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Review

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# A Review of Fibre Reinforced Polymer Bridges

Jawed Qureshi 

School of Architecture, Computing and Engineering (ACE), University of East London, 4-6 University Way, Beckton, London E16 2RD, UK; j.qureshi@uel.ac.uk; Tel.: +44-020-8223-2363

**Abstract:** Fibre-reinforced polymer composites (FRPs) offer various benefits for bridge construction. Lightweight, durability, design flexibility and fast erection in inaccessible areas are their unique selling points for bridge engineering. FRPs are used in four bridge applications: (1) FRP rebars/tendons in concrete; (2) repair and strengthening of existing bridges; (3) new hybrid-FRP bridges with conventional materials and (4) all-FRP composite new bridges made entirely of FRP materials. This paper reviews FRP bridges, including all-FRP and hybrid-FRP bridges. FRP bridges' history, materials, processes and bridge components—deck, girder, truss, moulded parts and cables/rebars are considered. This paper does not discuss the use of FRP as an architectural element and a strengthening system. While lack of design codes, material specifications and recycling are the major challenges, the high cost of FRPs still remains the most critical barrier to the progress of FRPs in bridges.

**Keywords:** FRP bridges; FRP composite material; FRP deck; FRP beam; FRP sandwich construction; hybrid-FRP bridges; recycling; FRP truss; FRP girder; FRP design code; FRP rebars; fire performance

## 1. Introduction

Fibre Reinforced Polymer (FRP) composites have been used in decks and superstructure members of bridges since the 1970s [1–4]. The first pedestrian bridge is reported to have been built by the Israelis in 1975 [5]. FRP footbridges can be truss, cable-stayed or girder bridges [6]. The first all-composite vehicular bridge is Miyun Bridge, built in 1982 in Beijing, China [7]. Since then, many FRP pedestrian and road bridges have been constructed in Europe, China, Japan, and the USA. FRPs have various advantages for bridge engineering, such as lightweight, pre-fabrication, corrosion resistance, mouldability, fast installation in inaccessible areas and electrical insulation—glass FRP [8,9]. Although major impediments to the wider application of FRPs in construction are lack of design codes, material specifications and recycling, the high cost is still the main barrier to their widespread growth.

Construction represents 25% of global FRP production [10–12]. FRP contains fibres placed in a polymer resin matrix. Carbon and glass fibres are the most common fibres in bridges. Aramid fibres are sometimes used in cables of cable-stayed bridges. Basalt fibres are also being researched for potential use in bridges. Thermoset resins, such as polyester, vinylester or epoxy resins are used as matrices. Resins give shape to the fibres and protect them from environmental factors. Resin also sticks the fibres together and transfers forces between them. Fibres provide strength and stiffness to FRP parts [3,13–17].

Limited research publications have emerged in the last two decades on the review of FRP bridges. A book published in 2014 [18] on FRP bridges mainly relates to strengthening, repairing and retrofitting applications of FRP. It also covers FRP prestressing tendons and sheets, and cables. New hybrid-FRP bridges with conventional materials and all-FRP composite new bridges made entirely of FRP materials are not discussed in this book. Research papers are also available on specific bridge components or areas: highway decks—most of them dormant now [9,19–25], railway applications [26], girders [27] tendons [28,29] and cables [30–33]. From 2000 to 2010, a few review papers were written on all-FRP and



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hybrid-FRP bridges [4,34–36]. More recently, two papers in 2021–2022 [10,37] reviewed materials, methods and history of all-FRP bridges.

Most review papers [4,34–36] were published in the early 2000s. The FRP bridge industry has changed ever since and some FRP products have become dormant, in particular off-the-shelf vehicular decks and girders. This paper presents a state-of-the-art review of FRP bridges, mainly focusing on all-FRP and hybrid-FRP bridges. FRP composites in new-build bridges only are considered in this paper. FRP bridges often use moulded or pultruded FRP elements. Pultrusion is an automatic process for producing constant section profiles. Moulding is a manual method of fabricating complex sections virtually into any shape. Quite often, moulding leads to aesthetically pleasing bridge elements. The use of FRP in strengthening, retrofitting and repair of existing bridges made with steel or concrete is not discussed in this paper.

The aim of this paper is to present a historical perspective of materials, methods, structural form, fire performance, challenges and outlook for fibre-reinforced polymer bridges. This is presented in a review format. The use of FRP materials was quite popular during the 1980s and 1990s on several road and footbridges. However, FRP in road bridges has seen a decline in the last decade or so with many FRP parts becoming either dormant or no longer in use. The cost seems to be driving this change. The use of FRP in footbridges has seen growth though, mainly due to geometric possibilities that can be achieved using moulded FRP elements. The challenges and opportunities of FRP composites in bridges will also be among the key highlights of this paper.

The history of FRP bridges, including pedestrian and vehicular bridges, is presented in Section 2. FRP constituent materials and sandwich panel construction are examined in Section 3. FRP manufacturing methods are considered in Section 4, including automatic and manual processes. Various custom-made and standard FRP bridge components are reviewed in Section 5. The structural behaviour of FRP bridges under elevated temperatures and fire is reported in Section 6. Challenges and outlook for the use of FRP composite materials in bridge engineering are appraised in Section 7. Finally, the main conclusions are drawn in Section 8. Information about selected all-FRP and hybrid-FRP bridges constructed around the world is included in Appendix A.

## 2. History of FRP Bridges

Steel and concrete materials still dominate bridge construction. Fibre-reinforced polymer (FRP) materials provide an alternative to traditional materials in new bridges. Applications of FRP are in all-FRP or hybrid-FRP pedestrian and road bridges. In all-FRP bridges, the substructure (piers and abutments) is usually constructed using traditional materials. While the superstructure (decks, girder and cables) is made of FRP. In hybrid-FRP bridges, the main FRP components are girders, decks, external cables and parapet elements [36].

Prototype FRP composite bridges are believed to have been first conceived in Europe and North America around the 1970s. It is hard to establish when the first ever FRP bridge was constructed. The first all-FRP road bridge in the world, Miyun Bridge, was constructed in 1982 in Beijing, China. The bridge had a span of 20.7 m with six hand-laminated glass fibre/polyester sandwich girders. At the same time, the first hybrid-FRP bridge, Ginzi Highway Bridge, 11.9 m long was constructed in Ginzi, Bulgaria, in 1981/82. It used FRP composite beams and other bridge parts were constructed with traditional materials. Both bridges used energy and the labour-intensive hand lay-up method [8,36,38,39]. The major developments in FRP bridges happened in the 1990s when Aberfeldy Footbridge and Bonds Mill Lift Bridge were built in the UK and the No-Name Creek Bridge in the USA. Many FRP bridges were constructed after that using pultrusion, filament winding, wet or hand lay-up and resin infusion processes. In the following sections, selected examples of all-FRP and hybrid-FRP bridges are presented.

## 2.1. Examples of All-FRP Bridges

### 2.1.1. Aberfeldy Footbridge, Scotland, 1992

The Aberfeldy pedestrian bridge was the UK's first major footbridge completed in 1992 in Scotland. This was a key development towards large-scale all-FRP bridge construction. The bridge connects two halves of a golf course on either side of the River Tay. The bridge comprised a GFRP deck, suspended by Parafil aramid ropes (cables) from two A-shaped GFRP towers. This cable-stayed bridge had a major span of 64 m, which was then believed to be the longest span in the world. It had an overall length of 113 m with a load capacity of 10 kN/m. Aberfeldy Footbridge was an all-composite bridge except for concrete foundations. The bridge was initially designed to carry pedestrians but later strengthened with CFRP to carry motorised golf buggies [4,34,38,40]. Structural health monitoring of the bridge was carried out by Stratford [41] after 20 years of service. Figure 1 shows Aberfeldy Footbridge.



**Figure 1.** Aberfeldy cable-stayed pedestrian bridge, Scotland [42].

### 2.1.2. Bonds Mill Lift Bridge, UK, 1994

Lightweight FRP offers great benefits when moveable bridges are required. The lifting machinery is significantly reduced with the lightweight components of the bridge [40]. Bonds Mill Lift Bridge, shown in Figure 2, was the first UK all-composite road bridge, installed in Gloucestershire in 1994. This 8 m single bascule bridge provides access to a private industrial estate for heavy trucks over the Thames–Severn canal. The bridge used the same cellular pultruded GFRP system—Advanced Composite Construction System (ACCS) as in Aberfeldy Footbridge. To resist local bending under wheels, the upper portion of the cellular system was filled with structural foam. The bridge was designed to carry full highway loading including a 38-tonne truckload. After eight years of service, an inspection was carried out by Hollaway [43] with no deterioration in GFRP. However, there was a wearing surface at the south end of the bridge due to the impact of lorries running at a steep slope from the industrial estate [8,40,43].

### 2.1.3. No-Name Creek Bridge, USA, 1996

No-Name Creek Bridge is the first all-FRP composite road bridge in the USA. This 8 m span bridge was built in 1996 in Russel, Kansas, by Kansas Structural Composites. It consisted of a sandwich deck with GFRP laminated skins and a honeycomb core. It is a single-span bridge supported on steel abutments. Static and fatigue field tests were carried out on the bridge in 1997, 2004 and 2008 to investigate the environmental degradation of FRP material [44].



**Figure 2.** Bonds Mill Lift Bridge over the Thames–Severn canal in Gloucestershire, UK [40].

#### 2.1.4. Kolding Bridge, Denmark, 1997

Kolding Bridge, Denmark (Figure 3) is the first FRP footbridge over a busy railway line. The cable-stayed bridge was constructed completely of glass fibre-reinforced polymer in 1997. This 40 m-long footbridge had two spans of 27 m and 13 m. The bridge had  $100 \times 100$  mm square hollow tube GFRP cables, a 1.5 m deep girder and 18.5 m pylons made of standard FRP profiles. The bridge weighed 12.5 tonnes, half of the steel alternative, and was installed in 18 h [45]. Kolding Bridge is an all-FRP bridge, except for abutments at the foundations; and bolts are made of stainless steel [46].



**Figure 3.** The 40 m Fiberline Composites bridge in Kolding, Denmark [46].

#### 2.1.5. Pontresina Truss Footbridge, Switzerland, 1997

Pontresina Truss Footbridge is a 25 m long all-FRP temporary footbridge constructed in Pontresina Switzerland in 1997, shown in Figure 4. The bridge crosses Flaz Creek in the Swiss Alps at an altitude of 1790 m. This temporary bridge is mainly used in winter for ski tourism. During summer, the bridge is removed due to the potential risk of high water and is stored on the bank. Each year the bridge is installed in the autumn and removed in the spring. The bridge used five different types of pultruded GFRP profiles assembled into two multi-layer truss girders connected by cross beams and stabilised by the bracing. It has two 12.5 m spans with bonded joints in one span and bolted in the other [36,47,48].



**Figure 4.** Pontresina Truss Footbridge, Switzerland [36,46].

#### 2.1.6. Halgover Footbridge, UK, 2001

Halgover Footbridge shown in Figure 5 is the first bridge using a different processing method than pultrusion. The bridge was installed in 2001 over the A30 in Cornwall, UK. This 47 m span suspension bridge used resin-infused glass FRP decking [49]. Later in 2015, a geometrically nonlinear static and dynamic analysis of the bridge was carried out by Gunaydin et al. [43] and the results of this all-FRP bridge were compared with an identical steel bridge.



**Figure 5.** Halgover Footbridge, Bodmin, UK, 2001 [49].

#### 2.1.7. Lleida Footbridge, Spain, 2001

Lleida Footbridge is a double-tied arch bridge spanning 38 m over a high-speed train line between Madrid and Barcelona in Spain. The bridge used Fiberline profiles [46], as seen in Figure 6. It was completed in 2001 and officially opened in 2004. The arches and bridge deck girders used rectangular hollow sections. All joints were bolted using stainless steel bolts and brackets [50]. The bridge weighed 19 tonnes and all profiles used E-glass fibres with polyester resin. It was designed for a  $4 \text{ kN/m}^2$  serviceability load as per Spanish bridge design codes. The partial safety factors for materials to verify ULS were 2 and 3 for normal and shear stresses. The design was mainly controlled by deflection with some elements of arches, where buckling stability governed [39].



**Figure 6.** Lleida Footbridge, Spain, 2001 [50].

#### 2.1.8. West Mill Bridge, UK, 2002

West Mill highway bridge seen in Figure 7 was constructed over the River Cole near Shrivenham in Oxfordshire, UK in 2002. It was the first all-FRP road bridge in Western Europe, incorporating glass and carbon fibre-reinforced composites. The bridge span was 10 m and the width was 6.8 m. The bridge contained four 10 m GFRP box beams stiffened by CFRP flanges. A total of 34 GFRP ASSET deck profiles (transverse) were bonded to these beams. The bridge used reinforced concrete abutments and reinforced concrete parapet beams with steel parapets [34,51]. Structural health monitoring and repair of the bridge were carried out by Canning et al. [52] and Sebastian et al. [53].



**Figure 7.** West Mill Bridge, Oxfordshire, UK, 2002 [52].

#### 2.1.9. Fredrikstad Bascule Footbridge, Norway, 2003

The Fredrikstad pedestrian bascule FRP footbridge in Norway was the first moveable lifting bridge in Europe. The bascule footbridge is shown in a closed state in Figure 8a and an open state in Figure 8b. This 60 m long and 3 m wide pedestrian bridge was completed in 2003. The bridge did not have any counterweights to operate the opening mechanism. Instead, it had a large hydraulic cylinder at each side to lift the bridge. By using FRP material the weight of each moveable part was reduced to 20 tonnes, with FRP elements weighing 9 tonnes. The bridge uses double-curved boxed girders with longitudinal and transverse stiffeners inside. The deck is a sandwich structure with CFRP reinforcements and a balsa core. All FRP parts, except side panels, were manufactured by vacuum-assisted resin infusion [54,55].



