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Fiber-Reinforced Polymer Bridge Design in the Netherlands: Architectural Challenges toward Innovative, Sustainable, and Durable Bridges

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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.

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

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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.

2. Engineers' solutions in fiber-reinforced polymer (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. As early as 1940, Henry Ford produced a pioneering composite car from hemp fiber and resin under the motto: "ten times stronger than steel" (Fig. 1 and Fig. 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.

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 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

Fig. 1. Henry Ford demonstrated his hemp car on impact (Ford, 1940).

Fig. 2. Engineers from the aerospace, maritime, automotive, and sports industries have preceded bridge engineers in their use of FRP.

Table 1
Material properties of FRP compared to those of steel and aluminum[a].

Properties	Density, ρ ($kg\cdot m^{-3}$)	Young's modulus in x-direction, E_x ($N\cdot mm^{-2}$)	Young's modulus in y-direction, E_y ($N\cdot mm^{-2}$)	Tensile/compression strength in x-direction, $f_{x,k}$ ($N\cdot mm^{-2}$)	Tensile/compression strength in y-direction, $f_{y,k}$ ($N\cdot mm^{-2}$)
GFRP UD, V_f 50%	1.875	36.569	10.924	740.00	n/a
GFRP 625, V_f 50%, anisotropic lay-up (0/90/45/–45) (62.5%/12.5%/12.5%/12.5%)	1.850	27.600	15.200	331.00	182
CFRP UD, V_f 50%	1.450	120.000	60.000	1.56	n/a
Steel S355	7.850	210.000	210.000	355.00	355
Aluminum 6063	2.720	69.600	69.600	110.00	110

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

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.

2.1. Hand lamination: A footbridge in Harlingen

In December 1995, the Dutch Ministry of Infrastructure and the Environment (*Rijkswaterstaat*) was the first to initiate a 100% FRP footbridge in the Netherlands (Fig. 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.

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].

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 (Fig. 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.

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 (Fig. 5).

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-

Fig. 3. Footbridge in Harlingen, the Netherlands (Poly Products, 1997).

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 (Fig. 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 (Fig. 7).

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.

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 ap-

(a) (b) (c)

Fig. 4. Bridge structures from pultruded profiles and material substitution (Fiberline, 2013). (a) Pontresina, Switzerland; (b) Lleida, Spain; (c) Kolding, Denmark.

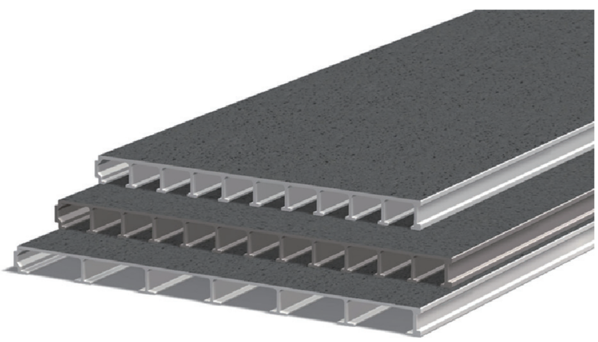


Fig. 5. Pultruded bridge deck panels (Transportation Research Board, 2006).

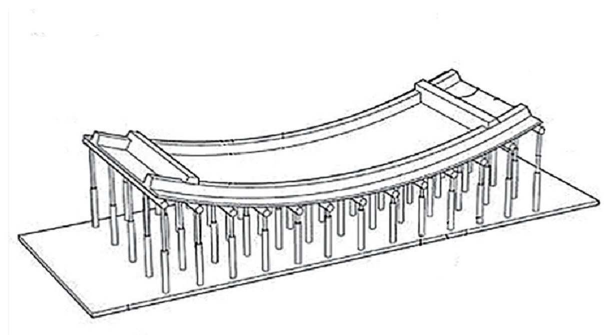


Fig. 6. A flexible mold system for cambered decks with variable width and length.

