TU Delft

Delft University of Technology

The Art of Bridge Design

Identifying a design approach for well-integrated, integrally-designed and socially-valued bridges

Smits, Joris

DOI
10.7480/abe.2019.3

Publication date
2019

Document Version
Final published version

Citation (APA)
Smits, J. (2019). *The Art of Bridge Design: Identifying a design approach for well-integrated, integrally-designed and socially-valued bridges*. [Dissertation (TU Delft), Delft University of Technology]. A+BE | Architecture and the Built Environment. https://doi.org/10.7480/abe.2019.3

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Architecture and the Built environment

#03
2019



The Art of Bridge Design

Identifying a design approach for well-integrated, integrally-designed and socially-valued bridges

Joris Smits

The Art of Bridge Design

Identifying a design approach for well-integrated, integrally-designed and socially-valued bridges

Joris Smits
Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Architectural Engineering + Technology

Architecture and the Built environment

abe.tudelft.nl

Design
Sirene Ontwerpers, Rotterdam

Photography
Cover: One of the two Navel Bridges in Getsewoud, Nieuw Vennep, the Netherlands, photo by Bart Nijs 2004. **Pages 42-44:** Dommelbrug Eindhoven, photos by Jan van Oevelen 2006. **Pages 68-69:** Julianabrug Zaanstad, photos by Jane van Raaphorst 2010. **Page 70:** Julianabrug Zaanstad, photo by Luuk Kramer 2009. **Page 96:** ShArc Bridge Berlin, image by Rafail Gkaidatzis 2017.**Page 122:** Nelson Mandela Bridge Alkmaar, foto by Jane van Raaphorst 2016.**Page 144:** Bio-composite footbridge Eindhoven, foto by Heijmans 2018. **Pages 182-183:** Hoogtijbrug Zaanstad, photo by Bart Nijs 2006. **Page 184:** Kolenhavenbrug Delft, photo by Bart Nijs 2004.

All bridges designed by Joris Smits, Royal HaskoningDHV/Delft University of Technology

ISBN 978-94-6366-164-5
ISSN 2212-3202

© 2019 Joris Smits

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without written permission from the author.

Unless otherwise specified, all the photographs in this thesis were taken by the author. For the use of illustrations effort has been made to ask permission for the legal owners as far as possible. We apologize for those cases in which we did not succeed. These legal owners are kindly requested to contact the publisher.

The Art of Bridge Design

Identifying a design approach for well-integrated, integrally-designed and socially-valued bridges

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Tuesday 7, May 2019 at 10:00 o'clock

by

Joseph Egidius Petrus SMITS
Master of Science in Architecture & Master of Science in Civil Engineering
Delft University of Technology, the Netherlands
born in Amsterdam, the Netherlands

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairman
Prof.ir. R. Nijsse,	Delft University of Technology, promotor
Dr. ing. S. Nijhuis,	Delft University of Technology, copromotor

Independant members:

Prof. O. Popovic Larsen	The Royal Danish Academy of Fine Arts, Denmark
Prof. P.J.S. Cruz	University of Minho, Portugal
Prof. Dr. sc. techn. M. Schlaich	Technische Universität Berlin, Germany
Prof.dr.ir. M.J.C.M. Hertogh	Delft University of Technology
Prof.dr.ir. T. Klein	Delft University of Technology, reserve member

Other members:

Prof. Dr.-Ing. P.M. Teuffel	Eindhoven University of Technology
Dr.ir. F.D. van der Hoeven	Delft University of Technology

To my parents
Annemijn
Sofie & Tom



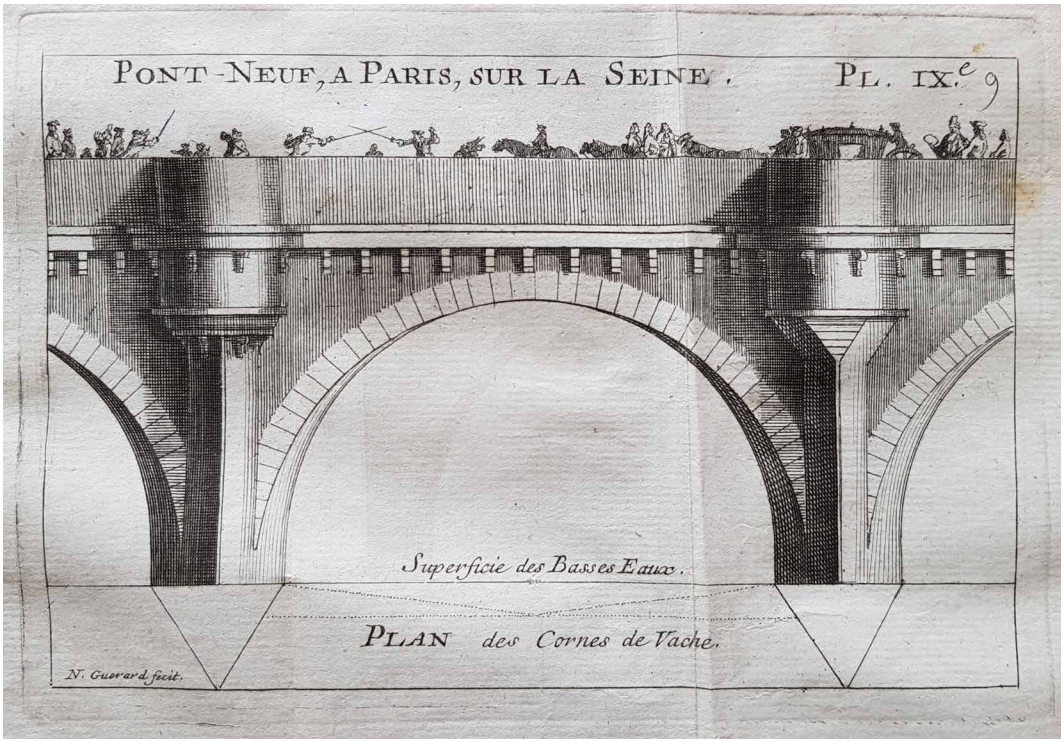
TRAITÉ DES PONTS.

Preface

Early 2017 I read an old book that shed a new light on the writing of this dissertation. At that time I had been working on my dissertation on and off for over five years and the end was not in sight. Ever since I took a part-time position as a lecturer in 2012, I had been engaged in a balancing act between two busy jobs, having one foot in the academic world and one foot in practice as an architect and designer of bridges. At first, teaching and working with students gave me a lot of energy and opened my mind to new ideas, and was as such very beneficial to my work as an architect. However, the combination of working two jobs and writing a dissertation as well proved no easy task. Even though I managed to write some journal papers during brief bursts of writing frenzy, I had become aware that the balance between work and family life had imperceptibly tilted to the wrong side. By the end of 2016 it became clear to me that my inner machine needed a major revision. I needed time for myself to think about the further development of my career(s), so come Christmas eve I took a six week break from work.

To distract my mind, I started reading Henri Gautier's 'Traité des Ponts' [1], the very first comprehensive handbook for bridge designers (figure 1). My fellow board member of the Dutch Bridge Foundation and a fervent Francophile, Jan de Boer, had lent me his first edition from 1716, a beautiful leather-bound specimen with intriguing engravings of bridges, details of joints and depictions of various tools employed in the art of early eighteenth century bridge building. I have always had a fascination for old books and history and I was curious about this fellow bridge designer from the time of Louis XIV. Despite the old French language and the somewhat different typography, the 'Traité des Ponts' turned out to be surprisingly accessible reading material. Reading the Traité provided me with a whole new lens to look at my dissertation subject. In fact, looking back on my subject across a bridge of three hundred years proved to be a very good remedy against my writers block.

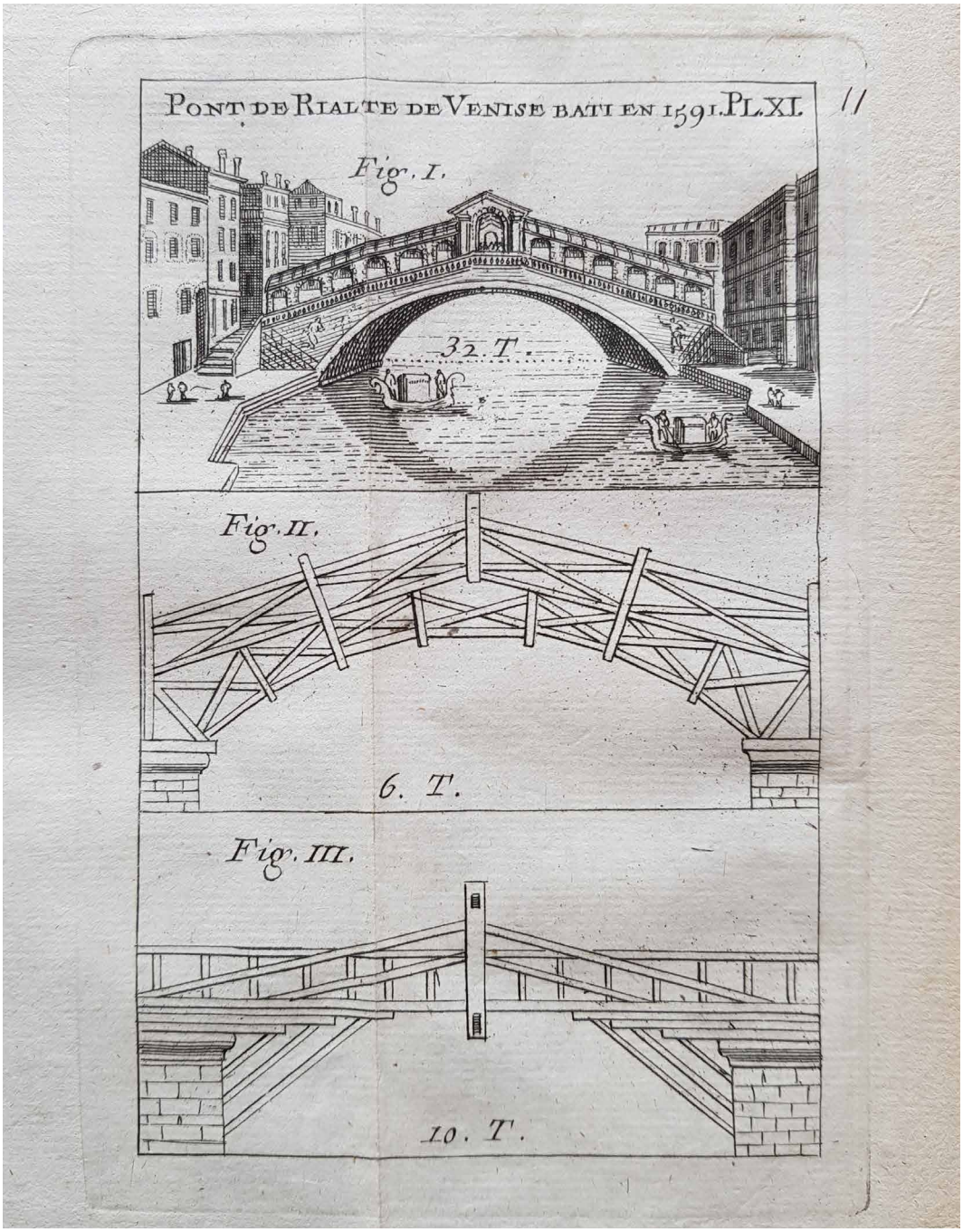
Henri Gautier (1660-1737), who was sometimes referred to as Hubert Gautier, was an architect, engineer and inspector of the 'Corps des grands Chemins, Ponts, & Chaussées du Royaume', the erstwhile corps of engineers for roads and bridges at the service of the king of France. From his own rich working experience, Gautier writes about a discipline that he and I both share. For an engineer in the service of the king, his writing is remarkably down-to-earth. He writes very spontaneously and with plenty of self-reflection about his metier. I especially enjoyed discovering parallels between Gautier's practice and the current bridge building practice.



The Pont-Neuf in Paris, one of Gautier's many drawings from the *'Traité des Ponts'*.

Gautier wrote his Traité out of dire necessity as he had noticed that not a single architectural author had so far concerned himself with the art of bridge building. To his frustration only sideway glances on the subject of bridge design were offered in the literature of those days and he wondered how a schooled architect was supposed to learn the art of bridge design if his training was deprived of the right books on the subject. He further notes that even the great Vitruvius, the Roman architect of antiquity, doesn't dignify to write on the art of bridge design. For this reason Gautier took it upon himself to collect what little had been written on the subject and to comment on it. More important however is that Gautier shares with us his own practice experience acquired through the many bridges he had built in his lifetime. It is interesting to note that Gautier does not write to impress the reader with the vast extent of his knowledge. Rather he writes out of a personal motivation to share his knowledge, dedicating his work to '*those that are ignorant*' (on this specific subject, red.). Gautier deeply feels it to be his duty to share his experience, describing the tools and the means that he employed to come to a bridge designs, all in a way that makes it easy to understand. According to Gautier bridges are '*amongst the most difficult of structures (to design and to build, red.), deserving our full attention, and belong to a domain of Architecture where there are the most precautions to keep, more place to fear and to doubt, and to which one can never take too much care*'.

At times, reading the Traité was like a déjà vu; the parallels to my own practice brought a smile on my face. I found it most refreshing to note that a certain amount of friction between architects, engineers and contractors appears to be of all ages. Gautier doesn't hold contractors in a very high regard. According to him '*Contractors do not hesitate to enrich themselves at the expense of the King or of those who work for them. Engineers or inspectors of the works, on the contrary, have only in mind the honesty with which they act and [the desire red.] to be highly esteemed. They do not hesitate to regard the former as their enemies, when they are unfaithful.*' (p.248). Nowadays, it is fortunate for all parties involved in the building of a bridge that the laws and fines imposed for building faults have been adapted to modern times, as can be appreciated from this fragment on legal guaranties. '*If the structure is made out of earth or out of a mediocre material, a six year warranty must be given and in case of a fault committed by the contractor, the law indicates that said contractor shall be whipped, shaven and banned.*" (p.225). Gautier however finds these laws to be unjust as he believes that the responsibility for a fault should to some extent be shared by the architect if it is the design that is to blame.



The *'Traité des Ponts'* describes at great length how bridges are build. Example of scafolding structure of the Rialto Bridge in Venice.

These amusing notes set aside, Gautier concludes his preface with the following recommendation that I choose to quote in Gautier's original words:

> *'Le sujet des Ponts est assez vaste pour donner de l'occupation aux plus habiles. Jusqu'ici personne n'a traité de cette matière autant qu'elle le mérite. J'ai osé l'entreprendre, & je souhaite que quelqu'autre fasse mieux, afin que tout le monde en profite davantage.'*

I would translate this ancient French text as follows :

> *'The topic of Bridges is vast enough to give occupation to the most skilled. So far no one has dealt with this subject as well as it deserves to be treated. I have dared to undertake it, and I wish someone else would do better, so that everyone can benefit from it to the full.'*

Three hundred years later, reading this very personal recommendation from a fellow bridge designer opened my eyes. What more encouragement did I need to write a dissertation on the topic of bridge design! And like Gautier, I have undertaken this task to the best of my knowledge and experience, hoping it will benefit those who choose to venture in the challenging art of bridge design.

Reference

[1] Gautier, H. (1716). *Traité des Ponts, ou il est parlé de ceux des romains & de ceux des Modernes* ... (1st ed.), Paris, France : Chez André Cailleau.

Acknowledgements

This dissertation could not have been written without the help and support of a great many people. During the writing of it I have experienced valuable support and contributions from my colleagues, both from Delft University of Technology and from Royal HaskoningDHV, as well as from my students who contributed both mentally and physically to some chapters. Also, my family and friends gave me the necessary mental support to carry on with the task. My thanks goes out to every one of them, but some of them should be mentioned in particular, in the hope that I have omitted none.

First of all my gratitude goes out to my promotor Rob Nijsse and to my co-promotor Steffen Nijhuis without whom there wouldn't have been a dissertation in the first place. Throughout his long and vast career, Rob has always proven to be greatly receptive to the subject of bridge design. Thank you Rob for giving me the support and encouragement, but also the liberty that was necessary to find my own voice in this matter. I would like to thank Steffen in particular for showing me all the secret paths to academic thinking and writing, I can assure you that this was not an easy task for someone like myself who had worked outside of the academic field for nearly two decades.

To all the other members of my PhD committee, to Olga Popovic Larsen, to Paolo Cruz, to Patrick Teuffel, to Marcel Hertogh and to Frank van der Hoeven, I owe my grateful acknowledgements. It has been a great honour to receive your expert comments on the concept of my dissertation and I enjoyed discussing with you in detail. For that I thank you all.

The chair of Structural Design & Mechanics, of which I am a staff member since 2012, is a very pleasant and stimulating environment to work in. First, I would like to thank my closest colleagues Ate Snijder, Peter Eigenraam and Rafail Gkaidatzis for their moral support and for participating in my bridge research projects. Thanks to Fred Veer for keeping me downwind at times when I needed to write. Thanks to our lecturers of the old guard, Jan Arends, Wim Kamerling and Hans Daane, for letting me in on the chairs' ways and for making me feel welcome. And thanks to the 'young ones', Faidra Oikonomopoulou, Telesilla Bristogianni, Andrew Borgart and Dirk Rinze Visser for being the great colleagues you are!

From the department of Architectural Engineering + Technology I would especially like to thank prof. Ulrich Knaack for spotting my potential as an academic and for hiring me back in 2012. My warm thanks to prof. Andy van den Dobbelsteen for offering practical and moral support in the writing of my dissertation and for the late night Bebop sessions.

Craig Martin and Tillmann Klein have been invaluable during my first years working as a university teacher, Sarajevo laid the basis of an academic friendship. And thanks to Linda, Barbara, Bo, Francoise, Tessa and Danielle for enduring me.

In terms of research collaboration I would like to acknowledge the input of various researchers and students. My first paper 'A bridge with a view, a view with a bridge' would not have seen the light of day without the indispensable help of my co-author Frank van der Hoeven. I would further like to acknowledge Steffen Nijhuis for his valuable advice on writing my first paper. For the chapter 'Shaping Forces', my thanks go to all my co-authors, Peter Eigenraam, Rafail Gkaidatzis, Dirk Rinze Visser, Kaitlin Wong and Stephan Wassermann-Fry. For the chapter 'the Bio-based composite footbridge' my special thanks to my co-author Rijk Blok without who's intellectual and physical efforts there would have been no bridge at all. Furthermore thanks to Patrick Teuffel, Rafail Gkaidatzis, Dorine van der Linden, Mark Lepelaar, Willem Bottger, Alwin Hoogendoorn and all those students from Eindhoven University of Technology and Avans Hogeschool Breda for building the bio-composite bridge together. And last but not least my gratitude to Marcel Hertogh and Hans de Boer for offering me the invaluable platform of DIMI to boost my research projects and to accommodate my Bridge Research Group.

This dissertation would never have been written without the many colleagues from Royal HaskoningDHV that have worked with me on more than three hundred bridge designs for over 22 years. Designing a bridge is always a matter of teamwork. Often there is more than one author responsible for the design. I would like to acknowledge my (former) colleagues for their valuable contribution to the various projects that appear in this dissertation. However, the one person that deserves my special thanks is Syb van Breda who introduced me to the art of bridge design and with whom I have designed my first bridges. Thanks for taking me along those first years. And later on, thanks for letting me proceed on my own! A special thanks to Freerk Hoekstra who taught me how to be an architect in an engineering environment and who sheltered me on numerous occasions. For the projects featured in this dissertation, in order of appearance, I would further like to thank: Karel Vis, Barend Bekkers, Alessandro De Santis, Corine Zwart, Richard van den Brule, Frank Sengers, Obbe Norbruis, René Rijkers, Sven Spierings, Rafail Gkaidatzis and Carien ten Cate. I further need to acknowledge that there is more to running an office than just a bunch of architects. The invaluable support behind the screens of our direct executives is not always held in high enough esteem. So thank you Joachim Verheij and Niek Joustra for creating the right circumstances for us architects to do what we do best, designing bridges. I am equally grateful to the many commissioning clients of all the bridges that I have had the privilege to design. I realize it is no small matter to commission a bridge and to hire an architect to design it, so I would like to thank you all for the trust you gave me and my team, and for making it possible to build all those wonderful bridges.

Since 2012 I have had the privilege and pleasure to work with my fellow board members of the Nederlandse Bruggenstichting (Dutch Bridge Association). I would like to thank them all, in particular Heico de Lange, Rob Lutke Schipholt, Hans de Haan, Fred Westenberg, Gert Jan Luijendijk and Jan de Boer for your support and your patience with the odd architect on the board.

The start of my professional career was somewhat unconventional. Thank you Carel Weeber for saving me from the boredom of military service by offering me the escape to fulfilling my tour of duty as a conscientious objector at the Architecten Cie. Thank you Pi de Bruin for being my first mentor and for teaching me the politics of being an architect.

To my graduation mentor professor Jan Vambersky I am in twofold debt; first for awakening my architectural interest through your High-rise Building project, a course that aimed to bring architectural and civil engineering students together. And second for warning me that I cannot be an architect and an engineer in one, an advice that I have so far foolishly failed to heed. To my main mentor at the faculty of Achitecture, Fridjof van den Berg, I owe my thanks for showing me why hand drawing and sketching is a way of educating the eye.

On a more personal note, my high-school friends Andrea, Bas, Jeroen, Elbert-Jan, Guido and Chiel have shaped me more than I would care to admit and have stayed very close to me throughout the years. More recently my friends from Toonkunst Rotterdam have added a new dimension to my life that has become very dear to me. Thank you Hester, Jaap, Rinie, Benno, Paul and all the other choir members for sharing your friendship and your love of music with me. Thank you Maria van Nieukerken for being a wonderful conductor and friend, and for seeing in me talents that I didn't know I had. And thank you Maarten Warffemius for standing by me during our last St. Matthew Passion in Texel, and for giving us your last and unforgettable Judas impersonation, as only you could do. Rest in peace my friend!

Today, a very warm thanks goes to two very dear friends who have accepted to be my paranymphs for this defence ceremony. Hester Hazelaar, driving you weekly to and from our choir rehearsals has never been boring. In my car we have discussed the big issues of life and, equally important, the smaller things for which you always display such a youthful curiosity. We share a deep love for J. S. Bach's work; his music speaks straight to the heart, by-passing all other organs. To my other paranymph, Bert Nap, I would say this: you and I have shared friendship for over three decades. in Delft we studied together, we both sang at Krashna Musika, we took classes in drawing nudes and we frequently had a beer or two. You were best man at our wedding, a position you take very seriously to this day by frequently checking up on the state of our marriage. I thank you for many years of friendship and for our numerous laughs and talks about the arts, love and life in general.

Marijke and Ben, my dear parents, I would not have become who I am today without you. Yours was a very warm and caring nest and I could not have wished for better parents. Dad, you were always the one to bring thrill and new adventure into our young lives, making us the cosmopolitans we are today. Your many bold courses of action could have easily turned into catastrophes if it weren't for you mum. Your love and wisdom has always been the strongest glue of all that kept us all together. You were the kind of mother that always puts her children on the first plan, often to the danger of erasing your own interest. I wish you would have been a little less unselfish at times. Then my darling siblings Bram and Anne, as the elder and wiser brother I must have been insufferable at times. I apologize for that, just know that I love you dearly. You now have families of your own and having Debora, Dennis, Joep, Rik, Felix and Hidde around is a joy and has deepened our sibling relationship as well. Of my very large family to the second-degree I would like to highlight my fun and non-conformist godfather Pierre and my learned and caring uncle Wim in particular. Thanks to my dear parents-in-law Tanneke and Thomas for entrusting me with your daughter's hand and for taking me in. And thank you Tanneke for never missing out on any of my concerts! Thanks to my brother-in-law Clive-John for your angels' patience and dedication. A bear hug to my big friend Colm and to you Frouke, I would like to say that you are like a sister to me.

And finally I reach my comforting home base. Annemijn, I count myself incredibly lucky to have you as my life companion. For more than 30 years you have been my love and my steady rock. You have encouraged me from the start to write this dissertation, and most importantly, at times that I doubted if I could ever achieve it. I could not have written this work without your support. To Sofie Jorisdochter and to Tom Joriszoon, my beautiful and amazing children, your given names say it all, you are the most precious gifts of all and you make me so happy and proud. I love you all dearly.

Thank you all!

Joris Smits
Delft, March 2019

Contents

List of Tables 22
List of Figures 23
Summary / The Art of Bridge Design 29
Samenvatting / The Art of Bridge Design 35

PART 1 Introduction

1 Introduction 45

1.1 Bridges for growth 46

1.2 The architects role; from cosmetic advisor to design integrator 47

1.2.1 The engineer's era 49
1.2.2 The great wars era 52

1.3 Commissioning authorities and good procurement 53

1.4 Problem statement; the segregation of knowledge 60

1.5 Hypothesis; introducing a design integrator for better bridges 61

1.6 Objective 62

1.7 Research questions 62

1.8 Research method; a project review through lenses and scales 64

1.9 Structure of dissertation 67

PART 2 Bridge Design

2 A bridge with a view, a view with a bridge 71
Identifying design considerations for bridges to strengthen regional identity

2.1 Introduction 72

2.2 Strengthening regional identity through means of infrastructural design 73

2.3 Bridges in the Zaan region, the Netherlands 75

2.4 The Juliana Bridge 79

2.4.1 Rhythm and harmony 80
2.4.2 Layering and partitioning 81
2.4.3 Manifestation and articulation 83
2.4.4 Defined space and orientation 85
2.4.5 Awards 86

2.5 Wildlife crossing in Rijssen 87

2.5.1 Experiencing a wildlife crossing 87
2.5.2 Typology 88
2.5.3 Design approach 90

2.6 Conclusion 93

3 Shaping Forces 97
Review of two bridge design methodologies towards architectural and structural symbiosis

3.1 Introduction 98

3.2 Shaping Forces 98

3.3 Navel Bridges in Nieuw Vennep 100

3.4 The ShArc, Berlin 2017 104

3.4.1 Conceptual design 105
3.4.2 Digital form finding 108
3.4.3 Physical form-finding 109
3.4.4 Reflection on the performance 111
3.4.5 Elaborating the parametric model 112
3.4.6 Use of FEM with the Grasshopper script 116

3.5 Conclusions 120

4 Fiber-Reinforced Polymer Bridge Design in the Netherlands 123
Architectural challenges toward innovative, sustainable, and durable bridges

4.1 Introduction 124

4.2 Engineers' solutions in FRP 125

4.2.1 Hand lamination: A footbridge in Harlingen 128
4.2.2 Assembly from pultruded profiles 128
4.2.3 Bridge decks 130
4.2.4 Load-bearing uniform deck 130

4.3 Challenges for the architect 132

4.3.1 Modular deck edge elements 132
4.3.2 Monocoque structures 135
4.3.3 Origami structures and shell structures 138
4.3.4 Smart formworks 140

4.4 Conclusion 141

5 Bio-based composite footbridge 145
Design, production and in situ monitoring

5.1 Introduction 147

5.2 Integrated design and project approach 150

5.2.1 Design variations 151
5.2.2 Structural optimization of selected design 152
5.2.3 Final materialization and detailing 154

5.3 Material selection and tests for obtaining safe design values 155

5.3.1 Initial material tests 156
5.3.2 Full scale production test – mock-up. 157
5.3.3 Moisture tests 158
5.3.4 Creep tests 159
5.3.5 Monitoring strains using optical sensors 160

5.4 Production process 162

5.5 Structural behaviour of the bridge 165

5.5.1 Load test after production, installation 165
5.5.2 In situ measurements in use phase 168
5.5.3 Dynamic test 15-03 2017 168
5.5.4 Static Test 17-08-2018 169
5.5.5 Long term behaviour 174

5.6 Life Cycle Assessment 175

5.6.1 Production 175
5.6.2 Use phase 178
5.6.3 End of life scenario 179

5.7 Conclusion 179

PART 3 Synthesis

6 Discussion and Conclusions 185

6.1 Integrated, Integral and Valued bridges 186

6.2 Regional Identity 186

6.3 Form follows Force 187

6.4 Fibre Reinforced Polymer bridge design 188

6.5 A bio-composite footbridge 189

6.6 Durable and sustainable bridge design 190

6.7 The Design Integrator 193

6.8 Reflection 195

7 Recommendations 199

Bibliography 203
Curriculum Vitae 205

List of Tables

4.1 Material properties of FRP compared to those of steel and aluminum[1] 127

5.1 Results per configuration and resulting values for the characteristic strength 156

5.2 Summary of Structural Product data from N5010 Nabasco 157

5.3 quantities of materials used to construct the bridge 175

5.4 LCA per kg of the main constituent materials of the bridge8- 13 176

List of Figures

1.1 Artisit impression of Julius Caesar's Rhine Bridge, by John Soane (1814) 46

1.2 The Vitruvian adage. 48

1.3 Palladio's values illustrated. 48

1.4 An engineering approach. 49

1.5 Salginatobelbrücke in Zwitserland (Robert Maillart, 1872- 1940). Photo from https://grandtour.myswitzerland.com. visited on 25/02/2019. 50

1.6 Boerenwetering Bridge in Amsterdam with sculptures from Hildo Krop. Photo from http://adambeeldenva1900.blogspot.com visited on 25/02/2019. 51

1.7 Shift to efficient and cheap. 52

1.8 Architecture as a guiding principle. 53

1.9 The transition from a three-party market to a two-party market. 54

1.10 HSL railway line near Zoetermeer-Bleiswijk, 2000-2009. Photo from https://mapio.net/images-p/85420570.jpg visited on 25/02/2019. 55

1.11 A50 bridge at Ewijk - Valburg, photo by Thea van den Heuvel/DAPh 2014. 56

1.12 Animation from the Architectural Requirements document N31 Harlingen, Royal HaskoningDHV, Joris Smits et al. (2016). 58

1.13 Traverse N31 Harlingen after realisation. Royal HaskoningDHV, Joris Smits et al. Photo by Jane van Raaphorst 2018. 58

1.14 Structure of this dissertation. 66

2.1 The Dommel Bridge. The identity of the city of Eindhoven as the cradle of both the Philips light bulb industry and the Design Academy is expressed in this bridge. Royal HaskoningDHV, Joris Smits et al. (2007), photo by Jan van Oevelen 2006. 74

2.2 Sustainability through innovation is the theme that stands at the base of the highway of the future in Oss, the Netherlands. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Jane van Raaphorst 2014. 74

2.3 The Hoogtij Bridge for cyclists in the Westzanerpolder. Royal HaskoningDHV, Joris Smits et al. (2005). Photo by Bart Nijs 2006. 76

2.4 The pedestrian bridge in the Zuidelijke Randweg, Royal HaskoningDHV, Joris Smits et al. (2005). Photo by Joris Smits 2011. 76

2.5 The 'Butterfly Bridge' for buses spans road and water. Royal HaskoningDHV, Syb van Breda et al. (2003). Photo by Bart Nijs 2004. 77

2.6 The Prins Bernhard Bridge, a multi-layered bridge with access to the quays. Royal HaskoningDHV, Syb van Breda and Joris Smits et al. (2007). Photo by Jan van Oevelen 2008. 77

2.7 The Juliana Bridge, adjacent to the UNESCO world heritage site Zaanse Schans. Royal HaskoningDHV, Joris Smits et al. (2009). Photo by Jane van Raaphorst 2010. 79

2.8 The Zaan Bridge in Wormer is of the traditional drawbridge typology. Approach spans and drawbridge form two different entities. Royal HaskoningDHV, Joris Smits et al. (2015). 80

2.9 The opening part of the Juliana Bridge is in harmony with the approach spans. Royal HaskoningDHV, Joris Smits et al. (2009). Photo by Jane van Raaphorst 2010. 81

2.10 Pedestrians and cyclists have a bridge of their own. A void separates them from motorised traffic. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Luuk Kramer 2009. 82

2.11 Daylight underneath the bridge increases due to the void between the decks. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Elroy Blom 2012. 83

2.12 Vertical accentuation of the piers in a design proposal for the new Sebastiaans Bridge in Delft. Royal HaskoningDHV, Joris Smits (2012). 84

2.13 The horizontal manifestation of the deck with set-back of the piers puts the emphasis on the larger scale and blends into the landscape. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Jane van Raaphorst 2010. 84

2.14 Light masts define the space and viewing directions. They emerge from the void in order not to obstruct the outward view. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Luuk Kramer 2009. 85

2.15 Wildlife crossing over the N350 between Rijssen and Wierden. Royal HaskoningDHV, Joris Smits et al. (2014). Photo by Jane van Raaphorst 2014. 87

2.16 Artist impression of the wildlife crossing. On the foreground the open heathlands landscape, behind lies the fragmented Essen and Kampen landscape. Royal HaskoningDHV, Joris Smits et al. (2014). 89

2.17 The highway as the ruling principle with a functional crossing (left), or nature as the ruling principle (right). Royal HaskoningDHV, Joris Smits et al. (2014). 89

2.18 The wildlife crossing at Rijssen. Nature has the supremacy, in the form of soil and vegetation; the road is just a perforation of the earth, a guest that is temporally tolerated underneath it. Royal HaskoningDHV, Joris Smits et al. (2014). Photo by Jane van Raaphorst 2014. 90

2.19 The asymmetric shape of the wildlife crossing reacts to the two different kinds of landscape on either side; a confined Essen-Kampen landscape to the west and an open landscape to the east. Royal HaskoningDHV, Joris Smits et al. (2014). 91

2.20 'Lifting the carpet' leaves a slit-like opening underneath the green structure. The low parts of the slit are filled with solid abutments with a set back from the edge. They are materialised in a dark grey colour in order to blend with the ground rather than with the crescent edge. This results in the impression of one long continuous edge. Royal HaskoningDHV, Joris Smits et al. (2014). Photo by Jane van Raaphorst 2014. 92

2.21 The use of a middle pier inevitably has a negative effect on our experience of spaciousness; the view of the beholder is partitioned right through the middle and the focus diverted to this odd element rather than to the surrounding space. Royal HaskoningDHV, Joris Smits et al. (2014). 93

3.1 Heinz Islers' frozen fabric. https://safetythird.wordpress.com/2011/04/18/heinz-isler-ice-structures/, visited on 27/2/2019. 99

3.2 One of two Navel Bridges in Nieuw Vennep. Royal HaskoningDHV, Joris Smits et al. (1999). Photo by Bart Nijs 2004. 100

3.3 Initial proposal for a culvert and an underpass. 101

3.4 Setting the vaulted ceiling. 101

3.5 Taking away the surplus of concrete. 102

3.6 Tapering the sides. 102

3.7 Creating a longitudinal cavity. 102

3.8 View on the intersecting cavities in the abutment on the water side. Clearly visible are the rough timber planks in the formwork of the vault and the sides. The cavities are smooth inside. Royal HaskoningDHV, Joris Smits et al. (1999). Photo by Bart Nijs 2004. 103

3.9 Artist impression of the ShArc in Berlin. Delft University of Technology, Joris Smits et al. (2017). 104

3.10 Plan view of the ShArc at the confluence of the Spree and the canal. Delft University of Technology, Joris Smits et al. (2017). 106

3.11 3D printed Daedalus Pavilion at the GPU. Photo from https://ai-build.com/daedalus.html, visited on 27/2/2019. 107

3.12 First sketches for Berlin; introducing a double surface within a shell structure. Delft University of Technology, Joris Smits et al. (2017). 108

3.13 Initial model for a double surface. Delft University of Technology, Peter Eigenraam et al. (2017). 109

3.14 Form-finding experiments in microfiber cloth and gypsum. Delft University of Technology, Peter Eigenraam et al. (2017). 110

3.15 Schematic cross sectional properties. Delft University of Technology, Peter Eigenraam et al. (2017). 112

3.16 Schematic load distribution of the cross section. Delft University of Technology, Peter Eigenraam et al. (2017). 112

3.17 Subdivision of deck (left) and grid (right). Delft University of Technology, Peter Eigenraam et al. (2017). 113

3.18 Grasshopper script to monitor the resulting slopes. Delft University of Technology, Peter Eigenraam et al. (2017). 114

3.19 Wrinkling near the abutment. Delft University of Technology, Peter Eigenraam et al. (2017). 115

3.20 Weighting functions. BuroHappold, Dirk Rinze Visser et al. (2017). 117

3.21 Node utilization against relative position. BuroHappold, Dirk Rinze Visser et al. (2017). 118

3.22 Relative node positions. BuroHappold, Rinze Visser et al. (2017). 118

3.23 Artist impression, view on the bridge. Delft University of Technology, Joris Smits et al. (2017). 119

4.1 Engineers from the aerospace, maritime, automotive, and sports industries have preceded bridge engineers in their use of FRP. 126

4.2 Henry Ford demonstrates his hemp car on impact (Ford, 1940). from https://ga-institute.com/Sustainability-Update/tag/henry-ford/, visited on 27/02/2019. 126

4.3 Footbridge in Harlingen, the Netherlands, made by Poly Products for Rijkswaterstaat (1997). From http://www.polyproducts.nl, visited on 27/2/2019. 128

4.4 Bridge structures from pultruded profiles and material substitution, Fiberline (2013). Pontresina, Switzerland (a); Lleida, Spain (b); Kolding, Denmark (c). From https://fiberline.com/international-award-innovative-grp-footbridge, visited on 27/02/2019. 129

4.5 Pultruded bridge deck panels. (Transportation Research Board, 2006). 130

4.6 A flexible mold system for cambered decks with variable width and length. 131

4.7 The InfraCore patented technique for creating unitized structures. Peeters (2011). 131

4.8 Installation and final assembly of the edge elements in the fly-over Waarderpolder. Royal HaskoningDHV, Joris Smits et al. (2012). Photo's by Ballast Nedam (2011). 133

4.9 Some projects in the Netherlands with FRP edge elements, clockwise from top left: Edge elements on the Juliana Bridge in Zaanstad (a); The fly-over Waarderpolder in Haarlem (b); The wildlife crossing and tunnel in Rijssen-Wierden (c, d). Royal HaskoningDHV, Joris Smits et al., (2007, 2013,2013). Photo's Jane van Raaphorst. 133

4.10 Installation of red light in the panels of the highway N201 viaducts. Royal HaskoningDHV, Richard van den Brule et al. (2013). Pictures a. and b. by Smit Kunststoffen (2012). Photo c. by Jane van Raaphorst (2014). 135

4.11 A lobster pincer, an example of a monocoque structure in nature. From https://dumielauxepices.net/wallpaper-18809, visited on 27/02/2019. 136

4.12 The Dragonfly footbridge in Harderwijk. Royal HaskoningDHV, Jorge Moura et al. (2014). 136

4.13 A design for a monocoque FRP drawbridge for pedestrians and bicycles across the Rhine in Katwijk Royal HaskoningDHV, Joris Smits et al. (2014). 137

4.14 Some tree leaves are natural folded structures. From https://www.bonsaiempire.com, visited on 27/02/2019. 138

4.15 An origami bridge design. R. Gkaidazis, Delft University of Technology (2014). 138

4.16 The razor or Ensis shell, thin and strong. From https://en.wikipedia.org/wiki/Razor_shell. 139

4.17 Pringles, a fried potato snack with optimized stiffness. https://www.ikgastarten.nl/bedrijf-starten/bedrijfsplan/de-start-van-pringles, visited on 27/02/2019. 139

4.18 The Delft Design Composite Bridge. Royal HaskoningDHV & FiberCore, Joris Smits et al. (2008). 139

4.19 Test setup for single-curved elements. H. Schipper et al. Delft University of Technology (2011). 140

4.20 Wizard with 200 simultaneously computer-adjusted actuators. D. Rietbergen et al., Delft University of Technology (2008). 140

5.1 The bio-composite footbridge, 18 months after the installation across the river Dommel. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). Photo by Heijmans (2018). 146

5.2 Flax in a field. From https://www.faay.nl/wp-content/uploads/Faay-Wanden-en-Plafonds_Duurzaam-bouwen-met-vlas_vlasveld_3.jpg, visited on 28/02/2019. 148

5.3 Greenpoxy, an epoxy-resin with a 56% bio-content. From a: http://intrey.com/epoksidka/, b: https://www.timeout.de/sicomin-greenpoxy-56-5-kg, visited on 28/02/2019. 148

5.4 Woven flax fibres. Photo by Dorine van der Linde (2016). 149

5.5 Workshop output on variable bridge cross-sections. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 151

5.6 Different sizes and shapes of mid-span sections evaluated. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 153

5.7 Milled test samples from 1:1 model and Tension test with optical strain measurement. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 157

5.8 Typical result of a repeated loading-unloading and reloading tension test in the laboratory on a test specimen of Woven (90 degrees) flax fibre composite showing hysteresis behaviour. 158

5.9 Creep test set-up at TU/e laboratory. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 159

5.10 Creep curves at three stress levels 5, 15 and 25 MPa in three-point bending tests. 160

5.11 Preparation of optical (glass) Fibre Brag Grating sensors. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 161

5.12 Location of Sensors. Line SG-01 and SG-04 are mainly compression (in bridge deck). Line SG-02 and SG-03 are mainly tension (under-side bridge). R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 161

5.13 Change in shape from rectangular to triangular using laser cut PLA foam elements. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 163

5.14 Meltdown of the PLA foam occurred when the thickness of the lay-up exceeds 10mm. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 163

5.15 Part of a Production drawing, (half of section in middle of the bridge, in red/dark is indicated the position the woven fibres. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 164

5.16 Bridge beam during Vacuum injection. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 165

5.17 Impression of the load test using 7 water tanks.R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 166

5.18 Elastic Model, calculated vertical deflections, the longitudinal compression and tension stresses and the strains. 166

5.19 Results measured LDVT Deflections at Production facility test October 21th 2016. 167

5.20 Strain deformations as function of the applied load. 167

5.21 Strain development versus time during loading; Lines 2 and 3 are positive strains in tension (underside bridge-beam) line 1 shows negative strains in compression (in bridge deck). 168

5.22 Strain results versus time of Sensors 1-7 and 2-4 showing eigenfrequency and damping. 169

5.23 Cyclic loading test performed one year and ten months after installation. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). 170

5.24 Three load cycles during the test on 17-08-2018 showing applied load, max strain in middle and maximum measured vertical deflection. 170

5.25 First Load Cycle; Results of strains in tension sensors along the bridge (Line 2), Loading and unloading to 2x 6,0 kN. 171

5.26 Second Load Cycle; Results of strains in tension sensors along the bridge (Line 2), Stepwise Loading and unloading to 2x 10,0 kN. 171

5.27 Third Load Cycle; Results of strains in tension sensors along the bridge (Line 2), Loading and unloading directly to 2x 10,0 k. The dotted line shows the remaining strains. 172

5.28 Measured deflections (in middle of the bridge) during second loading (10 kN) and unloading cycle. 173

5.29 Elastic Model, calculated vertical deflections, the longitudinal compression and tension stresses and the strains based on Young's modulus 10.000 MPa under maximum of 2x 10 kN: maximum deflection = 14,6 mm. 173

5.30 Strain measurement results of unloaded bridge
(only self-weight) of 5 measurements in time. 174

5.31 Environmental cost impact for the total material used in to build the bridge. 178

Summary / The Art of Bridge Design

It is hard to imagine a world without bridges. Bridges lie at the heart of our civilization bringing growth and prosperity to our society. It is by virtue of bridges that communities are able to physically connect to new people and to new places that were previously disconnected. However, bridges are more than mere functional assets. A well designed bridge reflects mankind's creativity and ingenuity. One could even state that the way bridges are designed tells us something about our identity.

