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