**Figure 8.** Fredrikstad Bascule Footbridge Norway, built in 2003 [55]: (a) Bridge in a closed state; (b) Bridge in an open state for navigation.

#### 2.1.10. St Austell Railway Bridge, UK, 2007

St Austell Railway Bridge was installed over the Paddington–Penzance railway line near St Austell station, Cornwall, UK in 2007. The front and side view of the bridge is given in Figure 9a,b, respectively. This all-FRP footbridge replaced an old corroded wrought-iron bridge built in the early twentieth century. It used the same FRP cellular system (ACCS) as in Bonds Mill and Aberfeldy FRP bridges. The bridge had three simply supported spans, with a main span of 14 m and two side spans of 6 m each. The main 14 m span weighted just 5 tonnes replacing the 26 tonnes old structure. It had a U-shaped cross-section made from pultruded FRP elements with an outer FRP moulded shell. The bridge had to be supported on existing masonry piers and abutments. This bridge is designed for a standard footbridge loading of  $5 \text{ kN/m}^2$ . It was fabricated off-site and installed in only eight hours [26,56,57].



**Figure 9.** St Austell Railway Bridge, Cornwall, UK, built in 2007 [56]: (a) Front view of the bridge; (b) Side view of the bridge.

#### 2.1.11. ApATeCh Arched Footbridge, Russia, 2008

ApATeCh arched footbridge (seen in Figure 10) is an all-composite bridge installed by ApATeCh [58] in Moscow Russia in 2008. Except for metal hinges and fence fasteners, all parts are made of FRP composites. The bridge had a central arch and two beams. It is 22.6 m long, 2.8 m wide and weighs just 4.5 tonnes. The bridge was the first FRP bridge in Russia made by the vacuum infusion process. Using vacuum infusion reduced assembly and manufacturing time resulting in low cost. This production technology improved aesthetic possibilities with new pleasing structural forms.





**Figure 10.** ApATeCh arched footbridge, Moscow, Russia, built in 2008 [39].

#### 2.1.12. Bradkirk Footbridge, UK, 2009

Bradkirk Footbridge is one of the first few bridges using moulded FRP composites and is shown in Figure 11. This all-FRP bridge was installed near Kirkham in Lancashire over the Preston–Blackpool North Line. The bridge contained two 12 m spans with a staircase at each end. Each span weighed just two tonnes. The bridge installation was completed in just six hours overnight. The moulded FRP composite used two layers of woven E-glass cloth with resin in between them. Then, a vinylester tie coat was applied with a polyester gelcoat. The material was then placed in the mould, bagged and cured at 70 °C [59]. Halgavor footbridge also used the same moulding process [8]. The structural health monitoring system was used to measure the effect of train buffeting on the dynamic behaviour of the bridge [59].



**Figure 11.** Bradkirk Footbridge, Kirkham, Lancashire, UK, built in 2009, with permission from Taylor & Francis, License Number: 5538760110498 [59].

#### 2.1.13. Dawlish Footbridge, Exeter, Devon, UK, 2012

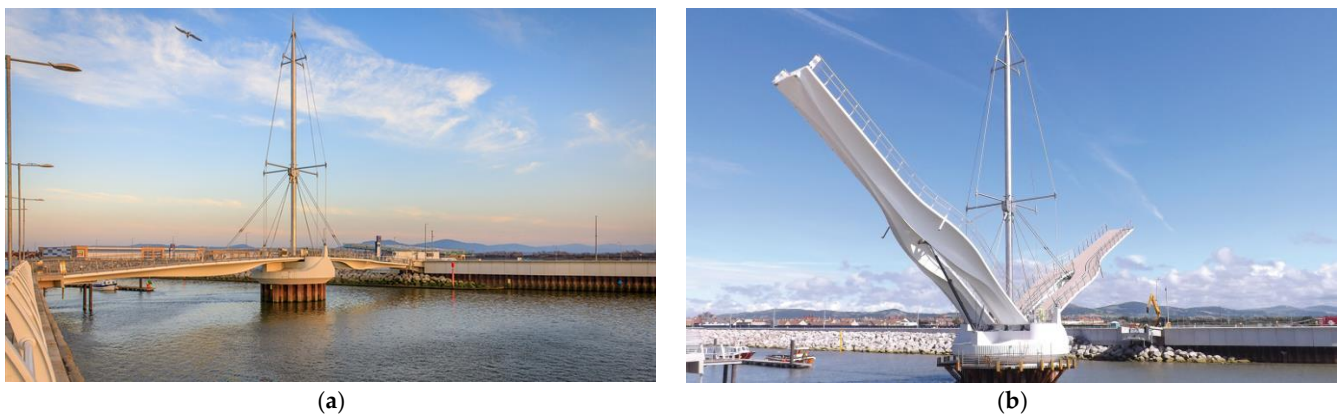
Dawlish Footbridge was constructed in 2012 at Dawlish train station in Exeter, South Devon, UK. The new FRP bridge is shown in Figure 12a. The bridge replaces the old, corroded steel bridge built in 1937 seen in Figure 12b. On completion, Dawlish bridge became the first Grade II listed FRP bridge. It uses standard pultruded FRP profiles using bonded and bolted joints, sandwich parapets made by film infusion and moulded FRP stair elements. The bridge has a span of 17.5 m and the walkway is 1.8 m wide. Due to its proximity to the beach, the bridge is constantly exposed to coastal erosion and salt spray-induced corrosion. The all-FRP bridge was proposed to reduce maintenance cost, and installation time and withstand the hostile coastal environment. The new FRP bridge replicated the form of the old steel bridge [60].



**Figure 12.** Dawlish Railway Footbridge, Exeter, South Devon, UK [1]: (a) Old rusty steel bridge using riveted built section and cross bracing, 1937; (b) New FRP bridge using pultruded FRP profiles, moulded parapet and stairway, 2012.

#### 2.1.14. Pont y Ddraig Bridge or the Dragon's Bridge, Wales, 2013

Pont y Ddraig Bridge or the Dragon's Bridge is a double bascule FRP footbridge as shown in Figure 13a in a lowered position and Figure 13b in a raised position. The bridge was installed at Rhyl Harbour, North Wales in 2013. It contains two mirroring 30 m long decks connected to a central stainless-steel tower with lifting cables. The bridge deck can be lifted by the cables for navigation purposes. It combines glass and carbon resin-infused FRPs. The deck is curved in both plan and elevation. Each deck span weighed 10.6 tonnes. The deck used mainly glass fibre sandwich shells with carbon fibre unidirectional longitudinal plates at highly stressed regions. It also used Corecell M-Foam as core material and Ampreg 21 resin. The lightweight of the bridge enabled two composite decks or dragon wings to be raised [8,61,62].



**Figure 13.** Pont y Ddraig or the Dragon's Bridge, Rhyl Harbour, North Wales, built in 2013 [62]: (a) Bridge in a lowered position; (b) Bridge in a raised position.

#### 2.1.15. Eindhoven University of Technology Pedestrian Bridge, The Netherlands, 2016

Eindhoven Pedestrian Bridge is a bio-composite footbridge over the river Dommel in Eindhoven, The Netherlands. The bridge shown in Figure 14 was completed in 2016. This 14 m span and 1.2 wide bridge was designed and installed within a year. The structural elements in the bridge used a mix of hemp and flax fibres in epoxy resin with a 56% fibre volume fraction. The non-structural parts employed an aliphatic thermoplastic polyester made of renewable resources. The bridge deck had a rectangular cross-section near abutments and a nearly triangular section in the middle. To facilitate this geometry the vacuum-assisted resin infusion process was used to produce the bridge.

The railings of the bridge also used bio-composite material and resembled grass cutters. The Fibre Brag sensor technique was used to embed sensors in the bridge for structural health monitoring [63]. The data was monitored by Blok et al. [63] in their paper continuously for two years. The sensors applied to the woven flax material on the tension

side proved to be successful and gave reliable results until the writing of their paper in 2019. The sensors embedded in non-woven hemp fibre composite on the compression side failed after initial readings. This bridge is an excellent example of using eco-friendly sustainable bio-based materials for structural elements.



**Figure 14.** Eindhoven bio-composite footbridge over the river Dommel, Eindhoven, The Netherlands, built in 2016 [63].

#### 2.1.16. Dover Sea Wall Footbridge over a Rail Line, Dover, Kent, UK 2017

The storms of 2015 completely damaged the existing steel footbridge near Dover Sea Wall, Dover, Kent, UK. The steel bridge was replaced with a hybrid-FRP bridge with pultruded and resin-infused parts, as shown in Figure 15. The bridge deck, top chords and anti-slip phenolic wear plates for stairways were resin infused. On the other hand, the truss members, landings, stairwell and parapet were fabricated from pultruded FRP profiles and plates. The sections were prefabricated, and the completed bridge was 31 m long and 2.415 m wide. It consisted of two simply supported 14.5 m bridge spans over concrete abutments with one span on top of the railway track. The bridge design life was for 120 years. The bridge weighed about a third of its steel equivalent [8]. Human-induced vibrations, dynamic properties and serviceability of the bridge were studied in a recent paper by Russell et al. [64].



**Figure 15.** Dover Sea Wall Footbridge, Dover, Kent, UK, built in 2017 [64]: (a) Complete footbridge over a railway line; (b) Bridge span directly on top of rail tracks.

#### 2.2. Examples of Hybrid-FRP Bridges

Hybrid-FRP bridges have been used for the past 20 years. FRP composites can be used in combination with traditional materials, such as steel and concrete. Main examples of these bridges include road bridges with CFRP girders with concrete slabs on top and

supported on concrete piers. Another common example relates to an FRP deck supported by steel or concrete girders or steel cables. In the sections to follow, real-life examples of hybrid-FRP bridges are described.

#### 2.2.1. Asturias Bridge, Spain, 2004 (Hybrid-FRP Beam—Concrete Slab)

Asturias Bridge, seen in Figure 16, is the first FRP vehicular bridge constructed in Spain in 2004. It is a four-span bridge with CFRP girders supported on three intermediate supports. The length of the bridge is 46 m with two middle spans of 13 m and two end spans of 10 m. The concrete slab was supported on a permanent GFRP formwork, which was connected to the CFRP girders underneath. A polyurethane mould was wrapped by CFRP prepregs to produce the girder. The girder was a trapezoidal box section with a 1.2 m top flange, 0.8 m bottom flange and 0.8 m web. The core of the box girder was filled with polyurethane [27,65]. To validate the serviceability and ultimate load capacity limits of the 46 m long bridge, the 13 m full section of the bridge was tested in the laboratory by Gutiérrez et al. [66].



**Figure 16.** Asturias composite bridge CFRP girders and concrete deck, Spain, built in 2004 [66].

#### 2.2.2. M111 Bridges, Madrid, Spain 2007 (Moulded FRP Girders and Concrete Deck)

The M111 twin bridges are located near Madrid, Spain along the M111 motorway (shown in Figure 17). Built in 2007 by Acciona construction, Spain, the bridges had three simply supported spans of 10, 14 and 10 m and a 20.4 m wide box girder deck. The deck slab is supported by four FRP girders. The girder had a reverse omega shape. Its top and bottom flanges are made of hybrid carbon and glass fibre laminates. The girder webs consist of sandwich panels having glass fibre skins and a polyurethane core [27,65,67].



**Figure 17.** M111 road bridges, Madrid, Spain, consisting of moulded FRP primary beams and concrete deck, were built in 2007 [65,68].

### 2.2.3. Standen Hey Overbridge, UK, 2007 (Deck)

Standen Hey Overbridge was installed by Network Rail, UK. It is a built-up bridge deck made of all-FRP pultruded panels in 2007 near Clitheroe, Lancashire. This was perhaps the UK's first purpose-built deck for a road bridge. The bridge had a clear span of 9.5 m with 3 m wide single-lane rural road access (see Figure 18). The deck was designed using ASSET profiles consisting of two triangular cells creating a rhombus shape. The ASSET profiles were produced in Denmark and transported in required lengths to the UK. The original bridge had cast-iron beams supporting a timber deck. The new FRP bridge deck had double layers of ASSET profiles and a third layer to act as a plinth for the parapet. The deck was installed in the standard 8 h rail closure [26]. Each profile was 225 mm deep and 300 mm wide, and the webs were inclined at 60° to the horizontal. The profiles were bonded with epoxy adhesive. The 10 m long built-up deck weighed 20 tonnes, spanned between original abutments and was supported on new precast concrete beams. The deck used E-glass fibres in the form of bi-axial mats [69]. A similar deck with a single layer was used on Klipphausen Bridge, Germany [8].



**Figure 18.** Standen Hey Overbridge, Clitheroe, Lancashire, UK, built in 2007 [70].

### 2.2.4. Gądkki Footbridge, Poland 2008 (Deck)

Built in 2008, Gądkki Footbridge is located over road no. 11 (Poznan—Kornik expressway) in Gądkki, Poland. This hybrid steel arch bridge has FRP composite deck in the main central span, and steel–concrete composite and reinforced concrete access spans (see Figure 19). The complete bridge is 260 m long. The main span containing the FRP deck has in-plane curved girders supported by an inclined arch. The 40 m span main arch girder was a steel pipe section with 1200 mm diameter and 16 mm wall thickness. The deck girder was a 660 mm diameter and 20–30 mm thick steel pipe section. The deck is curved with an 80 m radius and the walkway is made of pultruded FRP profiles. The footbridge is supported on spot footing and the main arch is supported on prefabricated reinforced concrete piles [23].

