

# 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.*

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## Abstract

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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

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## § 4.1 Introduction

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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.

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## § 4.2 Engineers' solutions in FRP

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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.

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<sup>1</sup>

properties	Density $\rho$ [kg/m <sup>3</sup> ]	Young's modulus in x- direction Ex [N/mm <sup>2</sup> ]	Young's modulus in y- direction Ey [N/mm <sup>2</sup> ]	Tensile/compr. strength in x-direction fxRk [N/mm <sup>2</sup> ]	Tensile/compr. strength in y-direction fyRk [N/mm <sup>2</sup> ]
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.*

<sup>1</sup> 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

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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.

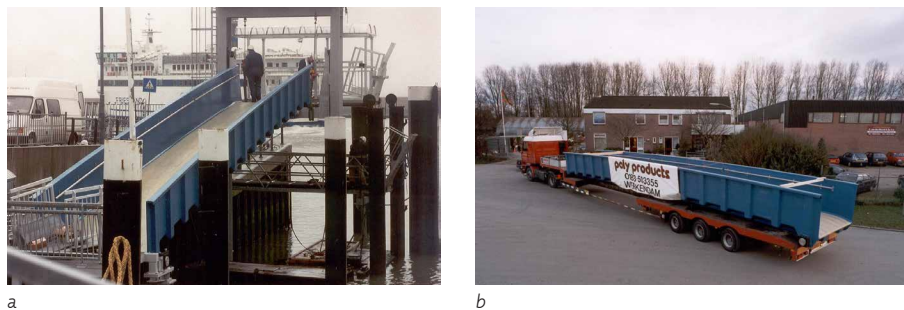


FIGURE 4.3 Footbridge in Harlingen, the Netherlands, made by Poly Products for Rijkswaterstaat (1997). From <http://www.polyproducts.nl>, visited on 27/2/2019.

### § 4.2.2 Assembly from pultruded profiles

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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

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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).

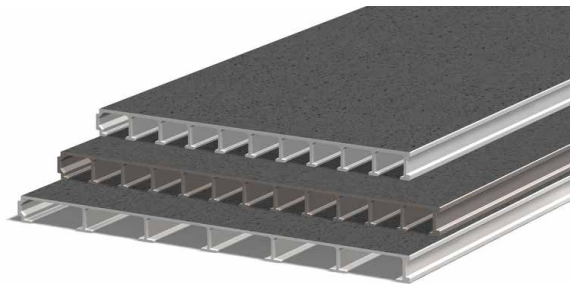


FIGURE 4.5 Pultruded bridge deck panels. (Transportation Research Board, 2006).

### § 4.2.4 Load-bearing uniform deck

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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).

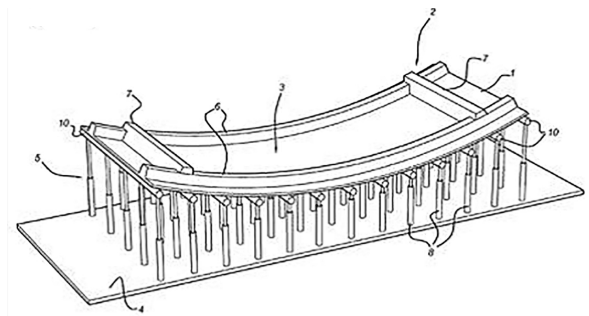


FIGURE 4.6 A flexible mold system for cambered decks with variable width and length.



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

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## § 4.3 Challenges for the architect

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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

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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.



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.



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.

