CHALMERS
UNIVERSITY OF TECHNOLOGY

FIBER REINFORCED POLYMER CULVERT BRIDGES – A FEASIBILITY STUDY FROM STRUCTURAL AND LIFE CYCLE COST POINTS OF VIEW

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ABOUT ME

MY RESEARCH

- Fiber reinforced polymer (FRP) composites

  → *Repair and strengthening (steel, concrete, timber)*

  → *Material characterization, testing and simulation*

  → *Durability of FRP structures*

  → *FRP structures – ABC (design, modularization, standardization, connections)*

- Timber and steel structures (stability & fatigue)
- Reuse of decommissioned/EoL FRP parts (e.g. turbine blades)
- Bio-composites

NyTeknik

Premium / Automation / Digitalisering / Energi / Fordon / Startup / Ingenjörskarriär / Lediga j

OPINION

Sverige rostar för 90 miljarder

2004-01-22 07:55 0 kommentarer

Dyrbart förfall

Det här är en debattartikel. Åsikterna som framförs är skribentens egna.

Kostnader för korrosion uppgår varje år till runt 90 miljarder kronor i Sverige. Satsar vi på forskning och utveckling av korrosionsskyddsteknik kan kostnaderna minskas med 25–30 procent. Att staten valt att skära ned anslagen till forskning på korrosion är därför anmärkningsvärt, skriver Korrosionsinstitutets vd, Björn Linder.

There exist about 617,000 bridges across the United States of which:

- 42% are at least 50 years old (avg. 44 years),
- 8% (50,000 bridges) are structurally deficient and accommodate 178 million trips every day.
- Backlog of bridge repair is $125 b
- Annual spending needs to be increased from $14.4b to $22.7b to catch up (58% ↑)

(www.infrastructurereportcard.org)

CULVERT BRIDGES

- Road and railway infrastructure rely on culverts
- Definition of culvert bridge (>8')
- 4500 culvert bridges in Sweden

Andersson et al. 2012

COLLAPSE CASES

OVERVIEW

- History of the culvert (bridges)
- Structural system
- Failure modes and maintenance
- FRP as an alternative building material
- Feasibility of FRP culvert bridges (behavior&cost)
- Conclusions
- Q&A

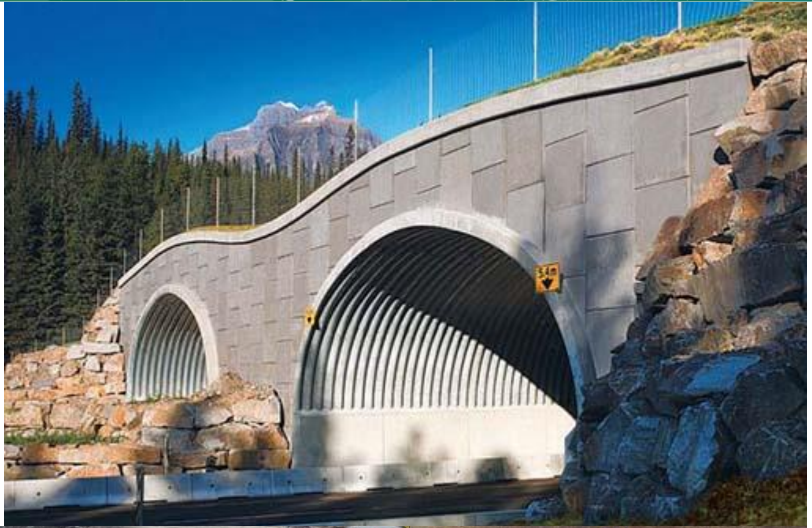
CULVERT BRIDGES

1890s
CMP, patented in by James Watson and Stanley Simpson

1930s
Merlin Spangler standardized the installation

1950s
Became very popular in the US (Federal highway act 1956)

1970s
FHWA proposed a rational design method

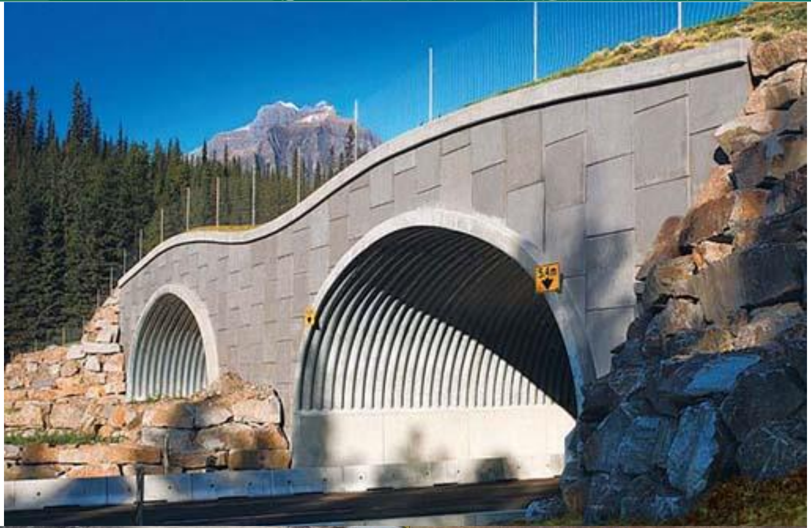


Source: BaTMan

CULVERT BRIDGES

+ Easy production
+ Cost efficiency
+ Geometric adaptability
+ Rapid construction
+ Aesthetics

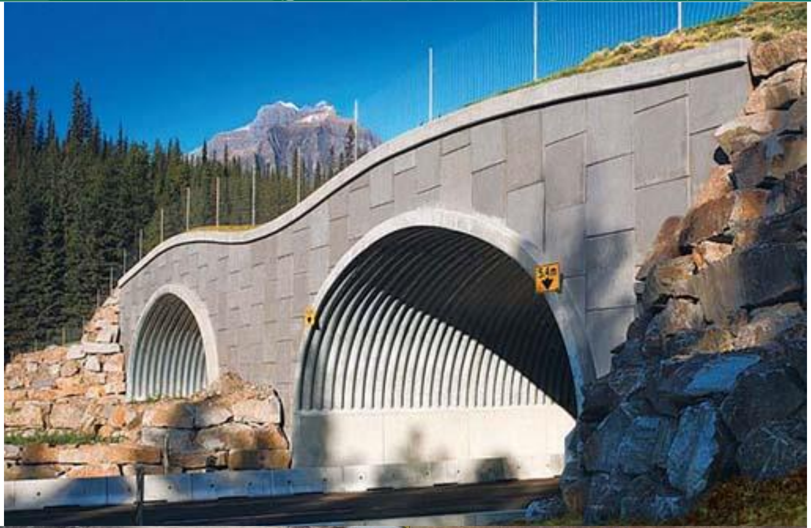
- Highly reliant on soil-structure inter.
- Catastrophic collapse
- Very costly to replace



Source: BaTMan

DESIGN ASPECTS

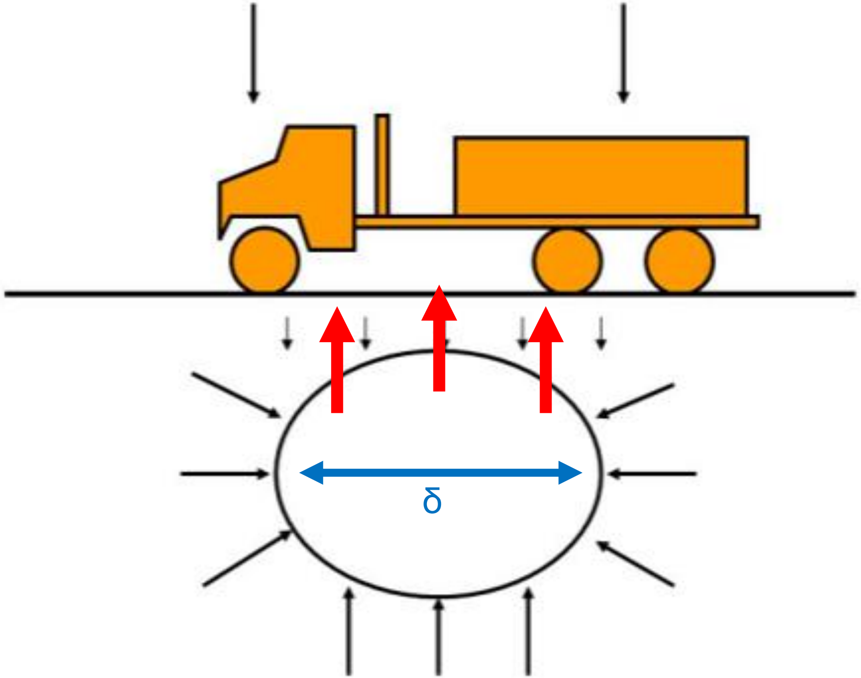
- Economy
- Hydrological aspects (flow calc.)
- Hydraulics of the culvert
- Geotechnical considerations
- Electrochemical props of soil
- Structural design
    - Steel structure
    - Soil compaction
    - Soil-structure interaction



