Eurocode and the Design, Manufacture and Installation of 62 Clear Span FRP Bridges to the City of Rotterdam (NL).

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ABSTRACT

FRP bridge design and construction is still very much geographically dispersed around the world. Europe has been at the forefront of FRP bridge technology and acceptance of this technology due to the combination of its dense infrastructure, its readily available technology and willing clients combined with an open legislation with regards to new technologies.

This has resulted in a dedicated design guide for FRP in civil engineering structures. The Netherlands leads the way, but surrounding countries are now following, and especially the UK now sees a great rise in the use of FRP bridge construction with dedicated design guides being prepared. The various available national design documents will eventually feed into a new addition to the Eurocode standards.

This paper will highlight key features of FRP single section bridge construction by reviewing a major completed project for the city of Rotterdam. The project involved the design, construction and installation of 62 FRP bridges. All bridges share the same design language but have different geometries, making full use of FRP's versatility in bridge design. The presented paper will also detail designing FRP bridges in Australia using Eurocode, and explore the relationship between Eurocode and Australian Standards and Codes.

1 INTRODUCTION

When the city of Rotterdam, back in 2013, was inaugurating the first of a series of 32 FRP bridges for pedestrians and cyclists, it was the realisation of making the city's infrastructure durable and sustainable. It also marked a mental shift: while FRP-bridges previously were considered 'special products', with the InfraCore-technology used to build them they have now become viable and within reach of everyone. The purchasing of FRP bridges in a series, rather than one-off as was done initially by this same client, shows that the technology is proven, accepted, and ready for further implementation in bridges worldwide. The client's appreciation was also expressed by the purchase of an additional second series of 30 bridges.

Figure 1 Opening ceremony of the first-of-series FRP bridge by the alderman of the City of Rotterdam.

The city of Rotterdam is a typical Dutch city: densely populated areas with an expansive network of roads and shared use bridges, crossing many streams and canals, as in the photograph of Figure 1. The climate is mild but humid, and soils are predominantly soft and only the lightest structures can do without piled foundations. Closing one bridge means that users have to make a detour to the next, or the city having to provide an alternative temporary access. As anywhere, the costs of maintenance were pressing heavily on the city council’s budget that wanted more control and predictability in their spending.

Lightweight, low-maintenance and moldable are just a few of the benefits of FRP – besides meeting the required aspects of stiffness and strength. The bridges that the City of Rotterdam purchased, feature all these benefits. It is the first of a series of 32 FRP bridges to be built in 2013. The bridges were designed by Olaf Gipser together with Vista Landschapsarchitectuur en Stedenbouw for the landscaping and urban design. FiberCore Europe developed the FRP construction and supplied them to a main contractor, responsible for the construction of the abutments and installation as well as the overall coordination and client-liaison.

Since 2013, the use of FRP in civil engineering structures has only increased. Over 800 FRP bridges have now been manufactured by FiberCore Europe and installed worldwide. Many of them are bridges for pedestrians and cyclists of typically 2 to 3 metre width, and spans between 5 and 41 metres. These have become standard products among both clients and their advisors. However, ‘standard’ does not need to imply ‘monotonous’ or ‘boring’, because FRP especially lends itself to materialise architectural features, as will be explained further on. Moreover, FRP has meanwhile been used to span 31 metres without intermediate supports, and has been used in road bridges, both static and movable.

2 CLIENT NEEDS AND MATERIAL POTENTIAL OF CONSTRUCTING IN FRP

FRP is emerging as the material of choice for lightweight civil engineering structures. Infrastructure managers are embracing FRP because it offers peace of mind without the strain of maintenance budgets and designers see opportunities to break free from conventional structural shapes imposed by standardisation of the construction industry. Instead they can now do justice to the specific urban context. Last but not least, contractors appreciate the speed of construction and reduced on-site times and associated cost reductions. It gives them an edge with their tender applications, and enables them to focus on the groundworks while they bring in the bridge as a prefabricated element. In short, the qualities of FRP are undisputed. There is only one catch: if and only if FRP is used in the right way, since designing and constructing in FRP requires a considerable amount of expertise.

