvert structure and the steel one

- Reduced thickness of soil cover above the culvert crown level in the FRP alternative design. In the design of steel culvert bridge, the thickness of soil cover above the culvert crown level is advised to be not less than 1 meter regarding the fatigue problem in the critical crown section [1], [37]. For instance, in the selected case the thickness of the soil cover is 1 meter. Due to high fatigue strength of FRP materials, which resembles no fatigue problems in the design, the soil cover thickness is reduced to 0.75 meter in the design of FRP alternative.

Regarding these two major differences, approximate investment cost of an FRP culvert bridge can be expressed by equation (3).

$$INV_{FRP} = INV_{steel} + Diff_1 + Diff_2 \quad (3)$$

Where,

INV_{FRP} The approximate investment cost of the FRP culvert bridge

INV_{steel} The investment cost of steel culvert bridge, recorded in BaTMan system

$Diff_1$ The price difference between FRP culvert structure and SuperCor® steel culvert

$Diff_2$ The price difference due to reduced thickness of soil cover above the FRP culvert

The price of the considered FRP culvert structure in this case study, see Section 5, is estimated in Appendix B-1. The investment cost of the FRP alternative is included in Appendix B-2.

6.3.2 Agency cost in the operation and maintenance phase (O&M)

6.3.2.1 *O&M cost of the steel culvert bridge*

According to Trafikverket, the components of a whole bridge structure is categorized into 14 elements. For a steel culvert bridge, seven components are usually relevant, see Table 6.**1** [38].

Table 6.1 Bridge components of a bridge in general and the components included in the culvert bridge [38]

Bridge components	Included in a culvert bridge

1	**Foundation**	**x**
2	**Slope and embankment**	**x**
3	**Abutment and support**	**x**
4	**Retaining and wing walls**	**x**
5	**Bearings**	
6	**Main load-bearing structure**	**x**
7	**Secondary load-bearing structure**	
8	**Bridge deck**	
9	**Edge beam**	
10	**Waterproofing**	
11	**Pavement**	**x**
12	**Railing**	**x**
13	**Expansion joint**	
14	**Drainage system**	
x - the component is included in a common culvert bridge system		

Quantifying these components and the measures required during the operation and maintenance phase of culvert bridges is essential input data for the O&M cost. The data regarding the selected case was obtained from BaTMan's web-based system and is summarized in Table 6.2. The measures required to keep the bridge serviceable during the O&M are listed In Table 6.3 [32], [33], [39].

Table 6.2 Quantification of the steel culvert bridge 20-1335-1

	Unit	**Quantity**	**Note**
Total bridge length	m	27	Same with parapet length
Effective bridge width	m	6.9	Road width
Main load-bearing structure length	m	12.4	Span of culvert structure
Total bridge width	m	10	Width of culvert structure
Total bridge area	m^2	270	
Inner surface area of culvert structure	m^2	150	

Slope and cones area	m^2	243	
Asphalt pavement	m^2	186.3	
Railings	m	54	
Parapets' length	m	54	Same with railing length

Table 6.3 O&M activities required in the steel culvert bridge 20-1335-1 [32], [33], [39]

	Time		**Reference Target Quantity**			**Unit cost**
	Interval	Fixed year	%	of	Unit	SEK
Inspection						
Superficial inspection	1		100	Total bridge area	m^2	12
General inspection	3		100	Total bridge area	m^2	40
Major inspection	6		100	Total bridge area	m^2	70
Operation and maintenance						
Cleaning vegetation and other impurities from the bridge	1		10	Total bridge area	m^2	7
Maintenance of paving, surface finishes and lining	2		10	Pavement area	m^2	600
Maintenance of parapets, and railings	2		10	Railing length	m	250
Repair, replacement and rehabilitation						
Slopes and cones dressing	25		10	Slope and cones area	m^2	1600
Shotcrete--repair of corrugated steel sheets		30	50	Culvert sheet's inner surface area	m^2	2500
Extra cost due to shotcrete *(according to BaTMan's helpdesk, email on July 2nd 2015)* --water deviation, culvert inner surface cleaning and preparation						100000
Railings repainting	25		20	Railing	m	1600

			length		
Railings replacement	50	40	Railing length	m	2800

6.3.2.2 *O&M cost of the FRP culvert bridge*

During the operation and maintenance phase, the only difference between the FRP alternative and the steel culvert bridge would result from the culvert structure. For steel culvert structure, the corrosion of culvert inner surface cannot be avoided. The measure of shotcrete is usually applied to deal with the corrosion issue. Related activities before shotcrete, such as deviation of water passage, and surface cleaning and preparation result in extra cost. However, the shotcrete activity dealing with corrosion problems is no longer necessary for the FRP culvert bridge. Therefore, for the FRP culvert bridge, the calculation of O&M cost is almost the same with the steel one, except for eliminating the shotcrete activity. The O&M cost analysis of the steel and FRP alternatives is included in Appendix B-3 and Appendix B-4.

6.3.3 Agency cost at the end of service life

The disposal cost estimation mainly covers two aspects:

- The disposal cost of a culvert bridge in general. In references [38], [40], the disposal cost of bridge project is assumed to be about 10 percent of the investment cost of the project. Details are included in Appendix B-5. According to the latest statistic data from BaTMan (Correspondence on June 30th 2015), the unit price of constructing a culvert bridge is 17 100 SEK/m^2. So, the first component that contributes to the disposal cost can be assumed as 1 710 SEK/m^2, as one tenth of the culvert bridge's unit price.
- The disposal cost of different culvert structures in specific. The major difference between the steel culvert bridge and the FRP alternative is delivered by considering the different disposal cost of materials. The recycle of steel material can provide a profit of 500 SEK/ton, while the FRP materials are assumed to be sent to recycling plant which costs 1100 SEK/ton [41].

The calculation of disposal cost for both steel and FRP alternatives are included in Appendix B-5.

6.4 User cost

The user cost refers to the indirect cost for drivers and vehicles due to construction or maintenance work on the bridge site. Travel delay cost and vehicle operation cost (Equations 4-6) are considered in the following analysis.

$$C_{user} = C_{TDC} + C_{VOC} \tag{4}$$

$$C_{TDC} = T \times ADT_t \times N_t \times (r_T w_T + (1 - r_T) w_p) \tag{5}$$

$$C_{VOC} = T \times ADT_t \times N_t \times (r_T O_T + (1 - r_T) O_p) \tag{6}$$

Where,

C_{user}	User cost
C_{TDC}	Travel delay cost
C_{VOC}	Vehicle operation cost
T	Travel time delayed for one vehicle (hours)
ADT_t	Average daily traffic on the bridge at time t
N_t	Number of days of road work at time t
r_T	Percentage of trucks among all the ADT
w_T	Hourly cost for one truck
w_p	Hourly cost for one passenger car
O_T	Hourly operation cost for one truck
O_p	Hourly operation cost for one passenger car

It is feasible to combine the latter two equations into Equation 7. Therefore, in the user cost analysis, the vehicle operation cost and traffic delay cost are combined in the calculation, which gives a total cost of 347 SEK/h for trucks (T_T) and 167 SEK/h for passenger cars (T_p) [35]. Traffic in the case project is shown in Table **6.4**.

$$C_{user} = T \times ADT_t \times N_t \times (r_T T_T + (1 - r_T) T_p) \tag{7}$$

$$T_T = w_T + O_T \tag{8}$$

$$T_p = w_p + O_p \tag{9}$$

Where,

T_T Total hourly cost for one truck, including travel delay and truck operation

T_p Total hourly cost for one passenger car, including travel delay and car operation

Table 6.4 Traffic on the bridge 20-1335-1

Maximum allowable speed	km/h	50
ADT car on bridge	car/per day	136
ADT truck on bridge	truck/per day	10

During the investment phase, the traffic through construction site was blocked, so that the vehicles needed to make a detour, see Figure 6.4. The situation shown on the right side is not taken into account due to its little difference of routes length. The traffic block time due to construction on site is assumed to be one month.

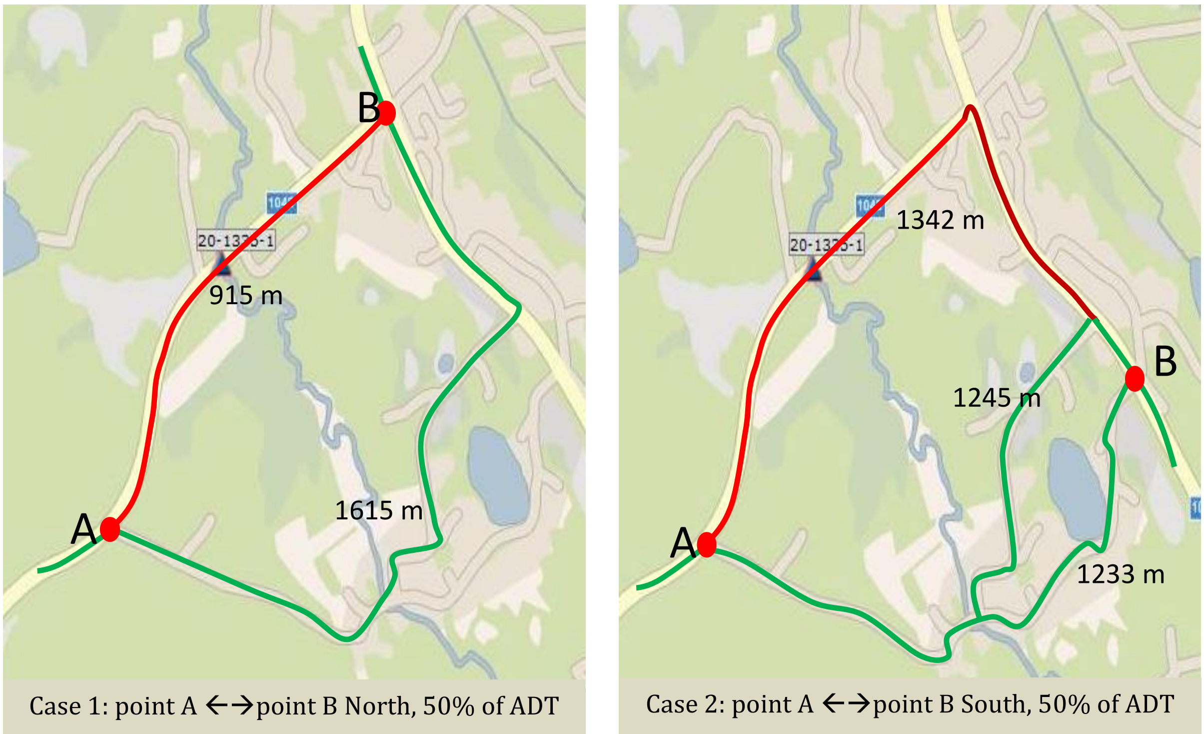


Figure 6.4 Traffic detour routes due to bridge construction during the investment phase

During the service life, the normal traffic flow would be disturbed due to the O&M activities, for example, repainting the traffic line on the pavement. The following assumptions are made to calculate the user cost during O&M phase:

- The work zone length is assumed to be 200 meters
- The speed of vehicles is reduced from 50 km/h to 40 km/h
- Two workdays are required for activities including:
    - Maintenance of paving, surface finishes and lining,
    - Shotcrete--repair of corrugated steel sheets

- One workday are required for activities including:
    - Maintenance of parapets, and railings
    - Railings repainting
    - Railings replacement

6.5 Results and conclusions of LCC analysis

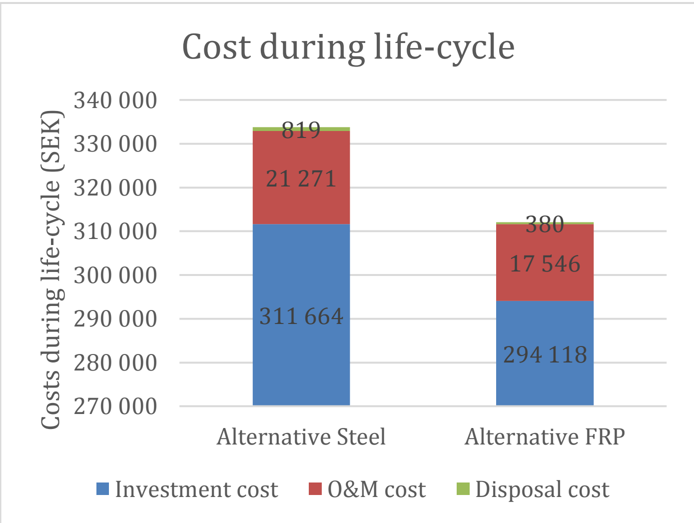
LCC analyses of two alternatives made in steel and FRP are performed. The LCC results are presented in Appendix B-7. Important results are summarized in Table 6.5. The design service life of steel alternative is obtained from the project record in BaTMan, while 100-year life span is assumed for FRP culvert bridge.

Table 6.5 Introduction of alternatives for LCC analysis

Alternatives for LCC analysis	**Steel alternative**	**FRP alternative**
Replacement strategy	Steel culvert bridge	[1]FRP culvert bridge
Design service life, year	80	100
Discount rate	4%	

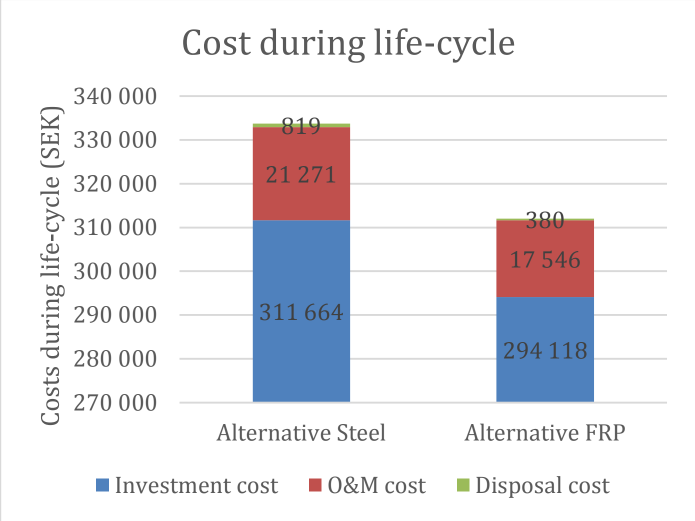
[1]FRP culvert bridge refers to the case with vacuum infusion technique and PP honeycomb

The LCC results are expressed in EAC for comparison due to different life spans. Investment cost, O&M cost, disposal cost and the total LCC are shown in Table 6.6



and

Figure 6.5.



The benefits of the more cost-efficient alternative, which is FRP alternative, are presented in terms of annual saving and net saving in Table 6.6. The concept of annual saving and net saving is introduced in Section 6.2.3.

Table 6.6 LCC analysis results expressed in EAC

Result in EAC	**Steel alternative**	**FRP alternative**	**Annual Saving**	**[4]Saving ratio**	**Net Saving**
[1]Investment cost	311 664	294 118	17 547	6%	429 985
[2]O&M cost	21 271	17 546	3 724	21%	91 266
[3]Disposal cost	819	380	439	116%	10 761
Total LCC	333 754	312 044	21 710	7%	532 012

[1]Investment cost—Cost during the investment phase, and both agency cost and user cost are included.

[2]O&M cost—cost during the O&M phase, and both agency cost and user cost are included.

[3]Disposal cost—cost paid by agency at the end of service life.

[4]Saving ratio-- the ratio of annual saving to EAC of the cost-efficient alternative, which is Alternative FRP in the case study according to the LCC results.

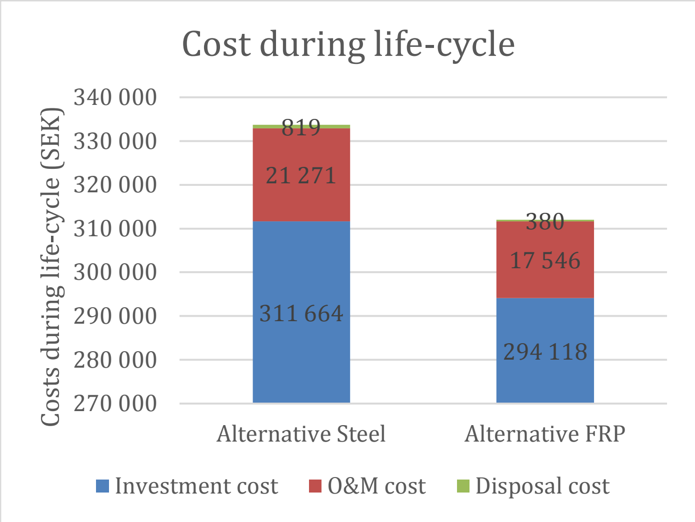


Figure 6.5 LCC costs of two alternatives during life-cycle phases expressed as EAC

Conclusions

From the results above, the cost benefits of the FRP alternative are clearly seen by comparing the EAC values and the saving ratio throughout all life-cycle phases:

- In terms of the investment cost, the saving ratio of FRP alternative is 6 percent, which, excluding the impact of longer life span, results from 1) the cheaper FRP culvert structure and 2) thinner soil cover above the culvert structure. Considering that the investment cost of the steel alternative (27 600 SEK/m^2) is 61% higher than the average level (17 100 SEK/m^2) (Indicated by BaTMan as an average cost value for steel culvert bridges dated 30th June, 2015), it is reasonable to expect a higher saving ratio in the investment cost for other culvert bridges in general.
- In the O&M phase, the elimination of shotcrete activities in the FRP alternative results in a 21 percent saving ratio due to the relatively high cost of this measure. In this regard, the LCC analysis helps to reveal the saving of FRP culvert bridge during service life, while this is usually neglected in the conventional cost analysis.
- At the end of service life, the disposal cost of Alternative FRP is much lower after taking into account the time value of cash and the longer life span of the FRP bridge, even though the recycling of FRP material is more expensive than the steel.

6.6 Sensitivity analysis

Even though the abovementioned conclusions are based on LCC analyses of a real case, the uncertainty in the assumptions always exists. In order to add more credit to the LCC analyses performed in this report, a sensitivity analysis is carried out to investigate the impact of variability in six important parameters on the overall results. These parameters include:

1) The discount rate
2) The ADT volume over the bridge
3) The price of FRP culvert structure
4) Expected life span of FRP culvert bridge
5) The extent of shotcrete rehabilitation on steel culvert bridge during service life
6) The thickness of soil cover over the FRP culvert structure

Like former section, the cost results in the sensitivity study are also expressed and compared in EAC values, if not specifically clarified.

6.6.1 Discount rate

The change of discount rate would influence the cost result during the whole life-cycle. The total LCC is picked out to see the impact of discount rate. The value of discount rate that investigated ranges from 1 percent to 8 percent [36], [38], see Figure 6.6.