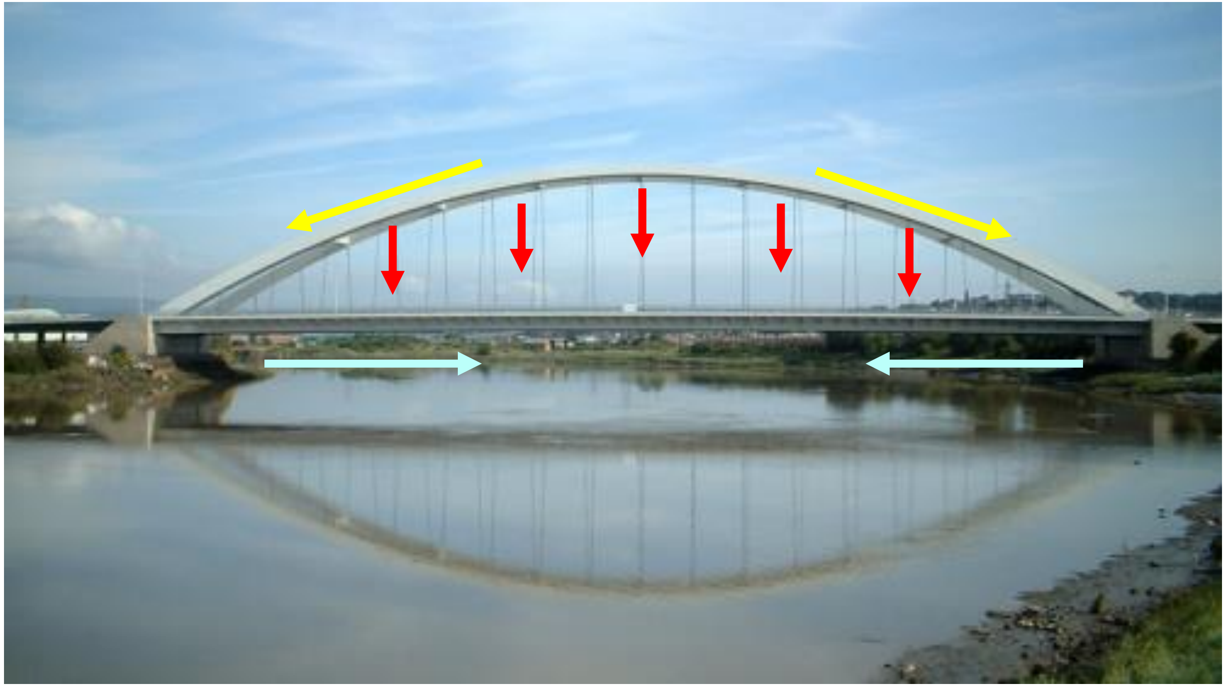
Source: BaTMan

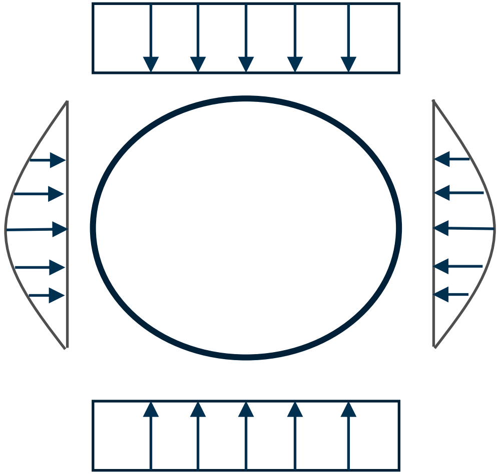
STRUCTURAL SYSTEM

Rafiee et al. 2018



STRUCTURAL SYSTEM



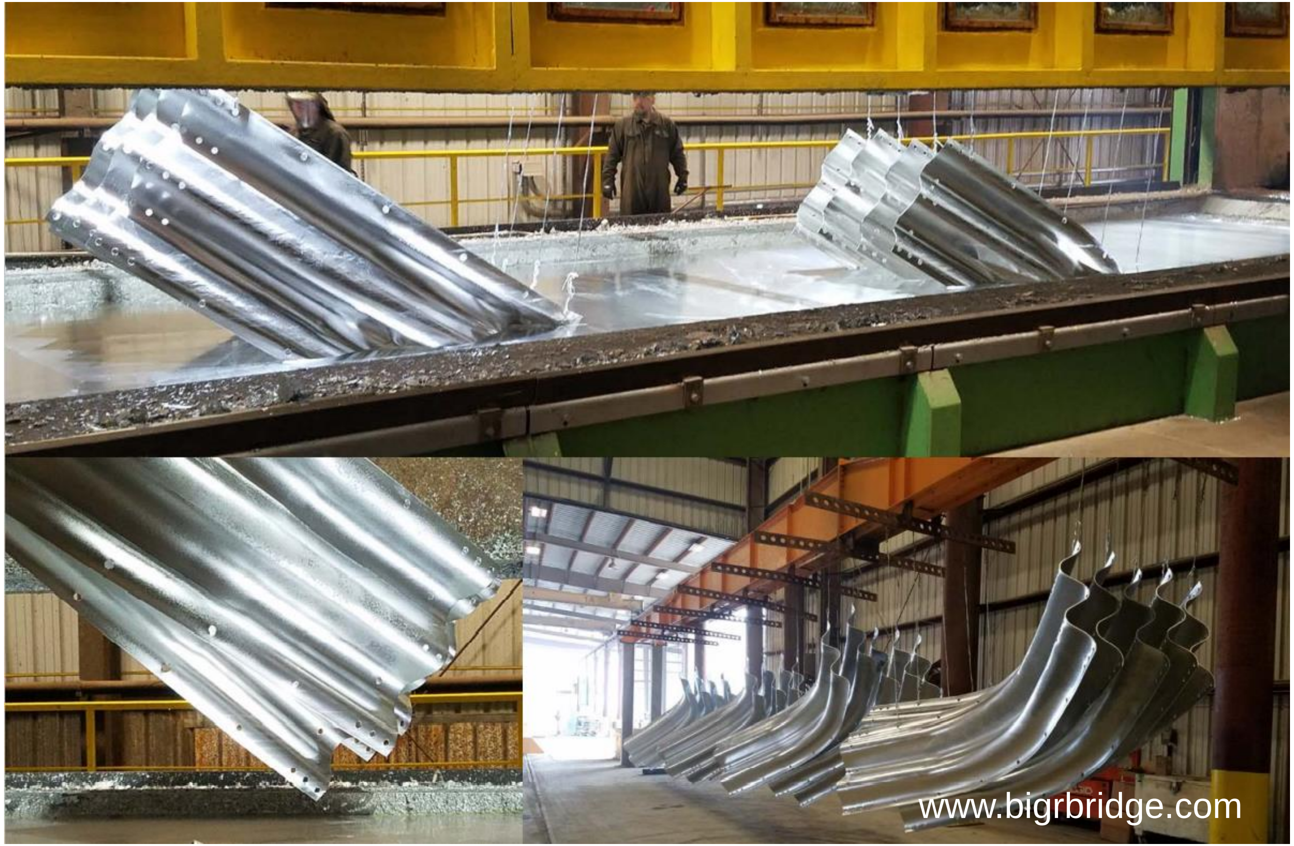


MANUFACTURING AND CONSTRUCTION


PACIFIC


www.bigrbridge.com

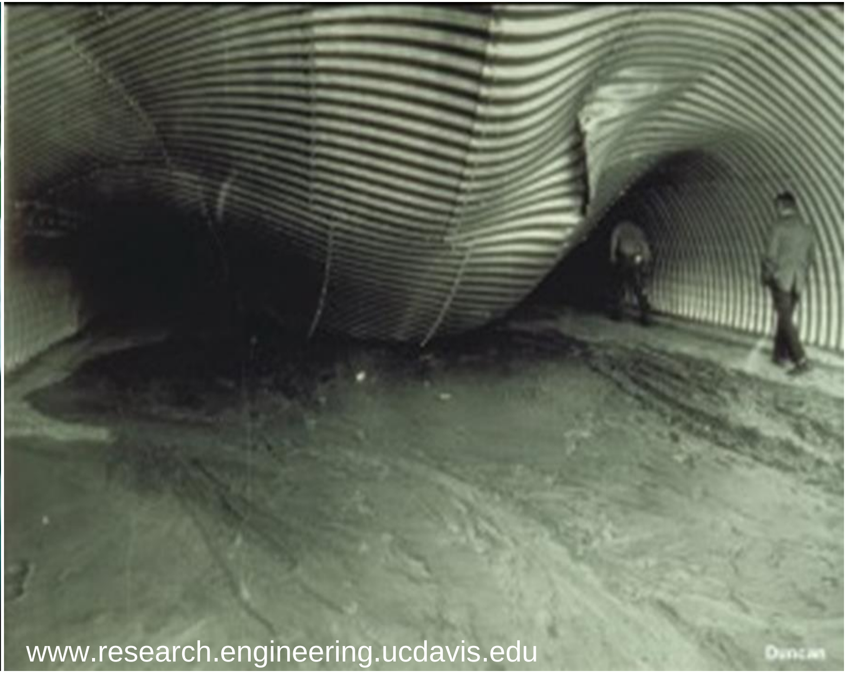

SOUTHWO
www.bigrbridge.com


www.bigrbridge.com


www.bigrbridge.com


www.ailmining.com

PROPER SOIL COMPACTION IS THE KEY



COMMON ISSUES

- Excessive backup of water at the upstream,
- Diminished ability to carry the water,
- The road settlement,
- Movements of the headwalls,
- Washout at the downstream
- **Significant corrosion of the steel/compromised backfill,**
- **Fatigue issues**

ASSESSMENT AND EVALUATION

- According to TRV: general inspections (every two years) and detailed inspections (every three-five years)
- Visual inspection combined with the overall assessment of the culvert geometry
- Ultrasonic testing is widely used during detailed inspections to measure the residual thickness.

Visual inspection

Hammer sound test

Laser ring scanner

Ultrasonic test

REHABILIATION

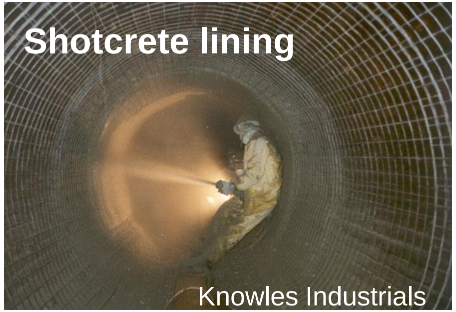
Soil-structure
Interaction&stability

Soil condition
- Sound
- Compromised

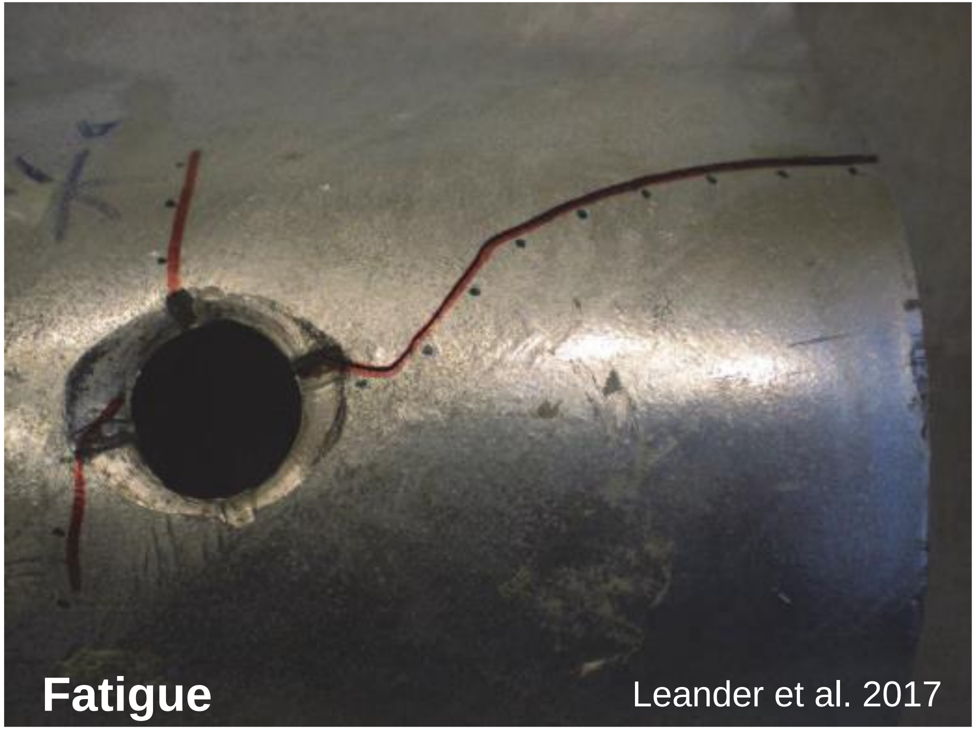
- Hydraulic capacity of the culvert
- Design constraints
- Site conditions
- Extent of damage to steel pipe and soil

Rehabilitation strategies
- Flexible
- Rigid

- Liner solutions (full/partial)
- Parallel alternatives (jack & bore)
- Pipe consumption method
- Partial tunneling
- Protective (shotcrete/geopolymer lining)



SPECIFIC ISSUES



LONG-TERM PERFORMANCE CONSIDERATIONS

Corrosion

Zinc protection

Bare steel corrosion

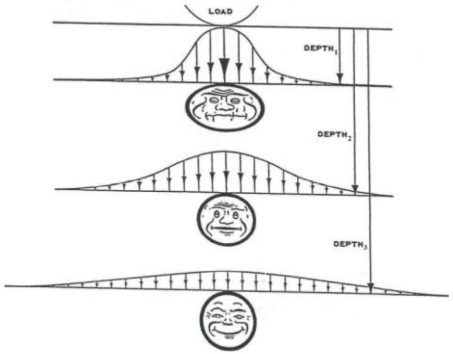
- Expected service life of 80 years
- Extra steel thickness (in Sweden 20% extra material)
- Electrochemical props of backfill

Alternative materials?