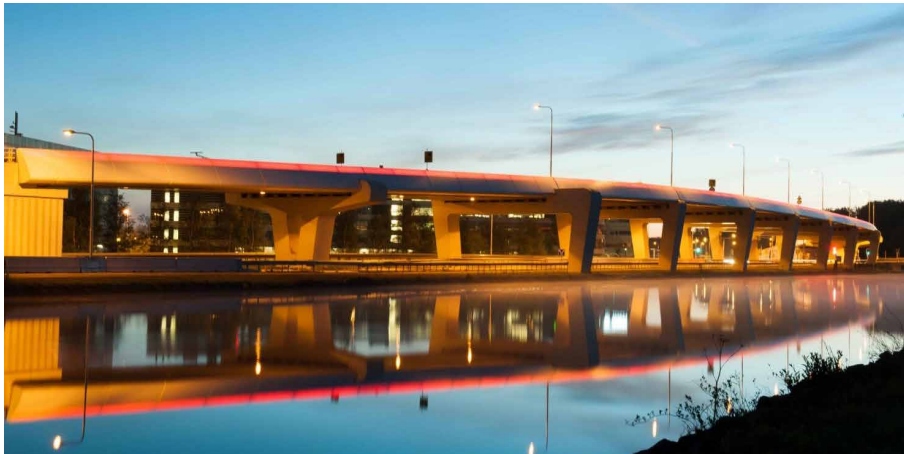
The design of the highway N201 viaducts proved that the possibilities of fiber-reinforced plastic edge elements extend beyond shape, color, and texture. In this project, the idea of a structure that glowed at night was introduced by installing lights behind the upper part of the composite panels. To 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

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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.

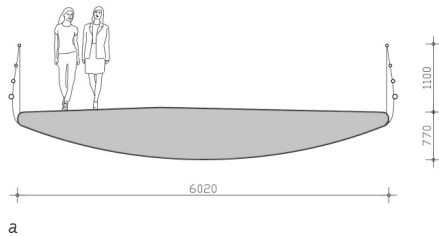


FIGURE 4.13 A design for a monocoque FRP drawbridge for pedestrians and bicycles across the Rhine in Katwijk Royal HaskoningDHV, Joris Smits et al. (2014).

### § 4.3.3 Origami structures and shell structures

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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.

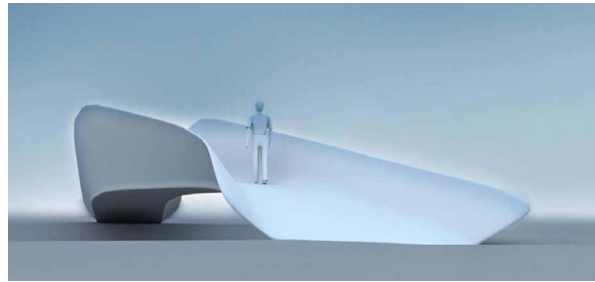


FIGURE 4.15 An origami bridge design. R. Gkaidazis, Delft University of Technology (2014).





FIGURE 4.16 The razor or Ensis shell, thin and strong. From [https://en.wikipedia.org/wiki/Razor\\_shell](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

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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.

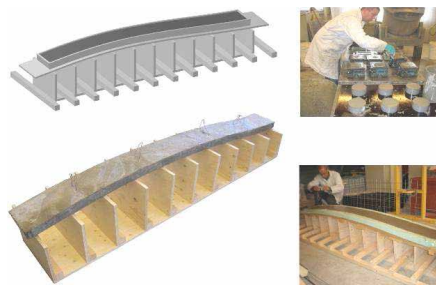


FIGURE 4.19 Test setup for single-curved elements. H. Schipper et al. Delft University of Technology (2011).

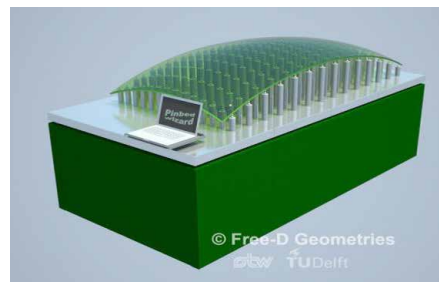


FIGURE 4.20 Wizard with 200 simultaneously computer-adjusted actuators. D. Rietbergen et al., Delft University of Technology (2008).

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## § 4.4 Conclusion

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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.

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