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# Fiber-Reinforced Polymer Composites in the Construction of Bridges: Opportunities, Problems and Challenges

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**Abstract:** In this review, we discuss the basic issues related to the use of FRP (fiber-reinforced polymer) composites in bridge construction. This modern material is presented in detail in terms of the possibility of application in engineering structures. A general historical outline of the use and development of modern structural materials, such as steel and concrete, is included to introduce composites as a novel material in engineering, and the most important features and advantages of polymers as a construction material are characterized. We also compare FRP to basic structural materials, such as steel and concrete, which enables estimation of the effectiveness of using of FRP polymers as structural material in different applications. The first bridges made of FRP composites are presented and analyzed in terms of applied technological solutions. Examples of structural solutions for deck slabs, girders and other deck elements made of FRP composites are discussed. Particular attention is paid to the systems of deck slabs, especially those composed of pultruded profiles, sandwich panels and hybrid decks. The disadvantages of composites, as well as barriers and limitations in their application in engineering practice, are presented. Exemplary analyses of the costs of construction, maintenance and demolition of FRP composite bridges are presented and compared with the corresponding costs of concrete and steel bridges. The directions of development of composite bridge structures and the greatest challenges facing engineers and constructors in the coming years are discussed.

**Keywords:** composites; bridges; fiber-reinforced polymer (FRP); fibers; novel structural materials; polymers

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**Citation:** Kossakowski, P.G.; Wciślik, W. Fiber-Reinforced Polymer Composites in the Construction of Bridges: Opportunities, Problems and Challenges. *Fibers* **2022**, *10*, 37. https://doi.org/10.3390/fib10040037

Academic Editors: Ahmad Rashed Labanieh and Vincent Placet

Received: 7 December 2021
Accepted: 12 April 2022
Published: 18 April 2022



## 1. Introduction

The development and modernization of the bridge industry, which has been continually observed since ancient times, is closely linked to the materials used for bridge construction. For a long time, wood and stone were the basic construction materials. Later on, brick became common in construction. It was not until the late 18th century when bridges began to be made of other materials. The first modern material was cast iron, which was used to erect the Iron Bridge in England in 1779. Later, in the 19th century, steel was used to build metal bridges. It is worth mentioning at this point that iron materials were used earlier for bridge building in China and India. According to Plowden [1], cited by Kanji Ono [2], the first iron bridge, Jihong Bridge, may have been erected in China in AD 56 in the Eastern Han era, and another iron structure was possibly built around 200 BC. At the end of the 19th century, reinforced concrete was introduced into the bridge industry. It is believed that the first bridge to be built using reinforced concrete is the 50 ft (15 m) Homersfield Bridge over the Norfolk/Suffolk border in 1870 [3]. In the 20th century, this material was improved in the form of prestressed concrete. It revolutionized concrete bridges, allowing for much longer structures. The 20th century was a period of development and bringing into general use of modern structural steels in bridge construction but also a period of application of aluminum alloys [4–6]. It is also interesting to note the use of stainless steels for bridge structures [7]. On the other hand, the turn of the 21st century is a period of using fiber composites in the bridge industry [8]. Bearing in mind the new possibilities offered by fiber composites, mainly due to their favorable mechanical parameters, especially the weight–strength–stiffness relation, further applications in the bridge industry should be observed with interest.

Among a group of composites, fiber-reinforced polymer composites are one of the most widely used novel materials. Their range of applications covers civil, mechanical, automobile, aerospace, marine and biomedical industry [9]. Although the best results are achieved using synthetic fibers [10–14], very interesting effects can be obtained using natural fibers [15,16]. A separate stream of research is in the field of development of nano-composites [17–19]. It can be said with certainty that fibrous composites are novel materials of the future. Due to their properties and the possibility of use, composites were used in building engineering quite early. This applies to architecture, construction and bridge engineering. The latter branch was most interested in the possibilities of using composites. Two general fields of application of FRP composites are repair and strengthening possibilities and methods [20,21], as well as research and solutions to make parts, in addition to the entire supporting structure of bridges [22–27]. In this respect, the issues of the response of bridge structures under static and dynamic load are important, which is also the subject of the latest intensive research [28–30]. To sum up, it seems that FRP composites will certainly be increasingly used for the construction of bridges.

The aim of this review is to present the issues associated with using fiber-reinforced polymer composites as a structural material in bridge construction. The most important benefits of using this type of materials are presented, and the basic solutions for the construction of platforms using FRP technology are discussed. The most important problems and limitations related to the use of composites in bridge engineering are characterized. However, the scope of this review does not cover the important issue of using composites to strengthen existing structures.