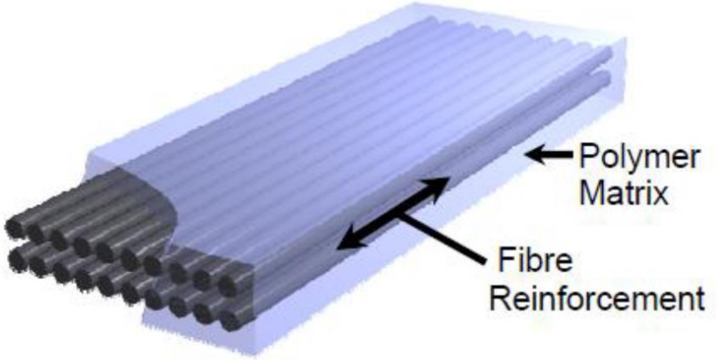
Fatigue

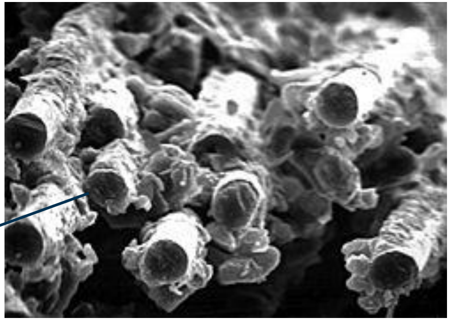
Increasing design loads

- The soil cover is advised to be at least 1m (3'3") in Sweden



FIBER REINFORCED POLYMER (FRP)

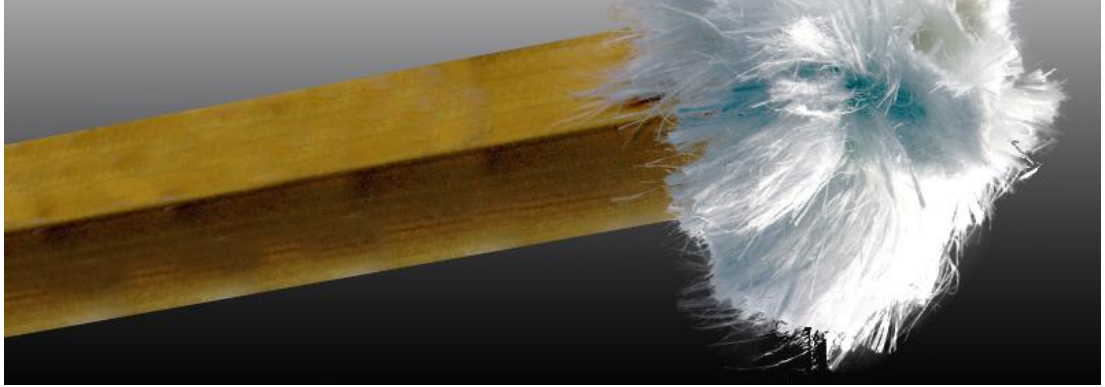




25 µm

Combinations

Fiber	**Matrix**
Carbon	Polyester
Glass	Vinylester
Aramid	Epoxy
Basalt	Polyurethane



CHARACTERISTICS

FRP

- Low carbon footprint
- Fatigue resistance
- Industrialized production (prefabrication)
- Lightweight
- Tailored properties
- High specific stiffness
- Durability
- High strength

Published 11/16/2020 | 2 MINUTE READ

Strength of composite whale tail sculpture saves runaway train car

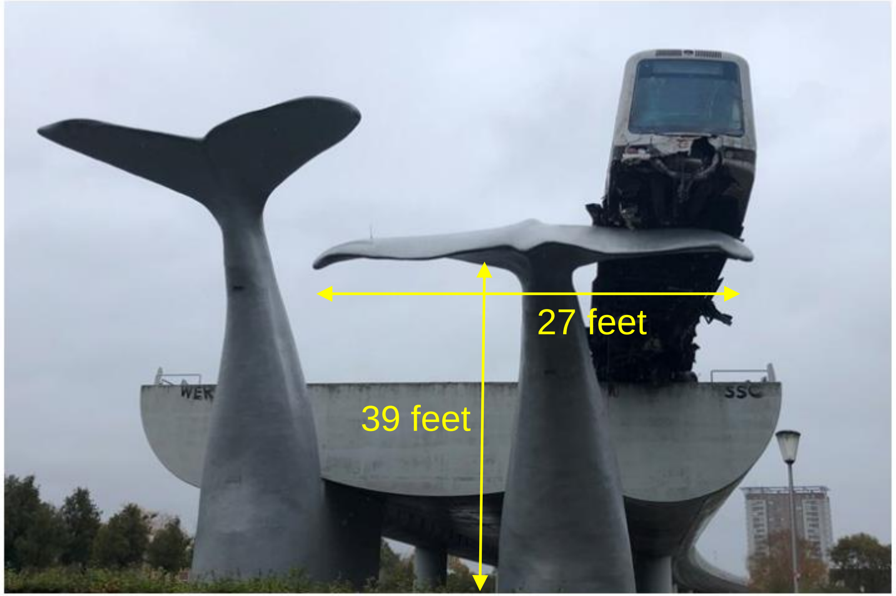
A 19-year-old, glass fiber-reinforced composite urban sculpture designed by Dutch engineering firm Solico was able to safely bear the weight of an off-track rail vehicle.

EDITED BY HANNAH MASON
Associate Editor, *CompositesWorld*

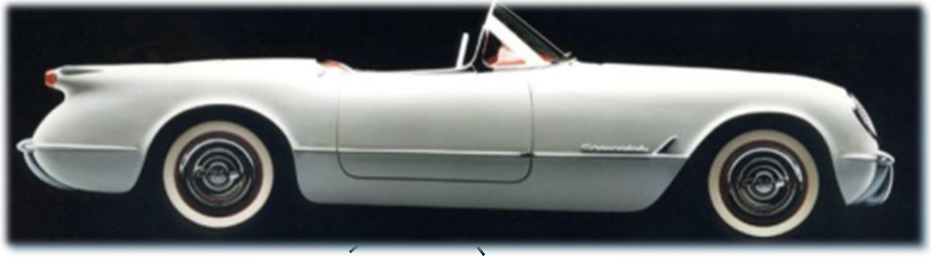
SHARE

READ NEXT

- Building the Museum of the Future
- Composites fill the gaps in museum dinosaur skeletons
- Composites industry continues 2022 upswing



Non-metallic radar domes 1941

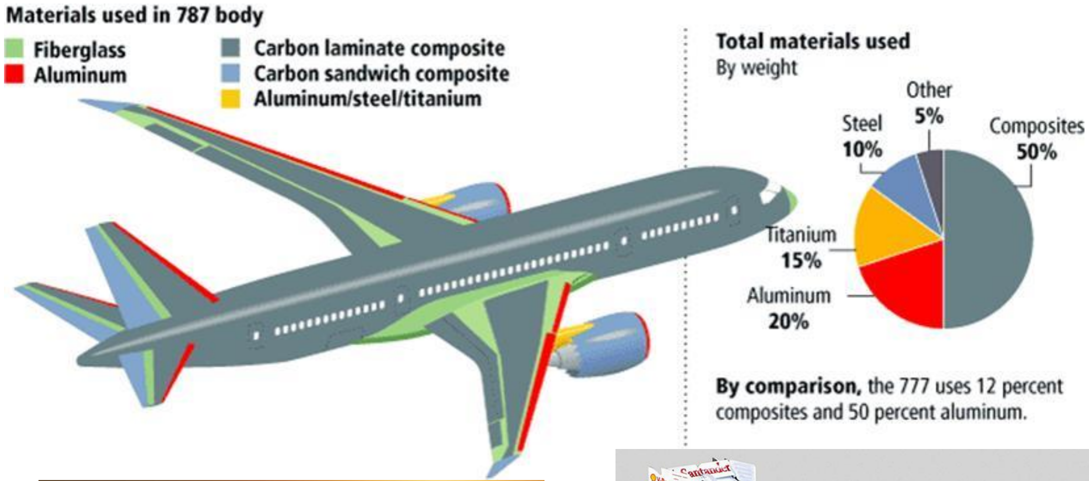


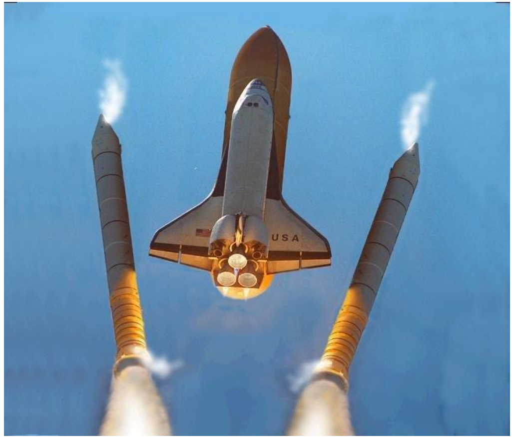
Chevrolette Corvette 1953

Vultee BT-15 1944

Wind energy 1970s

WELL-ESTABLISHED IN AEROSPACE, MARINE, SPORTS AND WIND ENERGY





FRP IN CONSTRUCTION


The Monsanto House of Future” 1957-1967


Marine infrastructure 1990s


Strengthening & repair 1980s

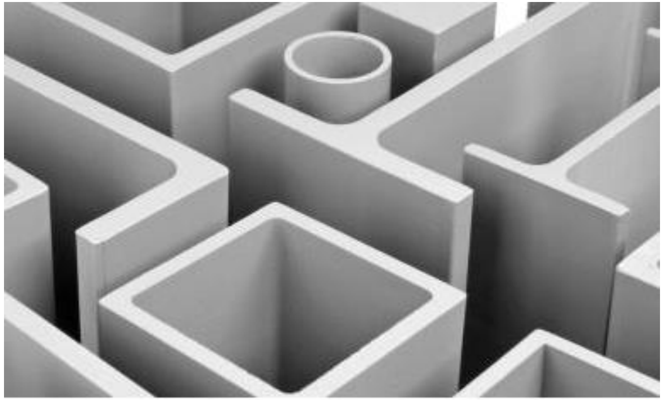

Bridge construction 2000s

PRODUCTION METHODS

Vacuum injection

Filament winding

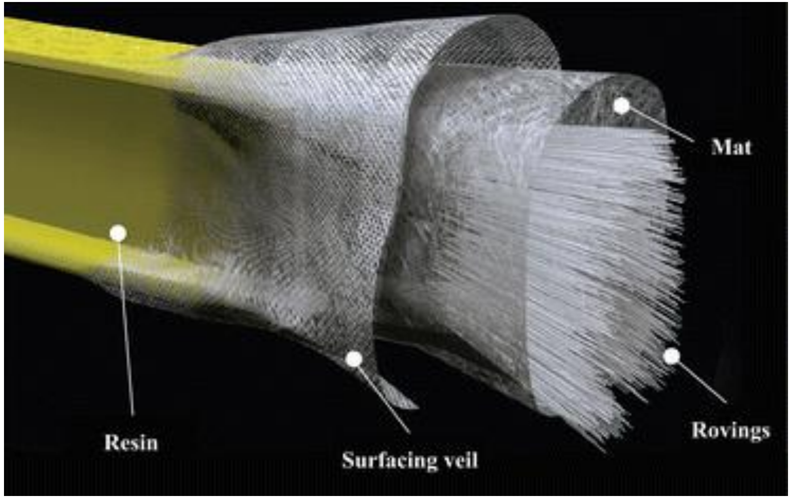
Pultrusion

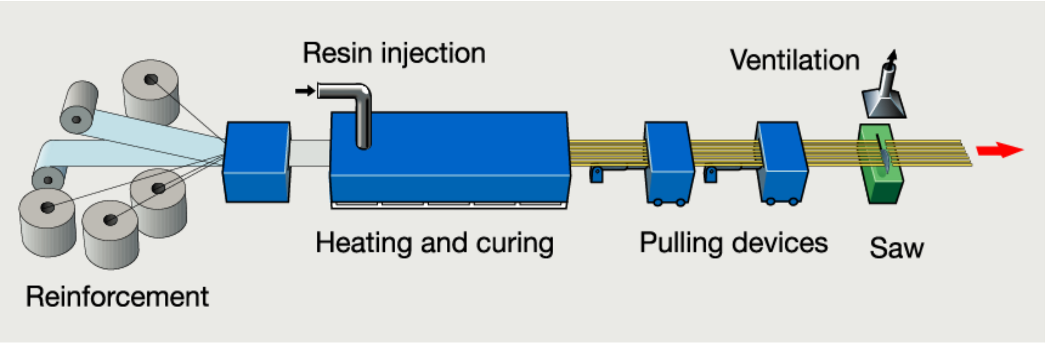


PULTRUSION

+ Good production tolerances
+ Well-controlled quality

- Limited flexibility (form & properties)



