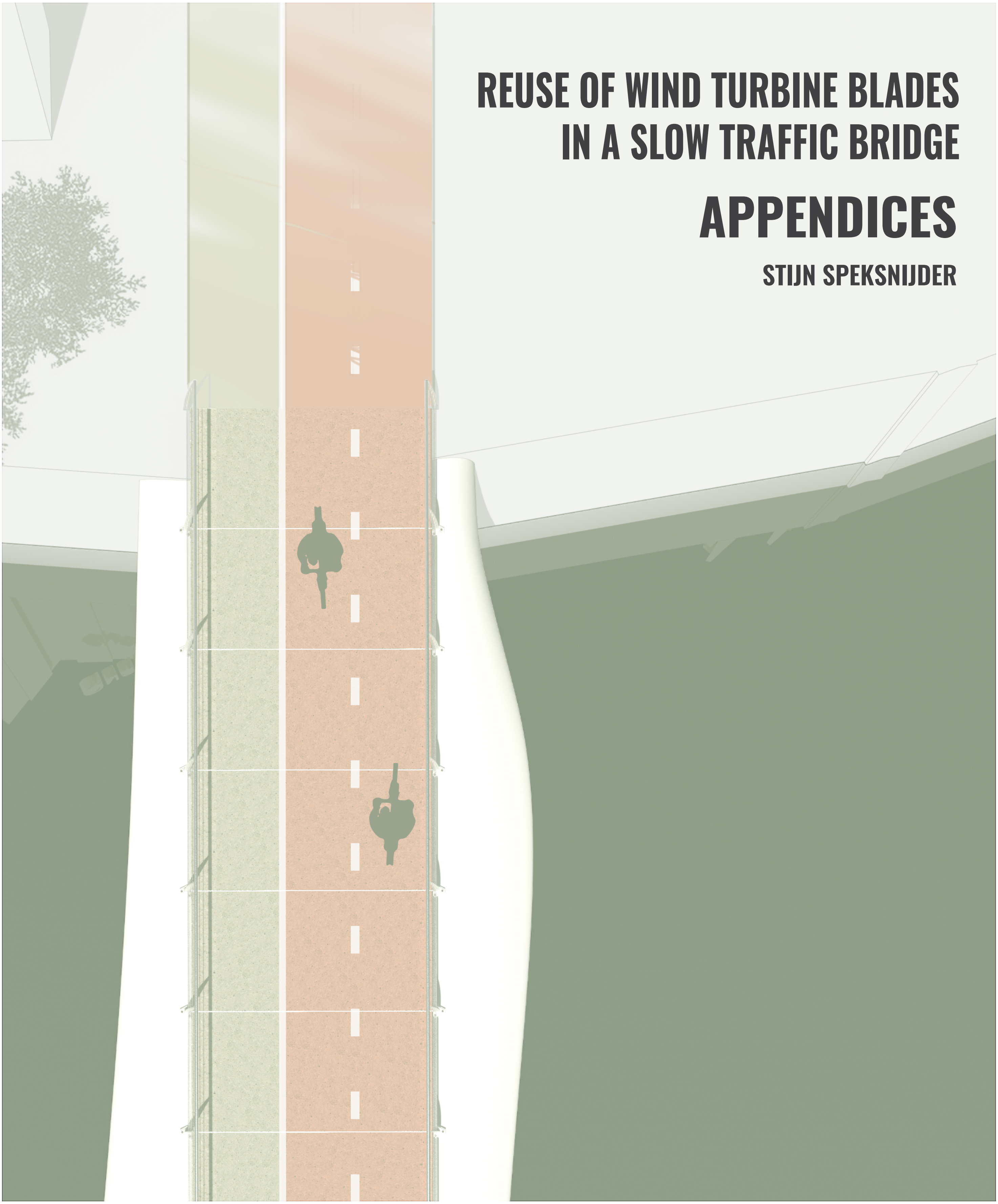
REUSE OF WIND TURBINE BLADES IN A SLOW TRAFFIC BRIDGE

APPENDICES

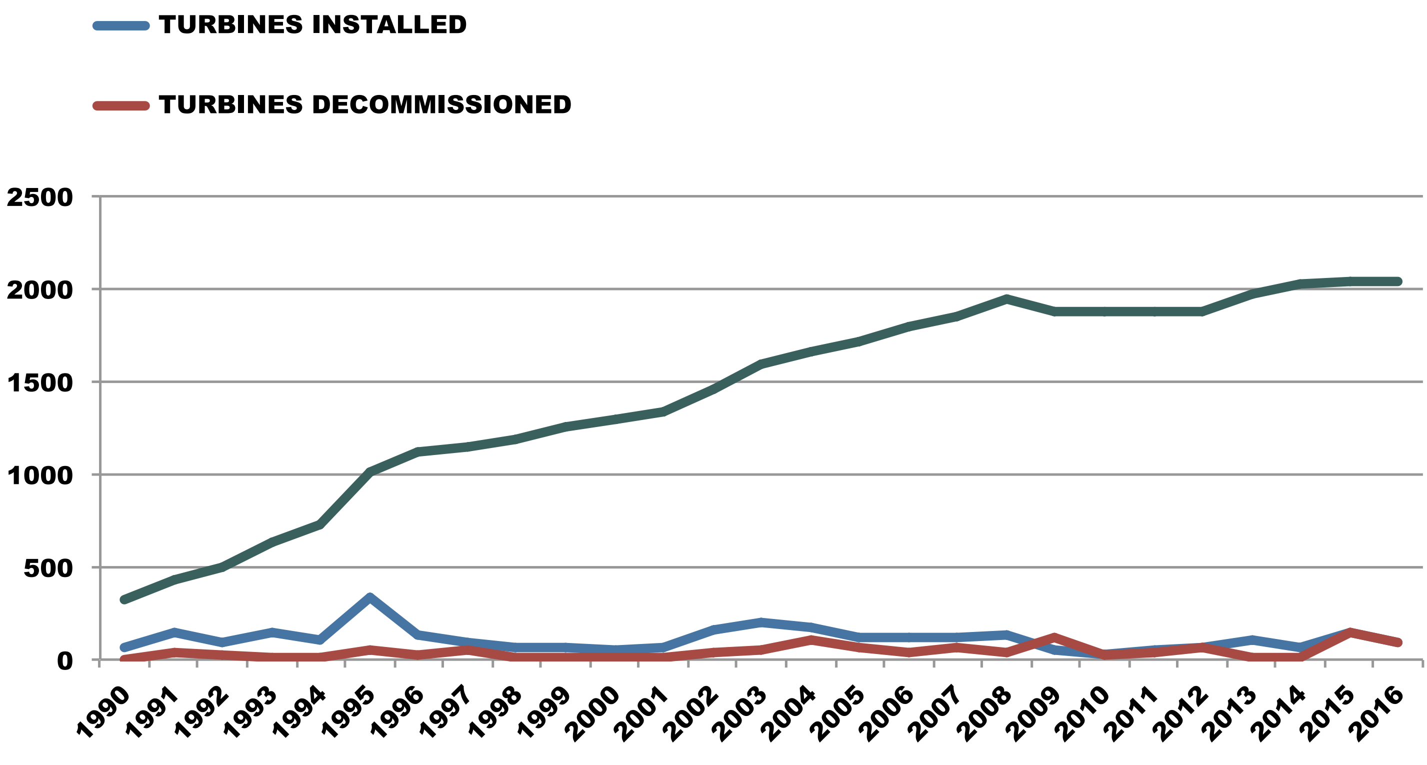
STIJN SPEKSNIJDER



APPENDIX A: MARKET ANALYSIS DATA

Windenergie op land; productie en capaciteit per provincie				
		Turbines installed	Turbines decommissioned	Turbines in use at the end of the year
Nederland	1990	70	.	323
Nederland	1991	143	37	429
Nederland	1992	88	20	497
Nederland	1993	145	9	633
Nederland	1994	106	15	724
Nederland	1995	336	52	1008
Nederland	1996	131	24	1115
Nederland	1997	89	56	1148
Nederland	1998	62	17	1193
Nederland	1999	70	10	1253
Nederland	2000	47	9	1291
Nederland	2001	60	9	1342
Nederland	2002	153	41	1454
Nederland	2003	200	56	1598
Nederland	2004	168	112	1654
Nederland	2005	125	69	1710
Nederland	2006	121	37	1794
Nederland	2007	123	62	1855
Nederland	2008	131	44	1942
Nederland	2009	52	118	1876
Nederland	2010	28	27	1877
Nederland	2011	47	42	1882
Nederland	2012	65	65	1882
Nederland	2013	111	16	1977
Nederland	2014	62	11	2028
Nederland	2015	148	144	2032
Nederland	2016	98	89	2041