### 2.2.5. Moss Canal Bridge, UK, 2011 (Deck)

The use of the largest FRP profile as a deck on Moss Canal Bridge, Rochdale, UK was a step change for FRP bridges in 2011. The original bridge with in-situ concrete portal frame is shown in Figure 20a and the new FRP bridge is seen in Figure 20b. The FRP profile was a double web beam about 900 mm deep and 450 mm wide. The bridge was 12 m long and 3 m wide. The FRP deck used multi-axial pultruded sections of E-glass fibres in vinyl ester resin to support the 9 m bridge span. The deterioration of the existing reinforced concrete deck required deck replacement. Again, the lightweight of FRPs reduced both installation and fabrication costs [72].



Figure 19. Gądkki Footbridge, Poland, built in 2008 [71].



Figure 20. Moss Canal road bridge, Rochdale, UK, built in 2011 [72]: (a) Original bridge with in situ concrete portal frame; (b) New FRP bridge using double web pultruded FRP beams and FRP deck with multiaxial E-glass fibres.

#### 2.2.6. St. Mateus—GFRP–Steel and São Silvestre Footbridges, Portugal 2013

St. Mateus Footbridge is a GFRP–steel hybrid footbridge constructed in Viseu, Portugal. This represents a typical GFRP deck combined with a steel girder. The span of the bridge was 13.3 m and the width was 2.5 m. The GFRP slab was fabricated using thin-walled multicellular deck panels. Experimental, numerical, and analytical study of St. Mateus Bridge is presented in papers [73,74]. São Silvestre Footbridge is a 10.5 m span hybrid bridge in Portugal constructed using pultruded GFRP profiles and a very thin concrete deck made of steel fibre-reinforced self-compacting concrete (SFRSCC) pre-cast slabs. The prototype of the bridge with a 5.5 m span was tested in a laboratory by Gonilha et al. [75].

#### 2.2.7. Mapledurham Footbridge, UK, 2015 (Deck)

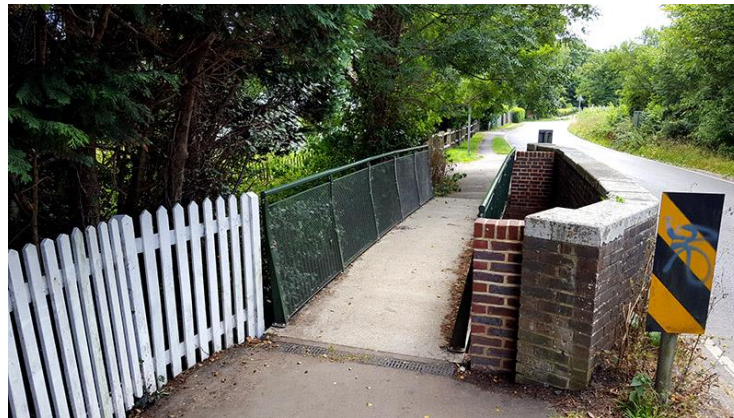
Mapledurham Footbridge was a replacement bridge, which was installed on the river Thames in Mapledurham, Oxfordshire, UK in 2015. This 13 m bridge uses a sandwich system with GFRP skin and foam core. Due to limited access to the site, the bridge was floated to the site on a barge along River Thames as shown in Figure 21a and the installed FRP bridge, with no physical joints, is seen in Figure 21b. The bridge span was fabricated as a single unit. The FRP bridge decks were one-third the weight of equivalent steel or concrete slabs. The prefabrication and lightweight of FRPs allowed easy transportation of the bridge on a freight boat [8].



**Figure 21.** Mapledurham Footbridge, Mapledurham, Oxfordshire, UK, built in 2015 [8]: (a) FRP bridge deck delivered to site by floating on a barge along River Thames; (b) Mapledurham FRP bridge installed with no physical joints.

#### 2.2.8. Sedlescombe Footbridge, UK, 2015 (Deck)

Sedlescombe Footbridge was installed in Sedlescombe village in East Sussex, UK to replace an existing timber bridge in 2015, as shown in Figure 22. The lightweight, quick installation time, low maintenance and whole-life cost controlled the design. The bridge was designed for 60 years. The bridge used a resin-infused FRP composite deck with powder coated steel parapet. It was 8 m long and 1.35 m wide, and the depth of sections was 250 mm. The bridge weighed only one tonne compared to the four-tonne original timber bridge [8].



**Figure 22.** Sedlescombe Footbridge, East Sussex, UK, built in 2015 [8].

### 3. FRP Composite Constituent Materials

FRP composites contain fibres embedded in a resin matrix. The fibres provide strength to the FRP part. The resin matrix provides shape, protects fibres and transfers force [1–3,13,76,77].

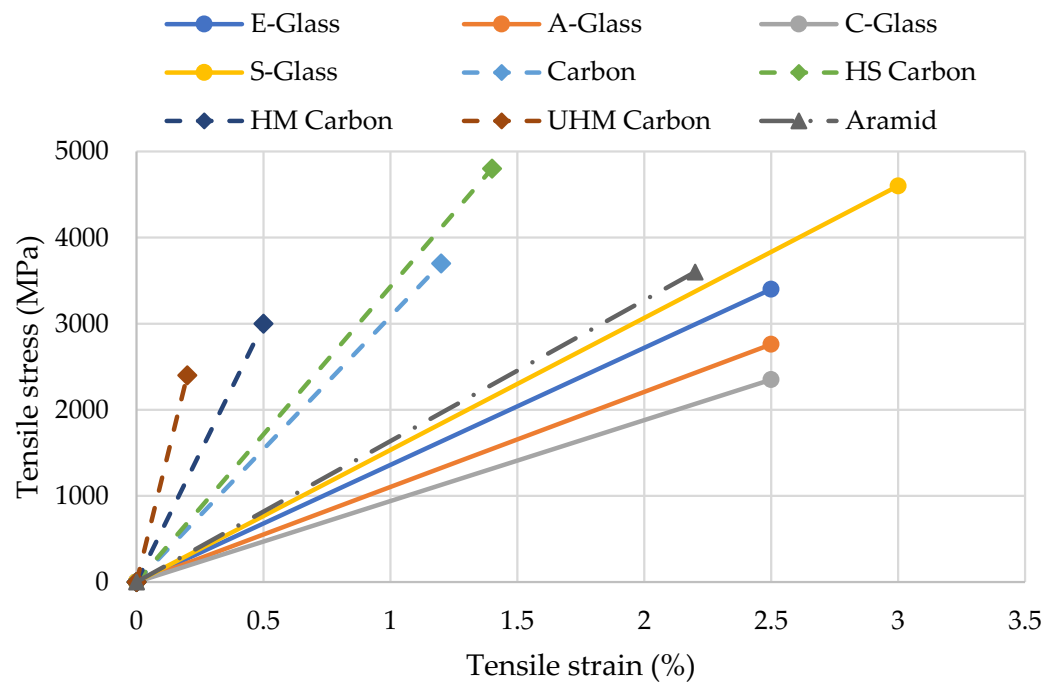
#### 3.1. Fibres

Synthetic fibres, such as glass, carbon and aramid fibres are used in bridge applications. These fibres are the main load-bearing elements in an FRP composite system. The typical properties of plain fibres are presented in Table 1. The tensile strength of a finished FRP product, which includes plain fibres embedded in a resin matrix, will be much less than the strength of plain fibres. The behaviour of these fibres is linear–elastic under tensile loading up to failure [7]. Aramid fibres exhibit nonlinear ductile stress–strain response

under compression [78]. Tensile stress–strain curves for carbon, glass and aramid fibres are shown in Figure 23.

**Table 1.** Mechanical properties of fibres and thermoset resin matrices [1–3,13].

Material	Grade	Density (g/cm <sup>3</sup> )	Tensile Modulus (GPa)	Tensile Strength (MPa)	Max Elongation (%)	Fibre Architecture	Glass Transition Temperature (°C)	
Fibre	Glass	E	2.57	73	3400	2.5	Isotropic	–
		A	2.46	73	2760	2.5		
		C	2.46	74	2350	2.5		
		S	2.47	88	4600	3.0		
	Carbon	Standard	1.70	250	3700	1.2	Anisotropic	–
High strength		1.80	250	4800	1.4			
High modulus		1.90	500	3000	0.5			
Ultrahigh modulus		2.10	800	2400	0.2			
Aramid	–	1.40	70–190	2800–4100	2.0–2.4	Anisotropic		
Polymer Resin	Polyester	–	1.20	4.0	65	2.5	–	70–120
	Epoxy	–	1.20	3.0	90	8.0	–	100–270
	Vinylester	–	1.12	3.5	82	6.0	–	102–150
	Phenolic	–	1.24	2.5	40	1.8	–	260
	Polyurethane	–	varies	2.9	71	5.9	–	135–140 [79]



**Figure 23.** Uniaxial tension stress–strain curves for unidirectional glass, carbon and aramid fibres.

### 3.1.1. Glass Fibres

Glass fibres dominate the FRP composite market in civil engineering. More than 90% of all commercial FRP products use glass fibres [80]. E-glass formulation (for electrical grade) is the most widely used form of glass fibres. Almost 80–90% of all commercially produced glass is E-glass [81]. Glass FRP was used in No-Name Creek Bridge in the USA in 1996. The bridge used a sandwich deck with GFRP laminated outer skins and a honeycomb core [44]. Glass fibre-reinforced cables and pultruded profiles were also used in Kolding cable-stayed footbridge in Denmark. The bridge had two girder spans and a pylon. This 40 m footbridge was fabricated by Fiberline in 1997 and was believed to be the first pedestrian overpass over a busy railway line [45,46]. Lleida Footbridge, Spain also used pultruded GFRP profiles with polyester resin in 2001. The structural form of the bridge was



a double-tied arch mechanism [39,50]. Halgover Footbridge, UK used resin-infused glass FRP decking in 2001. This was the first use of any other manufacturing method rather than pultrusion [49]. In 2002, West Mill Bridge, UK used GFRP box beams stiffened by CFRP flanges and GFRP ASSET deck profiles bonded to these beams [34,51].

### 3.1.2. Carbon Fibres

Carbon fibres have the highest tensile strength and Young's modulus among all synthetic fibres. The main reason for using carbon fibres in bridge applications is their high tensile modulus—comparable to structural steel. In addition, carbon fibres have high fatigue, creep and chemical resistances [13]. Carbon fibres are suitable for chemically aggressive and other harsh environments. Carbon fibres are at least 10–30 times more expensive than E-glass fibres [1,82,83]. Different grades of carbon fibres and their properties are given in Table 1. The high modulus reduces the tensile stress and strain, making it a brittle material [84].

Carbon FRP cable strands were first used as tensioning materials in a prestressed concrete bridge in the USA in the late 1980s [85]. West Mill Bridge, UK (2002) was an excellent example of combining carbon and glass fibres. GFRP box girders with CFRP flanges were used in the bridge [34,51]. Pont y Ddraig Bridge, Wales (2013) is yet another instance where carbon and glass resin-infused FRPs were used. The deck used glass fibre sandwich shells with carbon fibre unidirectional longitudinal plates [8,61,62]. The M111 twin road bridges in Spain (2007) used girders with hybrid glass and carbon laminates and the web used sandwich panels with glass fibre skins and polyurethane core [65]. Fredrikstad Bascule Footbridge, Norway (2003) used a sandwich deck with carbon fibre skins and a balsa core [54]. Asturias Bridge, Spain (2004) used CFFP box girders with polyurethane core. The girders supported the permanent GFRP formwork for the concrete slab [66]. Carbon fibres were also used to strengthen Aberfeldy Footbridge, Scotland (1992) for supporting motorised golf buggies [34].

### 3.1.3. Aramid Fibres

Aramid fibres (Kevlar or Twaron fibres) are rarely used in engineering applications. They are mainly used in FRP rebars, prestressing tendons, and cables in bridges [86]. Aramid fibres show good toughness, creep, fire resistance, damage tolerance and tensile fatigue properties [78]. The main weakness of aramid fibres is their low compressive strength (500–1000 MPa); their compressive strength being less than 20% of their tensile strength (2800–4100 MPa). Aramid fibre–Kevlar 49 exhibits brittle linear elastic stress-strain behaviour in tension. However, it behaves in a nonlinear ductile manner under compressive load resulting in high energy absorption. It also gives a plastic behaviour in compression when subjected to bending. This type of behaviour increases the impact resistance of aramid fibres [2,78,82]. Due to lower compressive strength (only 20% of the tensile strength), a cautious approach must be taken when using aramid fibres as a compression or flexural reinforcement [8]. Aramid fibres are only used in applications where tensile forces are dominant, such as tension cables in cable-stayed bridges.

Aramid fibres are used as tendons in prestressed concrete, and cable stays in bridges and ropes in the marine industry due to their high tensile strength and corrosion resistance [87]. The use of aramid rods for prestressing began in the early 1980s in the Netherlands as pultruded flat strips and round bars [40]. Aramid FRP prestressing tendons were used in the deck of a stressed ribbon pedestrian bridge near Tokyo, Japan in 1991 [86]. The Parafil aramid rope (cable) system was developed in the 1970s for mooring offshore platforms and stabilising large radio antennae [40]. Aberfeldy Footbridge, Scotland (1992) used the Parafil aramid ropes (cables) connected to two A-shaped GFRP towers and supported a GFRP suspended slab [34]. The Parafil rope system was also used as a tension tie in the Oppegaard tied arch footbridge in Norway. The bridge is built on a golf course crossing a small stream [40].