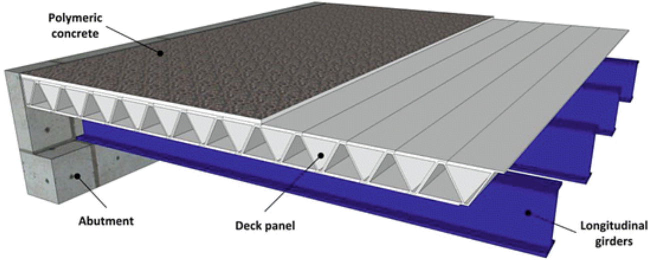


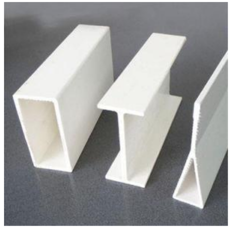
PULTRUSION

FRP deck – Fiberline, DK

Span:	27 m (89 feet)
Bridge width:	5,0 m (16 feet)
Weight:	60 t

Friedberg bridge (Hybrid) – Frankfurt 2008

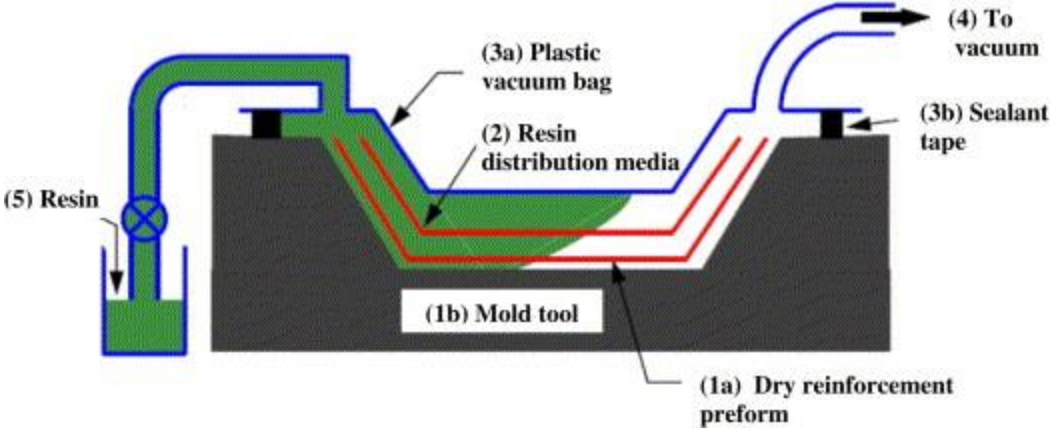


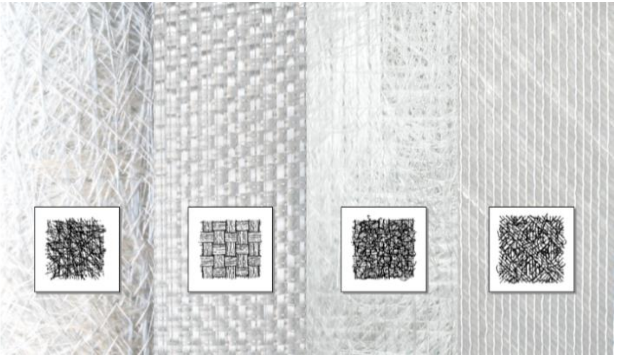


VACUUM INJECTION

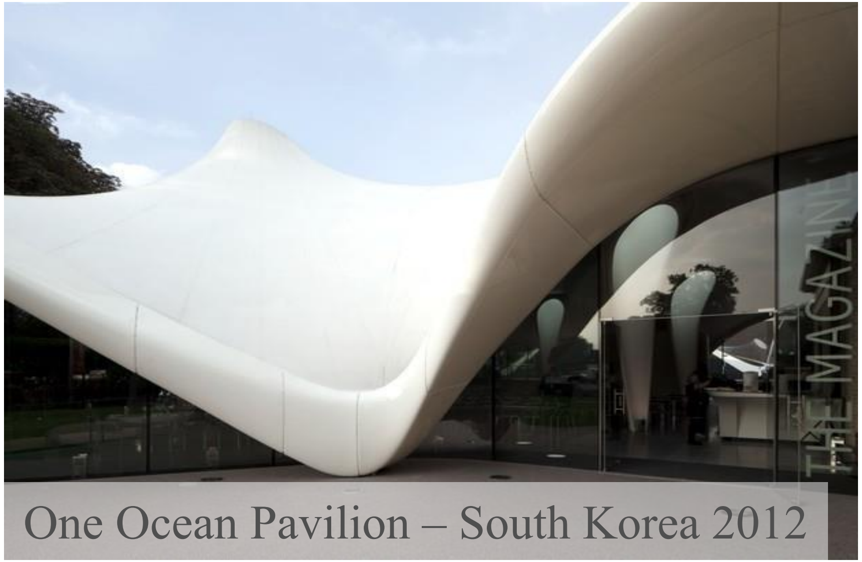
+ More suitable for large elements
+ Respects "bridge uniqueness"

- "Low repeatability"
  - still not considered "industrial"
- Expensive formwork





VACUUM INJECTION



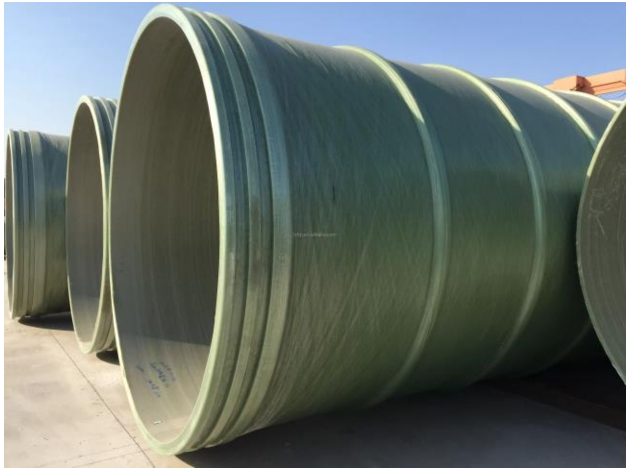
One Ocean Pavilion – South Korea 2012

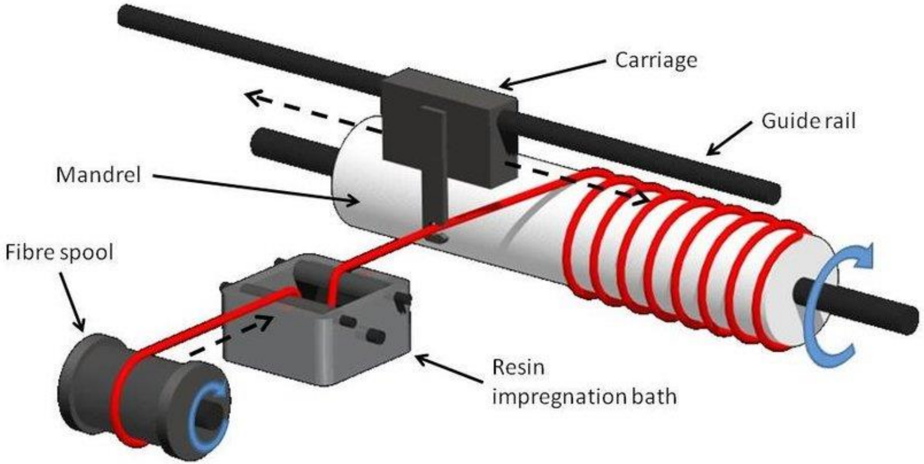
Foryd Harbour – North Wales 2013

FILAMENT WINDING

+ Suited for circular sections
+ Possible on-site production

- High QC measures needed



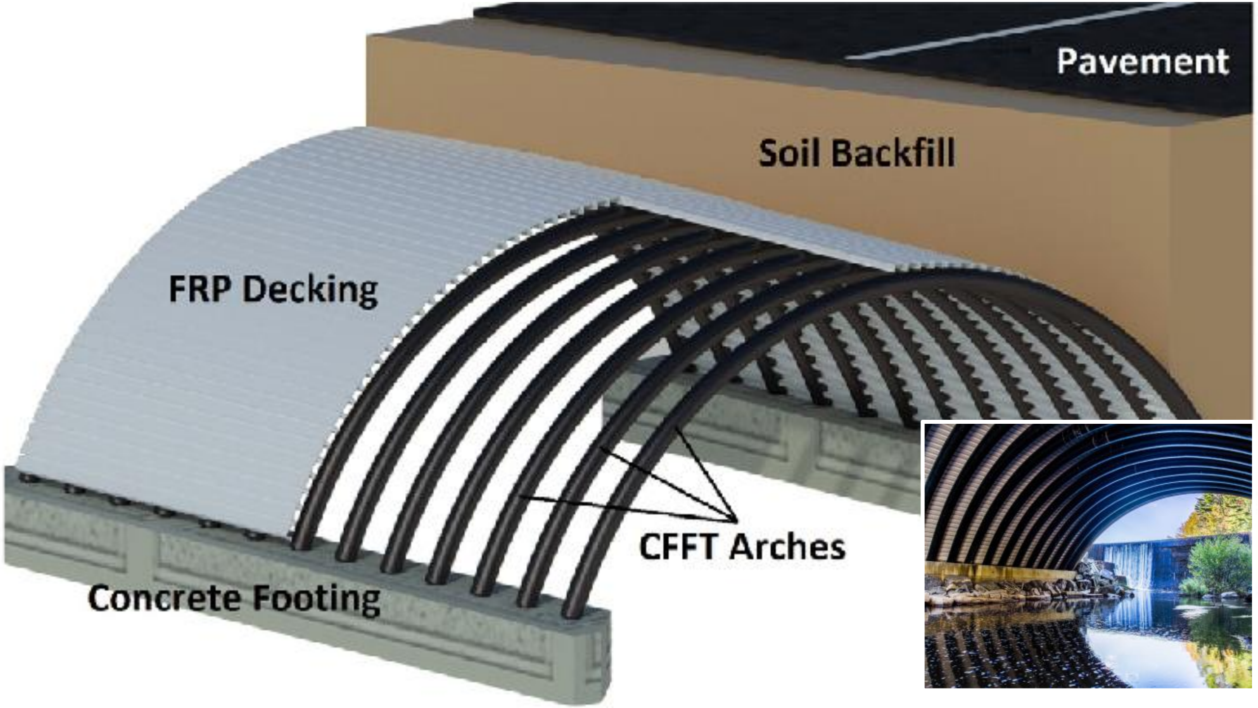


FRP IN UNDERGROUND APPLICATIONS

REPAIR AND REFURBISHMENT

Relining using FRP

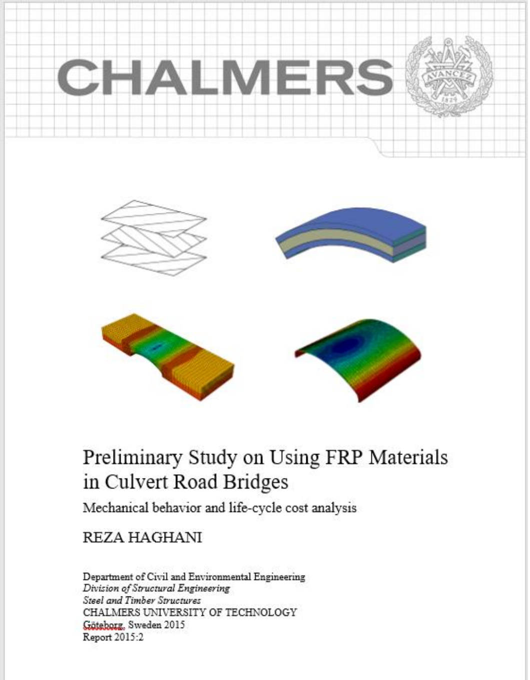
FRP IN CULVERT BRIDGES



(composite arch bridge)