Source: CBS StatLine (2017) Windenergie op land; productie en capaciteit per provincie. Retrieved February 23, 2018, from http://statline.cbs.nl/StatWeb

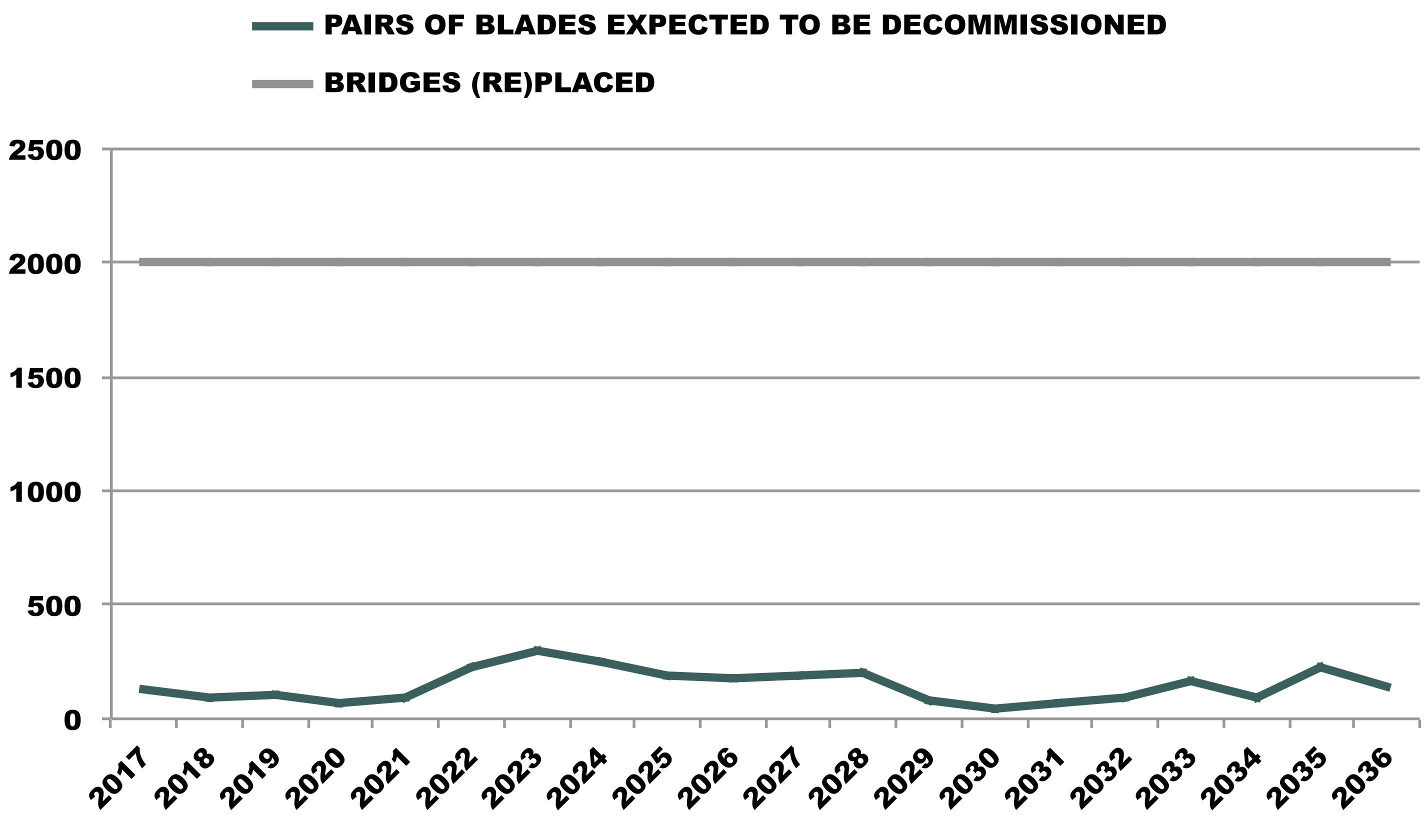


TURBINES INSTALLED
TURBINES DECOMMISSIONED
2500
2000
1500
1000
500
0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016

APPENDIX A: MARKET ANALYSIS DATA

Year	Pairs of blades expected to be decommissioned	Bridges (re)placed
2017	133,5	2000
2018	93	2000
2019	105	2000
2020	70,5	2000
2021	90	2000
2022	229,5	2000
2023	300	2000
2024	252	2000
2025	187,5	2000
2026	181,5	2000
2027	184,5	2000
2028	196,5	2000
2029	78	2000
2030	42	2000
2031	70,5	2000
2032	97,5	2000
2033	166,5	2000
2034	93	2000
2035	222	2000
2036	147	2000

Own interpretation of CBS StatLine (2017)



PAIRS OF BLADES EXPECTED TO BE DECOMMISSIONED
BRIDGES (RE)PLACED
2500
2000
1500
1000
500
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036

APPENDIX B: FINITE ELEMENTS ANALYSIS CONNECTOR

An FEA was done to see if the connectors could be produced from Conenor's thermoset FRP-waste reinforced composites.

For the analysis, research data presented by the company was used (Figure 4). The yield strength and Young's modulus were taken from the FRC1 properties (flexural strength & modulus; no other values exist).

The density and poisson's ratio of the material was estimated by combining these values from the source materials and their share in the material (Figure 1).

The load was derived from EN 1317-6: *No structural failure should occur when a line force of 1kN/m acts either vertically or horizontally on the parapet*. Because the parapet is connected to the deck every 2 meters, a horizontal load of 2 kN was applied.

The critical aspect in this analysis was the maximum stress (vonMises) that would occur in the connector. This value came out at 35 MPa, just safely within the 36,2 MPa yield strength. Although this is close, the vonMises indicates an absolute maximum, so the structure is likely to be sufficient. For safety reasons, further testing could be done.