### 3.2. Resin Matrix

The matrix contains polymer resin and other additives and fillers. The resin glues the fibres and protects them from environmental factors. It transfers forces between fibres and prevents the buckling of fibres under compression. The matrix constitutes 30–60% by volume of the FRP part [82]. There are two types of polymer resins: thermosetting resins and thermoplastic resins. The properties of thermosetting resins are presented in Table 1. At its glass transition temperature ( $T_g$ , °C), amorphous polymers undergo a change from a hard to a soft or rubbery state. A unidirectional FRP composite component's glass transition temperature is often taken as equal to a resin's glass transition temperature [2].

#### 3.2.1. Thermoset Resin

Thermoset resins are most commonly used in structural FRP products [82]. Thermoset resins contain five types: polyester, epoxy, vinyl ester, phenolic and polyurethane. Their molecules are connected by strong bonds. Once cured, they cannot be remoulded to other shapes. Placing fibres in these resins is easy due to their low viscosity. Most FRP parts use polyester resins; this is roughly 75% of FRP composites [13].

Epoxy resins can also be used as a matrix in an FRP part or as a binder to connect two FRP products. Epoxy is used in FRP tendons, cables, and strengthening applications. The high cost and processing difficulty due to high adhesion makes epoxy unsuitable for FRP profiles [1]. Epoxy resins offer the best adhesive bonding properties. Polyester resins have the least bonding ability. High adhesion properties make epoxy resin suitable for the fabrication of sandwich panels with a honeycomb core [8]. Phenolic resins are the oldest resins with good fire resistance. Their use is limited due to problems in reinforcing and curing them [3]. Polyurethane resins offer high toughness resistance. Using them with glass fibres can produce high-impact and tensile-resistant FRP composites [1].

#### 3.2.2. Thermoplastic Resin

Thermoplastic resins have four categories: polypropylene, polyamide, polyethylene and polybutylene. Due to weak molecular bonds, thermoplastic resins can be moulded, remoulded, and reshaped. By exposing them to temperatures higher than their forming temperature, they can be repeatedly softened and hardened. They can also be easily recycled. Due to their sticky nature, fibre impregnation is very hard, and this leads to the higher costs of FRPs. They are mainly used in aerospace applications [3,88]. Polyethylene thermoplastic resins were first used in the 1990s in the USA. The first bridge that used high-density polyethylene (HDPE) thermoplastic resin was built at Fort Leonard Wood, Missouri, USA. Thermoplastic composite I-beams were used as main girders in a vehicular bridge built in Wharton State Forest, New Jersey, USA in 2002. In 2009, two bridges were built at Fort Bragg, North Carolina, USA using thermoplastic resin composite with glass fibres. The world's first thermoplastic-based all-FRP composite railroad bridge was built at Fort Eustis, Virginia, USA in 2010 [89]. Despite this limited use in bridges, thermoplastic-based FRPs are rarely used in structural applications [8].

### 3.3. Laminated Shells and Sandwich Panels

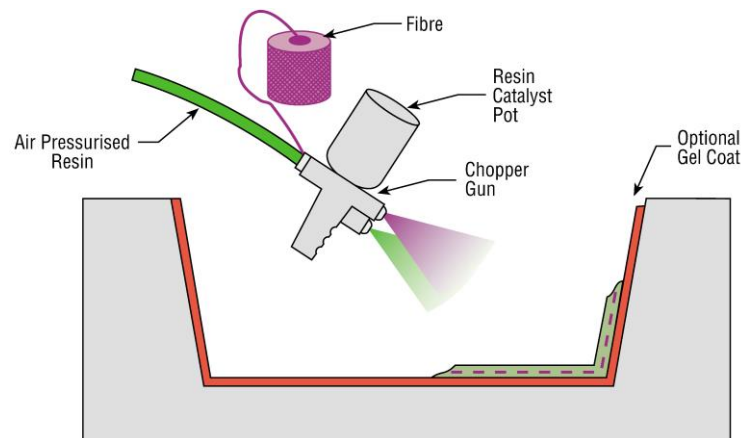
Freedom of geometry allows FRP bridge elements to be moulded into any shape. The moulded shapes can be realised by either laminated shells or sandwich panels. Several FRP bridges, Halgavor Bridge [49], Bradkirk Footbridge [59], Pont y Ddraig Bascule Bridge [62], Purfleet Footbridge [10], Sedlescombe Footbridge [8] and Mapledurham Bridge [8] used sandwich panels and laminates. Laminated shells consist of single-skin laminations and sandwich panels containing a core (foam, wood or honeycomb) enclosed by adhesively bonded outer skins or laminates. The skins or face sheets are usually glass or carbon fibre-reinforced polymer laminates. Mechanical properties of both laminated shells and sandwich panels are obtained by testing the individual plies from coupon testing. Panel, core and beam failure modes must be considered when designing sandwich panels [8].

#### 4. Manufacturing Methods

The main materials used in fibre-reinforced polymer composites include fibre reinforcement layers, the resin matrix, and the core in the case of sandwich construction. Fibre reinforcement layers can be dry (without resin), wet (with resin) or prepreg reinforcing layers with partially cured resin [8]. The advantages, disadvantages, applications, and materials used for different FRP manufacturing methods are presented in Table 2.

##### 4.1. Spray Lay-Up (Contact Moulding)

The method consists of a hand-held spray gun directed into a mould. The fibres are chopped in the gun and fed into the resin spray of the gun. The mould is treated with mould release and a gel coat is applied. Then, the catalysed resin and fibres are sprayed into the mould. The resulting laminate is compacted with hand rollers. This method is only limited to polyester resin and glass fibres. Fibres must be short, and the resin should have low viscosity. If required, the core material, such as wood or foam is added, and a second spray layer is applied. In this way, the core is embedded between two laminate skins. The composite part is then cured, cooled, and removed from the mould [90,91]. The schematic diagram of the spray lay-up is shown in Figure 24.



**Figure 24.** Schematic representation of spray lay-up method [90].

##### 4.2. Wet or Hand Lay-Up (Contact Moulding)

Hand or wet lay-up is the most basic process. It consists of stacking either dry fabrics in the resin system or prepregs (fibre system pre-impregnated with resin) to form a laminate stack. The part is then allowed to cure and takes the shape of the mould. The curing is at room temperature, no extra heat is required. This manual method can either be used onsite or offsite. For bridge applications, FRP components are usually fabricated offsite. Although hand lay-up is a reliable method, it is more time-consuming than other methods, as each ply is handled only by hand. Any fibre system in any form (chopped, woven, continuous) is suitable for this method. Brushes and rollers are generally used to apply the resin and reduce air bubbles [13,90,91]. Miyun Bridge, in Beijing, China and Ginzi Highway Bridge in Bulgaria used the hand lay-up method [8,36,38,39]. The diagram in Figure 25 shows the process of hand or wet lay-up.

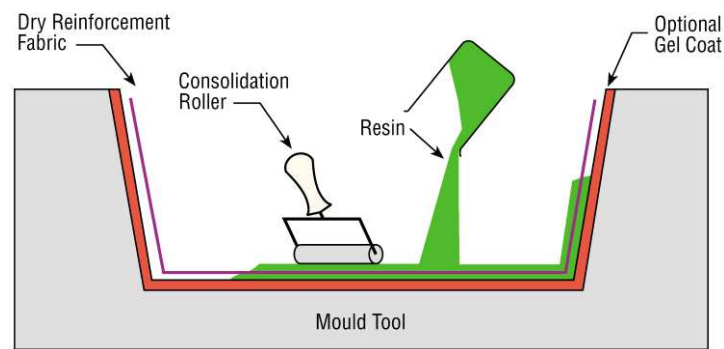
Table 2. Applications, strengths, weaknesses, and material options for different manufacturing methods [92].

Method	Material			Applications	Strengths	Weaknesses
	Resin	Fibre	Core			
<b>Spray lay-up (contact moulding)</b>	Mainly polyester	Glass roving only	None. To be added separately	<ul style="list-style-type: none"> <li>• Simple enclosures</li> <li>• Lightly loaded structural panels, e.g., caravan bodies, truck fairings</li> </ul>	<ul style="list-style-type: none"> <li>• Widely used</li> <li>• Low-cost tools</li> <li>• Competitive cost for rapidly depositing fibres and resin</li> </ul>	<ul style="list-style-type: none"> <li>• Manual method</li> <li>• Laminates resin rich and heavy</li> <li>• Only short fibres can be used</li> <li>• Resins need to be of low viscosity to be sprayable</li> </ul>
<b>Wet or hand lay-up (contact moulding)</b>	Any resin, epoxy, polyester, vinylester, phenolic	Any, heavy aramid fibres hard to wet-out	Any	<ul style="list-style-type: none"> <li>• Standard wind turbine blades</li> <li>• Production boats</li> <li>• Architectural mouldings</li> </ul>	<ul style="list-style-type: none"> <li>• Widely used</li> <li>• High fibre content and large fibres</li> <li>• Low-cost tools</li> <li>• Choice of suppliers and materials</li> </ul>	<ul style="list-style-type: none"> <li>• Manual method</li> <li>• Laminate quality relies on skills of workers</li> <li>• Low resin content cannot be achieved</li> </ul>
<b>Vacuum bagging—wet lay-up (moulded)</b>	Mainly epoxy and phenolic Polyester resin will have problems due to the extraction of styrene by the vacuum pump	A variety of heavy fabrics can be wet-out	Any	<ul style="list-style-type: none"> <li>• Large, one-off cruising boats</li> <li>• Racing car components</li> <li>• Core-bonding in production boats</li> </ul>	<ul style="list-style-type: none"> <li>• High fibre content</li> <li>• Lower void content than wet lay-up</li> <li>• Good fibre wet-out due to pressure and resin flow</li> <li>• Better health and safety as less volatiles emitted during curing</li> </ul>	<ul style="list-style-type: none"> <li>• Manual method</li> <li>• Extra cost for labour and vacuum bagging</li> <li>• Skilled labour</li> <li>• Vacuum bags reduce volatiles, but exposure is still higher than prepreg and infusion methods</li> </ul>
<b>Filament Winding</b>	Any resin, epoxy, polyester, vinylester, phenolic	Any, straight fibres used, not woven or stitched	Any, usually used for single-skin elements	<ul style="list-style-type: none"> <li>• Hollow circular or oval structural profiles</li> <li>• Chemical storage tanks and pipelines,</li> <li>• Gas cylinders</li> </ul>	<ul style="list-style-type: none"> <li>• Continuous automatic process</li> <li>• Fast and economic</li> <li>• Fibre cost is minimised as no need to convert fibre into fabric</li> <li>• Good properties of structural laminates, as fibres laid into complex patterns</li> </ul>	<ul style="list-style-type: none"> <li>• Limited to convex-shaped parts only</li> <li>• Mandrel cost can be high</li> <li>• Fibres cannot be laid easily along the length</li> <li>• Only low-viscosity resins used</li> </ul>
<b>Pultrusion</b>	Epoxy, polyester, vinylester, phenolic	Any	Not used	<ul style="list-style-type: none"> <li>• Beams and girders used in structures, bridges, ladders, and frameworks.</li> </ul>	<ul style="list-style-type: none"> <li>• Continuous automatic process</li> <li>• Fast and economic</li> <li>• Good structural properties due to straight fibres</li> <li>• Controlled resin content</li> <li>• Low volatile emissions</li> </ul>	<ul style="list-style-type: none"> <li>• Limited to constant cross-sections</li> <li>• Expensive heated die</li> </ul>

Table 2. Cont.

Method	Material			Applications	Strengths	Weaknesses
	Resin	Fibre	Core			
<b>Resin transfer moulding, RTM (moulding)</b>	Epoxy, polyester, vinylester and phenolic	Any, stitched fabrics allow resin flow	No honeycomb	<ul style="list-style-type: none"> <li>• Small complex aircraft and automotive components, train seats</li> <li>• Bridge components</li> </ul>	<ul style="list-style-type: none"> <li>• High fibre volume and low void content</li> <li>• Good health and safety due to enclosed area</li> <li>• Moulded surface on both sides of the element</li> </ul>	<ul style="list-style-type: none"> <li>• Expensive and heavy tools</li> <li>• Limited to smaller components</li> <li>• More scrap parts</li> </ul>
<b>Other methods—SCRIMP, RIFT, VARTM, resin film infusion (moulded) *</b>	Epoxy, polyester and vinylester	Any stitched fabrics	Any except honeycomb	<ul style="list-style-type: none"> <li>• Large bridge elements</li> <li>• Semi-production small yachts</li> <li>• Train and truck body panels</li> <li>• Wind energy blades</li> </ul>	<ul style="list-style-type: none"> <li>• All RTM advantages, except one side, has moulded finish</li> <li>• Fewer tools than RTM</li> <li>• Core produced in the same process</li> </ul>	<ul style="list-style-type: none"> <li>• Relatively complicated method</li> <li>• Resins need to be low viscosity</li> <li>• Unimpregnated areas can lead to very expensive scrap parts.</li> </ul>
<b>Prepreg—autoclave</b>	Epoxy, polyester, phenolic and other high-temperature resins	Any	Special foam due to high temperature and pressure	<ul style="list-style-type: none"> <li>• Aircraft structural components (e.g., wings and tail sections)</li> <li>• F1 racing cars</li> </ul>	<ul style="list-style-type: none"> <li>• Accurate resin level and content</li> <li>• High-quality dense and void-free composite</li> <li>• Extended working times</li> <li>• Complex lay-up can be achieved</li> </ul>	<ul style="list-style-type: none"> <li>• Time-consuming and labour intensive</li> <li>• High-skilled workers needed</li> <li>• Autoclaves are slow, expensive, and limited in size</li> <li>• High material cost</li> </ul>

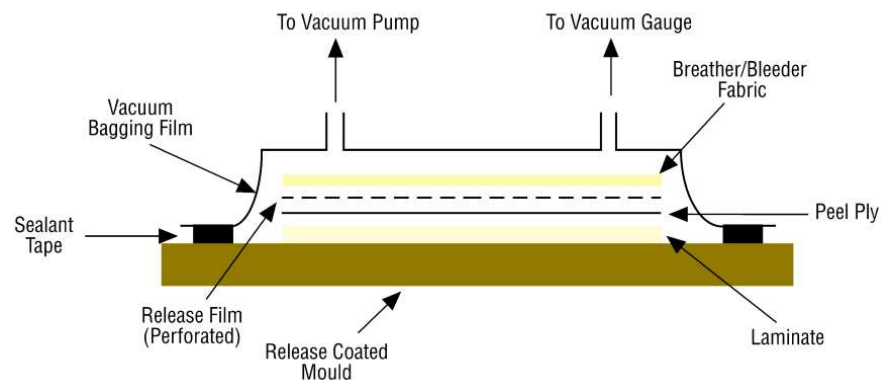
\* SCRIMP = Seemann Composites Resin Infusion Moulding Process, RIFT = Resin Infusion under Flexible Tooling, VARTM = Vacuum Assisted Resin Transfer Moulding.