The way that our bridges are commissioned, designed and procured is rapidly changing. Ideally the design of a bridge is made through an integrated approach that addresses all relevant technological angles, practiced by all involved disciplines through all phases of the design. In reality, many different people from many different disciplines work on the design during different phases of the project. The segregation of knowledge into discipline-specific fields, and the fragmented approach to bridge procurement, have resulted in a general lack of cohesion in bridge design. Critical investigation into how to pursue good integrated design is absent. Therefor the objective of this research is to identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, that are integrally-designed and that are valued by society. Accordingly, the main research question of the dissertation is: How can we identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, that are integrally-designed and that are valued by society?

The objective and main research question are addressed in chapters 2 till 5 through the methodology of reviewing numerous projects from my own bridge design practice. The review is founded on the experience I have accumulated over a period of 25 years in which I have designed over 300 bridges and civil structures, more than 100 of which have been built. By identifying design considerations on four levels, namely the level of the landscape, on the level of the bridge, on the level of the detail and on the level of the material, this research demonstrates how an overall approach to well-integrated, integrally designed and valued bridges can be achieved by addressing each of these scales of the design. The demonstration of how the objective has been met can be found in the subsequent addressing and answering of the six research questions.

The first chapter is an introduction to the research and describes the way in which the interaction between the commissioning authorities, the architect and the structural engineer has changed over the past 150 years. It describes how each of these actors influences the others from within his role. The role of the actors is seen through the three lenses of Vitruvius; Beauty, Utility and Solidity. Furthermore, this chapter

addresses the changing role of the commissioning authorities in the bridge design process. The recent developments in bridge tender contracts where commissioning authorities are no longer active partners in the design process, instead acting as facilitators of a tender process, are discussed. The problem of segregation of knowledge is introduced and the hypothesis for the introduction of a design integrator is made. Chapter 1 is concluded with the formulation of the research questions and the description of the research methodology.

The second chapter addresses research question 1: What design considerations can be identified for bridges at the scale level of the landscape or of the urban texture, and how can bridges fulfil social, cultural and regional requirements and strengthening regional identity? This chapter discusses design considerations for creating high quality infrastructural works with an emphasis on bridges. A design study and analysis approach is pursued to highlight the specifics of infrastructure design for regional identity, based on the author's work on a bridge ensemble in the Dutch Zaanstreek region. Two highlights of this work, the award winning Juliana Bridge and the wildlife crossing in Rijssen, are used to illustrate how to create good infrastructure design in sensitive contexts.

The third chapter addresses research question 2: What design considerations can be identified for the design of a bridge at the scale of the object itself, and how can architectural and structural symbiosis in the design be achieved? This chapter investigates the symbiotic relationship between the architectural appearance of a bridge and the structural design. The research was conducted by reviewing and comparing the design methodology employed by the author in the conceptualization of two of his bridges; an early work from 1997 and a recent work from 2017. The review of the early work describes a design methodology that could be described as intuitive design, whereas the later work is the result of computational from-finding and optimization. Parallels are drawn and the historical development of the toolbox of the architect and the engineer is described. The way in which the two designs were achieved is analysed by looking from the perspective of the architect and that of the engineer. To conclude the key design considerations to achieve a beautiful yet structurally sound bridge are identified.

The forth chapter addresses research question 3: What design considerations can be identified for the design of a bridge at the scale of the detail and that of the materialization? Through a study of Fibre Reinforced Polymers (FRP) bridge designs in the Netherlands, design considerations to the use of FRP in bridge design are identified, both as a structural and as a non-structural application. The challenges and opportunities of this relatively new material, both for the architect and the engineer, are discussed. An inventory of recent structural solutions in FRP is included, followed by

a discussion on architectural FRP applications derived from the architectural practice of the author and of other pioneers.

The fifth chapter addresses research question 4: What design considerations can be identified for the design of a bridge at the scale of the chosen materials, and of the material properties, that constitute a bridge? The question is addressed through the study of bio-composite, a natural fibre reinforced bio-polymer, in a 14 metre span footbridge that has been designed and built across the river Dommel in the city of Eindhoven, the Netherlands. For this purpose, a multidisciplinary team of academic researchers and manufacturers from the bio-composite industry developed a feasible design that could be produced by unskilled hands in a short period of time and within a limited budget. The bio-composite footbridge was designed, built and installed within less than one year.

The sixth chapter addresses research questions 5 till 7. Firstly, design considerations are identified towards durable and sustainable bridges. The importance of a Life Cycle approach is discussed, the end-of-use value of bridges and bridge components are discussed.

The sixth chapter further tests the working hypothesis of this research: that the introduction of a design integrator will lead to better bridges and will increase public support for new infrastructure. If one person could oversee the design process in its entirety by fulfilling the role of design integrator and by defending the design in the public debate, the design process would greatly benefit. The design integrator should not be the omniscient master builder of old, but would instead act as the conscience of the design, the expert who directs and coordinates all design aspects of a bridge. When we look at other large structures in the public realm, it is noted that the role of design coordinator is not new in the building industry. For instance, every building already has a design integrator in the personification of the architect who oversees the entire design process, including the integration of the structure and of the technical installations. To bring about such a transition into the field of design of infrastructures, I propose that the role of the architect must be transformed from a mere aesthetical advisor to that of a design integrator. This way the objective of this research: to identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, that are integrally-designed and that are valued by society, can be met.

Finally, this chapter concludes with a discussion on the responsibility that the commissioning authorities have to secure the design quality of our future bridges through responsible procurement, is held.

Conclusions

If the mutations in the field of bridge design that have occurred over the past 150 years have taught us one thing, it is that the field of bridge design has become far too complex to be embodied by one person, whether it be an engineer or an architect. The role that the master builder played up until the late renaissance, bringing together aesthetic design and building craft into one person, is nowadays fulfilled by a team of specialists. You could say that the integrated design team is the contemporary version of the renaissance master builder. Within the integrated design team, all disciplines work together from the start in a holistic approach to get the best out of the design. The basis of the ideal team naturally consists of a lead architect and a chief engineer. Within this team, the architect should be the design integrator; he or she has the task of securing the equilibrium between Beauty, Utility and Solidity throughout every phase of the design process. This balancing act takes place at all scale levels and through all phases of the design. From the integration of the bridge in the landscape to the design of the main structure and the choice of the right construction materials.

Chapter 2 demonstrates that regional identity can be strengthened through good bridge design. A review of my projects in Zaanstad and in Rijssen demonstrates how properties as scale, orientation, rhythm, articulation, layering and partitioning of the design are the architects tools to make a design fit the context. To accomplish this we need to think from different perspectives, both literally and figuratively. The obvious perspectives are that of the driver, the cyclist, the pedestrian, the skipper or the badger that passes on or underneath our designs. But on a more abstract level we need to think from the point of view of the genius loci, the commissioning authorities, the tourists and most important of all, the people who live nearby.

Chapter 3 demonstrates that when it comes to the design of a bridge, architecture and structure, form and force, are involved in an interdependable and symbiotic relationship. In order to achieve symbiosis between architecture and structure in integral bridge design architects and structural engineers must be willing to overcome the current division between the work of the architect and the work of the structural engineer and get rid of the classical hierarchy. Although a unilateral form of bridge design within the boundaries of the forces at play is possible, it is important to acknowledge that a bridge design cannot be simplified as a mere display of forces. A coherent design is just as much influenced by thorough response to the boundary conditions imposed by the context, the choice of material, the building process and the maintenance and financing of the bridge.

Although the tools have changed since 2000, the methodology and the design parameters have remained the same. The ability to use the computer as a tool for

optimization and a way to search for new forms, allows for intuitive design. Through parametric models and graphic scripts, an interactive design process can be created that is open to both architects and structural engineers. However, it is important to note that physical tests with scale models add valuable insight in the behaviour of a structure.

Chapter 4 demonstrates that the use of FRPs in bridge engineering has grown significantly over the past two decades. Attracted by structural and economic benefits such as weight reduction and cost saving on maintenance, engineers have developed construction solutions using FRPs that compete with conventional structures. In the field of architecture, the recent establishment of FRP as a building material for bridges has resulted in numerous successful projects. The use of FRP as a cladding material around decks has been demonstrated. Also, more daring structural applications of FRP, including a load-bearing shell, folding structures, and non-standard curved monocoque structures have been demonstrated. FRP needs to be introduced as a mature material in our educational system so that future architects and engineers are educated in ways to do justice to the unique material properties and fabrication methods of this material.

Chapter 5 demonstrates that bio-composite can be applied as a load bearing structure in an outdoor environment. The conducted research on the bio-composite footbridge has enlarged the overall knowledge and experience with the design, production and use of a bio-composite footbridge structure. The strain measurement results of the bridge in use proved to be consistent with the measured material behaviour in laboratory tests. However, for future Bio-composite bridges the material behaviour in creep needs be improved. The LCA of the finalized footbridge proved a useful tool to determine the overall environmental impact of the bridge. The LCA has proven that the one ingredient of the bridge that is responsible for the vast majority of the total environmental impact is the (semi-) bio-resin. It is therefore necessary to conduct further research into bio-resins to further decrease the environmental impact of bio-composite structures.

To conclude, identifying a design approach that leads to better bridge design is only a first step. I believe that the other key that will lead to better bridges lies in the procurement process where the design quality needs to be secured. To achieve this, the architectural specifications for a bridge need to be an integral part of the procurement documents. This should be done either through the construction contract or, better still, through the planning permission, so that there is an obligation on the contractor, the designer and the client to maintain design quality even as cost and time pressures increase. If we want to further improve the design quality of our bridges, further discussion must be held on the role of the commissioning authorities in the design process.

Samenvatting / The Art of Bridge Design

Een wereld zonder bruggen is moeilijk voor te stellen. Bruggen vormen het hart van onze beschaving en brengen ons groei en welvaart. Bruggen verbinden mensen en plaatsen die voorheen niet meer met elkaar verbonden waren. Echter, bruggen zijn meer dan alleen functionele assets. Een goed ontworpen brug weerspiegelt de creativiteit en vindingrijkheid van de mensheid. Je zou zelfs kunnen stellen dat de manier waarop bruggen worden ontworpen ons iets vertelt over onze identiteit.

De manier waarop onze bruggen worden gepland, ontworpen en aanbesteed, verandert snel. Idealiter komt het ontwerp van een brug tot stand dankzij een geïntegreerde aanpak die rekening houdt met alle relevante technologische invalshoeken, uitgeoefend door alle betrokken disciplines in alle fasen van het ontwerp. In werkelijkheid werken veel verschillende mensen uit verschillende disciplines tijdens verschillende fasen van het project aan het ontwerp. De segregatie van kennis in discipline-specifieke vakgebieden en de gefragmenteerde aanpak van aanbestedingen hebben geleid tot een algemeen gebrek aan samenhang in het brugontwerp. Kritisch onderzoek naar hoe een goed geïntegreerd ontwerp kan worden bewerkstelligd ontbreekt. De doelstelling van dit onderzoek is dan ook het identificeren van een ontwerpbenadering, door alle schaalniveaus van het ontwerp, die leidt tot bruggen die goed geïntegreerd zijn, die integraal zijn ontworpen en die gewaardeerd worden door de samenleving. Dienovereenkomstig is de belangrijkste onderzoeksvraag van het proefschrift: hoe kunnen we een ontwerpbenadering identificeren, door alle schalen van het ontwerp, die leidt tot bruggen die goed geïntegreerd zijn, die integraal zijn ontworpen en die door de samenleving worden gewaardeerd?

De doelstelling en de belangrijkste onderzoeksvraag komen aan bod in de hoofdstukken 2 tot en met 5 op basis van de methodologie van de toetsing van talrijke projecten uit mijn eigen brugontwerppraktijk. De toetsing is gebaseerd op de ervaring die ik heb opgedaan in een periode van 25 jaar waarin ik meer dan 300 bruggen en kunstwerken heb ontworpen, waarvan er meer dan 100 zijn gebouwd. Door ontwerpoverwegingen te identificeren op vier niveaus, namelijk het niveau van het landschap, op het niveau van de brug, op het niveau van het detail en op het niveau van het materiaal, laat dit onderzoek zien hoe een algemene benadering van goed geïntegreerde, integraal ontworpen en gewaardeerde bruggen kan worden bereikt door elk van deze schalen van het ontwerp aan te pakken. De demonstratie van de manier waarop de doelstelling is bereikt, is terug te vinden in de daaropvolgende behandeling en beantwoording van de zes onderzoeksvragen.

Het eerste hoofdstuk is een introductie op het onderzoek en beschrijft de wijze waarop de interactie tussen de opdrachtgever, de architect en de bouwkundig ingenieur in de afgelopen 150 jaar is veranderd. Er wordt beschreven hoe elk van deze actoren vanuit zijn of haar rol de anderen beïnvloedt. De rol van de actoren wordt beschouwd door de drie lenzen van Vitruvius; Schoonheid, Nut en Degelijkheid. Daarnaast gaat dit hoofdstuk in op de veranderende rol van de opdrachtgevende instanties in het ontwerp van bruggen. De recente ontwikkelingen op het gebied van aanbestedingscontracten voor bruggen, waarbij de opdrachtgever niet langer een actieve partner in het ontwerpproces is, maar optreedt als facilitator van een aanbestedingsproces, worden besproken. Het probleem van de segregatie van kennis wordt geïntroduceerd en de hypothese voor de invoering van een ontwerp-integrator wordt gemaakt. Hoofdstuk 1 wordt afgesloten met de formulering van de onderzoeksvragen en de beschrijving van de onderzoeksmethodiek.

Het tweede hoofdstuk gaat in op onderzoeksvraag 1: Welke ontwerpoverwegingen kunnen worden onderscheiden voor bruggen op het schaalniveau van het landschap of van de stad, en hoe kunnen bruggen voorzien in sociale, culturele en regionale behoeften en bijdragen aan de versterking van de regionale identiteit? Dit hoofdstuk gaat in op ontwerpoverwegingen voor het maken van hoogwaardige infrastructurele werken in een landschappelijke context, met de nadruk op bruggen. Een ontwerpaanpak en analyse wordt gevolgd om de specifieke kenmerken van infrastructuurontwerp voor regionale identiteit te belichten, gebaseerd op het werk van de auteur aan een brugensemble in de Nederlandse Zaanstreek. Twee hoogtepunten van dit werk, de bekroonde Julianabrug en het ecoduct in Rijssen, worden gebruikt om te illustreren hoe een goed ontwerp van infrastructuur in een sensitieve context kan worden gemaakt.

Het derde hoofdstuk gaat in op onderzoeksvraag 2: Welke ontwerpoverwegingen kunnen worden onderscheiden voor het ontwerp van een brug op de schaal van het object zelf, en hoe kan architectonische en constructieve symbiose in het ontwerp worden bereikt? Het onderzoek is uitgevoerd door de ontwerpmethodiek van de auteur bij de conceptualisering van twee van zijn bruggen te evalueren en te vergelijken; een vroeg werk uit 1997 en een recent werk uit 2017. De review van het vroege werk beschrijft een ontwerpmethodiek die kan worden omschreven als intuïtief ontwerp, terwijl het latere werk het resultaat is van een computerondersteund 'form-finding' en optimalisatieproces. Er worden parallellen getrokken en de historische ontwikkeling van de gereedschapskist van de architect en de ingenieur wordt beschreven. De manier waarop de twee ontwerpen tot stand zijn gekomen wordt geanalyseerd door te kijken vanuit het perspectief van de architect en dat van de ingenieur. Tot slot worden de belangrijkste ontwerpoverwegingen om tot een mooie en constructief gezonde brug te komen in kaart gebracht.

Het vierde hoofdstuk gaat in op onderzoeksvraag 3: Welke ontwerpoverwegingen kunnen worden onderscheiden voor het ontwerp van een brug op de schaal van het detail en dat van de materialisatie? Door middel van een studie van vezelversterkte kunststof (VVK) bruggen in Nederland worden ontwerpoverwegingen voor het gebruik van VVK in het brugontwerp geïdentificeerd, zowel als constructieve als als niet-constructieve toepassingen. De uitdagingen en kansen van dit relatief nieuwe materiaal, voor zowel de architect als de ingenieur, worden besproken. Een inventarisatie van recente bouwkundige oplossingen in VVK is hierin meegenomen, gevolgd door een discussie over architectonische VVK-toepassingen vanuit de praktijk van de auteur en van andere pioniers.

Het vijfde hoofdstuk gaat in op onderzoeksvraag 4: Welke ontwerpoverwegingen kunnen worden geïdentificeerd voor het ontwerp van een brug op de schaal van de gekozen materialen, alsmede van de materiaaleigenschappen, die een brug vormen? De vraag wordt beantwoord via onderzoek naar bio-composiet, ofwel natuurvezelversterkt bio-polymeer, in een 14 meter lange voetbrug die is ontworpen en gebouwd over de rivier de Dommel in Eindhoven. Voor dit doel heeft een multidisciplinair team van academische onderzoekers samen met een fabrikant uit de bio-composiet industrie een uitvoerbaar ontwerp ontwikkeld dat in korte tijd en binnen een beperkt budget door ongeschoolde handen geproduceerd kon worden. De bio-composiet voetbrug werd in minder dan een jaar tijd ontworpen, gebouwd en geïnstalleerd.

Het zesde hoofdstuk gaat in op onderzoeksvragen 5 tot en met 7. In de eerste plaats worden ontwerpoverwegingen geïdentificeerd die gericht zijn op bestendige en duurzame bruggen. Het belang van een Life Cycle-benadering wordt besproken evenals de eindgebruikswaarde van bruggen en brugcomponenten.

In het zesde hoofdstuk wordt de werkhypothese van dit onderzoek nader getoetst: de introductie van een ontwerp-integrator zal leiden tot betere bruggen en zal het maatschappelijk draagvlak voor nieuwe infrastructuur vergroten. Als één persoon het ontwerpproces in zijn geheel zou kunnen overzien door de rol van ontwerper-integrator te vervullen en door het ontwerp te verdedigen in het publieke debat, zou het ontwerpproces daar veel baat bij hebben. De ontwerper-integrator zou niet de alwetende bouwmeester van oudsher moeten zijn, maar zou in plaats daarvan moeten optreden als het geweten van het ontwerp, de expert die alle ontwerpaspecten van een brug stuurt en coördineert. Als we kijken naar andere grote constructies in het publieke domein, wordt opgemerkt dat de rol van ontwerp-integrator niet nieuw is in de bouwsector. Zo heeft elk gebouw al een ontwerp-integrator in de personificatie van de architect die het hele ontwerpproces begeleidt, inclusief de integratie van de constructie en de technische installaties. Om een dergelijke overgang naar het domein

van het ontwerpen van infrastructuren tot stand te brengen, stel ik voor dat de rol van de architect wordt getransformeerd van een louter esthetisch adviseur naar die van een ontwerp-integrator. Op deze manier kan de doelstelling van dit onderzoek worden bereikt: het identificeren van een ontwerpbenadering, door middel van alle schalen van het ontwerp, die leidt tot bruggen die goed geïntegreerd zijn, die integraal zijn ontworpen en die gewaardeerd worden door de maatschappij.

Tot slot wordt dit hoofdstuk afgesloten met een discussie over de verantwoordelijkheid die publieke opdrachtgevers hebben om de ontwerpkwaliteit van onze toekomstige bruggen veilig te stellen door middel van een verantwoord inkoopproces.

Conclusies

Als de mutaties die zich de afgelopen 150 jaar op het gebied van brugontwerp hebben voorgedaan ons één ding hebben geleerd, dan is het wel dat het veld van brugontwerp veel te complex is geworden om door één persoon te worden belichaamd, of het nu een ingenieur of een architect is. De rol die de bouwmeester tot in de late renaissance heeft gespeeld, waarbij esthetisch ontwerp en bouwtechniek in één persoon werden samengebracht, wordt tegenwoordig vervuld door een team van specialisten. Je zou kunnen stellen dat het geïntegreerde ontwerpteam de hedendaagse versie van de bouwmeester uit de renaissance is.

Binnen het geïntegreerde ontwerpteam werken alle disciplines vanaf het begin samen vanuit een holistische benadering om het beste uit het ontwerp te halen. De basis van het ideale team bestaat logischerwijs uit een hoofdarchitect en een hoofdingenieur. In dit team moet de architect de ontwerp-integrator zijn; hij of zij heeft de taak om het evenwicht tussen Schoonheid, Nut en Robuustheid in elke fase van het ontwerpproces te borgen. Deze evenwichtsoefening vindt plaats op alle schaalniveaus en in alle fasen van het ontwerp. Van de integratie van de brug in het landschap tot het ontwerp van de hoofddraagconstructie en de keuze van de juiste bouwmaterialen.

Hoofdstuk 2 illustreert dat de regionale identiteit versterkt kan worden door een goed brugontwerp. Een studie van mijn projecten laat zien hoe eigenschappen als schaal, oriëntatie, ritme, articulatie, gelaagdheid en opdeling de architectonische instrumenten zijn om een ontwerp in de context te laten passen. Om dit te bereiken moeten we vanuit verschillende perspectieven denken, zowel letterlijk als figuurlijk. De voor de hand liggende perspectieven zijn die van de bestuurder, de fietser, de voetganger, de schipper of de das die door of onder onze ontwerpen passeert. Maar op een abstracter niveau moeten we denken vanuit het oogpunt van de genius loci, de opdrachtgevers, de toeristen en vooral de mensen die in de buurt wonen.

Hoofdstuk 3 demonstreert dat bij het ontwerp van een brug architectuur en constructie, vorm en kracht, verwikkeld zijn in een onderling afhankelijke en symbiotische relatie. Om tot een symbiose te komen tussen architectuur en constructie moeten architecten en constructeurs bereid zijn om de huidige scheiding tussen het werk van de architect en het werk van de constructeur te overwinnen en de klassieke hiërarchie te doorbreken. Hoewel een unilaterale vorm van brugontwerp binnen de grenzen van het krachtenspel denkbaar is, is het belangrijk om te erkennen dat het ontwerpen van een brug niet kan worden versimpeld tot louter een afspiegeling van krachten. Een samenhangend ontwerp wordt evenzeer beïnvloed door een zorgvuldige reactie op de randvoorwaarden die worden opgelegd door de context, de materiaalkeuze, het bouwproces en het onderhoud en de financiering van de brug. Hoewel de instrumenten sinds 2000 zijn veranderd, zijn de methodologie en de ontwerpparameters hetzelfde gebleven. De mogelijkheid om de computer te gebruiken als een hulpmiddel voor optimalisatie en als een manier om naar nieuwe vormen te zoeken, maakt een intuïtief ontwerpproces mogelijk. Door middel van parametrische modellen en grafische scripts kan een interactief ontwerpproces worden opgezet dat openstaat voor zowel architecten als constructeurs. Het is echter belangrijk op te merken dat fysieke proeven met schaalmodellen een waardevol inzicht geven in het gedrag van een constructie.

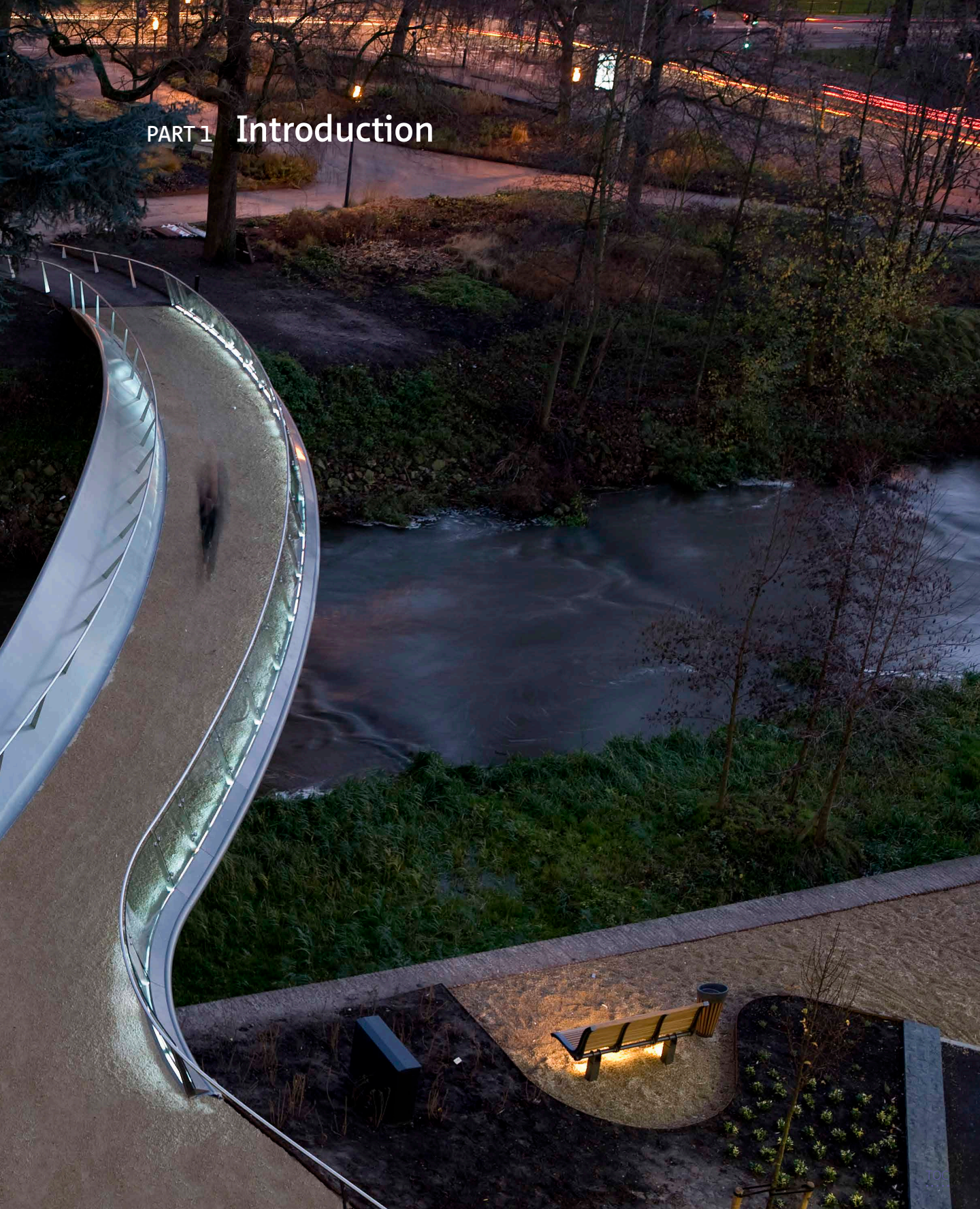
In hoofdstuk 4 wordt aangetoond dat het gebruik van vezelversterkte kunststof (VVK) in de bruggenbouw de afgelopen twee decennia aanzienlijk is toegenomen. Door de aantrekkingskracht van constructieve en economische baten zoals gewichtsbesparing en kostenbesparing op onderhoud, hebben ingenieurs constructies ontwikkeld van VVK die kunnen concurreren met conventionele constructies. Op het gebied van architectuur heeft de recente invoering van VVK als bouwmateriaal voor bruggen geleid tot tal van succesvolle projecten. De toepassing van VVK als bekledingsmateriaal langs de randen van brugdekken is aangetoond. Ook zijn er meer gedurfde constructieve toepassingen van VVK gedemonstreerd, waaronder een dragende schaal, vouwstructuren en niet-standaard gebogen monocoque structuren. Ten slotte moet VVK in ons onderwijssysteem worden geïntroduceerd als een volwaardig materiaal, zodat toekomstige architecten en ingenieurs worden opgeleid in de manier waarop ze recht kunnen doen aan de unieke eigenschappen en de fabricagemethoden van dit materiaal.

Hoofdstuk 5 demonstreert dat bio-composiet kan worden toegepast als een dragende constructie in een buitenomgeving. Het uitgevoerde onderzoek naar de bio-composiet voetgangersbrug heeft de algemene kennis en ervaring met het ontwerp, de productie en het gebruik van een bio-composiet voetgangersbrug vergroot. De resultaten van de rekbaarheidsmeting van de gebruikte brug bleken in overeenstemming te zijn met het gemeten materiaalgedrag in laboratoriumtests. Voor toekomstige Bio-composietbruggen moet het materiaalgedrag in kruip echter worden verbeterd. De LCA

van de voltooide voetgangersbrug bleek een nuttig instrument om de totale milieu-impact van de brug te bepalen. De LCA heeft bewezen dat het enige bestanddeel van de brug dat verantwoordelijk is voor het overgrote deel van de totale milieu-impact de (semi-)biohars is. Het is daarom noodzakelijk om verder onderzoek te doen naar bioharsen om de milieu-impact van bio-composietstructuren verder te verminderen.

Tot slot nog dit: het identificeren van een ontwerpbenadering die leidt tot betere brugontwerpen is slechts een eerste stap. Ik ben van mening dat de andere sleutel die tot betere bruggen zal leiden, ligt in het inkoopproces, waar de ontwerpkwaliteit moet worden gewaarborgd. Om dit te bereiken moeten de architectonische specificaties van een brug integraal deel uit gaan maken van de aanbestedingsdocumenten. Dit moet gebeuren via het bouwcontract of, beter nog, via de bouwvergunning, zodat de aannemer, de ontwerper en de opdrachtgever verplicht zijn om de kwaliteit van het ontwerp te garanderen, ook wanneer de kostendruk en de tijdsdruk toenemen. Als we de ontwerpkwaliteit van onze bruggen verder willen verbeteren, moeten we een verdere discussie voeren over de rol van de opdrachtgevers in het ontwerpproces.





PART 1 Introduction



1 Introduction

This chapter provides an introduction to the research. The research topic and the research aspects are briefly introduced. The changing role of the architect in the field of bridge design is analysed in an historical context. The role of the commissioning authorities is introduced. The problem of segregation of knowledge is introduced. The objectives and research questions are stated, a hypothesis is formulated and the methodology is discussed. Furthermore, an outline of the dissertation is provided.

The basis of this chapter was laid in 2009 when parts of it were published as a chapter in the book: Bruggen 1950-2000. Techniek in ontwikkeling (Zutphen: Walburg Pers, 2009, 267 (1), 366 + dvd (2) blz., ISBN 978 90 5730 631 0 (1), ISBN 978 90 5730 632 7 (2)).

§ 1.1 Bridges for growth

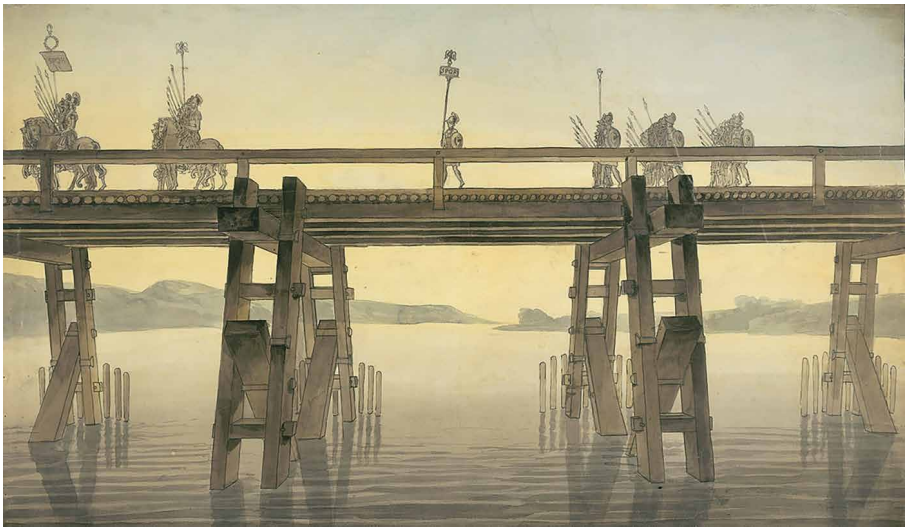


FIGURE 1.1 Artisit impression of Julius Caesar's Rhine Bridge, by John Soane (1814)

It is hard to imagine a world without bridges. Bridges lie at the very heart of our civilization bringing growth and prosperity to our society. It is by virtue of bridges that communities were able to physically connect to new people and to new places that were previously disconnected. However, bridges are more than mere functional assets. A well designed bridge reflects mankind's creativity and ingenuity. One could even state that the way bridges are designed tells us something about our identity [1].

The first bridges to be built by humans lie beyond historical records. In the early days of mankind one of our ancestors might have stumbled on a tree trunk fallen across a stream, or decided to lay flagstones across a wild ford to access new hunting grounds. Much later, when people began to organize themselves in permanent settlements and started to develop culture and trade, roads and bridges became quintessential for growth. All great civilizations in history thrived by means of a dependable infrastructural network that enabled swift mobility of goods and people. The ancient Romans knew this all too well. When Gaius Julius Caesar had submitted all of Gaul in 51 B.C. he had done so by means of efficient Roman highways that enabled his legions to travel great distances and to strike fast. The military bridges of those days were functional wooden structures that could be erected by skilled forces in little time.

Famous are the two wooden bridges that Caesar built in 55 and 53 B.C. to engage the Germanic tribes across the Rhine (figure 1.1). It took his soldiers and craftsman only ten days to build these multiple span bridges, and less to destroy them on their retreat. Directly in the wake of the conquest of Gaul came trading, civil servants and civilians, allowing Roman settlements to thrive in new territories. Roman roads were a marvel of technology, they were paved in stone, cambered, and flanked by footpaths, bridleways and drainage ditches. They were laid-out according to accurately surveyed alignments, cutting through hills, with permanent bridges and viaducts carrying them over rivers and ravines. These bridges and aqueducts were true works of art, skilfully crafted with highly precise and mortarless stone arches many of which still stand today.

From Antiquity all through to the late Middle Ages, the task of designing a bridge would typically be that of one person, usually referred to as the master builder. There was no distinction between technique and aesthetic design, the master builder was architect and engineer at once [2]. It wasn't until the late 18th century that the métier of the architect and that of the engineer went separate ways. When in 1794 the 'école *polytechnique*' was founded in Paris, followed by the 'école *des beaux art*', the division between the arts and technology became a fact. Two stand-alone educations for architects and engineers arose and other universities in Europe soon followed this example. The schism between architects and engineers remains the current practise until today and forms the premise of this dissertation.

§ 1.2 The architects role; from cosmetic advisor to design integrator

In the last two decades we have seen that bridges have become a trend-setting factor in the public realm. The time that bridges were designed as mere functional objects is past. Politicians and policymakers want to make good cheer with beautiful bridges. Whether it is as a part of a new building location, a historical city centre or out in the open landscape, bridges are seen more and more as symbols of culture and heritage. A noticeable trend in bridge design is the growing attention for the urban context or the landscape context. The beauty of the bridge design is taken beyond the architecture of the structure itself; society calls for bridges that are carefully integrated in the landscape or the urban fabric. The design can be subtle, it can be a beacon on the horizon and it can even be an iconic statement. What now is the role of the architect in the design process? In order for us to understand the current position of the architect in bridge design we must first go back in time to the antiquity.

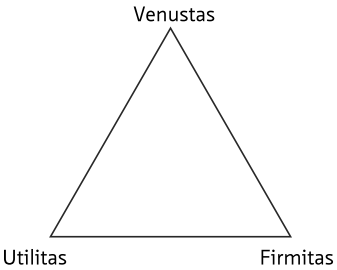


FIGURE 1.2 The Vitruvian adage.

More than 2000 years ago the influential Roman architect/engineer Vitruvius (80-25 BC), wrote his book "*de architectura*" [3]. From his book comes a famous adage that many today believe to be his greatest legacy to contribute to the education of architects. Vitruvius' adage states that in order for a structure to be of lasting value for society, there needs to be a balance between the three powers named *utilitas*, *venustas* and *firmitas* (functionality, aesthetics, firmness) (figure 1.2).

No other author has captured the essence of good design in such clarity. This adage defines the basis of all good design and is still very valid today. Vitruvius meant his adage to be valid for all manmade structures, not bridges in particular, although one can see how this trinity applies to bridge design as well. In the design process of a bridge the three powers are represented by the role of the commissioning authorities, the architect and the engineer. This delicate balance of power has shifted notably over the past 150 years.

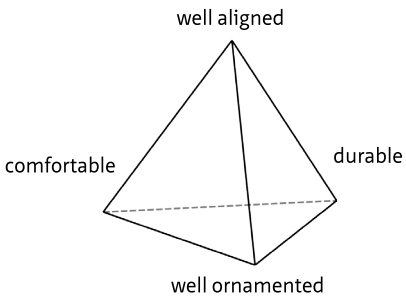


FIGURE 1.3 Palladio's values illustrated.

According to H. Gautier, A. Palladio (1508-1580) is the one exception of an author that writes at some length about bridges in his influential work *Quattro Libri dell' Architettura* (1570) [4]. In this work, Palladio acknowledges that bridges are the main

parts of a road, that it is surprising to see that they actually form a path on the water, and that bridges should be; 1st well aligned, 2nd comfortable, 3rd durable and 4th well ornamented (figure 1.3). As we can see Palladio adds the criterium of being well aligned to Vitruvius triangle of Venustas, Utilitas and Firmitas. Being well aligned according to Palladio means that a bridge should cross a stream at an oblique angle and that it should do so without a slope. As for beauty, this Palladio reduces this feature of the design merely to the ornamentation of the bridge. Perhaps Palladio was of the opinion that a bridge that is well aligned and designed according to the forces that act on it is already intrinsically beautiful.

§ 1.2.1 The engineer's era

The separation between the métier of the architect and that of the engineer is not that old and can be dated as precisely as the end of the Middle Ages. The latter, as we have all learned in school, ended in 1492 when Christopher Columbus discovered the Americas. An event of a slightly lesser magnitude ended the era of the Master Builder, who was architect and engineer at once. In 1794 the 'école *polytechnique*' was founded in Paris, followed by the 'école *des beaux art*'. From that date on the formal division between the arts and technology became a fact. Two stand-alone educations for architects and engineers emerged and other universities in Europe followed this example. For instance, in 1842 the forerunner of the present Delft University of Technology was founded after the example of the École Polytechnique in Paris. The school was founded by Antoine Lipkens, an engineer who himself studied at the école polytechnique in Paris. At this school lessons were given in a strict way, often by military staff.

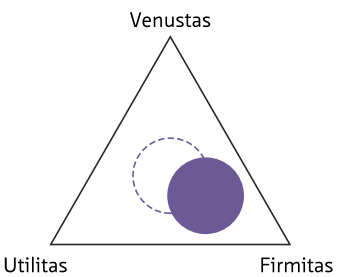


FIGURE 1.4 An engineering approach.

At the start of the industrial revolution in the *fin de siècle*, it was the engineer who ruled the field of bridge design. Technological discoveries, new insights on structural behaviour and new materials as steel and reinforced concrete were his playground (figure 1.4).

Some of these engineers were able to step beyond the boundaries of their discipline and turned out to be true craftsmen with a fine sense of aesthetics. Engineers such as Gustave Eiffel, Robert Maillart and Pier Luigi Nervi designed state of the art bridges. They let themselves be guided by the forces at play in the material and sometimes literally shaped those forces. The Salginatobelbrücke in Switzerland from the Swiss engineer Robert Maillart is a fine example of the elegant plasticity that concrete makes possible (figure 1.5).



FIGURE 1.5 Salginatobelbrücke in Zwitserland (Robert Maillart, 1872- 1940). Photo from https://grandtour.myswitzerland.com. visited on 25/02/2019.

Still the vast majority of engineers weren't endowed with such a fine sense of aesthetics [5]. Sometimes this called for the contribution of an architect, whose role was usually limited to the cosmetic upgrading of the final design by means of parapets and the use of colour. Needless to say that the relationship between the engineer and the architect wasn't always obvious and that there was a fair part of suspicion between the two.

An exception to this rule is found in the larger metropolitan cities. Dutch cities such as Amsterdam employed a town planner whom was usually an architect by profession. Such was the case with the Amsterdam town planner Piet Kramer. He built over 300

bridges in the period 1915-1940, the time of the influential *'Amsterdam School'*. Many of his bridges combined architecture with sculpture, such as the famous sculptor Hildo Krop (figure 1.6). H.P. Berlage was another famous town planner. His bridges were foremost objects in the urban fabric, including residential areas, benches and richly ornamented parapets and lampposts. The structure of his bridges was usually in service of the architectonic expression.



FIGURE 1.6 Boerenwetering Bridge in Amsterdam with sculptures from Hildo Krop. Photo from http://adambeeldenva1900.blogspot.com visited on 25/02/2019.

TOC

§ 1.2.2 The great wars era

In the era of the great wars and in the first post-war decades, the field of bridge design was dominated by two aspects, a shortage of resources and base materials. With only a few positive exceptions it was the engineer's task to bridge the gap from A to B in the most efficient and in the cheapest way (figure 1.7). Aesthetical aspects hardly mattered and the role of the architect was virtually non-existent. Due to the poor quality of materials at hand the durability of such bridges was quit inferior, not many examples from this era now remain to be seen and those that still stand are often in bad need of replacement or thorough refurbishment.

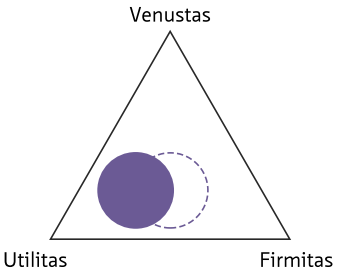


FIGURE 1.7 Shift to efficient and cheap.

The Star Architect's era

A turning point in the unilateral approach to bridge design came to us in the early 90's of the previous century [6]. In the Netherlands, commissioners of infrastructural projects and bridges in particular became culturally aware and were encouraged to do so by the Dutch government. The Spanish architect Santiago de Calatrava had just built his Alamillo bridge in Sevilla. In the Netherlands his former pupil Ben van Berkel completed the design of the Erasmus Bridge in Rotterdam in 1996. Even though the 75 million euro building costs exceeded the costs for a straight forward cable stayed bridge by far, the Erasmus Bridge has become the ultimate icon for the city of Rotterdam and the essential link to the new city expansion on the south shore of the Maas.

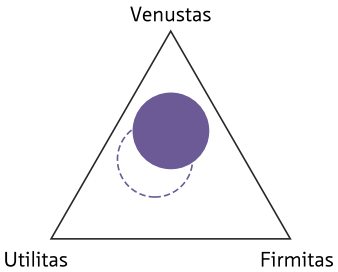


FIGURE 1.8 Architecture as a guiding principle.