Developed at the University of Maine, 18 bridges have been built

FRP CULVERTS



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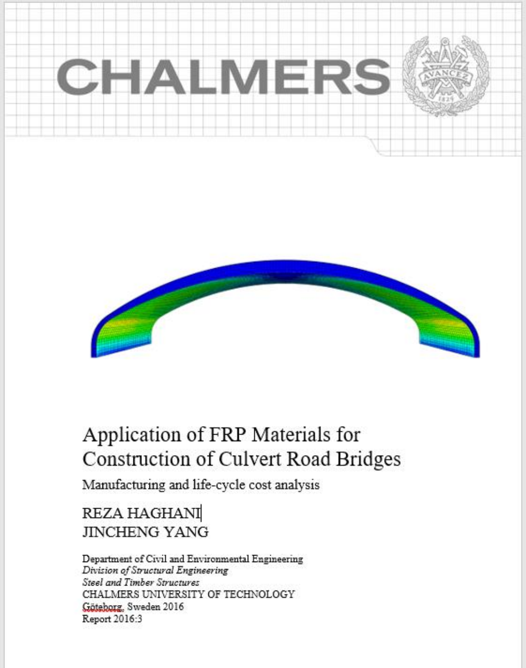
Preliminary Study on Using FRP Materials in Culvert Road Bridges

Mechanical behavior and life-cycle cost analysis

REZA HAGHANI

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2015
Report 2015:2

Vol1: Concept development



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Application of FRP Materials for Construction of Culvert Road Bridges

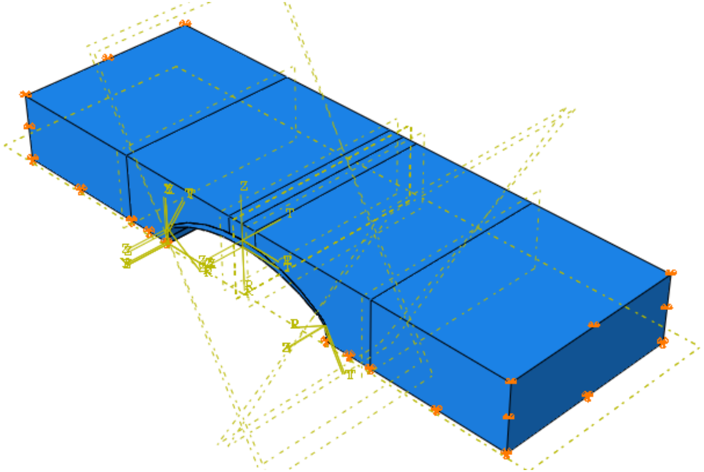
Manufacturing and life-cycle cost analysis

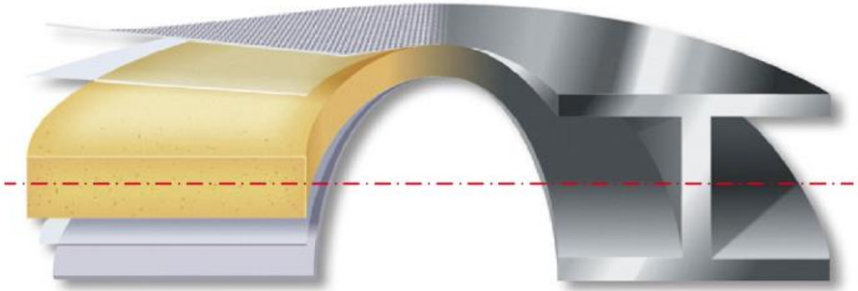
REZA HAGHANI
JINCHENG YANG

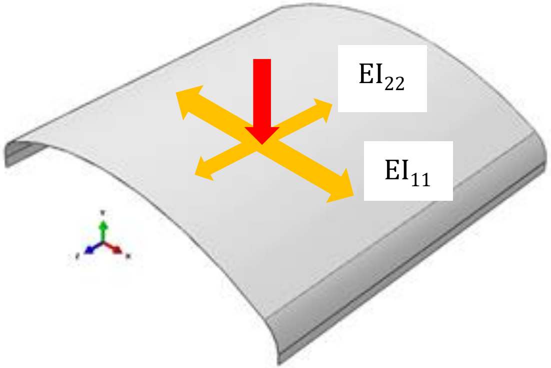
Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2016
Report 2016:3

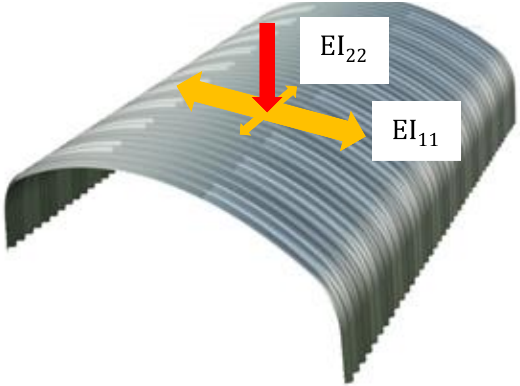
Vol2: Detailed design- LCC

STRUCTURAL DESIGN





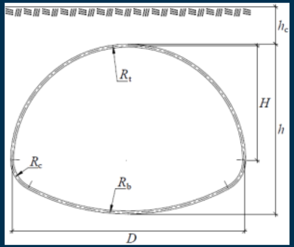
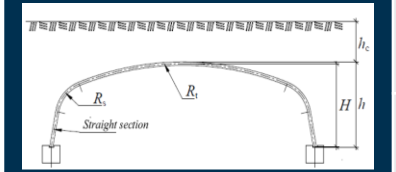




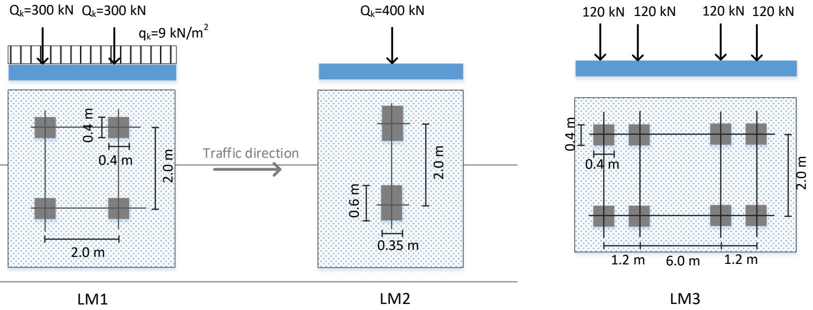
STRUCTURAL FEASIBILITY

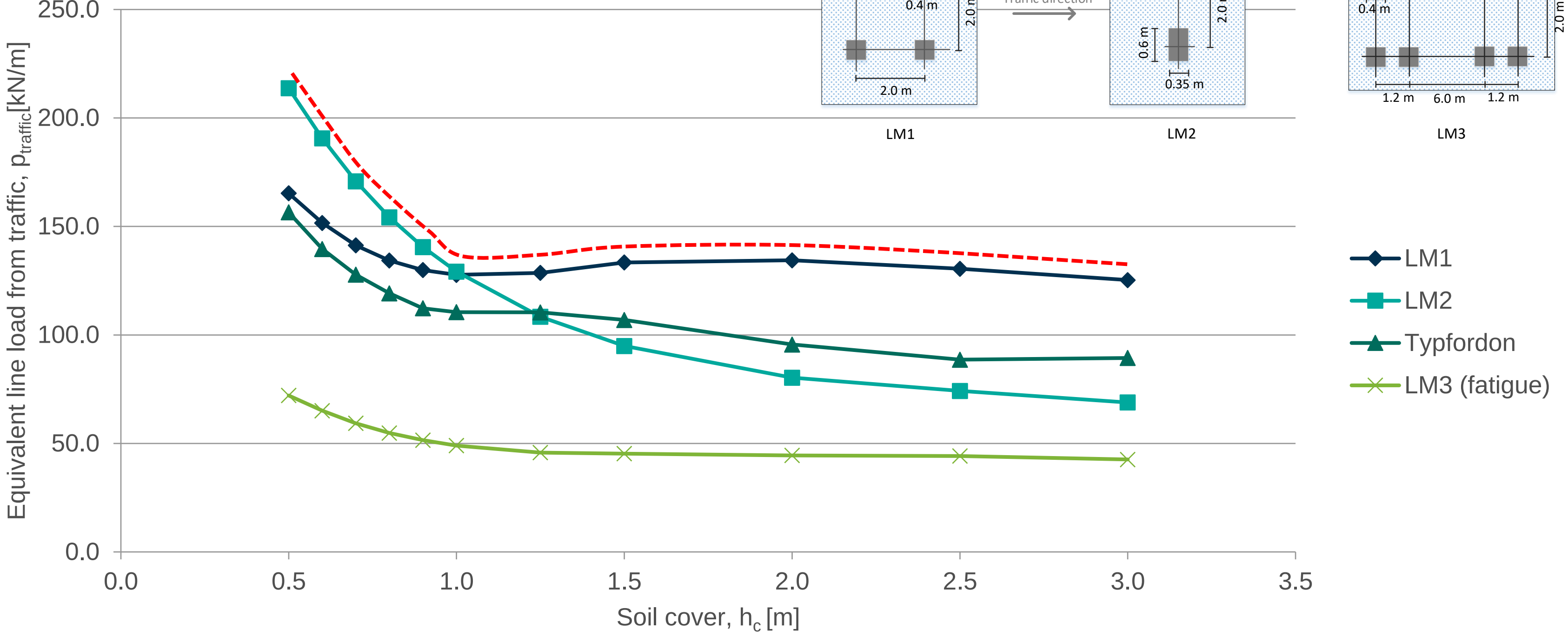
16 different cases:

- Two culvert types
- Three spans
- Four soil cover thickness

Culvert Profile	Span	Height of Soil Cover	Case No.
	[meter] (feet)	[meter] (feet)	
 Pipe-arch	3 (9’10”)	0,50 (1’8”)	01
		0,75 (2’6”)	02
		1,00 (3’3”)	03
		3,00 (9’10”)	04
	6 (19’8”)	0,50 (1’8”)	05
		0,75 (2’6”)	06
		1,00 (3’3”)	07
		3,00 (9’10”)	08
 Box	6 (19’8”)	0,50 (1’8”)	09
		0,75 (2’6”)	10
		1,00 (3’3”)	11
		3,00 (9’10”)	12
	12 (39’4”)	0,50 (1’8”)	13
		0,75 (2’6”)	14
		1,00 (3’3”)	15
		3,00 (9’10”)	16

LOAD MODELS


Qk=300 kN
Qk=300 kN
qk=9 kN/m2
0.4 m
0.4 m
2.0 m
2.0 m
LM1
Traffic direction
Qk=400 kN
2.0 m
0.6 m
0.35 m
LM2
120 kN
120 kN
120 kN
120 kN
0.4 m
0.4 m
2.0 m
1.2 m
6.0 m
1.2 m
LM3


Equivalent line load from traffic, ptraffic [kN/m]
250.0
200.0
150.0
100.0
50.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Soil cover, hc [m]
LM1
LM2
Typfordon
LM3 (fatigue)