**Figure 25.** Schematic illustration of wet or hand lay-up method [8].

#### 4.3. Vacuum Bagging—Wet Lay-Up (Moulded)

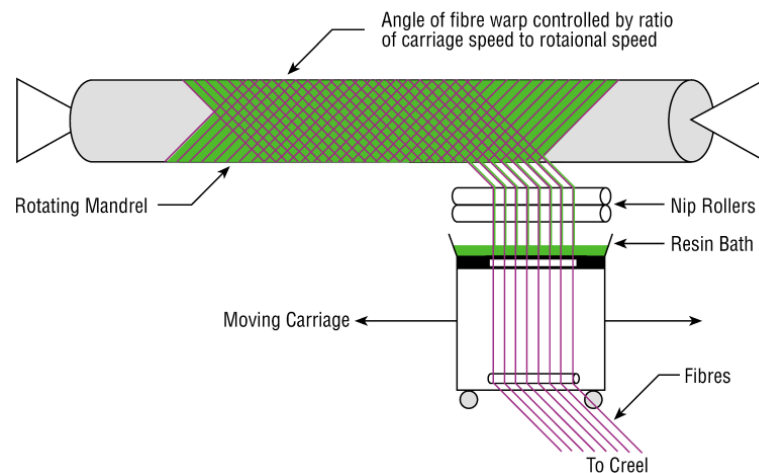
The vacuum bagging process is similar to wet lay-up except the pressure is applied to compact laminate layers [91]. The prepreg or fibre-resin system is staked to the desired thickness before covering it with a film layer, air breeder/breeder fabric and vacuum bagging film. This process uses a vacuum to remove excess resin and trapped air from the mould. It also gives better adhesion and concentration between layers [90]. The vacuum bagging is most suited to epoxy and phenolic resins. Polyester and vinylester resins can have problems due to the excessive removal of styrene from the resin by the vacuum pump. Styrene is a substance present in resin and up to 50% of that helps them reduce the viscosity and allows them to cure [92]. Consumable materials and equipment required for vacuum bagging are described in [92]. The illustration of vacuum bagging method is presented in Figure 26.



**Figure 26.** Schematic illustration of vacuum bagging method.

#### 4.4. Filament Winding

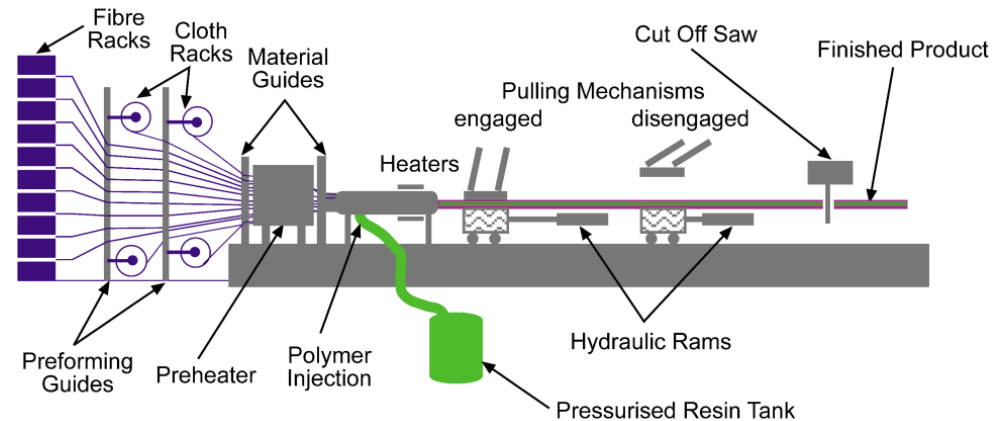
The filament winding process produces hollow circular or oval parts. The diagram in Figure 27 shows the filament winding process. It is highly automated and repeatable, and relatively inexpensive. The mould for this process is a rotating mandrel, an open mould. The mandrel is a long cylindrical tool on which fibres are wound. The process is similar to pultrusion where fibres are pulled through the resin bath [90]. The head travels along the rotating mandrel winding fibres on it in a specified configuration. The fibres are distributed equally throughout the length of the mandrel [91]. The fibres from the creel just pass through a resin bath before winding on the mandrel. Thermoset resin and straight fibres from creel (no stitched or woven fabric) are used in this method. After autoclave curing, the mandrel is either removed or becomes a permanent part of the finished product. The method is usually used with polymer matrices and synthetic fibres. The prepreg material can also be used in which case the fibres are wound without resin—dry winding [91,92]. Filament winding is used in hollow circular profiles in bridges.



**Figure 27.** Schematic illustration of filament winding method.

#### 4.5. Pultrusion

Pultrusion is an automatic and continuous process for producing constant section FRP parts. It is the most cost-competitive process for fabricating profiles, rebars and strips for structural engineering applications [2,93,94]. Fibres are pulled from creels via a resin bath and fed into a heated die. Fibres, continuous filament mat (CFM) and surface are passed through guide plates before the resin bath. The guide plates give a predetermined shape to the profile. I-beam, wide-fanged sections, channels and multicellular profiles can be produced by pultrusion [3,13,21]. The die controls the resin content and cures the material to its final shape. The finished profile is automatically cut to length. Figure 28 represents schematically the pultrusion process.



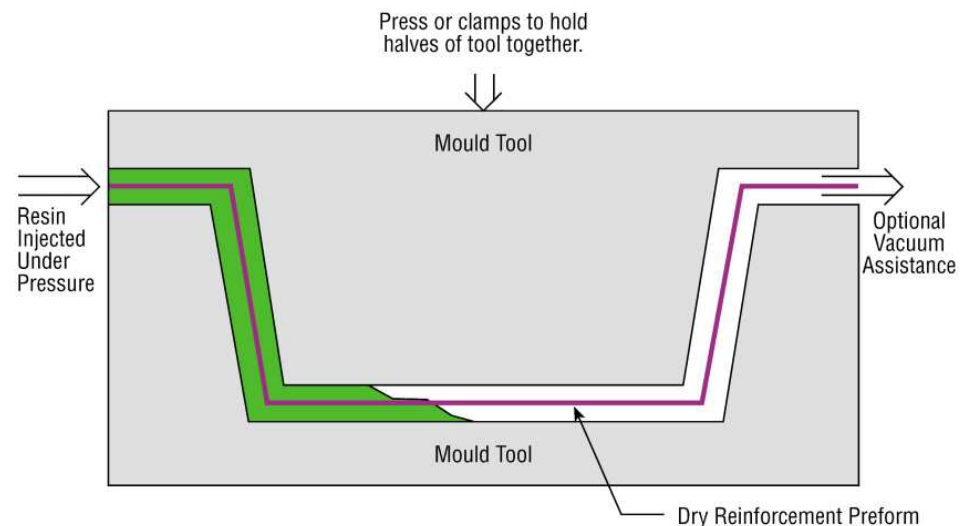
**Figure 28.** Schematic illustration of the pultrusion method.

Unidirectional fibres (rovings) give strength along the length of the profile and fabric mats provide strength in the transverse direction. Polyester surface veils are used for protection and finishing [92]. Examples of pultruded elements in bridges include Aberfeldy Footbridge, Scotland [4,34,38,40], Bonds Mill Lift Bridge, UK [8,40,43], Pontresina Truss Footbridge, Switzerland [36,47,48], St Austell Railway Bridge, UK [26,56,57], Dawlish Footbridge, UK [60], Dover Sea Wall Footbridge, UK [8], Standen Hey Overbridge, UK using a double layer of ASSET profiles [26], Gądki Footbridge, Poland [23], Moss Canal Bridge, UK [72] and many other bridges presented in Section 2.

#### 4.6. Resin Transfer Moulding, RTM (Moulding)

The resin transfer moulding (RTM) method produces complex geometries at reasonably high production rates. It contains two moulds with a fibre mat and resin pressed in between them. The moulds are made of either composites or steel. Due to the closed

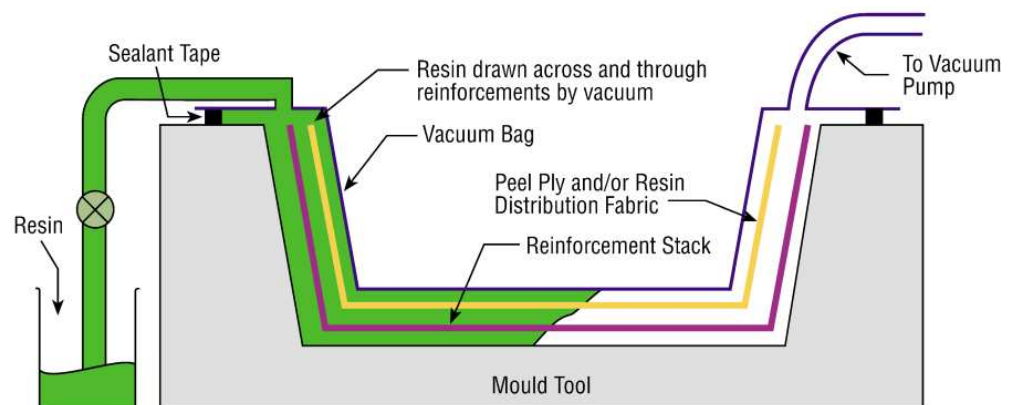
mould arrangement, the final product has finished surfaces on both sides [90]. Dry fabric layers are first laid at the bottom of the mould. The fabrics are held together by the binder or they are pre-pressed into the mould. The top mould is then clamped to the bottom and the cavity is filled with the resin. Sometimes vacuum is used to pump resin into the fabrics. This process is termed Vacuum Assisted Resin Injection (VARI). The resin inlets are closed after all the fabric has been wetted out, and the laminate is left to cure at either ambient or elevated temperature [92]. The resin transfer moulding process is represented schematically in Figure 29.



**Figure 29.** Schematic illustration of Resin Transfer Moulding (RTM) method.

#### 4.7. Other Methods—SCRIMP, RIFT, VARTM, Resin Film Infusion (Moulded)

Vacuum infusion moulding, vacuum assisted resin infusion or Vacuum Assisted Resin Transfer Moulding (VARTM), Seemann Composites Resin Infusion Moulding Process (SCRIMP) and Resin Infusion under Flexible Tooling (RIFT) are recently developed FRP composite manufacturing methods. In these, a vacuum is used to draw resin into a fibre system placed on a mould covered with plastic bagging film. These processes are more suitable for large mouldings, such as wind turbine blades, all-FRP bridges, car body shells and boat hulls [95]. The VARTM process is shown in Figure 30.



**Figure 30.** Schematic diagram of Vacuum Assisted Resin Transfer Moulding (VARTM) method.

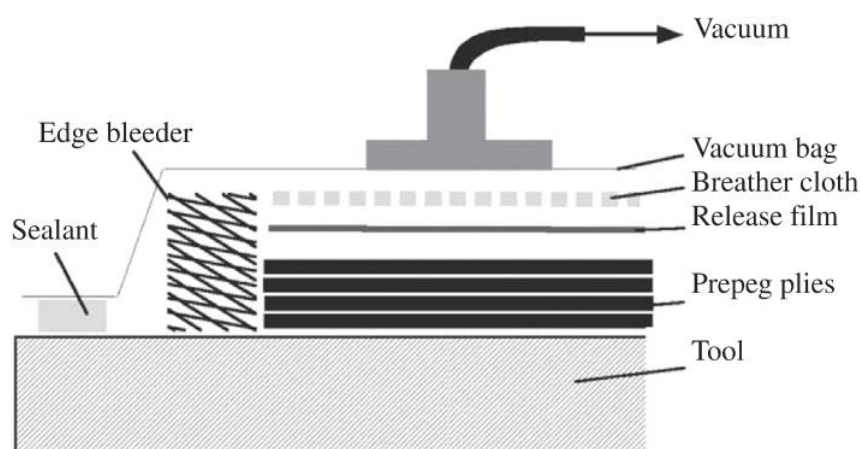
In these methods, dry fabrics are stacked in a one-sided mould in the same way as in RTM. Next, the stacked fabrics are covered with peel ply and a knitted type of non-structural fabric. Vacuum bagging is then applied to the whole dry stack, and after bag leaks have been removed, the resin flows into the laminate. The non-structural fabric is soaked in the resin from above, distributing it over the laminate [92]. The vacuum infusion



process was used in various ApATeCh bridges in Russia [58], Pont y Ddraig or the Dragon's Bridge in Wales [61,62], Fredrikstad Bascule Footbridge in Norway [54,55], Eindhoven Bridge in The Netherlands [63] and many other bridges requiring large moulded parts.