## 2. Materials

Fiber-reinforced polymer composites are two-phase materials consisting of a base material and filler material. Base material is referred as a matrix or a binder material. This is a polymer (plastic), either thermoset or thermoplastic. Polymer matrices are natural or synthetic. The latter kind is petrochemical-based and includes polyester, polypropylene (PP), polyethylene (PE) and epoxy. Due to its specific mechanical properties, a polymer matrix needs to be reinforced by filler material. FRP composites consist of fibers or other reinforcing material, which provide sufficient strength in one or more directions. From this point of view, the most effective fibers used in structural engineering are glass, carbon, basalt and aramid. FRP composites made with these fibers are denoted as GFRP, CRFP, BFRP and AFRP, respectively.

In FRP composites, most of the load is carried by the fibers. Composites with glass, carbon or aramid fibers are most often used in building structures.

Due to the relatively low cost, the most widely used are glass fibers. Their other advantages are hardness, high corrosion resistance and a small influence of temperature (in the scope in which the bridges operate) on mechanical properties. Their most important disadvantages include a low modulus of longitudinal elasticity and sensitivity to moisture.

From a constructional point of view, it is preferable to use carbon fibers that have a high modulus of elasticity (see comparison, Table 1). Their further advantages are very high fatigue strength and high creep resistance. However, these are expensive materials.

**Table 1.** Comparison of basic properties of different kinds of fibers, concrete and structural steel [31,32].

| Properties | Carbon Fibers | | Glass Fibers | | Aramid Fibers | | Basalt Fibers | Steel | Concrete |
|---|---|---|---|---|---|---|---|---|---|
| | High Strength | High Modulus | E-Glass | S-Glass | | Kevlar 29 | Kevlar 49 | | |
| Density [kg/m$^3$] | 1800 | 1900 | 2540 | 2530 | 7850 | 1440 | 1440 | 2700 | 2500 |
| Modulus of elasticity [GPa] | 230 | 370 | 72 | 89 | 200 | 83 | 124 | 90 | 27–43 |
| Tensile strength [MPa] | 2480 | 1790 | 3400 | 4600 | 355–900 | 2920 | 3600 | 4000 | 1.57–5.04 |
| Compressive strength [MPa] | - | - | - | - | - | - | - | - | 12–98 |
| Extension [%] | 11.00 | 0.50 | 2.12 | 1.93 | 2.50 | 3.5 | 2.90 | 2.25 | - |

Aramid fibers are characterized by high fatigue strength, but due to their creep susceptibility, high cost and complicated production technology, they are rarely used in construction.

In recent years, basalt or boron fibers have been used more and more often [8].

The resin primarily acts as a binder for the fibers. The choice of the type of resin depends on the adopted technology for the composite production and the expected properties of the material. Elements of building structures usually use polyester, epoxy and vinyl ester resins.

The vast majority of elements in the construction industry are made with the use of polyester resins. Composites based on polyester resins are characterized by lightness, high strength and good chemical resistance. These are therefore advantages that are particularly desirable in bridge construction.

The use of epoxy resins ensures high strength and high chemical resistance, but the problem with bridge structures is their low resistance to UV radiation.

Vinyl ester resins are characterized by relatively high elongation, as well as good impact strength and fatigue strength. The main disadvantages include high shrinkage [8].

## 3. Benefits of FRP in Bridges

As with other FRP composite applications, they are increasingly used for bridges. Decisive in this regard are four fundamental benefits [9]:

(a) excellent mechanical parameters, which enables a reduction in weight due to a positive strength/stiffness–density relation;
(b) high corrosion resistance, increasing the durability;
(c) low maintenance requirements;
(d) possibility to form varied complex geometries and shapes of bridge elements and structure.

These advantages encourage the use of FRP composites to form different parts of bridges, as well as large-span structures. Particular benefits are discussed in detail below.

### *3.1. Mechanical Parameters*

Generally, every modern FRP composite has a better tensile strength in comparison to structural steels used in bridges, as well as in civil engineering (Table 1). For deformations corresponding to the range of live loads typical for bridges, the differences in the strength are significant, which is shown schematically in Figure 1. Typical structural steels used in bridges, i.e., S355, have much lower strength compared with basically every kind of FRP composite [32,33].

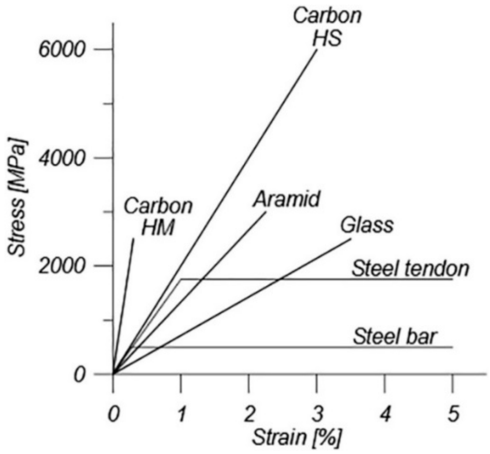


**Figure 1.** Schematic comparison of stress–strain characteristic for FRP composites and steel [32].

In the case of modulus of elasticity, it depends on fiber type. However, composites are much lighter in terms of density. To sum up, every FRP composite currently used in engineering has a much better strength/stiffness–density ratio compared to that of structural steels (Table 1).