All of a sudden it seemed as if architecture and bridge design had rediscovered each other. Al over Europe a huge increase in architectonic bridge design immersed. As if wanting to make up for the lost years when architects were only allowed to operate in the margins of bridge design. This probably explains the overenthusiastic attitude some of these architects manifest when it comes to the structural logic of the design. The shift of power had taken place and it was now the engineer's job to make sure that all the merry creations that architects came up with would not collapse at first sight. The bridge designs that these 'star architects' came up with had to be judged as sheer masterpieces of fine art, with a capital A (figure 1.8). This approach often resulted in structurally absurd bridge designs with an overkill of stay-cables for relatively small spans, arches burdened with point loads or bended compression rods. These are just a few examples of the inability of engineers and architects to speak the same language.

§ 1.3 Commissioning authorities and good procurement

The role of the commissioning authorities in the design process has always been an important one. To put it in terms of Vitruvius, the authorities represent the aspect "Utilitas" that lies at the basis of every bridge design. Until the end of the 20th century it was still common practice for the commissioning authorities to play an active and participating role in the design process. Authorities involved in bridge development were in the lead of the process. Public authorities that wanted a bridge were most of the time not only looking for the cheapest way to get from A to B but were equally culturally engaged to the point of sometimes acting as a patron of arts by instigating fine architecture. Basically the bridge building business was a three-party market economy; the client would commission an independent architectural office and an engineering office to make the design for, and with, the client. At the same time the architect and engineer would play a vital role in contracting, guiding and controlling the

building contractor. Although this kind of design approach is still practised at times, Belgian authorities for example still use the three-party market system if they want to stay in the lead of the design, such a practice is unfortunately become more and more rare.

At the beginning of the 21st century the market for infrastructural projects has undergone drastic changes, triggered largely by to the economic recession. Public authorities were forced to downsize their organizations and focus on their core business; initiating infrastructural projects and securing an affordable result. Thus the authorities retreated from their participating role to make way for the market economy. Basically the 20th centuries three-party market had changed into a two-party market; on the one hand there is a public authority in the role of the commissioner of the bridge and on the other hand there is the contractor or commissionee (figure 1.9).

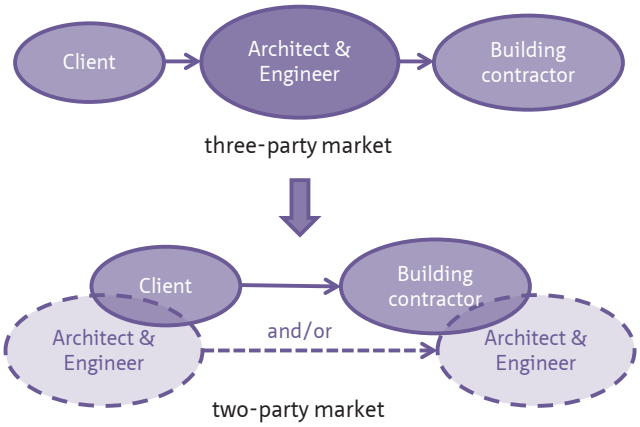


FIGURE 1.9 The transition from a three-party market to a two-party market.

The authorities had changed from an active partner in the design process into the initiator and facilitator of a process. Authorities no longer assume the responsibility for the design process.

In the Netherlands the former Director General Bert Keijts of Rijkswaterstaat (Ministry of Infrastructure) introduced the adage 'market, unless' between 2003 and 2010, pleading for maximum of freedom for the contractors to develop the most efficient and cheapest solutions. His successor Jan Hendrik Dronkers then turned back 'market, unless' and put the emphasis back on 'working together with the market'. Dronkers still found the introduction of integrated contracts a good idea, in which the roles have

changed and the market has been given much more room for manoeuvre, "*Nobody is going to turn that back.*" according to Dronkers. To date, Rijkswaterstaat still works as a standard with D&C contracts. And as always, lesser authorities like provinces and municipalities follow the path led by Rijkswaterstaat.

When it comes to the role of aesthetics in integrated contracts we can see that the authorities are still searching for the best place to secure good design in the process, as much as they are searching for their own role and responsibility. In the early years of D&C contracts we have seen some very badly designed infrastructural projects in the Netherlands. The High speed railway line HSL near Zoetermeer-Bleiswijk (2000-2009) is such an example (figure 1.10). Here we see that aesthetics were clearly left out of the equation. The railway fly-over does not respect the laws of rhythm and symmetry and displays a haphazardous sequence of pillars and prefabricated beam in various depths with no attempt to bring harmony or to integrate it into the landscape. The unfortunate conclusion of the 'market unless' approach was that by taking a step back and leaving the design process to the market the authorities are no longer in control of the design.



FIGURE 1.10 HSL railway line near Zoetermeer-Bleiswijk, 2000-2009. Photo from https://mapio.net/images-p/85420570.jpg visited on 25/02/2019.

In later examples of D&C contracts authorities have tried allocating fictional price reductions by introducing EMVI scores for aesthetics. This strategy obliged the contractors to hire an architect in order to secure the price reduction. The problem with this scheme is that authorities had to indicate to what criteria a tender design will be judged. For this reason vaguely formulated sentences as *'we are looking for unity in diversity'* were part of the tender specifications for the new A50 bridge across the Waal at Ewijck-Valburg (2010-2013) that was to be built adjacent to the old cable stayed bridge (figure 1.11).

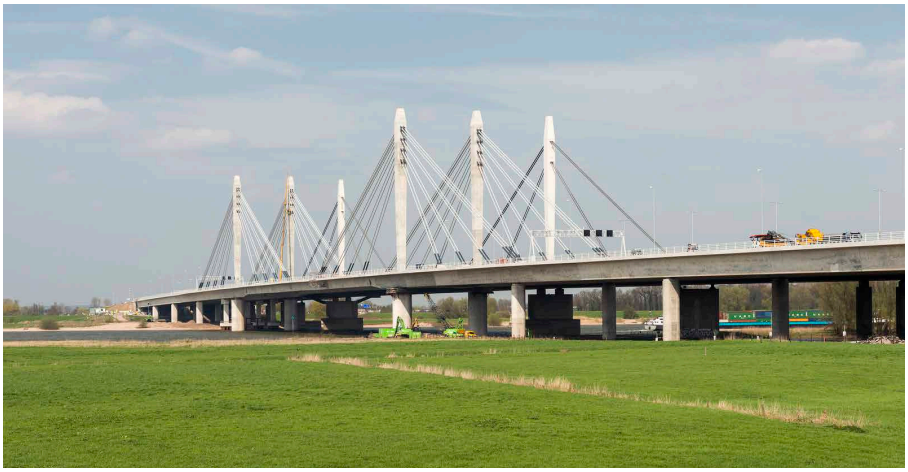


FIGURE 1.11 A50 bridge at Ewijk - Valburg, photo by Thea van den Heuvel/DAPh 2014.

The steering mechanism of the architectural design consisted of the introduction of the so called 'pro-competitive dialogue' with the contractor and their architect. However, from first-hand experience of the author of this dissertation, these dialogues are better described as monologues were the contractors' architect presents a proposed design whilst the authorities are shy to comment, for fear of legal repercussions if too much steering would have given the competition legal arguments to contest the outcome. The result of this kind of 'pro-competitive dialogue' is that contractor and architect are left pretty much in the dark when it comes to assessing what the client would like to see. The disappointing configuration of the winning design proved that what the client was looking for was something almost, but not quite, the same as the original bridge. The result does not convince as the composition of the original two steel pylons, solitary and slender, is not complemented nor enhanced by the addition of twice as many and slightly heavier concrete pylons with twice the amount of cable stays.

After the first child sicknesses of D&C contracts had been cured, authorities took back some degree of control over the aesthetical design by taking the drafting of the basic architectural requirements back in their own hands. In the Netherlands these documents are known by the generic term 'Beeldkwaliteitplan' (Plan for the quality of the appearance), or more recently the term 'aesthetical requirements' (AR). These AR documents, while at the beginning vague and multi-interpretable, became more on more concrete over the past years. The recent example of the N31 Traverse in Harlingen (2012-2018) shows that the authorities, in this case an alliance of Rijkswaterstaat, Province of Fryslân and the municipality of Harlingen, commissioned an architectural specification document, drafted by the author of this thesis (figures 1.12, 1.13).

In previous years one might have called such a document an architectural preliminary design. One difference is that these new kind of AR documents that are part of the tendering specifications cannot be specific about the type of construction methods used. The argument is that the benefits of a free market would be lost if the bridge design were to be defined in advance. Architecture is now reduced to the purely cosmetic description of the outer appearance. In AR documents the challenge for the architect and his client is that even though the construction cannot be shown, it still must be explored as the feasibility in terms of finance and constructability must be assessed before the publication of it.

We must now consider what the change to a two-party market means for the role of the bridge designers in the design process, architects and engineers alike. The former position of the bridge designer in the leading role between the authorities and the contractors no longer applies. It seems that nowadays Bridge designers have two choices. Either they supply manpower, knowledge and expertise to the organization of the authorities, thus acting on their behalf by drafting the tender documents, reference designs and in the best of cases including aesthetic requirements. The other choice that bridge designers have is to provide their services as a sub-consultants to building contractors. In this last case the architect and the engineer no longer answers directly to the responsible authorities but rather to the building contractor who in his turn is the commissioner to the architect and engineer. In both cases the architects and engineers are no longer leading in the design process. And in both cases the architects and engineers must make a clear choice on which side to opperate as they can not legally do both.



FIGURE 1.12 Animation from the Architectural Requirements document N31 Harlingen, Royal HaskoningDHV, Joris Smits et al. (2016).

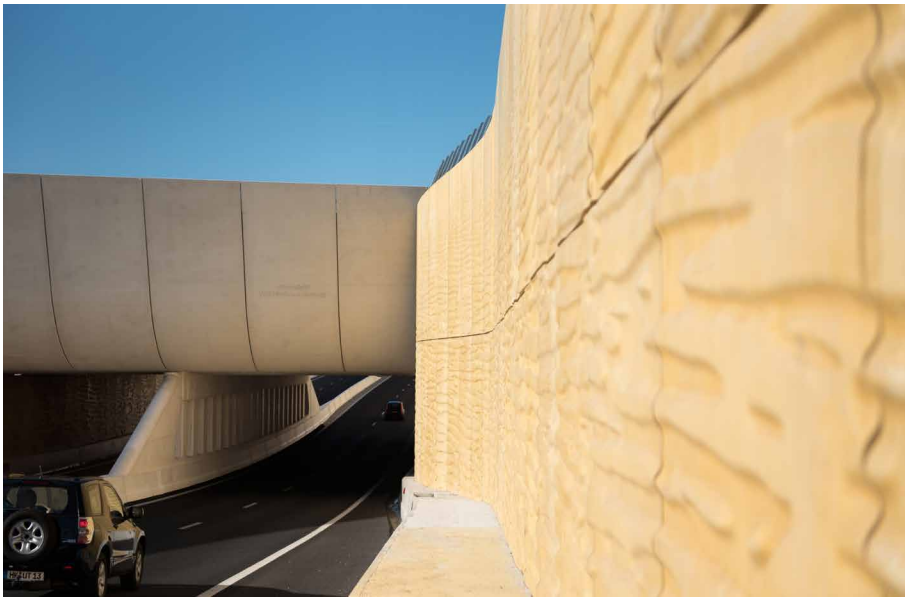


FIGURE 1.13 Traverse N31 Harlingen after realisation. Royal HaskoningDHV, Joris Smits et al. Photo by Jane van Raaphorst 2018.

These developments raise the question of how best to secure good design when commissioning a bridge. In the case that the architect works directly for the authorities, their job is restricted to formulating the requirements for aesthetical quality rather than making an integral bridge design. This kind of conceptual design is per definition limited to the description of the outward appearance of the project, for fear that the benefits of a free market would be lost if the bridge design were to be defined in advance. On the other hand architects working for the contractor within the tender team are usually restricted to the making of the tender design. Once the contract is awarded and the contractor starts on the detailed design and the building phase, there is no good way of controlling the aesthetics of the final product. In the detail engineering phase the winning contractor will mainly be driven by costs and will have little interest in going the extra mile for good design.

So the question that needs answering is how best to ensure design quality in our future infrastructure projects? How can we achieve well integrated bridges and infrastructure that works for the people in the communities, that are valued for their design and aesthetically appearance and at the same time allow the market economy to work? The key to the answer lies in the procurement process were the design quality needs to be secured. One way to achieve that is to claim back the 'D' in Design & Construct contracts, thus transforming them into E&C (Engineer & Construct) contracts. This would be a natural response to the loss of control that authorities experience when they leave everything up to the market, including the design. A next step would be to also claim back the preliminary engineering and cost estimate, thus leaving the detailed design to the market. The opposite approach to reclaiming the design would be to truly leave every aspect of the design process to the market. This can deliver good value if design can be turned into a key assessment for procuring the assignment. This approach resembles architectural competitions, the difference being that all competition entries will be accompanied by a price tag from the building contractors that minimizes the risks of overspending at a later stage.

A good friend of mine and renowned bridge designer from London, Martin Knight, puts it this way: "*Bad procurement is the biggest threat to design quality... The key to good design and procurement is to tie them together contractually, either through the construction contract or, better still, through the planning permission, so that there is an obligation on the contractor, the designer and the client to maintain design quality even as cost and time pressures increase.*" Another great bridge designer from the United Kingdom, the structural engineer Ian Firth, says in his TED talk of June 2018: "*We need to start talking to those who procure our bridges. Procurement is key. Bad procurement is prejudicated against good design.*" [1]

§ 1.4 Problem statement; the segregation of knowledge

After the schism of 1794 (page 6) when bridge engineers and architects went their own ways, bridge technology and material science developed at a fast pace. These developments resulted in a technological field too vast for one person to master. A typical bridge design project nowadays comprises specialists from many different disciplines such as (urban) planners, landscape architects, traffic designers, architects, structural engineers, mechanical engineers and material specialists. All these content experts work alongside the various managers that control the process such as project managers, permit managers, stakeholder managers, procurement managers, tender managers, contract managers and supervisors.

Ideally the design of a bridge is made through an integrated approach that addresses all relevant technological angles and stakeholders. In reality, many different people from many different disciplines work on the design during different phases of the project. The consequences are that the cohesion between the different design aspects often gets lost and that a symbiotic working relation between the different disciplines is missing.

Furthermore, it is noted that under the authority of the commissioning authorities the current practice in the procurement of our bridges does not promote an integrated approach either. In the past two decades we have seen how fragmentation in the design process has further increased due to an equally fragmented procurement approach, reminiscent of the 'divide and rule' policy of colonial times. It is no exception nowadays to commission the drafting of the landscape planning to one party, the writing of the brief of architectural requirements (Beeldkwaliteitplan in Dutch) to the another party, to occasionally commission a reference design to yet another party and to have the final bridge design being made by the architects and engineers that work for the contractor. It goes without saying that such a fragmented approach to procurement is incompatible with good design. And that in turn bad design makes for lowly valued bridges and a decline in public support for new infrastructure.

This leads to the following problem statement: the segregation of knowledge into discipline-specific fields, and the fragmented approach to bridge procurement, have resulted in a general lack of cohesion in bridge design. Furthermore, it is noted that the field of bridge design lacks critical investigation into how to pursue good integrated design.

§ 1.5 Hypothesis; introducing a design integrator for better bridges

The working hypothesis of this research is the assumption that the introduction of a design integrator will lead to better bridges and will increase public support for new infrastructure. If one person could oversee the design process in its entirety by fulfilling the role of design integrator and by defending the design in the public debate, the design process would greatly benefit. The design integrator should not be the omniscient master builder of old, but would instead act as the conscience of the design, the expert who directs and coordinates all design aspects of a bridge.

§ 1.6 Objective

The objective of the research is:

To identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, integrally-designed and that are valued by society.

§ 1.7 Research questions

Accordingly, the objective can be met by answering the principal research question of the dissertation:

How can we identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, integrally-designed and that are valued by society?

The research questions associated with the principal research question are:

1 **What design considerations can be identified for bridges at the scale level of the landscape or of the urban texture, and how can bridges fulfil social, cultural and regional requirements and strengthening regional identity?**

This question is answered in chapter 2.

2 **What design considerations can be identified for the design of a bridge at the scale of the object itself, and how can architectural and structural symbiosis in the design be achieved?**

This question are answered in chapter 3.

3 **What design considerations can be identified for the design of a bridge at the scale of the detail and that of the materialization?**

By taking the example of an innovative material in bridge design, Fibre Reinforced Polymers (FRP), a sub-question can be asked:

What design considerations can be identified to the use of FRP, both as a structural and as a non-structural application, in bridge design?

These questions are answered in chapter 4.

4 **What design considerations can be identified for the design of a bridge at the scale of the chosen materials and of the material properties that constitute a bridge?**

By taking the example of bio-composite, a natural fibre reinforced bio-polymer, a sub-question can be asked:

Can a fully bio-composite footbridge be produced form natural fibres and bio-resins?

These questions are answered in chapter 5.

5 **What design considerations can be identified to achieve a higher standard of durability and sustainability for bridges?**

The answer to this question is discussed in chapter 6.

6 **Will the transformation of the role of the architect as the aesthetical advisor, to the role of the design integrator, lead to well-integrated, integrally-designed and socially-valued bridges?**

The answer to this question is discussed in chapter 6.

7 **How can the commissioning authorities secure the design quality of our future bridges and infrastructural projects?**

The answer to this question is discussed in chapter 6.

§ 1.8 Research method; a project review through lenses and scales

The methodology through which the research questions are answered and the hypothesis is proven is that of a review of projects from my own bridge design practice. The choice to review my own projects is based on the fact that I have been fortunate to work on hundreds of integral bridge projects over the past 22 years, projects that have taken me through all phases of the design; from the initiative phase and the conceptual design at the start, to the detailed design and on site supervision at the end of every project.

The choice to review my own working practice was born out of practical considerations. First of all, the integral design of bridges is an important aspect of my dissertation and there are only two integral bridge design practices in the Netherlands that incorporate every aspect of the design. Of course, there are several architectural practices in the Netherlands that design bridges, just as there are several engineering practices and landscape architectural practices. These practices work in changing constellations on various bridge projects. However, it would have proven to be very arduous and time consuming to interview all these different parties involved in the design of a bridge. The second practical consideration was that I wanted to be able to review in length and detail all the challenges, problems and opportunities that a designer faces within every integral design process during the course of a project. The best way to achieve this was to write about it from the perspective of someone who has been involved in every aspect of the process from first-hand experience. Having said that, it is important from an academic point of view to maintain a critical and unbiased attitude toward the reviews of one's own work. There are in my opinion two factors that are able to create distance and can guarantee an unbiased view: time and knowledge. On the former, I have chosen to review mostly older work from my portfolio, with the exception of the bridges in Fibre Reinforced Polymers for obvious reasons. Being able to look back at my own work from a time induced distance has proven to be a good way to obtain critical and open-minded observations on my own working methods. On the latter, I have found from personal experience that the more you know about a certain art or discipline, the more critical you become to your own performance in this field, and the less likely you become to turn a blind eye on your deficiencies.

The chosen methodology has explicitly not resulted in a comprehensive manual that discusses all the involved disciplines, all bridge typologies and every possible material available to the engineer or architect. Rather, through the method of reviewing my own work, I have aimed to give an insight in bridge design as an integrating discipline. One that is practised across several technical disciplines, seen through various lenses and applied through a multitude of scale levels. For this reason the framework of this

dissertation is broad, and focusses on the integration of the various disciplines that are involved in the design of a bridge. Each discipline typically looks at bridge design through its own lens and at its own preferred scale.

The mechanism through which the projects are reviewed and evaluated is based on three Vitruvian lenses and on four scale levels of design. The choice of the various lenses and scales is based on my own experience in the bridge design practice accumulated over a period of 22 years.

The three lenses are derived from the classical Vitruvian values; Utilitas, Venustas and Firmitas (functionality, aesthetics, firmness). In turn, each lens is represented by one or two of the most important actors in terms of content; the architect, the structural engineer, the builder and the client. The client operates from the perspective of Utilitas, asking for a certain functionality to serve the goal within planning and budget. The architects is the keeper of the value Venustas; he or she is in charge of the aesthetics of the bridge and responsible for making a design that is meaningful to the people who use it and contextually aware. The engineer and the builder both serve the purpose of Firmitas; the responsibility for structural integrity and durability lies with them.

The four scale levels are derived from the typical scales through which urbanists, architects, engineers and material experts bring their skills top practice at different phases of the design. In the planning phase of a project, planners, urbanists and architects practise their skills at the scale level of the city and that of the landscape (scale 1:1000). In the preliminary design phase of a bridge, the perspective of the architect is mostly directed at the scale of the bridge itself and that of its direct surroundings, while the engineer operates at the scale of the object itself (scale 1:100). In the detail design phase the architectural and engineering perspective typically zooms in at the structure itself and the forces at play within the structure (scale 1:10). The mechanical engineer and the material expert look at individual components and materials that compose the structure at the level of the mechanical and material properties (scale 1:1).

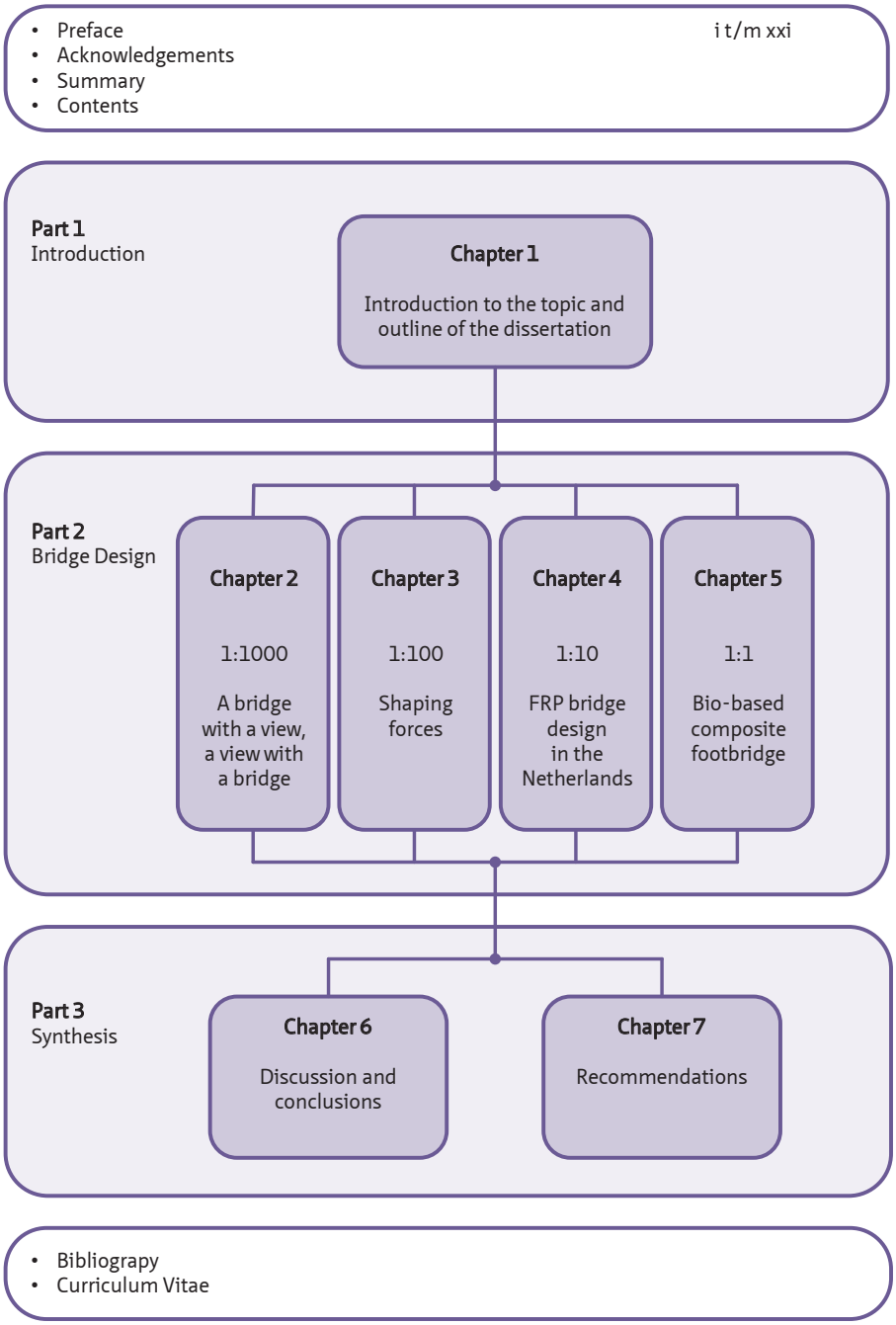


FIGURE 1.14 Structure of this dissertation.

§ 1.9 Structure of dissertation

The structure of this dissertation consists of three parts and seven chapters, each with its specific focus. Figure 17 presents these parts and chapters.

Part one is the current chapter and provides an introduction to the research. The research topic and the research aspects are briefly introduced. The changing role of the architect in the field of bridge design is analysed in an historical context. The role of the commissioning authorities is introduced. The problem of segregation of knowledge is introduced. The objectives and research questions are stated, a hypothesis is formulated and the methodology is discussed.

Part two of this dissertation comprise the theoretical framework of this research and addresses the topic of Bridge Design through four journal papers, here included in chapters 2 till 5. These chapters consist of journal papers that have been published, or are currently under review in the case of the last chapter, in various journals. These papers discuss the design of bridges at the scale of the landscape (chapter 2), the scale of the object (chapter 3), the scale of the detail (chapter 4) and at the scale of the materialization (chapter 5).

Part three is the synthesis and consists of chapter 6, an integrated discussion and conclusions of the research results, and chapter 7 that provides recommendations for the future of bridge design.

References

[1] TED. (2018, April). Ian Firth: Bridges should be beautiful [Video file]. Retrieved from https://www.ted.com/talks/ian_firth_bridges_should_be_beautiful

[2] Kamerling, J. W. (1969, May 2nd). *Bouwen voor de gemeenschap,* inauguration speech (in Dutch). Eindhoven: Eindhoven University of Technology.

[3] Granger, F. (2007). *Vitruvius on architecture*. Bakhsh Press.

[4] Palladio, A. (1570), *Quattro Libri dell'Architettura*. Venice, Italie: Domenico de Franceschi.

[5] Virlogeux, M. (1996). Structural and Architectural Design of Bridges. *Structural Engineering International 6*(2), 80-83

[6] Walter, R. (1996). Engineers, Architects and Bridge Design. *Structural Engineering International 6*(2).



PART 2 Bridge Design





2 A bridge with a view, a view with a bridge

Identifying design considerations for bridges to strengthen regional identity

Smits, J., & van der Hoeven, F. (2015)

Scale 1:1000

In the previous chapter the research method of reviewing a design process through the four typical scale levels at which urbanists, architects, engineers and material experts bring their skills to practice, is discussed. The current chapter identifies bridge design considerations at the biggest scale level; that of the city and the landscape.

This chapter was first published in the Research In Urbanism Series (RiUS), 3(1), 135-158. doi:10.7480/rius.3.833. RiUS is a refereed open access publication indexed by Scopus and Google Scholar. IOS Press, under the imprint Delft University Press. Series ISSN 1875-0192, E-ISSN 1879-8217. The layout and paragraph numbering has been adjusted for reasons of consistency, as well as minor textual adjustments.

Abstract

This paper discusses design considerations for creating high quality civil works with an emphasis on bridges. The authors pursue a design study and analysis approach to highlight the specifics of infrastructure design for regional identity, based on their own work on a series of bridges in the Dutch Zaanstreek region. Subsequently two highlights of the authors work, the award winning Juliana Bridge and the wildlife crossing in Rijssen, are used to illustrate how to create good infrastructure design in sensitive contexts, without making use of a neo-vernacular vocabulary.

Keywords: regional identity, architecture, bridge, wildlife crossing, Zaanstad, Dommel Bridge, Highway of the Future, Hoogtij Bridge, Zuidelijke Randweg Bridge, Butterfly Bridge, Prins Bernhard Bridge, Zaanbridge, Juliana Bridge, Rijssen wildlife crossing.

§ 2.1 Introduction

In his book *A view from the road* Donald Appleyard states: "*ugly roads are often wrongly taken to be the price of civilization, like sewers or police*"[1]. The boring, chaotic, disorientated roadscape seems to be the natural habitat of that useful but awkward monster, the automobile. Most infrastructure and civil structures that we pass on our daily journeys through our landscapes seem to have little or no connection to the landscape they traverse, be it urban or rural. This anonymity of civil structures along the highway leads to animosity among the users. This chapter analyses in depth the design decisions regarding a key type of civil structure in our infrastructure landscapes: bridges. Its point of departure is that designing bridges as part of an urbanized landscape should be a self-evident matter.

In this context this paper addresses the question: which design considerations allow us to design bridges that fit our social and cultural requirements? What does it take to make bridges contextually aware? How can bridges be designed in such a way that they are appreciated by their users as well as those who live nearby while contributing positively to the identity of place and region?

The second paragraph of this paper addresses the importance of strengthening regional identity by means of infrastructure design, and more specifically by means of civil structures such as bridges. Different approaches to designing bridges and other civil structures within a landscape, be it rural or urban, are discussed.

The third paragraph demonstrates the contribution of a regional approach to the identity of an area through some of our projects in the Zaan region, in the Netherlands. Together these bridges form an ensemble that provides a sense of regional belonging.

The fourth and fifth paragraphs analyse two of our projects to illustrate the outcome of the design approaches that are presented in this paper. Both projects differ in terms of typology, context and design approach. The Juliana Bridge responds to a world heritage site, while the wildlife crossing in Rijssen deals with an ecologically sensitive area and with differences between two landscape types in the Netherlands.

§ 2.2 Strengthening regional identity through means of infrastructural design

The on-going process of European integration seems to downplay the role of nation states while allowing regions to play a stronger role than before. The subsidiarity principle of the European Union states that no unnecessary centralization should take place and that tasks should be delegated if possible to lower tiers of government. This leads to a trend in which decisions on for instance spatial planning or infrastructure planning are increasingly delegated to regional authorities while in the past such decisions were taken nationally. This process strengthens the power of regional authorities and in parallel creates a need to develop or emphasize a newfound regional identity. While maintaining the socio-cultural characteristics of a region, administrators and politicians feel at the same time a need to underscore the economic value of their 'brand'.

When it comes to strengthening the identity of a region at the interface of infrastructure and (urban) landscapes, architects and engineers hold strong tools. Hundreds of thousands of travellers and commuters pass our local roads and highways daily. Users of bridges, roads and tunnels outnumber the number of visitors of our city halls, museums and music centres by a large margin. That is why the road with all its bridges, viaducts, tunnels and noise barriers can become a means to bestow character and identity to a region, if not standardized across the country.

As early as 1941, the Dutch designer ir. G.A. Overdijkink wrote in his book *Langs onze wegen* ('Along Our Roads'), that the character of a region must be expressed in road design [2]. By road design he meant the alignment, the planting, the width and lane configuration of the road. This adage should be extended to include the civil structures underneath, above and next to the road. If architects and engineers succeed in bringing across the feeling that a design is tailor made for a specific location, then ultimately these civil structures can contribute to the sense of pride and dignity that ties people to their region.

Of all civil structures along a road or highway, bridges are the main highlights in the route design. The presence of a bridge enhances the sense of orientation and gives an idea of the kind of place you are going through. A bridge is one of the few objects along a road or rail line that manifest itself to the traveller as an elevation with a facade. Traditionally the façade is the architectural element that articulates the design of the building, sometimes even becoming monumental like the front facades of cathedrals. Bridge design can be approached in a similar way, as an act of culture, bestowed with an identity that is contextually aware.

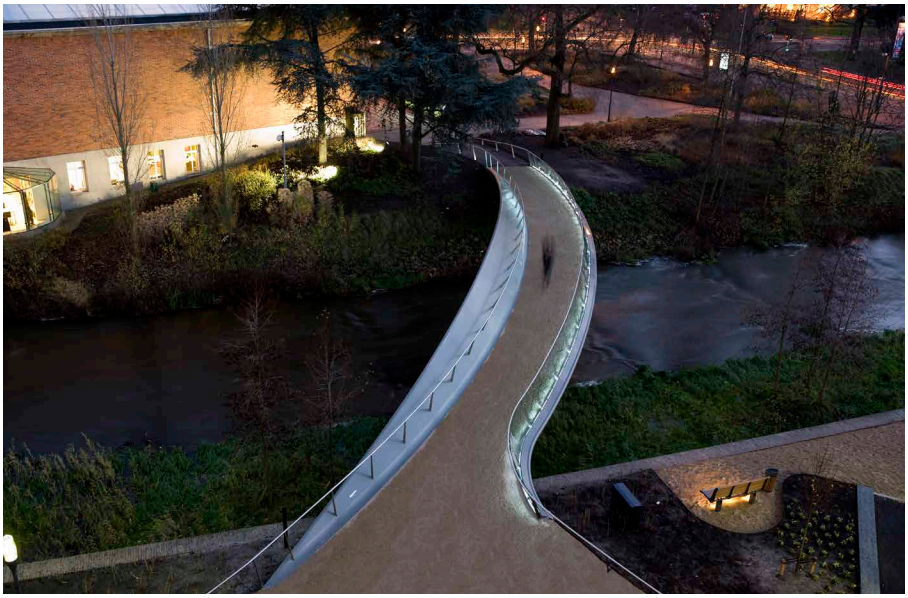


FIGURE 2.1 The Dommel Bridge. The identity of the city of Eindhoven as the cradle of both the Philips light bulb industry and the Design Academy is expressed in this bridge. Royal HaskoningDHV, Joris Smits et al. (2007), photo by Jan van Oevelen 2006.



FIGURE 2.2 Sustainability through innovation is the theme that stands at the base of the highway of the future in Oss, the Netherlands. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Jane van Raaphorst 2014.

When we look at the literature we can find many books and papers that treat the design of mobility on the larger scale of the highway and its surroundings [1-8]. However, the subject of the design of individual civil structures such as bridges is hardly subject of research. This is why the following theories are based on our own experience in our projects and on our observations in the field.

There are several approaches for creating infrastructure that is contextually aware. By and large we can say that there are two opposite ends in the appreciation of civil structures and the subsequent design approach. First there are those who are alarmed by the ugliness of the highway. They preach the repression of vice; their adage is to hide infrastructure or to melt it into the landscape. Scars of construction should be camouflaged by planting. In the best of cases the genius loci is interpreted as an elaboration on the historic idiom. On the other hand there are those who believe in the power of the design as a weapon against mediocrity. This calls for a more contemporary approach and a less literal interpretation of the characteristics of the place and the people that live there.

In *The Joyless Economy* Tibor Skitovsky states that an excess of standard goods, for example non-exceptional goods, will lead to increased social dissatisfaction, because the goods are devoid of real sensory stimulation for human beings [9]. If that is the case we must provide people with a satisfactory sensory and at the same time pluralistic experience for their everyday mobility. What better way than to raise the quality of design of our infrastructure? Can bridge design be an act of culture that creates value in the eyes of the beholder? According to Houben and Calabrese in there book *Mobility: A room with a view*, there is little discussion about turning the highway experience into a positive account. Show it off with pride, design it! Just as the polder landscape was designed [5] (figures 2.1, 2.2)

§ 2.3 Bridges in the Zaan region, the Netherlands

The award winning Juliana Bridge in the Zaan region by Joris Smits, demonstrates best practice in strengthening the regional identity through means of good design of infrastructure. What elements constitute the regional identity of the Zaan region and how is this reflected in the bridges that we designed and built in this region? This chapter describes how the character of the Zaan region was captured in the bridge design, through the use of local elements.



FIGURE 2.3 The Hoogtij Bridge for cyclists in the Westzanerpolder. Royal HaskoningDHV, Joris Smits et al. (2005). Photo by Bart Nijs 2006.



FIGURE 2.4 The pedestrian bridge in the Zuidelijke Randweg, Royal HaskoningDHV, Joris Smits et al. (2005). Photo by Joris Smits 2011.



FIGURE 2.5 The 'Butterfly Bridge' for buses spans road and water. Royal HaskoningDHV, Syb van Breda et al. (2003). Photo by Bart Nijs 2004.



FIGURE 2.6 The Prins Bernhard Bridge, a multi-layered bridge with access to the quays. Royal HaskoningDHV, Syb van Breda and Joris Smits et al. (2007). Photo by Jan van Oevelen 2008.

The Zaan region has always been a very industrious part of the Netherlands inhabited by a very industrious people. It was in the Zaan region that the first signs of industrialisation appeared along the river Zaan. That is why traditional values and state of the art industry have always gone hand in hand in the Zaan. The traditional wooden houses, spotlessly clean in shades of white and green, stand alongside the massive silhouettes of silos, among which the famous 36 meter tall Lassie silo that was Netherland's first concrete silo, built for the shipping of rice, cacao and coffee to and from the rest of the world. Nowadays the industrial heritage of the Zaan region is an important asset for tourism in the Zaan. We must not forget that the famous line-up of windmills at the Zaanse Schans was not designed for tourism but to process the wheat and the barley for the food industry. This region and its people have core values that reflect tidiness as well as a strong belief in modern technology.

How does one reflect such a regional identity into the design of a series of bridges? Some architects believe the answer lies in a neo-vernacular approach, a semi historical style with a very caricatural reference to an architecture of the past. This belief is most strongly advocated by the Dutch architect Sjoerd Soeters. Two of his recent designs in Zaanstad for the city town hall and an adjacent hotel are much discussed and quite controversial. We on the other hand believe that in the Zaan region contemporary solutions are needed that fit in with the industrious character of the location. In the design of the series of bridges for the Zaan region this approach is demonstrated. In a period of ten years, beginning in 2001, the architectural office of Royal HaskoningDHV was responsible for a series of six bridges, five of which have been built, the sixth being on the way. (figures 2.3 to 2.6).

Although they are all individual projects on different locations and designed for different authorities, there is a visual bond that ties them together and makes them belong to this region. For lack of a better word we will call this regional identity. All five bridges are modern in appearance and reflect state-of-the-art design. They have a consistent look and feel and are constructed from slender steel shapes. The use of steel reflects the many industrious cranes along the shores of the Zaan. The gentle curved shapes and arches mean that these bridges are not the iconic statements that modern bridges so often are: dominating shapes with a focus on their own presence and little relation to their surroundings. Rather the elegant arched silhouettes emphasise their binding function in the urban fabric, manifesting a strong connection with the ground level from which they emerge: rather earthly than stretching towards the skies. All five bridges have a uniform colour scheme in the local shade of white called 'Zaans wit' or Zaan white, a well-defined off-white, with a touch of another local colour: Zaan green. This specific colour scheme makes these bridges blend in harmoniously with the local architecture and with the green and blue colours of the Dutch landscape without them being neo-vernacular.

§ 2.4 The Juliana Bridge

The setting of the Juliana Bridge is unique. Adjacent to the UNESCO world heritage site of the Zaanse Schans (figure 2.7). The bridge design has been kept rather modest: undoubtedly a contemporary design, but one that respects its historical surroundings. The design is light-footed and transparent but also unpretentious. It offers plenty of space for tourists and cyclists by providing them with their own bridge deck. Maximum attention has been placed on experiencing the landscape, both from on the bridge and underneath the bridge. The panorama deck offers unhindered views of the Zaanse Schans to the north and the industrial heritage to the south. Even the shape of the lampposts, emerging from the void in between the two bridge decks, puts the emphasis on the outward view. The following section describes the design considerations that have been implemented to make the Juliana Bridge a fitting design in this delicate context.

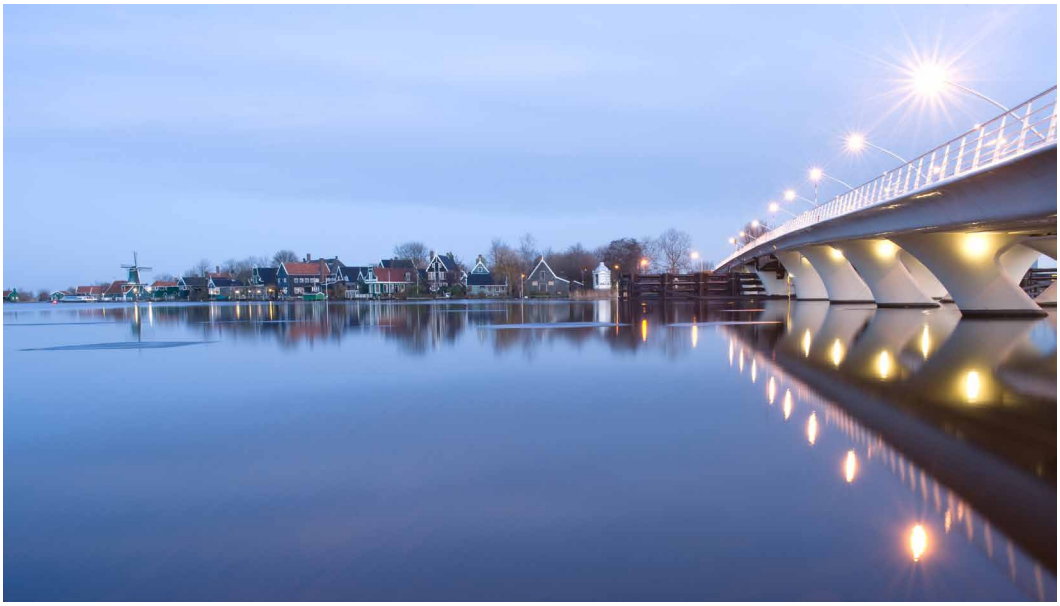


FIGURE 2.7 The Juliana Bridge, adjacent to the UNESCO world heritage site Zaanse Schans. Royal HaskoningDHV, Joris Smits et al. (2009). Photo by Jane van Raaphorst 2010.

§ 2.4.1 Rhythm and harmony

The most manifest design decision was that no obtrusive structure above the level of the deck was allowed, be it a lifting structure or a load bearing structure such as an arch or a cable stay. The Juliana Bridge is an opening bridge in a busily navigated channel, with an eighteen meter opening clearance within a total bridge length of 200 meters. Most lifting bridges in the Netherlands are of the traditional drawbridge typology (figure 2.8).



FIGURE 2.8 The Zaan Bridge in Wormer is of the traditional drawbridge typology. Approach spans and drawbridge form two different entities. Royal HaskoningDHV, Joris Smits et al. (2015).

But having such a prominent structure with towers and an overhead balance plate would start to compete with the windmills of Zaanse Schans and would make the design fall into three parts: two approach spans flanking a lifting part. Instead, we decided to go for a more harmonious approach (figure 2.9) and to have the counterweight integrated and almost invisible underneath the deck and to incorporate the span of the moving part into the rhythm and materialisation of the approach spans. By making ten spans roughly twenty meters apart we ensured an undisturbed rhythm of piers across the Zaan. Integrating the lifting part and the counterweight into this sequence was the next challenge. The lifting part is operated by a series of vertical hydraulic jacks that have been integrated into the actuator pier. For this reason the actuator pier needed to be much thicker than the other piers that are only supporting the approach spans. A solution was found in making each consecutive pier grow a little in size, until the required final width of two meters was reached in the actuator pier. This 'growing' of the thickness of the piers is accompanied with an increase in height, thus respecting the proportions of every individual pier.