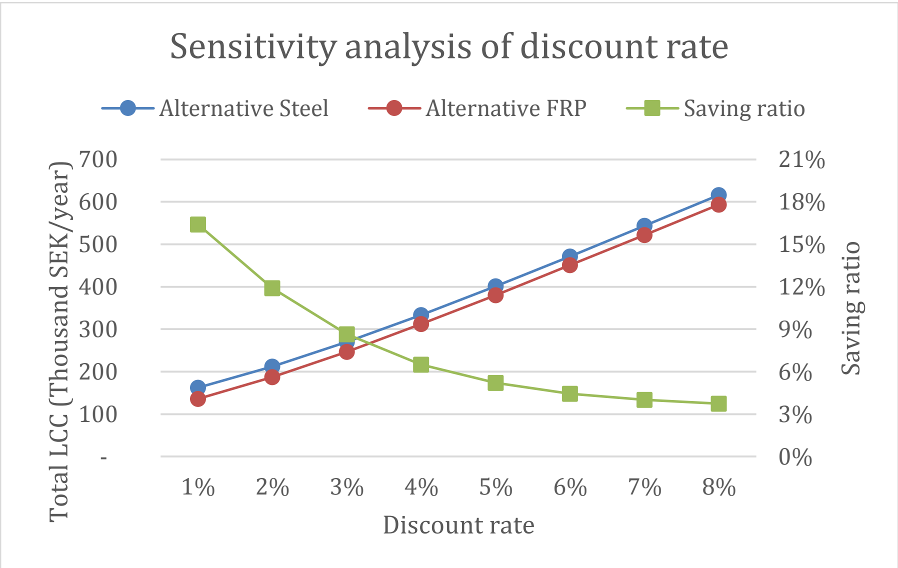


Figure 6.6 Impact of discount rate on total LCC and saving ratio

In the primary LCC calculation, the discount rate is assume to be 4 percent each year. The result of sensitivity (Figure 6.6) analysis shows that the uncertainty in the discount rate does not change the conclusion that FRP alternative is more cost-efficient compared to steel alternative. The tendency of saving ratio reveals that the cost benefits of Alternative FRP become minimized when the discount rate is higher.

6.6.2 ADT volume

According to the record data (2004) from BaTMan, the ADT volume over the culvert bridge is 146 vehicles per day, including 136 cars and 10 trucks. However, in urban areas with busy traffic, the ADT volume can reach as high as 20,000 vehicles per day [35]. In should be noticed that in the primary LCC analysis, the contribution of user cost to the LCC result is limited due to low ADT volume.

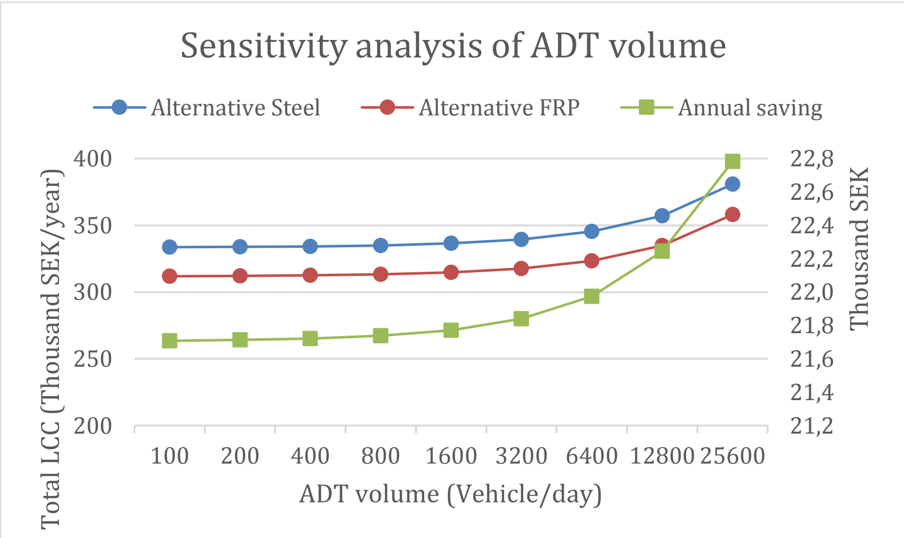


Figure 6.7 Impact of ADT volume on the total LCC and annual saving

It is seen from Figure **6.7** that 1) both of the alternatives result in higher LCC when the ADT volume is increasing, and 2) the annual saving does not increase (1 076 SEK) significantly compared to the value of LCC results (ranging from 311 961 SEK to 380 848 SEK). Therefore, it can be concluded that the uncertainty in ADT volume does not influence the conclusion that FRP alternative is more competitive.

6.6.3 Price of the FRP culvert structure

The price of culvert structure can result in significant changes in LCC for the two alternatives. In steel alternative, the culvert structure is assembled by corrugated steel plates, while FRP sandwich segments (FRP alternative 3 by vacuum infusion with PP honeycomb) are bonded to form the FRP culvert. A sensitivity analysis is performed to investigate how the price of FRP culvert structure influences the cost-benefits of the FRP alternative.

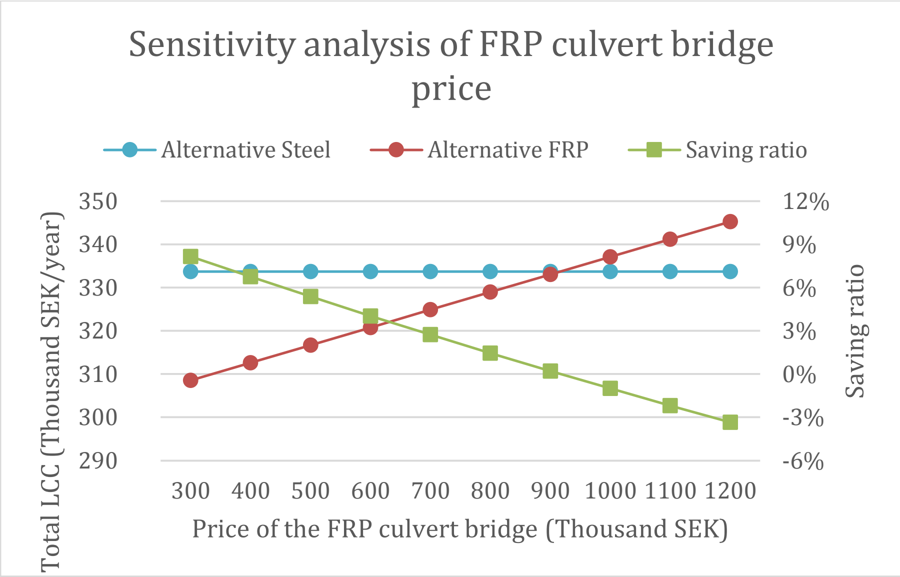


Figure 6.8 Impact of FRP culvert structure price on the investment cost and saving ratio

Figure 6.8 shows that the price of FRP culvert structure plays a critical role in determining which alternative is more cost-efficient. In the primary LCC analysis, the price of FRP culvert bridge was estimated as 385 500 SEK, which results in an annual saving of 21 710 SEK and saving ratio of 7.0% compared to the steel alternative. However, if the price of FRP culvert structure goes beyond 915 000 SEK in this case, the FRP alternative will no longer be competitive, and the steel alternative becomes cheaper regarding the LCC.

Table 6.7 Cost benefits of Alternative FRP in terms of different FRP culvert design investigated in Section 5

FRP alternatives	No. 1 Pultrusion	No. 2 Filament winding	No. 3 Vacuum infusion with PP honeycomb	No. 3 Vacuum infusion with PVC foam
Price of FRP culvert structure (SEK)	313 200	543 100	385 500	614 000
Saving or loss	Saving	Saving	Saving	Saving
Saving ratio	8.0%	4.8%	7.0%	3.9%

6.6.4 Design life span of the FRP culvert bridge

The design service life of the existing steel culvert bridge is 80 years, which results in a LCC of 333 754 SEK/year. When it comes to the FRP culvert structure, great concerns are focusing on the uncertainty of its service life and its impact on the LCC.

In the sensitivity analysis, Figure 6.9 shows that the FRP alternative can achieve a lower LCC as long as the life span is longer than 63 years. Otherwise, the steel alternative would become more cost-efficient instead. Assumption of a minimum life span of 80 years is reasonable and it is believed that FRP structures can reach a life span of +100 years.

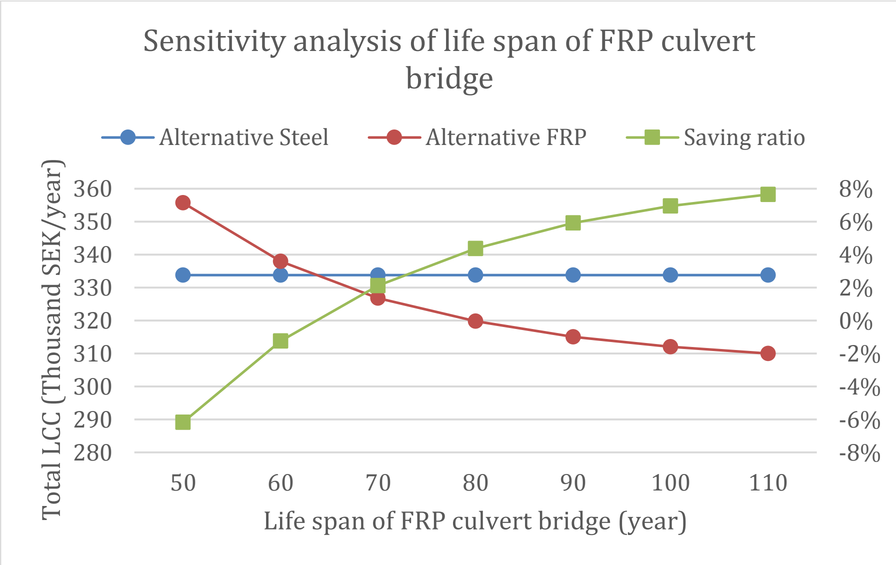


Figure 6.9 Impact of FRP culvert bridge's life span on the total LCC and saving ratio

6.6.5 Extent of shotcrete rehabilitation applied to the steel culvert

As a measure to deal with corrosion problems in steel culverts, applying shotcrete to repair corroded steel plates is a regular practice during the service life. The extent of area that requires shotcrete measure after 30-year-operation depends on how serious the corrosion problem is. In the LCC calculation, the target quantity is assumed to be 50 percent of the total culvert inner surface area. This is a reasonable assumption as usually the lower half of the culvert which is in contact with water suffers from corrosion problems. Due to the relatively high cost of shotcrete activity, the amount of corrosion area would directly influence the O&M cost during the service life.

Figure 6.10 shows that, with no doubt, when the corrugated surface area is larger, the LCC of the steel alternative becomes larger compared with the FRP alternative.

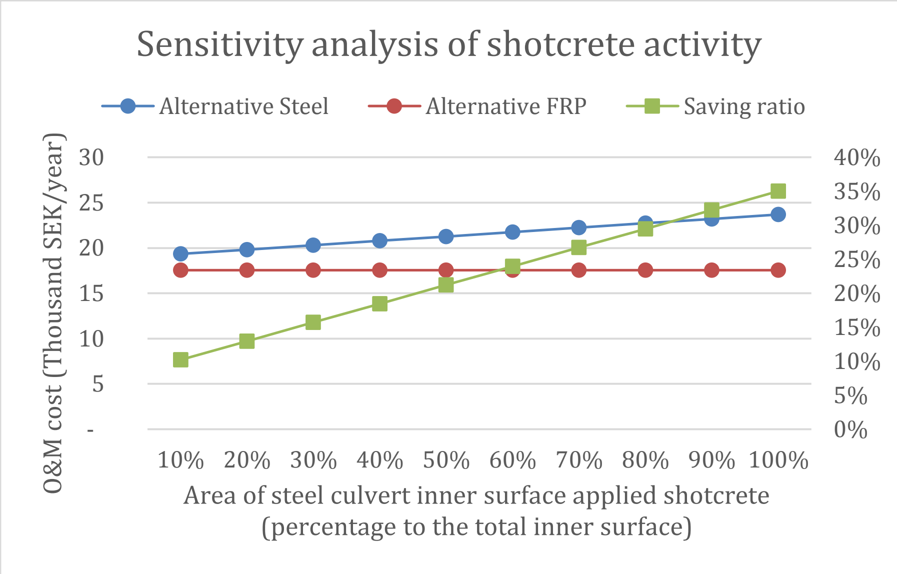


Figure 6.10 Impact of the extent of shotcrete rehabilitation on the O&M cost and saving ratio

6.6.6 Thickness of the soil cover over FRP culvert

Since the fatigue is not an issue in FRP culvert alternative, the thickness of the soil cover over FRP culvert crown can be reduced. The reduction of soil cover leads to less earthwork and reduced cost during construction.

From Figure 6.11 it is obvious that the thinner soil cover results in better cost-efficiency of the FRP alternative. The sensitivity study shows that increasing the soil cover thickness on the FRP alternative from 1000 mm to 1500 mm, would reduce the saving ratio by 0.9% (from 5.5% to 4.6%) with regard to the investment cost. It is important to address the fact that increasing the soil cover thickness is favorable for the culvert structure to work against the traffic load on the road.

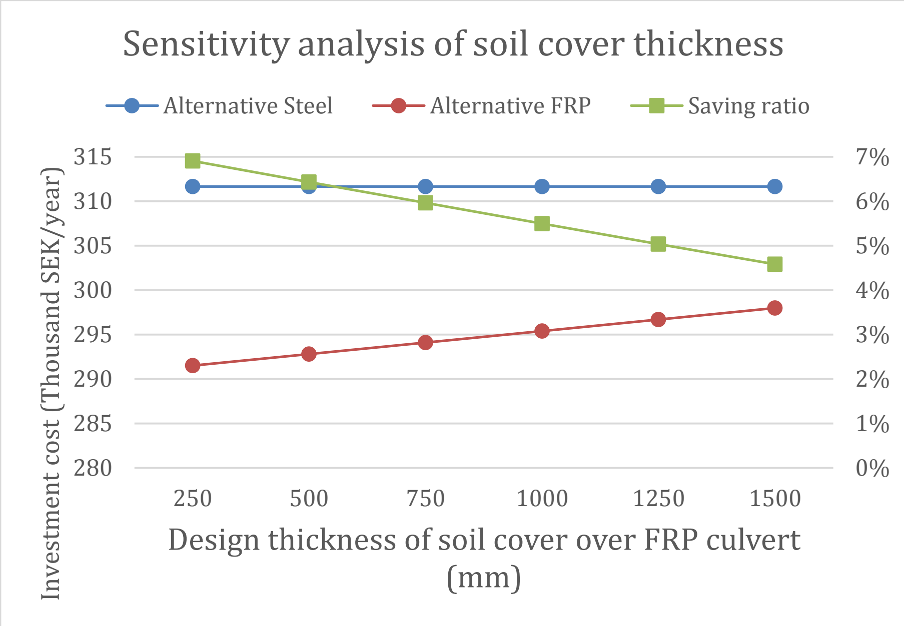


Figure 6.11 Impact of reduced soil cover thickness on the investment cost and saving ratio

Therefore the conclusions drawn from the sensitivity study of soil cover thickness includes:

- Regarding this case study, the varying thickness of soil cover within a reasonable range would not change the cost-efficiency of FRP alternative.
- In terms of mechanical behavior, it is worth to increase the soil cover thickness in the FRP culvert bridge in order to achieve a better structural behavior, at the expense of little loss of cost-benefits.

6.7 Summary of the LCC and sensitivity analyses

6.7.1 Contribution of the LCC analysis

The LCC analysis of the case study introduced in this report demonstrates that the FRP alternative achieves better cost-efficiency along all the life-cycle phases—investment phase, O&M phase and disposal phase.

6.7.2 Contribution of the sensitivity analysis

The sensitivity analysis in this report aims to investigate whether the uncertainty of important input data would influence the conclusion of LCC analysis. In terms of their impact on the LCC result, six important parameters are divided into two groups for further discussion, see Table 6.8.

Table 6.8 Six parameters divided into two groups in terms of their impact on the LCC result and conclusion

Parameters in Group 1	Discount rate ADT volume Area of shotcrete Soil cover thickness	The uncertainty of parameters in Group 1 would **not contradict** the better cost-efficiency of the Alternative FRP.
Parameters in Group 2	Price of FRP culvert structure Life span of FRP culvert bridge	The uncertainty of parameters in Group 2 would **challenge** the cost-efficiency of the FRP alternative.

For the parameters in Group 1, the uncertainty in values would not change the conclusion that the FRP alternative is more cost-efficient than the steel alternative. More cost-benefits can be expected from FRP if any of the following conditions is satisfied:

1) A reduction of discount rate
2) An increase of ADT volume
3) An increase of corroded area that needs shotcrete
4) A reduction of soil cover thickness

For the parameters in Group 2, the uncertainty of the values would challenge the competitiveness of the FRP alternative. The FRP may lose its cost-efficiency if any of the following conditions cannot be guaranteed:

1) The price of building a FRP culvert structure is less than 915 000 SEK.
2) The FRP culvert bridge can service longer than 63 years.

7 Conclusions and suggestion for future study

7.1 Structural performance of FRP culvert bridges

Regarding the structural design of the FRP culvert structure, the FE modeling results performed in the previous study [42] were used. It was confirmed in the previous study that 1) the strength of FRP laminate is sufficient enough in the ULS, and 2) the deflection in the mid-span becomes the governing issue in the design.

In order to obtain better understanding of the culvert bridge's behavior of deflection, FE modeling of the box-profile steel culvert bridge with a 12.4-meter-span is also implemented. The results show that:

- In the crown section, an increased sectional stiffness due to extra reinforcement plates helps the culvert structure resist the traffic load, which results in a more-evenly-distributed-deflection at mid-span along the bridge width direction
- In the corner section, an increased sectional stiffness due to extra reinforcement plates enhances the capacity of the culvert structure under soil load, which can reduced the deflection in the culvert along the span direction.

These conclusions could provide good guide to the cross-sectional design of FRP culvert structure to achieve a better structural performance.

7.2 Manufacturing methods of FRP composite for culvert structure

The potential composite manufacturing methods are reviewed for manufacturing of culvert structures. Among them pultrusion, filament winding, and VARTM are investigated as promising methods for FRP culvert manufacturing. The practical construction proposals and design alternative of FRP culvert structure are developed from these three methods.

7.3 Economic competence of FRP culvert bridges

In the case study performed in this report, the LCC analysis demonstrates that the FRP alternative, compared with the steel alternative, is more cost-efficient along all the life-cycle phases, including investment phase, O&M phase and disposal phase.

Based on the LCC analysis, the sensitivity analysis gives further instruction that the FRP alternative could keep its better cost-efficiency if 1) the price of FRP culvert structure is lower than 915 000 SEK and 2) the FRP culvert bridge has a service life longer than 63 years.

7.4 Suggestions for future study

Regarding structural performance

In order to have a better control of the deflection in FRP culverts, the following work can be investigated to improve the structural performance.