### 3.2. Fatigue Resistance

FRP composites have high fatigue strength, which allows them to be used in bridge engineering. Most importantly, their application in bridges meets the high durability requirements according to the EN-1990 standard for anticipated traffic [28–30]. Composites used to strengthen bridge elements and their structures also increase the fatigue life of both reinforced concrete and steel structures. This phenomenon is also observed with regard to the reinforcement of joints.

### 3.3. Low Weight

A favorable strength/stiffness–density ratio results in FRP profiles that are significantly lighter than those of steel and especially of concrete. CFR profiles can achieve the same great strength as steel, thanks only a quarter of the density. Thus, bridge structures made of FRP material have a noticeably lower weight [23–26]. It is also possible to reduce structure mass in comparison to aluminum structures as a result of 30% lower density of FRP structures.

### 3.4. Corrosion-Free

Modern FRP materials are highly resistant to aggressive environment effects. This is especially true of corrosion attack, which is fundamental in the case of bridges. They are extremely susceptible to risk of corrosion and reduction in their durability and load-carrying capacity. FRP profiles are resistant to aggressive chemicals, liquids and alkalis [23].

### 3.5. Minimal Maintenance

The high durability of FRP structures, including bridges, ensures a long life, even in demanding conditions. This is important for structures located in different world regions, where atmospheric actions are extreme. The corrosion-free property of FRP structures results in low maintenance, which is very important for long-span bridges with limited access [8,20,22].

### 3.6. Free Formability

The manufacturing technologies of FRP material allow for production and forming of different, complex and sometimes custom shapes of bridge components. This is important for composite decks, which often have quite complicated cross-sections made as one element (module), and FRP profiles used as a main load-carrying members. The free formability of composites allows for the formation of practically any shape of formworks dedicated to particular bridge elements [8].

### 3.7. Competitive Life Cycle Cost

High corrosion resistance, low maintenance requirements and the long overall service life of FRP bridges reduce their costs. In the long run, one should hope that FRP bridges will be cost-competitive with traditional bridges made of steel or reinforced concrete [8].

### 3.8. Electrical and Thermal Insulation

High electrical insulation is another favorable parameter of FRP composites. Application of these materials minimizes the complexity of earthing. It allows for a reduction in the costs of both installation and future inspections.

FRP composites provide a significantly lower heat distribution gradient than metals, i.e., steel and aluminum. This is important, considering that temperature gradients causes additional internal forces in the bridge structure during the summer and winter.

## 4. FRP Composites in the Bridge Industry

Although composite materials came into common use relatively long ago, their application as a basic material in construction was very limited and late. The first use of composites took place in boatbuilding, with the first FRP composite boats built in the 1940s. It is estimated that currently about 90% of boats are built from composite materials. In the next decade, the automotive industry began to use composites to make car bodies. This material was also used in later years for the construction of cabs and fairings for trucks. The 1970s saw the use of composites in the aviation industry for the construction of aircraft fuselages. These materials began to be the basic construction material in many other applications, such as the green energy industry for the construction of windmill components, as well as in the chemical industry for pipelines, tanks and many other purposes.

The first applications of FRP composites in the building industry were related to the reinforcement of existing structural elements or as architectural elements. In the first case, the reinforcements included mainly reinforced concrete structures, as well as masonry, steel and wooden structures. It was only since the 1980s that the first attempts were made to construct building objects with the main load-bearing structure made of composites. Bridges were the first construction objects to use composite as the basic construction material.

Generally, the scope of application of FRP composites in the bridge industry is very wide. They are used as material to strengthen bridges, as well to build their structure. FRP composites are applied to repair deteriorated bridges and make them useful in terms of actual standard requirements, which are being updated or, in cases of necessity, to increase load-carrying capacity. The second field of application includes new construction. FRP composites are used to form bridge decks, as well as reinforcement in concrete decks instead steel bars. These materials are also used for composite columns or piers. In suspension bridges, the cables are made of FRP materials. Another application of these composites is in stay-in-place formworks.

The first attempts at application of FRP composites in the bridge industry were made in the mid-1970s. FRP profiles were used in the decks and superstructure members of bridges [33,34]. Short-span pedestrian bridges were the first to be made of FRP composites, such as the first FRP pedestrian bridge completed in Israel in 1975 [35]. Footbridges are the most common type of bridge built using FRP composites.

One of the two road bridges mentioned in the literature as the first made of FRP composite is the Ginzi Highway bridge (Figure 2). It was built in Bulgaria in 1981/82 [29,36,37]. Its structure was a GFRP slab fabricated as one element by the hand layup method [22]. The span of the Ginzi bridge is 11.9 m, and the width is 6.1 m [38].