For the replacement of a range of dilapidated bridges, the city of Rotterdam specified FRP because of their low self-weight, their resistance to corrosion and de-icing salts and environmental impacts, the very low maintenance-requirements and the design life of 100 years. Since the bridges are lightweight, the foundation can be kept simple and cost-efficient, such that the bridges not only feature an excellent score on total cost of ownership, but also on initial cost.

As one of the first clients, the city of Rotterdam had been trialing with FRP for five years, and when the material was proved by application and time, moved to a more systematic approach of putting FRP, together with high performance concrete, on their list of preferred materials for future bridge construction. Considering the size of this series and the impact it would have on the city appearance, an architectural design was commissioned as shown in Figure 2. This design is characterized by the facetted underside at non-orthogonal angles. These features also appear in the steel railings. Length and width of the bridges varies, the longest being 17.3 metres, the widest 4.5 metres, as does the assembly of the inclined and flat parts.

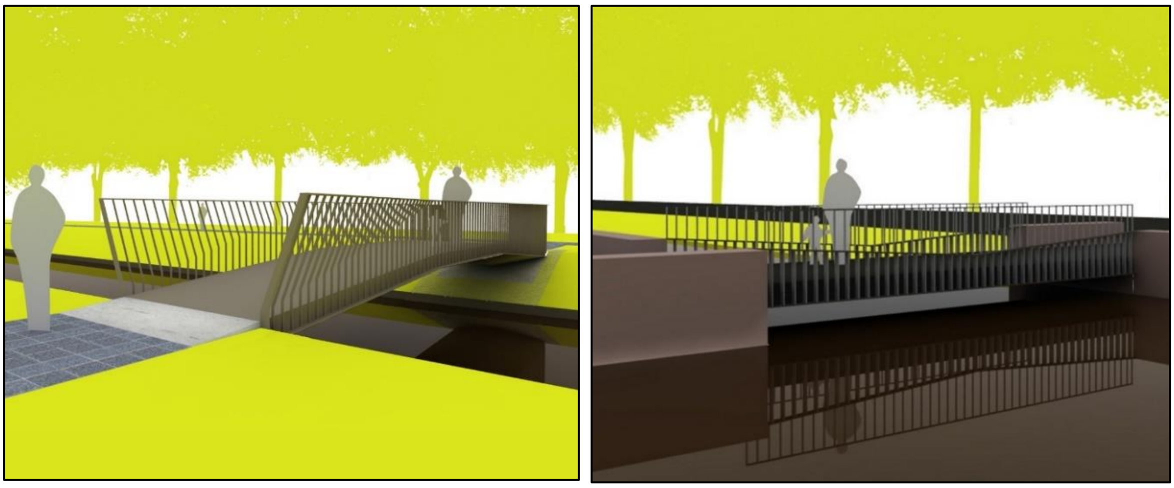

Figure 2 Design impression of the replacement bridges, all of the same architectural family. Pictures courtesy Olaf Gipser and Vista Landschapsarchitectuur en Stedenbouw.

3 FRP'S WEAK SPOT AND THE 3D-FOLDING SOLUTION USING INFRACORE

3.1 FRP's constituent materials and their processing

In FRP, the fibres are the load-bearing structural component, that is kept in place, and is internally stabilised by a matrix of cured resin. This way, the combined (composite) material outperforms that of its constituents: loose fibres can only take tensile forces but no compression. When surrounded by cured resin however, the fibres can take compression, tension and shear forces. This way FRP also has bending strength.

The fibres are mostly glass fibres for their favorable ratio between properties and cost, but also stronger and stiffer carbon fibres may be used. The fibres used are continuous, tens of metres long and thinner than stitching yarn. The fibres are incredibly strong: at least ten times stronger than steel (tensile strength around 2750 N/mm^2, compared to a tensile strength of 360 N/mm^2 for regular steel, that has a yield strength of only 235 N/mm^2). The fibres in FRP are like the reinforcement steel in reinforced concrete, with the difference that unlike concrete, in FRP the matrix plays no significant role, and the fibres in FRP work both in tension and in compression.