1) Optimization of the section and use of stiffer fibers such as carbon, in combination with glass fibers to form a stiffer and yet strong FRP skin. Cross-sectional profile for the FRP culvert structure can also be subjected to optimization to take advantage of geometrical stiffness.
2) Design the fiber orientation in the FRP laminate to achieve better material utilization with the help of FE modeling
3) Improve the FE modeling method. In this report, the FRP laminate is modeled by shell elements, using equivalent mechanical properties. To study the behavior in more detail, FRP material can be modelled as orthotropic laminate that has a correct stack up with regard to fiber orientation.
4) Verification of the bonding strength in the FRP culvert design to investigate whether the shear strength is sufficient or not in the bonding interface.

Regarding economic-efficiency analysis

The LCC analysis can be refined by improving the reliability of the following aspects:

In the calculation of FRP culvert price, the tooling cost of FRP alternative 2 (filament winding) and alternative 3 (vacuum infusion) during composite manufacturing is calculated using the same labor cost. However, the real tooling costs should be different and depend on manufacturing methods. More accurate data from suppliers should be obtained.

Social cost, as one of the three categories in the LCC analysis, is included in the current study. This topic could be further evaluated by performing a life-cycle assessment (LCA) study to investigate the environmental impact.

8 References

[1] J. YANG and L. KALABUCHOVA, "Application of FRP materials in Culvert Road Bridges - A feasibility study with focus on mechanical behavior and lifecycle cost analysis." Chalmers University of Technology, 2014.

[2] W. Cantwell, "Composite Forming Techniques." [Online]. Available: https://www.flickr.com/photos/core-materials/albums/72157627122081332. [Accessed: 06-Aug-2015].

[3] Gurit, "Gurit's Guide to Composites."

[4] S. G. Advani and K.-T. Hsiao, "Manufacturing Techniques for Polymer Matrix Composites (PMCs)," in *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*, Elsevier, 2012, pp. 1–12.

[5] F. C. Campbell, *Manufacturing Processes for Advanced Composites*. Elsevier, 2003.

[6] S. T. Peters and J. L. McLarty, "Filament Winding, Composites, Vol 21," in *ASM International Handbook*, 2001, pp. 536–549.

[7] J. Mack and R. Schledjewski, "Manufacturing Techniques for Polymer Matrix Composites (PMCs)," in *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*, Elsevier, 2012, pp. 182–208.

[8] M. Bannister, "Challenges for composites into the next millennium — a reinforcement perspective," *Compos. Part A Appl. Sci. Manuf.*, vol. 32, no. 7, pp. 901–910, Jul. 2001.

[9] F. Henninger and K. Friedrich, "Thermoplastic filament winding with online-impregnation. Part A: process technology and operating efficiency," *Compos. Part A Appl. Sci. Manuf.*, vol. 33, no. 11, pp. 1479–1486, Nov. 2002.

[10] T. Sakai and S. Somiya, "Analysis of creep behavior in thermoplastics based on visco-elastic theory," *Mech. Time-Dependent Mater.*, vol. 15, no. 3, pp. 293–308, Feb. 2011.

[11] A. Khennane, *Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications*. Elsevier, 2013.

[12] "Composite Fabrication by Filament Winding - An Insight." [Online]. Available: http://tifac.org.in/index.php?option=com_content&view=article&id=536:composite-fabrication-by-filament-winding-an-insight&catid=85:publications&Itemid=952. [Accessed: 06-Aug-2015].

[13] "Epoxy Suestem Technical Manual - controlling epoxy cure time." [Online]. Available: https://www.glen-l.com/supplies/pxman-exotherm.html. [Accessed: 05-Aug-2015].

[14] E. M. Sozer, P. Simacek, and S. G. Advani, "Manufacturing Techniques for Polymer Matrix Composites (PMCs)," in *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*, Elsevier, 2012, pp. 245–309.

[15] K.-T. Hsiao and D. Heider, "Manufacturing Techniques for Polymer Matrix Composites (PMCs)," in *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*, Elsevier, 2012, pp. 310–347.

[16] S. Bickerton and P. A. Kelly, "Manufacturing Techniques for Polymer Matrix Composites (PMCs)," in *Manufacturing Techniques for Polymer Matrix Composites (PMCs),* Elsevier, 2012, pp. 348–380.

[17] T. Creasy, "Manufacturing Techniques for Polymer Matrix Composites (PMCs)," in *Manufacturing Techniques for Polymer Matrix Composites (PMCs),* Elsevier, 2012, pp. 123–138.

[18] F. C. Campbell, *Structural Composite Materials*. ASM International, 2010.

[19] M. C. Y. Niu, *Composite Airframe Structures - Practical Design Information and Data (3rd Edition)*. AD Adaso/Adastra Engineering LLC, 1992.

[20] M. Zoghi, *The International Handbook of FRP Composite in Civil Engineering*. 2013.

[21] C. S. Lee, D. G. Lee, and J. H. Oh, "Co-cure bonding method for foam core composite sandwich manufacturing," *Compos. Struct.*, vol. 66, no. 1–4, pp. 231–238, Oct. 2004.

[22] Hexcel, "Honeycomb sandwich design technology," *Publ. No. AGU*, no. December 2000, pp. 1–28, 1995.

[23] Gurit, "Core Materials: processsing guide," 2015.

[24] V. Menta, S. Sundararaman, K. Chandrashekhara, N. Phan, and T. Nguyen, "Hybrid composites using out-of-autoclave process for aerospace sub-structures," *Faculty Research & Creative Works*. 2008.

[25] Plascore, "PP honeycomb." [Online]. Available: http://www.plascore.com/download/datasheets/honeycomb_core_documentation/PP_Honeycomb.pdf.

[26] Plascore, "Closed Molding, Lite RTM and Vacuum Infusion." [Online]. Available: http://www.plascore.com/products/honeycomb-cores/thermoplastic/closed-molding/. [Accessed: 21-Oct-2015].

[27] "International Road Transport Operations in Sweden." [Online]. Available: http://www.transportsfriend.org/int/country-sweden.html. [Accessed: 05-Aug-2015].

[28] "PERMISSIBLE MAXIMUM DIMENSIONS OF LORRIES IN EUROPE." [Online]. Available: http://www.internationaltransportforum.org/IntOrg/road/pdf/dimensions.pdf. [Accessed: 05-Aug-2015].

[29] "Filament Winding Machine for Vertical FRP Vessels." [Online]. Available: http://www.frpmachine.com/frpmachine/vertical-frp-tank-winding-machine.html. [Accessed: 06-Aug-2015].

[30] DIAB, "Core Infusion by DIAB." [Online]. Available: http://www.diabgroup.com/en-GB/Products-and-services/Core-Infusion. [Accessed: 22-Oct-2015].

[31] "DIAB Core Infusion Technology." [Online]. Available: http://www.stm-boats.com/articles/Infusion_Brochure.pdf. [Accessed: 22-Oct-2015].

[32] M. Safi, "LCC Applications for Bridges and Integration with BMS," KTH Royal Institute of Technology, Stockholm, 2012.

[33] M. Safi, "Life-Cycle Costing : Applications and Implementations in Bridge

Investment and Management." KTH Royal Institute of Technology, 2013.

[34] U. A. Khashaba, "In-plane shear properties of cross-ply composite laminates with different off-axis angles," *Compos. Struct.*, vol. 65, no. 2, pp. 167–177, Aug. 2004.

[35] L. S. Amanda Sagemo, "Comparative study of bridge concepts based on life-cycle cost analysis and life-cycle assessment," Chalmers University of Technology, 2013.

[36] SIKA, "Värden och metoder för transportsektorns samhällsekonomiska analyser – ASEK 4," 2009.

[37] L. Petterson, "Full Scale Tests and Structural Evaluation of Soil Steel Flexible Culverts with Low Height of Cover," KTH, 2007.

[38] H. Sundquist and R. Karoumi, "life cycle cost methodology and LCC tools," 2012. [Online]. Available: http://etsi.aalto.fi/Etsi3/PDF/TG3/LCC Description.pdf. [Accessed: 07-Aug-2015].

[39] M. Safi, H. Sundquist, and R. Karoumi, "Cost-Efficient Procurement of Bridge Infrastructures by Incorporating Life-Cycle Cost Analysis with Bridge Management Systems," *J. Bridg. Eng.*, vol. 20, no. 6, p. 04014083, Jun. 2015.

[40] M. Safi and G. Du, "Holistic Approach to Sustainable Bridge Procurement Considering LCC, LCA, Lifespan, User-Cost and Aesthetics : Case Study." 2013.

[41] V. Mara, R. Haghani, and P. Harryson, "Bridge decks of fibre reinforced polymer (FRP): A sustainable solution," *Constr. Build. Mater.*, vol. 50, pp. 190–199, Jan. 2014.

[42] Haghani, R., Preliminary Study on Using FRP Materials in Culvert Road Bridges- Mechanical behavior and life cycle-cost analysis, Report 2015:2, Chalmers University of Technology, Sweden.

9 Appendices

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Appendix A-1 Cross-sectional design of FRP alternatives

Based on the prelinary design method developed for FRP culvert in Ref. [1]

ORIGIN := 1

Part 1 Program: Stiffness matrices of the designed FRP cross-section

Q matrix for each FRP ply

Total stiffness matrix of each lamina with a certain fiber orientation angle

$$Q(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta) := \left|\begin{array}{l} \upsilon_{21} \leftarrow \dfrac{E_{22}}{E_{11}} \cdot \upsilon_{12} \\ Q_{11} \leftarrow \dfrac{E_{11}}{1 - \upsilon_{12} \cdot \upsilon_{21}} \\ Q_{22} \leftarrow \dfrac{E_{22}}{1 - \upsilon_{12} \cdot \upsilon_{21}} \\ Q_{12} \leftarrow \dfrac{\upsilon_{12} \cdot E_{22}}{1 - \upsilon_{12} \cdot \upsilon_{21}} \\ Q_{21} \leftarrow \dfrac{\upsilon_{21} \cdot E_{11}}{1 - \upsilon_{12} \cdot \upsilon_{21}} \\ Q_{66} \leftarrow G_{12} \\ U_1 \leftarrow \dfrac{1}{8} \cdot (3 \cdot Q_{11} + 3 \cdot Q_{22} + 2 \cdot Q_{12} + 4Q_{66}) \\ U_2 \leftarrow \dfrac{1}{2} \cdot (Q_{11} - Q_{22}) \\ U_3 \leftarrow \dfrac{1}{8} \cdot (Q_{11} + Q_{22} - 2 \cdot Q_{12} - 4Q_{66}) \\ U_4 \leftarrow \dfrac{1}{8} \cdot (Q_{11} + Q_{22} + 6 \cdot Q_{12} - 4Q_{66}) \\ U_5 \leftarrow \dfrac{1}{2} \cdot (U_1 - U_4) \\ \theta \leftarrow \mathrm{stack}(\theta, \mathrm{reverse}(\theta)) \\ QQ_{11} \leftarrow U_1 + U_2 \cdot \cos(2 \cdot \theta) + U_3 \cdot \cos(4 \cdot \theta) \\ QQ_{12} \leftarrow U_4 - U_3 \cdot \cos(4 \cdot \theta) \\ QQ_{22} \leftarrow U_1 - U_2 \cdot \cos(2 \cdot \theta) + U_3 \cdot \cos(4 \cdot \theta) \end{array}\right.$$

$$
\begin{aligned}
&QQ_{16} \leftarrow \frac{1}{2}\cdot U_2\cdot \sin(2\cdot\theta) + U_3\cdot \sin(4\cdot\theta) \\
&QQ_{26} \leftarrow \frac{1}{2}\cdot U_2\cdot \sin(2\cdot\theta) - U_3\cdot \sin(4\cdot\theta) \\
&QQ_{66} \leftarrow U_5 - U_3\cdot \cos(4\cdot\theta) \\
&QQ \leftarrow \begin{pmatrix} QQ_{11} & QQ_{12} & QQ_{16} \\ QQ_{12} & QQ_{22} & QQ_{26} \\ QQ_{16} & QQ_{26} & QQ_{66} \end{pmatrix}
\end{aligned}
$$

Q matrix for each FRP ply

Coordinates of each FRP ply

h_i refers to the distance from the midplane to the top of the i^{th} lamina.

$$
h(t,no,d) := \left|
\begin{aligned}
&\text{for } i \in 1..(no+1) \\
&\quad h_i \leftarrow \left[\frac{-(t\cdot no\cdot 2 + d)}{2} + (i-1)\cdot t\right] \\
&\text{for } i \in (no+2)..(2no+2) \\
&\quad h_i \leftarrow \left[\frac{-(t\cdot no\cdot 2 + d)}{2} + d + (i-2)\cdot t\right] \\
&\text{return } h
\end{aligned}
\right.
$$

Coordinates of each FRP ply

Matrices A B D for the FRP Sandwich

Extensional stiffness matrix for the FRP sandwich (unite: N/m)

$$
A(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d) := \left|
\begin{aligned}
&\text{for } i \in 1..no \\
&\quad ha_i \leftarrow \left[h(t,no,d)_{(i+1)} - h(t,no,d)_i\right] \\
&\text{for } i \in (no+1)..(2\cdot no) \\
&\quad ha_i \leftarrow \left[h(t,no,d)_{(i+2)} - h(t,no,d)_{(i+1)}\right] \\
&\text{for } i \in 1..3 \\
&\quad \text{for } j \in 1..3 \\
&\quad\quad A_{i,j} \leftarrow Q(E_{11},E_{22},\upsilon_{12},G_{12},\theta)_{i,j}\, ha \\
&A
\end{aligned}
\right.
$$

Coupling stiffness matrix for the FRP sandwich (unit: N)

$$B(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d) := \left|\begin{array}{l} \text{for } i \in 1..no \\ \quad hb_i \leftarrow \left[\left(h(t,no,d)_{i+1}\right)^2 - \left(h(t,no,d)_i\right)^2\right] \\ \text{for } i \in (no+1)..(2\cdot no) \\ \quad hb_i \leftarrow \left[\left[h(t,no,d)_{(i+2)}\right]^2 - \left[h(t,no,d)_{(i+1)}\right]^2\right] \\ \text{for } i \in 1..3 \\ \quad \text{for } j \in 1..3 \\ \quad\quad B_{i,j} \leftarrow \left(Q(E_{11},E_{22},\upsilon_{12},G_{12},\theta)\right)_{i,j} hb\cdot\frac{1}{2} \\ B \end{array}\right.$$

Bending stiffness matrix for the FRP sandwich (unit: N*m)

$$D(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d) := \left|\begin{array}{l} \text{for } i \in 1..no \\ \quad hd_i \leftarrow \left[\left(h(t,no,d)_{i+1}\right)^3 - \left(h(t,no,d)_i\right)^3\right] \\ \text{for } i \in (no+1)..(2\cdot no) \\ \quad hd_i \leftarrow \left[\left[h(t,no,d)_{(i+2)}\right]^3 - \left[h(t,no,d)_{(i+1)}\right]^3\right] \\ \text{for } i \in 1..3 \\ \quad \text{for } j \in 1..3 \\ \quad\quad D_{i,j} \leftarrow \left(Q(E_{11},E_{22},\upsilon_{12},G_{12},\theta)\right)_{i,j} hd\cdot\frac{1}{3} \\ D \end{array}\right.$$

Matrices A B D for the FRP Sandwich

Stiffness parameters derived from matrices

The equivalent membrane elastic constants

$$EA_{xx}(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d) := \frac{1}{\left(A(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d)^{-1}\right)_{1,1}}$$

$$EA_{yy}(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d) := \frac{1}{\left(A(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d)^{-1}\right)_{2,2}}$$

$$EA_{xy}(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d) := \frac{1}{\left(A(E_{11},E_{22},\upsilon_{12},G_{12},\theta,t,no,d)^{-1}\right)_{3,3}}$$

The equivalent bending elastic constants

$$EI_{xx}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d) := \frac{1}{\left(D(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d)^{-1}\right)_{1,1}}$$

$$EI_{yy}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d) := \frac{1}{\left(D(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d)^{-1}\right)_{2,2}}$$

$$EI_{xy}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d) := \frac{1}{\left(D(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d)^{-1}\right)_{3,3}}$$

Stiffness parameters derived from matrices

Part 2 Design Process

FRP alternative 1 by pultrusion

Step 1: Choose the materials for the FRP composite

Fiber: E-glass

$E_f := 70GPa$ $\upsilon_f := 0.22$ $G_f := 30GPa$

Matrix: Epoxy resin

$E_m := 3.3GPa$ $\upsilon_m := 0.34$ $G_m := 1.3GPa$

Fiber volume fraction

$v := 65\%$ 0.1-0.3 (random), 0.3-0.6 (woven) or 0.5-0.8 (unidirectional)

Mechanical properties of FRP lamina

$E_{k.11} := E_f \cdot v + E_m \cdot (1 - v)$ $\upsilon_{12} := \upsilon_f \cdot v + \upsilon_m \cdot (1 - v)$

$E_{k.22} := \dfrac{E_f \cdot E_m}{E_f \cdot (1 - v) + E_m \cdot v}$ $\upsilon_{21} := \dfrac{E_{k.22}}{E_{k.11}} \cdot \upsilon_{12}$

$$G_{k.12} := \frac{G_f \cdot G_m}{G_f \cdot (1 - v) + G_m \cdot v}$$

$E_{k.11} = 46.655 \cdot GPa$ $E_{k.22} = 8.67 \cdot GPa$ $G_{k.12} = 3.438 \cdot GPa$

$\upsilon_{12} = 0.262$ $\upsilon_{21} = 0.049$

$E_{11} := E_{k.11}$ $E_{22} := E_{k.22}$ $G_{12} := G_{k.12}$

Core Material Not used

Step 2: Design the geometry of the pultruded member for the required bending stiffness

Design the geometry for FRP alternative 1

FRP alternative 1--pultrusion

Span to be satisfied: 5.8 meter
Culvert profile: semi-circular

According to the steel culvert design conducted in the preliminary study (Ref. [1])

In the design case no.6 with 6-meter span and pipe-arch shape

Corrugated steel plates type: 200*55

Thickness required: 7 mm

$$EI_{k.steel} := 6.526 \times 10^5 \frac{N \cdot m^2}{m}$$ Bending stiffness in span direction

In the preliminary design of FRP culvert, it is on the safe side to design the geometry of cross-section with the same bending stiffness with the steel culvert case according to Ref. [1].

$$EI_{k.frp} := EI_{k.steel}$$

Thicknesss of FRP $t_{face} := 6mm$

$t := 2mm$ Thickness of each ply

$no := \frac{t_{face}}{t} = 3$ Number of plies for one laminate face

Fiber orientation for each ply (0 degree in the preliminary design)

$\theta := stack(30deg, 0deg, -30deg)$

$$CheckInput := \begin{cases} \text{"OK"} & \text{if } no = rows(\theta) \\ \text{"Error"} & \text{otherwise} \end{cases}$$

$CheckInput = \text{"OK"}$

Thickness of core $d := 77mm$

Bending stiffness

$$EI_{xx}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d) = 649.772 \cdot 10^3 \frac{N \cdot m^2}{m}$$

$$Diff := \frac{\left(EI_{k.frp} - EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right)\right)}{EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right)}$$

$Diff = 0.435 \cdot \%$

Design the geometry for FRP alternative 1

FRP alternative 2 by filament winding

Step 1: Choose the materials for the FRP composite

Fiber: E-glass

$E_f := 70GPa$ $\upsilon_f := 0.22$ $G_f := 30GPa$

Matrix: Epoxy resin

$E_m := 3.3GPa$ $\upsilon_m := 0.34$ $G_m := 1.3GPa$

Fiber volume fraction

$v := 55\%$ 0.1-0.3 (random), 0.3-0.6 (woven) or 0.5-0.8 (unidirectional)

Mechanical properties of FRP lamina

$E_{k.11} := E_f \cdot v + E_m \cdot (1 - v)$ $\upsilon_{12} := \upsilon_f \cdot v + \upsilon_m \cdot (1 - v)$

$E_{k.22} := \frac{E_f \cdot E_m}{E_f \cdot (1 - v) + E_m \cdot v}$ $\upsilon_{21} := \frac{E_{k.22}}{E_{k.11}} \cdot \upsilon_{12}$

$G_{k.12} := \frac{G_f \cdot G_m}{G_f \cdot (1 - v) + G_m \cdot v}$

$E_{k.11} = 39.985 \cdot GPa$ $E_{k.22} = 6.934 \cdot GPa$ $G_{k.12} = 2.744 \cdot GPa$

$\upsilon_{12} = 0.274$ $\upsilon_{21} = 0.048$

$E_{11} := E_{k.11}$ $E_{22} := E_{k.22}$ $G_{12} := G_{k.12}$

Core Material Divinycell H 45 from DIAB

Step 2: Design the geometry to obtain the required bending stiffness

Design the geometry for FRP alternative 2

FRP alternative 2--filament winding

Span to be satisfied: 2.8 meter
Culvert profile: circular

According to the steel culvert design conducted in the preliminary study (Ref. [1])

In the design case no.2--steel culvert with 3-meter span and the pipe-arch profile

Corrugated steel plates type: 200*55

Thickness required: 4 mm (requirements of ULS and SLS are satisfied)

$EI_{k.steel} := 3.71 \times 10^5 \frac{N \cdot m^2}{m}$ Bending stiffness in span direction

In the preliminary design of FRP culvert, it is on the safe side to design the geometry of cross-section with the same bending stiffness with the steel culvert case according to Ref. [1].