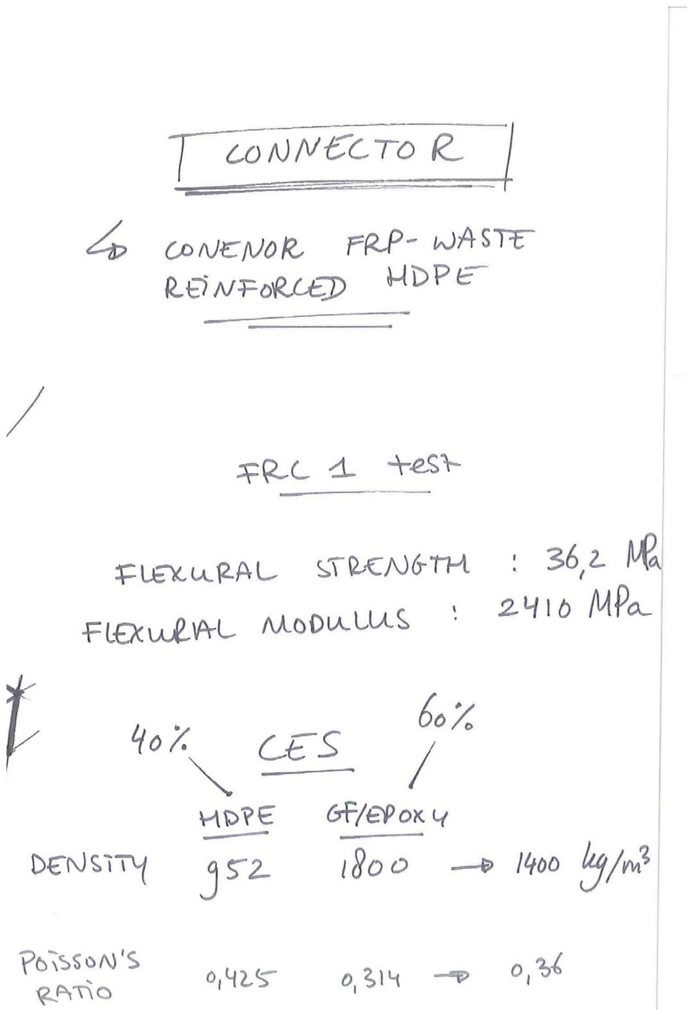


Figure 1: Material properties

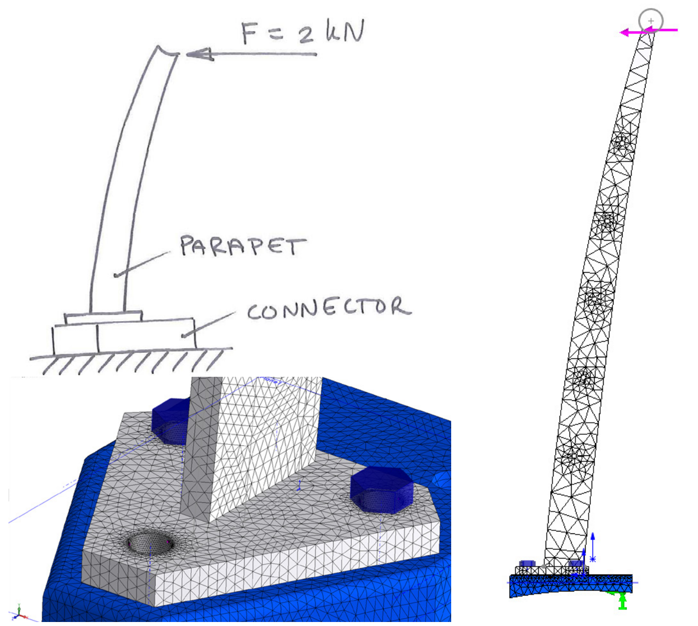


Figure 2: FEA conditions

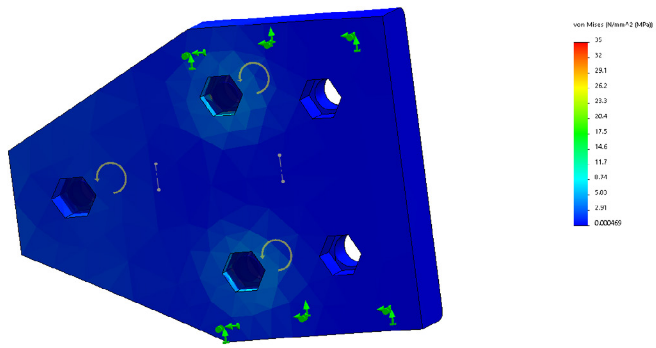
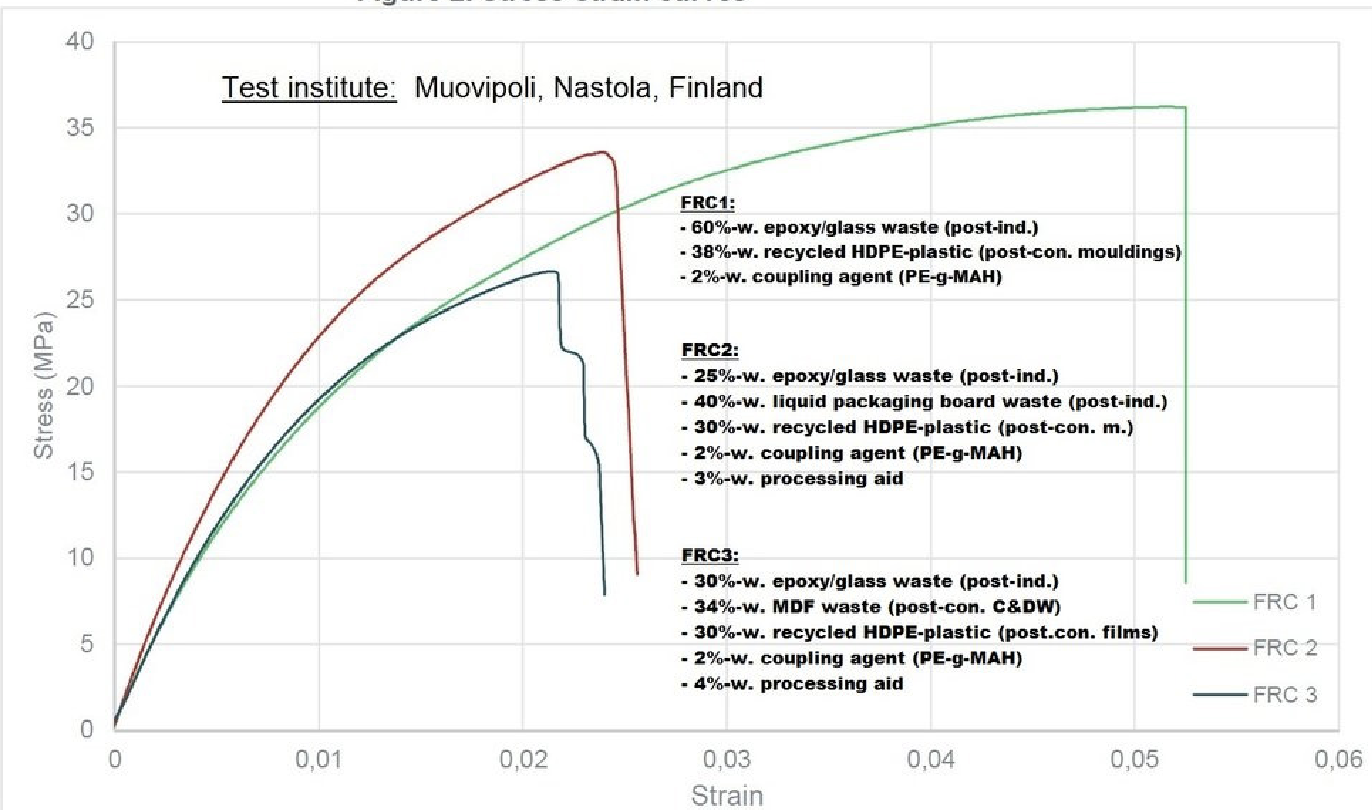


Figure 3: Result

Table 1. Flexural properties, EN ISO 178

Sample	Maximum Load (N)	Flexural Strength σ_{Max} (MPa)	Strain at flexural strength ε_{Max}	Stress at Break σ_B (MPa)	Strain at Break ε_B	Flexural Modulus E_f (MPa)
FRC 1	170 ± 14,6	36,2 ± 2,34	0,052 ± 0,003	20,40 ± 16,10	0,053 ± 0,003	2410 ± 145
FRC 2	157 ± 3,2	33,6 ± 0,81	0,024 ± 0,001	15,40 ± 10,70	0,025 ± 0,001	2970 ± 50
FRC 3	135 ± 4,3	27,0 ± 0,55	0,022 ± 0,002	10,50 ± 7,17	0,023 ± 0,002	2530 ± 155

Figure 2. Stress-strain curves



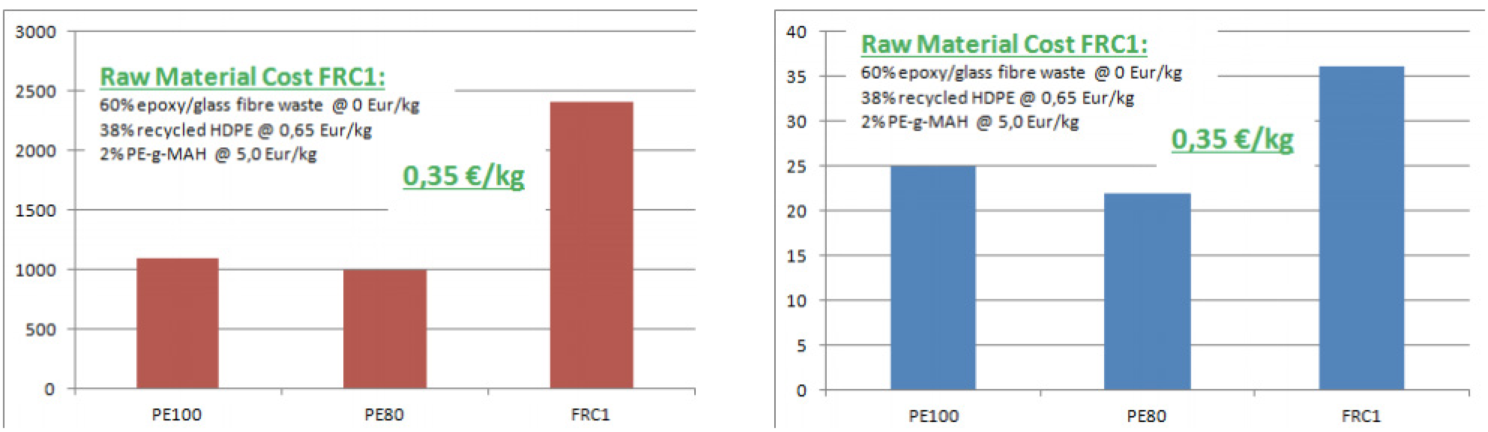


Figure 4: Conenor material properties

APPENDIX C: FINITE ELEMENTS ANALYSES BRIDGE

MODEL

Because of the highly complicated hybrid design of the blades, within this project, no accurate finite element analysis could be performed. However, because of the importance of such an analysis for the design to be realistic, a very rough approximation of the analysis was done.