While there are many ways to process fibres and resin, for larger structures beyond several meters in size, the infusion technique is most appropriate. This involves preparing the glass fibre fabrics in their dry state – thus without the time pressure of curing resin – in a mold or around shaped core blocks. When ready, the product is wrapped in airtight foil, the air is pumped out, and resin is let in while the pump keeps on running. This fuses the resin through the product, turning it from white to green, and creating a fibre-content of around 50%.

3.2 Differences between FRP, composites and plastics

The denomination of FRP, or its synonym composites, is typically used for fibres set in a thermosetting resin. Thermosetting materials cannot be melted and re-formed, and therefore do not soften when exposed to sunlight or in warm weather. Plastics however, such as those of packaging and disposables, do soften in such conditions. Also, plastics typically have low fibre content, or none at all, and they burn easily. For load bearing structures these properties are unacceptable and hence thermoplastic materials are not suitable.

Consequently, FRP’s are resistant to UV-radiation and do not turn brittle over time. Also, they are difficult to set on fire as they only char, like thick pieces of wood. The charring only affects the resin and not the fibres. Consequently, fire damage of this nature can be repaired.

3.3 External shape versus the importance of the internal configuration

With the structural performance of FRP being dominated by fibres, the design of structures is effectively an exercise of placing the fibres in a 3-dimensional space, such that they can collect all the loadings and transfer them to the supports. The principle of this is generic, and was at the basis for the development of InfraCore. InfraCore is FiberCore Europe’s proprietary construction method of folding fabrics. It is an industrial, prefabricated system that can be scaled to the dimensions and shape requirements per structure in the form of panels, in this case bridges. It consists of stacking custom-cut internal lost-mold formwork elements combined with glass fibre mats, acting as reinforcement.

As in beams of concrete and steel, the top and bottom are structurally most effective, and hence it is in these skins where the fibres are concentrated. For the transfer of shear forces, FRP webs connect the top and bottom skins. Characteristic to InfraCore is that these webs are integral to the structure. Hence they are made of fibres running from the top skin, bending downward through the web, and at the bottom bend again into the bottom skin, like a Z-shape (Figure 3). The connection of the webs is thus made out of fibres of the aforementioned properties, rather than relying on a brittle bond. Additional layers of fabric, with specific fibre orientations, are placed in between the Z-layers.