$EI_{k.frp} := EI_{k.steel}$

Thicknesss of FRP $t_{face} := 5mm$

$t := 5mm$ Thickness of each ply with the same fiber direction

$no := \frac{t_{face}}{t} = 1$ Number of plies for one laminate face

Fiber orientation for each ply (0 degree in the preliminary design)

$\theta := \text{stack}(0deg)$

$$CheckInput := \begin{cases} \text{"OK"} & \text{if } no = \text{rows}(\theta) \\ \text{"Error"} & \text{otherwise} \end{cases}$$

$CheckInput = \text{"OK"}$

Thickness of core $d := 55mm$

<u>Bending stiffness</u>

$$EI_{xx}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d) = 360.698 \cdot 10^3 \frac{N \cdot m^2}{m}$$

$$Diff := \frac{(EI_{k.frp} - EI_{xx}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d))}{EI_{xx}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d)}$$

$Diff = 2.856 \cdot \%$

Design the geometry for FRP alternative 2

FRP alternative 3

Step 1: Choose the materials for the FRP sandwich

Fiber: E-glass

$E_f := 70GPa$ $\upsilon_f := 0.22$ $G_f := 30GPa$

Matrix: Epoxy resin

$E_m := 3.3GPa$ $\upsilon_m := 0.34$ $G_m := 1.3GPa$

Fiber volume fraction

$v := 55\%$ 0.1-0.3 (random), 0.3-0.6 (woven) or 0.5-0.8 (unidirectional)

Mechanical properties of FRP lamina

$E_{k.11} := E_f \cdot v + E_m \cdot (1 - v)$ $\upsilon_{12} := \upsilon_f \cdot v + \upsilon_m \cdot (1 - v)$

$$E_{k.22} := \frac{E_f \cdot E_m}{E_f \cdot (1 - v) + E_m \cdot v} \qquad \upsilon_{21} := \frac{E_{k.22}}{E_{k.11}} \cdot \upsilon_{12}$$

$$G_{k.12} := \frac{G_f \cdot G_m}{G_f \cdot (1 - v) + G_m \cdot v}$$

$E_{k.11} = 39.985 \cdot GPa$ $E_{k.22} = 6.934 \cdot GPa$ $G_{k.12} = 2.744 \cdot GPa$

$\upsilon_{12} = 0.274$ $\upsilon_{21} = 0.048$

$E_{11} := E_{k.11}$ $E_{22} := E_{k.22}$ $G_{12} := G_{k.12}$

Core Material Divinycell H 45 from DIAB

Step 2: Design the geometry to obtain the required bending stiffness

Design the geometry for FRP alternative 3

FRP alternative 3--resin transfer molding

Span to be satisfied: 12 meter
Culvert profile: box shape

According to the steel culvert design conducted in the preliminary study (Ref. [1])

In the design case no.15 with 12-meter span and box shape
Corrugated steel plates type: 380*140

Extra reinforcement plates in the crown section

Thickness required: 7 mm

Bending stiffness in span direction

$EI_{k.steel.top} := 2.944 \times 10^{7} \frac{N \cdot m^{2}}{m}$ in the crown section with reinforced plates

$EI_{k.steel.cor} := 4.42 \times 10^{6} \frac{N \cdot m^{2}}{m}$ in the corner section

In the preliminary design of FRP culvert, it is on the safe side to design the geometry of cross-section with the same bending stiffness with the steel culvert case according to Ref. [1].

$EI_{k.frp.top} := EI_{k.steel.top}$

$EI_{k.frp.cor} := EI_{k.steel.cor}$

Thicknesss of FRP $t_{face} := 9mm$

$t := 9mm$ Thickness of each ply with the same fiber direction

$no := \frac{t_{face}}{t} = 1$ Number of plies for one laminate face

Fiber orientation for each ply (0 degree in the preliminary design)

$\theta := stack(0deg)$

$$CheckInput := \begin{vmatrix} "OK" & \text{if } no = rows(\theta) \\ "Error" & \text{otherwise} \end{vmatrix}$$

CheckInput = "OK"

<u>Bending stiffness in the crown section</u>

Thickness of core $d := 400mm$

$$EI_{xx}(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d) = 3.01 \times 10^{4} \cdot 10^{3} \frac{N \cdot m^{2}}{m}$$

$$Diff := \frac{\left(EI_{k.frp.top} - EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right)\right)}{EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right)}$$

$$Diff = -2.206 \cdot \%$$

Bending stiffness in the corner section

Thickness of core $d := 150mm$

$$EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right) = 4.554 \times 10^{6} \cdot \frac{N \cdot m^{2}}{m}$$

$$Diff := \frac{\left(EI_{k.frp.cor} - EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right)\right)}{EI_{xx}\left(E_{11}, E_{22}, \upsilon_{12}, G_{12}, \theta, t, no, d\right)}$$

$$Diff = -2.937 \cdot \%$$

Design the geometry for FRP alternative 3

Appendix A-2 Mechanical properties of FRP laminates for FE modeling

A-2-1 FRP laminate used in FRP alternative 1 by Pultrusion

1. Choose the material for FRP composites

Fiber: E-glass

$E_f := 70GPa$ $\upsilon_f := 0.22$ $G_f := 30GPa$

$\rho_f := 2500\frac{kg}{m^3}$

Matrix: Epoxy

$E_m := 3.3GPa$ $\upsilon_m := 0.34$ $G_m := 1.3GPa$

$\rho_m := 1250\frac{kg}{m^3}$

Fiber volume fraction

$v := 65\%$ 0.1-0.3 (random), 0.3-0.6 (woven) or 0.5-0.8 (unidirectional)

Fiber weight fraction

$$w := \frac{(\rho_f \cdot v)}{[\rho_f \cdot v + \rho_m \cdot (1-v)]} = 78.788 \cdot \%$$

Mechanical properties of FRP lamina (unidirectional fiber composite)

$$E_{k.11} := E_f \cdot v + E_m \cdot (1-v)$$

$$E_{k.22} := \frac{E_f \cdot E_m}{E_f \cdot (1-v) + E_m \cdot v}$$

$$G_{k.12} := \frac{G_f \cdot G_m}{G_f \cdot (1-v) + G_m \cdot v}$$

$$\upsilon_{12} := \upsilon_f \cdot v + \upsilon_m \cdot (1-v) \qquad \upsilon_{21} := \frac{E_{k.22}}{E_{k.11}} \cdot \upsilon_{12}$$

$$\upsilon_{23} := \upsilon_{12} \cdot \frac{(1-\upsilon_{21})}{1-\upsilon_{12}}$$

Ref. R.M. Christensen, The numbers of elastic properties and failure parameters for fiber composite, 1998

$$G_{k.23} := \frac{E_{k.22}}{2(1+\upsilon_{23})}$$

2. Safety factors for FRP materials

Paritial factor for FRP laminate

Reference: Eurocomp Design Code and Handbook, Section 2.3.3.2, Table 2.4-Table 2.6

$\gamma_{M1} := 1.5$ Derivation of properties

$\gamma_{M2} := 1.1$ Method of manufacture: Pultrusion

$\gamma_{M3.SLS} := 1.0$ 1.0 for short-term loading in SLS

$\gamma_{M3.ULS} := 2.5$ 2.5 for long-term loading in ULS

$\gamma_{M.SLS} := \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3.SLS} = 1.65$

$\gamma_{M.ULS} := \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3.ULS} = 4.125$

3. Design value of mechanical properties

$E_{k.11} = 46.655 \cdot GPa$ $E_{k.22} = 8.67 \cdot GPa$

$\upsilon_{12} = 0.262$ $\upsilon_{21} = 0.049$ $\upsilon_{23} = 0.338$

$G_{k.12} = 3.438 \cdot GPa$ $G_{k.23} = 3.24 \cdot GPa$

Note: All the fiber is modeled as placed along the span direction.
For SLS analysis--deflection

$E_{d.11.SLS} := \dfrac{E_{k.11}}{\gamma_{M.SLS}} = 2.828 \times 10^4 \cdot MPa$ $G_{d.12.SLS} := \dfrac{G_{k.12}}{\gamma_{M.SLS}} = 2.083 \times 10^3 \cdot MPa$

$E_{d.22.SLS} := \dfrac{E_{k.22}}{\gamma_{M.SLS}} = 5.254 \times 10^3 \cdot MPa$ $G_{d.23.SLS} := \dfrac{G_{k.23}}{\gamma_{M.SLS}} = 1.964 \times 10^3 \cdot MPa$

For ULS analysis--stress

$E_{d.11.ULS} := \dfrac{E_{k.11}}{\gamma_{M.ULS}} = 1.131 \times 10^4 \cdot MPa$ $G_{d.12.ULS} := \dfrac{G_{k.12}}{\gamma_{M.ULS}} = 833.367 \cdot MPa$

$E_{d.22.ULS} := \dfrac{E_{k.22}}{\gamma_{M.ULS}} = 2.102 \times 10^3 \cdot MPa$ $G_{d.23.ULS} := \dfrac{G_{k.23}}{\gamma_{M.ULS}} = 785.55 \cdot MPa$

A-2-2 FRP laminate used in FRP alternative 2 by Filament Winding

1. Choose the material for FRP composites

Fiber: E-glass

$E_f := 70GPa$ $\upsilon_f := 0.22$ $G_f := 30GPa$

$\rho_f := 2500\frac{kg}{m^3}$

Matrix: Epoxy

$E_m := 3.3GPa$ $\upsilon_m := 0.34$ $G_m := 1.3GPa$

$\rho_m := 1250\frac{kg}{m^3}$

Fiber volume fraction

$v := 55\%$ 0.1-0.3 (random), 0.3-0.6 (woven) or 0.5-0.8 (unidirectional)

Fiber weight fraction

$$w := \frac{\left(\rho_f \cdot v\right)}{\left[\rho_f \cdot v + \rho_m \cdot (1 - v)\right]} = 70.968 \cdot \%$$

Mechanical properties of FRP lamina (unidirectional fiber composite)

$$E_{k.11} := E_f \cdot v + E_m \cdot (1 - v)$$

$$E_{k.22} := \frac{E_f \cdot E_m}{E_f \cdot (1 - v) + E_m \cdot v}$$

$$G_{k.12} := \frac{G_f \cdot G_m}{G_f \cdot (1 - v) + G_m \cdot v}$$

$$\upsilon_{12} := \upsilon_f \cdot v + \upsilon_m \cdot (1 - v) \qquad \upsilon_{21} := \frac{E_{k.22}}{E_{k.11}} \cdot \upsilon_{12}$$

$$\upsilon_{23} := \upsilon_{12} \cdot \frac{\left(1 - \upsilon_{21}\right)}{1 - \upsilon_{12}}$$

Ref. R.M. Christensen, The numbers of elastic properties and failure parameters for fiber composite, 1998

$$G_{k.23} := \frac{E_{k.22}}{2(1 + \upsilon_{23})}$$

2. Safety factors for FRP materials

Paritial factor for FRP laminate

Reference: Eurocomp Design Code and Handbook, Section 2.3.3.2, Table 2.4-Table 2.6

$\gamma_{M1} := 1.5$ Derivation of properties

$\gamma_{M2} := 1.1$ Method of manufacture: Filament winding

$\gamma_{M3.SLS} := 1.0$ 1.0 for short-term loading in SLS

$\gamma_{M3.ULS} := 2.5$ 2.5 for long-term loading in ULS

$$\gamma_{M.SLS} := \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3.SLS} = 1.65$$

$$\gamma_{M.ULS} := \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3.ULS} = 4.125$$

3. Design value of mechanical properties

$E_{k.11} = 39.985 \cdot GPa$ $E_{k.22} = 6.934 \cdot GPa$

$\upsilon_{12} = 0.274$ $\upsilon_{21} = 0.048$ $\upsilon_{23} = 0.359$

$G_{k.12} = 2.744 \cdot GPa$ $G_{k.23} = 2.55 \cdot GPa$

For SLS analysis--deflection

$$E_{d.11.SLS} := \frac{E_{k.11}}{\gamma_{M.SLS}} = 2.423 \times 10^{4} \cdot MPa \qquad G_{d.12.SLS} := \frac{G_{k.12}}{\gamma_{M.SLS}} = 1.663 \times 10^{3} \cdot MPa$$

$$E_{d.22.SLS} := \frac{E_{k.22}}{\gamma_{M.SLS}} = 4.202 \times 10^{3} \cdot MPa \qquad G_{d.23.SLS} := \frac{G_{k.23}}{\gamma_{M.SLS}} = 1.546 \times 10^{3} \cdot MPa$$

For ULS analysis--stress

$$E_{d.11.ULS} := \frac{E_{k.11}}{\gamma_{M.ULS}} = 9.693 \times 10^{3} \cdot MPa \qquad G_{d.12.ULS} := \frac{G_{k.12}}{\gamma_{M.ULS}} = 665.11 \cdot MPa$$

$E_{d.22.ULS} := \frac{E_{k.22}}{\gamma_{M.ULS}} = 1.681 \times 10^{3} \cdot MPa$ $G_{d.23.ULS} := \frac{G_{k.23}}{\gamma_{M.ULS}} = 618.224 \cdot MPa$

A-2-3 FRP laminate used in FRP alternative 3 by Vacuum Infusion

1. Choose the material for FRP composites

Fiber: E-glass

$E_f := 70GPa$ $\upsilon_f := 0.22$ $G_f := 30GPa$

$\rho_f := 2500 \frac{kg}{m^3}$

Matrix: Epoxy

$E_m := 3.3GPa$ $\upsilon_m := 0.34$ $G_m := 1.3GPa$

$\rho_m := 1250 \frac{kg}{m^3}$

Fiber volume fraction

$v := 55\%$ 0.1-0.3 (random), 0.3-0.6 (woven) or 0.5-0.8 (unidirectional)

Fiber weight fraction

$$w := \frac{\left(\rho_f \cdot v\right)}{\left[\rho_f \cdot v + \rho_m \cdot (1 - v)\right]} = 70.968 \cdot \%$$

Mechanical properties of FRP lamina (unidirectional fiber composite)

$$E_{k.11} := E_f \cdot v + E_m \cdot (1 - v)$$

$$E_{k.22} := \frac{E_f \cdot E_m}{E_f \cdot (1 - v) + E_m \cdot v}$$

$$G_{k.12} := \frac{G_f \cdot G_m}{G_f \cdot (1 - v) + G_m \cdot v}$$

$\upsilon_{12} := \upsilon_f \cdot v + \upsilon_m \cdot (1 - v)$ $\upsilon_{21} := \frac{E_{k.22}}{E_{k.11}} \cdot \upsilon_{12}$

$$\upsilon_{23} := \upsilon_{12} \cdot \frac{(1 - \upsilon_{21})}{1 - \upsilon_{12}}$$

Ref. R.M. Christensen, The numbers of elastic properties and failure parameters for fiber composite, 1998

$$G_{k.23} := \frac{E_{k.22}}{2(1 + \upsilon_{23})}$$

2. Safety factors for FRP materials

Paritial factor for FRP laminate

Reference: Eurocomp Design Code and Handbook, Section 2.3.3.2, Table 2.4-Table 2.6

$\gamma_{M1} := 1.5$ Derivation of properties

$\gamma_{M2} := 1.2$ Method of manufacture: Resin Transfer Molding

$\gamma_{M3.SLS} := 1.0$ 1.0 for short-term loading in SLS

$\gamma_{M3.ULS} := 2.5$ 2.5 for long-term loading in ULS

$$\gamma_{M.SLS} := \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3.SLS} = 1.8$$

$$\gamma_{M.ULS} := \gamma_{M1} \cdot \gamma_{M2} \cdot \gamma_{M3.ULS} = 4.5$$

3. Design value of mechanical properties

$E_{k.11} = 39.985 \cdot GPa$ $E_{k.22} = 6.934 \cdot GPa$

$\upsilon_{12} = 0.274$ $\upsilon_{21} = 0.048$ $\upsilon_{23} = 0.359$

$G_{k.12} = 2.744 \cdot GPa$ $G_{k.23} = 2.55 \cdot GPa$

For SLS analysis--deflection

$$E_{d.11.SLS} := \frac{E_{k.11}}{\gamma_{M.SLS}} = 2.221 \times 10^{4} \cdot MPa \qquad G_{d.12.SLS} := \frac{G_{k.12}}{\gamma_{M.SLS}} = 1.524 \times 10^{3} \cdot MPa$$

$$E_{d.22.SLS} := \frac{E_{k.22}}{\gamma_{M.SLS}} = 3.852 \times 10^{3} \cdot MPa \qquad G_{d.23.SLS} := \frac{G_{k.23}}{\gamma_{M.SLS}} = 1.417 \times 10^{3} \cdot MPa$$

For ULS analysis--stress

$$E_{d.11.ULS} := \frac{E_{k.11}}{\gamma_{M.ULS}} = 8.886 \times 10^{3} \cdot MPa$$

$$G_{d.12.ULS} := \frac{G_{k.12}}{\gamma_{M.ULS}} = 609.685 \cdot MPa$$

$$E_{d.22.ULS} := \frac{E_{k.22}}{\gamma_{M.ULS}} = 1.541 \times 10^{3} \cdot MPa$$

$$G_{d.23.ULS} := \frac{G_{k.23}}{\gamma_{M.ULS}} = 566.706 \cdot MPa$$

Appendix A-3 FE modeling of FRP culvert bridge-FRP Alternative 1 Pultrusion

Material properties and loads

Table 1 Material properties of FRP composite and soil for FRP Alternative 1

[1]**Elastic constants**	**FRP composite by pultrusion**						**Soil**		
Design value	E_1	E_2	v_{12}	G_{12}	G_{13}	G_{23}	E	v	ρ
	MPa	MPa		MPa	MPa	MPa	MPa		kg/m^3
In SLS model	28280	5254	0.262	2083	2083	785	26	0.3	2600
In USL model	11310	2102	0.262	833	833	785	26	0.3	2600

[1]The calculation of elastic constants for FRP composite made by pultrusion, see Appendix A-2.