The shape of the blades was based on the 29m blade that was offered by Virol in this project (brand and model unknown). Dimensions were estimated from photos, and measured from a section cut out of the blade. This shape was heavily simplified, and the amount of materials reduced, to be able to mesh and simulate properly using SolidWorks Simulation.

The span of the bridge was chosen to be 25 meters, which is 86% of the 29m blade length and a rather extreme circumstance. Although the blade actually has a second shear web in a part of the blade, this was not modelled to make the model less complex. This also generates more extreme results.

The deck was designed as a one-piece aluminium sheet with a thickness of 68mm. This way, the deck had the same deformation properties as a BRS Lightdeck-110-CPM-03, while making meshing and simulation doable in a reasonable time.

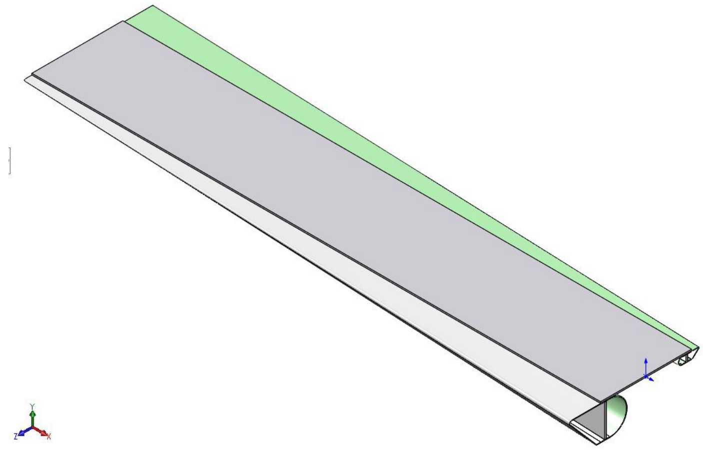


Figure 5: Model in isometric view

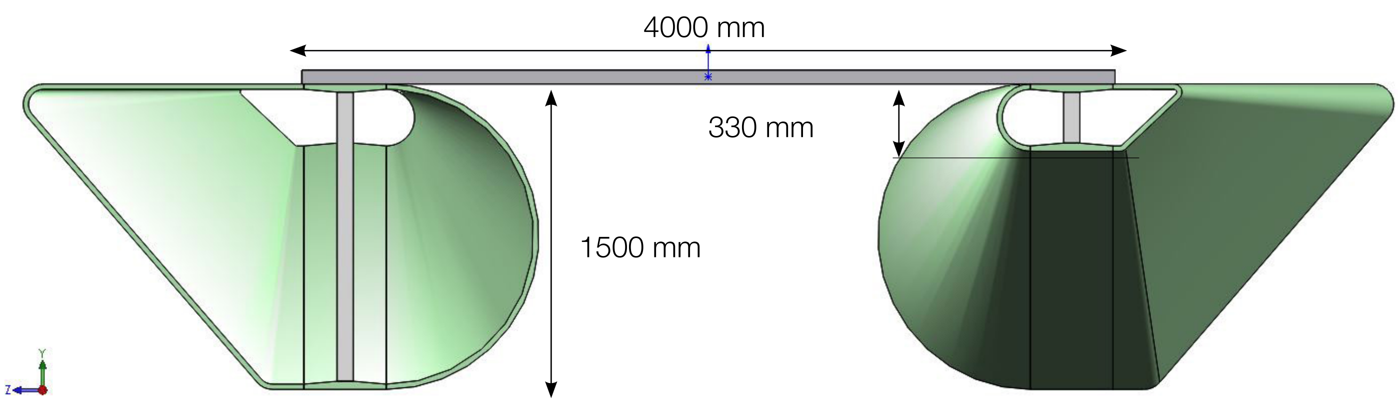


Figure 6: Model in front view

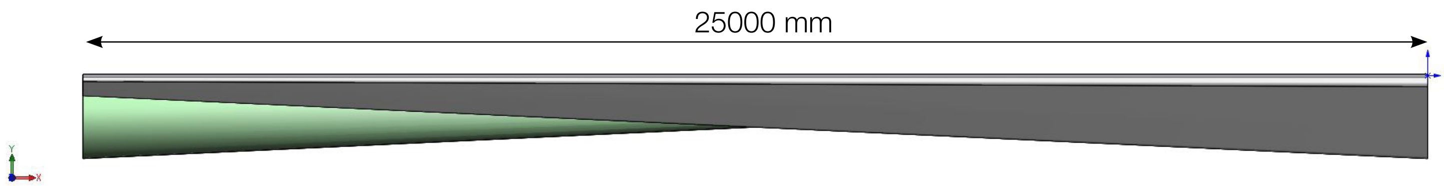


Figure 7: Model in side view

LOADS

Loads were based on requirements as described in requirement 10 of the list of requirements, based on NEN-EN 1991-2 (2003). The most critical circumstances were identified:

- A distributed vertical pressure (q_{fk}) of 5 kN/m^2

- A combination of the vertical pressure q_{fk} and the horizontal load $Q_{flk} = q_{fk} * 0.10$

The maximum deflection in the Y-direction was biggest when only a vertical load was applied. All other results were most critical under the combination load.

FIXTURES

The fixtures were modelled as a fixed support on one end and a roller support on the other end, which is most similar to how bridges are supported on both ends.

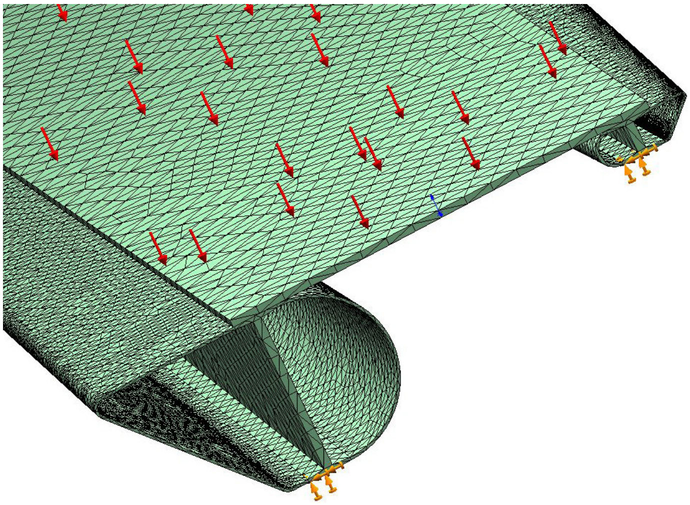


Figure 9: Mesh detail

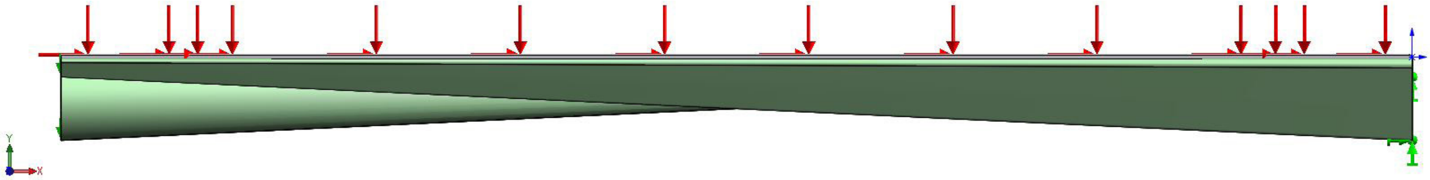


Figure 8: Loads & fixtures

DATA TO ANALYSE

WHAT	LOAD	VALUE	MATERIAL	ALLOWED VALUE
Maximum deflection (Y-direction)	q_{fk}			
Stress in spar caps (vonMises)	$q_{fk} + Q_{flk}$			
Stress in shell (vonMises)	$q_{fk} + Q_{flk}$			
Stress in shear web (vonMises)	$q_{fk} + Q_{flk}$			
Sideways deck angle	$q_{fk} + Q_{flk}$			