#### 4.8. Prepreg—Autoclave

The autoclave method generally uses a prepreg material. The prepreg contains fabrics and fibres with pre-impregnated partially cured resin. This method uses pressure and high heat, and this leads to high-quality void-free and dense composites. The drawback of this process is that the prepreg material is temperature sensitive. The prepreg must be shipped and stored at an extremely low temperature of  $-40\text{ }^{\circ}\text{C}$  to stop it from reacting. The material is laid up manually or by machine on a mould, vacuum bagged and heated in the autoclave to  $120\text{--}180\text{ }^{\circ}\text{C}$ . The process requires highly skilled workers as it has many manual steps. It is time-consuming and labour-intensive [90,92]. The prepreg method is presented in Figure 31.



**Figure 31.** Schematic diagram of prepreg autoclave method [90].

### 5. FRP Bridge Components

The bridge elements include decks, planks, girders, truss systems, moulded elements, and cables. Various structural forms for pedestrian bridges are used, such as truss, girder, and cable-supported bridge forms. Decks and girders have also been used in vehicular bridges using either all-FRP or hybrid composites.

#### 5.1. FRP Bridge Decks

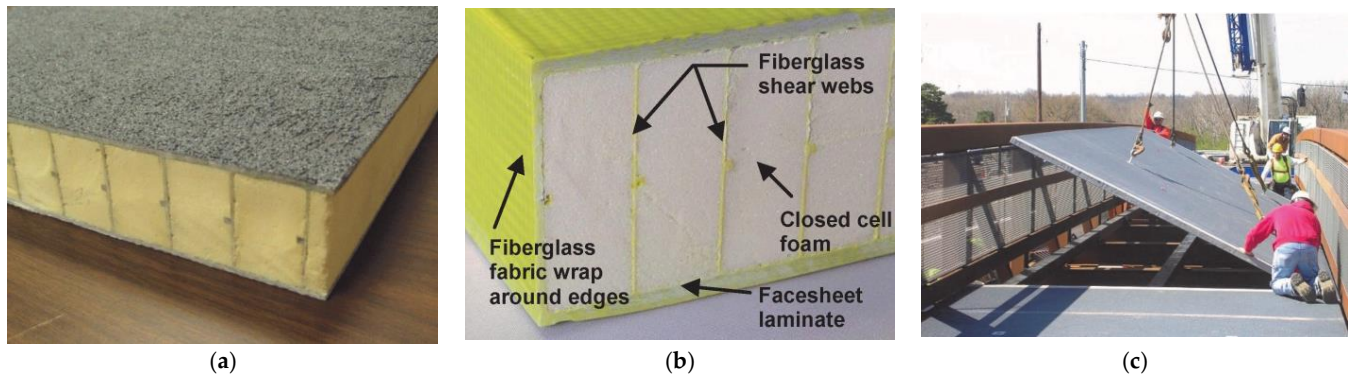
A bridge deck is a structural element that transfers the load to supports. The supports include longitudinal beams, cross beams, and abutments. The shear connection between the deck and support is ensured by shear studs or bolted joints. There are two types of FRP decks: sandwich panels and adhesively bonded pultruded shapes [35].

##### 5.1.1. Sandwich Panel Decks

Sandwich decks are mainly used for FRP footbridges. They contain a core material sandwiched between two skins or face sheets. The strong and stiff skins carry flexural loads. Whereas the low-density core material takes the shear load and ensures composite action between top and bottom skins [35]. The core materials include foams, honeycombs, woods (balsa) and cork [8]. The core can also include thin-walled cellular materials. These core materials result in efficient lightweight bridge decks. Sandwich construction presents flexibility in terms of designing for different shapes, depths, and deflection limits. An open or closed moulding process is used to manufacture FRP sandwich bridge decks.

Creative composites produce FiberSPAN [96] sandwich deck panels for FRP pedestrian bridges, as shown in Figure 32. The deck panel contains thick glass fibre skins on top and bottom with glass fibre shear webs. The fibres in the webs are oriented at  $\pm 45^{\circ}$  to maximise

shear properties. A closed-cell foam is used as a core to create shape and prevent water ingress in cavities. FiberSpan composite bridge decks are available in standard depths of 75 mm, 100 mm and 125 mm and can be custom-made as well [96].



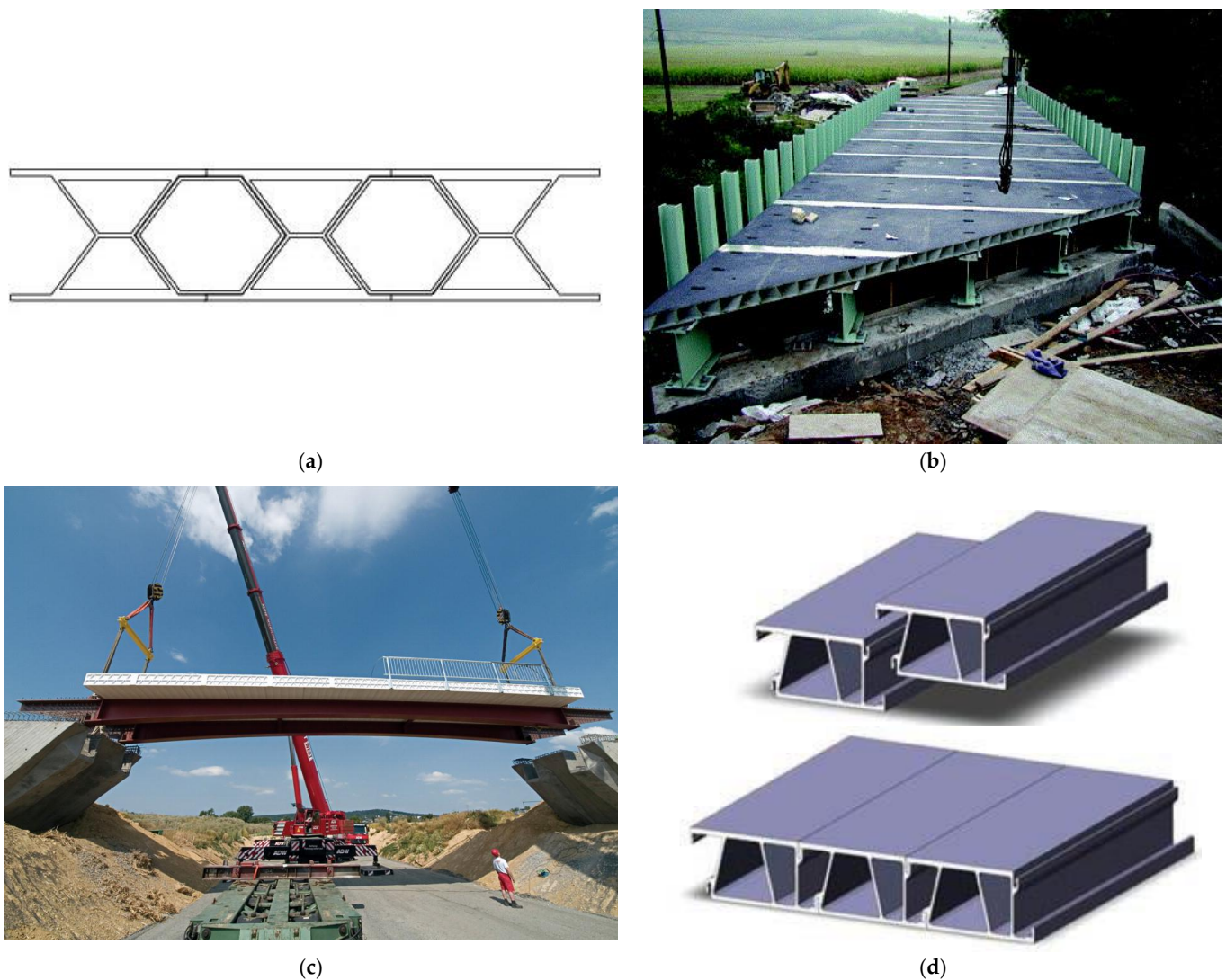
**Figure 32.** FiberSPAN FRP Pedestrian Bridge Decks by Creative Composites [96]: (a) Moulded FiberSPAN deck panels; (b) Reinforcement and core details for FiberSPAN sandwich panels; (c) Installation of FiberSPAN deck on a pedestrian bridge.

#### 5.1.2. Decks with Adhesively Bonded Pultruded Shapes—No Longer Produced

FRP composite bridges using adhesively bonded pultruded shapes are no longer produced. In the 1990s, many pedestrian and highway bridges were constructed using these decks. A review of pultruded FRP bridge decks is presented in [4,19]. Prefabrication, light weight, and corrosion resistance of FRPs led to the development of pultruded FRP deck panels. Commercially available pultruded FRP decks from the 1990s to early 2000s are listed below (no longer available now or are dormant):

1. Superdeck (Creative Composites Group)—USA [97]
2. DuraSpan (Martin Marietta Composites)—USA [98]
3. ASSET (Advanced Structural SystEMs for Tomorrow's Infrastructure) bridge deck—Europe [9]
4. Delta deck—Korea [24]

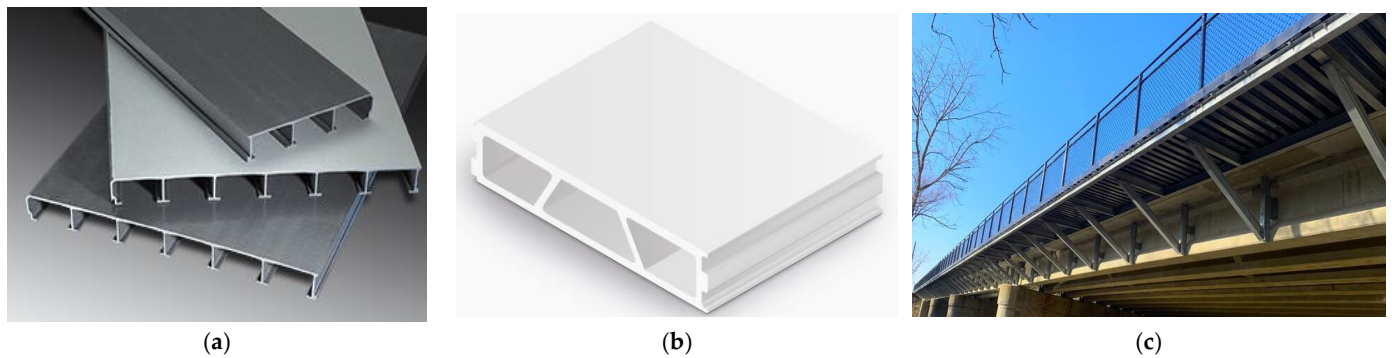
Superdeck by Creative Composites, USA employs bridge truss elements with hexagonal shear keys, as shown in Figure 33a. More than 50 bridges used the DuraSpan deck in the USA [19]; the DuraSpan is presented in Figure 33b. The ASSET deck contains triangular hollow pultruded profiles fabricated by Fiberline Composites, Denmark. The ASSET European project started in 1999. The first application of this deck was seen in 2002 on West Mill Bridge near Shrivenham in Oxfordshire, UK. Standen Hey Overbridge in the UK also used a double layer of ASSET profiles in 2007. Later in 2008, Friedberg Bridge in Germany used the ASSET deck as shown in Figure 33c. Further details about the ASSET system are given in [25]. In Korea, the Delta deck shown in Figure 33d was developed in the 2000s and has been used in more than 30 bridges ever since [22,24]. These highway bridge decks are no longer produced now. One barrier to the wider growth of FRP decks is the cost, which was 800 USD per m<sup>2</sup> versus 250 USD per m<sup>2</sup> in 2008 [9]. The bridge industry also finds it hard to integrate FRP composite workflows with steel and concrete.



**Figure 33.** FRP bridge decks fabricated using adhesively bonded pultruded shapes: (a) Superdeck by Creative Composites Group—USA [35]; (b) DuraSpan by Martin Marietta Composites installed at Dunnings Creek bridge, USA [99]; (c) FRP composite ASSET double deck by Fiberline bonded to steel beams at Friedberg Bridge, Germany [9]; (d) Delta deck—Korea [24].

### 5.2. FRP Plank Deck System for Pedestrian Walkways

FRP composite lightweight plank or deck system is used for pedestrian walkways and bicycle paths, as seen in Figure 34. Cantilever sidewalks using lightweight FRP decking and connecting to the existing road bridges are becoming popular. An FRP cantilever sidewalk contains decking on steel or FRP supports that attach to a highway bridge's exterior beams. Being 80% lighter than concrete, the FRP decking is quick to install [100]. Pultruded decking is produced by all pultruders including Fiberline, Strongwell and Creative Composites [46,100,101]. This type of plank/deck system is cost-competitive with steel and timber.



**Figure 34.** Lightweight FRP plank/deck system for walkways: (a) Strongwell plank  $80 \times 333$  mm [101]; (b) Fiberline Ultra Duty Plank  $80 \times 333$  mm [46]; (c) A cantilever sidewalk using FRP planks at Cass Avenue Bridge, Clinton, Southeast Michigan, USA, built in 2019, using Creative Composites' deck system.

### 5.3. Pultruded FRP Road Bridge Girders or Beams—Not Produced Now (Not Cost-Competitive)

Pultruded FRP bridge girders were used in road bridges until the early 2000s. A classic example is Strongwell's EXTERN DWB (double web beam), seen in Figure 35a. It comes in two sizes:  $200 \times 150$  mm or  $900 \times 450$  mm. The EXTERN girders are made from glass fibre continuous strand mat and stitched mat, glass fibre rovings and carbon tows, a synthetic surfacing veil and a vinyl ester thermoset resin system. The large EXTERN beams were once used in the 11.9 m span Route 601 highway bridge in Sugar Grove, Virginia, USA back in 2001 (see Figure 35b). Another vehicle bridge in Figure 35c is Tom's Creek Bridge, Blacksburg, Virginia, USA. The bridge was built in 1997 and used EXTERN DWB  $200 \times 150$  mm [101]. The EXTERN girders are dormant too, as they are no longer cost-competitive with steel.