The second whole FRP bridge was the Miyun bridge, built in 1982 in Beijing, China (Figure 3). It was initially built as a simply supported two-lane bridge with a span of 20.7 m and a width of 9.2 m. The structure of Miyun bridge comprised a beam system consisting of six honeycomb sandwich GFRP box girders [39].

**Figure 2.** First FRP bridge in Ginzi, Bulgaria [40].

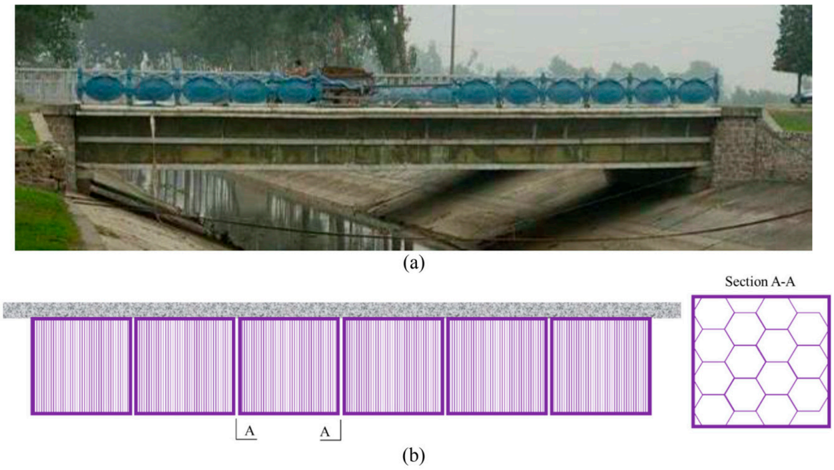


**Figure 3.** View (**a**) and cross section (**b**) of Miyun bridge [39].

Due to local buckling and damage observed in the FRP girders after five years of operating, it was necessary to repair and strengthen the Miyun bridge structure. Therefore, a decision was made to cast a 100 mm thick reinforced concrete slab on the GFRP box girders. Steel bolts were used as the shear connectors, which joined the concrete slab with the composite beams and ultimately made the Miyun bridge structure an FRP–concrete hybrid beam bridge. In 2004, the bridge was demolished [39].

To date, more than 300 FRP composite bridges have been built. The overwhelming majority are footbridges (more than 200), most often with a small span. More than 100 road bridges have been built as whole FRP structures, although so far, no decision has been made to build any railway FRP bridges.

The bridges described above should be treated historically. The structural solutions and technologies used in their construction have been significantly changed and improved, as described below.

## 5. Structural Elements of Bridges Made of FRP Composites

Taking into account the high durability of fiber-reinforced polymer composites, they are most often used for the construction of deck slabs, which are most exposed to aggressive environments. In addition, FRP composites, due to their high strength, are used to build deck girders.

The most widespread FRP bridge systems are presented below. However, there are also many systems that are used locally in different regions.

### *5.1. FRP Deck Panels*

The widest application of FRP composites in bridge engineering involves construction of deck slabs. This is due to high durability of FRP compared to traditional materials, especially concrete. The issues of durability and resistance to environmental conditions are of particular importance here [41] because the deck slab is the most exposed to destructive factors, such as aggressive rainwater, concentrated loads from vehicle wheels, temperature changes and freezing/defrosting cycles, among others.

FRP slabs can be divided into three main groups: decks composed of pultruded profiles; sandwich panels; and hybrid decks, most often composed of FRP composite and concrete [42].

Among the solutions for bridge structures using FRP composites, pultruded profiles are the most popular. They consist of individual beam elements joined by glue or mechanical fasteners, forming the deck slab. A slab constructed in this way is then attached to the main girders of the deck (beams) with fasteners. Pultruded profiles are most often positioned across the bridge.

Due to current production technology, pultruded profiles must have a constant cross-section, which causes certain difficulties in shaping the transverse slopes of the deck. Therefore, an additional slope layer is made on the deck using low-shrink grouts [43].

The process of designing pultruded profiles mainly includes the selection of materials, as well as the location and orientation of the fibers. The shape of the cross-section can, in principle, be of any type, although for ease of manufacturing and associated cost reduction, triangular and rectangular sections are typically used in a variety of configurations. The implementation of a new type of section in production is associated with significant investment expenditure; hence, it is economically justified only in the case of large-scale production [44].

Due to their relatively low cost, polyester resins are often used for production, although in humid environments, it is preferable to use vinyl ester resins.

The undoubted advantage of this type of structure is the repeatability of the pultruded elements, which allows for their mass production with the use of refined and widely known technology. It is recommended [44] to adhesively bond the individual profiles in the factory in order to ensure better quality control.

Standardized system solutions for pultruded profile decks have been developed based on many years of research and experience, primarily in the United States. Some examples are presented in Figure 4.

EZ-Span decks (Figure 4a) consist of triangular-sectioned pultruded beams glued to each other and to the lower and upper flanges. The thickness of such a constructed panel is constant and amounts to 216 mm. The weight of the structure is approximately 96 $\frac{kg}{m^2}$ [43].