APPENDIX C: FINITE ELEMENTS ANALYSES BRIDGE

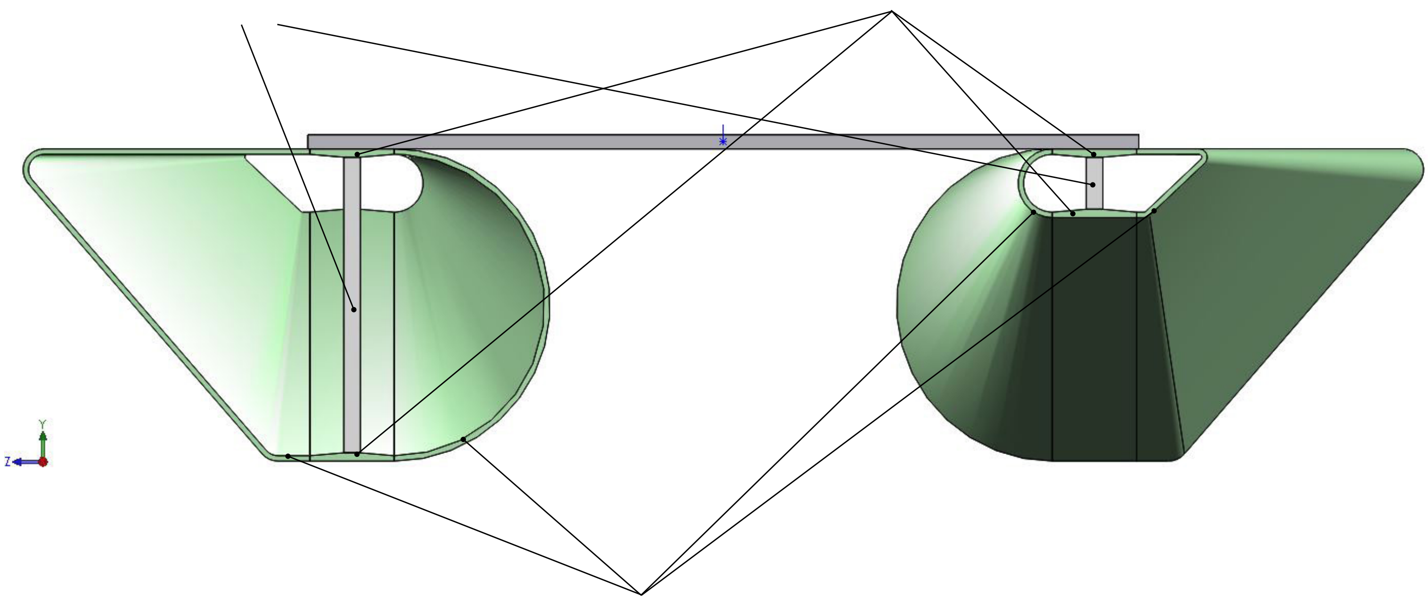
ANALYSIS 1: SHELL = FRP

RIGID POLYMER FOAM
POLYMETHACRYLIMIDE RIGID 60 WIND-F
(Rohacell, 2017)

Mass density: 60 kg/m3
E-modulus: 0.08 GPa (CES EduPack, 2017)
Poisson’s ratio: 0.3 (CES)
Shear modulus: 30 MPa
Tensile strength: 1.7 MPa
Compressive strength: 1.0 MPa
Yield strength: 1.5 MPa (Ces EduPack, 2017)

EPOXY / E-GLASS FIBER
UNIDIRECTIONAL LAYUP - LOW END
(CES EduPack, 2017)

Mass density: 1800 kg/m3
E-modulus: 35 GPa
Poisson’s ratio: 0.2
Shear modulus: 14.5 GPa
Tensile strength: 500 MPa
Compressive strength: 400 MPa
Yield strength: 500 MPa



EPOXY / E-GLASS FIBER WOVEN BI-AXIAL - LOW END
(CES EduPack, 2017)

Mass density: 1800 kg/m3
E-modulus: 26.4 GPa
Poisson’s ratio: 0.15
Shear modulus: 5 GPa
Tensile strength: 400 MPa
Compressive strength: 300 MPa
Yield strength: 400 MPa

Figure 10: Model in front view

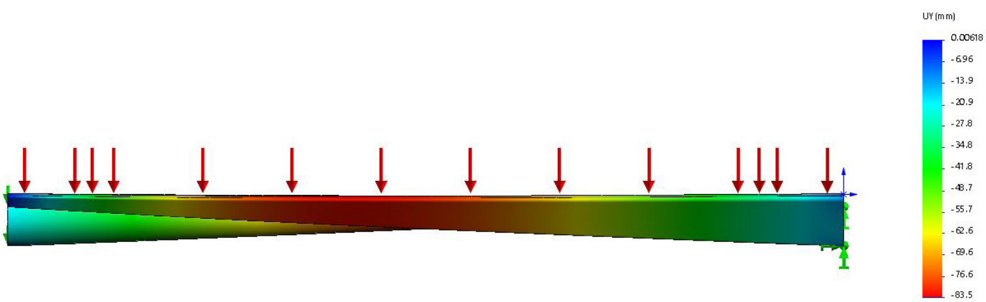
RESULTS

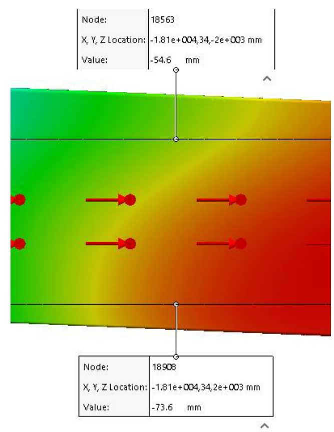
Maximum allowed deflection = 1/200 * span = 1/200 * 25000 = 125 mm

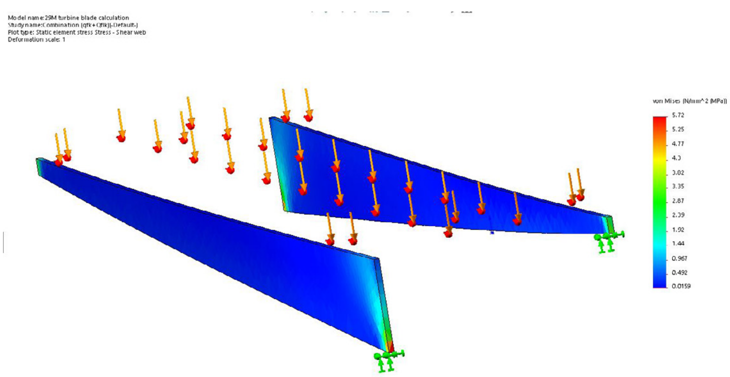
Maximum sideways deck angle = ?

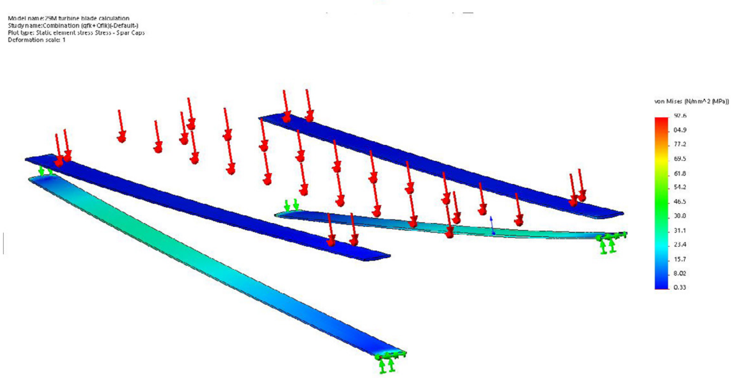
Other allowed values are defined by material’s yield strength.