DETAILED DESIGN

Culvert Profile	Verification	
Pipe-arch Culvert	SLS	Check 1: yielding in the upper section when backfilling till crown
		Check 2: yielding in the upper section when soil cover completed
		Check 3: Local buckling
	ULS	Check 4: Plastic hinge in the crown, N & M
		Check 5: Plastic hinge in the crown, N (M=0)
		Check 6: Capacity in the bottom section
		Check 7: Capacity of Bolts, shear stress
		Check 8: Capacity of bolts, tensile stress
		Check 9: Capacity of bolts, interaction
	Fatigue	Check 10: Fatigue of the plate
		Check 11: fatigue of Bolts, shear stress
		Check 12: fatigue of Bolts, tensile stress
		Check 13: fatigue of Bolts, interaction

Culvert Profile	Verification	
Box Culvert	SLS	Check 1: yielding in the upper section when backfilling till crown
		Check 2: yielding in the upper section when soil cover completed
		Check 3: Local buckling
	ULS	Check 4: Plastic hinge in the crown, N & M
		Check 5: Plastic hinge in the crown, N (M=0)
		Check 6: Plastic hinge in the corner, N & M
		Check 7: Plastic hinge in the corner, N (M=0)
		Check 8: Capacity of Bolts, shear stress
		Check 9: Capacity of bolts, tensile stress
		Check 10: Capacity of bolts, interaction
	Fatigue	Check 11: Fatigue of the plate
		Check 12: fatigue of Bolts, shear stress
		Check 13: fatigue of Bolts, tensile stress
		Check 14: fatigue of Bolts, interaction

DETAILED DESIGN

Plastic hinge at crown

Fatigue in the steel plate

Fatigue in bolted joints

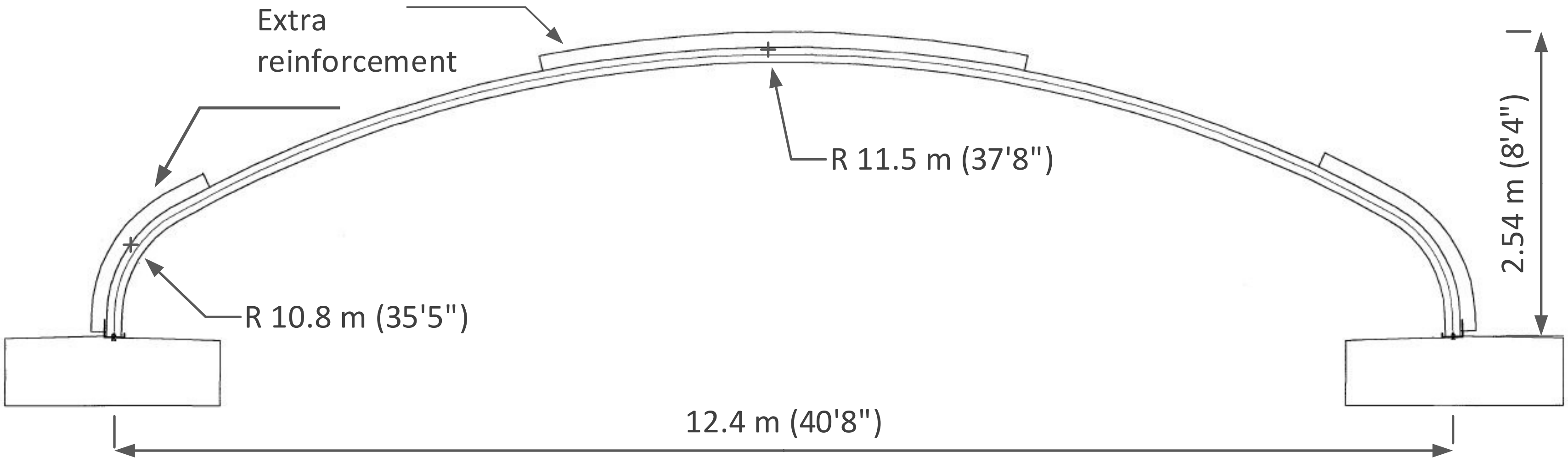
	No	Span	[1] h_c	Corrugated Plates	Thickness	[2] Reinf. Top	Reinf. Corner	Bolts: [3] Number of Bolts	Verification: SLS Check 1	SLS Check 2	ULS Check 4	ULS Check 5	ULS Check 6	ULS Check 7	ULS Check 8	ULS Check 9	ULS Check 10	Fatigue Check 11	Fatigue Check 12	Fatigue Check 13	Fatigue Check 14
		[m]	[m]		4-7mm			[1/m]													
Box	9	6	0,50	380*140	7	Yes	No	15	0,05	0,51	0,99	0,74	0,73	0,13	0,21	0,55	0,61	1,11	0,28	3,95	61,47
Box	10	6	0,75	380*140	5	Yes	No	15	0,07	0,46	0,83	0,52	0,79	0,12	0,25	0,33	0,43	0,92	0,22	2,32	12,54
Box	11	6	1,00	380*140	4	Yes	No	15	0,08	0,42	0,73	0,41	0,86	0,13	0,29	0,23	0,34	0,76	0,19	1,55	3,69
Box	12	6	3,00	380*140	7	No	No	10	0,15	0,87	0,99	0,21	0,74	0,09	0,38	0,40	0,67	0,52	0,19	0,85	0,61
Box	13	12	0,50	380*140	7	Yes	No	15	0,04	0,56	1,59	1,16	0,87	0,19	0,28	0,57	0,69	1,05	0,28	3,74	52,38
Box	14	12	0,75	380*140	7	Yes	No	15	0,04	0,47	1,22	0,80	0,83	0,14	0,28	0,46	0,61	0,76	0,22	2,70	19,73
Box	15	12	1,00	380*140	7	Yes	No	15	0,04	0,43	1,02	0,63	0,84	0,12	0,29	0,41	0,58	0,59	0,19	2,12	9,51
Box	16	12	3,00	380*140	7	Yes	Yes	15	0,04	0,70	0,95	0,28	0,68	0,10	0,53	0,64	0,99	0,26	0,16	0,95	0,85

[1] h_c—Height of the soil cover
[2] Reinf.—Reinforcement plates in the top region or corner region
[3] The maximum number of bolts that can be used in the steel plates with corrugation 380*140 is 15 per meter.

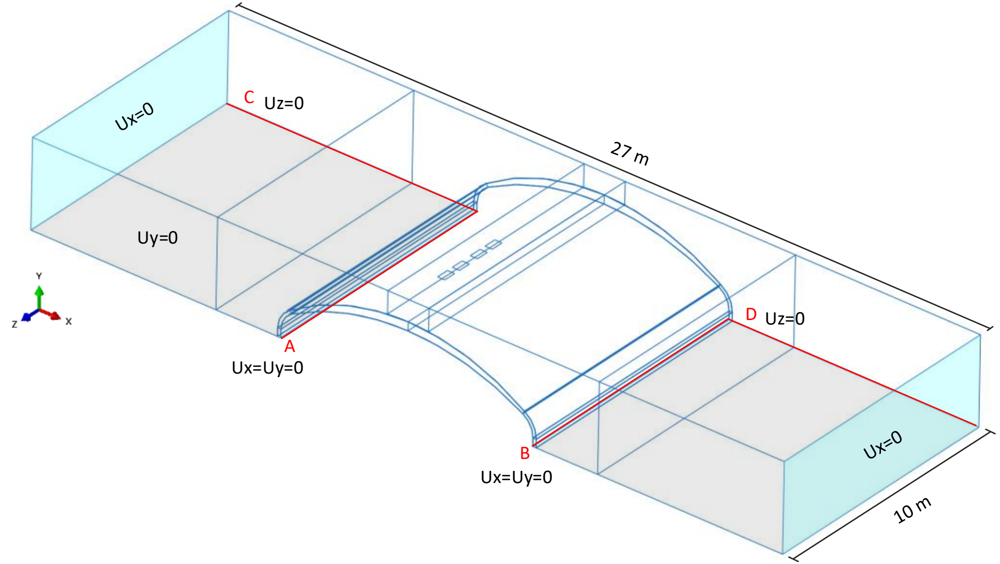
CASE STUDY

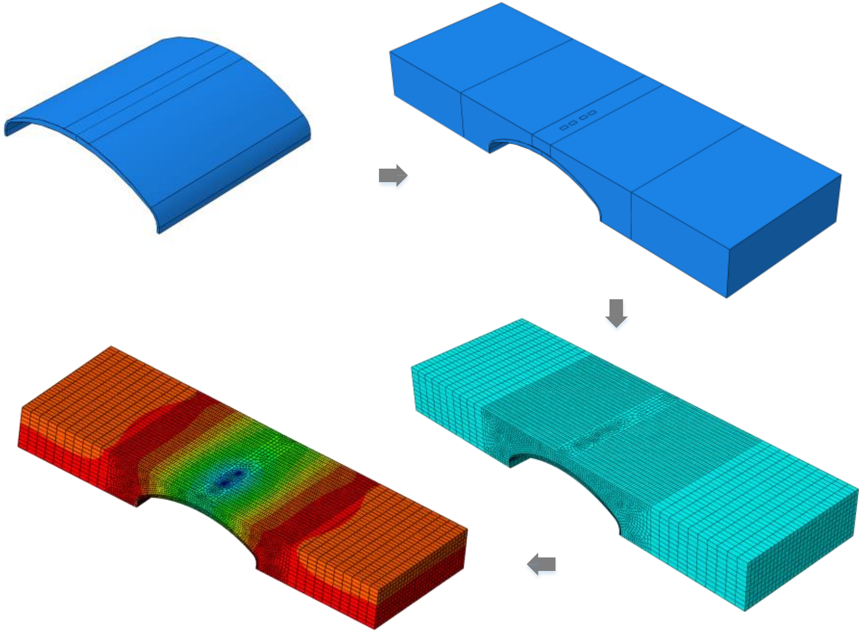
Siktån at Rörbäcksnäs

CASE STUDY



CASE STUDY

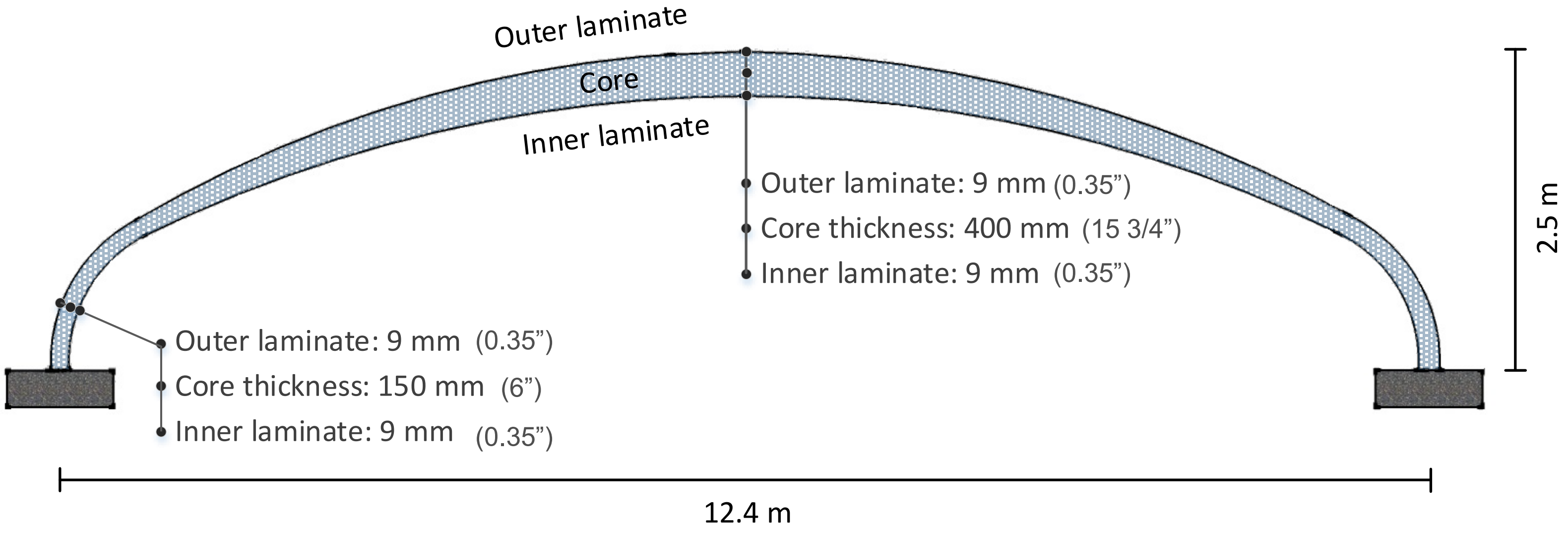




A limit of L/400 was imposed in the SLS!
e_{max}<0.15e_{ult}
Soil-FRP: Hard contact, No friction