The SuperDeck system (Figure 4b) was first used in 1997 in the United States. The deck consists of octahedron and double-trapezoidal sections arranged alternately and glued to each other with polyurethane adhesive. Before gluing, the adjoining surfaces of the sections are shot-blasted until the fibers are exposed [42].

Another system developed in the United States and used all over the world is the DuraSpan system (Figure 4c). It consists of pultruded sections with a several-chamber trapezoidal cross-section. Individual sections are joined with polyurethane glue. The system comes in several variants, the most popular of which are DuraSpan500, with a span up to 1.5 m, and DuraSpan766, with a span up to 3 m [42]. DuraSpan decks are most often combined with steel beams, although they are also used in conjunction with timber and prestressed concrete beams [45].

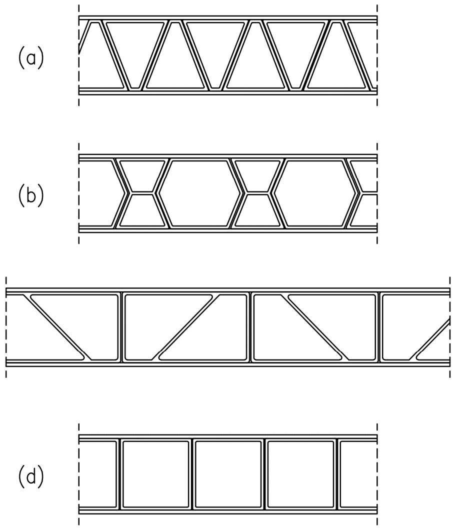


**Figure 4.** Examples of bridge decks made of adhesively bonded pultruded profiles: (**a**) EZ-Span, (**b**) Superdeck, (**c**) DuraSpan, (**d**) Strongwell FRP Deck System; from [44].

The Strongwell system (Figure 4d) consists of pultruded square profiles joined by gluing. The profile width/height is 152.4 mm, and the wall thickness is 9.5 mm. The number of profiles in a prefabricated panel depends on the specific application. Additionally, the individual profiles are connected by pultruded plates glued to their upper and lower surfaces. Moreover, the joining of the individual profiles is ensured by a steel transverse bar. A panel has length equal to the width of the deck. Consequently, the construction of the entire deck requires multiple panels to be laid one after the other. The connections occur only in the direction across the bridge and are made by gluing the appropriately profiled edges of the panels [46].

In Europe, the first and most popular composite deck is the ASSET system deck (Figure 5), produced by Fiberline, a Danish company. The system consists of profiles with double triangular chambers. The individual profiles are connected by means of a glued joint. ASSET was first used during the reconstruction of the Westmill Bridge in Oxfordshire, England. Another example is the Friedberg Bridge in Germany, where an ASSET deck is supported by steel beams. The weight of the bridge superstructure was approximately $14\frac{\text{kN}}{\text{m}}$. For comparison, in the case of the reinforced concrete slab deck, it was $84\frac{\text{kN}}{\text{m}}$, and for the composite deck (steel beams + reinforced concrete slab), $62\frac{\text{kN}}{\text{m}}$ [47].

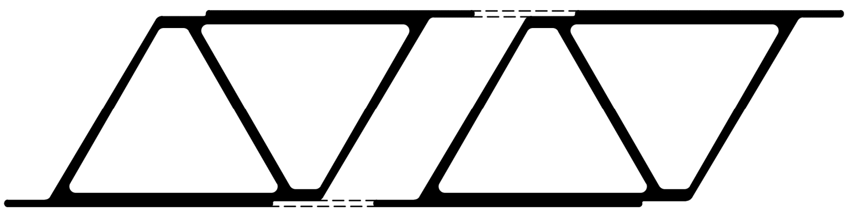

**Figure 5.** ASSET FRP deck, based on [47].

Among the composite structures used in bridge engineering, composite sandwich panels have been used the longest [8]. These types of decks most often consist of two FRP sheets combined with a core (Figure 6). The concept of sandwich panels was first implemented in the aviation industry [48], then in automotive, shipbuilding and finally in construction and other industries.

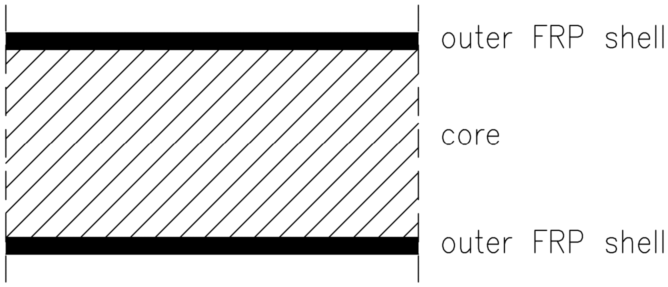


**Figure 6.** Typical structure of a sandwich panel.

Whereas the outer shells are made of a material of high stiffness and strength, the core itself is characterized by relatively low strength parameters. Its task is primarily to transfer shear stresses, as well as to increase the distance between the outer shells, which greatly increases the moment of inertia and stiffness of the entire panel while maintaining low weight of the structure. In terms of mechanics, sandwich panels can therefore be compared to traditional I-beams, where the outer panels, like the flanges of the beam, carry the normal stresses from bending, whereas the core function corresponds to the web of the beam. Additionally, the core stabilizes the shells, preventing them from locally buckling.