Fig. 7. The InfraCore patented technique for creating unitized structures (Peeters, 2011).

preciated 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.

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 Fig. 8 and in Fig. 9(a). 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

Fig. 8. (a) Installation and (b) final assembly of the edge elements in the fly-over Waarderpolder.

Fig. 9. Some projects in the Netherlands with FRP edge elements. (a) The fly-over Waarderpolder in Haarlem; (b) edge elements on the Juliana Bridge in Zaanstad; (c, d) the wildlife crossing and tunnel in Rijssen-Wierden (Royal HaskoningDHV, 2007, 2013, 2013).

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 Juliana Bridge in Zaanstad, the Netherlands, shown in Fig. 9(b). 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 Fig. 9(c, d), and the viaducts of highway N201 near Schiphol, shown in Fig. 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.

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 (Fig. 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.

Producing a monocoque bridge with double curvatures can be a challenging procedure (Fig. 12 and Fig. 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

Fig. 10. Installation of red light in the panels of the highway N201 viaducts.

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.

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 (Fig. 14 and Fig. 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 (Fig. 16 and Fig. 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 (Fig. 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.

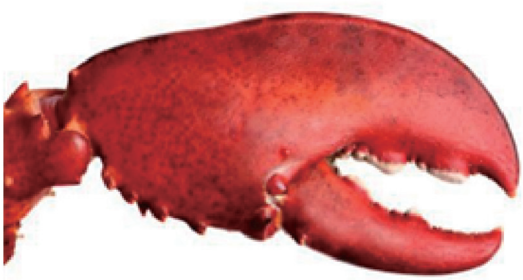
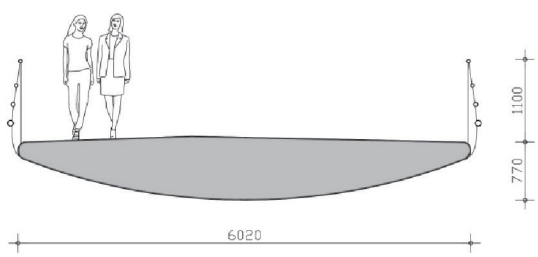


Fig. 11. A lobster pincer, an example of a monocoque structure in nature.

Fig. 12. The Dragonfly footbridge in Harderwijk (Royal HaskoningDHV, 2014).



(a)

(b)

Fig. 13. A design for a monocoque FRP drawbridge for pedestrians and bicycles across the Rhine in Katwijk (Royal HaskoningDHV, 2014). (a) Cross section of the deck (unit: mm); (b) artist impression.

Fig. 14. A tree leaf as an example of folded structures in nature.

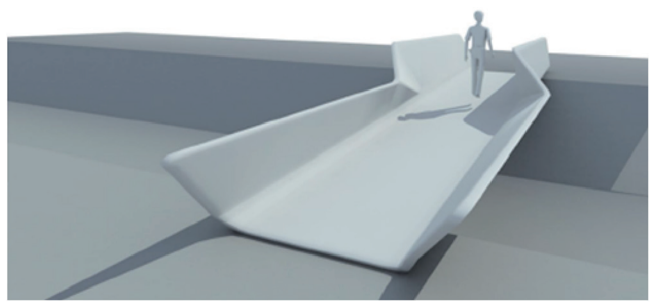


Fig. 15. An origami bridge design (R. Gkaidazis, Delft University of Technology).

Fig. 16. An *Ensis* shell, thin and strong.

Fig. 17. Pringles, a fried potato snack with optimized stiffness.

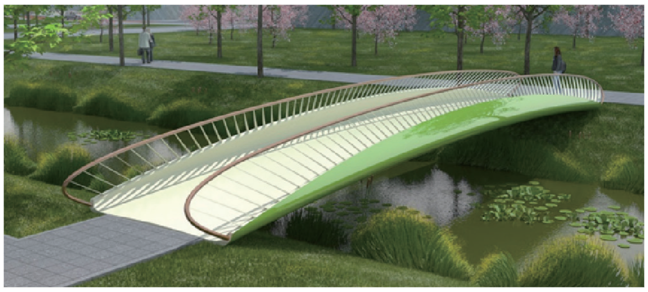


Fig. 18. The Delft Design Composite Bridge for pedestrians and bicycles (Royal HaskoningDHV, FiberCore, 2008).