Table 2 Input data of loads in SLS and ULS model

	Partial factor	**Input data in Abaqus**
In SLS model		
Self-weight of soil	1.0	Gravity: -9.8 (Component 2)
[1]Traffic load LM2	1.0	Pressure: 0.95 MPa
In ULS model		
Self-weight of soil	1.35	Gravity: -13.2 (Component 2)
Traffic load LM2	1.35	Pressure: 1.28 MPa

[1]Traffic load LM2: two point loads, each load (200kN) acting on an area of 350 mm*600mm

Modeling in Abaqus

Figure 1 shows:

1. Cross-sectional profile of FRP culvert structure (span 5.6 meter)
2. PART-FRP culvert structure (Shell-Extrusion)
3. Mesh-FRP culvert and surrounding soil (Soil-extrusion for PART-Soil)
4. Vertical deflection under soil and traffic load

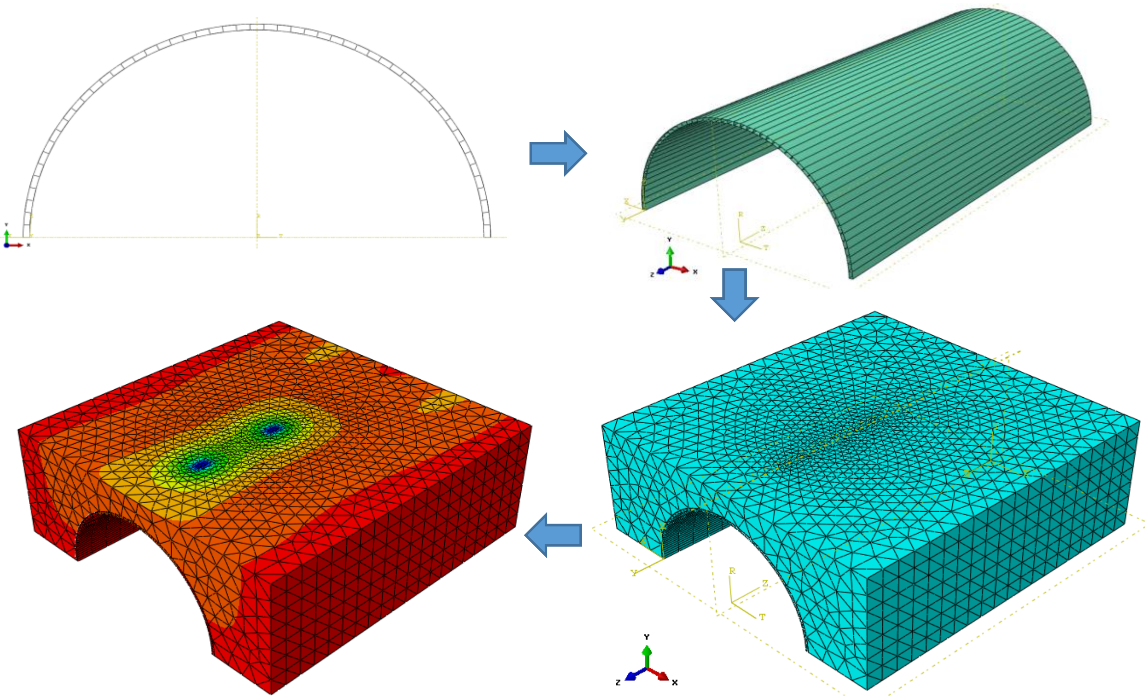


Figure 1 Finite element model in Abaqus

Verification of vertical deflection

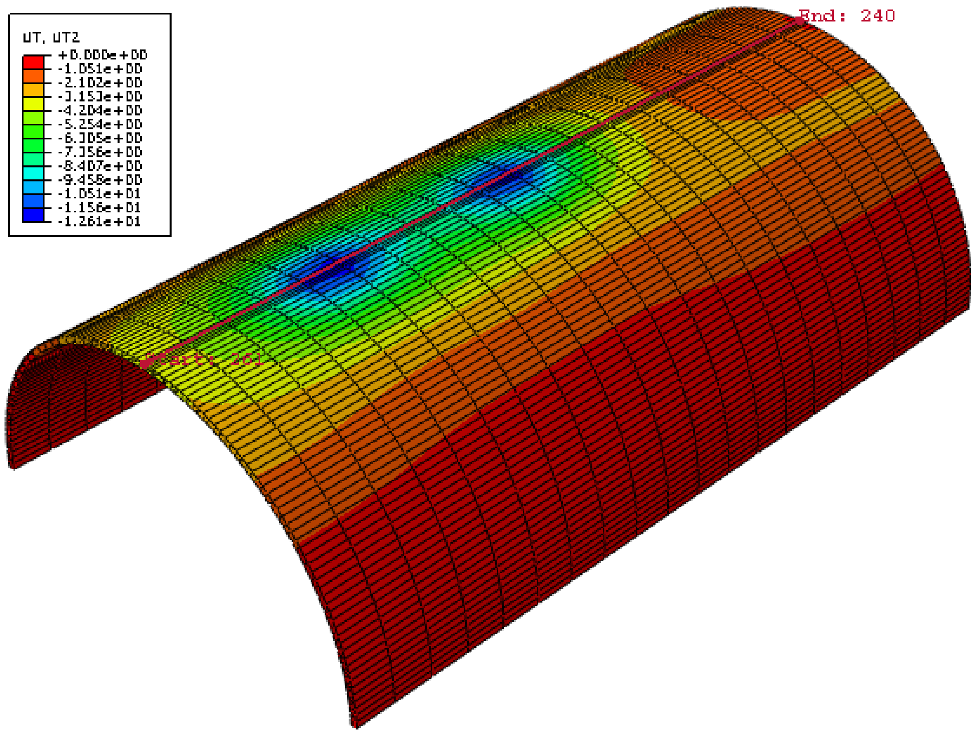


Figure 2 PATH (red line) in the mid-span along the bridge-width-direction

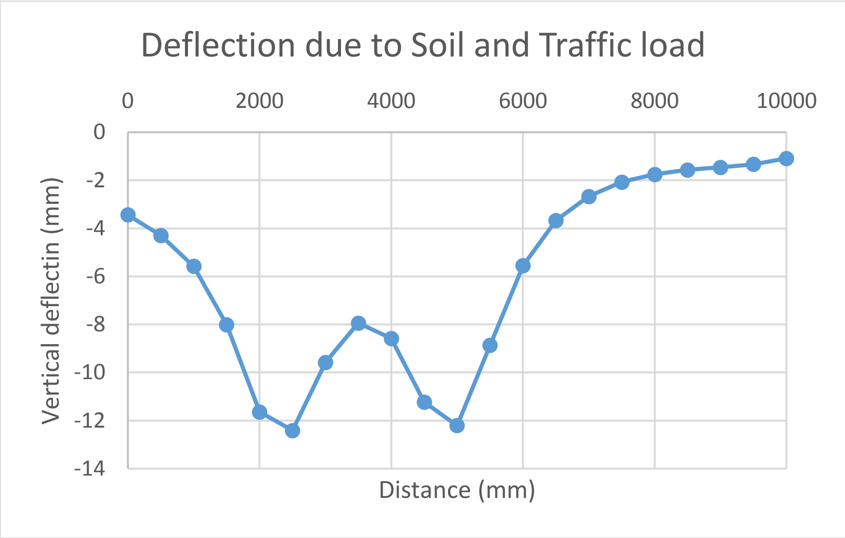


Figure 3 Vertical deflection in the mid-span, distributed along the bridge width direction

The maximum deflection is around 12mm that occurs in the position of traffic load (two point load). According to the design *criteria, the maximum allowable deflection is 1/400 of the span, which is 14 mm in this case. (*criteria—Reference: *"Guide Specifications for Design of FRP PEDSTRIAN BRIDGES",* American Association of State Highway and Transportation Officials) So, the design of FRP culvert can satisfy the requirement of deflection.

Verification of normal stress

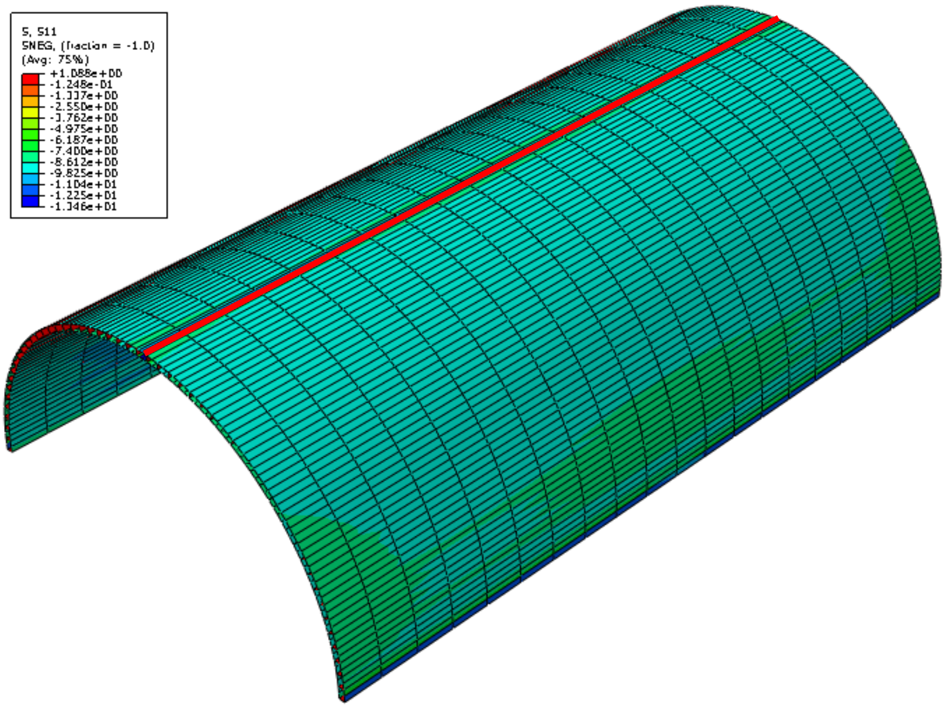


Figure 4 PATH (red line) in the mid-span along the bridge-width-direction, for both top edge and bottom edge

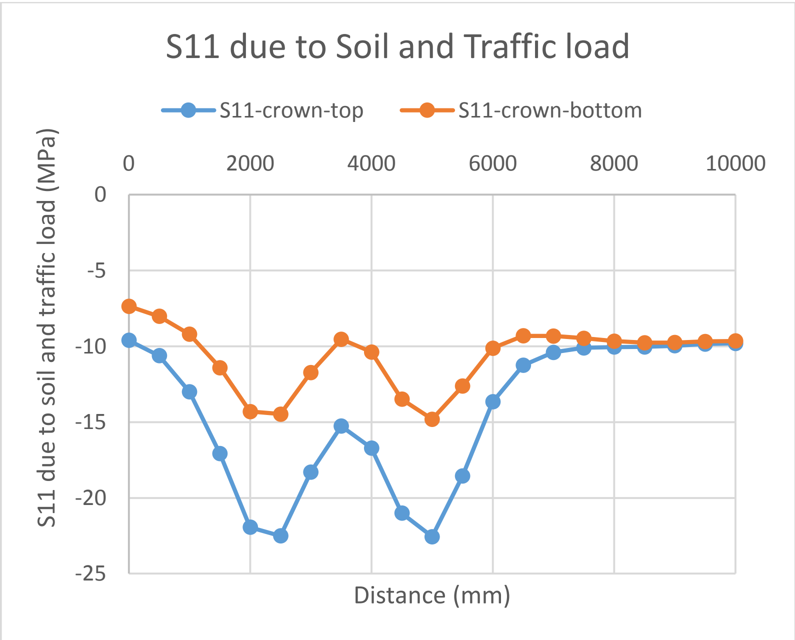


Figure 5 Normal stress (in the span direction) in the mid-span of culvert distributed along the bridge width direction, including both the top edge and the bottom edge (Positive: tension, negative: compression)

In the critical crown section of FRP culvert structure, the maximum normal stress due to soil and traffic load is detected as -22.5 MPa in the bottom edge. The Figure 4 above shows the normal stress in the culvert structure at the mid-span that distributed along the bridge-width direction (red line in Figure 5). The maximum utilization ratio of FRP composite is 23%, see Table 3 below.

Table 3 Maximum utilization ratio of FRP material in the culvert structure

Maximum stress	**[1]Compressive strength**	**Partial factor of FRP material**	**Compressive strength (design value)**	**Utilization ratio**
MPa	MPa	SLS: 1.65; USL: 4.13	MPa	
22.5	414	4.13	100	23%

[1]According to ASM International Handbook (Pultrusion, Composite Volume 21), the tensile strength and compressive strength of the FRP composite (65% fiber volume fraction, or 80% fiber weight fraction) is assumed as 690 MPa and 414 MPa, respectively.

Appendix A-4 FE modeling of FRP culvert bridge-Alternative 2 Filament winding

Material properties and loads

Table 1 Material properties of FRP composite and soil for FRP Alternative 2

[1]Elastic constants	FRP composite by filament winding						Soil		
Design value	E_1	E_2	v_{12}	G_{12}	G_{13}	G_{23}	E	v	ρ
	MPa	MPa		MPa	MPa	MPa	MPa		kg/m^3
In SLS model	24230	4202	0.274	1663	1663	1546	26	0.3	2600
In USL model	9693	1681	0.274	665	665	618	26	0.3	2600

[1]The calculation of elastic constants for FRP composite made by pultrusion, see Appendix A-2.

Table 2 Input data of loads in SLS and ULS model

	Partial factor	Input data in Abaqus
In SLS model		
Self-weight of soil	1.0	Gravity: -9.8 (Component 2)
[1]Traffic load LM2	1.0	Pressure: 0.95 MPa
In ULS model		
Self-weight of soil	1.35	Gravity: -13.2 (Component 2)
Traffic load LM2	1.35	Pressure: 1.28 MPa

[1]Traffic load LM2: Two point loads, each load (200kN) acting on an area of 350 mm*600mm

Modeling in Abaqus

Figure 1 shows:

1. PART-FRP culvert structure, FRP skins (Shell-Extrusion) and Foam core (Soil-Extrusion) are merged
2. PART-surrounding soil (Soil-Extrusion)
3. Mesh-FRP culvert and surrounding soil
4. Vertical deflection under soil and traffic load

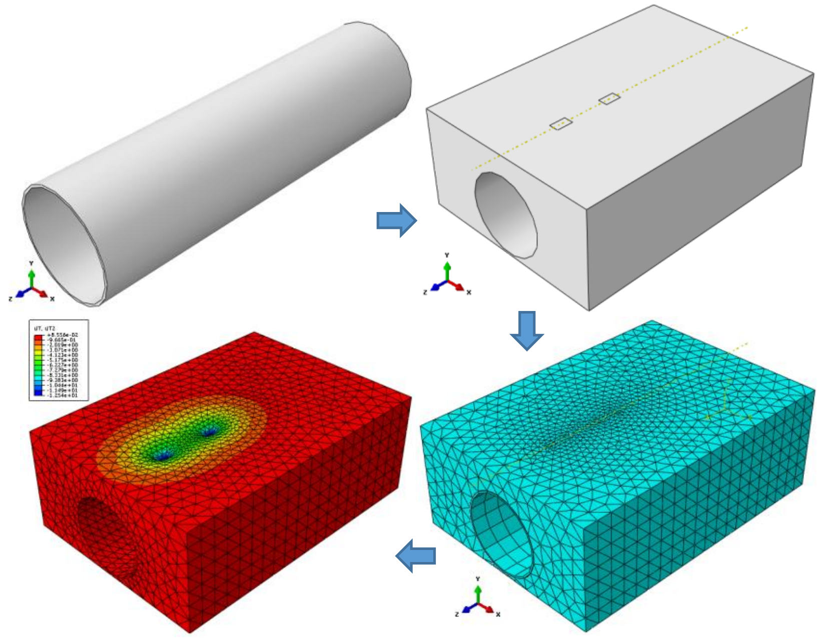


Figure 1 Finite element model in Abaqus

Verification of vertical deflection in the mid-span

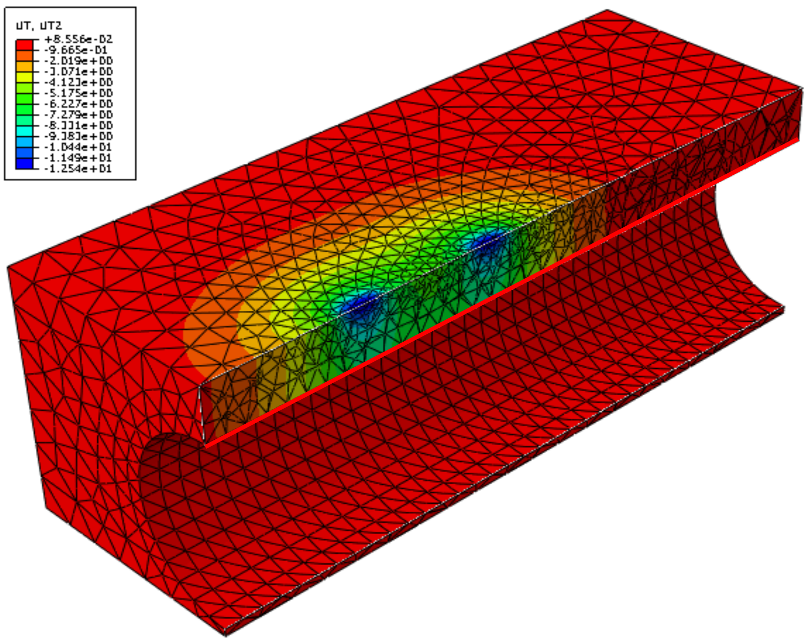


Figure 2 PATH (red line) in the mid-span along the bridge-width-direction

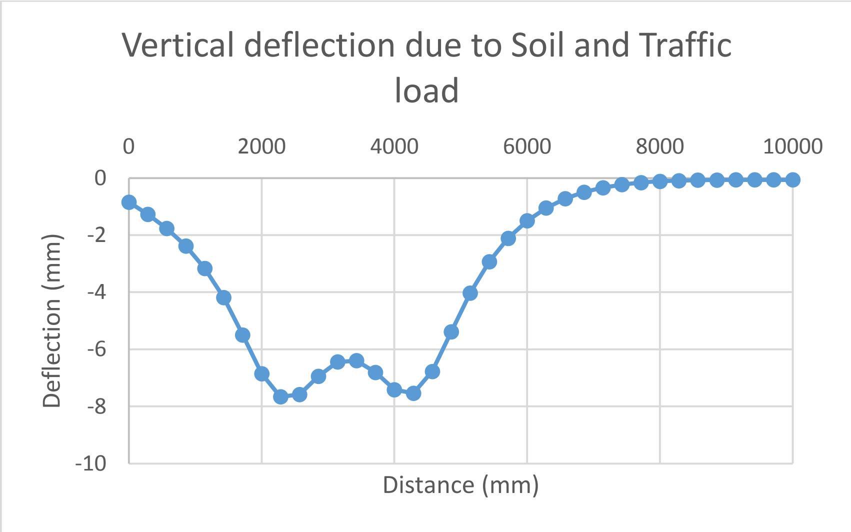


Figure 3 Vertical deflection in the mid-span, distributed along the bridge width direction

The maximum deflection is 7.5 mm that occurs in the position of traffic load (two point load). According to the design *criteria, the maximum allowable deflection is 1/400 of the span, which is 7 mm in this case. (*criteria—Reference: *"Guide Specifications for Design of FRP PEDSTRIAN BRIDGES",* American Association of State Highway and Transportation Officials)

Appendix A-5 FE modeling of FRP culvert bridge-FRP Alternative 3 Vacuum infusion

Material properties and loads

Table 1 Material properties of FRP composite and soil for FRP Alternative 3

[1]Elastic constants	FRP composite by vacuum infusion						Soil		
Design value	E_1	E_2	v_{12}	G_{12}	G_{13}	G_{23}	E	v	ρ
	MPa	MPa		MPa	MPa	MPa	MPa		kg/m^3
In SLS model	22210	3852	0.274	1524	1524	1417	26	0.3	2600
In USL model	8886	1541	0.262	610	610	567	26	0.3	2600
[1]The calculation of elastic constants for FRP composite made by pultrusion, see Appendix A-2.									