The outer shells are connected to the core by an adhesive, the primary function of which is to transfer shear stresses between these two elements.

Although the structure of the outer shells is relatively standardized, the cores have different forms (Figure 7). Their configuration and thickness, as well as the shell thickness, largely determine the global parameters of the entire panel [49].

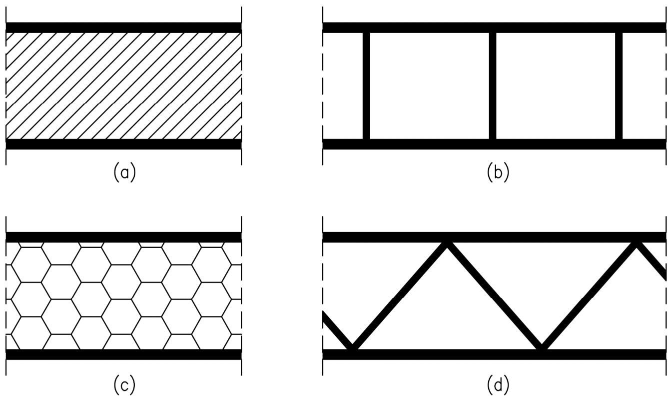


**Figure 7.** Basic types of cores in sandwich panels: (**a**) foam filling, (**b**) vertical webs, (**c**) honeycomb structure, (**d**) truss core; based on [49].

Honeycomb fillings are a relatively popular solution in composite decks. In structures of this type, the outer sheets are connected to the core made of corrugated sheets. Research has shown that panels of this type are characterized by high load-bearing capacity and low weight [49,50]. Their significant disadvantage, in turn, is the time-consuming production technology, which translates into the high cost of the panel. The internal profiles are attached to the rest of the elements with adhesive, which creates a risk of detachment of the core from the facings.

Foam cores (most often made of polyvinyl chloride (PVC) and polyurethane) are characterized by a simple production technology, which translates into a lower final cost of the structure than in the case of honeycombs. On the other hand, structures of this type are characterized by poorer strength characteristics and a less favorable weight-to-load capacity ratio [49].

*5.2. FRP Beams and Girders*

Regardless of the structure of the deck slabs, attempts are made to use FRP beams in bridge engineering, but designers and constructors face limitations of low stiffness of these elements, which is a serious barrier to the construction of long spans.

Despite this inconvenience, many bridges with FRP beams have been erected, usually with small or medium spans. The first implementations of this type used box-section beams manufactured by the traditional method of manual lamination.

For example, in the second half of the 1990s, in the United States, the Ineel system was developed. The system is schematically presented in Figure 8. The deck structure is based on U-shaped composite beams made of glass fibers and polyester and vinyl ester resin. The rounding of the beams in their lower part provides stability during the formation of the element and improves its stiffness at the stage of operation. Near the supports, a steel frame was designed inside the beam to ensure greater stiffness and safe transfer of support reactions. The beams are combined with the sandwich composite deck slab with a thickness of about 14 cm. Moreover, bolted connections are used to join the beams and the platform.

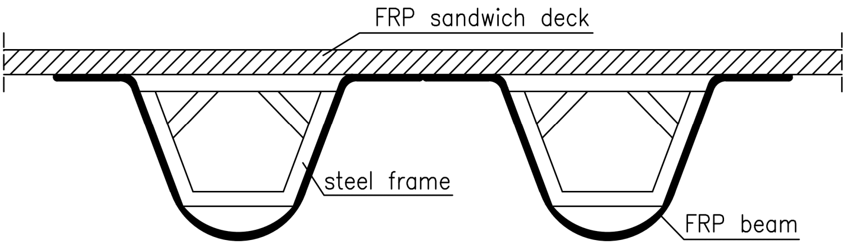


**Figure 8.** Schematic of an Ineel deck using composite beams with a box cross-section [51].

An example of a composite beam system implemented for practical use is the SuperFiberSpan system (Figure 9), in which prefabricated elements are delivered to the construction site in the form of a set of T-beams made of glass–vinyl ester laminates factory-assembled with the sandwich deck slab, which eliminates the need to connect these elements on the construction site. The interior of the beams and the deck slabs is filled with PUR foam [8].