**Figure 35.** Pultruded FRP highway bridge girders [101]: (a) Strongwell EXTERN DWB; (b) Route 601 highway bridge in Sugar Grove, Virginia, USA using EXTERN DWB  $900 \times 450$  mm, built in 2001; (c) Tom's Creek Bridge, Blacksburg, Virginia, USA, built in 1997 and used EXTERN DWB  $200 \times 150$  mm.

### 5.4. FRP Light Truss Bridge System

The light FRP truss system is suitable for pedestrian bridges. Pultruded FRP structural hollow tubes or other shapes are generally used in trusses. Pontresina Truss Footbridge [36] is a typical example of an FRP light truss system. Dover Sea Wall Footbridge [8,64] also uses trusses made of pultruded FRP members. E.T. Techtonics (now part of Creative Composites Group) were the pioneers in the relatively short span (10–30 m) light truss bridges as shown in Figure 36. They have successfully fabricated several FRP through-truss pedestrian, cycle and trail bridges for over 50 years. The truss bridges use small square tubes as diagonals and posts. The top and bottom chords are back-to-back parallel flange channel (PFC) sections [4].



**Figure 36.** FRP light truss bridges [3]: (a) FRP truss ready to install; (b) Full FRP truss bridge.

### 5.5. Moulded FRP Bridges and Components

Moulded bridge components or entire moulded bridges are used where geometric freedom and lightweight are required. The process mainly uses infusion moulding, described earlier in Section 4. The elements are usually project specific and cost more than off-the-shelf pultruded components. In addition, the benefit is that any geometric shape can be realised with enough reinforcements at critical locations and suitable core materials to avoid instability. Moulded FRP bridges or elements are very popular in bascule pedestrian bridges. A bascule or lifting bridge is a type of moveable bridge, where the bridge deck is lifted for navigation. Pont y Ddraig or the Dragon's Bridge in Wales [62] and Fredrikstad Bascule Footbridge in Norway [55] are typical examples of moulded FRP bascule bridges. Moulded CFRP primary girders were used in Asturias [66] and M111 road bridges in Spain [65,68]. Some manufacturers also have standard moulded FRP decks for footbridges or they can be custom made too.

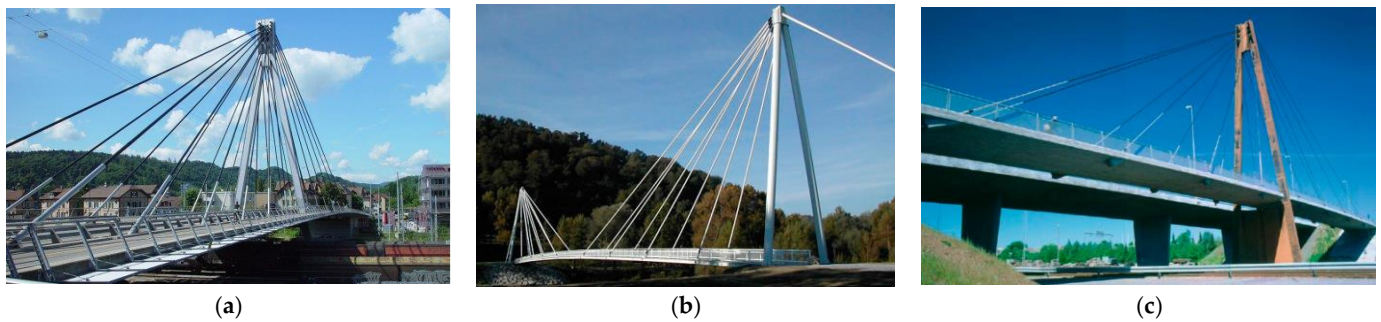
### 5.6. FRP Cables

Tensile cables are used in cable-stayed or suspension bridges. With high tensile strength, lightweight, fatigue and corrosion resistance and low thermal expansion, FRP cables offer a great replacement for steel cables. FRP cables can overcome shortcomings of high-strength steel cables, such as heavy weight, and corrosion. Their density is about 14–40% of the traditional high-strength steel cables. Wang and Wu [33] suggest that FRP cables are potentially suitable for cable-stayed bridges with super-long spans between 1 km to 10 km. FRP cables contain parallel or twisted wire tendons, plates or sheets as shown in Figure 37.



**Figure 37.** Types of FRP cables [30,31]: (a) FRP parallel wire cable; (b) FRP twisted wire cable; (c) FRP plate cable; (d) FRP sheet cable.

The material used for cables are carbon, glass, aramid and basalt fibre-reinforced polymer [30]. Glass fibres are not commonly used for very long cable-stayed bridges due to stress corrosion at elevated stresses [102]. Aberfeldy Footbridge in Scotland first used Parafil aramid ropes (cables) in 1992 [40]. FRP cables have been used in small and medium-span cable-stayed bridges, such as the 124 m span Stork Bridge in Switzerland with two CFRP and 22 steel cables, Laroin CFRP Footbridge in France with 110 m span and 16 CFRP cables and the 80 m span Herning Bridge in Denmark with 16 CFRP cables attached to a single pylon [31]. These bridges are shown in Figure 38 in the same order.



**Figure 38.** Applications of FRP cables in cable-supported bridges [31]: (a) Stork Bridge in Winterthur, Switzerland, 1996; (b) Laroin CFRP Footbridge, France, 2002; (c) Herning Footbridge in Denmark, 1999.

### 5.7. FRP as Internal Reinforcement in Concrete Members

The use of FRPs as internal reinforcement in concrete members dates to the 1950s. FRP internal reinforcements consist of bars and pre- and post-tensioned tendons. Excellent corrosion resistance and chemical resistance, lightweight and electrical neutrality are some of the key beneficial properties of FRP reinforcements. FRP reinforcements are used in harsh alkaline, corrosive, and chemical environment. Today, glass (GFRP), carbon (CFRP) and aramid (AFRP) internal reinforcements are commercially available [103]. Mechanical properties of FRP rebars are reported elsewhere [1,82]. Various design guides for FRP internal reinforcements are available, these include, fib 40 [82] and TR55 [83,104] in Europe and ACI 440.1R-15 [105] in America. Design guides for bridge beams prestressed with CFRP bars or cables are included in NCHRP research report 907 [106].

## 6. FRP Composites Exposed to Elevated Temperature and Fire

The durability of FRP composites under elevated temperatures and fire is an important consideration. Fire can start from arson, accident, natural disasters, and terrorist attacks. For instance, fires in FRP bridges can spread from arson, fuel spill from a vehicle accident or bush fire. This fire can heat the composites to 100 °C in a few seconds and can reach over 400 °C in minutes. The polymer resin matrix softens when exposed to high temperatures, usually over 100 °C. Pyrolysis—decomposition of matrix happens at 250–400 °C. This is accompanied by smoke, heat and toxic fumes. Polymer resins in civil engineering applications are often highly flammable and require expensive fire protection coatings. Understanding the fire properties of FRPs by civil engineers is critical [103]. The mechanical properties of FRP materials are significantly affected by exposure to elevated temperatures [107,108].

Three main areas will be discussed: fire reaction properties, structural degradation, and fire protection methods.

### 6.1. Fire Reaction Properties of FRP Composites

Fire reaction properties measure flammability and fire hazard. The properties to determine flammability include the time-to-ignition, limiting oxygen index (LOI), heat release rate (HRR) and flame spread rate. Fire hazard properties are smoke density and smoke toxicity.

FRP materials can be readily heated by thermal radiation or hot gas. The intensity of thermal radiation is measured by heat flux rather than temperature. Heat flux is the amount of thermal energy radiated on a solid surface, measured in  $W/m^2$ . Typical room fire has a heat flux of 50–100  $kW/m^2$  and hydrocarbon fire has 100–150  $kW/m^2$ .

#### 6.1.1. Time-to-Ignition

How quickly a material can be combusted is determined by time-to-ignition. The organic resins used in FRP bridges can ignite within a short period of time. Ignition happens at pyrolysis temperature, 250–400 °C. The time-to-ignition is determined using the ISO ignitability test and the cone calorimeter. Ignition properties of FRP in civil engineering are in various scientific publications [109–114]. The ignition time for polyester, vinylester and epoxy-based FRPs is generally 1–2 min when exposed to a heat flux of 50  $kW/m^2$  [103]. Phenolic resins have long ignition times but have low strength and durability concerns in moist areas. Ignition resistance can be improved by using thicker composites and increasing the fibre content.

#### 6.1.2. Limiting Oxygen Index (LOI)

The LOI is the minimum oxygen needed to sustain flaming combustion. The standard LOI test consists of a sample with a candle flame. The test does not represent realistic fire conditions. The LOI for typical thermoset resins is below 40 [103]. Phenolic and thermoplastic resins have high LOI values.

#### 6.1.3. Heat Release Rate (HRR)

The heat release rate (HRR) is the most important fire reaction property. It controls the spread and growth of a fire. The HRR is measured by the cone calorimeter method. The peak HRR values for typical civil engineering composite range from 250 to 350  $kW/m^2$ . While phenolic-based composite has a low value of 75  $kW/m^2$  [103]. FRP composites that emit large organic volatiles into the flame have high HRR values.

#### 6.1.4. Flame Spread Rate

The flame spread rate relates to the speed at which the fire grows. Most civil engineering FRP composites have high flammability. This is one of the key properties in fire safety for FRP buildings and bridges. ASTM's radiant panel flame spread technique is the most common testing method for flame spread rate [103]. Phenolic resins have a low flame spread.

#### 6.1.5. Smoke Properties

FRP composites produce thick and dense smoke in the event of fire. The smoke produced by highly flammable resins (polyester, vinylester and epoxy) is usually thicker as compared to phenolic resin. The smoke properties of FRP composites are determined by the specific extinction area (SEA). The SEA measure density of the smoke.

#### 6.1.6. Smoke Toxicity

The effect of smoke toxicity varies from skin and eye irritation to acute respiratory issues. The greatest hazard to people is toxic gas instead of heat and flames. The amount of carbon mono oxide produced by FRP depends on a matrix, available oxygen and temperature. Another risk could be airborne fibre particles that cause irritation.

### 6.2. Structural Properties of FRP Composites in Fire

In the event of fire, FRP components can soften, distort and fail. The structural properties of FRP composites weaken at elevated temperatures. This is due to visco-elastic softening and decomposition of the matrix, delamination cracking and fibre weakening. The mechanical properties of FRP composites are severely degraded even below the pyrolysis temperature (250–400 °C). The strength and stiffness of the composite material are

significantly degraded when heated to the glass transition temperature ( $T_g$ ) of the resin matrix. The composites start to warp at the heat distortion temperature of 80–120 °C for typical resins. The strength of polymer composite drops quickly 100–150 °C. The compression properties are weakened more rapidly compared to tension properties. Thick composites are usually better at resisting loading for a long period of time before the matrix thermally decomposes. In the case of FRP composite sandwich bridge components, the mechanical properties of both FRP skins and core materials are affected by elevated temperatures.

### 6.3. Methods to Improve FRP Fire Resistance

The fire resistance of FRP parts can be improved by flame-resistant coatings, fillers, or polymer modification. These are briefly discussed in the sub-sections below.

#### 6.3.1. Fire Protection Coatings

Applying a flame-resistant coating is a typical method for improving the fire resistance of composites. There are three main types: flame-retardant polymer, thermal barrier and intumescent coatings. Flame-retardant polymer coatings are essentially fire-resistant resins. These coatings act as a barrier to heat conduction and prevent flammable matrix material from reaching flame. Thermal barrier coatings are ceramic-based, non-flammable and low-heat conducting materials. Typical examples of thermal barriers include ceramic (silica or rockwool) fibrous mats and ceramic (zirconia or alumina) plasma-sprayed films. Intumescent coatings swell into a highly porous, thick and thermally stable char on the composite part. These coatings act as an insulation barrier against flame due to high void content and thickness.

#### 6.3.2. Flame-Retardant Fillers

The most cost-effective method to reduce the flammability of resin is to add flame-retardant fillers. The filler with an average content of 50–60% is usually mixed with the liquid resin at the final processing stages. Non-combustible fillers dilute the mass fraction of polymer resin. Fillers can be inert or active flame retardants. They reduce the flammability and smoke yield of polymer composites. A few common inert flame retardants include silica, calcium carbonate and carbon black. Active fillers are more effective than inert fillers. They have a cooling effect that slows the decomposition of the polymer matrix.

#### 6.3.3. Matrix Modification with Flame-Retardant Polymers

Polymers can be modified using halogen compounds with bromine or chlorine to reduce their flammability. During fire reactive halogen species are released which stops the combustion. This leads to lower flame temperature, and it slows down the polymer decomposition.

## 7. Challenges and Outlook

Fibre-reinforced polymer materials have been very successful in footbridges, especially in inaccessible areas or where fast installation is essential. Although the use of FRPs set out very well in the 1980s and 1990s in road bridges, it has seen a decline over the past decade. There are three major challenges: lack of standard design codes and material specifications, and high cost. Another problem in the coming years would be difficulty in recycling non-biodegradable FRPs. The pace of development of design codes for pultruded structures has taken longer than initially thought. The American Society of Civil Engineers (ASCE) has been working on the development of a design standard for pultruded FRP since 1997. This led to the publication of the ASCE Pre-standard [115] for pultruded structures in 2010, but it has still not been approved as a formal design code.