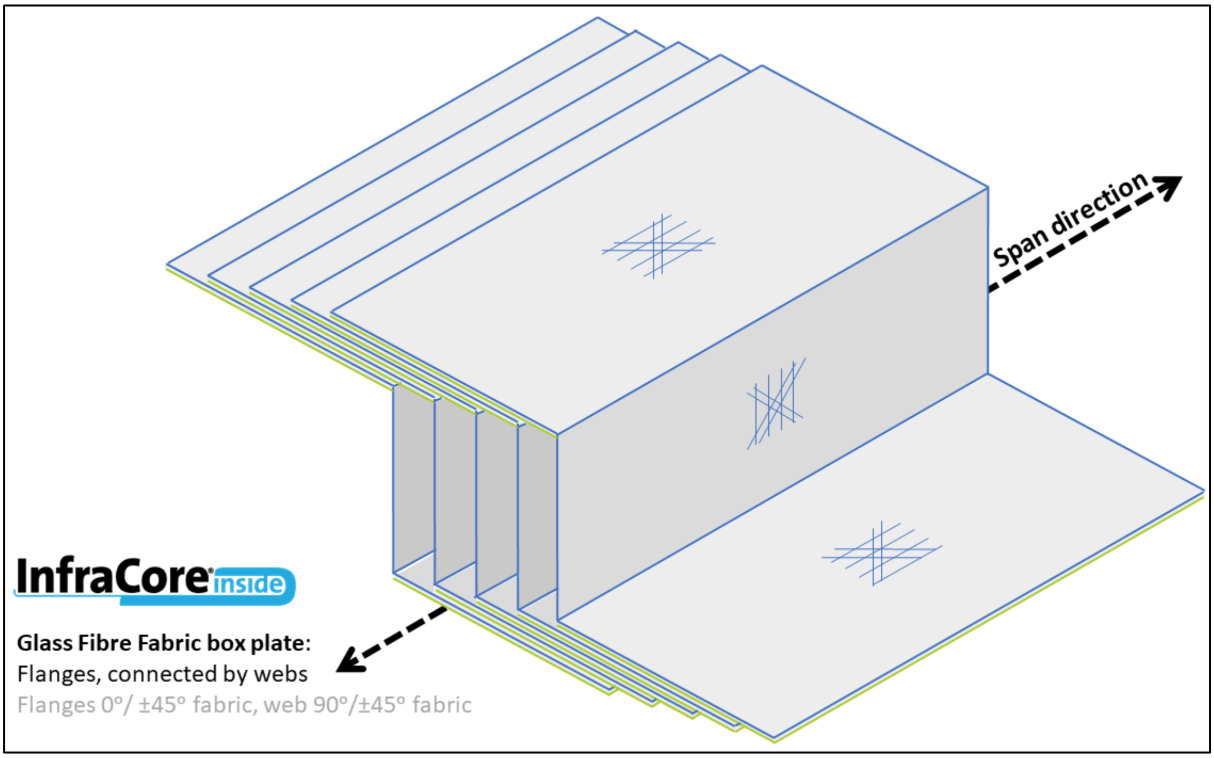

Figure 3 The InfraCore construction method is like a series of combined Z-beam, each consisting of continuous long fibres running through the webs. Depending on its structural function, the fibre orientation and quantity are optimized per situation.

InfraCore was developed to provide a robust, fail-safe solution to the conventional sandwich structure. These only involve skins bonded to a core material, this way relying fully on the core material and its bonding capacity. In failure, this gives a sudden, fatal, collapse. As per Eurocodes, this failure mode is not robust and therefore not acceptable. Instead, InfraCore was tested successfully in fatigue loading, preceded by creating intentional damage, to demonstrate robustness. This build-up can be scaled and shaped, while preserving InfraCore's intrinsic properties of strength, durability, sustainability and safety. Other than in pedestrian bridges (FRP bridges, 2014), it was already used in traffic-loaded hybrid bridges (Structural Engineering International, 2014) and lock gates.

Alternative construction methods are shown in Figure 4. While they all result in structures of the same external appearance, their internal structures are radically different, and so will be their capacity and failure-behavior. Consequently, as for any material, to advise on the most appropriate technical solution requires an understanding of the material behavior, rather than simply approaching the material only quantitatively by its specific engineering values.