**Figure 9.** Installation of prefabricated elements of a SuperFiberSpan composite deck [52].

As previously mentioned, the main disadvantage of FRP beams is their low stiffness. This limitation is less severe in the case of footbridges due to the lower values of the loads. For this reason, composite beam and slab structures are currently used primarily in footbridges. The dynamic development of this type of structure that has taken place in recent years has introduced many system solutions for composite girders. An example is the EcoSafe system of the Dutch company Lightweight Structure [8,53].

In bridge construction, girders made of pultruded profiles are also used, similarly to steel sections (Figure 10). Therefore, angle bars, channels, I-sections, and rectangular and square profiles are produced. They can be used as platform beams in structures with small spans or constitute elements of trusses or even arched structures.

**Figure 10.** Examples of composite pultruded profiles [54].

The problem of low stiffness of FRP beams can be solved by using hybrid girders, which are a combination of composite beams with other materials, most often concrete. An example of such a solution is shown in the Figure 11.

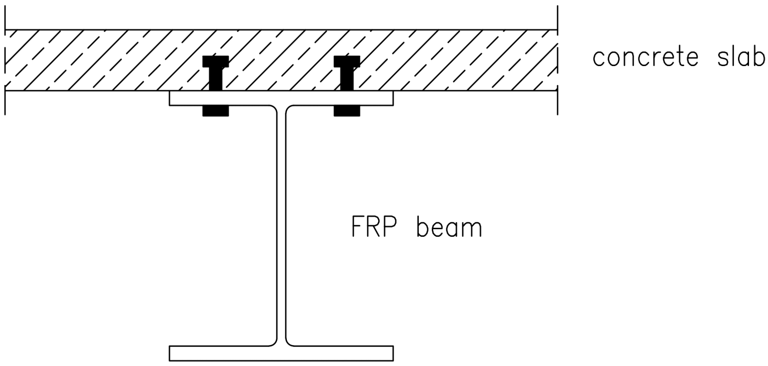


**Figure 11.** Hybrid girder, FRP–concrete.

The use of a massive concrete slab effectively increases the stiffness of the entire girder, allowing for the effective use of the properties of individual components. In a girder subjected to bending, the compressive stresses are transferred by concrete, while the tensile stresses occur in the composite element. The use of concrete also allows the cost of the entire structure to be reduced. Hybrid solutions have been in use for about 20 years [8].

Their excellent strength-to-weight ratio, unattainable for traditional building materials [55], predestines composites for use in portable bridges, especially in the case of temporary military bridges, where low weight and ease of transport, combined with high strength, are features of particular importance. Therefore, FRP composites are used to make both pontoon bridges (Figure 12), as well as trusses, beams and other structures. The first objects of this type were built at the turn of the 20th and 21st centuries in the United States.

**Figure 12.** An example of a military pontoon bridge made of FRP composites [56].

A composite army bridge (CAB) is made of carbon fiber composite. The sandwich deck consists of two outer FRP panels with balsa wood filling between them. The structure, 14 m long and 4 m wide, weighs less than 600 kg [57].

Another example of a military bridge using FRP composite is the modular composite bridge (MCB). The span, 26 m long and 4 m wide, is made of box-sectioned modules [57].

Since the 1980s, composite bars for concrete reinforcement and tendons for prestressing concrete structures have also been used. Their main advantage is much higher corrosion resistance than their steel counterparts. Their high strength and high fatigue resistance are also of great importance. Composite tendons are also used in suspension systems of bridge structures, mainly in footbridges. It should be borne in mind that at present, a major barrier to the use of FRP tendons is the lack of a reliable and easy-to-apply anchoring system [8].

## 6. Difficulties and Limitations

Regardless of the numerous advantages of FRP composites mentioned above, there is a number of problems and limitations that make their use in bridge structures difficult.

The basic limitation mentioned in the literature is the high cost of composite structures—higher than in the case of traditional materials [38]. This is due, firstly, to the cost of the material itself and, secondly, to the production technology of composite elements. Technologies used in industry allow for achievement of relatively low costs for repetitive elements produced in large series (e.g., in the aviation industry). In the case of bridge structures, individually designed elements dedicated to a specific design solution are usually used, which increases the cost.

For example, in [58], cited by Brown et al. [59], the cost of material for the production of 1 m$^2$ of an FRP honeycomb panel was estimated at about $484.38, and the corresponding reinforced concrete slab at $215.28.

However, it should be remembered that this remark concerns the cost of the composite structure itself. Its lightness allows for the use of smaller (cheaper) foundations and facilitates assembly, which, to some extent, reduces the costs of the whole structure. Moreover, composite structures are characterized by high durability, which, in the long term, implies a reduction in the cost of their repair and maintenance compared to steel or concrete structures. On the other hand, taking into account that the first composite bridges were built about 40 years ago, this advantage has not been practically proven. The current Eurocode standards require 100 years of durability of bridge structures. Therefore, taking into account the above, the final balance of costs related to the construction and maintenance of composite bridges has not yet been fully verified in engineering practice.