Table 2 Input data of loads in SLS and ULS model

	Partial factor	Input data in Abaqus
In SLS model		
Self-weight of soil	1.0	Gravity: -9.8 (Component 2)
[1]Traffic load LM2	1.0	Pressure: 0.95 MPa
In ULS model		
Self-weight of soil	1.35	Gravity: -13.2 (Component 2)
Traffic load LM2	1.35	Pressure: 1.28 MPa
[1]Traffic load LM2: two point loads, each load (200kN) acting on an area of 350 mm*600mm		

Modeling in Abaqus

The figure below shows:

1. PART-Core material of the FRP culvert (Soil-Extrusion)
2. PART-Surrounding soil (Soil-Extrusion)
3. Mesh-FRP culvert structure and surrounding soil
4. Vertical deflection under soil and traffic load

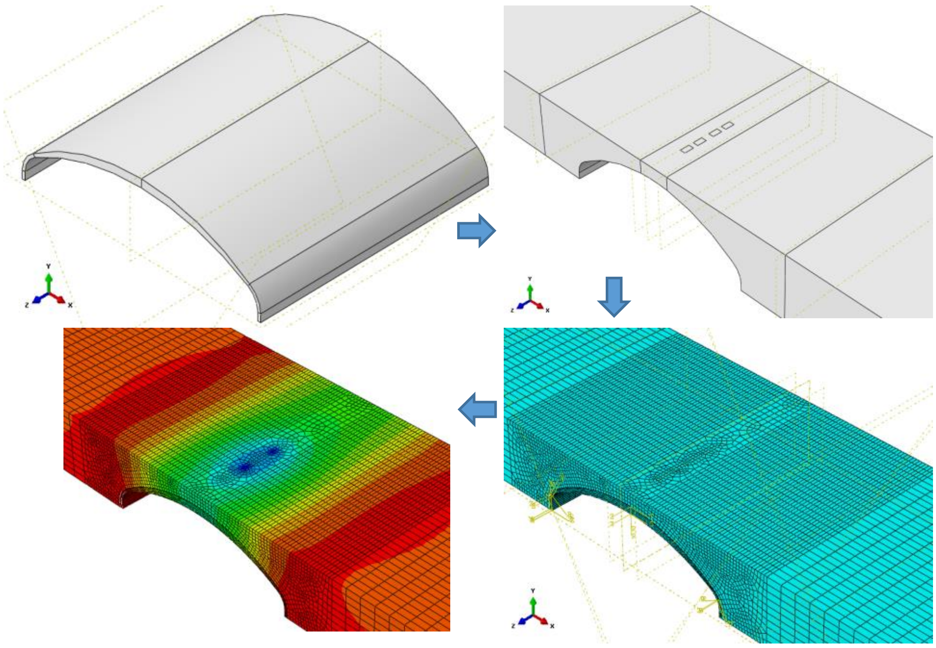


Figure 1 Finite element model in Abaqus

Verification of vertical deflection

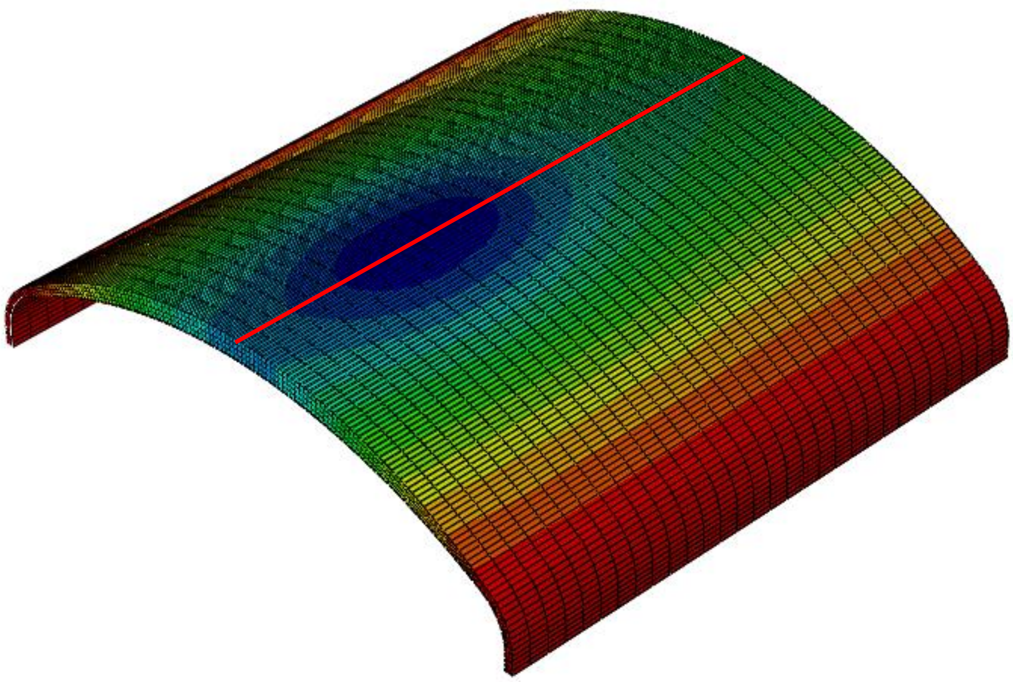


Figure 2 PATH (red line) in the mid-span along the bridge-width-direction

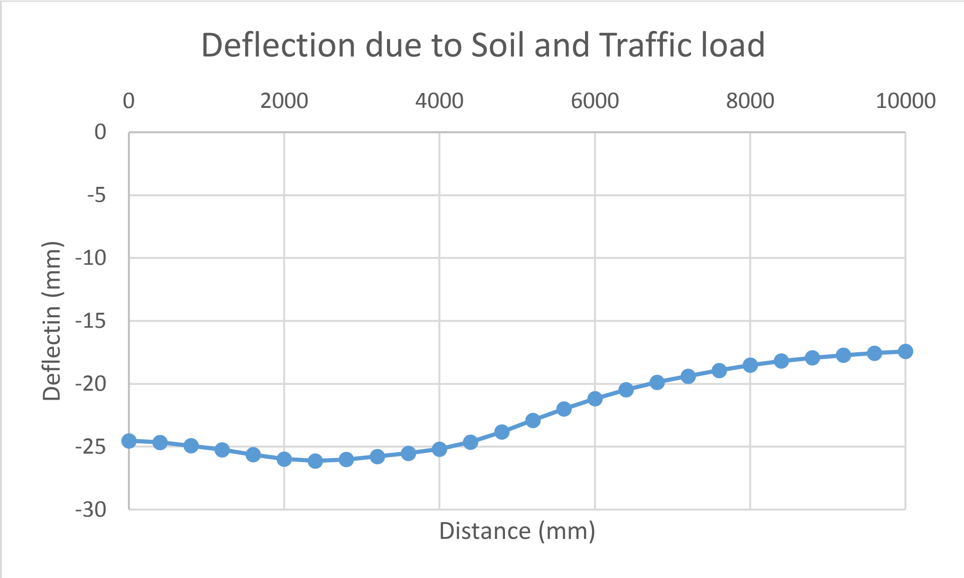


Figure 3 Vertical deflection in the mid-span, distributed along the bridge width direction

The maximum deflection is 26 mm that occurs in the position of traffic load (two point load). According to the design *criteria, the maximum allowable deflection is 1/400 of the span, which is 30 mm in this case. (*criteria—Reference: *"Guide Specifications for Design of FRP PEDSTRIAN BRIDGES"*, American Association of State Highway and Transportation Officials) So, the design of FRP culvert can satisfy the requirement of deflection.

Verification of normal stress

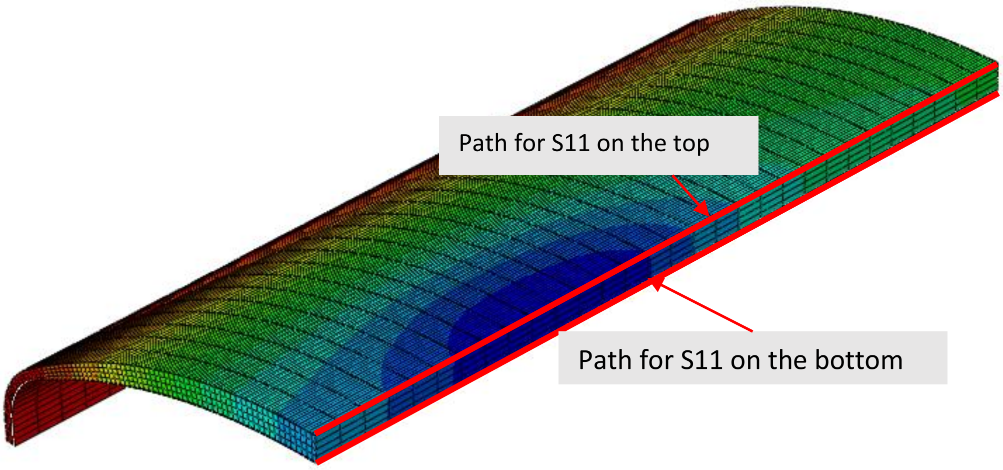


Figure 4 PATH (red line) in the mid-span along the bridge-width-direction, for both top edge and bottom edge

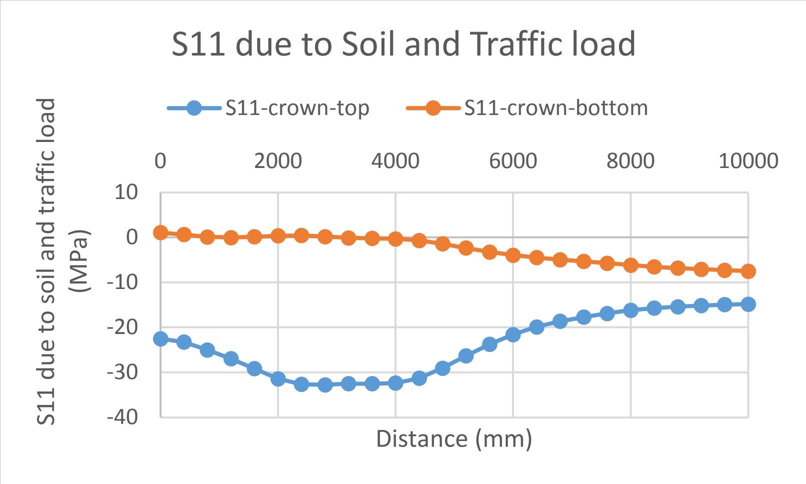


Figure 5 Normal stress in the mid-span of culvert distributed along the bridge width direction, including both the top edge and the bottom edge (Positive: tension, negative: compression)

In the critical crown section of FRP culvert structure, the maximum normal stress due to soil and traffic load is detected as -32.7 MPa in the bottom edge. The Figure 5 above shows the normal stress in the culvert structure at the mid-span that distributed along the bridge-width direction (red line in Figure 4). The maximum utilization ratio of FRP composite is 23%, see Table 3 below.

Table 3 Maximum utilization ratio of FRP material in the culvert structure

Maximum stress	[1]**Compressive strength**	**Partial factor of FRP material**	**Compressive strength (design value)**	**Utilization ratio**
MPa	MPa	SLS: 1.8; USL: 4.5	MPa	
32.7	380	4.13	84.4	38%

[1]According to ASM International Handbook (Pultrusion, Composite Volume 21), the tensile strength and compressive strength of the FRP composite by pultrusion (65% fiber weight fraction) is assumed as 310 MPa and 380 MPa, respectively.

Appendix B-1 Price of FRP culvert structures

1. Price of materials

1.1 Price of fiber and resin

Reference: Carl-Johan Lindholm, DIAB, Oct.14th 2015

Unit price of resin

$$p_r := 90 \frac{SEK}{kg}$$

Polyester: 2 EUR/kg
Vinlyester: 6 EUR/kg
Epoxy: 10 EUR/kg

Unit price of glass fiber

$$p_{f.1} := 15 \frac{SEK}{kg}$$ continuous fiber roving

$$p_{f.2} := 25 \frac{SEK}{kg}$$ 20-35 SEK/kg for woven fabric

Density of glass fiber

$$\rho_f := 2.5 \cdot 10^3 \frac{kg}{m^3}$$

Density of epoxy

$$\rho_r := 1.25 \cdot 10^3 \frac{kg}{m^3}$$

1.2 Price of foam material

Reference: Carl-Johan Lindholm, DIAB, Oct.14th 2015

Unit price of PVC foam in weight

$$p_{foam} := 180 \frac{SEK}{kg}$$ Divinycell H45

Unit price list from DIAB consultant

DIAB, Divinycell H80, 160 SEK/kg, 80 kg/m^3

DIAB, Divinycell H45, 180 SEK/kg, 48 kg/m^3

Density of foam

$$\rho_{foam} := 48 \frac{kg}{m^3}$$ Divinycell H45

Unit price of PVC foam in volume

$$p_{foam.v} := p_{foam} \cdot \rho_{foam} = 8.64 \times 10^{3} \frac{SEK}{m^{3}}$$

1.3 Price of PP honeycomb

Reference: Robin Sun, Holycore Composite Material Co., Sep. 29th 2015

Details of PP honeycomb product

Product from Company Holycore

8 mm cell size

Dimension (L*W*T) 1000mm*1000mm*20mm

Price 60 SEK/m^2 *According to Sales Manager, robin.sun@hzccl.com*

Density 80 kg/m^3

Unit price of PP honeycomb in volume

$$p_{pp.v} := \frac{60SEK}{1000mm \cdot 1000mm \cdot 20mm} = 3 \times 10^{3} \frac{SEK}{m^{3}}$$

Density

$$\rho_{pp} := 80 \frac{kg}{m^{3}}$$

Unit price of PP honeycomb in weight

$$p_{pp.w} := \frac{p_{pp.v}}{\rho_{pp}} = 37.5 \frac{SEK}{kg}$$

2. Price of FRP culvert structures in three alternatives

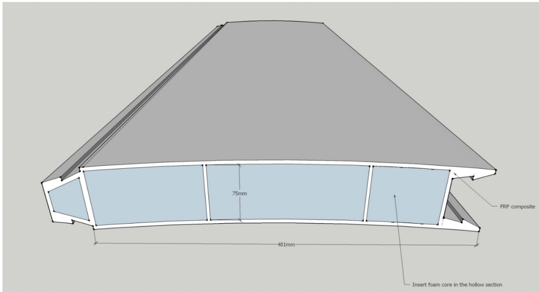
2.1 FRP Alternative 1 by pultrusion

Reference: Lone Døjbak Andersen, Fiberline Composites, Oct.7th 2015

Price offerd by company Fiberline

Unit price of producing the segment by pultrusion

$$p_{1} := 870 \frac{SEK}{m}$$ Including tax, freight and etc.