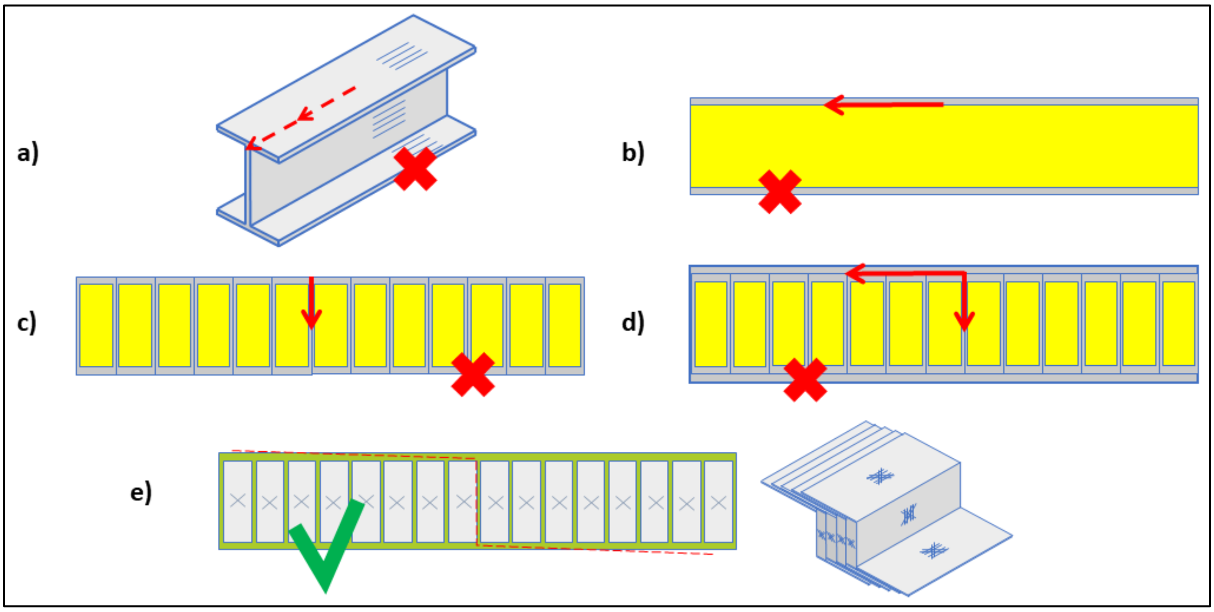

Figure 4 Alternative internal configurations of FRP structures: a) pultruded elements with its sensitivity to cracking; b) pure sandwich construction with its total reliance on skin-core adhesion; c) glued box plate with its reliance on bonding for transverse load distribution; d) plated glued box with additional failure modes due to the bonded plates; and e) the Z-shaped folding principle of InfraCore with inherent robustness, even in the unlikely event of delamination.

4 INNOVATION, DESIGN GUIDANCE AND LEGAL COMPLIANCE

4.1 Codes and other design guidance

Although FRP has been around for several decades in many high-end applications such as aerospace and wind energy, its application into civil engineering is relatively new. Consequently design standards do not yet cover this material. However, as the knowledge is in place, published design guidance are available but require the knowledge and willingness of all stakeholders involved to use and accept this.

With the Netherlands being leader in the number of FRP bridges installed, by 2003 design guidance for the specific application in the civil engineering sector was set up. This follows the limit state design procedure as is generally accepted in civil engineering, and which involves reduction factors to account for various exposure conditions. This guidance was expanded and revised in 2017 (CUR96, 2017). As it serves as an input document for the upcoming Eurocode on FRP, an English translation is now being prepared. Setting up the CUR96, and subsequentially revising it, was a joint initiative between clients, consultants and the industry, all having an interest in an agreed and accepted design basis. The bridges for the city of Rotterdam, themselves reviewer of the design guidance, were all designed based on this guidance. Meanwhile stakeholders in the United Kingdom have also published bridge-specific design guidance (CIRIA, 2018), albeit more qualitative in nature.

The systematic approach of the Eurocodes, legally binding in Europe but widely used beyond, is a general set of design principles, followed by the distinction between loadings on the one hand, and checks that are specific per material on the other hand. This means that FRP structures should carry all the loads that structures in conventional materials are supposed to carry.

Finally, the Eurocodes are stringent on safety (ultimate limit state), but consider deflections and dynamics (serviceability limit state) as matters to be specified on a project-specific basis by the client.

4.2 Load-testing as an acceptance procedure

With the understanding of the material behavior already in place through other applications, it is clear that the design of FRP structures is governed by serviceability requirements. Margins of a factor 5 to 10 on aspects of strength (or inversely: the outcome of unity checks between 0.1 and 0.2) are not uncommon in FRP-design.

In the Eurocodes, a provision is in place to use testing as an alternative method of demonstrating compliance to safety requirements. It was therefore stipulated by the client that a load test be performed on the first bridge of the series. During this test both the stiffness and dynamic behavior should be measured, and demonstrate compliance between the stiffness characteristics from the design phase and the actual realised product. Considering the degree of repetition across the full series, and in the case of InfraCore construction effectively all FRP structures, this approved the whole series.

Figure 5 shows how the load test was carried out by stacking water tanks weighing 900 kg each on the bridge. Figure 6 shows how the displacements developed over time, with clearly visible step-wise deformation due to setting down of the tanks. The test showed near-perfect compliance.

For dynamic, assessment heel-drop tests were performed in both the loaded and the unloaded stage, to measure the natural frequency. Again, natural frequencies were well within limits, meaning that pedestrian usage could not excite the bridge and bring it into resonance.

Figure 5 Load test of the full live load on the bridge, with monitoring of deflection and dynamic behavior.