One example of attempts to comprehensively assess costs is a study by Haak [60], in which the author estimated the cost of making 1 m$^2$ of a pultruded FRP deck at around $363.29. In contrast, the cost of making 1 m$^2$ of concrete deck was estimated at about $263.07, which is a difference of almost 40%. Simultaneously, the cost of maintenance and subsequent demolition of the concrete structure was almost three times higher. Finally, for the model two-span road structure described in [60], the total cost of erecting and operating of the FRP and concrete bridge was similar.

An example of a comparative cost analysis of a bridge structure with an FRP and a traditional structure is discussed in [61]. Three concepts of a road bridge with a span of 21 m and a width of 10.54 m, differing in terms of girder cross-section and material, were compared. In the first variant, box-sectioned FRP beams were used; the second concept involved T-section beams made of prestressed concrete; and the last variant included typical I-sectioned steel beams. In each case, the girders were combined with a concrete slab. Apart from the material and shape of the main beams, the individual concepts did not differ significantly. Using the LCCA (life-cycle cost analysis) procedure, an analysis of the costs of erecting, maintaining (repairing, renovating) and dismantling and utilizing each type of bridge was carried out. The obtained results are summarized in Table 2. The cost of erecting a bridge with FRP girders turned out to be higher by about 13% compared to prestressed concrete structures and only about 7% higher than in the case of traditional steel beams. In turn, the maintenance costs of the FRP bridge turned out to be almost half lower than in the case of traditional structures. In total, after taking into account the costs of demolition, the bridge with FRP structure turned out to be the cheapest solution.

**Table 2.** Comparison of construction, maintenance and demolition costs of different types of bridges [61].

| Cost [million PLN] | FRP Girders | Prestressed Concrete Beams | Steel Girders |
|---|---|---|---|
| Initial construction | 3.358 | 2.965 | 3.133 |
| Operation, maintenance and repair | 0.814 | 1.212 | 1.443 |
| Disposal | 0.092 | 0.111 | 0.092 |
| **Total** | 4.263 | 4.288 | 4.669 |

Another limitation is the characteristics of the material itself and, more precisely, the lack of a plastic scope of work [62], which is particularly desirable in bridge structures, as it enables the redistribution of internal forces. More importantly, such a property of the composite implies a brittle failure mechanism with no visible plastic deformation, so the possible failure of a structural element is sudden.

Moreover, the behavior of FRP under the influence of temperature changes is a major engineering problem. First, the thermal expansion coefficient of typical composites differs significantly from that of steel and concrete, which makes it difficult for these elements to work together after bonding. However, a particular problem for designers is the low resistance of composites to high temperatures. For example, in the case of composites with a polyester matrix, a decrease in strength is already observed at 80 °C [38]. It is therefore a significant problem not only in fire situations, but even in normal use, especially in the case of specific renovation work.

Regardless of the above, the factor limiting the development of FRP composites bridges is the lack of engineer experience, as well as the lack of national standards for the design of this type of structure. Each design case is considered individually; the design process is supported by research, which extends the entire process and generates additional costs.

The lack of standardized design methods mainly concerns connections that have been "borrowed" from metal structures without being specifically adapted to a new type of material.

Among the limitations of the use of FRP composites in bridge engineering, some other issues are also discussed in the literature, namely the creep susceptibility of the material and low resistance to the impact of loads, which, when applied directly to the composite element, easily lead to its failure.

## 7. Conclusions

The use of polymer composites in bridge engineering has a relatively short, approximately 40-year history. A number of features of FRP composites indicate their suitability for building bridges. These include very high strength, low weight, good fatigue durability and resistance to difficult environmental conditions. Previous experience with the operation of FRP bridges seems to confirm the above-mentioned advantages, although due to the short service life of this type of structure, these conclusions are still premature.

A testing ground for composite bridge structures are footbridges, in which, due to relatively low loads, new materials and construction solutions are tested. For this reason, the construction of footbridges is currently the fastest growing branch of bridge construction.

Despite decades of world experience in the construction of composite bridges, there are still many unresolved problems limiting the development of composite structures. These barriers can be divided into basic groups: technical and socioeconomic barriers.

Bridges of this type should still be treated as experimental structures, which translates into the need for constant and thorough inspection of their technical condition. Non-destructive testing (NDT) methods, especially systems for continuous monitoring of structures (intelligent bridges), may turn out to be particularly useful.

The most important challenge for the future is the unification of methods of designing FRP structures, the development of national standards and rules for designing connections.

Education of the engineering community and the promotion of new materials and design solutions are also of key importance.

**Author Contributions:** Conceptualization, P.G.K. and W.W.; methodology, P.G.K. and W.W.; validation, P.G.K. and W.W.; formal analysis, W.W.; investigation, P.G.K. and W.W.; resources, P.G.K.; data curation, P.G.K. and W.W.; writing—original draft preparation, P.G.K. and W.W.; writing—review and editing, P.G.K. and W.W.; visualization, P.G.K. and W.W.; supervision, P.G.K. and W.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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