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 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 (Fig. 19) [6,7] and on adjustable formworks for curved glass panes (Fig. 20) [8] could be successfully adjusted and applied to FRPs, and could eventually permit more design possibilities and form freedom for architects.

3.5. Bio-composites

In current practice, architects and clients have an increasingly strong focus on sustainability. Although recent Dutch studies proved that FRP footbridges perform better in terms of carbon footprint in comparison with footbridges made from traditional building materials such as steel and concrete, the majority of FRPs are still based on non-renewable sources. The FRP used in structural applications is normally composed of synthetic fibers such as glass and carbon, combined with petroleum-based resins.

Under the environmental consciousness of recent years, materials based on renewable raw resources have entered the composite industry and have found application in various products. Natural fibers have been successfully used to replace artificial fibers, and new types of resins based on natural substances have been introduced into the market, aiming to reduce the environmental impact and embodied energy of FRPs. Although bio-composites have been embraced by other industries, such as the automotive industry, they are only just making their appearance in the building industry. For load-bearing structural applications such as footbridges, the use of bio-based polymers and natural fibers is still in the experimental stage. In Emmen, the Netherlands, a bridge deck that claims to be bio-composite spans 5 m. However, the deck uses glass fibers in addition to natural flax fibers.

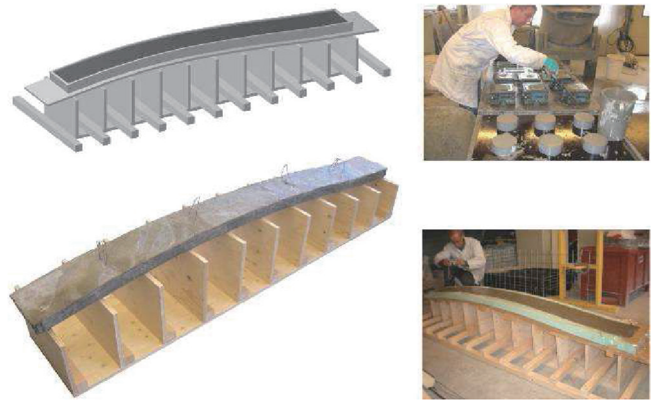


Fig. 19. Test setup for single-curved elements.

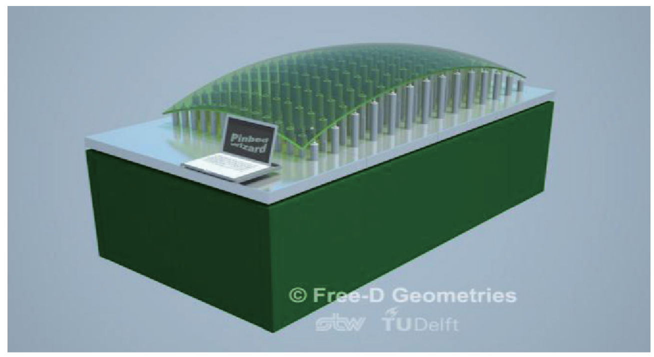


Fig. 20. Wizard with 200 simultaneously computer-adjusted actuators.

Before identifying design considerations for bridge designers using bio-composites, it is useful to consider the material side of bio-composites and examine the different ingredients they are composed of. The following subsections discuss ongoing research and a realized experimental project for a bio-composite footbridge in Eindhoven that the author of this paper is currently involved in.