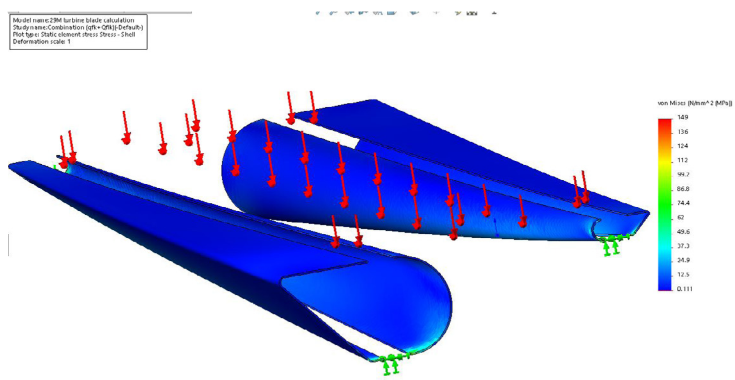
WHAT	LOAD	MATERIAL	ALLOWED VALUE	VALUE
Maximum deflection (Y-direction)	q_{flk}	-	< 125 mm	83.5 mm
Stress in spar caps (vonMises)	$q_{fk} + Q_{flk}$	E-GFRP Unidirectional	< 500 MPa	92.6 MPa
Stress in shell (vonMises)	$q_{fk} + Q_{flk}$	E-GFRP Bi-axial	< 500 MPa	149 MPa
Stress in shear web (vonMises)	$q_{fk} + Q_{flk}$	Rigid Polymer Foam	< 1.5 MPa	5.72 MPa
Sideways deck angle	$q_{fk} + Q_{flk}$	-	??	0.27°











APPENDIX C: FINITE ELEMENTS ANALYSES BRIDGE

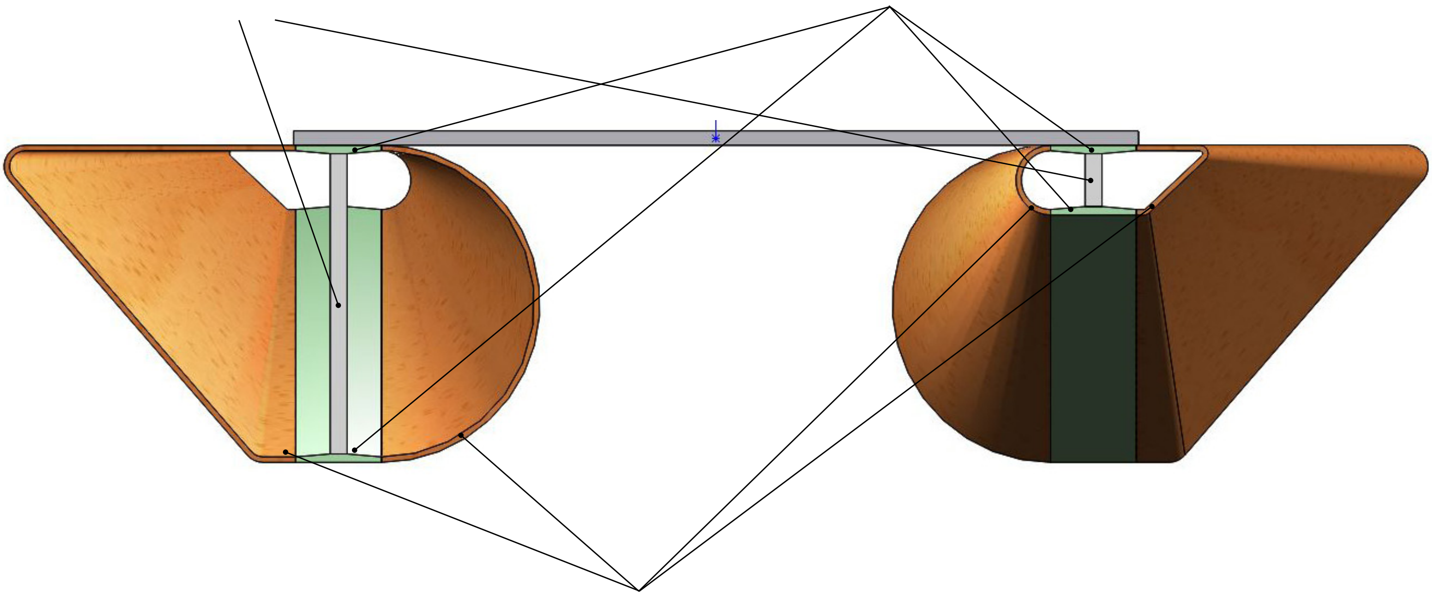
ANALYSIS 2: SHELL = BALSA

RIGID POLYMER FOAM
POLYMETHACRYLIMIDE RIGID 60 WIND-F
(Rohacell, 2017)

Mass density: 60 kg/m3
E-modulus: 0.08 GPa (CES EduPack, 2017)
Poisson's ratio: 0.3 (CES)
Shear modulus: 30 MPa
Tensile strength: 1.7 MPa
Compressive strength: 1.0 MPa
Yield strength: 1.5 MPa (Ces EduPack, 2017)

EPOXY / E-GLASS FIBER
UNIDIRECTIONAL LAYUP - LOW END
(CES EduPack, 2017)

Mass density: 1800 kg/m3
E-modulus: 35 GPa
Poisson's ratio: 0.2
Shear modulus: 14.5 GPa
Tensile strength: 500 MPa
Compressive strength: 400 MPa
Yield strength: 500 MPa



BALSA WOOD
ULTRA LOW DENSITY
(CES EduPack, 2017)

Mass density: 160 kg/m3
E-modulus: 3.0 GPa
Poisson's ratio: 0.4
Shear modulus: 0.25 GPa
Tensile strength: 12 MPa
Compressive strength: 8 MPa
Yield strength: 9 MPa

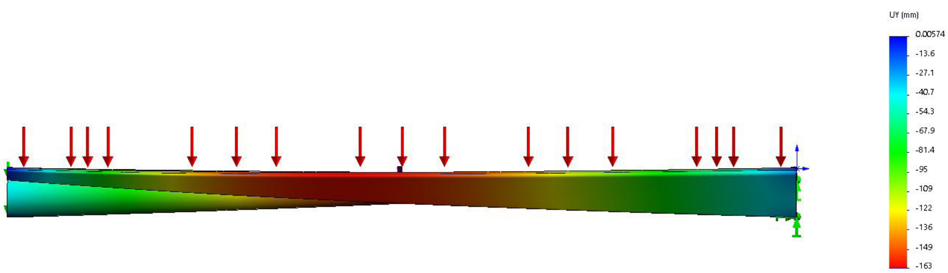
RESULTS

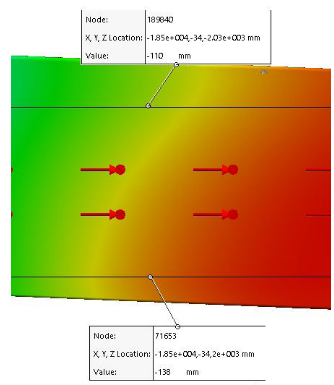
Maximum allowed deflection = 1/200 * span = 1/200 * 25000 = 125 mm

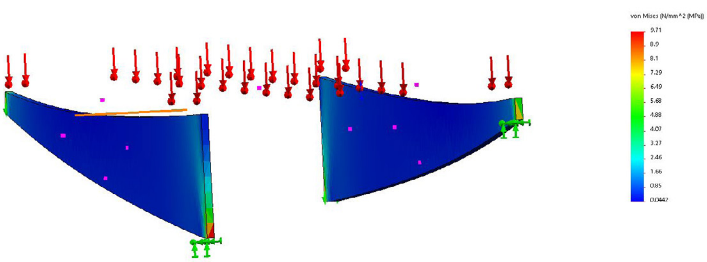
Maximum sideways deck angle = ?

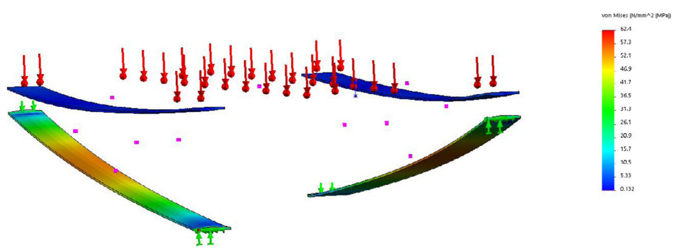
Other allowed values are defined by material's yield strength or compressive strength, whichever is more critical.