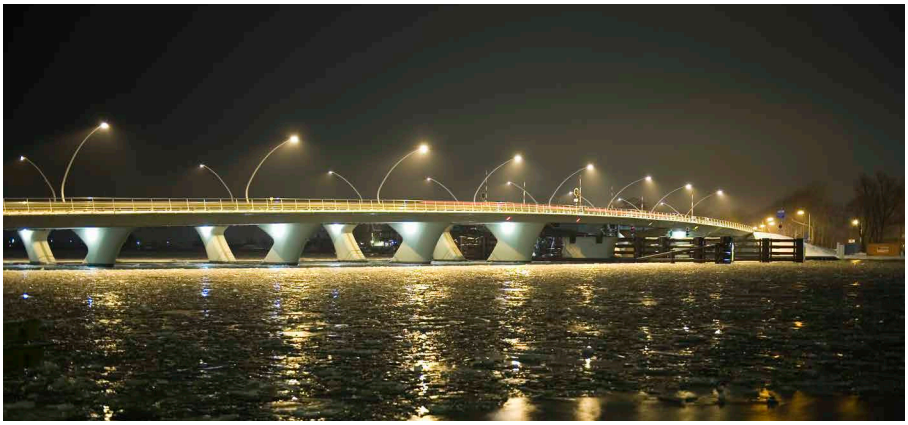


FIGURE 2.9 The opening part of the Juliana Bridge is in harmony with the approach spans. Royal HaskoningDHV, Joris Smits et al. (2009). Photo by Jane van Raaphorst 2010.

The result is a natural sequence of supports that reaches its crescendo in the middle part of the bridge. The absence of an enclosed bascule volume and the resulting transparency underneath the bridge is much appreciated by the inhabitants of the historical housing on the shores of the Zaan. To quote one:

"What a beautiful bridge! So light and transparent; sitting on the sofa in my living room I can actually look right through it and see the landscape behind the bridge. The combination of modern design in a historical context works really well."

§ 2.4.2 Layering and partitioning

Another decision taken early on in the design process was to untangle the hectic flow of motorised traffic from the more easy-going flow of pedestrians and cyclists, including the thousands of tourists that pass through every year. The old bridge was infamous for the frequent accidents that occurred when tourists stepped into the path of motorised traffic to take photographs of the Zaanse Schans and the general scenery. Considering the new bridge as a wide balcony with a panoramic view was a first step, and allocating pedestrians and cyclists a bridge of their own was the next (figure 2.10).



FIGURE 2.10 Pedestrians and cyclists have a bridge of their own. A void separates them from motorised traffic. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Luuk Kramer 2009.

The spatial consequences of splitting a rather wide deck into two slender decks and a void are significant. From the point of view of the traveller on the bridge, the visual contact with the landscape and the river is increased. As you are always close to an edge with a view of the water, people experience the bridge much more as a bridge. The void between the decks adds a dynamic quality to the experience of travelling across the bridge, offering exciting views of the sequence of piers emerging from the river. From a landscape point of view, the difference is perceptible in the amount of daylight underneath the bridge. Even though the actual width of the total structure increases with the extra width of two more edges with parapets, the amount of shadow on the water and on the piers decreases and the bridge is experienced as less of an obstacle. This has to do with the factor of ambient light that has access to the space underneath the bridge from all sides. This diffuse light supplements the direct sunlight and gives the substructure a less obscure and more pleasant feeling (figure 2.11).



FIGURE 2.11 Daylight underneath the bridge increases due to the void between the decks. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Elroy Blom 2012.

§ 2.4.3 Manifestation and articulation

There are two basic elements in the design of a multi-span bridge that determine the scale and the inner harmony of the bridge design. The first of these elements is the deck that manifests itself as a horizontal element of a larger scale level. The other element is the pier, or the series of piers, that are basically vertical elements of a smaller sub-scale.

In the design process the architect can choose to make the position and manifestation of the piers dominant over the deck, thus reducing the tectonic scale of the design to the size of each individual span and accentuating the vertical rhythm (figure 2.12). This first approach lends itself to an enclosed and dense urban setting where lots of visual stimuli and vertical elements predominate. The second approach would be to give the deck a more prominent position, thus accentuating the horizontality and the total length of the design in the larger scale of a landscape (figure 2.13).



FIGURE 2.12 Vertical accentuation of the piers in a design proposal for the new Sebastiaans Bridge in Delft. Royal HaskoningDHV, Joris Smits (2012).



FIGURE 2.13 The horizontal manifestation of the deck with set-back of the piers puts the emphasis on the larger scale and blends into the landscape. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Jane van Raaphorst 2010.

In an open landscape with wide panoramic views the second approach is more suitable. The vertical line tends to blend in with the horizon in a calm way. Consequently the designer chose the second approach for the design of the Juliana Bridge. We designed a series of twin piers that emerge from the water underneath the central void, then cantilever sideways to support both decks. We gave the piers a setback from the edge where the pier meets the deck, thus putting the emphasis on the continuous line of the edge. This edge was manufactured out of fibre reinforced polymer segments in Zaan-white, a well-defined local shade of off-white, with a touch of this other local colour Zaan-green.

§ 2.4.4 Defined space and orientation

On the level of the deck the Juliana Bridge is free of structure. The only appearance from the traveller's perspective is the prominent sequence of curved light masts (figure 2.14). These are positioned along the inner void.

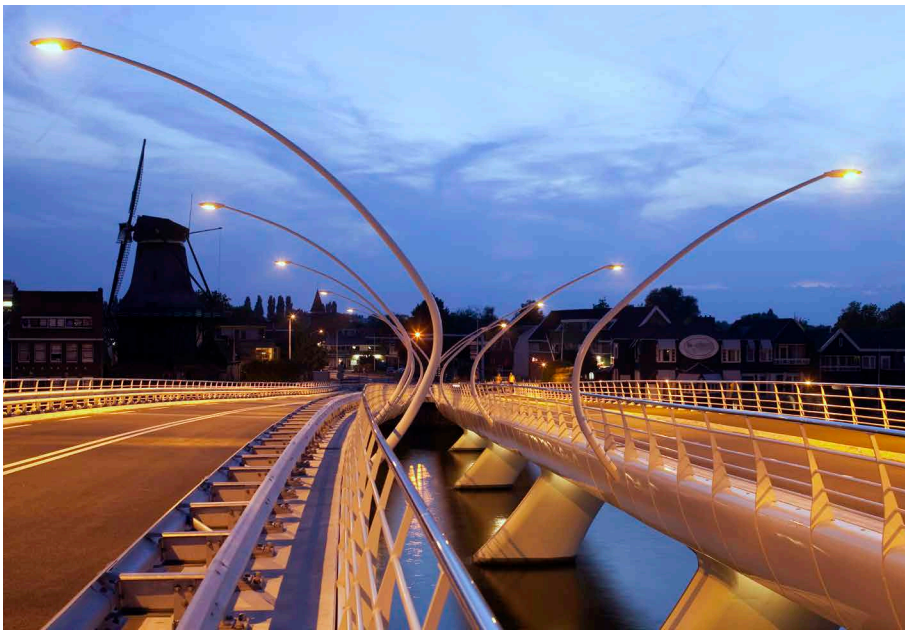


FIGURE 2.14 Light masts define the space and viewing directions. They emerge from the void in order not to obstruct the outward view. Royal HaskoningDHV, Joris Smits et al. (2013). Photo by Luuk Kramer 2009.

Research by Schöne and Coeterier (1997) on the way that drivers experience the highway demonstrates that drivers have a restricted field of vision. As they are largely preoccupied by watching traffic in front and behind, their field of vision is largely limited to the right side of the road. In the case of the Juliana Bridge the best views are experienced outwards, to the right of the driver. As the Juliana Bridge is foremost a bridge with a view, we did not want to obstruct that view by a repetition of a mast along the edge of the bridge. Rather we chose to let the masts define the space on top of the deck by opening up towards the panorama, thus directing the view outward. In a way the central position of the mast enhances the dynamic experience of the void between the two bridges. If you look closely you will see that the curve of the masts is a continuation of the inner shape of the piers.

To conclude regarding the design of the Juliana Bridge, we must remember that a bridge is foremost a facility for the people who use it or live nearby. During the construction of the bridge, and also after the completion of it, we had the chance to talk to many of them. It is worth noting that, when pressed to give their opinion on the aesthetic qualities of the design, most people living near this bridge are full of praise, with most mentioning the curved masts. Maybe it is a good sign that the bridge itself is so natural and uncontroversial in its presence that it is not notable to the public.

§ 2.4.5 Awards

The Juliana Bridge won both the Betonprijs in 2009 and the European Concrete Award in the category civil engineering in 2010, issued by the European Concrete Societies Network [10], demonstrating the value of this design approach. These awards are a clear recognition that the design work is outstanding and contributing to the body of knowledge in the field of civil engineering. Final praise came from the Dutch Ministry of Infrastructure and the Environment in the form of the 'Routepluim 2011', an award granted for exemplary integration of infrastructural artworks into their context.

§ 2.5 Wildlife crossing in Rijssen

If the design of a bridge in a historical urban area is all about capturing the character of the place and of the people who live there, then the design of a wildlife crossing is more a matter of listening to the scale, the morphology and the character of the landscape. How can we translate the intrinsic function and nature of a wildlife crossing in its design? And do the fragmented landscapes of Essen and Kampen require a different design approach then the open heathlands?



FIGURE 2.15 Wildlife crossing over the N350 between Rijssen and Wierden. Royal HaskoningDHV, Joris Smits et al. (2014). Photo by Jane van Raaphorst 2014.

§ 2.5.1 Experiencing a wildlife crossing

When we ask ourselves what the visual and emotional impact of a bridge design, or more specifically a wildlife crossing, implies in the eye of the beholder, we must distinguish three aspects: perceiving, experiencing and appreciating (Boekhorst, Couterier &

Hoeffnagel, 1986; Buijs & Kralingen, 2003). The first step, perceiving, is quite obvious. An overhead structure of this magnitude results in a perception that cannot be denied, nor do we have many means to influence the perception as the structure cannot be hidden or softened. It is in the second step, in the experience that our structure offers, that we as designers can offer something more. If we do our job well we can be rewarded by the appreciation of the people who pass our design or who live adjacent to it.

When seen through the eyes of a driver travelling along a road in a relatively open landscape, the passing of an overhead structure marks an important event in the trip. The structure will attach itself as a visual beacon in the awareness of the driver, marking a specific place along the route. The psychological impact of passing beneath an overpass, such as an ecoduct, is notable. On the visual and emotional impact of passing underneath an overpass when driving through a landscape, McCluskey states in his book *Roadform and Townscape*: *"A notable event relating to contrasts occurs when the route encounters an overpass. The approach embankments to the overbridge block the view on either side of the main road and after passing through the gap spanned by the structure a feeling of release is enjoyed on sighting the uncontained view."*[6].

In the case of Rijssen the challenge for us, as the designers of the wildlife crossing, was to turn the event of passing underneath into a pleasant rather than an eerie experience.

§ 2.5.2 Typology

The wildlife crossing in Rijssen (figures 2.15, 2.16) stands apart from the vast bulk of wildlife crossings where the road is the ruling principle and the crossing itself is designed as a functional straight viaduct. Rather, the wildlife crossing in Rijssen stands in the tradition of that other notable wildlife crossing in the Netherlands: the 'Woeste Hoeve'. Both crossings are primarily designed from the green perspective; here it is nature that has the supremacy, in the form of soil and vegetation, the road is just a perforation of the earth, a guest that is temporally tolerated underneath it (figures 2.17, 2.18). Such a grand gesture places nature above technology even though it is evidently a manmade structure (Nijenhuis & van Winden, 2007). The wildlife crossing in Rijssen is therefore a token of vigour, not so much of Dutch policy-making but more as an act of our ecological movement.



FIGURE 2.16 Artist impression of the wildlife crossing. On the foreground the open heathlands landscape, behind lies the fragmented Essen and Kampen landscape. Royal HaskoningDHV, Joris Smits et al. (2014).

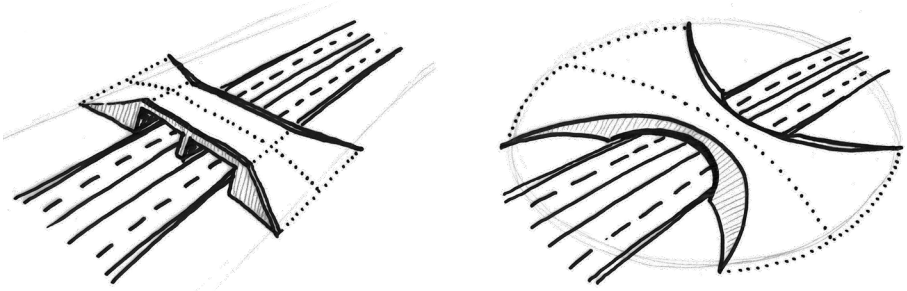


FIGURE 2.17 The highway as the ruling principle with a functional crossing (left), or nature as the ruling principle (right). Royal HaskoningDHV, Joris Smits et al. (2014).

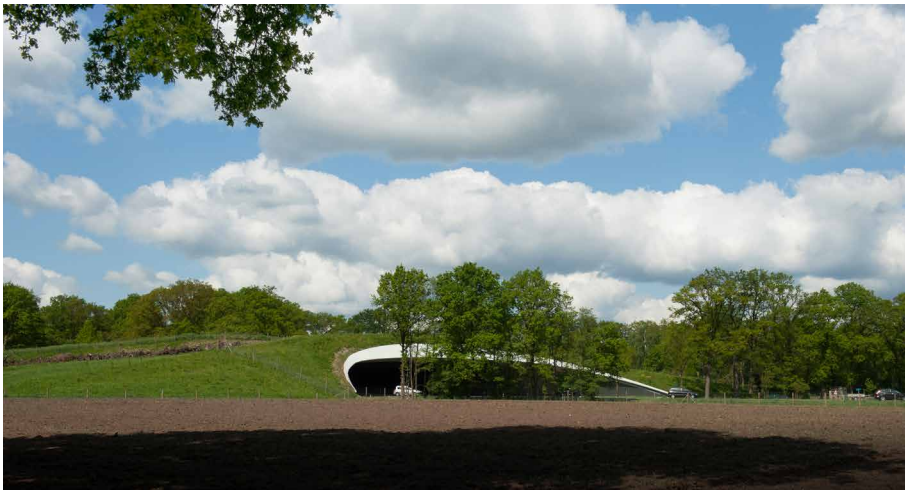


FIGURE 2.18 The wildlife crossing at Rijssen. Nature has the supremacy, in the form of soil and vegetation; the road is just a perforation of the earth, a guest that is temporally tolerated underneath it. Royal HaskoningDHV, Joris Smits et al. (2014). Photo by Jane van Raaphorst 2014.

§ 2.5.3 Design approach

Having said that the landscape has the supremacy over the highway where they cross, that still does not answer the question of how to make the design fit into the landscape, or better, be a part of the landscape. After doing an analysis of the two types of landscape that are traversed when driving from Rijssen to Wierden, we decided on a twofold approach: on the larger scale we manipulated the overall shape of the wildlife crossing to react in an asymmetric way to the two very different characters of the two landscapes on either side of the crossing. And on the local scale we integrated the shape of the wildlife crossing to the extent that the alignment and the edges seem to come forth from the landscape in a natural way, reacting to existing lines in the landscape such as tree lanes and watercourses.

On the larger scale we distinguished two types of landscape (figure 2.19). On the west approach to the wildlife crossing we travel through a small-scale 'Essen and Kampen' landscape, a scenic landscape with an arbitrary sequence of smaller open spaces, patches of woodland and green lanes lined with trees. This landscape offers the driver a confined experience with restricted views and without any vistas. The wildlife crossing reacts to this landscape by capturing the driver into a crescent shape on the west approach as he nears the overpass, thus containing the view.

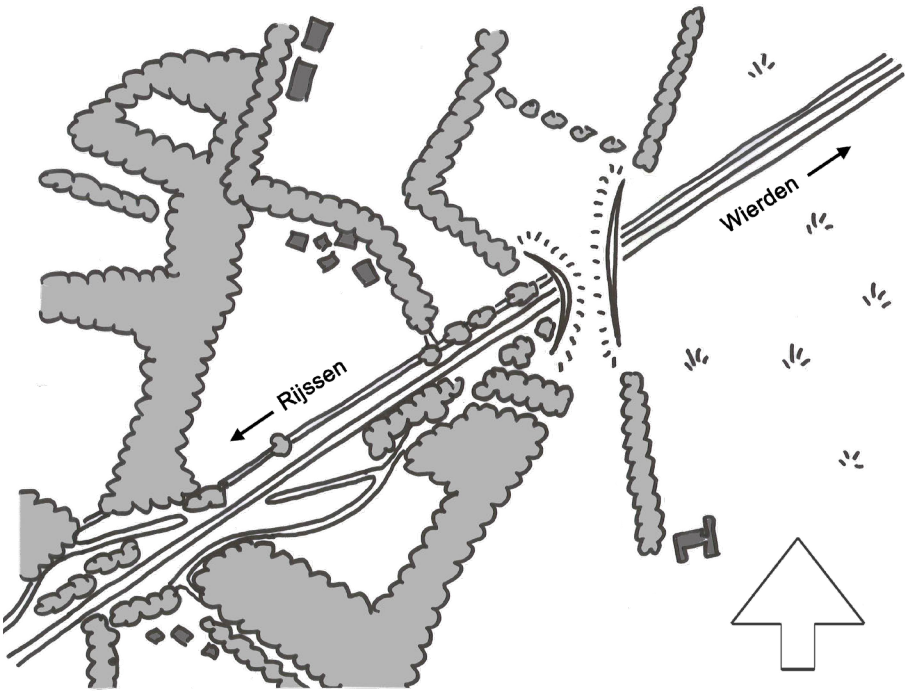


FIGURE 2.19 The asymmetric shape of the wildlife crossing reacts to the two different kinds of landscape on either side; a confined Essen-Kampen landscape to the west and an open landscape to the east. Royal HaskoningDHV, Joris Smits et al. (2014).

On the eastside the landscape is very different. Here we have a much younger and rational landscape consisting of heathlands and large land exploitations. The wildlife crossing therefore marks a boundary between those two landscapes: the confined versus the open. The eastern edge of the wildlife crossing reacts to this open landscape with a much wider opening that offers the driver a full panorama of the entire open landscape.

On the local scale the alignment of the edges of the wildlife crossing was carefully fine-tuned to match existing lines in the landscape such as tree lanes and watercourses. As it turned out this approach of reacting to the structure of the landscape also proved to be the best approach from the wildlife point of view. Animals have a strong tendency to move along lines in the landscape such as the edge of a wood or a brook. Thus having our funnel shape in line with those natural elements proved to match wildlife patterns.

From a drivers' point of view the funnel shape of the wildlife crossing seems to come forth from the landscape in one fluent motion, as a green carpet that is locally lifted up to make room for traffic, then blends back into the landscape on the other side. Instead

of retaining fences along the edges of the crossing we designed green ridges, steep on the inside to retain wildlife within the passage, but green and slanted on the outside were they that form the dominant gesture as they sweep across the road. Last but not least the experience that the wildlife crossing bestows on the traveller is determined by the actual event of passing underneath the structure (figure 2.20).



FIGURE 2.20 'Lifting the carpet' leaves a slit-like opening underneath the green structure. The low parts of the slit are filled with solid abutments with a set back from the edge. They are materialised in a dark grey colour in order to blend with the ground rather than with the crescent edge. This results in the impression of one long continuous edge. Royal HaskoningDHV, Joris Smits et al. (2014). Photo by Jane van Raaphorst 2014.

To turn this experience into a pleasant one we looked at the size, the shape and the partitioning of the overhead structure. The design approach of 'lifting the carpet' leaves a slit-like opening underneath the green structure. To reduce the span and the costs of the concrete deck, the low parts of the slit had to be filled with solid abutments. These abutments are set back from the edge of the carpet, and are materialised in a dark grey colour in order to blend with the ground rather than with the crescent edge. This results in the impression of one long continuous edge. To further increase the sensation of a single arch spanning the road, the soffit of the deck follows a vertical curvature just like the crescent edges and spans both lanes in one span. Inclined abutments further emphasise the dynamic gesture of an arch. Also notable in the design is the absence of the traditional middle pier. The use of a middle pier inevitably has a negative effect on our experience of spaciousness; the view of the beholder is partitioned right through the middle and the focus is diverted to this odd element rather than to the surrounding space. Using a middle pier is in that way comparable to building a pillar in the middle of the central nave of a church. Therefor the absence of a supporting structure in the middle turns the act of passing underneath into a spacious and panoramic experience with an unhindered view to what lies beyond (figure 2.21).

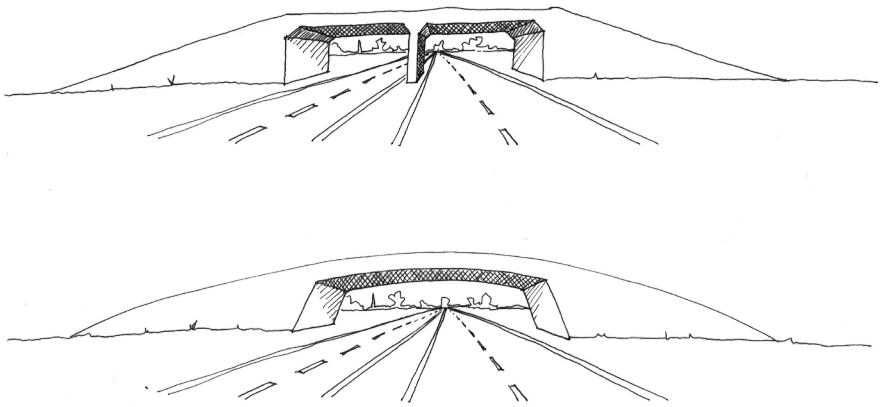


FIGURE 2.21 The use of a middle pier inevitably has a negative effect on our experience of spaciousness; the view of the beholder is partitioned right through the middle and the focus diverted to this odd element rather than to the surrounding space. Royal HaskoningDHV, Joris Smits et al. (2014).

§ 2.6 Conclusion

This chapter discusses ways to strengthen the regional identity through means of civil structures such as bridges. It is our experience that the best approach to designing bridges within a landscape is to start from the context without making use of neo-vernacular methods. Bridges are worth our attention as designers and give us powerful tools to strengthen the local identity. This adage is demonstrated through some of our projects in Zaanstad and in Rijssen. Properties as scale, orientation, rhythm, articulation, layering and partitioning of the design are our tools to make a design fit the context. To accomplish this we need to think from different perspectives, both literally and figuratively. The obvious perspectives are that of the driver, the cyclist, the pedestrian, the skipper or the badger that passes on or underneath our designs. But on a more abstract level we need to think from the point of view of the genius loci, the commissioning authorities, the tourists and most important of all, the people who live nearby. The proof that this is a fruitful approach lies in the many positive reactions that we get on all of our projects. This varies from the carpenter who complains about the difficulty in making the formworks but at the same time stresses how proud he is of being able to show his craftsmanship, the alderman who likes to show off with 'his' brand new bridge, or the lady who sees the improvement on the view from her backyard. This is the reason why we have such a rewarding profession.

Acknowledgements

Designing a bridge is always a matter of teamwork. Often there is more than one author responsible for the architectural design and in some cases the landscape design. Joris Smits is the designer of the projects discussed in this paper. He would like to acknowledge his (former) colleagues for their valuable contribution to the design of the various projects that appear in this paper. In chronological order: Alessandro De Santis is co-designer of the Dommel Bridge for which Corine Zwart is the landscape architect, Richard van den Brule is co-designer of the Highway of the Future, Obbe Norbruis is the landscape designer for the Hoogtij Bridge, René Rijkers is co-designer of the Zuidelijke Randweg Bridge, Syb van Breda and René Rijkers are the designers of the Butterfly Bridge, Syb van Breda is co-designer of the Prins Bernhard Bridge, Sven Spierings is co-designer of the Zaanbridge, Syb van Breda and Alessandro De Santis are co-designers of the Juliana Bridge, Sven Spierings is co-designer of the wildlife crossing in Rijssen of which Carien ten Cate is the landscape designer. We would further like to acknowledge Steffen Nijhuis for his valuable advice on writing this paper.

References

[1] Appleyard, D., Lynch K., & Myer, J.R. (1964) *The view from the road*. Cambridge Mass: MIT Press.
[2] Overdijkink, G.A. (1941) *Langs onze wegen*. Amsterdam: Allert de Lange.
[3] Boekhorst, J.K.M.T., Couterier, J.F. & Hoeffnagel, W.J.C. (1986) *Effecten van Rijkswegen op de beleving*. Wageningen: RBL De Dorschkamp.
[4] Buijs, A.E., & Kralingen, R.B.A.S. (2003) *Het meten van beleving. Inventarisatie van bestaande indicatoren en meetmethoden*. Wageningen: Alterra, p 782
[5] Houben, F., & Calabrese, L.M. (2003) *Mobility: A room with a view*. Rotterdam: NAi Uitgevers.
[6] McCluskey, J. (1992) *Roadform and Townscape*. Architectural Press. p 155
[7] Nijenhuis, W. & van Winden, W. (2007) *De diabolische snelweg*. Rotterdam: 010 Publishers
[8] Schöne M.B., van den Toorn, M.W.M. & Coeterier, J.F. (1997) *Autosnelwegen in het Landschap; beleving door weggebruikers*. Wageningen: DLO-Staring Centrum
[9] Scitovsky, T. (1976) *The joyless economy, an inquiry into human satisfaction and consumer dissatisfaction*. Oxford: Oxford University Press.
[10] ESCN. European Concrete Award 2010. Retrieved from http://www.ecsn.net/award/downloads/Concrete_Award_2010.pdf



3 Shaping Forces

Review of two bridge design methodologies towards architectural and structural symbiosis

Smits, J., Eigenraam, P., Gkaidatzis, R., Visser, D., Wong, K., & Wassermann-Fry, S. (2018)

Scale 1:100

In the previous chapter the fitting of the design at the scale of the landscape is discussed. This chapter addresses bridge design considerations at the scale of the object such as a bridge or a civil structure itself. This chapter was first published in the J.IASS Journal, June 1 2018. DOI: https://doi.org/10.20898/j.iass.2018.196.884. Published by the International Association for Shell and Spatial Structures (IASS) in print (ISSN 1028-365X) and on line (ISSN 1996-9015). The layout and paragraph numbering has been adjusted for reasons of consistency, as well as minor textual adjustments.

Abstract

This paper investigates the symbiotic relationship between the architectural appearance of a bridge and the structural design. The research is done by reviewing and comparing the design methodology employed by the first author in the conceptualization of two of his bridges; an early work from 1997 and a recent work from 2017. The review of the early work describes a design methodology that could be described as intuitive design, whereas the later work is the result of computational from-finding and optimization. Parallels are drawn and the historical development of the toolbox of the architect and the engineer is described. The paper analysis the way the two designs were achieved by looking from the perspective of the architect and that of the engineer. The paper concludes by identifying the key design considerations to achieve a beautiful yet structurally sound bridge. The question whether beauty can be the sole result of a rational design process towards the most efficient form according to the laws of mechanics, is addressed. This paper demonstrate the belief that when it comes to the design of a bridge, architecture and structure, form and force, are involved in an interdependable and symbiotic relationship.

Keywords: Bridge design, Architecture, Structural design, Optimization, Parametric design, Form-finding, Concrete, FRP.

§ 3.1 Introduction

Over the past two decades architects have found their way into the practice of bridge design, a field of expertise that was formerly considered the sole domain of structural engineers. Ever since the 90's a strong growth of the involvement of architects in bridge design has taken place. The beginning of this new era of architectural bridge designs is clearly marked by the realization of the Alamillo Bridge, built for the '92 Seville Expo, by the world famous architect and engineer Santiago Calatrava. His design for a cable stayed bridge stands out for the massive pylon which, by its backward inclination, formed a counterbalance to the forces from the cable stays, thus creating a bold demonstration of the forces at play. At the same time the Alamillo Bridge was a defiance to traditional bridge designers demonstrating that the easiest way to design a cable stayed bridge was not necessarily the only way, and that structurally sound solutions can also be found in a not-so-straightforward approach. Ever since the Alamillo Bridge a closer collaboration between architects and structural engineers has resulted in many beautiful and well-integrated bridge designs all over the world. The downside to this development is that at the same time a lot of farfetched bridge designs have also seen the light of day.

What are the key design considerations to achieve a beautiful and yet structurally sound bridge? Does a structure always need to follow the most efficient form, according to the laws of mechanics and/or finance? Or is there such a thing as symbiosis between Form and Force, a way of working that ensures that the final result becomes greater than the sum of its parts?

Two bridge designs from the author, one marking the beginning of his career in 1997 and the second one only recently accomplished, demonstrate the belief that structure and architecture are involved in a symbiotic relationship. One cannot be successful without the other. Just how successful this interaction is, forms the subject of this paper.

§ 3.2 Shaping Forces

In 1997 W. Zalewski and E. Allen wrote the book 'Shaping Structures' for students of Architecture and structural engineering. In the preface it is written that 'The essence of structural design is to shape each structure to respond effectively to the forces that it must withstand and to the human activities that it nurtures' [1]. It is interesting to

compare Zalewski's theory with the well-known trinity Venustas, Firmitas and Utilitas described by the influential Roman architect/engineer Vitruvius (80-25 BC) in "de architectura" [2]. Zalewski's theory addresses both force and utility, or as Vitruvius would put it, Firmitas and Utilitas. However, the aesthetic dimension, Venustas, has been left out of the equation. Or rather an assumption seems to have been made that a structure that responds effectively to the forces and to human needs is intrinsically beautiful.

The title Shaping Forces is based on the well-known adage 'Form follows Force'; the assumption that an architectural design that follows a path of structural logic also holds a greater aesthetical value. But what exactly is structural logic, and how can it be achieved? There are of course many design methodologies that lead to a structurally logic bridge.

One method is to pursue a minimal use of materials for the required program and load case by following the path of the loads to the foundations in such a way that the least amount of material is used. A very popular approach among academics and professionals nowadays is achieved through computational design using advanced parametric form-finding and optimization software like Grasshopper, Karamba and Kangaroo [3].

One has to acknowledge that these types of form-finding and optimization software are in fact nothing more than a tool to achieve structural logic. The method behind it is not new. An eminent pioneer in this field was Heinz Isler who used his 'frozen towel' technique to create poetic natural shells (figure 3.1). He states: "One does not actually create the form; one lets it become, as it has to according to its own law." [4] Before that Antoni Gaudí used his now famous inverted chain model to find the most efficient vaulted shape for the Sagrada Família.



FIGURE 3.1 Heinz Islers' frozen fabric. https://safetythird.wordpress.com/2011/04/18/heinz-isler-ice-structures/, visited on 27/2/2019.

A third way of deriving architectural form through structural ideals relies on greater design intuition. Instead of letting the form create itself, such as Isler did, a skilled designer with a profound understanding of structural mechanics and a fine sense of aesthetics can accomplish good results. They can shape a structural geometry based on the functional constraints, a befitting architectural typology that fits the context and an understanding of the forces and materials used. It is this intuitive way of determining a structure that is demonstrated in the first case study on the Navel Bridges in chapter 3.3.

§ 3.3 Navel Bridges in Nieuw Vennep

The design of the Navel Bridges in Nieuw Vennep, the Netherlands, is a clear demonstration of the authors' conviction that structure and architecture are involved in a symbiotic relationship (figure 3.2). The Navel Bridges were designed and drafted in 1999 at his architectural office at a time when he was freshly graduated from both the School of Architecture as well as the School of Civil Engineering in Delft [5].

When planning a new thoroughfare road in a new suburb of Nieuw Vennep, the authorities at first considered making a two-short-span bridge, one span over the canal and the other for a bicycle underpass directly adjacent to the bridge. The short span caused a visual disruption of the recreational water in the park, while at the same time the bicycle passages faced issues of poor visibility on the surroundings.



FIGURE 3.2 One of two Navel Bridges in Nieuw Vennep. Royal HaskoningDHV, Joris Smits et al. (1999). Photo by Bart Nijs 2004.

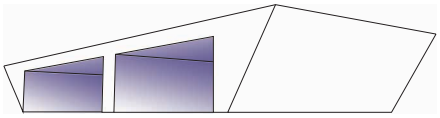


FIGURE 3.3 Initial proposal for a culvert and an underpass.

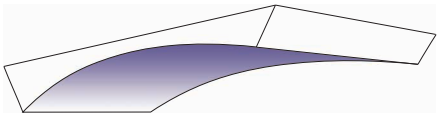


FIGURE 3.4 Setting the vaulted ceiling.

The first step in the design process was to combine the bridge and the tunnel into one structure spanning both water and bike passage, thus increasing the spaciousness and transparency under the road and improving the perception of the bicyclists of being protected (figure 3.3). The chosen material to achieve this span was in situ concrete. This had to do with the specific urban context of the surroundings and the wishes of the municipality to have a sturdy design with little maintenance issues. It was argued that two larger span bridges could be built within the budget if they would be identical (although rotated 180 degrees from each other) and could share the same formwork. An alternative in prefabricated concrete beams was dismissed because both the client and the architect wanted a unique design with a homogenous sculptural appearance that would benefit the identity of the entirely new town.

Second step in the design process was to determine the soffit level underneath the structure, both for bicycles and pedestrians as for boats and ice skaters, to determine the height and alignment of the ceiling. The thoroughfare road was allowed to raise by one meter locally. As it turned out the ceiling needed to be at its highest above the bicycle path, as an optimization between the vertical alignment of the path and the most slender part of the bridge deck.

The resulting elevation of the bridge now showed a vaulted arch with an asymmetrical profile (figure 3.4). The asymmetry of the profile determined the static scheme of a clamped connection on the side of the abutment near the water, and a rolling hinge near the bicycle path. Whilst the landing on the side of the bicycle path was relatively slender, a very massive piece of concrete appeared above the water. Therefore, the third step in the design process was to eliminate the surplus of concrete by creating a cavity between the deck and the vault (figure 5). Sharp inner corners in the concrete cavity were avoided to allow for a fluent flow of stresses, reducing concentrated areas of high stress, and to avoid cracking in the corners. The resulting shape was a combination of a straight, flat slab for the motorized traffic and an arch beneath, which merged with the slab as it rose up vertically. Statically speaking, it is not entirely correct to speak of an arch, as it does not receive any vertical loads after separating from the deck, other than its own weight. One could also see it as a slanted pillar under the deck.

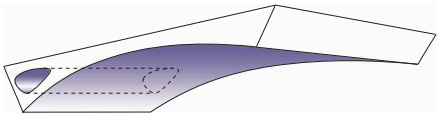


FIGURE 3.5 Taking away the surplus of concrete.

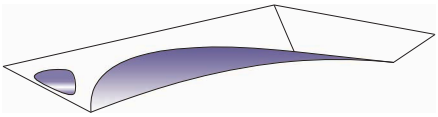


FIGURE 3.6 Tapering the sides.

The fourth step in the design process was to further reduce the amount of concrete by tapering the sides of the bridge deck as well as the arch under a 45 degree angle (figure 3.6). This resulted in a much lighter appearance, the cavity became shorter and thus more transparent when seen at an oblique angle, and daylight penetration under the bridge, on the bicycle path and on the water improved greatly.

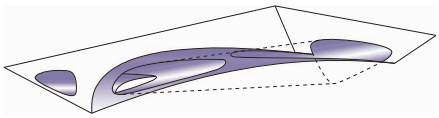


FIGURE 3.7 Creating a longitudinal cavity.

The design could have stopped there as a pleasing architectural space under the bridge had formed. However, it was soon realised that further weight savings and greater elegance could be achieved by further opening up the vault and the cavity. The fifth and last step, therefore, was to create another cavity at a 90 degree angle to the first cavity along the longitudinal span of the bridge (figure 3.7).

A T-junction of cavities was created, splitting the arched vault into two separate arches and opening up unexpected perspectives through these cavities to the surroundings (figure 3.8). The bridge was completed by designing matching parapets out of concrete and stainless steel. The bridge was accessible to motorised traffic, so the parapets, which acted as side walls, were required to be robust in design. In addition, the design consciously accommodated for unhindered views of the river for drivers. This was achieved by employing low walls with cavities, which succinctly tied in with the overall design of the bridge. The stainless steel railing was kept light and simple with short posts mounted directly on top of the concrete.



FIGURE 3.8 View on the intersecting cavities in the abutment on the water side. Clearly visible are the rough timber planks in the formwork of the vault and the sides. The cavities are smooth inside. Royal HaskoningDHV, Joris Smits et al. (1999). Photo by Bart Nijs 2004.

§ 3.4 The ShArc, Berlin 2017



FIGURE 3.9 Artist impression of the ShArc in Berlin. Delft University of Technology, Joris Smits et al. (2017).

Eighteen years after completing the design of the two Navel Bridges, the author's university team participated in the design competition for a new footbridge for the International Footbridge 2017 Berlin conference, together with the London based offices of BuroHappold (figure 3.9). The accepted conference paper focussed on the final product and images, not on the design process itself. The current paper is a review of the used methodology to get to the final design.

The ShArc is a hybrid structure that combines the characteristics of a shell with those of an arc, hence ShArc. The design was created using a computational design methodology by means of parametric software and scripting. The form-finding methods that was used was not limited to optimizing solely the structural behaviour, it was also used to improve the aesthetical and functional design. The iterative design process that was used resulted in a good balance between these three aspects, which interacted in a symbiotic relationship.

Pioneers like Gaudí, Isler and Frei Otto worked on form-finding through physical models such as suspended chain models, frozen textile and soap films. This form of physical form-finding results in one solution for the specific situation. Thereby

not taking into account other load combinations that will also be applied during the lifespan of the bridge. The design methodology employed for the ShArc equally started from a unilateral form-finding model, translating self-weight and additional equally distributed loads into a shape that is convenient for the distribution of loads.

The difference however with the methods of physical modelling, described above, is that the authors did not stop when the first correct shape for the constraints was found. The team proceeded to investigate ways to alter the initial form-finding geometry in order to comply better with different load cases, functional requirements and aesthetical requirements. For this purpose, a next step was made by introducing specific additional loads so that the result of the form-finding would include an solution for other loads than equally distributed. This way the curvatures of the sides, the steepness of the slopes and the transparency of the overall design could be controlled intuitively. For this purpose a script was developed allowing for adaptation of the shape of the model, and showing immediate feedback on structural behaviour. The specific steps for the design of the ShArc in Berlin are now further described.

§ 3.4.1 Conceptual design

Like all designs, this design was based on an initial idea. The concept is to create more than just a bridge from A to B; but rather a bold design that will become a destination in itself and a cultural landmark for the metropolitan city of Berlin. Instead of the two linear bridges with a medium span, as the program suggested, it was decided to create one bridge connecting the three landings resulting in a tripod-shaped bride, located at the confluence of the river "Spree" and the "Landwehrkanal", connecting the downtown districts Charlottenburg and Moabit, would serve both purposes (figure 3.10).



FIGURE 3.10 Plan view of the ShArc at the confluence of the Spree and the canal. Delft University of Technology, Joris Smits et al. (2017).

The goal was to span both the Spree and the canal with one fluent and single span structure, each of the three bridge members being reciprocally restrained by the other two. Another design decision was that the deck of the bridge had to be a fluent arc above the water; shallow enough for pedestrians to be able to walk on top of it, but high enough to allow ships to pass under, and for the arc to act in compression. At the confluence of the three bridge members, the bridge should provide a public platform where people can enjoy panoramic views of the surroundings.

It should be mentioned that although the materialisation and detailing of the structure is not a subject for this paper, as it focusses on form finding, it was necessary to consider such details in order to conceive a feasible design. The longest span of the bridge is approximately 170m. To achieve the desired fluent and fluid appearance without additional supports, materialisation was rather important. The ShArc is conceived and engineered from a composite sandwich structure material, which is formed from Fibre Reinforced Polymer (FRP) outer layers with a foam or honey comb-core. Sandwich structures can be created from various combinations of outer layer and core materials, enabling flexibility in the design, with the outer layers designed to resist bending and axial stresses and the core to resist shear [7]. For the ShArc, it was proposed to use Glass Fibre Reinforced Plastic for the outer layers and a foam core material. These materials were chosen for their high compressive and shear strength properties, as well as low self-weight [8]. High compression strength also boded well

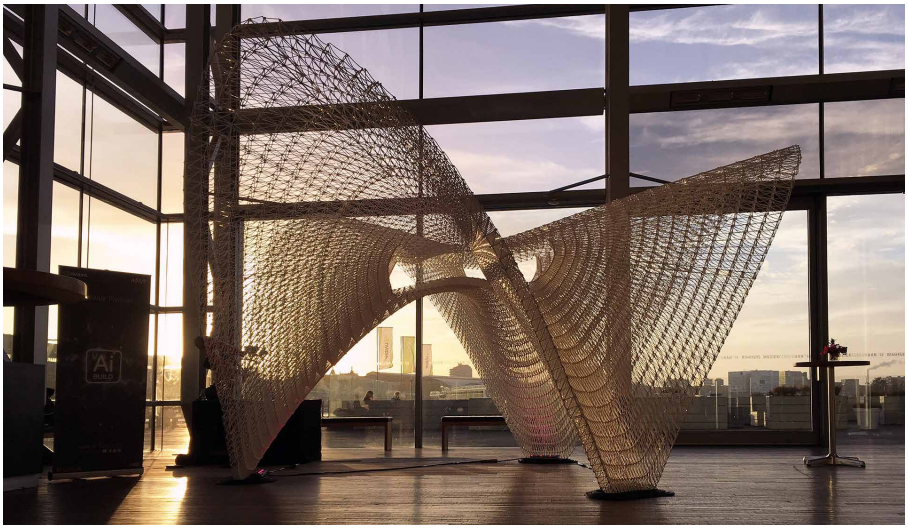


FIGURE 3.11 3D printed Daedalus Pavilion at the GPU. Photo from https://ai-build.com/daedalus.html, visited on 27/2/2019.

for the arch-like structure incorporated into the design, as pure arches behave in pure compression, and in turn relieving the induced bending stresses in the structure and reducing deflections; through the design process, the optimum arch radius was evaluated, trading off the structural implications and functionality of the bridge. In order to reduce the deck weight further, and to maintain the open character, it was decided to create an opening in the deck at the junction of the three "legs", directing the flows of pedestrian around the void. Reducing the weight of the deck had structural benefits by reducing deflections and high stresses in these areas. Another advantage of FRP is that it can be easily moulded, which allows the process of creating the curvaceous deck to be considerably easier than traditional materials.