3.5.1. The fibers

The term "natural fibers" refers to fibers that occur within nature and are found in plants (cellulose fibers) or animals (protein fibers), although only plant fibers are used as reinforcement in composites [9]. Cellulosic fibers are obtained from various parts of plants, such as the seeds (cotton, kapok, milkweed), stems (flax, jute, hemp, ramie, kenaf, nettle, bamboo), leaves (sisal, manila, abaca), or fruit (coir); other grass-type fibers also exist. Depending on their origin, such fibers can be either long or short. Long fibers are extracted from the outer skin of the stalks of long plants such as flax and jute, and are normally preferred as reinforcement due to their higher mechanical performance compared with that of other fibers. Like artificial fibers, natural plant fibers can be processed to produce different types of technical textiles such as woven fabrics, non-crimp fabrics, chopped strand mats, and fleeces.

With the exception of a few long-fiber types, most natural plant fibers have lower mechanical properties than their artificial counterparts. However, one of their greatest advantages is their low density, which results in components that are much more lightweight than glass-fiber-reinforced composites. Due to their low specific weight, the specific strength and specific stiffness of natural fibers are increased. These are critical properties for bio-composites, especially in parts designed for bending stiffness, as natural fibers present better stiffness than strength. In addition, the mechanical properties of plants are strongly affected by the growing environment (temperature, humidity, soil and air composition, as well as the harvest and process method), resulting in deviated property values, even for fibers of the same type.

Natural fibers are also characterized by poor durability. Several studies [10,11] conclude that excessive moisture absorption due to the hydrophilic behavior of cellulosic fibers is the main reason for the accelerated reduction of their mechanical performance. Poor compatibility between natural fibers and hydrophobic resins is another reason for poor durability, as it is responsible for the degradation and loss of strength caused by premature ageing [12]. Natural fibers are also susceptible to ultraviolet (UV) radiation. Photochemical degradation by UV light results in changes in the molecular structure of the composite, promoting surface embrittlement, cracking, discoloring, and loss of tensile and impact strength. Nevertheless, much research has been done on developing treatment methods that improve the durability of natural fibers. These treatments are either physical or chemical methods that lead to reduction in moisture gain and improvement of the fiber-matrix adhesion by modifying the fiber surface, morphology, and composition [13].

3.5.2. The resin

With the aim of further improving the environmental impact of bio-composites by increasing the percentage of renewable raw materials, bio-resins have been developed. Bio-resins, also known as bio-based polymers or organic plastics, are synthetic polymers produced from renewable raw material such as starch and cellulose, or from agricultural waste products. Depending on their chemical composition, bio-resins are classified in terms of their biodegradability and durability.

Like natural fibers, biodegradable plastics tend to uptake moisture from their environment; in addition, they are more brittle than petroleum-based resins. Thus, biodegradable plastics are preferred in temporary applications, including packaging and short-lived consumer products. Durable bio-resins are the next generation of biodegradable polymers. These plastics, being based on vegetable oil, maximize the content of renewable raw materials while achieving long-lasting functionality. Natural degradation and brittleness are inhibited by the addition of fillers and additives during production. Because of their long-lasting properties, durable bio-resins are used in applications with a longer service life.

3.5.3. Experimental bio-composite footbridge in Eindhoven

The author of this paper is currently involved in research on the use of bio-composites in a load-bearing footbridge application (Fig. 21). The bridge is built out of flax fibers, bio-based resins, polylactic acid (PLA) foam, and natural cork. The project team members are: Eindhoven University of Technology, Delft University of Technology, the company NPSP BV, and the Center of Expertise Biobased Economy. The results of this research will lead to the manufacturing of a fully load-bearing bio-composite footbridge that was installed in Eindhoven in October 2016. More on this subject will be made public in a scientific paper that will present our research on the bio-composite bridge.

4. Conclusions

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 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 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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(a) (b)

Fig. 21. Flax fibers, bio-resin, polylactic acid (PLA) foam, and natural cork were used to produce the bio-composite bridge in Eindhoven. (a) The opening of the bio-composite footbridge in Eindhoven (copyright by the author, Oct 27, 2016); (b) the flax plant from which stems the flax fibers are extracted.

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