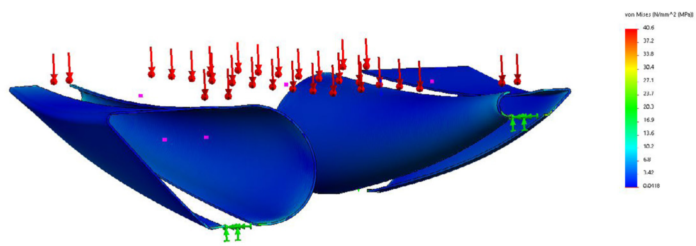
WHAT	LOAD	MATERIAL	ALLOWED VALUE	VALUE
Maximum deflection (Y-direction)	q_{flk}	-	< 125 mm	163 mm
Stress in spar caps (vonMises)	$q_{flk} + Q_{flk}$	E-GFRP Unidirectional	< 500 MPa	62.4 MPa
Stress in shell (vonMises)	$q_{flk} + Q_{flk}$	Balsa wood	< 9 MPa	40.6 MPa
Stress in shear web (vonMises)	$q_{flk} + Q_{flk}$	Rigid Polymer Foam	< 1.5 MPa	9.71 MPa
Sideways deck angle	$q_{flk} + Q_{flk}$	-	??	0.40°



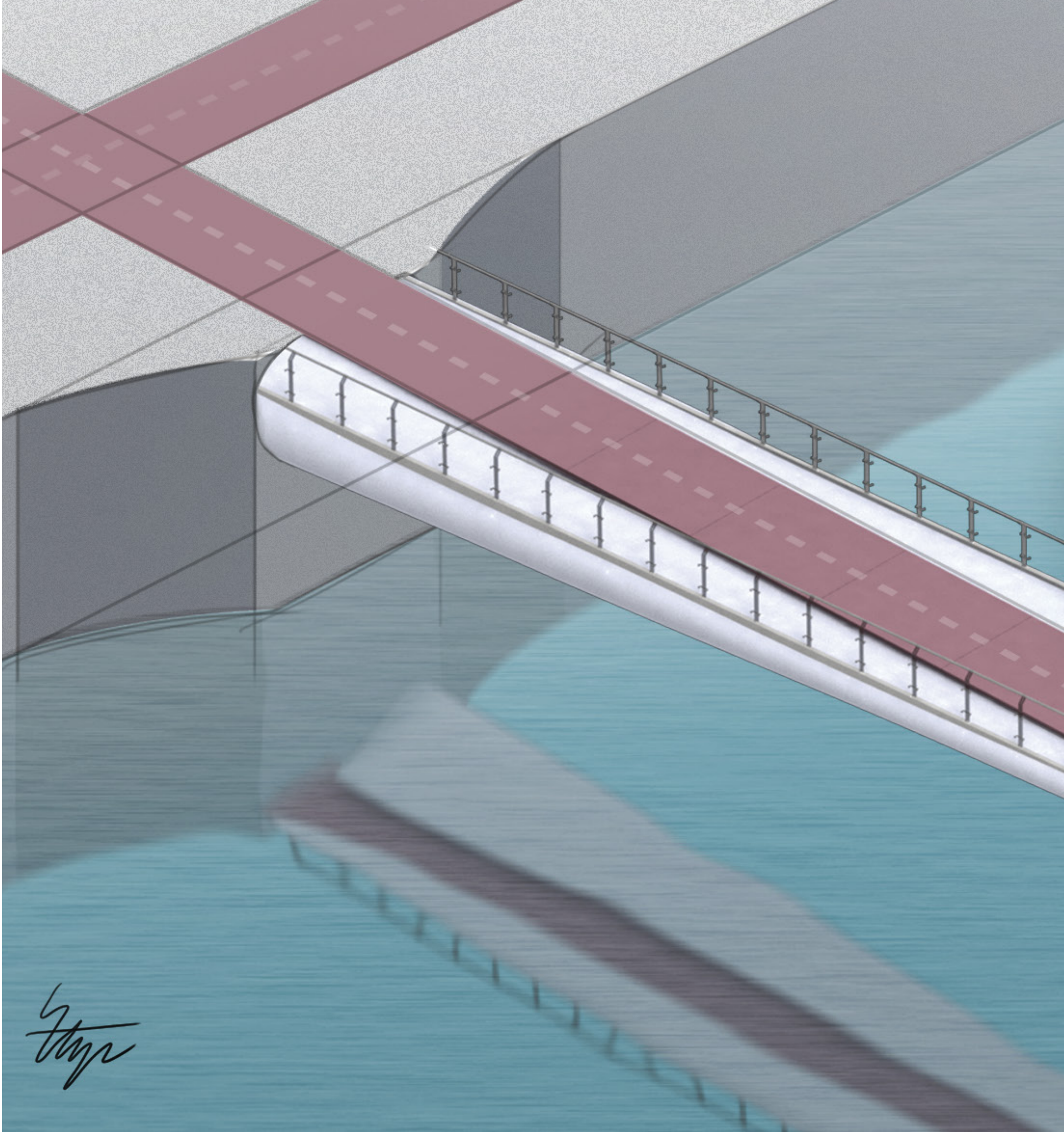


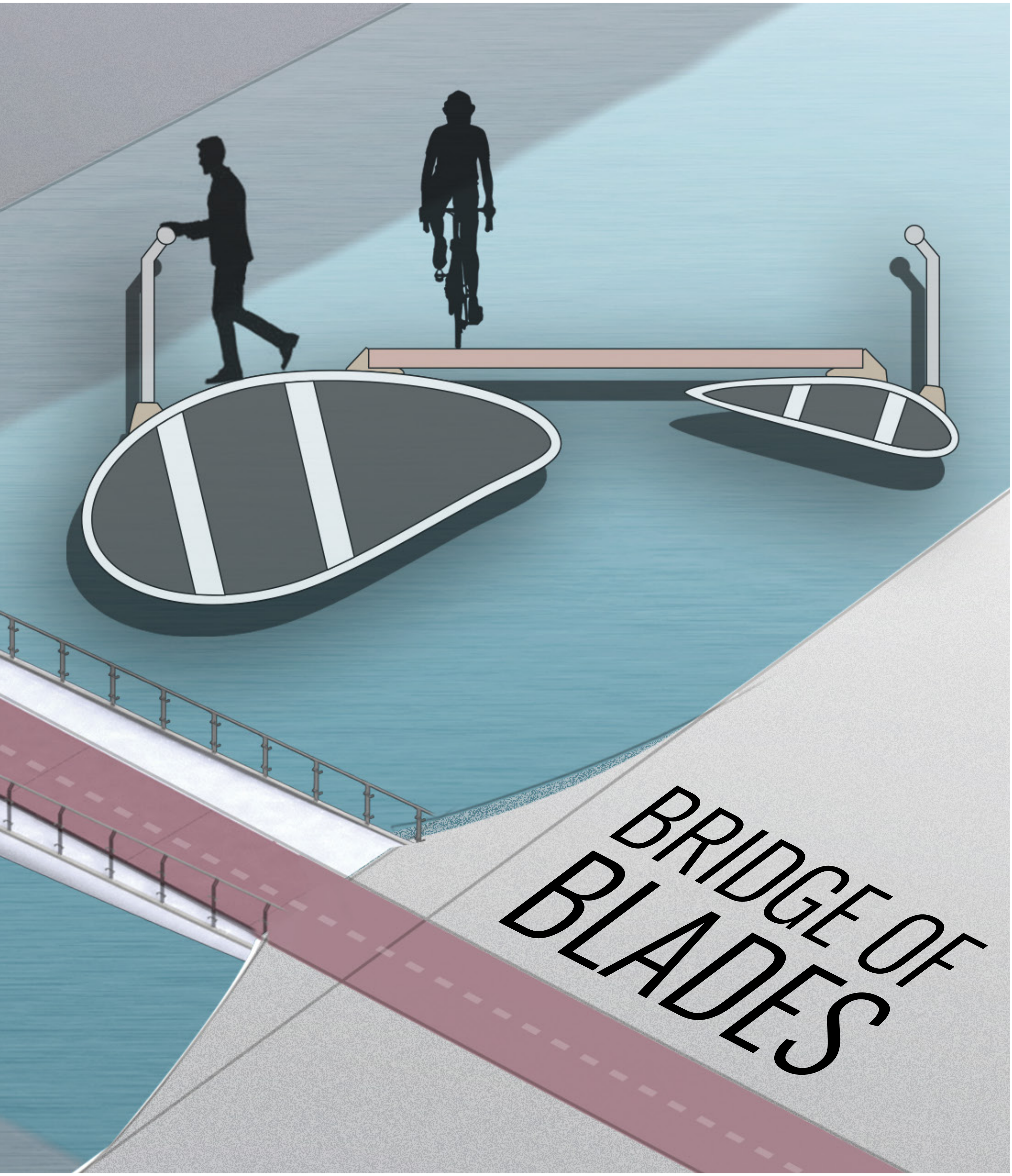




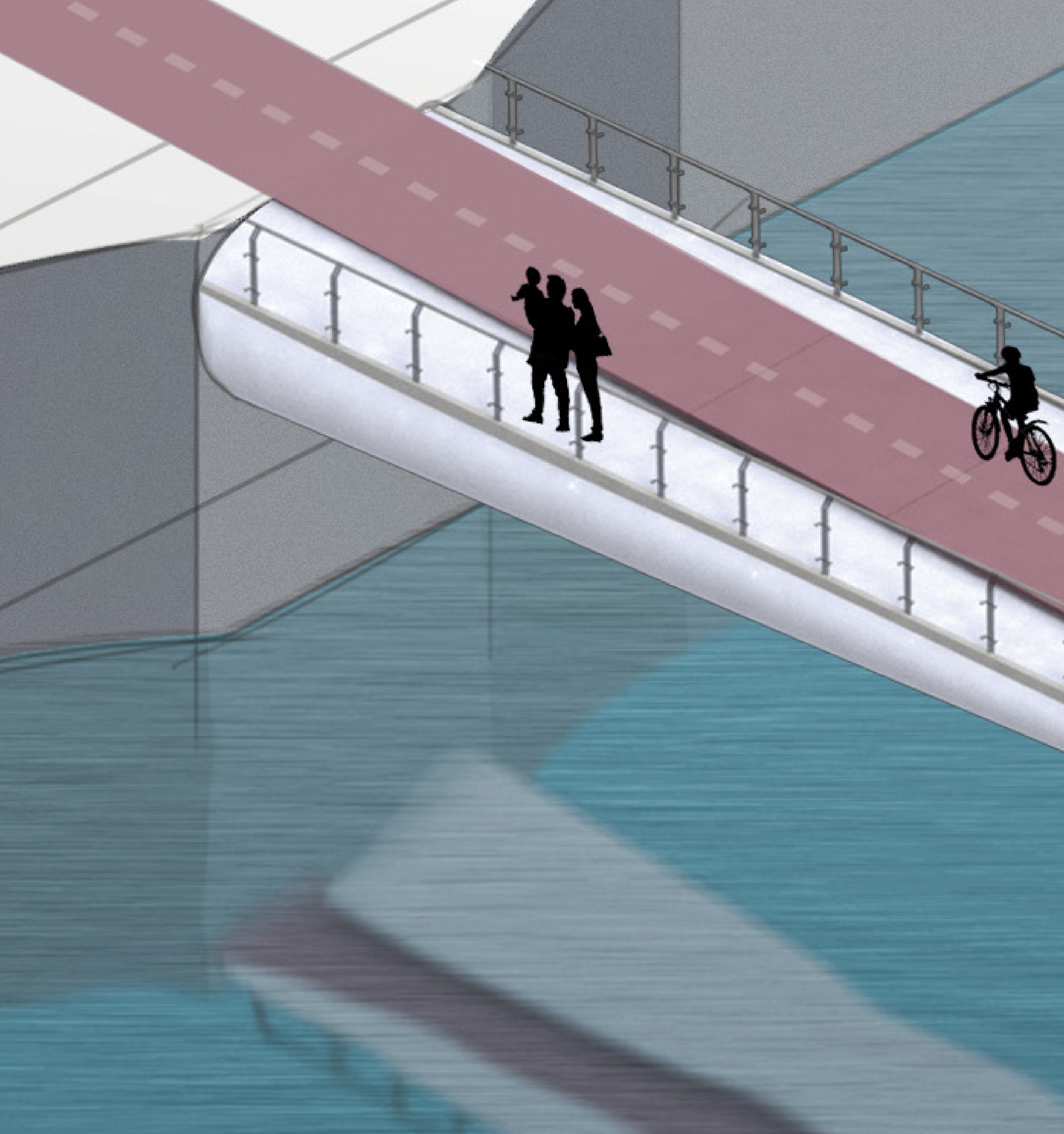


APPENDIX D: OLD BRIDGE DESIGNS

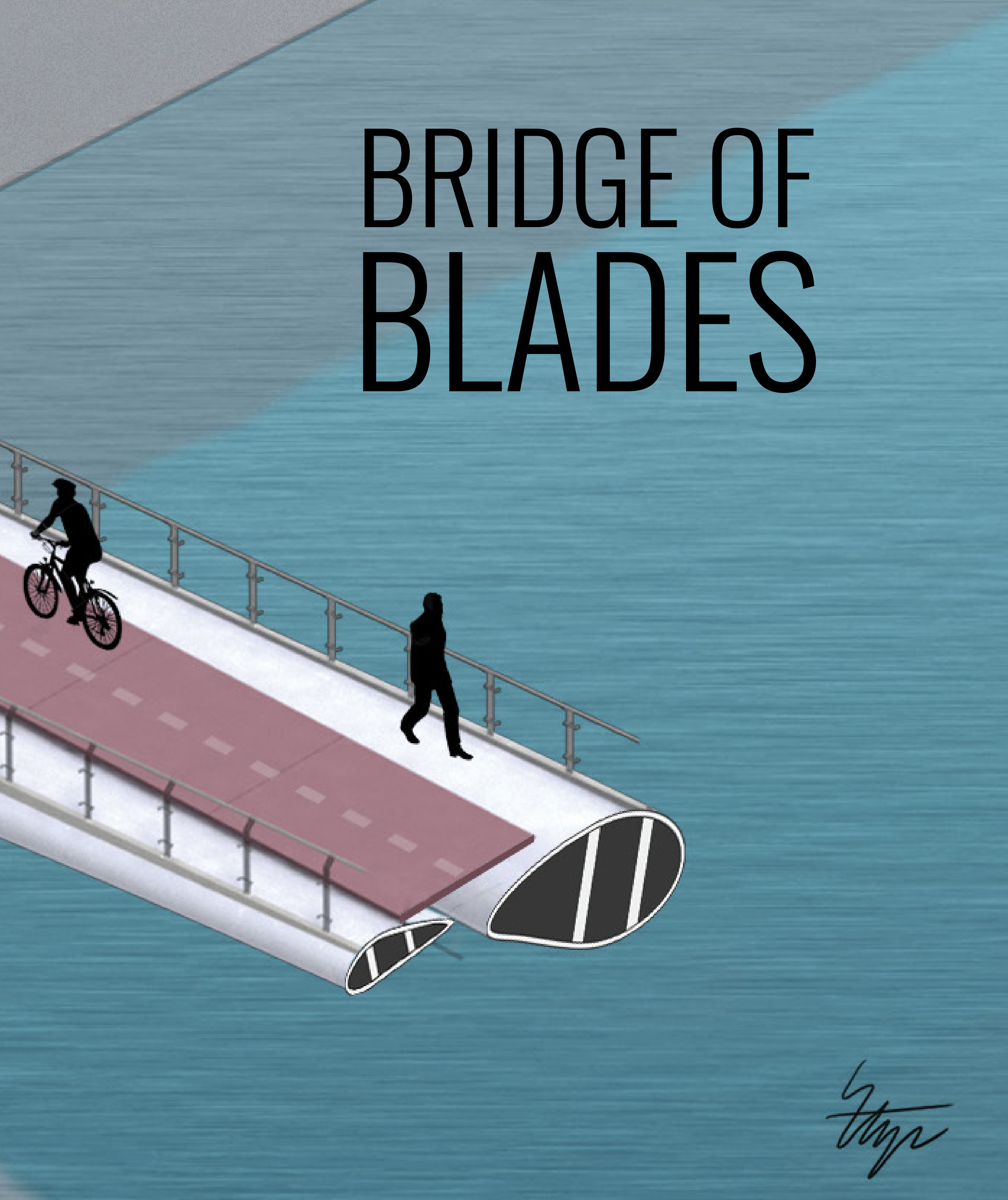



BRIDGE OF
BLADES

APPENDIX D: OLD BRIDGE DESIGNS



BRIDGE OF BLADES



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