Total amount in terms of segment length

$L := 10m \cdot 18 \cdot 2 = 360\,m$ 10-meter long for each segment, 36 segments are needed in total

Total price of FRP culvert made by pultrusion

$Culvert_{frp.1} := p_1 \cdot L = 3.132 \times 10^5\ SEK$

A startup cost (0.3 million SEK) is needed if the production volume is not high enough

2.2 FRP Alternative 2 by filament winding

Four FRP sandwich pipes, diameter of each pipe is 2.8 meter

Volume of FRP skins (55% fiber volume fraction)

FRP volume for each segment $V_{frp.1} := \pi \cdot 2.8m \cdot 10m \cdot 5mm \cdot 2 = 0.88 \cdot m^3$

Number of segments needed $n := 4$

$V_{frp} := V_{frp.1} \cdot n = 3.519 \cdot m^3$

Volume of core material

Core volume for each segment $V_{core.1} := \pi \cdot 2.8m \cdot 10m \cdot 55mm = 4.838 \cdot m^3$

$V_{core} := V_{core.1} \cdot n = 19.352 \cdot m^3$

Material cost

Volume of glass fiber $V_f := V_{frp} \cdot 55\% = 1.935 \cdot m^3$

Cost of fiber $cost_f := p_{f.2} \cdot V_f \cdot \rho_f = 1.21 \times 10^5\ SEK$

Volume of resin $V_r := V_{frp} \cdot (1 - 55\%) = 1.583 \cdot m^3$

Cost of resin $cost_r := p_r \cdot V_r \cdot \rho_r = 1.781 \times 10^5\ SEK$

Cost of core material $cost_{foam} := p_{foam} \cdot \rho_{foam} \cdot V_{core} = 1.672 \times 10^{5}\,SEK$

Material cost in total

$$cost_{material} := cost_{f} + cost_{r} + cost_{foam} = 4.663 \times 10^{5}\,SEK$$

Manufacturing and labor cost

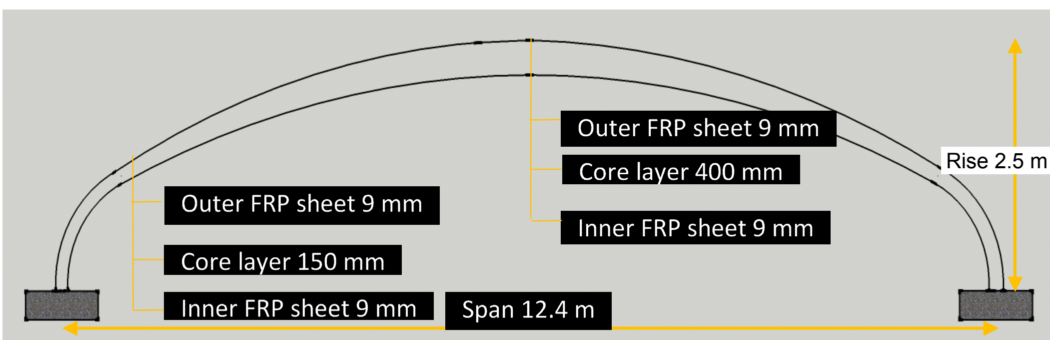
--converted to 1 month work time of 2 workers
--unit price of labor is assumed as 160 SEK per hour in Sweden

$$cost_{labor} := 2 \cdot 30 \cdot 8hr \cdot 160 \frac{SEK}{hr} = 7.68 \times 10^{4}\,SEK$$

Total price of FRP culvert alternative 2

$$culvert_{frp.2} := cost_{material} + cost_{labor} = 5.431 \times 10^{5}\,SEK$$

2.3 FRP Alternative 3 by vacuum infusion



Volume of FRP material

Thickness of FRP laminate $t_{frp} := 9mm + 9mm = 18 \cdot mm$

Surface area $A_{frp} := 14.6m \cdot 10m = 146\,m^{2}$

$V_{frp} := A_{frp} \cdot t_{frp} = 2.628 \cdot m^{3}$ FRP laminate total volume

Volume of glass fiber $V_{f} := V_{frp} \cdot 55\% = 1.445 \cdot m^{3}$

Volume of resin $V_{r} := V_{frp} \cdot (1 - 55\%) = 1.183 \cdot m^{3}$

Volume of core material

Cross-sectinal area $A_{core} := 4.05m^2$

Dimension perpendicular to cross-section $width := 10m$

$V_{core} := width \cdot A_{core} = 40.5 \cdot m^3$

Material cost

Cost of fiber $cost_f := p_{f.1} \cdot V_f \cdot \rho_f = 5.42 \times 10^4\ SEK$

Cost of resin $cost_r := p_r \cdot V_r \cdot \rho_r = 1.33 \times 10^5\ SEK$

PP honeycomb as core material

$cost_{pp} := p_{pp.v} \cdot V_{core} = 1.215 \times 10^5\ SEK$

PVC foam Divinycell H45 as core material

$cost_{foam} := p_{foam} \cdot \rho_{foam} \cdot V_{core} = 3.499 \times 10^5\ SEK$

Total material cost

$cost_{material.pp} := cost_f + cost_r + cost_{pp} = 3.087 \times 10^5\ SEK$

$cost_{material.foam} := cost_f + cost_r + cost_{foam} = 5.372 \times 10^5\ SEK$

Manufacturing and labor cost

--converted to 1 month work time of 2 workers
--unit price of labor is assumed as 160 SEK per hour in Sweden

$cost_{labor} := 2 \cdot 30 \cdot 8hr \cdot 160 \frac{SEK}{hr} = 7.68 \times 10^4\ SEK$

Price of FRP culvert alternative 3

$culvert_{FRP.3.pp} := cost_{material.pp} + cost_{labor} = 3.855 \times 10^5\ SEK$

$culvert_{FRP.3.foam} := cost_{material.foam} + cost_{labor} = 6.14 \times 10^5\ SEK$

Appendix B-2 *Investment cost of Alternative FRP

*Investment cost refers to the agency cost paid in the investment phase

1. Strategy of calculating the investment cost of FRP culvert bridge

Investment cost of steel culvert bridge

$INV_{steel} := 7448069SEK$ According to the record in BaTMan's database, bridge constructed in 2008

Investment cost of FRP cuvlert bridge

$INV_{FRP} := INV_{steel} + Diff_1 + Diff_2$

$Diff_1$ -- The price difference between FRP culvert structure and SuperCor® steel culvert

Diff2 -- The price difference due to reduced thickness of soil cover above the FRP culvert

2. Calculation of $Diff_1$

The price of the SuperCor steel culvert structure

Refence: Email from Lars Hansing, ViaCon, Jun. 30th 2015

$W\_plates := 18400kg$ Total amount of steel plates SC-54B, Viacon

$P := 31 \frac{SEK}{kg}$ Unit price of steel plates

$Culvert\_material := W\_plates \cdot P = 5.704 \times 10^5 SEK$ Fasteners cost included

$Labor := 160 \frac{SEK}{hr}$ Unit price of labor

$Time := 160hr$ 4 days, 4 workers, 10 hour per day

$Culvert\_labor := Labor \cdot Time = 2.56 \times 10^4 SEK$ Labor cost of assembly

$Culvert_{steel} := Culvert\_material + Culvert\_labor$

$Culvert_{steel} = 5.96 \times 10^5 SEK$

The price of FRP culvert structure (FRP culvert by vacuum infusion using PP honeycomb)

$Culvert_{FRP} := 385500SEK$ Appendix B-1

The price difference between FRP culvert structure and SuperCor® steel culvert

$Diff_1 := Culvert_{FRP} - Culvert_{steel} = -2.105 \times 10^5 SEK$

3. Calculation of $Diff_2$

$t := -250mm$ Reduced thickness of soil cover above FRP culvert

$L := 27m$ Bridge length

$W := 10m$ Bridge width

$V_{soil} := L \cdot W \cdot t = -67.5 \cdot m^3$ Reduction of soil cover in volume

$P_{cmp} := \frac{300SEK}{m^3}$ Unit price of soil compaction activity
Reference: Thomas Leggo Lechner, NCC, Oct.6th 2015

$P_{soil} := 100 \frac{SEK}{ton}$ Unit price of backfill--förstärkningslager 0-90 mm, transportation cost included

$\rho_{soil} := 1.7 \frac{ton}{m^3}$ Density of backfill

$Diff_2 := P_{cmp} \cdot V_{soil} + P_{soil} \cdot \rho_{soil} \cdot V_{soil} = -31725\,SEK$

4. Investment cost

$Diff_1 + Diff_2 = -2.422 \times 10^5\,SEK$

$INV_{FRP} := INV_{steel} + Diff_1 + Diff_2$

$INV_{FRP} = 7.206 \times 10^6\,SEK$ Please note that the user cost during the investment phase is not included.

Appendix B-3 O&M cost of Alternative Steel

Table 1 Quantification of the steel culvert bridge 20-1335-1

	Unit	Quantity	Note
Total bridge length	m	27	Same with parapet length
Effective bridge width	m	6.9	Road width
Main load-bearing structure length	m	12.4	Span of culvert structure
Total bridge width	m	10	Width of culvert structure
Total bridge area	m^2	270	
Inner surface area of culvert structure	m^2	150	
Slope and cones area	m^2	243	
Asphalt pavement	m^2	186.3	
Railings	m	54	
Parapets' length	m	54	Same with railing length

Table 2 Agency cost of activities during the O&M phase

Alternative Steel	**Time**		**Reference Target Quantity**			**Unit cost**	**Agency cost**
	Interval	Fixed year	%	of	Unit	SEK	per time
Inspection							
Superficial inspection	1		100	Total bridge area	m^2	12	3240
General inspection	3		100	Total bridge area	m^2	40	10800
Major inspection	6		100	Total bridge area	m^2	70	18900
Operation and maintenance							
Cleaning vegetation and other impurities from the bridge	1		10	Total bridge area	m^2	7	189
Maintenance of paving, surface finishes and lining	2		10	Pavement area	m^2	600	11178
Maintenance of parapets, and railings	2		10	Railing length	m	250	1350
Repair, replacement and rehabilitation							
Slopes and cones dressing	25		10	Slope and cones area	m^2	1600	38880
Shotcrete--repair of corrugated steel sheets		30	50	Culvert sheet's inner surface area	m^2	2500	287500
Extra cost due to shotcrete --water deviation, culvert inner surface cleaning and preparation *(according to BaTMan's helpdesk, email on July 2nd 2015)*						100000	

Railings repainting	25		20	Railing length	m	1600	17280
Railings replacement		50	40	Railing length	m	2800	60480

Table 3 O&M cost of Alternative steel (including agency cost and user cost during the O&M phase)

Alternative Steel	**Time**		**Agency cost**	**User cost**	**In total**	**Net present value (2008)**
	Interval	Fixed year	per time	per time	per time	
Inspection						
Superficial inspection	1		3 240	0	3 240	77 486
General inspection	3		10 800	0	10 800	82 435
Major inspection	6		18 900	0	18 900	67 892
Operation and maitenance						
Cleaning vegetation and other impurities from the bridge	1		189	0	189	4 520
Maintenance of paving, surface finishes and lining	2		11 178	52	11 230	131 170
Maintenance of parapets, and railings	2		1 350	26	1 376	16 074
Repair, replacement and rehabilitation						
Slopes and cones dressing	25		38 880	0	38 880	22 108
Shotcrete		30	287 500	52	287 552	88 658
Railings repainting	25		17 280	26	17 306	9 841
Railings replacement		50	60 480	26	60 506	8 514
						In total
Net Present Value (NPV)						508 698
Equivalent Annual Cost (EAC)						21 271

Appendix B-4 O&M cost of Alternative FRP

Table 1 Quantification of the FRP culvert bridge in Alternative FRP (same to the Alternative Steel 20-1335-1)

Alternative FRP	Unit	Quantity	Note
Total bridge length	m	27	Same with parapet length
Effective bridge width	m	6.9	Road width
Main load-bearing structure length	m	12.4	Span of culvert structure
Total bridge width	m	10	Width of culvert structure
Total bridge area	m^2	270	
Inner surface area of culvert structure	m^2	150	
Slope and cones area	m^2	243	
Asphalt pavement	m^2	186.3	
Railings	m	54	
Parapets' length	m	54	Same with railing length

Table 2 Agency cost of activities during the O&M phase

Alternative FRP	Time		Reference Target Quantity			Unit cost	Agency cost
	Interval	Fixed year	%	of	Unit	SEK	per time
Inspection							
Superficial inspection	1		100	Total bridge area	m^2	12	3240
General inspection	3		100	Total bridge area	m^2	40	10800
Major inspection	6		100	Total bridge area	m^2	70	18900
Operation and maintenance							
Cleaning vegetation and other impurities from the bridge	1		10	Total bridge area	m^2	7	189
Maintenance of paving, surface finishes and lining	2		10	Pavement area	m^2	600	11178
Maintenance of parapets, and railings	2		10	Railing length	m	250	1350
Repair, replacement and rehabilitation							
Slopes and cones dressing	25		10	Slope and cones area	m^2	1600	38880
Railings repainting	25		20	Railing length	m	1600	17280
Railings replacement		50	40	Railing length	m	2800	60480

Table 3 O&M cost of Alternative FRP (including agency cost and user cost during the O&M phase)

Alternative FRP	Time		Agency cost	User cost	In total	Net present value (2008)
	Interval	Fixed year	per time	per time	per time	
Inspection						
Superficial inspection	1		3 240	0	3 240	79 396
General inspection	3		10 800	0	10 800	84 713
Major inspection	6		18 900	0	18 900	69 585
Operation and maitenance						
Cleaning vegetation and other impurities from the bridge	1		189	0	189	4 631
Maintenance of paving, surface finishes and lining	2		11 178	52	11 230	134 681
Maintenance of parapets, and railings	2		1 350	26	1 376	16 504
Repair, replacement and rehabilitation						
Slopes and cones dressing	25		38 880	0	38 880	22 108
Railings repainting	25		17 280	26	17 306	9 841
Railings replacement		50	60 480	26	60 506	8 514
						In total
Net Present Value (NPV)						429 973
Equivalent Annual Cost (EAC)						17 546

Appendix B-5 Disposal cost of Alternative Steel and Alternative FRP

The strategy of calculating disposal cost is described in the report Section 6.3.3.

The disposal cost of a culvert bridge in general is assumed to be 10 percent of the investment cost, which is 17100 SEK/m^2 according to the BaTMan's helpdesk. The assumption is made according to:

1) Håkan's work (Ref. [38]), the disposal cost is assumed as 10 percent of the investment cost of the project.
2) In Safi's paper (Ref. [40]), the unit investment cost of culvert bridge is assumed as 5 398 SEK/m^2, and the disposal unit price is calculation as 1 500 SEK/m^2, about 10 percent of the invest cost.

The unit price of recycling the culvert structure is -500 SEK/ton for steel and 1100 SEK/ton for FRP material (Ref. [41]).

Table 1 Calculation of disposal cost of two alternatives

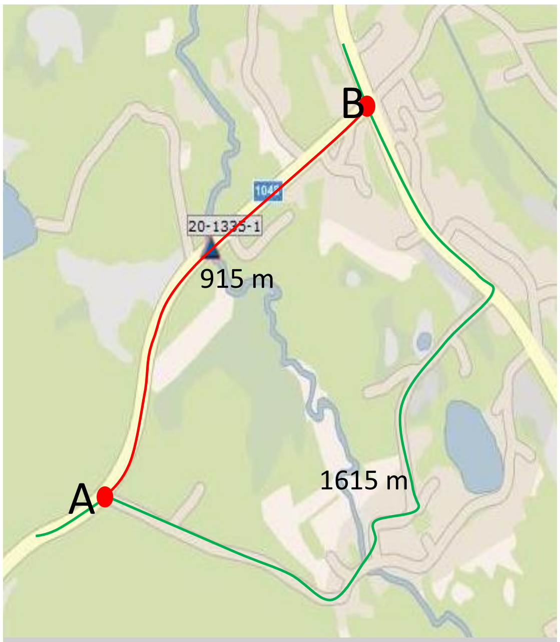
Disposal cost	Demolition and landscape in general			Recycling the culvert structure		
	Total bridge area	[1]Unit price	Cost 1	Weight	[2]Unit price	Cost 2
	m2	SEK/m^2	SEK	ton	SEK/ton	SEK
Alternative Steel	270	1710	461700	18,4	-500	-9200
Alternative FRP	270	1710	461700	7,6	1100	8316

[1]Unit price—Ref.[38, 40]
[2]Unit price—Ref.[41]

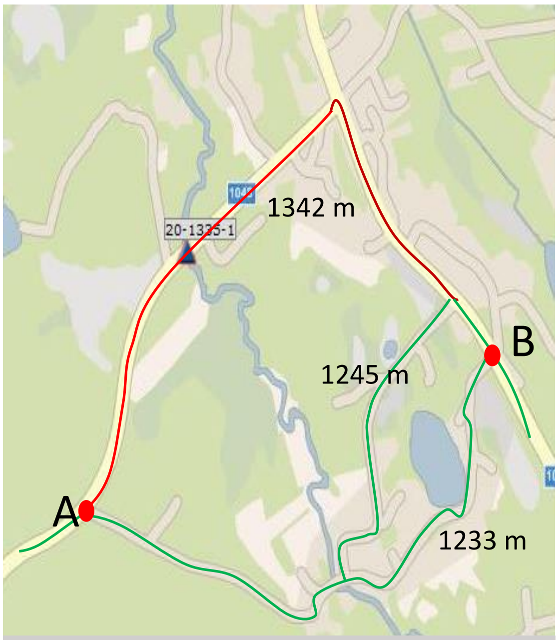
Table 2 Results of disposal cost of two alternative

Disposal cost	Cost 1	Cost 2	In total		NPV(2008)	EAC
	SEK	SEK	SEK	SEK/m^2	SEK	SEK
Alternative Steel	461700	-9200	452500	1676	19631	821
Alternative FRP	461700	8316	470016	1741	9306	380

Appendix B-6 User cost of Alternative Steel and Alternative FRP



Case 1: point A ←→point B North, 50% of ADT



Case 2: point A ←→point B South, 50% of ADT

Figure 1 Detour due to traffic block during the investment phase

Table 1 User cost during investment phase due to traffic block

User cost during investment phase	**Car**	**Truck**	**Length of detour**	**Normal length**	**Normal Speed**	**User cost per day**	[1]**Traffic blocked**	[1]**In total**
Detour due to traffic block			meter	meter	km/h	SEK/day	day	SEK
Siktån-Rörbäcksnäs North (Figure 1-Case 1)	68	5	1650	950	50	184	30	5507
Siktån-Rörbäcksnäs South (Figure 1-Case 2)	68	5	1245	1342	User cost in this case can be neglected.			

[1] The traffic-blocked period is assumed to be 30 days for both Alternative Steel and Alternative FRP. So, the alternatives' total user cost during investment phase are the same amount.

Table 2 User cost of activities during O&M phase due to work zone

User cost during O&M phase	**Car**	**Truck**	**Work zone length**	**Normal Speed**	**Reduced speed**	**User cost per day**	[1]**Traffic disturbed**	[2]**User cost**
			meter	km/h	km/h	SEK/day	day	SEK
Traffic disturb due to work zone	136	10	200	50	40	26	1 or 2	--

[1]Traffic disturbed time that required for different activities during O&M phase is described in Chapter 4.4 User cost.
[2]User cost of each activity is included in the O&M cost of alternatives, see Appendix B-3 for Alternative steel and Appendix B-4 for Alternative FRP.

Appendix B-7 LCC results of Alternative Steel and Alternative FRP

Table 1 Introduction of alternatives for LCC analysis

Alternatives for LCC analysis	Alternative Steel	Alternative FRP
Replacement strategy	Steel culvert bridge	[1]FRP culvert bridge
Design service life, year	80	100
Discount rate	4%	

[1]FRP culvert bridge refers to the design based on the FRP alternative 3 with PP honeycomb. It influences the price of FRP culvert structure as input data in the LCC analysis. More details of FRP culvert price can be found in Appendix B-1.

Table 2 LCC analysis results expressed in NPV and EAC.