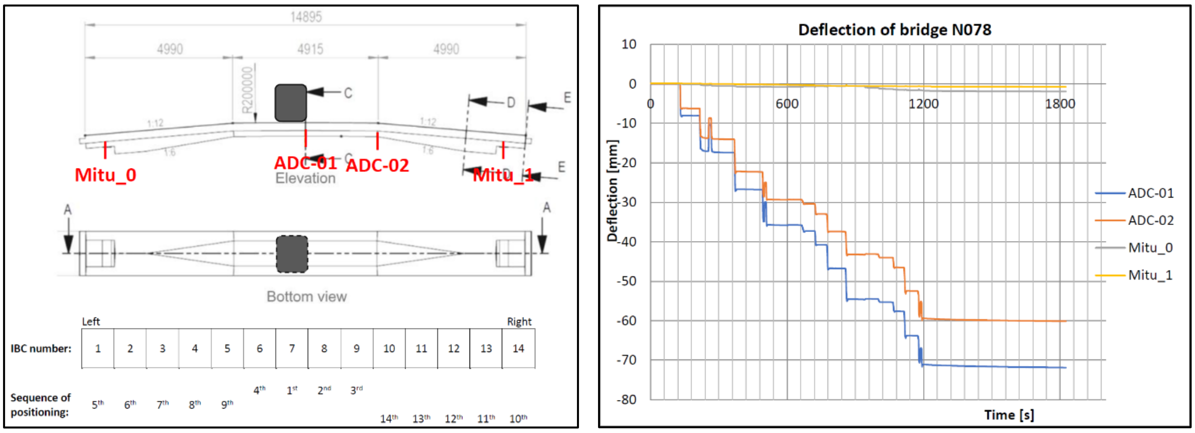

Figure 6 Measurement positions and loading sequence (left) and graph (right) showing the vertical displacements during the stepwise loading of 900kg water tanks, as a method to demonstrate compliance between the design and the realised structure.

5 TRANSPORTATION, INSTALLATION AND RELOCATION

Having completed the acceptance test, the remainder of the series was released for fabrication. Thanks to a step of off-mold prefabrication, these were produced at a rate of up to two per week, and the sides subsequently finished with a non-stick anti-graffiti coating. The road level was finished with a grit-in-epoxy wear surface of grit size 1-3 mm. The railings – in this case in galvanized and powder-coated steel and due to their dense design actually contributing a lot to the bridge's self-weight, were supplied and installed by a specialist contractor. The bridges were then ready for transportation (Figure 7) for the contractor's 'just-in-time' site planning, and were installed onto the prepared foundations. It was a simple single lift from the back of the truck to the foundations (Figure 8).

The series of bridges for Rotterdam have now been in use for several years, with no noticeable structural degradation or performance issues. There has been slight damage to the railings from grass mowers, and on the wear surface from vehicles that were too low to cross the 'kink' that was due to the architectural design. Both were easily repaired.

During their life span, the bridges can be picked up and moved easily should the urban infrastructure be revised, thus meeting the key principle of sustainable construction: use structures longer. As a result of the sustainability trend on all levels of governance, in the Netherlands a national online 'bridge-bank' is being set up that seeks to match offer and demand. Ultimately, bridge end-of-life scenarios are currently developed with to date already recycling options already available for the embedded energy to be reclaimed.

Figure 7 The finished bridge with railings already installed in the factory yard, prior to its transportation to site.

Figure 8 Example of another bridge installed on the abutments straight off the truck.

6 CONCLUSION

Composite materials cover a large family of materials, all with excellent properties and great potential for public authorities concerned about the cost of maintenance, and afraid of the consequences of any neglect. For structural applications thermosetting FRP using conventional glass fibres is most suitable. With significant design freedom, unrivalled fatigue behavior, low self-weight, a very low need for maintenance and re-use and recyclability, it becomes evident why an exemplar city like Rotterdam has chosen for FRP bridges.

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9 AUTHOR BIOGRAPHY

Dr. Martijn Veltkamp is a *Senior Engineer* with *FiberCore Europe* based in Rotterdam, the Netherlands and is working with Sustainable Infrastructure Systems (Aust.) Pty Ltd to deliver and implement FRP bridge technology. Involved with the design and manufacture of single span FRP bridges and linking his experience in FRP research, projects and stakeholder collaboration, he strives to design larger, lighter and more cost effective FRP bridge structures for clients worldwide.

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