Initially the inspiration for the shape came from the 3D printed prototype of the Daedalus Pavilion, presented at the GPU Technology Conference in Amsterdam (figure 3.11). The pavilion has an intricate shape with a double layered deck in the central part, consisting of an upper and a lower deck crossing over in a void (figure 3.12). Although this idea was later abandoned, as it proved impossible to create enough distance between the two decks for a person to be able to walk underneath, it lead to further use of the parametric script as the main design tool. Therefore pursuing the development of the idea proved to be crucial to the process of the design. It challenged the authors to use form finding to manipulate the shapes intuitively in a way that was aesthetically pleasing and not necessary resulting in a structural optimal shape. In this first step this was merely a convenient side effect and later implemented as part of the final design. The shape was manipulated by differentiating the ratio between loads and stiffness in the form finding model.

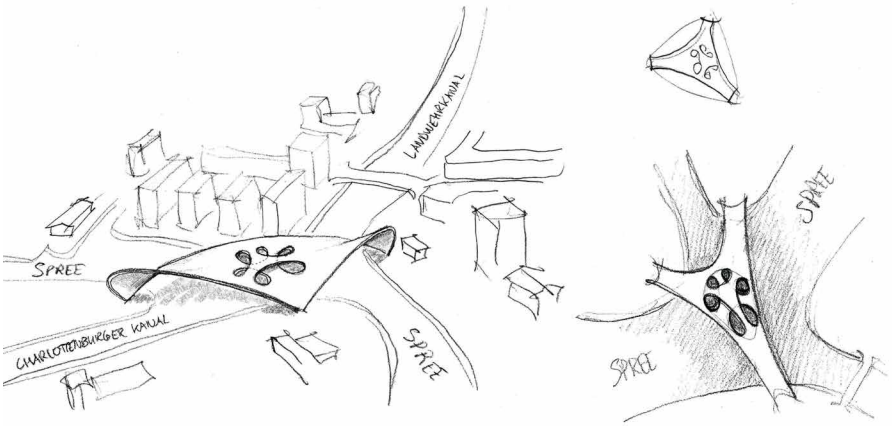


FIGURE 3.12 First sketches for Berlin; introducing a double surface within a shell structure. Delft University of Technology, Joris Smits et al. (2017).

§ 3.4.2 Digital form finding

Digital form-finding was used for exploring various possible geometries for this complex bridge. Therefore Grasshopper and Kangaroo were used. Both well-known and often applied software for form-finding. The first rough model of the desired shape allowed to create a model with surfaces that overlap in the middle (figure 3.13). Having physical modelling in mind it would be impossible to create this shape when starting from a single membrane because at the centre there are two layers on top of each other. For the initial model two ways to influence the geometry of the structure were applied; differentiating the stiffness within the membrane as if it was non-uniform in different directions but also in different areas of the entire model. A second method was to influence the shape of the structure by including line loads at the perimeter of the model, additionally to the equally distributed loads, which created more curvature within the cross section. This second method was predominantly used to fine-tune the shape of the bridge.

Working with a parametric script provided a great amount of design freedom. It allowed to intuitively modify the model. For example, it became much easier to move the landing areas along the quays in order to create bridge members that were more equal in length, and thus had less steep ramps.

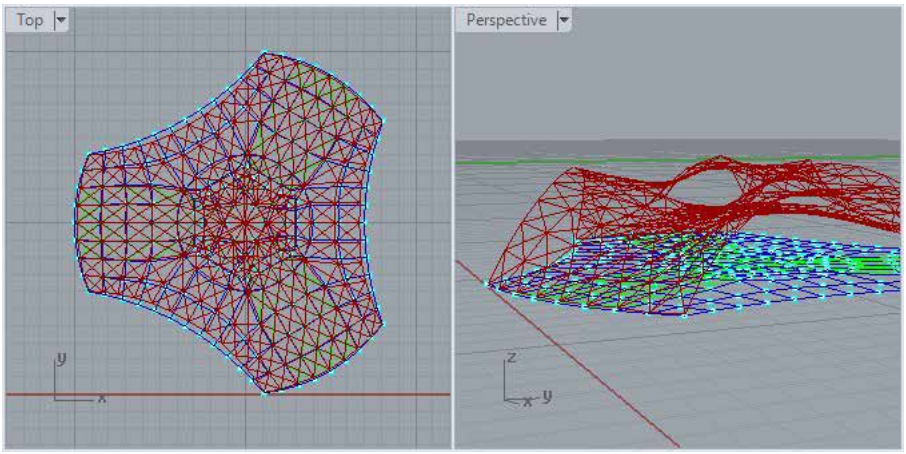
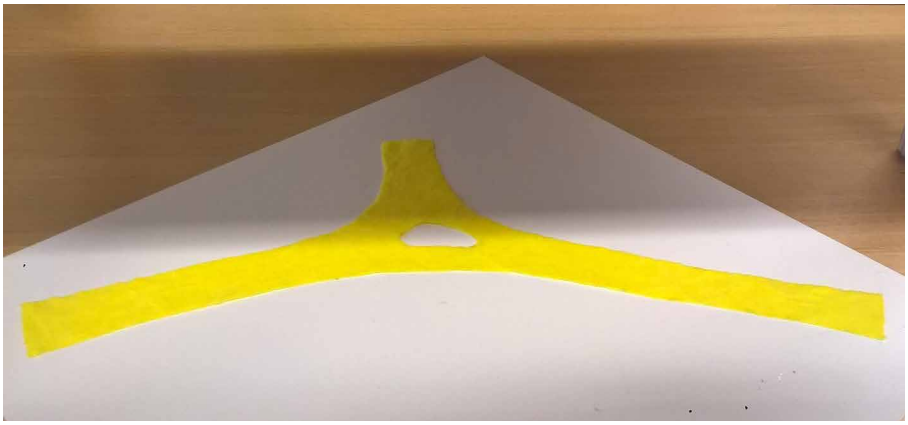


FIGURE 3.13 Initial model for a double surface. Delft University of Technology, Peter Eigenraam et al. (2017).

§ 3.4.3 Physical form-finding

Form-finding within a digital environment proved to be very powerful while allowing for a great amount of flexibility to modify the model. However, for structural purposes it does not necessary provide insight in the structural behaviour. Furthermore numerical models provide quantitative information which does not necessary lead to qualitative information. Therefore, parallel to creating the parametric script, physical form-finding tests were performed using experiments in fabric, paraffin and gypsum (figure 3.14).

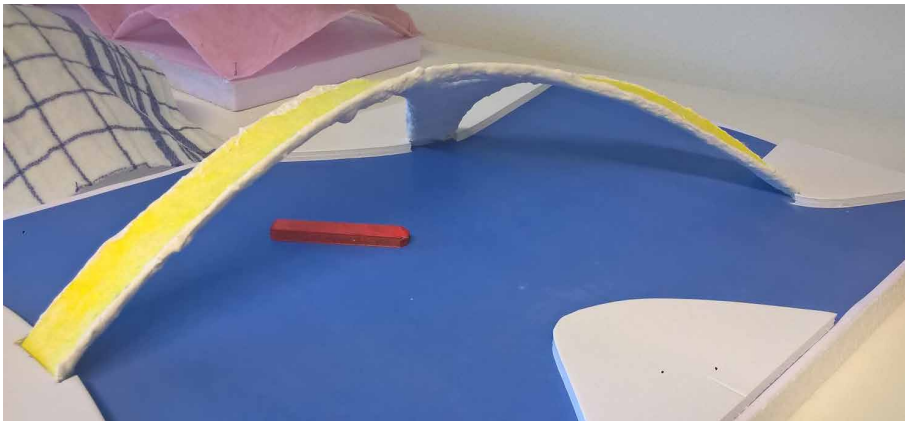
Physical models provide insight. Stiff and flexible parts can be identified quickly by applying loads by hand. Since models are often fragile the weaker parts break when the model is subjected to less gentile pushing. Thereby they are easily identified as well. Also the overall shape provides a reference for the shape resulting from form-finding within a digital environment. Physical modelling provides a context to think about the consequences of different shapes and boundary conditions or where to apply stiffening measures. The cutting pattern for example influences on the resulting shape, as does the positions of the three support points. The type of fabric also influences the shape. A microfiber cleaning cloth was used which has uniform stiffness in all directions.



1



2



3

FIGURE 3.14 Form-finding experiments in microfiber cloth and gypsum. Delft University of Technology, Peter Eigenraam et al. (2017).

The results provided a reference for the shape that was form-found digitally, using only a distributed load that represented self-weight. Also, by having a physical model, structurally weak places could be identified quickly. Therefore the model had to be damaged, but multiple models could be made easily. One essential flaw that was particularly demonstrated was that the model had a tendency to become flat in the perpendicular direction of the span. This made it sensitive for asymmetric loading, introducing bending in the structure.

Making a physical model created awareness of the aspects influencing the digital model. E.g. the initial layout, stiffness of the membrane in multiple directions and positions of the supports. Also, a physical model provides a sense of scale to the designer. Something that in a digital model is easily lost.

§ 3.4.4 Reflection on the performance

Both the physical models and the parametric model demonstrated one weakness in the shape. The shell was initially optimized for one load case only; that of an equally distributed load, the self-weight. However, as different load cases do not result in the same deformed shape, and will deflect according to their own load take-down (Isler), the physical model showed to be weak when subjected to asymmetric loading. Since the model was rather slender it was expected that other load combinations than self-weight could have significant effect. The first models resulted in a rather flat cross-section of the deck along the entire span of the bridge. The flatness wasn't well suited to resist the asymmetric loading; A flat geometry behaves in a beam-like manner, so induces higher bending stresses. Therefore it was required to design for more resistance to bending stresses in certain areas. In other words, the second moment of area of the cross section had to be increased at certain points. This can be done by increasing the structural height. This was applied in a gradual manner reducing towards the supports (figure 3.15).

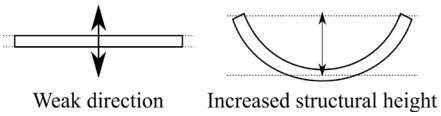


FIGURE 3.15 Schematic cross sectional properties. Delft University of Technology, Peter Eigenraam et al. (2017).

Manipulating the shape of the shell also altered the stress patterns throughout the structure. This resulted in two different curvatures for the top and bottom of the bridge. The thickness of the top and bottom FRP layers are able to be adjusted to suit the stresses in the panels throughout the structure.

§ 3.4.5 Elaborating the parametric model

Based on early findings the parametric model was modified in Kangaroo to create more resilience to bending and buckling. In order to increase the second moment of area the sides of the cross section were curved upwards by adding virtual line loads along the perimeter (figure 3.16). This unequal distributed load was in total approximately similar in magnitude to the total load of the equally distributed load. Therefore the overall shape of the model was similar but now with a curved cross section.

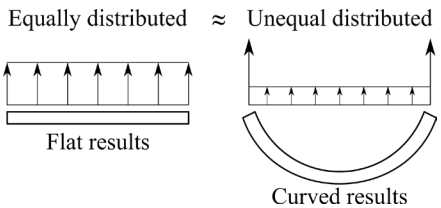


FIGURE 3.16 Schematic load distribution of the cross section. Delft University of Technology, Peter Eigenraam et al. (2017).

Another influence on the curvature of the deck was the shape of the supports at the bridge abutments. While a straight line support (and resultant flat deck) only offers limited stiffness, a concave line extends the 'half-pipe' (and more moment-resisting) section through to the pier. This would have consequences for the distribution of

stresses which should be taken into account later. For aesthetic reasons the walking surface at the landings changed from sinclastic to anticlastic. By raising the edges the second moment of area also increased at the area of transition.

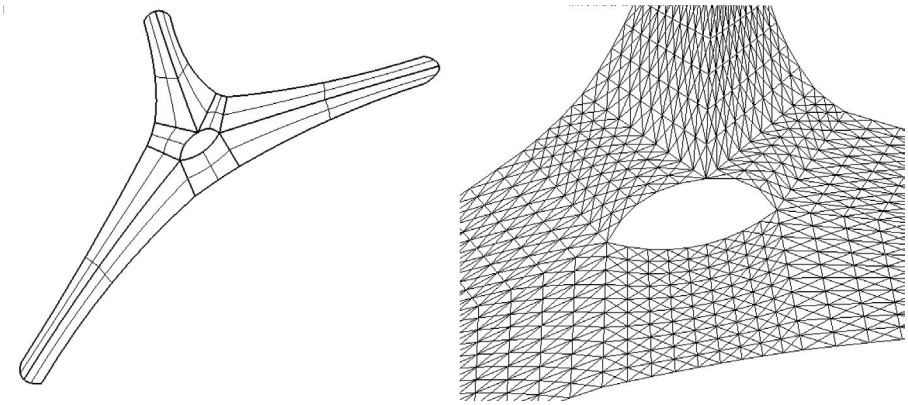
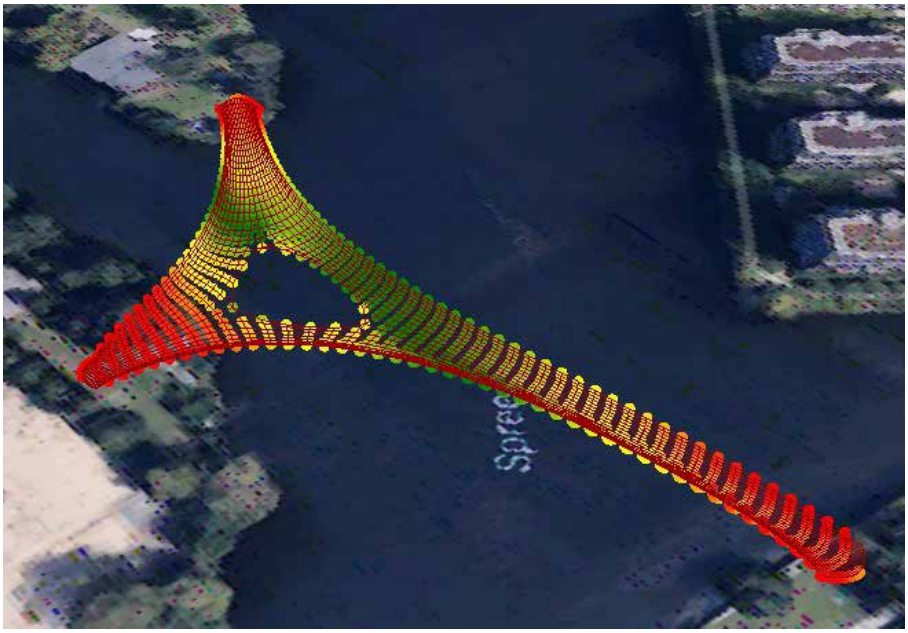


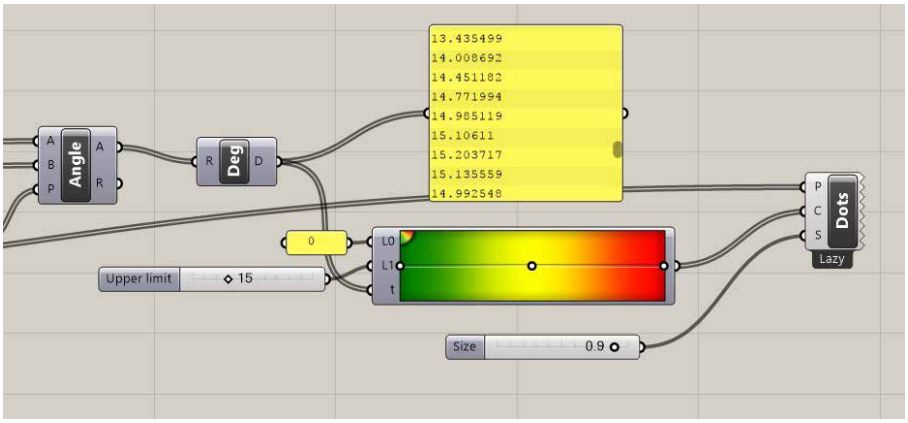
FIGURE 3.17 Subdivision of deck (left) and grid (right). Delft University of Technology, Peter Eigenraam et al. (2017).

For modelling purposes the model was subdivided into nine surfaces, each one subsequently divided in a grid and diagonals (figure 3.17). This set-up provided means to differentiate the stiffness in different directions.

While the authors were constantly modifying the geometry, realisation came that one of the most important functional requirements of the bridge, the slope percentage, was also constantly changing. In order to get visual feedback on the slope percentage from the model an addition to the script was made to provide direct feedback on actual slopes (figure 3.18). This became a useful tool to balance fulfilling requirements of different nature, namely structural, aesthetic and functional.



1



2

FIGURE 3.18 Grasshopper script to monitor the resulting slopes. Delft University of Technology, Peter Eigenraam et al. (2017).

During the process of form-finding, one of the challenges was to prevent the shape of the bridge from wrinkling. This can be seen in figure 3.19. Here the abutment remains fixed while the edges of the bridge are curved up- and inward. This proved to be problematic for both practical and structural reasons. A wrinkled surface would not be a good surface for further modelling. Structurally, a wrinkled surface would not transfer loads in a distributed way. The analytical model therefore had to be tidied up before

TOC

analysis, rendering the process less efficient. The wrinkling effect could be prevented by changing the properties of the line elements in the parametric model by setting a rest length smaller than the original length. This would be equivalent to changing the length of the springs during the form finding.

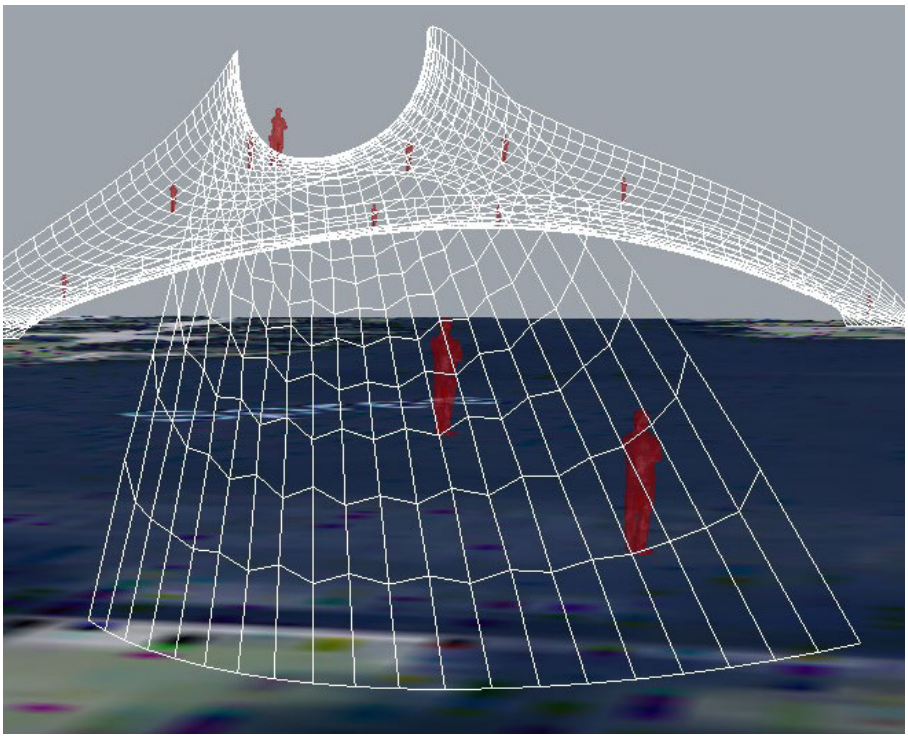


FIGURE 3.19 Wrinkling near the abutment. Delft University of Technology, Peter Eigenraam et al. (2017).

Like all shells, slenderness comes at a price. The bridge had the tendency to buckle laterally at the edges of the deck. Stiffening these edges by adding a separate edge beam was undesirable from an architectural point of view. Instead, the edges were strengthened by curling them, very much like a water lily leaf, to create thicker flanges.

§ 3.4.6 Use of FEM with the Grasshopper script

The parametric set-up that was used allowed direct communication between the Grasshopper model and the FE analysis software (Robot). This meant that all FE input data could be centrally-controlled via the GH interface, and all resultant FE output data (deflections and stresses) fed back to the script.

Relying on a rigorous node and panel-numbering system, each panel is individually selectable and properties controllable, allowing us to assign specific panel thicknesses and loads, model large-scale gradients of loading-scenarios, and effectively analyse a more realistic cross-sectional geometry.

FEM was used to determine areas for perforations. As with the concrete bridge design method mentioned before for the Navel Bridges in Nieuw Vennep, from the FEM analysis we were able to determine the areas of high and low stress. This ultimately indicated the areas where redundant material had been provided, informing the locations and sizes of the perforations. It was essential to implement the numbering system in the script. In such a way the tool could be used for both intuitive modification and structural analysis.

In order to optimize the structure and use the material to its full potential, an iterative Grasshopper form-finding process is adopted. The sandwich composition of glass-fibre outer layers with honeycomb interior provide only limited out-of-plane shear capacity. Instead, the doubly-curving geometry of the ShArc allows shear transfer to the curving edges to be transmitted to the piers via the parapets and hull, which we need to encourage the Kangaroo relaxation algorithm to converge to.

Weighting functions are developed for each of the utilization factors as follows (figure 3.20). This is to promote a high utilization in-plane (approaching 0.8), a low out-of-plane shear utilization and as low deflections as possible. The functions are at this point not academic and mainly serve comparative purposes.

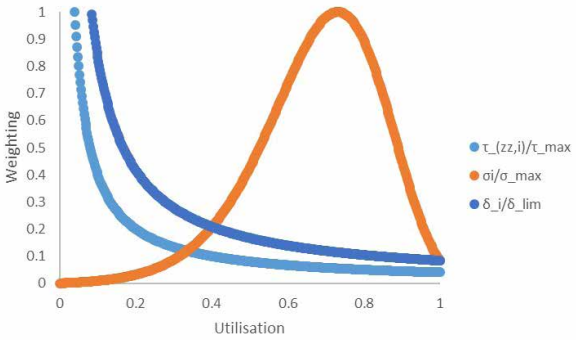


FIGURE 3.20 Weighting functions. BuroHappold, Dirk Rinze Visser et al. (2017).

$$f(UF_\tau) = f\left(\frac{\tau_{zz,i}}{\tau_{max}}\right) = \frac{k_1}{\left(\frac{\tau_{zz,i}}{\tau_{max}}\right)}$$

$$f(UF_\sigma) = f\left(\frac{\sigma_{v.Mises,i}}{\sigma_{max}}\right)$$

$$= \left(k_2\left(1 - \frac{\sigma_i}{\sigma_{max}}\right)\right)^{-1} * e^{-\ln\left(\left(k_2\left(1-\frac{\sigma_i}{\sigma_{max}}\right)\right)^2\right)}$$

$$UF_\delta = \frac{k_3}{\left(\frac{\delta_i}{\delta_{lim}}\right)}$$

$$UF_i = \overline{UF} = \frac{1}{3}\sum\left(f(UF_\tau) + f(UF_\sigma) + UF_\delta\right)$$

With:

$\tau_{zz,i}$ = out-of-plane shear at each node
τ_{max} = out-of-plane shear capacity
$\sigma_{v.Mises,i}$ = in-plane stress at each node
σ_{max} = in-plane stress capacity
δ_i = deflection at each node
δ_{lim} = deflection limit
$k_{i=1..3}$ = weighting factors

The average value of the utilization factors is calculated, and used as a utilization factor singular to each node (UF_i). The utilization factors for each node can then be plotted against their location relative to the bridge, either in a 2D plot graph or directly over the 3D geometry. As a result, areas of low material utilization can be identified rapidly and highlighted for required geometric alterations.

Shown are node utilization factors (UF_i) along the y-axis, with their relative position to the centre of the bridge shown along the x-axis (figures 3.21, 3.22). As can be seen between A and C, significant improvement can be made to make the material fully-utilized. A low point is shown at C, close to the centre, where the high stress concentrations associated with the piers are not as typical. The slight arch of the bridge and wide deck width presumably prevent the high flexural stiffness's typically associated with the mid-spans of structures.

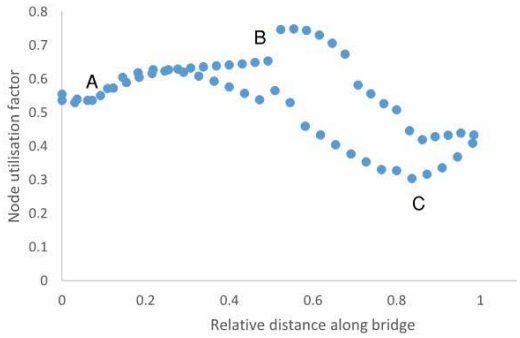


FIGURE 3.21 Node utilization against relative position. BuroHappold, Dirk Rinze Visser et al. (2017).

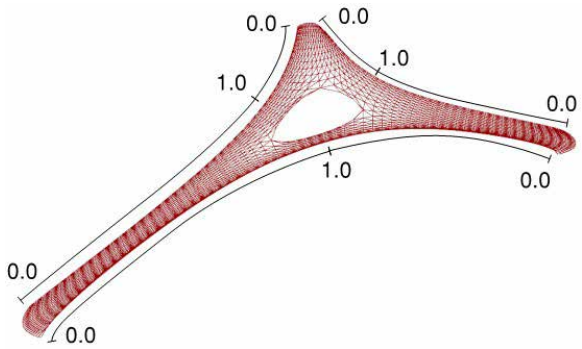


FIGURE 3.22 Relative node positions. BuroHappold, Dirk Rinze Visser et al. (2017).

The step at B is a result of an averaging function that we used to avoid the high local stresses at the corners where the two tracks meet around the opening, which we deem will require constructive mitigation and so deem to be unrepresentative.

Future scope for research include expanding the number of utilization factors to include factors such as susceptibility to dynamic excitation, material quantity, gradient of the bridge deck and visual prominence/ height of the bridge above the water.

Ultimately, a global fitness criteria is to be created ($UF_{glob,j}$), which provides a reading for the working efficiency of a specific geometry for all affecting parameters. As geometric input parameters are altered, the resultant utilization factors can then be tested for their improvement to the global utilization ($UF_{glob,j+1} > UF_{glob,j}$?) and the change retained or discarded as appropriate.

With sufficient computing power, this approach can be extended to the use of an evolutionary solver, with the geometric variables as input parameters and $UF_{glob,j}$ as the fitness criteria. As the analysis runs through multiple iterations, it is expected the analysis will converge toward a material and structural optimum.



FIGURE 3.23 Artist impression, view on the bridge. Delft University of Technology, Joris Smits et al. (2017).

§ 3.5 Conclusions

1 In order to achieve symbiosis between architecture and structure in integral bridge design architects and structural engineers must be willing to overcome the current division between the work of the architect and the work of the structural engineer and get rid of the classical hierarchy.

2 A pure and self-contained form of bridge design is possible when the designer observes a degree of self-restraint to stay within the boundaries of the forces at play. A bridge design must follow the laws of static, allowing minimal manoeuvre space for frivolity. This way each design visualises its own display of forces, showing nothing more than itself.

3 At the same time it is important to acknowledge that a bridge design cannot be simplified as a mere display of forces. A coherent design is just as much influenced by thorough response to the boundary conditions imposed by the context, the choice of material, the building process and the maintenance and financing of the bridge. A beautiful optimization design has little added value to society if it is impossible to build, maintain or finance.

4 Today, the need to carry out experiments and physical tests with scale models is put into question with the ability to use the computer as a tool for optimization and a way to search for new forms. But how useful is the computer really? In an interview with Juan Maria Songel in 2010 Frei Otto stated "The computer can only calculate what is already conceptually inside of it; you can only find what you look for in computers. Nevertheless, you can find what you haven't searched for with free experimentation." [6]

5 Although the tools have changed since 2000, the methodology and the design parameters have remained the same.

6 Much like design methods in the pre-computational period, computational design allows for intuitive design. Through parametric models and graphic scripts, an interactive design process can be created that is open to both architects and structural engineers.

7 Parametric design allows for exchange of disciplines in a multidisciplinary process.

8 A parametric model allows control over aspects that are hard to influence in a physical way.

References

[1] Zalewski, W., & Allen, E. (1997) *Shaping Structures: statics.* New York: John Wiley & Sons, Inc.
[2] Granger, F. (2007). *Vitruvius on architecture*. Bakhsh Press.
[3] Albertopugnale.com. (2013). Form-finding – comparison between karamba and kangaroo, Retrieved January 10, 2018, from http://www.albertopugnale.com/2013/03/29/form-finding-through-numerical-tools-comparison-between-karamba-and-kangaroo/
[4] Chilton, J. (2000). *The engineers' contribution to contemporary architecture, Heinz Isler*. London: Thomas Telford Publishing.
[5] Smits, J. (1999). *Twee bruggen Venneperweg*. Amsterdam: Haskoning.
[6] Songel, J. M., (2010). *'A Conversation with Frei Otto'*. Princeton Architectural Press: New York.
[7] Petras, A. (1999). *Design of Sandwich Structures* (doctoral dissertation). University of Cambridge.
[8] Avó de Almeida, M. I. (2009). *Structural behaviour of composite sandwich panels for applications in the construction industry*. (master thesis). Universidade Técnica de Lisboa.



TOC

4 Fiber-Reinforced Polymer Bridge Design in the Netherlands

Architectural challenges toward innovative, sustainable, and durable bridges

Smits, J., (2018)

Scale 1:10

In the previous chapter the design considerations at the scale of the bridge itself is discussed. This chapter addresses bridge design considerations at the scale of the detail and that of the materialisation.

This chapter was first published in Engineering, Elsevier, November 24 2016. DOI: http://dx.doi.org/10.1016/J.ENG.2016.04.004. 2095-8099. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company. *This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).*

Abstract

This paper reviews the use of fiber-reinforced polymers (FRPs) in architectural and structural bridge design in the Netherlands. The challenges and opportunities of this relatively new material, both for the architect and the engineer, are discussed. An inventory of recent structural solutions in FRP is included, followed by a discussion on architectural FRP applications derived from the architectural practice of the author and of other pioneers.

Keywords: Architecture, structural design, bridge design, FRP, flexible molding systems, monocoque structures

§ 4.1 Introduction

Despite the fact that the building industry tends to be more conservative than other sectors such as the automotive or aerospace industries, innovative materials and new techniques are finding their way into bridge construction in the Netherlands. One of the most promising group of new material in bridge design is fiber-reinforced polymer (FRP). FRPs are composite materials that consist of a polymer matrix reinforced with fibers. The fibers can be glass, carbon, basalt, or aramid, although other fibers such as paper, wood, or plant fibers have also been used. The polymer is usually an epoxy, vinyl ester, or polyester thermosetting plastic. The fibers and the matrix exhibit different physical and chemical properties that, when combined together, create a strong and rigid composite material.

Ever since the first FRP footbridge in Harlingen in 1995, practice in the Netherlands has shown a growing interest in this new material for bridge design. This interest has resulted in a significant number of realized bridges in which FRP has been applied. The bridge examples discussed in this paper show FRP being used both for the main load-bearing structure and in a more complimentary way, such as for modular edge elements and bridge deck systems. Although the pioneer years of FRP bridge design in the Netherlands were dominated by straightforward load-bearing boards, this author will prove that FRP has a great deal to offer in terms of the aesthetic appearance of a bridge.

The Netherlands has an extremely high density of roads, railway lines, and waterways. It is therefore no wonder that the country contains an excessively high number of traffic bridges and footbridges today, with most having been constructed after the Second World War [1]. Since the war, traffic intensity has grown by tenfold while design codes and regulations have become stricter, especially in terms of wear, dynamics, and fatigue. This development has resulted in a high number of post-war bridges being at the end of their technical life. Replacement is expensive, and since public authorities have been forced to downsize their organizations due to the economic recession, there is little budget for maintenance [2]. Therefore, when new bridges are being built, the question arises of whether traditional materials such as concrete and steel are still the best choice, both in terms of rational engineering arguments and for cultural and aesthetic reasons. New materials have been developed in the field of bridge design, one of which is FRP.

Although a significant number of FRP bridges have been built in the Netherlands over the past 20 years, it is noticeable that aesthetics were considered as a legitimate issue for only a handful of them. Most of these designs are extremely straightforward,

massive structures that do not visibly show the fact of dealing with a new and innovative material. These bridges are mere slabs across the water; in the few cases that aesthetics are considered, the new materials are used to imitate traditional materials such as wood (i.e., for parapets or deck planks) or steel. This tendency to refer to a traditional application is reminiscent of the first iron bridge designs, in which traditional wood connection details were indiscriminately translated into iron.

In order to answer the question of what FRP has to offer in the architectural design of a bridge, it is first necessary to identify how the use of FRP can change the appearance of a bridge, and what kind of shapes and tectonic applications of FRP can do justice to this relatively new material in bridge design. The goal of this paper is to set out a path that will enable designers, architects, and engineers to take FRP bridge design up to the next level, not just using this new material as a pragmatic engineering choice, but embracing it as an architectural challenge.

In order to understand what can be, we first need to know what is. Therefore, Section 2 investigates how engineers have pioneered FRP, including different typologies and production methods. This paper discusses and evaluates the aesthetic merits of these methods. Section 3 then addresses different opportunities and challenges for aesthetic improvement by evaluating the author's work and the work of other pioneers in the field.

§ 4.2 Engineers' solutions in FRP

A retrospect of the evolution of FRPs shows that engineers, rather than architects, were the first to experiment with this new material. The aerospace, marine, and automotive industries initially introduced these plastics decades before architects adopted them (figure 4.1). As early as 1940, Henry Ford produced a pioneering composite car from hemp fiber and resin under the motto: "ten times stronger than steel" (figures 4. 2). Plastic materials gradually began to attract other sectors as well, including product design, architecture, and construction. Architectural practices such as Future Systems Architects realized the potential of the molding technique in producing new forms, and developed futuristic FRP houses and structures. However, regarding bridge design, none of the early FRP designs considered the aesthetic potential of the material.



FIGURE 4.1 Engineers from the aerospace, maritime, automotive, and sports industries have preceded bridge engineers in their use of FRP.



FIGURE 4.2 Henry Ford demonstrates his hemp car on impact (Ford, 1940). from https://ga-institute.com/Sustainability-Update/tag/henry-ford/, visited on 27/02/2019.

TOC

Driven by issues such as maintenance and durability, bridge engineers seeking alternatives to traditional construction materials found that FRPs offered comparable and often superior properties (table 4.1). One of their strongest advantages is their low density, which results in reduced mass. Comparative case studies in this author's practice have shown that the average FRP composite bridge is about half the weight of a steel bridge, with the same performance; and it is five times lighter than its concrete equivalent. This benefit regarding weight also results in reduced energy and cost in transportation, hoisting, assembly, supporting structure, and foundations. In terms of the finite amount of raw building materials and their carbon footprint, FRP bridges are often a very rational choice. There are significant advantages in terms of durability as well, as FRP composites show high resistance to corrosion. Consequently, maintenance requirements are low.

TABLE 4.1 Material properties of FRP compared to those of steel and aluminum [1]

properties	Density ρ [kg/m3]	Young's modulus in x-direction Ex [N/mm2]	Young's modulus in y-direction Ey [N/mm2]	Tensile/compr. strength in x-direction fxRk [N/mm2]	Tensile/compr. strength in y-direction fyRk [N/mm2]
GFRP UD, Vf 50%	1.875	36.569	10.924	740	-
GFRP 625, Vf 50%, aniso-tropic layup [0/90/45/-45] [62,5%/12,5%/12,5%/12,5%]	1.850	27.600	15.200	331	182
CFRP UD, Vf 50%	1.450	120.000	60.000	1.560	-
Steel S355	7.850	210.000	210.000	355	355
Aluminum 6063	2.720	69.600	69.600	110	110

GFRP UD stands for unidirectional glass fiber-reinforced polymer; CFRP UD stands for unidirectional carbon fiber-reinforced polymer.

[1] *Both GFRP and CFRP have superior strength in a unidirectional fiber orientation. However, an anisotropic fiber lay-up is more realistic in bridge applications. Arguably, the relatively lower Young's Modulus in FRP demonstrates that deflection is key in FRP design.*

§ 4.2.1 Hand lamination: A footbridge in Harlingen

In December 1995, the Dutch Ministry of Infrastructure (Rijkswaterstaat) was the first to initiate a 100% FRP footbridge in the Netherlands (figure 4.3). Two years later, this hand-laminated bridge was open for use in the harbor of Harlingen. The bridge was half the weight of a traditional steel bridge and twice the price, and its span-to-depth ratio (L/D) was twice as low due to its U-beam concept with massive load-bearing parapets. Hand lamination, or hand lay-up, is a widely used and old technique for making composite parts based on repeatedly stacking layers of resin and fiber reinforcement. A simple but labor-intensive manual process, it allows for design flexibility, although the component quality depends on the skill of the operator. Concerning the fiber-per-volume fraction, high ratios cannot be achieved using this technique due to the manual processing.



a *b*

FIGURE 4.3 Footbridge in Harlingen, the Netherlands, made by Poly Products for Rijkswaterstaat (1997). From http://www.polyproducts.nl, visited on 27/2/2019.

§ 4.2.2 Assembly from pultruded profiles

Another common solution that is applied in many bridges is the use of pultruded FRP profiles. Pultrusion is a continuous automated process that produces large quantities of identical parts, translating into relatively low-priced elements of consistent quality. Complex cross-sectional shapes and high-fiber fractions can be achieved with this automated process. Reinforcement is pulled through a resin bath and subsequently through a heated die. The die tapers into the final profile shape along its length, and the continuous profile emerges fully cured to be cut to length. A wide range of solid

and hollow structures with a constant cross-section can be produced and applied as bridge beams, deck panels, grating systems, handrails, and so forth. The mechanical properties mostly dominate in the axial direction. To obtain a degree of bidirectional properties, woven fabrics or mats can be fed to the die to be integrated in the laminate, but the transverse properties remain limited [3].



a



b



c

FIGURE 4.4 Bridge structures from pultruded profiles and material substitution, Fiberline (2013). Pontresina, Switzerland (a); Lleida, Spain (b); Kolding, Denmark (c). From https://fiberline.com/international-award-innovative-grp-footbridge, visited on 27/02/2019.

In terms of detailing, an FRP bridge that consists of pultruded components closely resembles a steel bridge. Straight profiles and pultruded sheets are assembled into trusses, arches, pylons, or U-beams (figure 4.4). The joints are key when using pultrusion profiles. Because the fibers are often unidirectional in the length of the profile, they are apt to split near the joints, which are often thick with bolts and plates.

§ 4.2.3 Bridge decks

Decks are generally the least durable part for both footbridges and traffic bridges. Poor initial construction, lack of proper maintenance, and environmental conditions are the main factors that reduce the service life of a bridge deck. Excluding painting, bridge deck repair and replacement account for 75–90% of annual bridge maintenance costs in the Netherlands [4]. In addition to using them to replace deteriorated steel or concrete decks, composites can be applied to widen existing structures without the significant addition of dead loads for piers and abutments (figure 4.5).

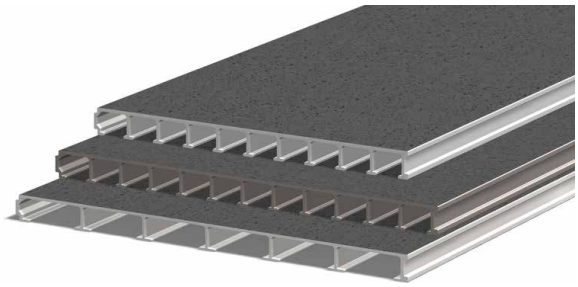


FIGURE 4.5 Pultruded bridge deck panels. (Transportation Research Board, 2006).

§ 4.2.4 Load-bearing uniform deck

As previously mentioned, the Netherlands has seen extensive growth in FRP pedestrian and bicycle bridges over the last decade. A significant number of these bridges have been constructed employing another efficient technique. These bridges consist of a hollow FRP plank with steel railings mounted on top of it. The production process comprises a series of parallel-positioned, non-load-bearing core elements, which are wrapped in fabrics. The reinforcement runs continuously from the element's horizontal face planes through the webs and the facings of the adjacent core elements. After the core and the reinforcement are positioned on a deformable mold plate (figure 4.6), the structure is sealed with a flexible bag. Resin is then drawn into the laminate by a vacuum technique consisting of a vacuum pump on the output side of the mold that draws the resin in from a reservoir on the input side of the mold. Depending on the equipment used, the web and flange thickness can be up to tens of centimeters, with fiber fractions

of up to 70%. Although the lightweight core has no structural role in the final product, it is necessary as formwork in the production process and stays enclosed in the structure after construction [5]. However, the core material, which is normally foam, should be strong enough to resist the vacuum pressure during the impregnation process.

Although the architectural design of these bridges is minimal and is limited to the design of the parapet, their lower span-to-depth ratio and the separation of their parapets from a structural load-bearing function cause these bridges to have a more slender appearance than bridges made using the approaches described above (figure 4.7).

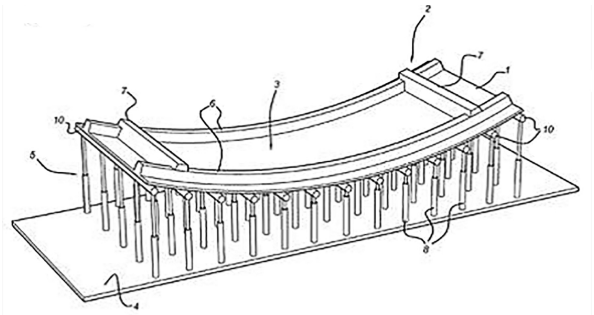


FIGURE 4.6 A flexible mold system for cambered decks with variable width and length.



FIGURE 4.7 The InfraCore patented technique for creating unitized structures. Peeters (2011).

§ 4.3 Challenges for the architect

The previous section reviewed how engineers have worked with FRP over the past two decades. However, the research question of this paper still remains unanswered: What architectural means and challenges do architects have when designing bridges from FRP? In order to answer this question, this section reviews a range of architectural FRP bridge applications, both from practice and from academic research projects in which this author has been involved over the past 10 years.

§ 4.3.1 Modular deck edge elements

Edge elements extensively define the appearance of a bridge because the design of the structure is mostly perceived and appreciated in elevation, as seen from an adjacent field or riverside, rather than from a perspective above the bridge. Driving on a bridge provides a nice view in the best cases, but the parts of the bridge itself that are visible from this perspective are mostly limited to the asphalt, the guardrails, and the parapets. Thus, using FRP for the production of edge elements broadens the design potential to a significant extend. Because FRP provides a greater degree of freedom than other conventional materials such as steel, curved surfaces and smooth edges can be achieved on a material with a highly polished surface finish.

Apart from the design possibilities, FRP edge elements eliminate crucial durability issues. Prior to the use of FRPs, edge elements were either made out of solid concrete with tapered endings, or constructed as hollow steel noses. Although the latter offered the advantage of a wide, accessible-for-inspection space for ducts and cables, low durability proved to be an issue. Steel noses tended to corrode from the inside due to moisture condensation, whereas fungi and moss grew on the faces of concrete elements.