Cost during life-cycle	Alternative Steel	Alternative FRP			
	Results in NPV (2008)				
[1]Investment cost	7 453 576	7 207 351			
[2]O&M cost	508 698	429 973			
[3]Disposal cost	19 585	9 307			
Total LCC	7 981 858	7 646 631			
	Results in EAC		**Annual Saving**	**[4]Saving ratio**	**Net Saving**
Investment cost	311 664	294 118	17 547	6%	429 985
O&M cost	21 271	17 546	3 724	21%	91 266
Disposal cost	819	380	439	116%	10 761
Total LCC	333 754	312 044	21 710	7%	532 012

[1]Investment cost—Cost during the investment phase, and both agency cost and user cost are included.
[2]O&M cost—cost during the O&M phase, and both agency cost and user cost are included.
[3]Disposal cost—cost paid by agency at the end of service life.
[4]Saving ratio-- the ratio of annual saving to EAC of the cost-efficient alternative, which is Alternative FRP in the case study according to the LCC results.

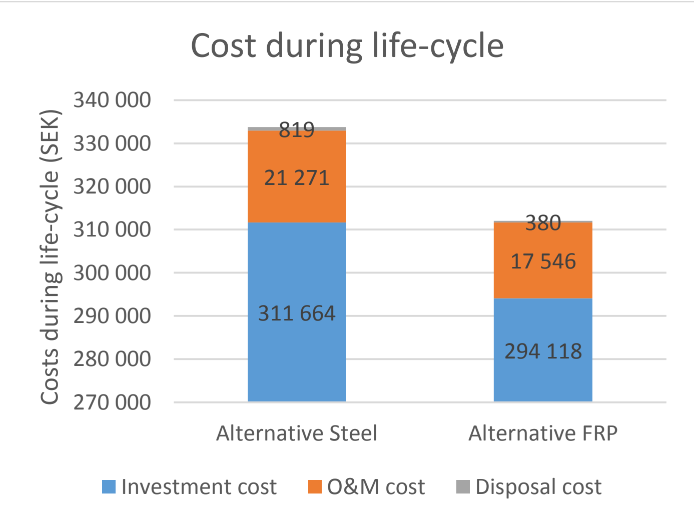


Figure 1 Comparison of the LCC results of the alternatives

Appendix C Sensitivity analysis

The uncertainty of important parameters in the LCC analysis is investigated in the sensitivity analysis. They include:

1) The discount rate, see results in Table 1
2) The ADT volume over the bridge, see results in Table 2
3) The price of FRP culvert structure, see results in Table 3
4) Expected life span of FRP culvert bridge, see results in Table 4
5) The corrugated area of steel culvert bridge during service life, see results in Table 5
6) Reduced thickness of soil cover over the FRP culvert structure , see results in Table 6

Table 1 Sensitivity analysis of discount rate

Discount rate		**Total LCC (NPV 2008)**		**Total LCC (EAC)**			
		Alternative Steel	Alternative FRP	Alternative Steel	Alternative FRP	Annual saving	Saving ratio
Default value	4%	7 981 858	7 646 631	333 754	312 044	21 710	6,5%
Range	1%	8 897 000	8 541 682	162 093	135 520	26 573	16,4%
	2%	8 433 619	8 056 608	212 196	186 935	25 260	11,9%
	3%	8 156 513	7 797 237	270 076	246 757	23 320	8,6%
	4%	7 981 858	7 646 631	333 754	312 044	21 710	6,5%
	5%	7 866 214	7 552 188	401 410	380 503	20 907	5,2%
	6%	7 786 187	7 488 867	471 629	450 660	20 969	4,4%
	7%	7 728 652	7 443 994	543 429	521 681	21 748	4,0%
	8%	7 685 928	7 410 744	616 180	593 129	23 051	3,7%

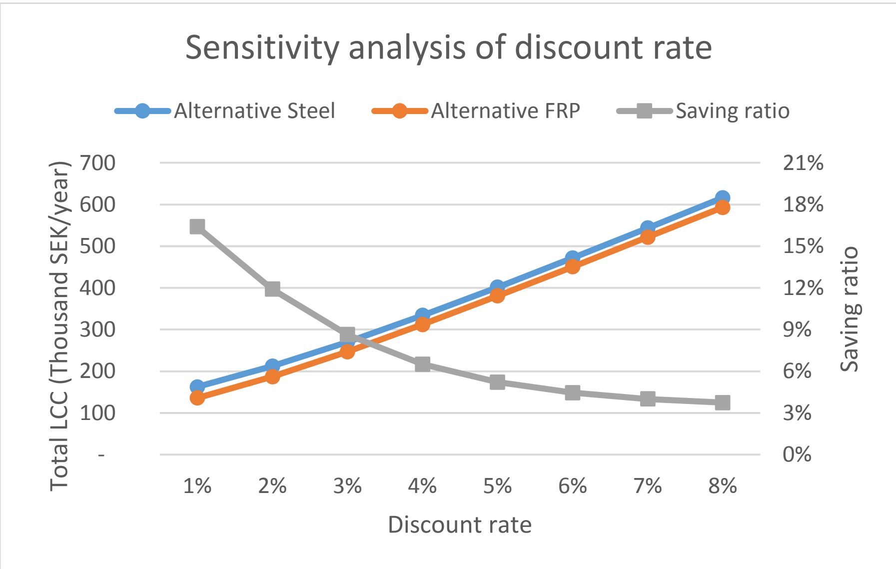


Figure 1 Impact of discount rate on total LCC and saving ratio

Table 2 Sensitivity analysis of ADT volume

ADT volume		Total LCC (NPV 2008)		Total LCC (EAC)			
		Alternative Steel	Alternative FRP	Alternative Steel	Alternative FRP	Annual saving	Saving ratio
Default value	146	7 981 858	7 646 631	333 754	312 044	21 710	7,0%
Range	100	7 979 823	7 644 593	333 669	311 961	21 708	7,0%
	200	7 984 248	7 649 023	333 854	312 141	21 713	7,0%
	400	7 993 097	7 657 884	334 224	312 503	21 721	7,0%
	800	8 010 796	7 675 606	334 964	313 226	21 738	6,9%
	1 600	8 046 194	7 711 050	336 444	314 673	21 772	6,9%
	3 200	8 116 990	7 781 938	339 404	317 565	21 839	6,9%
	6 400	8 258 581	7 923 714	345 325	323 351	21 974	6,8%
	12 800	8 541 763	8 207 265	357 166	334 922	22 244	6,6%
	25 600	9 108 128	8 774 368	380 848	358 064	22 784	6,4%

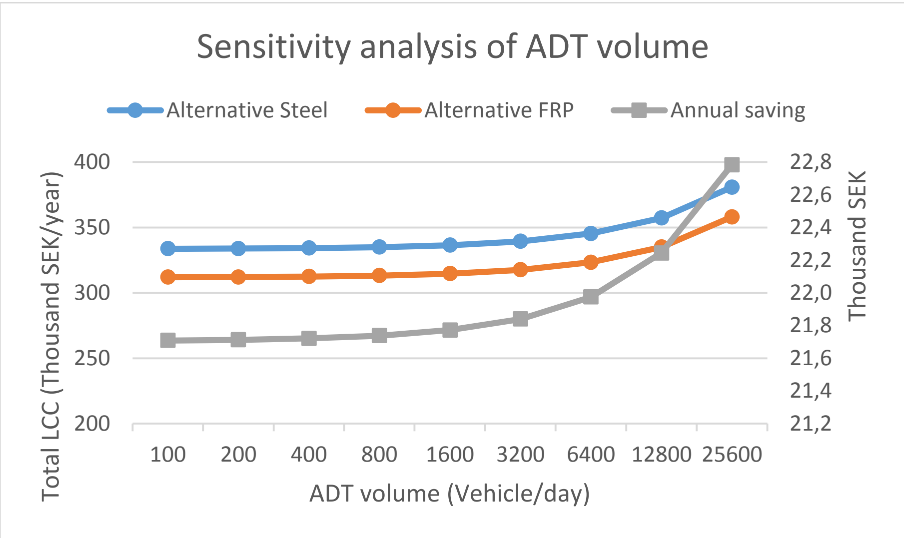


Figure 2 Impact of ADT volume on the total LCC and annual saving

Table 3 Sensitivity analysis of FRP culvert price

FRP culvert price		**Total LCC (NPV 2008)**		**Total LCC (EAC)**			
	SEK	Alternative Steel	Alternative FRP	Alternative Steel	Alternative FRP	Annual saving	Saving ratio
Default value	385 500	7 981 858	7 646 631	333 754	312 044	21 710	7,0%
Range	300 000	7 981 858	7 561 131	333 754	308 555	25 199	8,2%
	400 000	7 981 858	7 661 131	333 754	312 635	21 119	6,8%
	500 000	7 981 858	7 761 131	333 754	316 716	17 038	5,4%
	600 000	7 981 858	7 861 131	333 754	320 797	12 957	4,0%
	700 000	7 981 858	7 961 131	333 754	324 878	8 876	2,7%
	800 000	7 981 858	8 061 131	333 754	328 959	4 795	1,5%
	900 000	7 981 858	8 161 131	333 754	333 039	715	0,2%
	1 000 000	7 981 858	8 261 131	333 754	337 120	-3 366	-1,0%
	1 100 000	7 981 858	8 361 131	333 754	341 201	-7 447	-2,2%
	1 200 000	7 981 858	8 461 131	333 754	345 282	-11 528	-3,3%

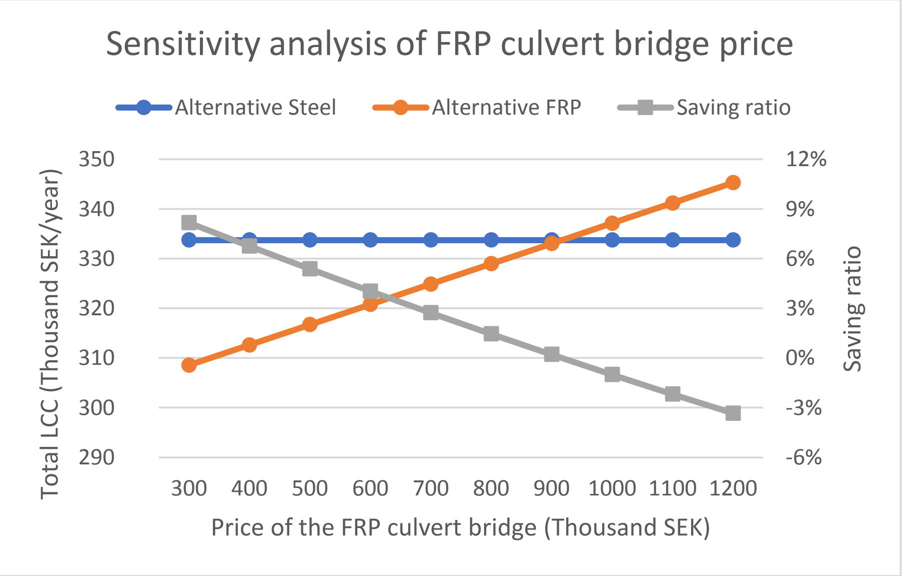


Figure 3 Impact of FRP culvert structure price on the investment cost and saving ratio

Table 4 Sensitivity analysis of FRP culvert bridge life span

Life span of FRP culvert		**Total LCC (NPV 2008)**		**Total LCC (EAC)**			
	year	Alternative Steel	Alternative FRP	Alternative Steel	Alternative FRP	Annual saving	Saving ratio
Default value	100	7 981 858	7 646 631	333 754	312 044	21 710	7,0%
Range	50	7 981 858	7 641 452	333 754	355 711	-21 957	-6,2%
	60	7 981 858	7 645 629	333 754	337 951	-4 197	-1,2%
	70	7 981 858	7 645 617	333 754	326 812	6 942	2,1%
	80	7 981 858	7 647 784	333 754	319 785	13 969	4,4%
	90	7 981 858	7 646 634	333 754	315 101	18 653	5,9%
	100	7 981 858	7 646 631	333 754	312 044	21 710	7,0%
	110	7 981 858	7 647 497	333 754	310 047	23 707	7,6%

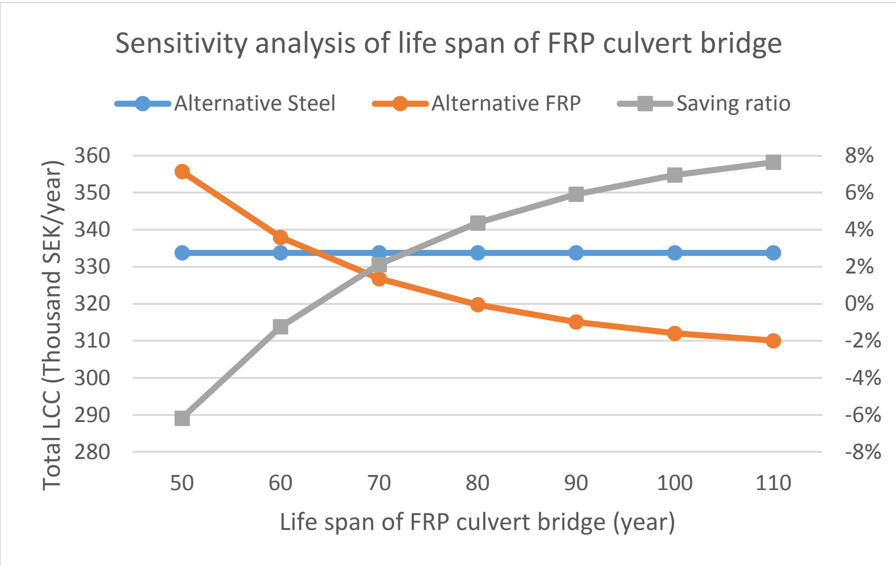


Figure 4 Impact of FRP culvert bridge's life span on the total LCC and saving ratio

Table 5 Sensitivity analysis of shotcrete activity in the steel culvert bridge

Shotcrete activity		**Total LCC (EAC)**		**O&M cost (EAC)**			
		Alternative Steel	Alternative FRP	Alternative Steel	Alternative FRP	Annual saving	Saving ratio
Default value	50%	333 754	312 044	21 271	17 546	3 724	21%
Range	10%	331 820	312 044	19 337	17 546	1 791	10%
	20%	332 304	312 044	19 820	17 546	2 274	13%
	30%	332 787	312 044	20 304	17 546	2 757	16%
	40%	333 271	312 044	20 787	17 546	3 241	18%
	50%	333 754	312 044	21 271	17 546	3 724	21%
	60%	334 237	312 044	21 754	17 546	4 208	24%
	70%	334 721	312 044	22 238	17 546	4 691	27%
	80%	335 204	312 044	22 721	17 546	5 175	29%
	90%	335 688	312 044	23 205	17 546	5 658	32%
	100 %	336 171	312 044	23 688	17 546	6 142	35%

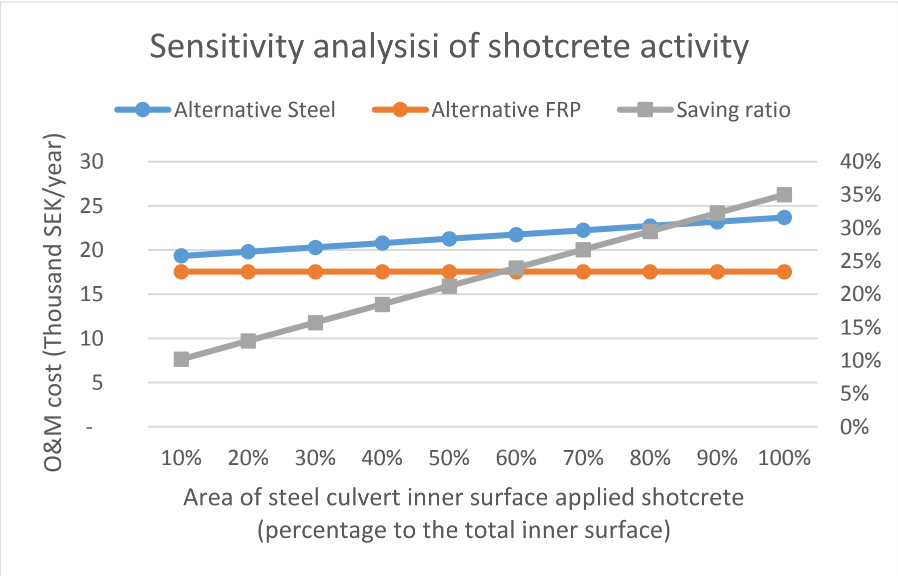


Figure 5 Impact of shotcrete activity the O&M cost and saving ratio

Table 6 Sensitivity analysis of soil cover thickness

Soil cover thickness		Investment cost (NPV)		Investment cost (EAC)			
	mm	Alternative Steel	Alternative FRP	Alternative Steel	Alternative FRP	Annual saving	Saving ratio
Default value	750	7 453 576	7 207 351	311 664	294 118	17 547	6,0%
Range	250	7 453 576	7 143 901	311 664	291 528	20 136	6,9%
	500	7 453 576	7 175 626	311 664	292 823	18 841	6,4%
	750	7 453 576	7 207 351	311 664	294 118	17 547	6,0%
	1 000	7 453 576	7 239 076	311 664	295 412	16 252	5,5%
	1 250	7 453 576	7 270 801	311 664	296 707	14 958	5,0%
	1 500	7 453 576	7 302 526	311 664	298 001	13 663	4,6%

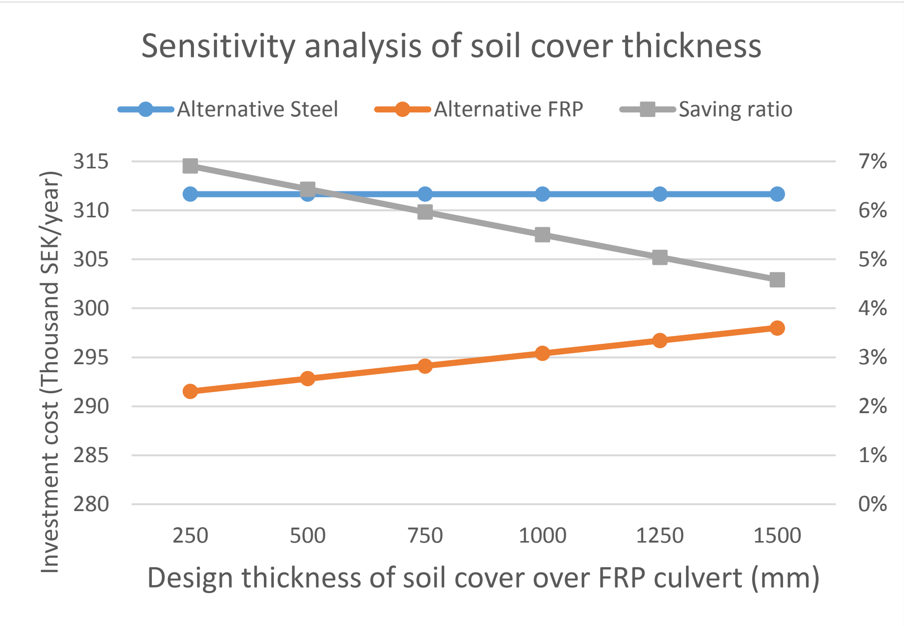


Figure 6 Impact of reduced soil cover thickness on the investment cost and saving ratio