Elastic Constants	FRP Composite by Vacuum Infusion							Soil		
Characteristic value	E_1 GPa	E_2 GPa	n_{12}	G_{12} GPa	G_{23} GPa	s_{LT} MPa	s_{LC} MPa	E MPa	n	ρ kg/m³
	39.98	6.93	0.27	2.74	2.55	480	320	26	0.3	2600

CASE STUDY



FRP Laminate (inner and outer face sheets)	Core Material (Divinycell H80)
Thickness: 9 mm	Thickness at the base: 150 mm
Length (along the curve): 14.6 m	Thickness at the crown: 400 mm
Fiber: E-glass, unidirectional, and epoxy matrix	Cross-sectional area: 4.05 m^2
Fiber volume fraction: 55%	Volume: 40.5 m^3

LIFE CYCLE COST ANALYSIS

Net Present Value

Service life

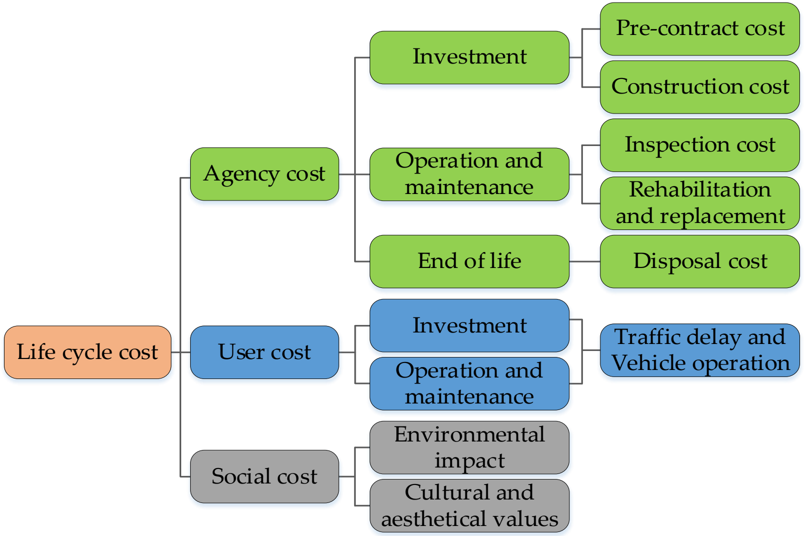
Cash flow in year n

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

Discount rate (4%)

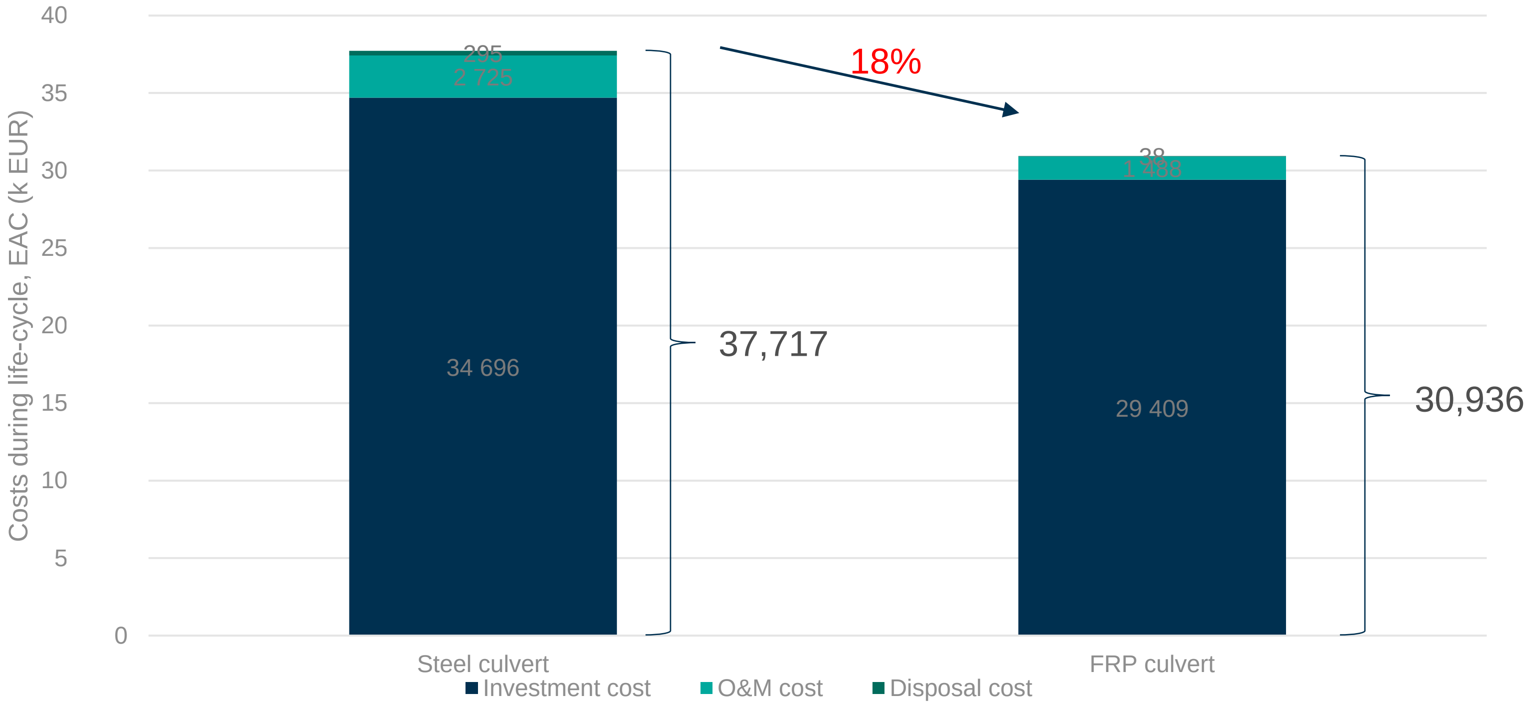
Equivalent Annual Cost

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



Design service life of 50 years for the steel and 100 years for the FRP

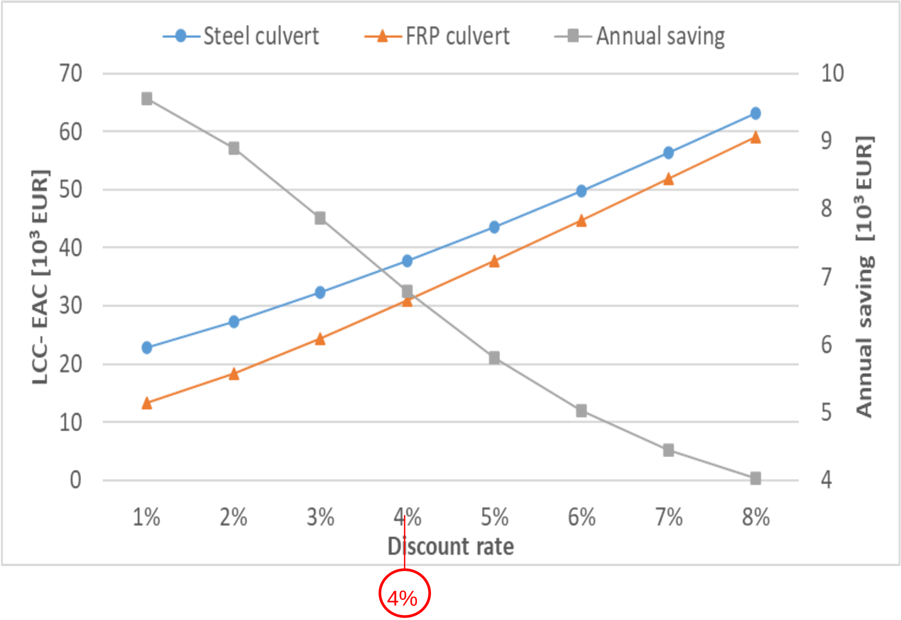
LCC ANAYSIS


Costs during life-cycle, EAC (k EUR)
40
35
30
25
20
15
10
5
0
295
2 725
34 696
37,717
18%
38
1 488
29 409
30,936
Steel culvert
FRP culvert
Investment cost
O&M cost
Disposal cost

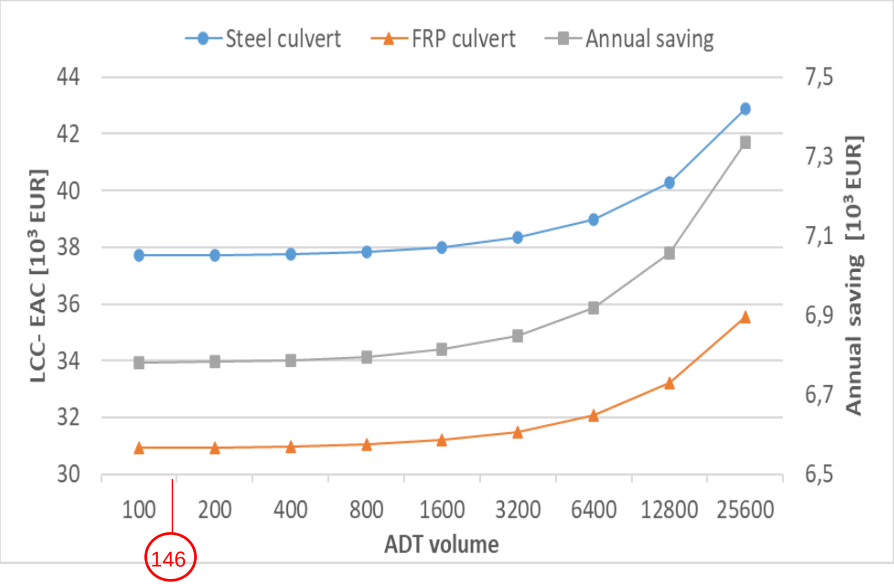
PARAMETRIC LCCA

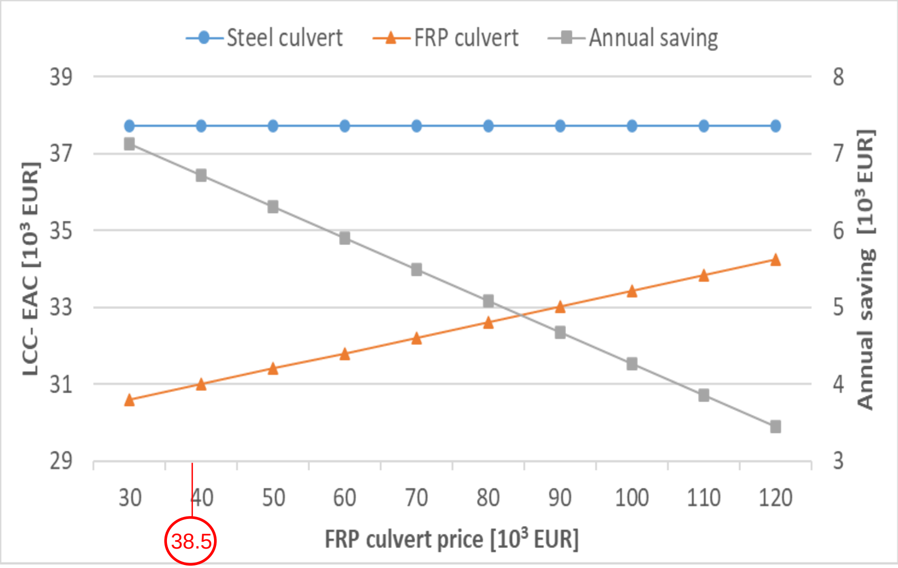
- Discount rate→ 4%
- ADT→ 146
- FRP culvert price* → 38,550 €
- Steel culvert price→ 596,000 €
- FRP culvert service life→ 100 y
- Soil cover thickness→ 750mm (2’6”)