The detailing and assembly of FRP edge elements are also advantageous. FRP edge elements are manufactured with flanges along the ending edges that are directed inwards. This not only bestows a fine and smooth end at the edge but also results in small tolerances that occur during assembly. Observing the joint from an angle, after the panels have been positioned on the secondary structure, reveals that the same material is extended up to the concrete structure instead of leaving a gap.



a b

FIGURE 4.8 Installation and final assembly of the edge elements in the fly-over Waarderpolder. Royal HaskoningDHV, Joris Smits et al. (2012). Photo's by Ballast Nedam (2011).

Normally, 60 mm of flange depth with a radius of 10 mm is enough to camouflage minor imperfections. In case the designer omits to specify these flanges, the result can be quite unappealing, as was eventually proved with the panels of the fly-over Waarderpolder shown in figure 4.8 and in figure 4.9b.



a b

d c

FIGURE 4.9 Some projects in the Netherlands with FRP edge elements, clockwise from top left: Edge elements on the Juliana Bridge in Zaanstad (a); The fly-over Waarderpolder in Haarlem (b); The wildlife crossing and tunnel in Rijssen-Wierden (c, d). Royal HaskoningDHV, Joris Smits et al., (2007, 2013,2013). Photo's Jane van Raaphorst.

The vertical gap between these panels is visible, and it is virtually impossible to adjust the spacing between all panels in order to achieve equal joint widths. However, the viaduct has a continuous linear appearance at a certain distance, as the naked eye can only distinguish wider gaps between some panels and kinks in the alignment from a closer perspective.

The advantages of the use of FRPs for the design of deck edge elements are clearly pronounced in the slender side edges of the Julianna Bridge in Zaanstad, the Netherlands, shown in figure 4.9a. The highly polished and smooth edge panels of this bridge have a curved and tapered cross-section, consisting of 900 mm cantilevers that are connected to the concrete deck. The parapets of the bridge are integrated in the modular element in a way that allows demounting for inspection and maintenance, such as cable replacement. The seam between the panels is specially detailed to have inner flanges of 60 mm depth, so that montage tolerances are covered and a visible dark gap between the elements is avoided. Other projects in the Netherlands with FRP edge elements are the Nelson Mandela Bridge in Alkmaar (realized in February 2016), the wildlife crossing with a pedestrian tunnel in Rijssen-Wierden, shown in figure 4.9(c, d), and the viaducts of highway N201 near Schiphol, shown in figure 4.10.

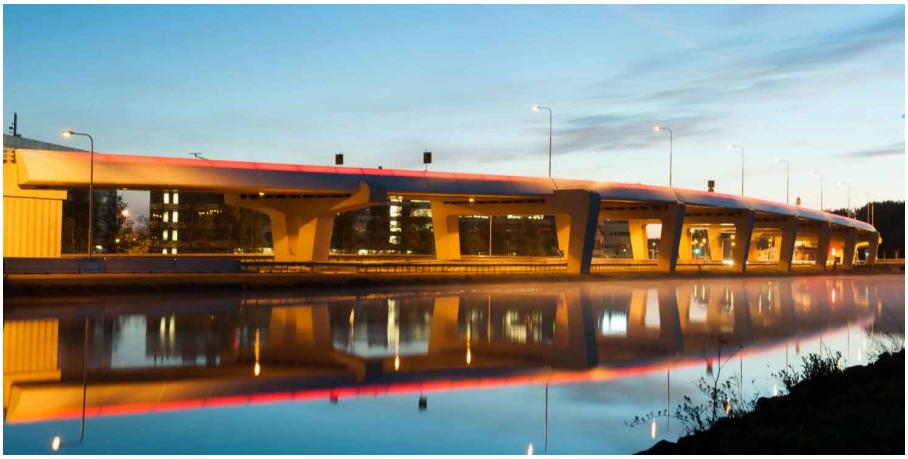
The design of the highway N201 viaducts proved that the possibilities of fiber-reinforced plastic edge elements extend beyond shape, color, and texture. In this project, the idea of a structure that glowed at night was introduced by installing lights behind the upper part of the composite panels. To achieve the desired effect, translucent FRP was employed along with a honeycomb core, which allowed for the even transmission of light within the thickness and over the surface of the panel, and which provided the panel with sufficient stiffness. For this project, red light was chosen for installation in the upper part of the edge panels, giving a final, linear glowing effect to the structure when it is approached from the motorway.



a



b



c

FIGURE 4.10 Installation of red light in the panels of the highway N201 viaducts. Royal HaskoningDHV, Richard van den Brule et al. (2013). Pictures a. and b. by Smit Kunststoffen (2012). Photo c. by Jane van Raaphorst (2014).

§ 4.3.2 Monocoque structures

The application of FRPs in construction is not limited to modular bridge elements, as entire load-bearing structures made from FRP have already been built. Inspired by the monocoque decks, such structures experiment with the design potential offered by FRPs. Monocoques are structures with a load-bearing exterior shell, comparable to shellfish (figure 4.11). These structures have efficiently concentrated material on the outer region of the cross-section, and offer the advantage of making slender forms achievable. From a maintenance and aesthetic point of view, the fact that the underside of the bridge is smooth and closed offers some advantages. Dirt does not accumulate on protruding flanges, and the creation of bird nests under the structure is avoided.

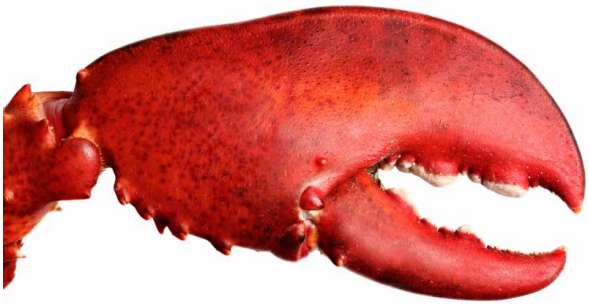


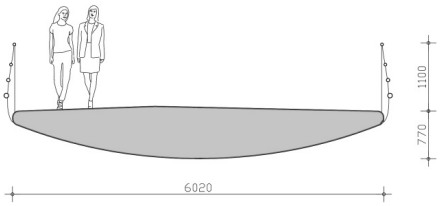
FIGURE 4.11 A lobster pincer, an example of a monocoque structure in nature. From https://dumielauxepices.net/wallpaper-18809, visited on 27/02/2019.



FIGURE 4.12 The Dragonfly footbridge in Harderwijk. Royal HaskoningDHV, Jorge Moura et al. (2014).

Producing a monocoque bridge with double curvatures can be a challenging procedure (figures 4.12, 4.13). In order to obtain a smooth and maintenance-friendly surface, the use of a mold is required. Mold-making can become an expensive part of the total manufacturing cost in the case of complex shapes that require a unique or special mold. Alternatively, mold cost can be effectively reduced by employing simple flat molds. The production method is also critical for the final result. With a single-mold vacuum injection, with which the bridge is produced upside down, the texture of the vacuum foil and the fibers becomes visible at the exposed underside of the bridge—similar to an old-fashioned canoe that has a bumpy surface on the inside.

The use of a double mold or a post-grinding and polishing treatment can overcome this disadvantage. Another process is hand lamination, in which the laminate is built around the surface of a specially designed core, encapsulating it in the final structure. Although this manual process permits more design freedom, it is not optimal in terms of material use due to its low fiber volume fraction, which leads to more resins being required and finally to a heavier structure with increased shell thickness. In the case of hand lamination, a smooth surface is possible only through extensive post-grinding, coating, and polishing.



a



b

FIGURE 4.13 A design for a monocoque FRP drawbridge for pedestrians and bicycles across the Rhine in Katwijk Royal HaskoningDHV, Joris Smits et al. (2014).

§ 4.3.3 Origami structures and shell structures

Load-bearing FRP structures can also be designed as shell structures or as three-dimensional folded shapes, and benefit structurally from the intrinsic stiffness that these structures offer. Folding relatively flat elements, such as FRP sandwich panels, into three-dimensional shapes significantly increases the stiffness of the structure. A U-beam geometry consists of the simplest variant of folded structures, but more intricate folded designs inspired by origami structures are also possible (figures 4.14, 4.15). However, an obvious downside of folded structures comes from the folds themselves and from the fact that forces within the material cannot be transmitted by axial forces only. Thus, bending momentum is introduced because of the folds, requiring extra material and preferably rounded edges at the corners.

Shell structures, as opposite to folded solutions, are more efficient regarding material use. In these cases, the deck itself can be quite thin as the structure derives its stiffness from three-dimensional curvatures (figures 4.16 and 4.17). An example of such a shell structure is this author's off-the-shelf design for a modular FRP pedestrian bridge, developed in cooperation with the company FiberCore (figure 18). The cross-section of the deck curves upward, forming part of the bridge's parapet. As the bending momentum increases toward the middle, so does the height of the shell.



FIGURE 4.14 Some tree leaves are natural folded structures. From https://www.bonsaiempire.com, visited on 27/02/2019.

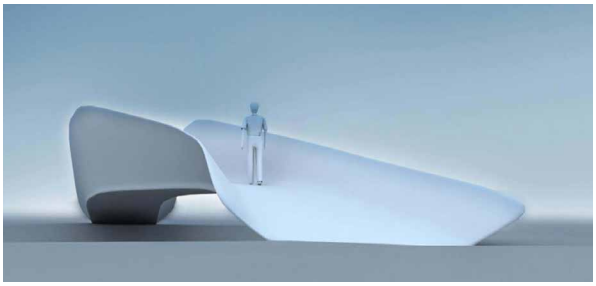


FIGURE 4.15 An origami bridge design. R. Gkaidazis, Delft University of Technology (2014).



FIGURE 4.16 The razor or Ensis shell, thin and strong. From https://en.wikipedia.org/wiki/Razor_shell.



FIGURE 4.17 Pringles, a fried potato snack with optimized stiffness. https://www.ikgastarten.nl/bedrijf-starten/bedrijfsplan/de-start-van-pringles, visited on 27/02/2019.



FIGURE 4.18 The Delft Design Composite Bridge. Royal HaskoningDHV & FiberCore, Joris Smits et al. (2008).

§ 4.3.4 Smart formworks

When it comes to realizing complex three-dimensional geometries in FRP, one of the most important determining factors is the cost of the formwork. For a large production in which a repetition of identical elements can be achieved, as for the bridge deck edges discussed in Subsection 4.3.1, production becomes affordable. However, when various unique elements with changing three-dimensional shapes are required, an individual, designated mold solution becomes unaffordable. Several researchers are investigating smart and flexible formworks and experimenting with new molding systems that could offer an efficient solution to geometric alterations. Research on flexible molds for concrete structures (figure 4.19) [6, 7] and on adjustable formworks for curved glass panes (figure 4.20) [8] could be successfully adjusted and applied to FRPs, and could eventually permit more design possibilities and form freedom for architects.

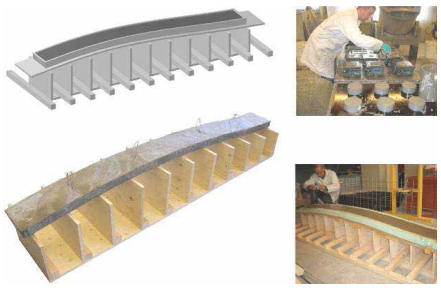


FIGURE 4.19 Test setup for single-curved elements. H. Schipper et al. Delft University of Technology (2011).

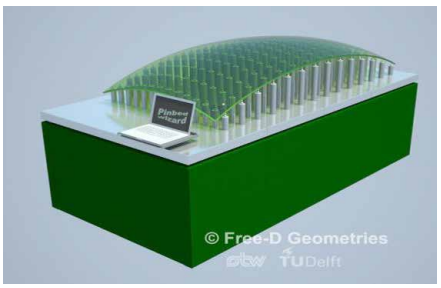


FIGURE 4.20 Wizard with 200 simultaneously computer-adjusted actuators. D. Rietbergen et al., Delft University of Technology (2008).

§ 4.4 Conclusion

The use of FRPs in bridge engineering has grown significantly over the past two decades. Applications vary from simple deck elements to pultruded members, and even entire load-bearing structures made of FRPs are now feasible. Attracted by structural and economic benefits such as weight reduction and cost saving on maintenance, engineers have developed construction solutions using FRPs that compete with conventional structures. In the field of architecture, the recent establishment of FRP as a building material for bridges has resulted in numerous successful projects in which FRP serves architectural purposes. Architects and engineers have demonstrated the use of FRP as a cladding material around decks, both in a simple form or translucent and combined with light. They have also demonstrated more daring structural applications of FRP, including a load-bearing shell, folding structures, and non-standard curved monocoque structures. Furthermore, this innovative material has clearly not yet reached its maximum capabilities and requires additional research. In particular, improvement of the environmental impact and the embodied energy of FRPs by the substitution of renewable raw materials (natural fibers, bio-based resins) for conventional materials should be further explored. Finally, FRP needs to be introduced as a mature material in our educational system so that future architects are educated in how to do justice to the unique material properties and fabrication methods of this material.

References

[1] Van Blankenstein E. (2009). *Bruggen in Nederland (1940–1950). Vernieling en herstel,* in Dutch. Zuthphen: Walburg Pers.

[2] Smits, J. (2013). Bridge design 2.0: recent developments in the field of integrated, sustainable and durable bridges. *Structural design. ICSA 2013: Proceedings of the 2nd International Conference: Structures and Architecture*; Guimaraes, Portugal. p. 1–10.

[3] Majumdar, P.K., Liu, Z., Lesko, J.J., Cousins, T.E. (2009). Performance evaluation of FRP composite deck considering for local deformation effects. *J Compos Constr 2009*;13(4):332–8. doi:10.1061/(ASCE)CC.1943-5614.0000008.

[4] Karbhari, V.M. (2001). Materials considerations in FRP rehabilitation of concrete structures. *J Mater Civ Eng13(2)*:90–7. doi:10.1061/(ASCE)0899-1561(2001)13:2(90).

[5] Veltkamp, M., Peeters, J. (2014). Hybrid bridge structure composed of fibre reinforced polymers and steel. *Struct Eng Intl;24*(3):425–7. doi:10.2749/101686614X13844300210515.

[6] Schipper, H.R., Janssen, B. (2011). Curving concrete—a method for manufacturing double curved precast concrete panels using a flexible mould. *Design and construction. IABSE-IASS 2011: Proceedings of the Joint Symposium of the International Association for Bridge and Structural Engineering (IABSE) and the International Association for Shell and Spatial Structures (IASS)*; 20–23; London, UK. London: Hemming Group Ltd. p. 8.

[7] Grünewald, S., Janssen, B., Schipper, H.R., Vollers, K.J., Walraven, J.C. (2012). Deliberate deformation of concrete after casting. *Structural engineering. ICFF 2012: Proceedings of the 2nd International Conference on Flexible Formwork; 2012 Jun 27–28; Bath, UK. Bath*: University of Bath. P. 132-139.

[8] Rietbergen, D., Vollers, K.J., (2008). A method and apparatus for forming a double-curved panel from a flat panel. *European patent EP* 20080741664. 2008 Apr 24.

[9] Nguong, C.W., Lee, S.N.B., Sujan, D.A. (2013) A review on natural fibre reinforced polymer composites. *World Acad Sci, Eng Tech. 73*:1123–30.

[10] Zini, E., Scandola, M. (2011). Green composites: an overview. *Polym Composite;32*(12):1905–15. doi:10.1002/pc.21224.

[11] Faruk, O., Bledzki, A.K., Fink, H.P., Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Prog Polym Sci;37*(11):1552–96. doi:10.1016/j.progpolymsci.2012.04.003.

[12] Alix, S., Philippe, E., Bessadok, A., Lebrun, L., Morvan, C., Marais, S. (2009). Effect of chemical treatments on water sorption and mechanical properties of flax fibres. *Bioresource Technol;100*(20):4742–9. doi:10.1016/j.biortech.2009.04.067. PMID:19477120.

[13] Maheswari, C.U., Reddy, K.O., Muzenda, E., Shukla, M. (2012). Effect of surface treatment on performance of tamarind fiber-epoxy composites. *ICICEMS 2012: Proceedings of International Conference on Innovations in Chemical Engineering and Medical Sciences*; Dubai, UAE; 2012. p. 16–19.



5 Bio-based composite footbridge

Design, production and in situ monitoring

Blok, R., Smits, J., Gkaidatzis, R., Teuffel P. (2019)

Scale 1:1

In the previous chapter the design considerations at the scale of the detail and that of the materialisation is discussed. This chapter addresses bridge design considerations at the scale of the composing materials and their material properties.

This chapter is currently under review in Structural Engineering International (SEI), the Journal of the International Association for Bridge and Structural Engineering (IABSE). Submitted 19 December 2018, accepted for publication with minor revision on 12 March 2019.

Abstract

This paper deals with the design, production and monitoring of a bio-composite footbridge with a span of 14 meters across the river Dommel in the city of Eindhoven, the Netherlands. The specific bio-composite material that was used for this research is a Natural-Fibre Reinforced Bio-Polymer (NFRBP). The goal of the research is to prove that NFRBP can be applied as a load bearing structure in an outdoor environment. For this purpose, a multidisciplinary team of academic researchers from two universities, together with a manufacturer from the NFRBP industry and the Centre of Expertise Biobased Economy (CoEBBE), developed a feasible design that could be produced by unskilled hands in a short period of time and within a limited budget. The footbridge was designed, built and installed within less than one year. In the two years after the installation of the footbridge, the structural behaviour of the bridge was monitored by means of optical fibre glass strands, integrated within the structure, with the purpose of measuring deformations and change in elasticity that occur over time.

Keywords: Bio-based Composites; Bio-based Materials; Circular Economy; Life Time Design; Sustainability.



FIGURE 5.1 The bio-composite footbridge, 18 months after the installation across the river Dommel. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017). Photo by Heijmans (2018).

§ 5.1 Introduction

As the level of impact of global warming and climate change is becoming evident, the search for renewable materials to replace our oil addiction has rapidly gained in urgency. In the field of science the plea for a transition towards a more circular approach of all facets of our economy is gaining in popularity. The necessity of a transition towards a circular economy is especially relevant to the building industry, which of all production industries is depleting our natural and mineral resources with the largest amounts. By way of illustration, at a European level an average of 37.5% of all the wood used is used in construction, 21% of all steel, 65.5% of all glass and 75% of all concrete [1]. That is why a paradigm shift in the building industry towards circular ways of building is unavoidable. In order to meet the ambitions resulting from the Paris Climate agreement it is essential to substantially increase the use of bio-based materials in the building industry [2]. Alternative materials and production techniques need to be found to set off towards a more circular approach. The use of Bio-based materials can be one of a number of different ways towards achieving a more circular economy and a sustainable environment. Furthermore, increasing the use bio-based building materials in the building industry is part of the Dutch National Research Agenda's themes: "Energy and raw materials: Circular economy" [3].

However, so far only a few experimental bio-based building projects have been realised world-wide, either using bio-based materials in non-structural elements such as building facades, or still making partial use of fossil based building materials. To test options for bio-based load bearing structures in the built environment, the authors of this paper have initiated the bio-based footbridge project.

The project aims were to design and build a small, but fully bio-based composite footbridge at the campus of TU/e, and to monitor the service life and degradation in relation to user safety. The project was initiated in November 2015 as a 3TU lighthouse project. The design process started in January 2016 and the bridge was opened by the Alderman of the city of Eindhoven on October 27th 2016. The main load bearing material that has been used to build the footbridge is a bio-composite, for which the scientific name Natural-Fibre Reinforced Bio-Polymer (NFRBP) is proposed. The fibres that were used were partially hemp fibres and partially flax fibres (figures 5.2, 5.4), combined with an epoxy resin that has a 56% bio content (figure 5.3). The non-structural core of the bridge was made out of PLA, also known as polylactide, an aliphatic thermoplastic polyester produced from renewable resources.



FIGURE 5.2 Flax in a field. From https://www.faay.nl/wp-content/uploads/Faay-Wanden-en-Plafonds_Duurzaam-bouwen-met-vlas_vlasveld_3.jpg, visited on 28/02/2019.



a *b*

FIGURE 5.3 Greenpoxy, an epoxy-resin with a 56% bio-content. From a: http://intrey.com/epoksidka/, b: https://www.timeout.de/sicomin-greenpoxy-56-5-kg, visited on 28/02/2019.



FIGURE 5.4 Woven flax fibres. Photo by Dorine van der Linde (2016).

The scope of the project has involved the architectural as well as structural design, the generation, development and selection of design options and the realisation, production and construction of a prototype footbridge of 14 m spanning the Dommel at TU/e campus Eindhoven (figure 5.1). The design follows the requirements in existing codes and standards. A LCA (Life Cycle Assessment) of the bridge as well as a report describing the design steps has been made as part of the project. This paper studies the specific material properties of bio-composites from an architectural as well as structural point of view and discusses the impact of working with bio-composite on the design process.

Furthermore, the research on the structural behaviour of the footbridge over time and under influence of Dutch weather conditions continued for two years after the installation of the footbridge. To this purpose optical Fibre Bragg Grating Sensors (FBG's) have been integrated in the main bio-composite compression and tension zones in order to monitor material strains and deformations.

§ 5.2 Integrated design and project approach

Right from the start of the project, early 2016, small multi-disciplinary teams, comprising architects, bridge designers and structural designers, as well as production experts, started generating preliminary design ideas. These design ideas were reported and discussed in combined design meetings. The resulting most promising ideas have been evaluated on their merits, both architectural and structural as well as from a production point of view and then further elaborated. From these first steps, very early on in the design process, a number of different design principles were formulated:

1 While composite materials can provide a lot of form freedom, the use of a separate mould to shape the bridge through vacuum injection would become too expensive for this project.

2 From early tests it was expected that the preferred combination of resin and fibres would perform better in tension than in compression (creep) therefore a design with relatively low compression stress would have preference.

3 The design would need to be optimised in material use, to keep the production cost sufficiently low while at the same time the aim to create an elegant structural design with a high aesthetical quality should remain an important focus.

§ 5.2.1 Design variations

In the design process, a number of different concepts have been explored. The most promising design alternatives have been further optimised in terms of structural efficiency, structural safety, aesthetical quality, functionality as well as feasibility and cost-effectiveness in production. A main design factor regarding the structural performance of the geometries has been the assumption of higher strength and stiffness of bio-composites in tension than in compression. As a result, the design variations are characterized by enlarged compression areas in order to reduce compression stresses, while tension zones could be kept more slender.

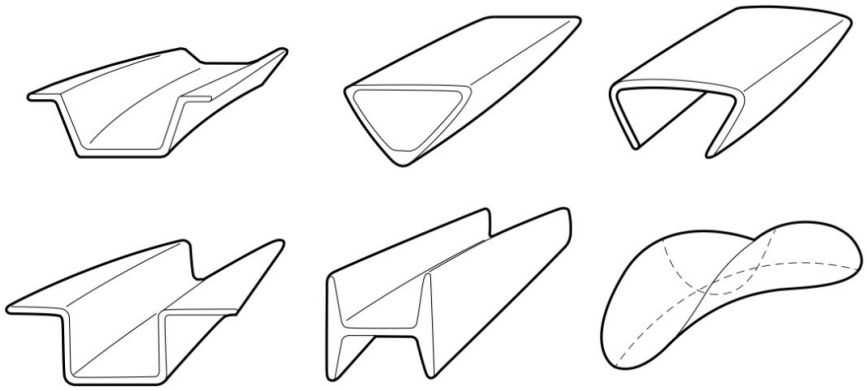


FIGURE 5.5 Workshop output on variable bridge cross-sections. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

The outcome of the first design phase consisted of multiple geometries as shown in figure 5.5, with various cross-sections that adopted the structural concept of either a beam, a shell or a monocoque. Solutions with U-shaped and I-shaped beams comprised solid bio-composite parapets, which increased the efficiency of the structure, while other design alternatives proposed horizontally extending top flanges, enlarging the compressive capacity of the geometry. Solutions with inverted U-shaped beams, whit enlarged compressive capacity, were considered weaker in tension and still required additional parapets on top of the structure. Also, a shell curved in two directions as shown in figure 5.5, bottom right, has been suggested as an elegant alternative solution. However, this design was not further elaborated because of the

complex and expensive mould it would have required. Finally, one of the suggested geometries had a triangular cross-section in the middle, with the point pointing down, that gradually turns into a rectangular cross section towards the abutments as shown in figure 5.5, top centre. This geometry offers high compressive strength at the level of the walking surface while still providing sufficient cross section area at the bottom for additional tensile reinforcement. Nevertheless, as this structure is in essence a monocoque shell, a vast core is required inside the NFRBP facing to act as a lost mold and to prevent collapse under vacuum production.

During the design evolution phase, the various geometries have been generated and modelled using digital parametric design tools, such as Grasshopper and Caramba, which enabled a preliminary structural evaluation of the different shape configurations, curvatures and material thicknesses in terms of maximum stresses and deflection. The sections have been evaluated on strength and section properties (second moment of inertia). The structural dimensioning of the structures were based on preliminary calculations which considered a required uniform live load of 5,0 kN/m^2 and estimated material properties.

The selection criteria that have been used to determine the geometry that was to be elaborated were: sufficient strength and stiffness, architectural appearance and cost-effective production. Besides the structural performance of the designs, aesthetical values have been equally considered throughout the design evaluation. Designs that expressed the plasticity of the new bio-composite material were favoured over more conventional solutions. As a conclusion, the solid structural parapets of the various U-beam solutions have been discarded as they would result in massive structures when seen from the side, while any attempt to create perforations in the sides would have increased production complexity and costs. Therefore, a non-structural railing solution, attached to the deck, has been justified as a more elegant and realistic solution. Weighting all parameters and evaluating the design concepts finally has resulted in the choice for the triangular monocoque deck as the design for further elaboration.

§ 5.2.2 Structural optimization of selected design

The selected deck geometry develops from a rectangular cross-section at the abutments of the bridge, into an almost triangular section of approximately 1m height in the middle of the span as shown in figure 5.6. One primary structural optimization in the direction of enhancing tensile capacity of the geometry without excessively increasing the structural height has been to turn the triangular middle cross-section

into a trapezoid with a minimum bottom width of 240mm. The bottom face increases in width towards the abutments, whilst the structural height drops and the inclined edges become perpendicular to the walking surface. This way the trapezoid cross section in the middle gradually changed into a flat rectangle at the abutments.

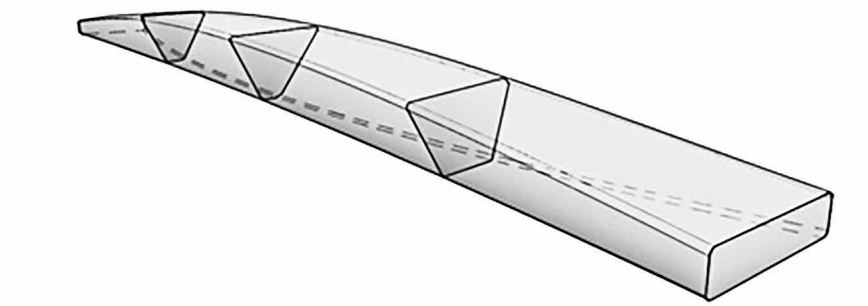


FIGURE 5.6 Different sizes and shapes of mid-span sections evaluated. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

Additionally, in order to further minimize deflection and increase shear capacity, the structural height at the supports of the bridge has been increased. Detailed deflection calculations have resulted in a beam height of 350mm at the abutments and a maximum beam height of 0,95m in the centre of the deck. The width of the bridge beam: the walking surface of the structure, has a constant measurement of 1,2m.

The use of NFRBP as a structural material allows for further optimization on the level of the orientation of the fibres. Thus, the bridge geometry can be further modelled and optimised using the 3D FEA software. Through the later, different material properties representing the resulting material stiffness of various combinations of fibre orientations and configurations, have been applied on areas of the bridge. Configurations with UD fibres (unidirectional), Woven fibres (two-directional) and Non-Woven fibres (random) have been compared with the aim of optimizing the deck in terms of fibre cost and structural performance. Although in design research directional fibre optimisation has been applied by using the locations and directions of the principles stresses, this has not been applied in the final design. Based on the relatively high cost of Non-Woven Uni-directional fibres the final design used woven 90 degrees flax fibres and Non-woven, randomly oriented Hemp fibres.

The areas with the lowest stresses for example the sides of the bridge-beam with low shear stresses have been designed using the low-cost Non-woven Hemp fibres. The Non-woven mats consist of randomly arranged short fibres that show consistent properties along the plane, without any dominant direction. In contrary to the woven layers that are made out of high-quality flax, the non-woven mats use the hemp fibres. The rough Hemp fibre mats have lower mechanical properties compared to flax and have been chosen to achieve a more cost-effective solution for the areas of the structure where low structural capacity is sufficient. In hindsight, when also taking into account cost of resin, this choice probably has not led to the most economical solution.

§ 5.2.3 Final materialization and detailing

The walking surface of the structure has been aligned with an upward camber with a radius of approximately 50 metre and a maximum slope angle of 6°. The deck geometry is characterized by its rounded edges that facilitate the chosen vacuum injection production technique. During a resin injection process, high pressure forces are applied evenly on the fibre mats that are wrapped around the deck. The chosen geometry from the first design phase uses a structural (hollow) bridge beam without a structural parapets, therefore and additional non-structural railing system has been designed. In order not to compromise the bio-based content of the entire structure, bio-composite has been used for the railing as well. The appearance of the railing is chosen to resemble an organic shape of grass blades, thus expressing the bio-based character of the bridge. The design consists of vertical tapered balusters that are slender at the top and widen towards the bottom where they connect with each other and to the bridge deck. For ease of fabrication, the parapets have been designed to be sawn out of sandwich laminate plates, using an open comb-like layout of the balusters allowing for two intertwined segments to be cut out of a single plate, thus minimizing cutting waste. The parapet segments have been manufactured flat, using the vacuum injection method. All segments have been bolted to the side of the deck into a timber beam that is integrated within the top corners of the core. A main characteristic of the design is the gradual outer inclination of the balusters moving away from their vertical position at the abutments of the bridge. This shifting from the vertical is a result of the evolving shape of the bridge beam itself: a gradually changing angle of the vertical sides of the bridge that is extended in the inclination of the railing. Being flexible due to its material and comb shape, the segments are able to be deformed under slightly torsional deformations that result from these changing inclinations, thus enhancing the leaf-like representation. The balusters lends a dynamic appearance to the design and bestows the feeling of an open and comfortable space to the users. To further

accentuate the leaf-like shape of the bridge, the railing has been designed with a non-constant height. The top follows an arced outline resulting in a parapet height of 1,2m in the middle of the span whilst at the abutments above the river banks the railing is only 0,9m in height.

§ 5.3 Material selection and tests for obtaining safe design values

Just like conventional fibre reinforced polymers, bio-composite is composed out of two materials; the fibres that provide the stiffness and strength are bound together by a resin, the so-called matrix that provides cohesion to the fibres and enables shear forces within the composite. Both the fibres and the resin in NFRBP can be replaced by its bio-based equivalents; natural fibres and bio-based resin. In literature [4] the approximate strengths of many different natural fibres can be found. At the start of the research project different combinations of resins and fibres that are known from literature [5] have been considered and reviewed [6]. Bamboo, hemp and flax fibres are among the fibres showing the highest failure strength. For sustainability reasons the use of locally grown fibres as hemp and flax has had our preference over bamboo. Of these two types only, the flax fibres were commercially available in directionally woven fibre mats. For this and economic reason, the flax has been applied in woven mats (90 degrees) while the cheaper hemp has been used in a non-woven (random directional) version.

With regard to the choice of resin the aim of the research has been to use a resin with a 100%, or else as high as possible, bio-based content. An epoxy-based resin has been preferred over a polyester resin because of better micro-moisture properties and also because of polyester production restrictions at the production facility. Furthermore, the number of possible resins has been reduced considerably, taken into account their commercial availability. The main important selection criteria besides availability for the remaining resins have been those properties that are most influential with regard to the vacuum injection technique. These properties are: viscosity, gel-time, hardening temperature and exothermal peak temperature. The first two properties directly influence the moulding injection plan (distances of injection to vacuum points), the latter (exothermal peak temperature) is of importance with regard of the use of the intended internal foam in relation to the maximum thickness of a single vacuum injection cycle. Some Furan based resins with a 100% bio-based content have proved unsuitable for normal production techniques because their high acid content makes them highly toxic during processing. Because of these criteria the initial goal to use a 100% bio-based resin had to be abandoned. Based on the availability of the resin as

well as the expertise of the project partner NPSP bv, Sicomin SR Greenpoxy56 with a plant based bio-content of 56% has been chosen. According to the product datasheet of the manufacturer this resin has a modulus of elasticity in tension and bending of approximately 3300 -3400 MPa and a tension breaking strength of 48 MPa.

§ 5.3.1 Initial material tests

Samples were made using the greenpoxy resin, the flax fibres, uni-directional (UD), as well as Hemp fibres (random-directional/ non-woven) to be tested.

The tension and the compression test were carried out in accordance to ISO 527 (tension) and ISO 604 (compression). The samples were 250 mm length and 25 mm width for the tension tests and 10 mm length and 20 mm width for the compression tests, 4 mm thickness. Of each fibre configuration 7 tests have been performed. Table 5.1 gives the strength results for the different resin-fibres configurations tested.

The Unidirectional fibres show higher strength values in both compression as well as tension. Table 5.2 gives expected strength and Young's modulus for the composites from a product data sheet of the supplier.

TABLE 5.1 Results per configuration and resulting values for the characteristic strength

Material	condition	Average Strength (MPa)	Standard deviation (MPa)	Characteristic (5%) Strength (MPa)
UD – Lineo	tension	202	12,6	181,3
	compression	-78,6	6,9	-67,3
UD - Scabro	tension	129,3	7,7	116,5
	compression	-104,1	4,4	-96,8
Woven Bi-direct.	tension	63,9	0,5	63
	compression	-73,5	2,1	-70
Non - woven	tension	36,1	3,4	30,5
	compression	-71,8	5,3	-63
Hybride	tension	47,5	2,9	42,8
	compression	-77,3	4,9	-69,2

TABLE 5.2 Summary of Structural Product data from N5010 Nabasco

	Tensile Strength (MPa)	Young's Modulus (MPa)
Non-woven	45	6.200
Woven, Bi-directional	69	10.500
Uni-directional	244	21.600

§ 5.3.2 Full scale production test – mock-up.

In order to test the production set-up and to establish the material properties as accurate as possible (matching the real production circumstances) a test production-run of a 2m long full-scale part of the bridge has been carried out. From this 1:1 scale element, material samples have been taken for testing. Figure 5.7 shows some milled test specimen and a test measurement set-up. Figure 5.8 shows typical test results of the composite using woven 90 degrees Flax fibres mats.

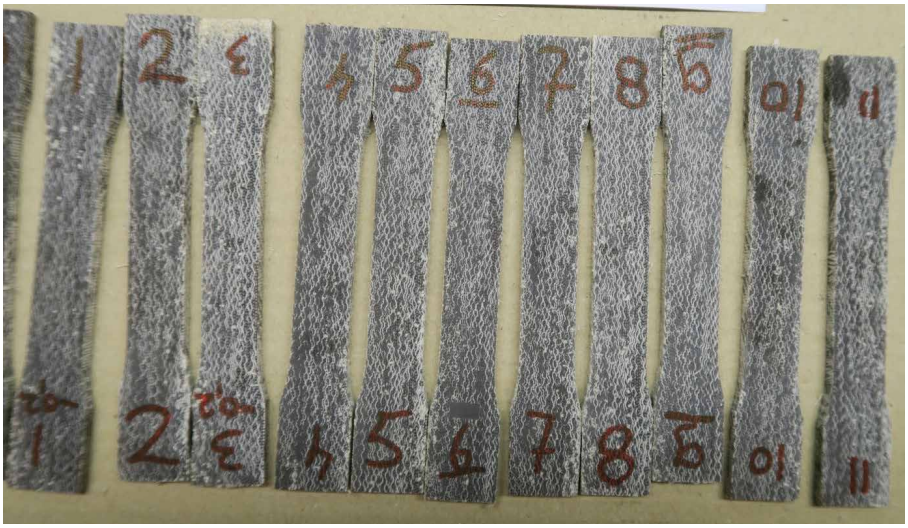


FIGURE 5.7 Milled test samples from 1:1 model and Tension test with optical strain measurement. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

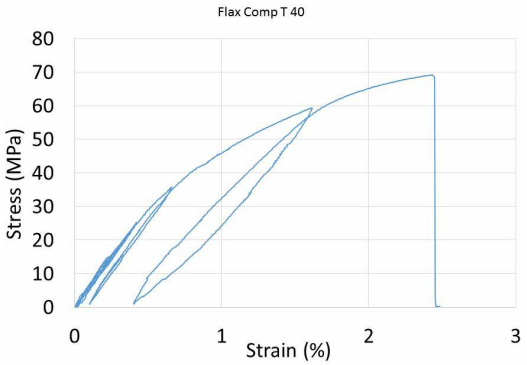


FIGURE 5.8 Typical result of a repeated loading-unloading and reloading tension test in the laboratory on a test specimen of Woven (90 degrees) flax fibre composite showing hysteresis behaviour.

From these tests, the average and characteristic strength as well as the Young's modulus has been calculated to be used in the final structural calculation. The characteristic 5% limit value of the material strength of these samples' (No's: 33) was 60 MPa. Calculating the Young's modulus from these data in the stress range of use resulted in an expected E_{avg} = 7.500 to 10.000 MPa. The Young's modulus value of 21.600 MPA provided by the supplier was thus found to be considerably higher than the value found in our own tests. To arrive at safe design strength values from experimental test data a similar approach as used in the Dutch recommendation design code for GFRP: CUR 96 has been followed. Based on this approach, the characteristic strength has been reduced by a material factor γ_m, representing mainly the estimated production influences as well as a conversion factor γ_c, representing estimated influences of long-term material behaviour due to temperature, moisture, fatigue and creep influences. This approach resulted in a applied design strength of roughly 25 % of the characteristic value. The material factor γ_m has been conservatively estimated as 1,89 while the conversion factor γ_c has been estimated as 2. The resulting design value Rd = Rk/ (γm * γc) was thus calculated as 15,9 MPa.

§ 5.3.3 Moisture tests

To estimate the influence of moisture, samples submersed in water have been tested, both at Delft University of Technology as at Eindhoven University of Technology. Tests have been performed in accordance to ASTM D 5229/5229M-14. The test in Delft were conducted using a weathering facility that mimics accelerated cycles of moisture/

draught, high/low temperatures and UV light cycles. These tests are not discussed here but have shown similar results to the test performed at Eindhoven. In these later tests, samples have been submersed in water and then tested after different periods of submersion. Oven dry samples have been compared to samples with other moisture content. The thus obtained values did not show a decrease in tensile strength for the submerging in water for 24, 48 and 96 hours compared to oven dried specimen (with a moisture content of 7,5 %). The measured strains however showed a large increase with longer submersion and higher water content compared to dry samples. The quality of these test and its results is questioned however, because test samples had been sawn out of a larger plate, leaving the end of its fibres exposed to direct water contact. No final conclusions have been drawn other than that strains clearly increase with increased (fibre-) water content and therefore protection measures of the composite material and in particular its fibres against outside water clearly was needed.

§ 5.3.4 Creep tests

Because it was expected that the bridge will also show time dependent non-linear behaviour, creep test have been performed (figure 5.9). Three-point bending material creep tests on three different stress levels (5 MPa, 15 MPa and 25 MPa) have been performed at TU/e. Figure 8 shows the results of these tests.



FIGURE 5.9 Creep test set-up at TU/e laboratory. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

The creep slope of the samples under lower stress levels (indicated with 5 MPa) hardly show a decrease in time. The higher stress level (25 MPa) shows only a very small reduction in the creep slope. Therefore, the long term deflection of the bridge can be estimated by a reduction in E-modulus approach, using with a reduction factor k_{def}:

$E_{mean,fin} = E\ mean / (1 + k_{def})$.

Based on the creep curves for the low stress-levels of 5MPa (figure 5.10) and preliminary calculations, a k_{def} = 0,8 was found and applied in the design calculations

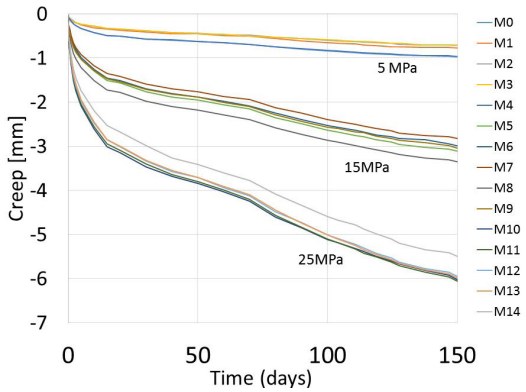


FIGURE 5.10 Creep curves at three stress levels 5, 15 and 25 MPa in three-point bending tests.

In order to avoid large creep deformations in the bridge design, the stress levels due to the permanent load (bridge beam and balustrade) needed to be kept low, preferably lower than the value of 5 MPa as used in the creep tests.

§ 5.3.5 Monitoring strains using optical sensors

Given the still remaining uncertainties of long-term material behaviour, as well as the opportunity to obtain more data during Service Life of the bridge, it has been decided to monitor the bridge on site by integrating sensors in the bridge structure. The monitoring is carried out by Eindhoven University of Technology, on whose campus the bridge lies. Optical Fibre Bragg Grating sensor technology (FBG) has been used because of its non-intrusive nature, its small dimensions as well as its high sensitivity

[7]. Constantly monitoring the bridge behaviour remains a goal for the future but for economic reasons (with regard to the necessary equipment for constant monitoring), a number of separate tests have been performed instead. The thin glass fibre based sensor lines (~100 – 200 µm diameter) that were used are extremely vulnerable during production. For this reason, the glass fibre has been glued between two layers of Uni-Directional (UD) fibres for protection. Figure 5.11 shows the preparation of these glass fibre sensors, UV-glueing the sensors between two layers of Uni-directional Flax fibres, before integrating the protected sensors in the production process.



FIGURE 5.11 Preparation of optical (glass) Fibre Brag Grating sensors. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

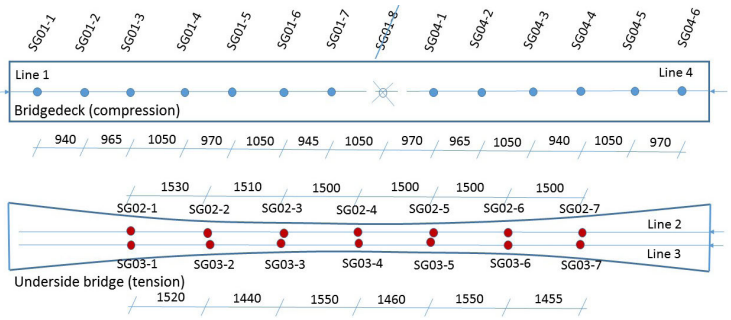


FIGURE 5.12 Location of Sensors. Line SG-01 and SG-04 are mainly compression (in bridge deck). Line SG-02 and SG-03 are mainly tension (under-side bridge). R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

A total of 28 sensors have been installed in initially 3 lines. Figure 5.12 shows the location of the 28 integrated sensors in a schematic top –and bottom view of the bridge.