* The cost of FRP shell

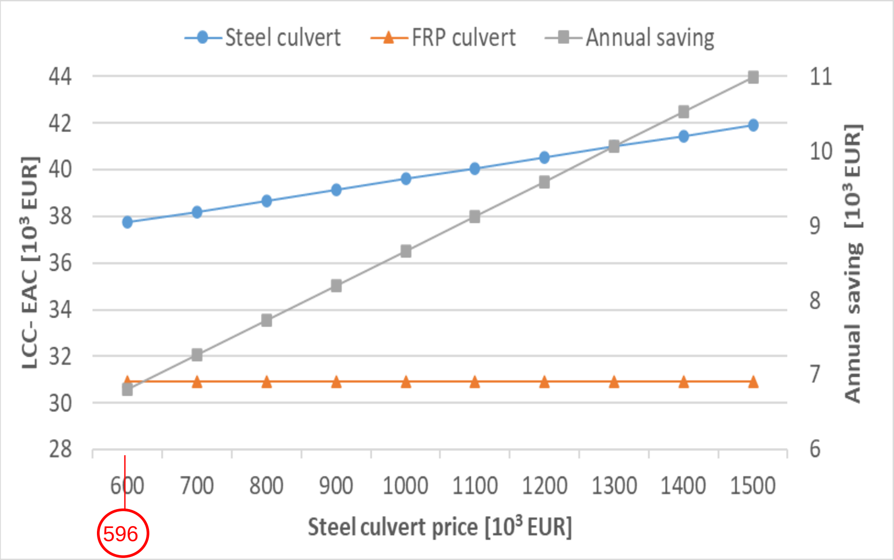


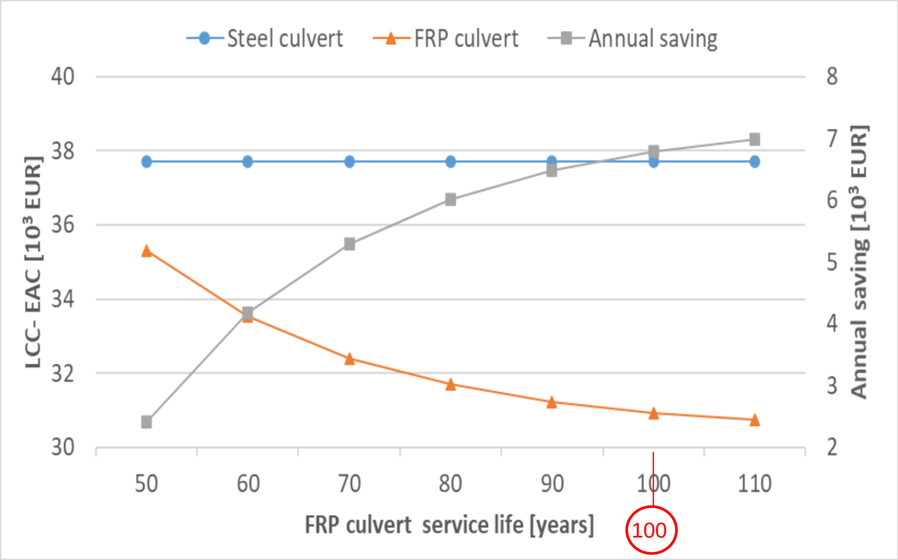
PARAMETRIC LCCA



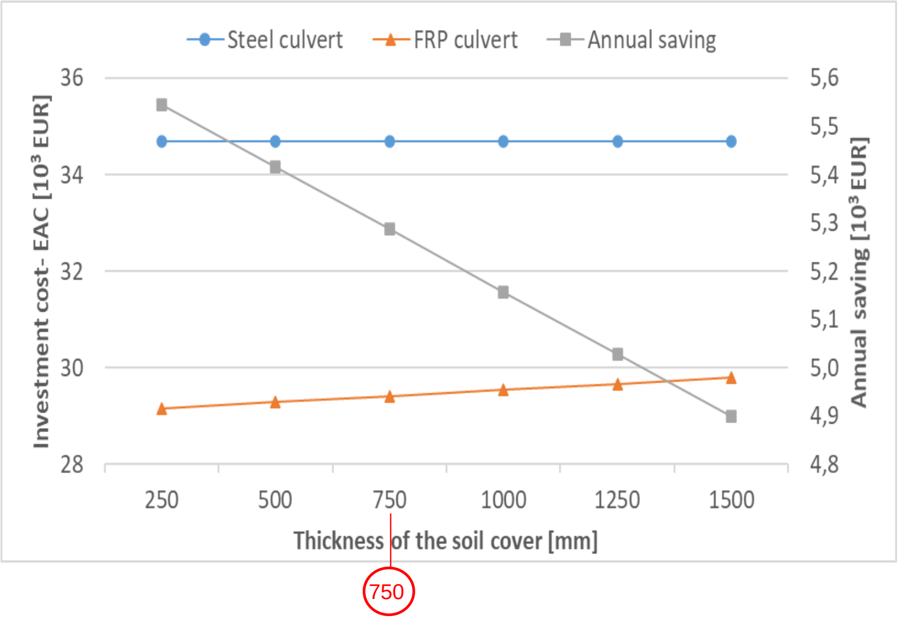


PARAMETRIC LCCA

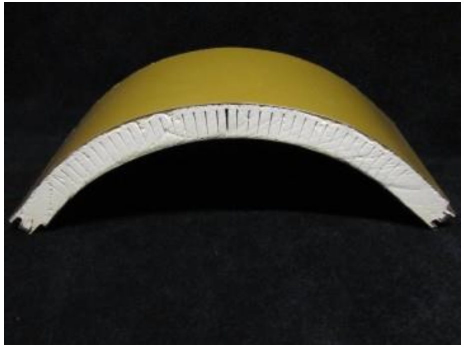


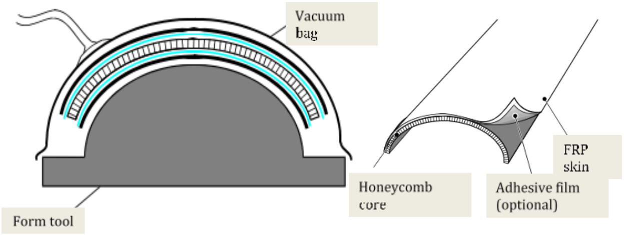


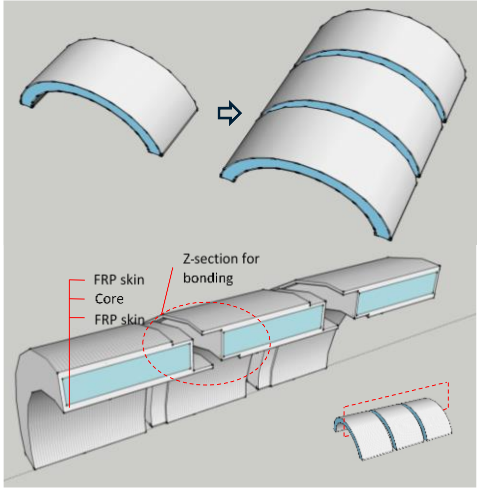
PARAMETRIC LCCA

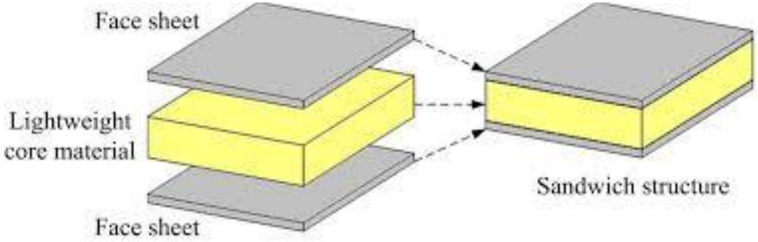


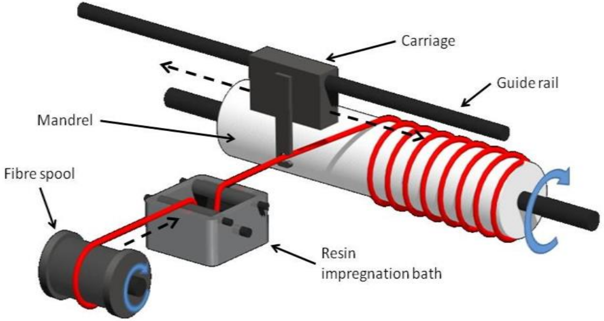
MANUFACTURING











FINAL REMARKS

Why FRP composites in bridges

- Very high specific strength (and stiffness) → **Low weight**

- Design flexibility
- Effective production

→ **Industrial manufacturing**

Quick and effective construction

- Corrosion resistant
- High fatigue strength

→ **Good durability**

Less maintenance costs

- Less energy-demanding
- Material reuse/recycling

→ **Sustainable**

In many cases …
”Winner” LCC / LCA

FINAL REMARKS

Why FRP composites in bridges

Properties		Benefit	Challenges
• Very high specific strength (and stiffness)	→	**Low weight**	Dynamic response
• Design flexibility • Effective production	→	**Industrial manufacturing**	Complex calculations Too many material comb. Quality assurance
• Corrosion resistant • High fatigue strength	→	**Good durability**	Long-term properties Inspection & mainteance Repair methods Fire, vandalism, collision
• Less energy-demanding • Material reuse/recycling	→	**Sustainable**	Limited basis for LCC/LCA

FINAL REMARKS

Knowledge gaps, challenges and the way forward

Research & Development

Knowledge transfer (from other fields)

Knwoledge development and dissemination

Create interest Create acceptance (& build trust)

- Design rules and simplified material models
- long-term performance (a bridge lasts at least 80 years!)
- Repair and strengthening methods
- Quality assurance, inspection methods, NDT
- SHM
- Hybrid solutions (many advantages and many challenges)
- Connections

RESOURCES

https://ncspa.org/

https://webstore.ansi.org/Standards/ASTM/astma998a998m982003

Haghani R, Yang J, 2016, Application of FRP materials for construction of culvert road bridges: manufacturing and life-cycle cost analysis, available at http://publications.lib.chalmers.se/records/fulltext/233171/233171.pdf

Haghani R, Yang J, Gutierrez M, Eamon C, Volz J, 2021, Fiber Reinforced Polymer Culvert Bridges—A Feasibility Study from Structural and LCC Points of View, Infrastructures 6(9), 128, Available at https://www.mdpi.com/2412-3811/6/9/128

Tenbusch A, Dorwart B, 2009, Failing Culverts – The Geotechnical Perspective, Available at: https://tenbusch.com/underground_equipment/files/FailingCulvertsGeotechnicalPerspective.pdf

THANK YOU FOR YOUR ATTENTION