Unfortunately, the compression line broke during production, for which reason only the sensors SG01-1 to 01-7 on the compression side were registered during the test of October. In the test of December 2016, the sensors SG 04-1 to 04-6 could be recovered by accessing them from the other side (line 04). Sensor 01-8 was lost

§ 5.4 Production process

The basis for the production of the bio-composite footbridge is a proven vacuum injection method with a lost mould system. In brief, the building process starts with the shaping of the internal core of the structure in bio-foam acting as a lost mould. Next a series of various bio-fibre mats are applied to all sides of the lost mould. The fibres are then wrapped in a vacuum bag with a network of injection and vacuum canals connecting to a vacuum machine on the one side and barrels of bio-resin connected to the vacuum bag on the other side. The vacuum results in the resin being sucked into the fibres where the hardening process of the resin (resin mixed with hardener) takes place.

The decision for a lost foam mould was taken to prevent the use of an external (costly) mould. PLA foam was chosen as a bio-based solution. PLA, also known as polylactide, is an aliphatic thermoplastic polyester produced from renewable resources that is compostable when exposed in the environment. The PLA foam core was made out of transversal laser cuts layers that gradually change the shape of the bridge over its length, from a rectangular shape at its ends, towards a triangular shape in the middle section. Figure 5.13 shows this approach for one half of the bridge design.

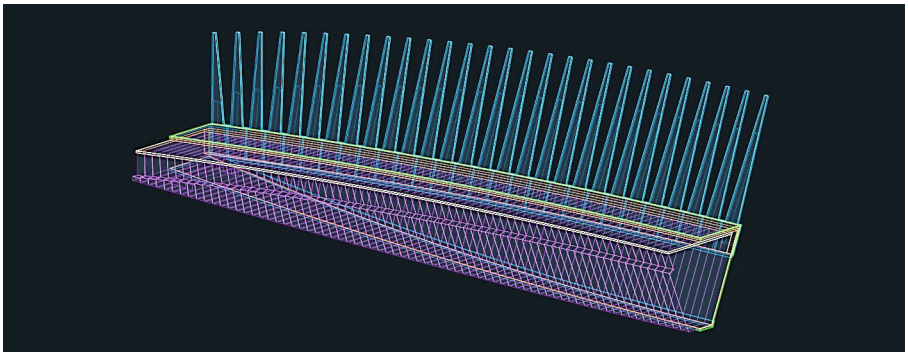


FIGURE 5.13 Change in shape from rectangular to triangular using laser cut PLA foam elements. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

This forming approach thus avoids an expensive mould-systems and it has been combined by producing the bridge top-side down on a curved ramp. This produces the slightly curved shape of the walking surface of the bridge. PLA has a low melting temperature of about 80 Celsius, while the exothermal peak of the used bio-resins while curing can become 135 Celsius or more. The temperature peak during curing depends on the thickness of the NFRBP layer. Figure 5.14 shows how the heat generated from curing increases with the thickness of the lay-up and causes melting of the PLA. It was therefore decided to prevent excessive heating and melting of the core limiting the maximum production thickness of the composite in contact with the PLA to 10 mm as well as d by avoiding direct contact between the bio-resin and the PLA through the use of a layer of insulated cork material between the PLA and the NFRBP. Additionally, water cooling was used to further prevent the internal PLA core structure from melting down.

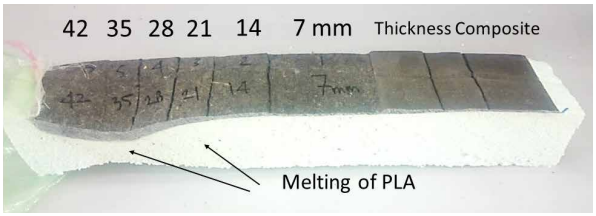


FIGURE 5.14 Meltdown of the PLA foam occurred when the thickness of the lay-up exceeds 10mm. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

Additionally, a prefabricated layer, a laminate of structural NFRBP was introduced to arrive at the structural required thickness of 20 mm in top and bottom flange of the bridge beam. This prefabricated laminate layer of 10 mm was added in both top and bottom of the bridge beam before the final injection, see figure 5.15, thus minimising the exothermic heating load on the PLA.

The final built-up of the structure is as follows: the PLA foam inner core is covered by a thin layer of cork material, on top of that the woven Flax (linen) is applied on bottom and top corners as well as the prefabricated (and perforated) laminates on top and bottom which itself is again covered with fibres. In the less loaded parts (the side flanges of the bridge beam) the non-woven flax and hemp mats are used. Figure 13 shows the position of the 90 degrees woven fabric, indicated in red. The whole bridge beam element has been vacuum injected with the bio-based epoxy resin Greenpoxy 56 (77,5% Greenpoxy 56 resin, 22,5% 4770 hardener). The hardening occurs effectively under the vacuum compression resulting in a high fibre to resin ratio and higher composite strength.

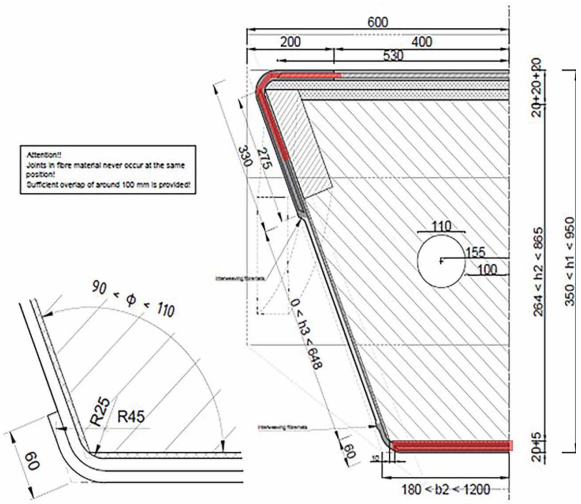


FIGURE 5.15 Part of a Production drawing, (half of section in middle of the bridge, in red/dark is indicated the position the woven fibres. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).



FIGURE 5.16 Bridge beam during Vacuum injection. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

Figure 5.16 shows the injection of the bridge beam (in top down position). In the dark green coloured areas, between the yellow injection canals, the resin has already penetrated the fibres. After the vacuum injection and the hardening, the bridge beam was turned 180 degrees and then cured at a temperature of approximate 50 Celsius for a 36-hour period using electrical air heaters. The bridge rail elements were then mounted and lastly, to prevent moisture accessing the structure over time, a coating system was applied.

§ 5.5 Structural behaviour of the bridge

§ 5.5.1 Load test after production, installation

Before the installation on site, the bridge has been tested as part of the construction permit application process on October 16th at the production facility. During a calibration test with water tanks the live load was gradually increased from 0 kg/m² up to 475 kg/m², in line with the standard requirement for footbridges (5,0 kN/m² minus a 5% reduction based on the length of the bridge). Figure 5.17 gives an impression of the load-test set up. The load has been applied evenly by filling 7 cubical tanks with water. During the test, the deformations of the bridge was measured using LVDT's (vertical and horizontal displacements) at 6 different points. At the same time the strains in the optical sensors were measured and compared to an elastic beam model as well as a FEA model.



FIGURE 5.17 Impression of the load test using 7 water tanks.R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

Figure 5.18 gives the calculated end-values of the vertical deflections, the longitudinal compression and tension stresses and the strains based on a linear elastic model with a Young's modulus of 10.000 MPa in the load test under the maximum load.

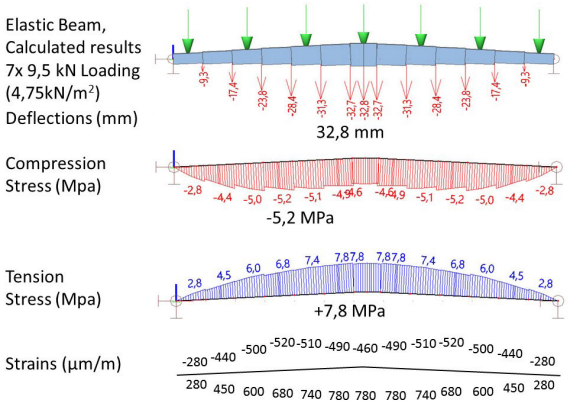


FIGURE 5.18 Elastic Model, calculated vertical deflections, the longitudinal compression and tension stresses and the strains.

The results of the measured LVDT deflections with water tanks filled in steps of approximately 100kg/m² can be seen in figure 5.17, The calculated value of 32,8 mm in the elastic model almost exactly matches the measured value: 33,1 mm. The measured strains in the optical sensors equally showed a very good correlation with calculated strains. The maximum measured strain on the tension side was about 800 μm/m compared to

780 µm/m calculated. On the compression side, the measured strain was about 550 µm/m compared to 520 µm/m calculated, this is within a 2,5% to 6% difference.

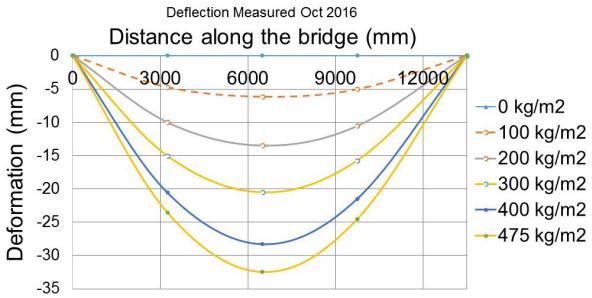


FIGURE 5.19 Results measured LDVT Deflections at Production facility test October 21th 2016.

In figure 5.20 the measured strain deformations are given as function of the applied load over the length of the bridge, again in steps of about 100 kg/m^2. The linear behaviour of the bridge for each sensing point is shown. A relationship between deformation and deflection could be derived and used during the field test to extract the deflection of the bridge during in-situ loading.

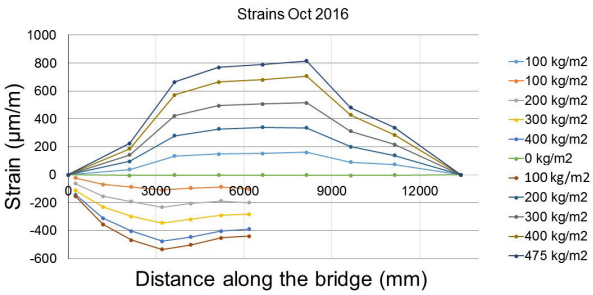


FIGURE 5.20 Strain deformations as function of the applied load.

Figure 5.21 shows the strain development of the same test but now with the strains in the indicated different sensors in relation to the time of an almost two-hour period, while filling the water tanks. The small horizontal parts are a pause in the filling of the water tanks.

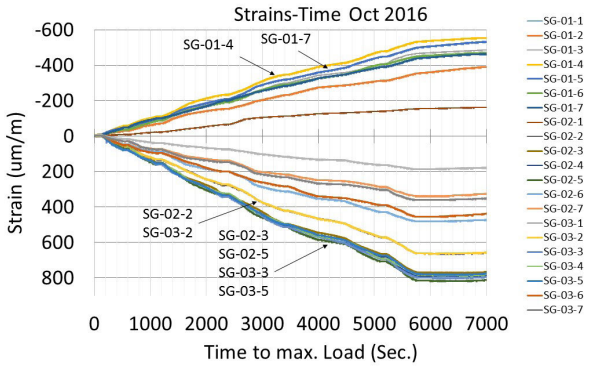


FIGURE 5.21 Strain development versus time during loading; Lines 2 and 3 are positive strains in tension (underside bridge-beam) line 1 shows negative strains in compression (in bridge deck).

The preliminary conclusions from the production facility test were that the bridge's initial (non-long term) behaviour closely follows the expected behaviour of the design models and that the bridge was able to successfully carry its full maximum design load.

§ 5.5.2 In situ measurements in use phase

After preliminary installation in November 2016 the bridge's bearings were slightly raised to prevent the curved bridge beam touching the retaining wall. For this reason, the test performed at 15-12-2016 after the adjustment of the bearings was taken as the initial Zero Measurement. The strains were measured without applying additional loads.

§ 5.5.3 Dynamic test 15-03 2017

On 15-03-2017 a static load test was performed but also a simple dynamic test was carried out. This was done through a simple heel test in the middle of the bridge. A person, standing on his toes and dropping flat to his feet, generated a vertical impulse load. Figure 5.22 shows the measured strains that were invoked in this way versus the time of sensors SG-01-1-7 and SG 01-2-4, both in the middle but at opposite sides, top and bottom, of the bridge.

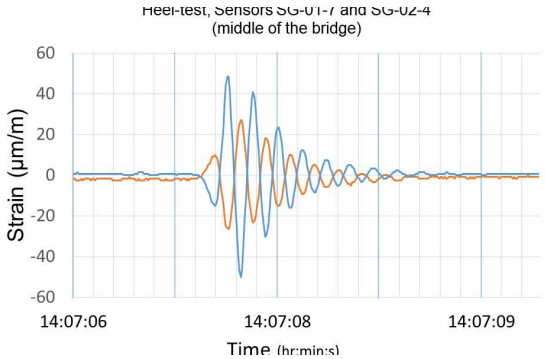


FIGURE 5.22 Strain results versus time of Sensors 1-7 and 2-4 showing eigenfrequency and damping.

Based on these measurements the Eigen frequency of the bridge the first (vertical) vibration mode has been calculated at 6 Hz (lying out of the zone of 2.5 Hz < f_n < 4,6 Hz where discomfort due to larger accelerations might occur). Also the logarithmic decrement δ = 0.58 in a free decay of the vibration and the damping factor ζ =0.093 was calculated using $\delta = \frac{1}{n} ln(\frac{x_0}{x_n})$ and $\zeta = \frac{\delta}{2\pi}$ in which ζ = damping factor, δ = logarithmic decrement, n = number of cycles, x_0' = amplitude of the 1st cycle, x_n = amplitude of the nth cycle. This relatively high damping compared to for example steel or concrete bridges further contributes to a good dynamic behaviour and pedestrian comfort.

§ 5.5.4 Static Test 17-08-2018

The latest test thus far has been the test performed on August 17th, 2018, 22 months after the installation. In this test two water containers have been used to impose a load of a maximum of 2x 10 kN in a cyclic loading test (figure 5.23). Each load cycle step involved loading by filling the water tanks and unloading by releasing the water. The first load cycle has been performed in 3 steps to 2x 6,0 kN. After each load step of 2,0 kN a five minute break was implemented during which time the load was kept constant in order to see if an increase in strains was measured. Figure 22 shows the full 3 loading and unloading cycles versus time. Load cycle 2 was the reloading to 2x 10 kN and the full unloading and cycle 3 was the reloading once more to 10 kN and unloading to 0 kN.



FIGURE 5.23 Cyclic loading test performed one year and ten months after installation. R. Blok, J. Smits et al., Eindhoven University of Technology & Delft University of Technology, (2017).

The strains have been measured using the integrated FBG sensors. On the tension side of the bridge the results have been successfully measured. The measurements in the compression side however showed unreliable results. It is expected that the reason for this is that the sensors were not embedded in woven flax material but in unwoven less structural functioning Hemp material (in the middle of the bridge deck). Therefore, the contact of the glass fibres with its sensors to the non-woven, randomly oriented hemp fibres was unstable. For this reason only the tension side results are shown here. During the test, vertical deflection of the bridge was also measured (middle of the bridge) using an optical device (see also figure 5.24 in the middle).

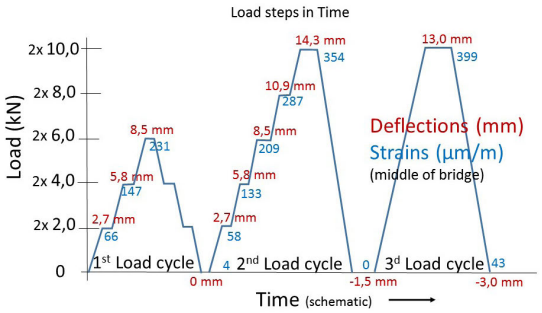


FIGURE 5.24 Three load cycles during the test on 17-08-2018 showing applied load, max strain in middle and maximum measured vertical deflection.

The strain results for the tension line 02 in the first load-cycle to approximately 600 mm water per tank (6,0 kN) and back to zero are shown in figure 5.25. The results of the second cycle are shown in figure 5.26.

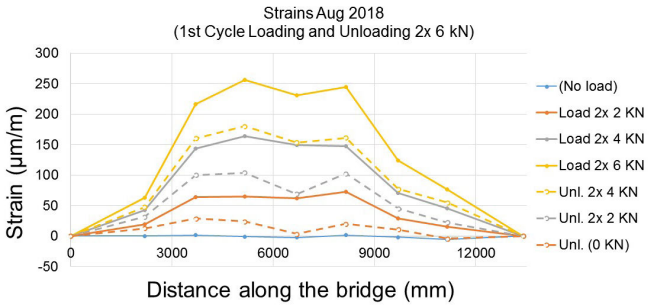


FIGURE 5.25 First Load Cycle; Results of strains in tension sensors along the bridge (Line 2), Loading and unloading to 2x 6,0 kN.

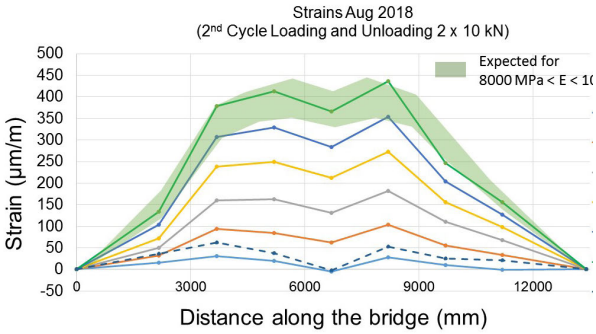


FIGURE 5.26 Second Load Cycle; Results of strains in tension sensors along the bridge (Line 2), Stepwise Loading and unloading to 2x 10,0 kN.

The green bandwidth shows the expected values of the strains calculated using an elastic calculation with a Youngs modulus between 8.000 and 10.000 MPa. While the strains in the middle of the bridge return to 0 there are small remaining strains on the left and right site of the bridge. The dotted line shows these remaining strains. This effect is increased after the third load cycle. Figure 5.27 shows the results of this third load cycle.

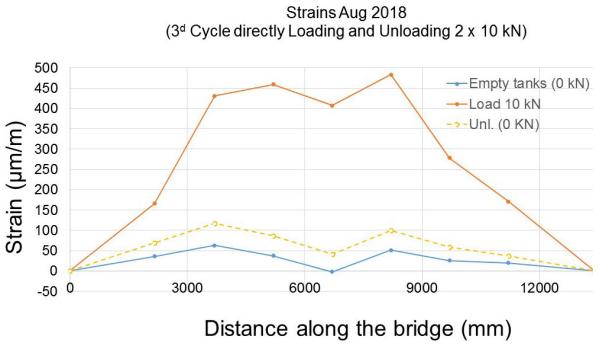


FIGURE 5.27 Third Load Cycle; Results of strains in tension sensors along the bridge (Line 2), Loading and unloading directly to 2x 10,0 k. The dotted line shows the remaining strains.

The second loading to the full 2x 10 kN load show almost 50 µm/m higher maximum strains near the middle of the bridge. Also, the unloading shows remaining overall strains of approximately 50 µm/m near the middle of the bridge. The sensors indicate a process of "yielding", the increasing deformation under the constant load, not fully returning to the starting position of the sensors. The visual deflection measurements however do not show this yielding effect. Figure 5.28 shows the measured deflection in the middle of the bridge. The bridge shows a lasting upward deflection of initially almost 2 mm and at the third cycle an upward deformation of about 3 mm. A cause for this could be sought in small horizontal reactions at the (rubber) bearings of the bridge in loading. Because horizontal movement here is not fully free due some friction, some very small compression arch-like action is possible. Also, during unloading of the bridge there might be some remaining horizontal inward reactions, resulting into small upward bending moments at the bearings. Since the horizontal deformations have not been measured other explanations such as temperature deformation might also be a cause for this phenomenon. The measurements started in the morning and during the testing period the sun gradually warmed the top of the bridge deck. Modelling a temperature difference of 10K between bridge deck and underside in an elastic beam model results also in a 2,8 mm upward deformation in the middle of the bridge. It can therefore be assumed that the influence of the sun may have influenced the variations found in strains and deflections.

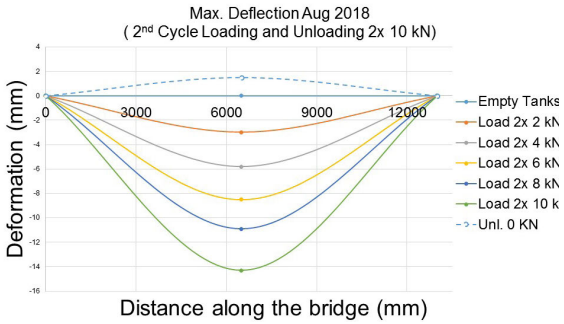


FIGURE 5.28 Measured deflections (in middle of the bridge) during second loading (10 kN) and unloading cycle.

The elastic response to short time loads seems to show a more or less constant or only slightly decreasing material stiffness of approximately 10.000 MPa similar to the elastic beam model. The strains show a good correlation when the additional "yielding" strain is ignored. The calculated maximum strains in tension of 350 µm/m is also measured using the FBG's. Also the maximum strain of about 450 µm/m minus the remaining strains after unloading, 85 and 100 µm/m show a difference of about 365 to 380 µm/m comparable to the calculated value of 350 µm/m. (Maximum reduced modulus of elasticity can be calculated as (350/380) x 10.000 MPa = 9200 MPa) Also the measured deflections of about 16 mm (figure 26) compared to the calculated deflection of 14,6 mm (figure 5.29) support this slight reduction in stiffness.

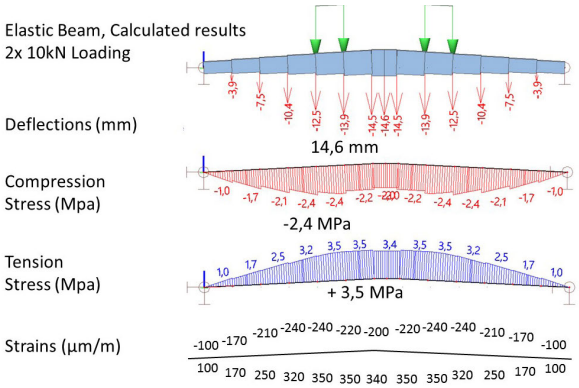


FIGURE 5.29 Elastic Model, calculated vertical deflections, the longitudinal compression and tension stresses and the strains based on Young's modulus 10.000 MPa under maximum of 2x 10 kN: maximum deflection = 14,6 mm.

§ 5.5.5 Long term behaviour

Differencing from the short time more or less elastic loading behaviour however, it could already be expected, from increasing strains under a constant load in the initial load tests and the strains not fully returning to 0 after unloading, as well as from the performed creep tests that the bridge itself would also show creep behaviour. The measurements conform this creep behaviour. Figure 5.30 shows the strain measurement results of the middle sensor (SG02-4) over a 20,6-month period. It compares the strains of the different tests in time. The strains show a considerable increase in time, indicating that the bridge shows considerable creep deformation. It appears that the creep process has not yet come to an end, despite the relative low stress levels of the long-lasting self-weight of the structure (maximum 2,1MPa in compression and 3,3 MPa in tension). The dotted line shows an expected behaviour however further tests are needed to confirm this.

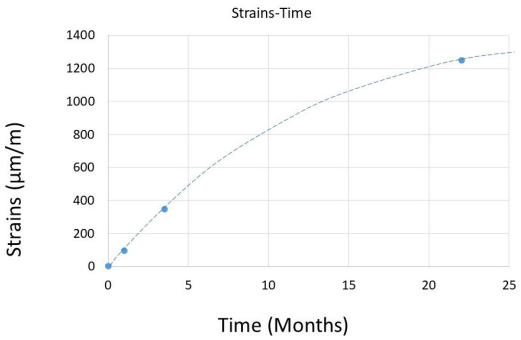


FIGURE 5.30 Strain measurement results of unloaded bridge (only self-weight) of 5 measurements in time.

Calculated from these strains the deformation in the middle of the bridge is now estimated at 51 mm. In the design stage the creep deformation (based on a calculated $E_{mean,fin} = E\ mean/(1 + k_{def})$ with a $k_{def} = 0,8$ was estimated at approximately 15 mm. The measured and calculated creep therefore is much larger than expected from the initial creep test results and also this creep deformation has most likely not reached its final value. For future use of NFRBP as a load bearing material for footbridges, a longer Service Life needs to be achieved. Therefore, the creep deformation needs to be further limited and kept within bounds.

§ 5.6 Life Cycle Assessment

To achieve complete insight over the environmental impact of the bridge, a literature-based LCA [8–13] focusing on the material production phase, the use phase and the end of life scenario, has been performed. The assessment has been based on the environmental impact over eight impact categories listed in ISO/TR 14047:2003: abiotic depletion potential (ADP), global warming potential (GWP100), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), and terrestrial ecotoxicity potential (TETP).

To achieve a clear comparison between the environmental costs of the different materials of the bridge, the LCA data shown in Table 4 have been translated into environmental cost impact (ECI) values, shown at the bottom the table. The ECI values, measured in Euros, balance the environmental impact categories by using shadow cost factors [14] which allow for adding the impact categories into one value.

§ 5.6.1 Production

The first step has been to determine the impact of the main raw constituent materials of the bridge individually in terms of their production. The materials that have been considered in this part of the analysis were the flax fibres, the hemp fibres, the bio-based epoxy resin, the PLA foam core, the cork layer, the coating and the anti-slip layer. Calculating the material quantities used for constructing the bridge (table 5.3) and linking them with the LCA data (table 5.4), has revealed the actual degree of environmental impact for the total of materials used to build the bridge (figure 29).

TABLE 5.3 quantities of materials used to construct the bridge

Material	Flax 2x2 twill (400g/m2)	Hemp non-woven mat (380g/m^2)	Bio-based epoxy	PLA (35 kg/m3)	Paint (125g/m^2)	Antislip layer (4,5kg/m^2)
Weight [kg]	136.53	84.10	661.89	247.10	11.65	75,69

Production of flax and hemp fibre is a result of a series of agricultural and fibre-processing operations. A typical production cycle consists of several stages, beginning with soil preparation and planting of the seed until harvesting, which is followed by processes such as retting, hackling and spinning. A number of these stages can be employed though by a wide range of different techniques which may vary in terms of energy demand. Once the fibres are spun into yarns, then technical textiles, mats and apparel fabrics are being produced by being either woven, knitted or processed through other techniques. Environmentally weak points of the production of flax and hemp fibre are mainly linked with the extensive use of chemical fertilizers and pesticides based on nitrogen, phosphorus and potassium. High nitrate and phosphate emissions contribute to increased eutrophication in local water-bodies and soil as these elements become main nutrients for algae growth. Subsequently, major deterioration of water quality results in the loss of aquatic life and hence disruption of the ecosystem.

TABLE 5.4 LCA per kg of the main constituent materials of the bridge8- 13

Impact category	Units	Hackled flax, 1kg (Duigou, Davies, & Baley, 2011)	Hemp mat, 1kg (Rosa et al., 2013)	Bio-based epoxy SuperSap, 1 ton (Rosa et al., 2013)	Corn based PLA 1kg (Environ-mental factsheet: Polylactic acid, 2016)	Spray painting, 1 kg (MRPI, 2013)	Petroleum based epoxy resin, 1 ton (Rosa et al., 2013)	stone chippings, 1 kg (Benelux Bitume & VBWAsfalt, 2005)
ADP	Ab eq.	1.70E-03	4.00E-03	0.01	-	0.03	59.4	1.50E-04
GWP100	CO_2 eq.	-14	0.531	4079	0.6-3.2	2.4	6663	2.10E-05
ODP	CFC-11 eq.	2.40E-08	6.88E-08	0	4.0E-10 -3.6E-07	1.40E-07	1.26E-06	5.10E-05
POCP	C_2H_4 eq.	7.30E-05	-	-	6E-04 -1E-03	0.12	-	0.02
AP	SO_2 eq.	2.20E-03	2.60E-03	25.44	7.3E-03 -3.8E-02	0.014	40.3	3.30E-03
EP	PO_4 eq.	1.40E-03	6.00E-04	6.9	1.8E-04 -7.5E-03	1.60E-03	6.6	2.50E-04
HTP	1.4-DCB eq.	0.215	0.136	545.17	7.50E-08	5.7	490.44	3.00E-03
FAETP	1.4-DCB eq.	0.059	0.0571	66.39	-	0.83	246.5	7.80E-04
MAETP	1.4-DCB eq.	-	131	-	0.03	45	-	-
TETP	1.4-DCB eq.	8.70E-03	1.52E-03	228.63	-	0.036	29.1	3.10E-05
ECI	€	0.0265	0.0701	0.4326	0.1597	0.9798	0.6070	0.0633

The use of mechanical agricultural operations and fibre extraction processes increase the energy consumption while extensive land use of agricultural productions is another factor that adds on the environmental impact of the fibre. Table 4 shows the environmental impact of hackled flax fibres that have been cultivated and processed in France. The negative sign of the total value is due to the negative Global Warming Potential (CO_2), which is a result of the consumption of CO_2 by plant fibres.

Regarding the bio-based resin, SR Greenpoxy56 has been used in combination with the non-bio-based hardener SD 4770 produced by the same company. Although up to 56% of the molecular structure of Greenpoxy has been derived from plants, the combined product, due to the hardener, drops to a total bio-based content of 43%. The unavailability of LCA data on Greenpoxy56 which has been used in the bridge has directed the research into data from a similar bio-based resin available in the market. Therefore, the bio-based epoxy SuperSap, which has a 37% bio-based content and is produced by Entropy resins, has been used as an alternative in the present analysis as LCA data on SuperSap are available.

The LCA has revealed that the epoxy resin is the highest total contributor in the total environmental cost of the bridge, while the painting has the highest relative costs per kg. According to Rosa et al. [9] global warming potential presents the highest values while acidification potential and human toxicity follow with significant environmental impact, compared to the other materials.

PLA foam, contrary to fossil fuel-based foams, consists of natural raw resources. The main two constituent products that synthesize polylactic acid are sugars, such as glucose or lactose, and Lactic acid which is produced by the fermentation of sugars based on biomass (starch, sugarcane, corn). The environmental impact data that has been used in table 4 concerns foam based on corn.

Concerning the protection of the composite laminate from moisture, UV light and other harmful environmental factors, the application of a layer of coating has been essential. Paint typically consists out of solvent, pigment, resin (binder) and additives. Negative environmental impact of paint is mostly linked with the emission of volatile organic compounds (VOCs) during the drying phase, causing excessive formation of ozone, a highly toxic component which increases human health risks. To reduce these harmful emissions, less-VOC or no-VOC products are currently becoming available in the market.

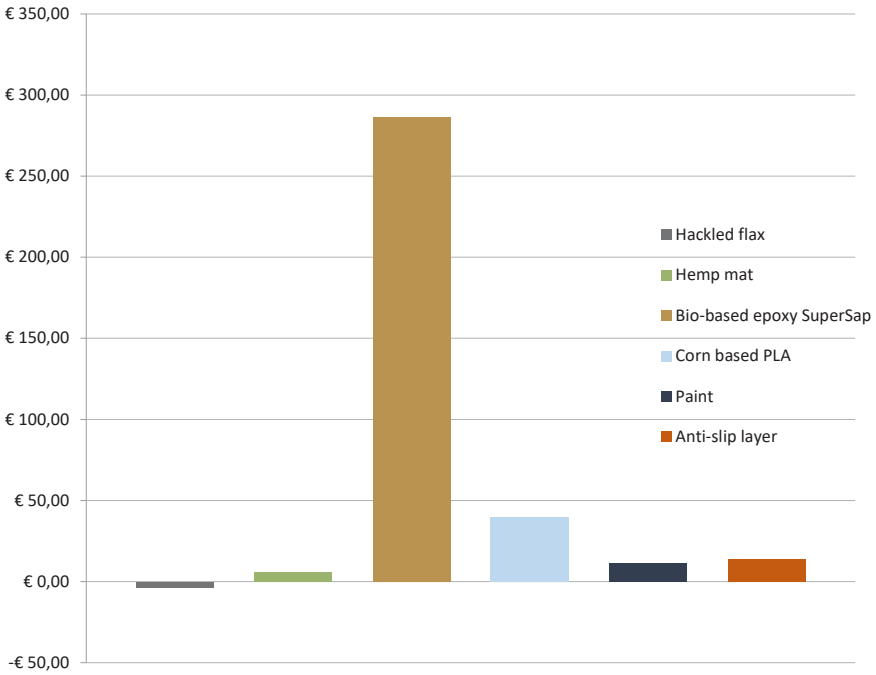


FIGURE 5.31 Environmental cost impact for the total material used in to build the bridge.

The anti-slip layer that has been applied for safety on top of the walking surface is composed out of a two-component epoxy system combined with grains (Mandurax). The LCA data that has been used for the grains refers to stone chippings, which are used in road construction for providing roughness to the asphalt [12]. The composition of the chippings has been based on a combination of different types of stones such as gravel and granite. The data includes transportation of the quarried raw material from the mining area, crushing into finer particles, washing and transportation to the asphalt manufacturer.

§ 5.6.2 Use phase

The environmental impact of the use phase of the structure focuses on the maintenance of the bridge during a service life of 50 years. Maintenance of the coating has been estimated to occur every 12,5 years for local surface deterioration areas while it has been suggested that the coating is to be totally renewed every 25 years (BECO 2013). The contribution of coating maintenance to the environmental impact of the bridge during its service life is € 11,42

Similarly, the anti-slip layer has been assumed to be renewed once during the 50-year life time. During that process, a new layer of grains mixed with an epoxy resin will have to be applied on the original walking surface after it is cleaned from remaining parts of the first layer. The addition of the new layer will add an environmental cost of € 13,94.

§ 5.6.3 End of life scenario

As bio-based composites are relatively new materials in the building industry, alternative end-of-life scenarios are still at the level of research. The most common assumption is that energy will have to be recovered by incinerating waste bio-composites. Nevertheless, the material offers recycling potentials that are currently under development.

A chemical recycling method that aims to detach and reuse the resin and the fibres is currently under examination by the Center of Expertise Biobased Economy in the Netherlands. The method performs solvolysis reactions on carbon fibre-reinforced composites which results in the separation of the two components [13]. The subtracted materials offer possibilities for down-cycling as they lose part of their initial properties during the chemical process.

Considering the experimental character of the bio-based composite bridge, a convenient and productive way to end its service life could be the continuation of further research through actual testing until failure on the bridge. The segmentation of the structure in units and the examination of these by different institutions could bring fruitful results in regard to reuse and recycling solutions of fibre-reinforced polymer structures.

§ 5.7 Conclusion

The starting goal of the project, namely to design and build a bio-composite bridge structure with a maximum bio-based content and monitor its behaviour in the use phase has proven to be successfully achieved. The conducted research on the NFRBP footbridge has enlarged the overall knowledge and experience with the design, production and use of a NFRBP footbridge structure.

The use of Fibre Brag sensor techniques in the bridge proved to be largely successful. The sensors applied in the Woven Flax material on the tension side are still operating reliable without problems. The sensors applied in Non-Woven Hemp fibre composite (the compression side of the bridge) were less successful. After the initial measurements these sensors gave unreliable results and at the last measurement session the connection did not work. In hindsight it would have been advisable to use also on the compression side two senor lines and to incorporate these lines in the woven Flax fibre composite materials instead of in the less structural middle part of the deck (with Non-woven hemp fibres). The strain measurement results of the bridge in use proved to be consistent with the measured material behaviour in laboratory tests. The long-term creep behaviour measured in the bridge proved to be larger than expected from laboratory creep tests. For future Bio-composite bridges the material behaviour in creep needs be improved.

The LCA of the finalized footbridge proved a useful tool to determine the overall environmental impact of the bridge. It also demonstrated that there is still room for improvement on the material side of bio-composites. The LCA has proven that the one ingredient of the bridge that is responsible for the vast majority of the total environmental impact is the (semi-) bio-resin. Part of this finding can be explained by the absence of LCA data for the SR Greenpoxy56 resin that was used. The bio-resin that was used instead to determine the environmental impact has a bio-content of 37%, whereas the Greenpoxy that we used has a 56% bio-content. It is also notable that the non-biological hardeners that were used for the curing constitute a substantial volume amount of the combined product, making its bio-content drop from 56% to 43%. It is therefore necessary to conduct further research into bio-resins as well as bio-hardeners to further decrease the environmental impact of NFRBP structures.

Acknowledgments

This Bio-based composite footbridge project research has been made possible under a so called 3TUlighthouse project funding. The project team members were: Eindhoven University of Technology (Project-leader), Delft University of Technology, the company NPSP BV, and the Centre of Expertise Bio-Based Economy, Breda, Netherlands. Because of close cooperation with the Bio-based bridge research project, financed through the Dutch Stichting Innovatie Alliantie (SIA RAAK) additional funding for the fabrication of a full footbridge became possible and results from this project could be incorporated. And last but not least, the Bio-based composite footbridge could not have been built without and the help of many students.

References

[1] Geldermans, B., Luscuere, P., Jansen, S., Tenpierik, M. (2016). Beyond Cities: Materialen, producten & circulair bouwen. *TVVL Magazine*. 45(1): 22-25.

[2] UNFCC Paris Climate agreement (2015). *Adoption of the Paris agreement*.

[3] NOW Dutch national research agenda (2016). *Theme Energy and raw materials: Circular economy.*

[4] Andersons, J. (2011). *Tensile strength model of UD flax fiber reinforced polymer composites*. 4th International Conference on Experiments/Process/System Modeling/Simulation/Optimization 4th IC-EpsMsO Athens, Greece, Volume: Vol. 2, pp. 620-625

[5] Al-Bahadly, E. (2013). *The mechanical properties of natural fibre composites*. Faculty of Engineering Swinburne University of Technology. Doctoral Dissertation.

[6] Zini, E., Scandola, M. (2011). Green composites: an overview. *Polym Composite;32*(12):1905–15. doi:10.1002/pc.21224.

[7] FBGS.com. (2018) Optical Fibre Bragg Grating sensor technology (FBG). Retrieved December 1, 2018, from http://www.fbgs.com/technology/dtg-technology/

[8] Le Duigou, A., Davies, P., Baley, C. (2011). Environmental impact analysis of the production of Flax Fibres to be used as Composite Material Reinforcement. *J. Journal of biobased materials and bioenergy*. 5: 1-13

[9] La Rosa, A.D., Recca, G., Summerscales, J., Latteri, A., Cozzo, G., Cicala, G. (2014) Bio-based versus traditional polymer composites. A life cycle assessment perspective. *J. Journal of cleaner production*. 74: 135-144

[10] Matos, C., Cristobal Garcia, J., Aurambout, J.P. (2015). Environmental factsheet: Polylactic Acid. *Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1*. European Commission. Joint Research Center. 35-38

[11] MRPI Stichting Milieu Relevante Product Informatie. (2012). *data gevel- en dakbekleding*. (In Dutch)

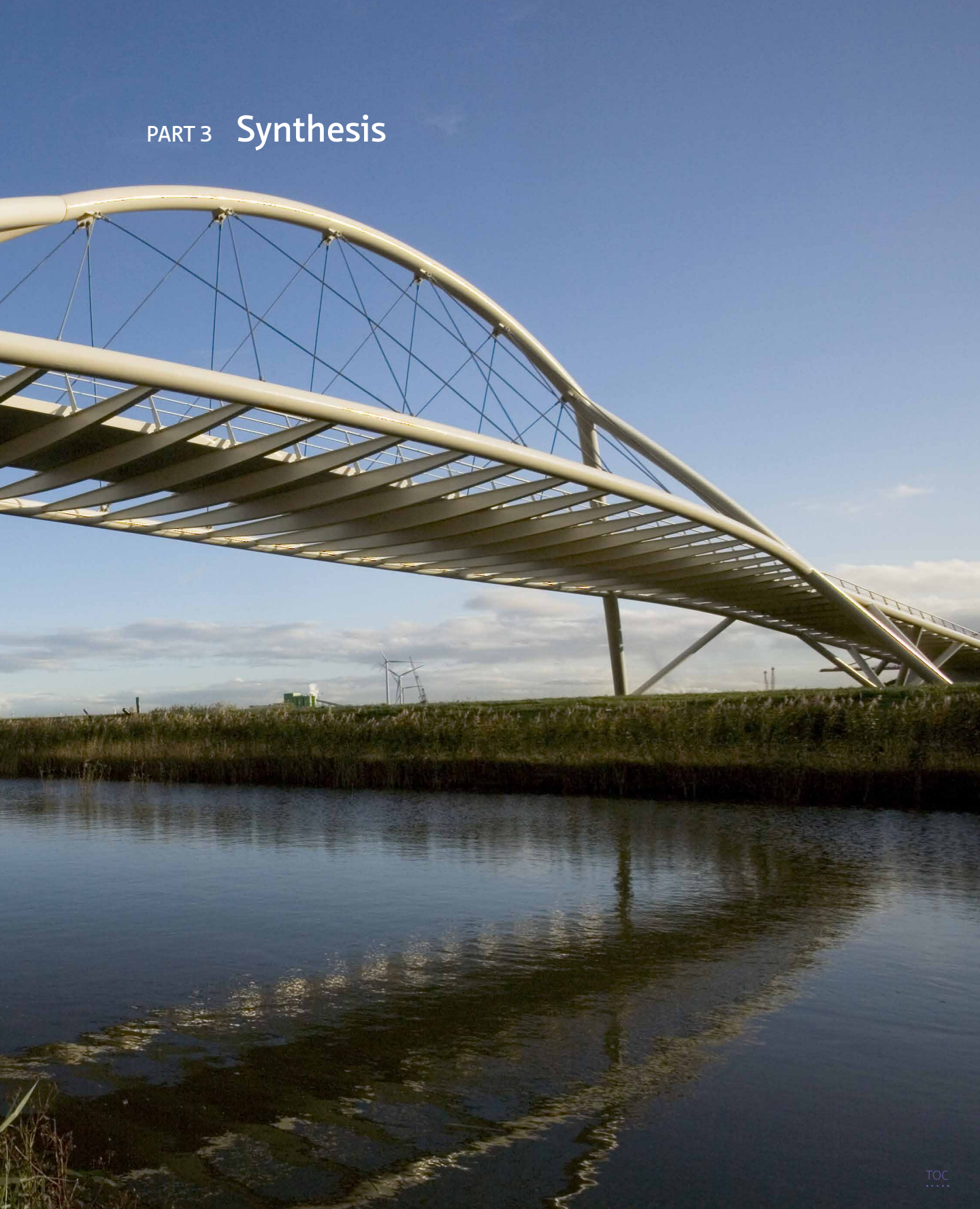
[12] Benelux Bitume, VBWAsfalt. (2005). Productie van Steenslag. Economische, milieu, maatschappelijke en technische verwegingen bij de keuze van verhardingsmaterialen. (In Dutch)

[13] Dauguet, M., Mantaux, O., Perry, N., Zhao, Y.F. (2015). Recycling of CFRP for high value applications: Effect of sizing removal and environmental analysis of the Super Critical Fluid Solvolysis. *J. Procedia CIRP*. 29: 734-739

[14] Klijn-Chevaleriasa, M., Javed, S. (2017). The Dutch approach for assessing and reducing environmental impacts of building materials. *J. Building and Environment*. 111: 147-159.



PART 3 Synthesis





6 Discussion and Conclusions

In the previous four chapters design considerations for bridges have been identified at the four principal scale levels of the design; the scale of the landscape and the city, the scale of the bridge itself, the scale of the detail and at the scale of the composing material and the material properties. This chapter provides an integrated discussion and conclusions on the broad field of bridge design as it is outlined in the main body of this dissertation. The following chapter, Chapter 7, presents the recommendations for future research.

§ 6.1 Integrated, Integral and Valued bridges

The objective of the research is:

To identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, integrally-designed and that are valued by society.

The objective of the research has been addressed in the theoretical framework of this research. Through the review of numerous projects from my own practice, as described in chapters 2 to 5, it has been demonstrated that the objective has been met. By identifying design considerations on four levels, namely the level of the landscape, on the level of the bridge, on the level of the detail and on the level of the material, it has been demonstrated how an overall approach to well-integrated, integrally designed and valued bridges can be achieved by addressing each of these scales of the design in turn. The demonstration of how the objective has been met can be found in the subsequent addressing and answering of the six research questions.

§ 6.2 Regional Identity

Research question 1 is:

What design considerations can be identified for bridges at the scale level of the landscape or of the urban texture, and how can bridges fulfil social, cultural and regional requirements and strengthening regional identity?

This question has been answered in chapter 2. This chapter identifies ways to strengthen the regional identity through means of civil structures such as bridges. In my experience the best approach to designing bridges within a landscape is to start from the context, without making use of neo-vernacular methods. The design of a new bridge is a powerful tool to strengthen the local identity. This theory is demonstrated through some of the authors' projects in Zaanstad and in Rijssen. Properties as scale, orientation, rhythm, articulation, layering and partitioning of the design are the designers' tools to make a design fit the context. To achieve a contextually aware design the architect must think from different perspectives, both literally and figuratively. The obvious perspectives are that of the driver, the cyclist, the pedestrian, the skipper or the badger that passes on or underneath our bridges. But on a more abstract level

we need to think from the point of view of the genius loci, the client, the tourists and most important of all, the people who live nearby and will use our bridge every day. My observations from the current practice of bridge design is that this first step of showing sensitivity to the context and of catching the essence of a place is often forgotten. The biggest trap for a bridge designer is to focus too much on the object itself, to approach the design as if it were a car or a chair. However, cars and chairs are objects that are not defined by their setting, bridges on the other hand can make or break a place.

§ 6.3 Form follows Force

Research question 2 is:

What design considerations can be identified for the design of a bridge at the scale of the object itself, and how can architectural and structural symbiosis in the design be achieved?

This question has been answered in chapter 3 through the review of different bridge design methodologies as employed by the author in the design of his projects over a period of two decades. It is my conclusion that in order to achieve symbiosis between architecture and structure in integral bridge design architects and structural engineers must be willing to overcome the current division between the work of the architect and the work of the structural engineer and get rid of the classical hierarchy.

Furthermore I conclude that a self-contained form of bridge design that can be described as 'Form follows Force' is one possible way to design a bridge. For this approach, the designers need to observes a degree of self-restraint to stay within the boundaries of the forces at play. For this, a bridge design must follow the laws of static, allowing minimal manoeuvre space for frivolity. This way each design visualises its own display of forces, showing nothing more than itself.

At the same time it is important to acknowledge that a bridge design cannot be simplified as a mere display of forces. A coherent design is just as much influenced by thorough response to the boundary conditions imposed by the context, the choice of material, the building process and the maintenance and financing of the bridge. A beautiful optimization design has little added value to society if it is impossible to build, maintain or finance.

Another conclusion is that nowadays the need to carry out experiments and physical tests with scale models is put into question with the ability to use the computer as a tool for optimization and a way to search for new forms. But we must always ask ourselves how useful the computer really is. In an interview with Juan Maria Songel in 2010 Frei Otto stated "The computer can only calculate what is already conceptually inside of it; you can only find what you look for in computers. Nevertheless, you can find what you haven't searched for with free experimentation.". Although the tools have changed over the last 18 years, the methodology and the design parameters have remained the same.

Finally, I conclude that much like design methods in the pre-computational period, computational design does allow for intuitive design. Through parametric models and graphic scripts, an interactive design process can be created that is open to both architects and structural engineers. When applied right, parametric design can allow for exchange of disciplines in a multidisciplinary process. Also, a parametric model allows control over aspects that are hard to influence in a physical way.

§ 6.4 Fibre Reinforced Polymer bridge design

Research question 3 is:

What design considerations can be identified for the design of a bridge at the scale of the detail and that of the materialization?

With the following sub-question:

What design considerations can be identified to the use of Fibre Reinforced Polymers, both as a structural and as a non-structural application, in bridge design?

These questions have been answered in chapter 4. By reviewing the use of Fibre Reinforced Polymers (FRP) in architectural and structural bridge design, design considerations have been formulated. The use of FRP in bridge engineering has grown significantly over the past two decades. Applications vary from simple deck elements to pultruded members, and even entire load-bearing structures made of FRP are now feasible. Attracted by structural and economic benefits such as weight reduction and cost saving on maintenance, engineers have developed construction solutions using FRP that compete with conventional structures. In the field of architecture,

the recent establishment of FRP as a building material for bridges has resulted in numerous successful projects in which FRP serves both architectural and aesthetic purposes. Architects and engineers have demonstrated the use of FRP as a cladding material around decks, both in a simple form or translucent and combined with light. They have also demonstrated more daring structural applications of FRP, including a load-bearing shell, folding structures, and non-standard curved monocoque structures. Furthermore, this innovative material has clearly not yet reached its maximum capabilities and requires additional research. In particular, improvement of the environmental impact and the embodied energy of FRP by the substitution of renewable raw materials (natural fibers, bio-based resins) for conventional materials should be further explored. Finally, FRP needs to be introduced as a mature material in our educational system so that future architects are educated in how to do justice to the unique material properties and fabrication methods of this material.

The current practice of bridge design could be much improved if clients and designers alike would focus less on immediate building costs, and instead pay more attention to long term benefits of innovative materials such as FRP. If this were to become common practice the total life cycle costs of a bridge could vastly improve and our bridges will become more sustainable.

§ 6.5 A bio-composite footbridge

Research question 4 is:

What design considerations can be identified for the design of a bridge at the scale of the chosen materials, and of the material properties, that constitute a bridge?

With the following sub-question:

Can a fully bio-composite footbridge be produced form natural fibres and bio-resins?

These questions have been answered in chapter 5. The starting goal of the project, namely to design and build a bio-composite bridge structure with a maximum bio-based content and monitor its behaviour in the use phase has proven to be successfully achieved. The conducted research on the bio-composite footbridge has enlarged our the overall knowledge and experience with the design, production and use of a bio-composite footbridge structure.

The strain measurement results that were the result of the in-situ monitoring of the bridge in use proved to be consistent with the measured material behaviour in laboratory tests. The long-term creep behaviour measured in the bridge proved to be larger than expected from laboratory creep tests. For future Bio-composite bridges the material behaviour in creep needs be improved.

Finally, the LCA of the finalized footbridge proved a useful tool to determine the overall environmental impact of the bridge. It also demonstrated that there is still room for improvement on the material side of bio-composites. The LCA has proven that the one ingredient of the bridge that is responsible for the vast majority of the total environmental impact is the use of a (semi-) bio-resin. It is therefore recommended to conduct further research into bio-resins as well as bio-hardeners to further decrease the environmental impact of bio-composite structures.

§ 6.6 Durable and sustainable bridge design

Research question 5 is:

What design considerations can be identified to achieve a higher standard of durability and sustainability for bridges?

In order to answer to the above question, we need to formulate a contemporary re-interpretation of the core Vitruvian values as discussed in paragraph 1.2, therefore the discussion is pursued here.

Discussion

The Vitruvian core values from antiquity need to be re-interpreted and supplemented in order to suit modern standards, especially when it comes to key values such as durability and sustainability. Albeit the fact that the building industry is quit conservative compared to other industries such as the automotive or the aerospace industry, new sustainable and durable materials are finding their way into the bridge industry. Yet it is not just a call for sustainability and innovation that is at the birth of new materials and techniques. As with most things the change in the bridge design industry is rather driven by financial aspects. The consequences of the financial crisis and the cuts in maintenance budgets of the authorities have stimulated developments

for new and durable materials. Authorities have started to realise that it is not only the realisation cost of a new bridge that has to be paid out of their budget. Maintenance costs for bridges have increased drastically together with the growing number of (older) bridges since the war. A Life Cycle Analysis (LCA) can help to reduce the environmental impact over the entire lifespan of the design in two ways.

Firstly, life cycle costs can be reduced by designing a bridge in such a way that it will last longer. For a long life span the design must be durable, in other words the bridge must have low maintenance costs throughout its operational life. A good example of new and durable construction materials is Fibre Reinforced Plastic, a lightweight low maintenance alternative for steel. Long life also means that a bridge must be future proof in the sense that the design can accommodate future changes in modality without the need to reinforce or replace the bridge. This last aspect is becoming increasingly important with the introduction of a wide array of electrical vehicles that require a wider profile, wider radii in the curves and provisions for higher speed.

Secondly, the end-of-use phase must be considered. The end-of-use of a bridge is not necessarily the equivalent of the end-of-life. Sometimes, early replacement of a bridge can be required in case it can no longer accommodate the traffic. In this case, a second life for bridges that are still in good enough condition can then become an option. That is why we need to consider the residual value of a bridge before it is removed. A bridge that still has enough residual value can then be reused in its entirety elsewhere, or in case it is a demountable and modular design, parts of that bridge can be reused in a circular process. One aspect that requires additional attention in such cases of re-allocation is the need for a bridge to fit the context. This can be particularly challenging as a design that was made for a specific location does not automatically fit elsewhere in the world.

Apart from these very pragmatic reasons there is also the more ethical call for sustainability. Governments, companies and citizens worldwide have become aware of our responsibility to take care of our planet. Yet, how do you design a sustainable bridge? Unlike the design of a building, there are no issues of thermal insulation or energy balance to be considered, nor are heat exchangers or vegetation roofs in order. First of all, I am convinced that sustainability starts with the making of a good design. The first law for sustainable bridge design would be: "If by its aesthetic quality a design proves to be valued by society then it will be cherished, now and for generations to come, and therefore it is intrinsically sustainable."

The second law for sustainable bridge design would be: "Use your common sense, avoid 'window dressing' and take only those measures that are effective to improve the sustainability of the design." But what are effective solutions for creating true sustainability? The first way is to look at a design and all the materials that are used

through the lens of circularity. The key is to look at the total lifecycle of materials and to try to close these cycles, in other words, to ensure that what remains at the end of the lifespan is equally valuable. First, an efficient bridge design that is optimised for minimal use of material will save resources and building materials, thus minimizing the ecological footprint. We talk about recycling or up-cycling when material properties such as strength, resilience and aesthetics stay the same in a second life. Steel, glass and aluminium are materials that can be recycled time and again without losing their properties. Concrete can be recycled to a certain point as granulate to replace the pebbles in new concrete, a form of down-cycling. For building materials we refer to the technical cycle in which the individual components of a product become the base (or technical nutrition) of a new product. This requires designing according to the IFD method (Industrial, Flexible and Demountable). In this method all the building components are prefabricated elements which can be re-used in another position or for another function and the use of glue and sealing is prevented. By minimizing fixed joints, and working with light building structures our designs can be put together in a fast and effective way. This results into a flexible design, not only flexible in use, but also flexible to the future.

Another effective solution to create sustainable bridges is to consider the energy balance within a project. The building industry is one of the chief producers of CO2 emission; direct emissions from the builders and indirectly by the suppliers. Notably in the design phase the use of energy and the emission of CO2 can be influenced. By choosing the right materials resources can be spared and transportation can be minimized. Lightweight structures, for instance through the use of FRP, can help to minimize the size of the foundation and to reduce the transportation emissions. A very practical way to save on energy and reduce CO2 emission in the building phase is to make use of a closed mass-haul diagram and avoid truckloads of earth.

Moving bridges are a chapter on their own. A moving bridge requires less energy throughout its lifetime if the moving part and the counterweight are properly balanced. Furthermore a well-balanced bridge can operate with simple mechanical installations that are subjected to smaller wearing. Here too we see the introduction of FRP in order to save considerable weight in the moving part of the deck, thus further minimizing the mechanical installations and foundation requirements. The remaining energy demand can be generated from sustainable energy sources such as local solar power or local wind power. Solar energy is practically infinite and widely available. One way of using the power of the sun is by employing asphalt as a heat collector. The accumulated heat in summer time is stored underground and put to work in wintertime to keep the road free from ice and snow. Finally the use of LED technology provides sustainable, functional and aesthetical lighting with a long lifespan.

§ 6.7 The Design Integrator

Research question 6 is:

Will the transformation of the role of the architect as the aesthetical advisor, to the role of the design integrator, lead to well-integrated, integrally-designed and socially-valued bridges?

The answer to the above questions lies enclosed in the findings on the historical role of the architect, the engineer and the commissioning authorities within the bridge design process, as described in paragraphs 1.2 and 1.3. These paragraphs are not part of a published journal paper, therefor the discussion is pursued here.

Discussion

If the mutations in the field of bridge design that occurred over the past 200 years have taught us one thing, it is that the field of bridge design has become far too complex to be embodied by one person, whether it be an engineer or an architect. The role that the master builder played up until the late renaissance, bringing together aesthetic design and building craft into one person, is nowadays fulfilled by a team of specialists. You could say that the integrated design team is the contemporary version of the renaissance master builder. The basis of the ideal team naturally consists of an architect and a chief engineer. Depending on the location and the nature of the bridge the team is completed with experts in various fields such as landscape, urbanism, traffic design, mechanical engineering and geotechnics. The role of the architect within the core team is to safeguard the three core values that were provided by Vitruvius and that should be at the heart of every design task for a bridge: Venustas, Utilitas and Firmitas. It is therefore the role of the architect to securing this equilibrium between Beauty, Utility and Solidity throughout every phase of the design process. This balancing act takes place at all scale levels, from the task of integrating the bridge in the landscape to the task of the design of the main structure and the choice of the right construction materials.

From a multidisciplinary approach to an integrated design approach

On the subject of integrated design it has to be noted that there is a difference between a multidisciplinary approach and integrated design approach. In the first case each discipline acts separately and from its own vested interest, which sometimes conflicts with another actor's interest. Here, instead of an iterative process between the disciplines,

the architect takes the lead in the design and, when his work is done, hands it over to the engineer who in turn is left with little creativity from which the design could have profited. Unfortunately such a drive-through-approach is still often practiced, resulting in ill designed bridges where aesthetics and structure have no symbiotic relation.

What is needed most for good bridge design is an integrated design approach. In an integrated approach we see all disciplines working together from the start in a true holistic approach in order to get the best out of the design. This ideal process asks for professionals that are well versed in the basic principles of both architectural design and structural design and are prepared to step over the boundaries of their own specialism. In the end it is the design that profits from this open attitude.

Over the decades the balance between the architects input and the engineers input in the design process of a bridge has shifted sides more than once. When it comes to designing bridges it is clear that one discipline cannot go without the other. The engineer needs the architect to provide the contextual frame for the design, let's call it the soul of the design. It is this soul that makes it unique for this specific location by reflection on the Genius Loci. Without this soul the bridge design will never be more than a technocrat's solution and people will not attach any emotional value to it. On the other hand the architect needs the engineer to provide the framework in which to conduct his or her architecture. In the best of designs the engineering expression of the solution to a problem becomes the background to the entire design [1]. For a good architect this attitude towards engineering is a conscious philosophical choice.

Introduction of the Design Integrator

The working hypothesis of this research is the assumption that the introduction of a design integrator will lead to better bridges and will increase public support for new infrastructure. If one person could oversee the design process in its entirety by fulfilling the role of design integrator and by defending the design in the public debate, the design process would greatly benefit. The design integrator should not be the omniscient master builder of old, but would instead act as the conscience of the design, the expert who directs and coordinates all design aspects of a bridge.

When we look at other large structures in the public realm, it is noted that the role of design coordinator is not new in the building industry. By far the largest part of manmade structures in the built environment are buildings. For every building design there is already a design integrator in the personification of the architect. For a building the architect oversees the entire design process, including the integration of the structure and of the technical installations.

To bring about such a transition into the field of design of infrastructures, I propose that the role of the architect must be transformed from a mere aesthetical advisor to that of a design integrator. This way the objective of this research: to identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, that are integrally-designed and that are valued by society, can be met.

§ 6.8 Reflection

The path that I have chosen for the writing of this dissertation was that of a review of my own work. It is needless to say that calling this work 'my own' doesn't do justice to the invaluable contribution of the landscape architects, urbanists, civil engineers, material engineers and mechanical engineers that have worked with me for all these years in an interdisciplinary exchange of ideas. Reviewing these projects, sometimes decades later, has helped me to acquire a greater appreciation for these men and women who are all top experts in their field of work. This is notably true for the urbanists and landscape designers whose invaluable contribution to a successful project cannot be emphasised enough. Being an architect and a civil engineer myself, my primary focus used to be on the object of the bridge itself, and not so much on the place it occupies in the landscape or in the city. This fixation on the object is a deficiency that many architects have, and also one that most of them deny having. Working with landscape architects and urban designers literally makes you look at a bridge through a different lens, as a part of a much bigger picture.

Another thing that writing this dissertation has made me realise, is that the making of the design is only half of the story. Selling it to the public is quit something else. What I do differently now, compared to my working methods in the past, is that as an architect and bridge designer I try to take accountability for softer aspects of the job, such as stakeholder management, an ugly word for a valuable thing. What I have realised is something that is actually quite simple: bridges are for everyone. Unlike most buildings that are paid by, and built for, a very select group of people, bridges are built with taxpayers money, yours and mine. This simple fact gives us a great responsibility towards these same people. On the one hand, people do not like their government to overspend tax money on fancy bridges. And yet, when a new bridge is to form part of their own neighbourhood, and is bound to be a part of it for a hundred years to come, it is not hard to explain why we must also strive for quality and good design. Because good design makes people happy and will give people a real sense of ownership for their bridge.

References

[1] Rice, P; Peter Rice: Engineering Profile, AJ 21- 28 Dec. 1983, p31



7 Recommendations

This final chapter closes this dissertation and provides recommendations for future research.

Recommendations

From this research several recommendations for future research follow.

Firstly, it goes without saying that bridges must be functional, strong and durable. However, bridges equally need to be beautiful and elegant, no matter how small or how modest the budget. Bridges are meant to stand in the public realm for a long time, a hundred years or more, and are used by thousands of people on a daily basis. In his TED talk the renowned British engineer Ian Firth says "*Nobody will remember the costs or if a bridge was delivered on time. But if it is ugly it will always be ugly, or just dull. Beauty on the other hand enriches life, it enhances our wellbeing. Ugliness and mediocracy do the exact opposite. We become numb to it. It is like institutionalized large scale vandalism*". That is why every bridge, no matter how small or how modest, deserves our fullest attention when it comes to good design that fits the context.

Secondly, it is for the above mentioned reason that bridge commissioners need to make aesthetics part of the design brief once again. We need to embed design in the day to day working practices of those responsible for programme delivery. For that leadership, integration, collaboration, early engagement, sustainability and a user focus must be part of the planning and delivery of our infrastructure. The recommendation is to establishing independent infrastructure design panels at all levels of governance, to act as a design champion and to prepare new infrastructure design principles. All infrastructure projects should be subject to review and consideration by these independent design panels. Authorities need to invest in design upfront. Upfront investment in concept development and design information minimises risk, providing both quality and cost certainty by reducing information asymmetry in the procurement process. Really successful outcomes can be achieved by reframing the brief to think more broadly about how infrastructure could deliver social, economic and environmental benefits, as opposed to a single fix solution.

Thirdly, it is recommended that for every bridge design a chief architect is appointed to fulfil the role of the design integrator throughout the design phase and the building phases. The role of the architect is not to be the omniscient master builder of old, but instead to be the conscience of the design and to direct and tie all design aspects of a bridge together.

Fourthly, an integrated design approach can greatly benefit form modern computational developments. With the current parametric software it is now possible for all parties involved in the design of a bridge to work together in one single computer model, parametrically programmed to facilitate interdisciplinary exchange of information and with the flexibility to make quick adjustments to the design without having to start all over again. In order to make this work we must find a mechanism that stimulates sharing of information and intelligence.

Fifthly, sustainability can be a driver in bridge design projects when approached as part of a fully integrated design process, but should not be seen as a technological gimmick. Instead, the whole life cycle of a bridge must be addressed through a circular approach. Durability of the composing materials of a bridge, and a focus on the residual value of a bridge and of its components, should be part of every design process.

Finally, the most effective way in the long run to improve integral design skills and to enhance the mutual understanding between architects and engineers is through education. It is therefore strongly recommended to invest in cross-faculty multidisciplinary courses and research in the field of design of bridges and all other kinds of civil structures.

Bibliography

Al-Bahadly, E. (2013). *The mechanical properties of natural fibre composites.* Faculty of Engineering Swinburne University of Technology. Doctoral Thesis.

Albertopugnale.com. (2013). Form-finding – comparison between karamba and kangaroo, Retrieved January 10, 2018, from *http://www.albertopugnale.com/2013/03/29/form-finding-through-numerical-tools-comparison-between-karamba-and-kangaroo/*

Alix, S., Philippe, E., Bessadok, A., Lebrun, L., Morvan, C., Marais, S. (2009). Effect of chemical treatments on water sorption and mechanical properties of flax fibres. *Bioresource Technol;100*(20):4742–9. doi:10.1016/j.biortech.2009.04.067. PMID:19477120.

Andersons, J. (2011). *Tensile strength model of UD flax fiber reinforced polymer composites.* 4th International Conference on Experiments/Process/System Modeling/Simulation/Optimization 4th IC-EpsMsO Athens, Greece, Volume: Vol. 2, pp. 620-625

Appleyard, D., Lynch K., & Myer, J.R. (1964) *The view from the road.* Cambridge Mass: MIT Press.

Avó de Almeida, M. I. (2009). *Structural behaviour of composite sandwich panels for applications in the construction industry.* (master thesis). Universidade Técnica de Lisboa.

Benelux Bitume, VBWAsfalt. (2005). Productie van Steenslag. Economische, milieu, maatschappelijke en technische verwegingen bij de keuze van verhardingsmaterialen. (In Dutch)

Boekhorst, J.K.M.T., Couterier, J.F. & Hoeffnagel, W.J.C. (1986) *Effecten van Rijkswegen op de beleving.* Wageningen: RBL De Dorschkamp.

Buijs, A.E., & Kralingen, R.B.A.S. (2003) *Het meten van beleving. Inventarisatie van bestaande indicatoren en meetmethoden.* Wageningen: Alterra, p 782

Chilton, J. (2000). The engineers' contribution to contemporary architecture, Heinz Isler. London: Thomas Telford Publishing.

Dauguet, M., Mantaux, O., Perry, N., Zhao, Y.F. (2015). Recycling of CFRP for high value applications: Effect of sizing removal and environmental analysis of the Super Critical Fluid Solvolysis. *J. Procedia CIRP.* 29: 734-739

ESCN. European Concrete Award 2010. Retrieved from *http://www.ecsn.net/award/downloads/Concrete_Award_2010.pdf*

Faruk, O., Bledzki, A.K., Fink, H.P., Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Prog Polym Sci;37*(11):1552–96. doi:10.1016/j.progpolymsci.2012.04.003.

FBGS.com. (2018) Optical Fibre Bragg Grating sensor technology (FBG). Retrieved December 1, 2018, from *http://www.fbgs.com/technology/dtg-technology/*

Gautier, H. (1716). *Traité des Ponts, ou il est parlé de ceux des romains & de ceux des Modernes ...* (1st ed.), Paris, France: Chez André Cailleau.

Geldermans, B., Luscuere, P., Jansen, S., Tenpierik, M. (2016). Beyond Cities: Materialen, producten & circulair bouwen. *TVVL Magazine. 45*(1): 22-25.

Granger, F. (2007). *Vitruvius on architecture.* Bakhsh Press.

Grünewald, S., Janssen, B., Schipper, H.R., Vollers, K.J., Walraven, J.C. (2012). Deliberate deformation of concrete after casting. *Structural engineering. ICFF 2012: Proceedings of the 2nd International Conference on Flexible Formwork; 2012 Jun 27–28; Bath, UK. Bath*: University of Bath. P. 132-139.

Houben, F., & Calabrese, L.M. (2003) *Mobility: A room with a view.* Rotterdam: NAi Uitgevers.

Kamerling, J. W. (1969, May 2nd). *Bouwen voor de gemeenschap,* inauguration speech (in Dutch). Eindhoven: Eindhoven University of Technology.

Karbhari, V.M. (2001). Materials considerations in FRP rehabilitation of concrete structures. *J Mater Civ Eng 13*(2):90–7. doi:10.1061/(ASCE)0899-1561(2001)13:2(90).

Klijn-Chevaleriasa, M., Javed, S. (2017). The Dutch approach for assessing and reducing environmental impacts of building materials. *J. Building and Environment.* 111: 147-159.

La Rosa, A.D., Recca, G., Summerscales, J., Latteri, A., Cozzo, G., Cicala, G. (2014) Bio-based versus traditional polymer composites. A life cycle assessment perspective. *J. Journal of cleaner production.* 74: 135-144

Le Duigou, A., Davies, P., Baley, C. (2011). Environmental impact analysis of the production of Flax Fibres to be used as Composite Material Reinforcement. *J. Journal of biobased materials and bioenergy.* 5: 1-13

Maheswari, C.U., Reddy, K.O., Muzenda, E., Shukla, M. (2012). Effect of surface treatment on performance of tamarind fiber-epoxy composites. *ICICEMS 2012: Proceedings of International Conference on Innovations in Chemical Engineering and Medical Sciences;* Dubai, UAE; 2012. p. 16–19.

Majumdar, P.K., Liu, Z., Lesko, J.J., Cousins, T.E. (2009). Performance evaluation of FRP composite deck considering for local deformation effects. *J Compos Constr 2009;*13(4):332–8. doi:10.1061/(ASCE)CC.1943-5614.0000008.

Matos, C., Cristobal Garcia, J., Aurambout, J.P. (2015). Environmental factsheet: Polylactic Acid. *Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1*. European Commission. Joint Research Center. 35-38

McCluskey, J. (1992) *Roadform and Townscape*. Architectural Press. p 155

MRPI Stichting Milieu Relevante Product Informatie. (2012). *data gevel- en dakbekleding.* (In Dutch)

Nguong, C.W., Lee, S.N.B., Sujan, D.A. (2013) A review on natural fibre reinforced polymer composites. *World Acad Sci, Eng Tech. 73*:1123–30.

Nijenhuis, W. & van Winden, W. (2007) *De diabolische snelweg*. Rotterdam: 010 Publishers

NOW Dutch national research agenda (2016). *Theme Energy and raw materials: Circular economy*

Overdijkink, G.A. (1941) *Langs onze wegen*. Amsterdam: Allert de Lange.

Palladio, A. (1570), *Quattro Libri dell'Architettura*. Venice, Italie: Domenico de Franceschi.

Petras, A. (1999). Design of Sandwich Structures (doctoral thesis). University of Cambridge.

Rice, P; Peter Rice: Engineering Profile, AJ 21- 28 Dec. 1983, p31

Rietbergen, D., Vollers, K.J., (2008). A method and apparatus for forming a double-curved panel from a flat panel. *European patent EP* 20080741664. 2008 Apr 24.

Schipper, H.R., Janssen, B. (2011). Curving concrete—a method for manufacturing double curved precast concrete panels using a flexible mould. *Design and construction. IABSE-IASS 2011: Proceedings of the Joint Symposium of the International Association for Bridge and Structural Engineering (IABSE) and the International Association for Shell and Spatial Structures (IASS)*; 20–23; London, UK. London: Hemming Group Ltd. p. 8.

Schöne M.B., van den Toorn, M.W.M. & Coeterier, J.F. (1997) *Autosnelwegen in het Landschap; beleving door weggebruikers*. Wageningen: DLO-Staring Centrum.

Scitovsky, T. (1976) *The joyless economy, an inquiry into human satisfaction and consumer dissatisfaction*. Oxford: Oxford University Press.

Smits, J. (1999). Twee bruggen Venneperweg. Amsterdam: Haskoning

Smits, J. (2013). Bridge design 2.0: recent developments in the field of integrated, sustainable and durable bridges. *Structural design. ICSA 2013: Proceedings of the 2nd International Conference: Structures and Architecture;* Guimaraes, Portugal. p. 1–10.

Songel, J. M., (2010). 'A Conversation with Frei Otto'. Princeton Architectural Press: New York.

TED. (2018, April). Ian Firth: Bridges should be beautiful [Video file]. Retrieved from *https://www.ted.com/talks/ian_firth_bridges_should_be_beautiful*

UNFCC Paris Climate agreement. (2015). *Adoption of the Paris agreement.*

Van Blankenstein E. (2009). *Bruggen in Nederland (1940–1950). Vernieling en herstel*, in Dutch. Zuthphen: Walburg Pers.

Veltkamp, M., Peeters, J. (2014). Hybrid bridge structure composed of fibre reinforced polymers and steel. *Struct Eng Intl;24*(3):425–7. doi:10.2749/101686614X13844300210515.

Virlogeux, M. (1996). Structural and Architectural Design of Bridges. *Structural Engineering International 6*(2), 80-83

Walter, R. (1996). Engineers, Architects and Bridge Design. *Structural Engineering International 6*(2).

Zalewski, W., & Allen, E. (1997) *Shaping Structures: statics*. New York: John Wiley & Sons, Inc.

Zini, E., Scandola, M. (2011). Green composites: an overview. *Polym Composite;32*(12):1905–15. doi:10.1002/pc.21224.

Curriculum Vitae



Joris Smits, MSc, born November 28 in Amsterdam

As an architect, my career has been strongly influenced by my civil engineering background. I studied at the Technical University in Delft where I combined the studies of Civil Engineering and Architecture. I graduated in both in 1994 and thus became an architect as well as a civil engineer. I believe that it is my understanding of structural design that has profoundly defined me as an architect.

In the field I have been widely recognized as an engineering architect due to the design of a wide range of structural works. With my projects I have won prizes all over the world. My designs are rational yet expressive. My fascination is to give shape to the forces at play. In this manner I have designed over three hundred of the finest bridges and buildings. Since 2012 I have combined my architect's practice with a lectureship at Delft University of Technology, faculty of Architecture, Structural Design.

I see it as my mission to bridge the gap that so often exists between architects, engineers and clients. After all, wasn't it Vitruvius who taught us that a structure can only be of truly lasting value if it respects the balance between aesthetics, structure and function? This adage is still very valid today and constitutes the crux of my professional work.

Education

2017 - 2019	**PhD candidate** - The Art of Bridge Design - Faculty of Architecture and the Built Environment, Delft University of Technology
1990 - 1994	**Master of Science** - Faculty of Architecture, Delft University of Technology
1987 - 1994	**Master of Science** - Faculty of Civil Engineering, Delft University of Technology
1984 - 1987	**Preuniversity education** – De Breul, Zeist, the Netherlands
1983 - 1984	**Preuniversity education** – Collège Clapparède, Geneva, Switzerland
1980 - 1983	**Preuniversity education** – Cycle d'orientation de la Florence, Geneva, Switzerland
1979 - 1980	**Preuniversity education** – École Internationale, Geneva, Switzerland

Working experience

2012 - to date	**Lecturer and Researcher** at the chair of Structural Design, Faculty of Architecture, Delft University of Technology, the Netherlands
1997 - to date	**Architect and Bridge Designer** at Royal HaskoningDHV, the Netherlands
1994 - 1997	**Architect** at Cie Architects, Amsterdam

Boards & other

2014 - to date	Scientific Board member Delft, Infrastructures & Mobility Initiative
2012 - to date	Board member of the Dutch Bridge Association
2018 - to date	Head of the Bridge Design Group at Delft University of Technology
2012 - to date	IABSE; Internat. Assoc. for Bridges and Structural Engineering

2012 - present	IASS; International Association for Shell and Spatial Structures
2018	Moderator at Symposium Fiets+Voetbruggen, NBS
2017	Jury Member at architectural competition cycle bridge Amstelveen
2017	Moderator at Symposium Fiets+Voetbruggen, NBS
2016	Moderator at Symposium Fiets+Voetbruggen, NBS
2016	Moderator at Symposium Bruggendag, NBS
2015	Keynote speaker at CompIC Amsterdam,
2014	Moderator at Symposium Bruggendag, NBS
2014	Jury Member at student competition cycle bridge Delft
2011	Keynote speaker at Concrete Bridge Conference Oxford
2006	Keynote speaker at Lightweight Structures, Rotterdam

Journal Papers

Smits, J., & van der Hoeven, F. (2015). A bridge with a view, a view with a bridge. Identifying design considerations for bridges to strengthen regional identity. Research In Urbanism Series, 3(1), 135-158. doi:10.7480/rius.3.833

Smits, J. (2016). Fiber-Reinforced Polymer Bridge Design in the Netherlands: Architectural Challenges toward Innovative, Sustainable, and Durable Bridges Engineering 2 (2016) 518–527. Elsevier LTD

Smits, J., Eigenraam, P., Gkaidatzis, R., Visser, D.R., Wong, K. And Wassermann-Fry, S. (2018). Shaping Forces; Review of two bridge design methodologies towards architectural and structural symbiosis. J.IASS, Vol 59 (2018), No 2 June n. 196

Blok, R., Smits, J., Gkaidatzis, R., Teuffel P. (2019). Bio-composite footbridge; design, production and in situ monitoring . Accepted for publication with minor revision on 12 March 2019.

Conference Papers

2017 IABSE Vancouver, Shaping Forces
2017 Footbridges Berlin, the shArc bridge
2016 IASS Tokyo, bio-composite bridge Eindhoven
2016 ICSA Guimarães, educating bridge design
2015 IABSE Nara, bio-composite bridge Schiphol
2015 CompIC Amsterdam, keynote
2014 IABSE Madrid, Architectural Engineering of FRP bridges
2013 ICSA Guimarães, Bridge design 2.0
2011 Concrete Bridge Conference Oxford, keynote
2006 Lightweight Structures, Rotterdam, keynote

Book chapters

2009 Bruggen in Nederland 1950-2000, chapter on architectural bridge design (Walburg Pers)

Awards

2014 Public Award, Houthaven Bridges Amsterdam
2012 Dutch Sustainability Award, highway of the future, Oss
2012 1st prize moving Bridge in FRP, Katwijk
2011 'Routepluim' for Juliana Bridge, from Dutch Ministry of Transport
2010 European Award for excellence in Concrete
2009 Dutch Concrete Award 2009, Juliana bridge, Zaanstad
2008 Da Vinci Award, Delft Design Composite Bridge
2008 Nom. National Steel Award, Bernhard bridge, Zaanstad
2006 Nom. National Steel Award, lifting bridge, Bedum
2004 2nd prize architectural bridge competition, Cambridge
2000 Nom. National Steel Award, Rembrandt Park bridges
1998 2nd prize architectural competition 60 bridges, Leidschenveen
1997 1st prize architectural competition Kloosterbrug; Assen

Projects

2018	Integrale design of the Overland Conveyor Bridge for Sirius Minerals, Redcar, UK.
2016 - to date	Detail design Wintrack II, High Voltage Transmission Towers for Tennet, Zeeland.
2016 – to date	Integral design Paradis Bridge, Fibre Reinforced Polymer foot- and bicycle bridge for Statens Vegvesen, Bergen, Norway.
2016 – to date	Architectural design Driefontijnen Bridge for Vlaamse Waterweg, Brussels, Belgium.
2016	Bio-composite footbridge in Eindhoven. Delft University of Technology with Eindhoven University of Technology and NPSP.
2016	Competition design for a footbridge in Mumbai, India.
2016 – to date	Tender design Movable Bridge Vilvoorde, Belgium, for Besix.
2016 – to date	Masterplan Civil structures for the N359 Bolsward-Leeuwarden for Province of Fryslân.
2016 – 2017	Architectural design Geinbrug for province Noord-Holland, Driemond, Amsterdam.
2016	Tender design Wildlife Bridge Zeepoort at Bloemendaal for BAM.
2014 – 2015	Tender design bicycle bridge Amsterdam Rijnkanaal at Nigtevecht, for BAM.
2014 – 2016	Supervisor Symbio Bridge, pedestrian bridge across the Karitaat Molensloot in Delft.
2014 – 2017	Bio-composite pedestrian bridge at Schiphol Logistics Park for SADC, Schiphol.
2014	Competition design, 14 bridges Amsterdam Houthaven. 2nd prize
2014 – to date	Architectural design viaduct Nauernaseweg, Zaanstad.
2014 – to date	Architectural design railroad underpass N345 for Province of Gelderland, Zutphen.
2014 – to date	Masterplan design motorway N345 for Province of Gelderland, Voorst.
2014 – to date	20 modular pedestrian bridges for the municipality of Jeddah, Saudi Arabia.
2013 – to date	Structural Works N244c Purmurend for the Province of Noord-Holland.
2013 – to date	Masterplan design for the N31 open tunnel traverse and 5 bridges in Harlingen for Rijkswaterstaat.
2012 – to date	Integral Design Nelson Mandela bridge in Alkmaar for the Province of Noord-Holland.
2012	Tender design Hogebrug for Franki Construct. Harelbeke, Belgium.
2012	Sketch Design Hockey clubhouse and tribune for HGC Wassenaar.
2012 – 2016	Architectural design wildlife crossing for province of Overijssel. Between Rijssen and Wierden.
2012	Tender design Sint Sebastiaansbrug for the Municipality of Delft.
2011	Tender design for a moving bridge in FRP in Muiden for VolkerWessels.
2010	Architectural design drawbridge Oude Rijn for municipality of Katwijk.
2011 – 2015	Eekwerderdraai, rotating bridge for the Municipality of Loppersum.
2011	Tjamsweersterbrug a moving bridge for the Municipality of Appingedam.
2010 – to date	Civil structures Westtangent N242 Heerhugowaard, Provincie Noord-Holland.
2010 – to date	Architectural design Zaanbrug for province of Noord-Holland, between Zaanstad and Wormerveer.
2010 – 2014	Five drawbridges across the Almelo- De Haandrik canal for the province of Overijssel.
2010 – 2017	Masterplan and design of the all civil structures for the N381 in Drachten.
2009 – 2010	Architectural design Three city bridges in 'Veur Lent' for the municipality of Nijmegen.
2009	Tender design for a highway bridge across the river Waal at Ewijk with Ballast Nedam.
2009	Delft Design Composite Bridge with Fiber Core Europe for the municipality of Delft.
2009	Competition design 2nd Hollandse Brug for Rijkswaterstaat, honourable mention.
2009	Urban Park Plateau on the A2 motorway for the municipality of Eindhoven.
2009	Tender design for a Control Centre in Maasbracht for Rijkswaterstaat.
2008 – 2013	Architectural Design 'Highway of the Future' for the municipality of Oss. Winner of the Dutch Sustainability Award.
2007	Three bridges for the Municipality of Heerhugowaard.
2007 – 2012	Fly-over to the Waarderpolder for the municipality of Haarlem.
2007 – 2015	Architectural design Windjammersingel bridges for the municipality of Den Haag, Ypenburg.
2007 – 2012	Integral design for the central office building of the Magnum Power Plant for NUON in the Eemshaven..
2006	City-bridge design as a Jubilee gift to the municipality of Nijmegen.
2006 - 2016	Rolpaal bridge at Verlaat for the Province of Noord-Holland.

2006 – 2011	Pedestrian bridge at the Southern ring road for the municipality of Zaanstad.
2005	Architectural design Two lifting bridges on the Van Starcken-borghkanaal for the Province of Groningen
2005 – 2015	Triple award winning design for the Juliana Bridge for the province of Noord-Holland, Zaandijk
2005 – 2006	integral design Dommel Bridge at van Abbe's Museum for the municipality of Eindhoven.
2005 – 2012	integral design Sea barrier with two bridges in Harlingen for the Wetterskip Fryslân.
2005 – 2007	Integral design lifting bridge for ING Real Estate. Bo'ness, Scotland
2004 – 2007	Architectural design Prins Bernhard Bridge for the municipality of Zaanstad.
2004	Competition Design for a bridge on the river Cam in Cambridge U.K., 2nd prize.
2004	Tender design Wijnbergse Bridge in Doetinchem.
2004	Two pedestrian bridges at Schiphol for the Province of Noord-Holland.
2004 – 2005	Lifting bridge at Maryport harbour in the U.K. for Maryport Developments Ltd.
2003 – 2012	Floating bridge with opening part at Koedijk for the Province of Noord-Holland.
2003 – 2006	Integral design Hoogtij Bridge for the municipality of Zaanstad.
2003 – 2005	Integral design Lifting bridge nYe Klap at Bedum for the municipality of Bedum.
2003	Architectural design all structural works in the ring road Alkmaar for the Province of Noord-Holland.
2002	Competition design for 3 bridges over the A7 motorway in Sneek, 2nd prize.
2002 – 2004	Integral design Kolenhaven Bridge for the municipality of Delft.
2002 – 2009	Bridge in the wetlands at Lexkesveer for the Dutch Ministry of Transport.
2002	Design for 15 bridges in the Houthaven for the municipality of Amsterdam.
2002 – 2004	Music and Sports accommodation 'de Meenthe' for the municipality of Steenwijk.
2001	Data Centre design in Almere City for B.T. Ignite.
2001	Competition design for a new City town hall in Rotterdam.
2000 – 2001	Preliminary design New Technology Centre for Shell in Amsterdam.
1999 – 2003	Integral design for two traffic bridges for the Municipality of Haarlemmermeer, Nieuw Vennep
1999 – 2003	Seven pedestrian bridges in Nieuw Vennep for the municipality of Haarlemmermeer.
1998 – 2000	Integral design Broadcasting Building in Hilversum for the NPS/VARA company.
1998	Competition design for 60 bridges in Leidschenveen, 2nd prize.
1997 – 2003	St. Hubertusduin tunnel design for the municipality of The Hague.
1998 – 2000	Integral design for 8 bridges in the Rembrandt Park for the municipality of Amsterdam.
1997 – 1999	Integral design Klooster bridge, for the municipality of Assen.