Similar efforts in Europe by EuCIA [116] are expected to produce a Eurocode for FRP structures in 2024. Another issue is the lack of agreed material specifications for FRP materials. Contrary to steel and concrete, there are no internationally accepted material specifications for FRP. Currently, each manufacturer publishes their own material properties



for pultruded FRP shapes. The properties of moulded FRP components are usually obtained through testing. The moulded FRPs are generally custom-made and designed by in-house structural engineers.

FRP bridges cost 20% more than conventional bridges [8]. This claim should be used with a caveat, as the author did not find any journal paper in the public domain to verify it, except the guide for FRP bridges in [8]. FRP materials usually cost higher than steel and concrete. One argument is that the initial cost is high, but the whole life cost could be equivalent to or even less than traditional materials. This is due to less maintenance required for FRPs in corrosive and marine environments. Automatic processes, such as pultrusion are cost-competitive and manual methods, such as moulding produce only one-off expensive bridge elements.

As many off-the-shelf pultruded road bridge girders and decks (Strognewell's EXTERN DWB—double web beam [117], Superdeck [97], DuraSpan [98], ASSET bridge deck [9] and Delta deck [24]) are no longer produced, the high cost is the obvious reason. The high cost of FRP bridge components seems to be a major barrier to the wider use of FRPs in bridges. Even in corrosive environments, the FRP material does not seem to be cost-effective. However, the use of FRPs in footbridges is still popular for inaccessible areas due to fast deployability. Unless radical changes are made to the production, procurement, and construction processes of FRP, the economic viability will control the bridge engineering market.

## 8. Conclusions

This paper presents a comprehensive review of the history, materials, methods, FRP bridge elements (decks, girders, moulded shapes, trusses and cables), fire performance and challenges and outlook of FRP new-build bridges. The use of FRP in strengthening, repairing and retrofitting existing steel or concrete bridges is not covered. Additionally, the use of a prestressing tendon or reinforcing bar in prestressed and reinforced concrete bridge elements is not included in the review. FRPs have been very successful in pedestrian bridges over the last two decades. Rapid installation, pre-fabrication and lightweight have helped build numerous FRP footbridges around railway tracks in as quick as eight hours in Europe and America. Lightweight FRP plank system for cantilever sidewalks attached to existing concrete bridges is becoming popular due to similar cost as timber or steel.

Contrarily, the use of FRP has seen a considerable decline in road bridges over the last decade. Many manufacturers have stopped producing standard vehicular bridge decks and girders. Many commercial bridge decks once used in many vehicular bridges are either dormant or no longer in production. These include Superdeck (Creative Composites Group)—USA [97], DuraSpan (Martin Marietta Composites)—USA [98], ASSET bridge deck—Europe [9] and Delta deck—Korea [24]. The double web girder for highway bridges by Strongwell (EXTERN DWB [101]) is dormant too. It was once used in Route 601 highway bridge, USA in 2001 and Tom's Creek Bridge, USA in 1997.

There are three major impediments to the widespread use of FRPs in roads and footbridges. These include a lack of internationally accepted design code and materials specifications, inability to recycle non-biodegradable FRP composites—especially glass FRPs, and high cost compared to traditional materials. The slow pace of development of standard design codes and material specifications is a contributing factor too. In addition, most FRP bridges are designed by in-house speciality structural engineers and material properties are either available from manufacturers or can be obtained by testing. Recycling is a major challenge at the end of the service life of an FRP, especially for glass FRPs. Considering the design service life of FRP bridges as 125 years as per [8], recycling of FRPs is not an imminent concern. However, research is underway to find the most eco-efficient and cost-effective recycling route for structural FRPs. The high cost of FRPs seems to be the main barrier to the wider growth of FRPs within the construction industry. This is evident from the fact that many FRP commercial products for highway bridges that were available in the early 2000s are dormant now or no longer in production.

The research needs of the future for FRP use in bridges will be around durability issues, especially fire performance and aggressive environmental conditions. Since FRPs have now been in use for more than three decades, this can provide useful data for studying the durability performance of FRP components in bridges. There is limited research on the recycling of FRP; glass-based FRPs will pose a major sustainability problem for the ageing bridge stock or decommissioned bridge components. More research is also required on slip-resistant FRP connections and joints in bridges. Some ideas, such as resin-injected bolted joints have been explored in the past. But more research work should be conducted to exploit the full potential of FRPs in bridges.

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## Appendix A

The list of selected all-FRP and hybrid-FRP pedestrian, road and railway bridges is given in Tables A1 and A2.

**Table A1.** Details of all-FRP bridges around the world [4,8,26,34,36,38,40,43,44,46–64].

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
1	Miyun Bridge	Beijing	China	1982	all	20.7	9.8
2	Chenjiawan Bridge	Chongqing	China	1988	all	60.0	4.0
3	Aberfeldy Footbridge	Aberfeldy	UK	1990	all	112.8	2.1
4	Shank Castle Footbridge	Cumbria	UK	1993	all	11.9	3.0
5	Bonds Mill Lift Bridge Stroud	Gloucestershire	UK	1994	all	8.2	4.3
6	PWRI Demonsration Bridge	Tsukuba	Japan	1996	all	20.1	2.1
7	Clear Creek Bridge	Bath	USA, Kentucky	1996	all	18.3	1.8
8	Kolding Fiberline Bridge	Kolding	Denmark	1997	all	39.9	3.0
9	Pontresina Truss Bridge	Pontresina	Switzerland	1997	all	25.0	3.0
10	INEEL Bridge	Idaho Falls	USA, Idaho	1997	all	9.1	5.5
11	Medway Bridge	Medway	USA, Maine	1997	all	16.5	9.1
12	West Seboeis Bridge	West Seboeis	USA, Maine	1997	all	13.4	4.9
13	Smith Creek Bridge	Hamilton/Butler	USA, Ohio	1997	all	10.1	7.3
14	Falls Creek Trail Bridge	Gifford Pinchot National Forest	USA, Washington	1997	all	13.7	0.9
15	Noordland Pedestrian Bridge	Noordland Inner Harbor	The Netherlands	2000	all	26.8	1.5
16	East Dixfield Bridge	East Dixfield	USA, Maine	2000	all	13.7	9.1
17	Five Mile Road Bridge #0171	Hamilton	USA, Ohio	2000	all	13.4	8.5
18	Lleida Footbridge	Lleida	Spain	2001	all	38.1	3.0
19	Sealife Park Dolphin Bridge	Oahu	USA, Hawaii	2001	all	11.0	0.9
20	West Mill Bridge over River Cole	Oxfordshire	UK	2002	all	10.0	6.8
21	Fredrikstad Bridge	Fredrikstad	Norway	2003	all	60.0	3.0
22	Den Dungen Bridge	Den Dungen	The Netherlands	2003	all	10.0	3.7
23	Emory Brook Bridge	Fairfield	USA, Maine	2003	all	21.9	10.7
24	Lake Jackson Bridge	Lake Jackson	USA, Texas	2003	all	27.4	1.8
25	Various ApATeCh footbridges	Moscow	Russia	2004–2007	all	11.2–58.2	2.3–5.0
26	St Austell Railway Bridge	St Austell	UK	2007	all	26	1.42

Table A1. Cont.

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
27	Nørre Aaby Footbridge	Nørre Aaby	Denmark	2008	all	23	Not given
28	ApATeCh arched footbridge	Moscow	Russia	2008	all	22.6	2.8
29	ApATeCh Bridge in Sochi	Moscow	Russia	2008	all	12.8	1.6
30	Whatstandwell Footbridge	Derbyshire	UK	2009	all	8.0	1.6
31	Bradkirk Footbridge	Bradkirk	UK	2009	all	24.0	Not given
32	River Leri Footbridge	Ynyslas	UK	2009	all	90.0	Not given
33	Manzanares Footbridge	Madrid	Spain	2011	all	44.0	Not given
34	Dawlish footbridge	Exeter	UK	2012	all	18.0	1.8
35	Pont y Ddraig	Rhyl, Wales	UK	2013	all	60.0	3.0–4.0
36	Bird Riding Footbridge	Coverham	Richmondshire, UK	2016	all	15.0	1.2
37	East Row Footbridge	Whitby	UK	2016	all	16.7	3.0
38	Dover Sea Wall Footbridge	Dover	Kent, UK	2017	all	31.0	2.42
39	Eindhoven bio-polymer bridge		The Netherlands	2017	all	14.0	1.2
40	Emersons Green East Cycle Footbridge	Bristol	UK	2020	all	54.0	5.0

Table A2. Details of Hybrid-FRP bridges around the world.

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
1	Neal Bridge	Pittsfield	USA, Maine	2008	arch shells	9.3	Not given
2	McGee Bridge	Anson	USA, Maine	2009	arch shells	8.5	Not given
3	Bradley Bridge	Bradley	USA, Maine	2010	arch shells	8.9	Not given
4	Belfast Bridge	Belfast	USA, Maine	2010	arch shells	14.6	Not given
5	Hermon Snowmobile Bridge	Hermon	USA, Maine	2010	arch shells	13.7	Not given
6	Aubum Bridge	Aubum	USA, Maine	2010	arch shells	11.6	Not given
7	Ginzi Highway Bridge	Ginzi	Bulgaria	1982	beams	11.9	6.1
8	Rijkerswoerd Footbridge	Arnhem	The Netherlands	1985	beams	10.0	3.7
9	Chongqing Communication Institute Bridge	Chongqing	China	1986	beams	50.0	4.6
10	Devil's Pool/Fairmount Park Bridge	Philadelphia	USA, Pennsylvania	1992	beams	15.2	1.5
11	Will Rogers State Park	Temescal Canyon Pacific	USA, California	1994	beams	6.1	1.2
12	Sierra Madre Footbridge	Sierra Madre	USA, California	1994	beams	12.2	1.2
13	Malibu Creek State Park Footbridge	Malibu	USA, California	1994	beams	6.1	1.5
14	Deukmejian Wilderness Park Footbridge	Glendale	USA, California	1994	beams	7.6	1.2
15	Will Rogers State Park Footbridge	Malibu	USA, California	1994	beams	12.2	1.5
16	Boulder County Bridge	Boulder	USA, Colorado	1994	beams	10.7	1.8
17	Philadelphia Zoo Footbridge	Philadelphia	USA, Pennsylvania	1994	beams	30.5	3.0
18	Staircase Rapids (Hoodspout)	Olympic National Park	USA, Washington	1994	beams	24.4	1.2
19	Point Bonita Lighthouse Footbridge	San Francisco	USA, California	1995	beams	21.3	1.2
20	Pardee Dam Bridge	Valley Springs	USA, California	1995	beams	7.6	1.5
21	Haleakala National Park (1)	Hana	USA, Hawaii	1995	beams	18.3	1.2

Table A2. Cont.

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
22	Antioch Composite Pedestrian Bridge	Antioch	USA, Illinois	1995	beams	13.7	3.0
23	Catholic University Access Bridge	Washington	USA, Washington D.C.	1995	beams	10.7	1.2
24	Medicine Bow National Forest	Medicine Bow	USA, Wyoming	1995	beams	6.1	1.5
25	San Dieguito River Park Footbridge	San Diego	USA, California	1996	beams	21.3	2.4
26	City of Glendora Bridge	Glendora	USA, California	1996	beams	5.5	1.8
27	Dingman Falls Bridge	Bushkill	USA, Pennsylvania	1996	beams	21.3	1.8
28	Koegelwieck Bridge	Harlingen	The Netherlands	1997	beams	14.9	2.1
29	Grant Cty Park Bridge (5)	San Jose	USA, California	1997	beams	15.2	1.5
30	Homestead Bridge	Los Alamos	USA, New Mexico	1997	beams	16.5	1.2
31	Powell Park Bridge	Raleigh	USA, North Carolina	1997	beams	4.6	1.2
32	Mountain Hood National Forest Bridge	Sandy	USA, Oregon	1997	beams	9.1	1.2
33	Santa Monica National Park	Calabasas	USA, California	1998	beams	12.2	1.5
34	Peavine Creek Bridge	Wallowa Whitman	USA, Oregon	1998	beams	6.7	1.8
35	Muir Beach Bridge	Muir Beach	USA, California	1999	beams	15.2	1.2
36	Tanner Creek/Weco Beach Bridge	Bridgman	USA, Michigan	1999	beams	10.1	1.8
37	Blue Ridge Parkway Bridge	Floyd	USA, Virginia	1999	beams	10.4	1.2
38	Santa Monica Bridge	Topanga	USA, California	2000	beams	18.3	1.8
39	Heil Ranch Bridge	Boulder	USA, Colorado	2000	beams	13.7	1.8
40	Sachem Yacht Club	Guilford	USA, Connecticut	2001	beams	16.5	1.8
41	Barclay Avenue Bridge	Staten Island	USA, New York	2001	beams	9.8	1.8
42	Clemson Experimental Trail Bridge	Clemson	USA, South Carolina	2001	beams	9.1	1.8
43	Petaluma Bridge	Petaluma	USA, California	2002	beams	12.2	1.8
44	Scenic Hudson Bridge	Tuxedo	USA, New York	2002	beams	10.7	1.2
45	FM 3284 bridge	San Patricio	USA, Texas	2003	beams	9.1	8.5
46	Asturias bridge	Asturias	Spain	2004	beam	46.0	8.0
47	M111 bridges	Madrid	Spain	2007	beam	34.0	20.4
48	Windy Creek	Ft Wainwright	USA, Alaska		beams	13.7	1.8
49	Audubon Canyon Ranch	Marshall	USA, California		beams	29.3	1.8
50	Middlebury Run Park	Akron	USA, Ohio		beams	17.7	3.0
51	Walker Ranch Park	San Antonio	USA, Texas		beams	22.9	1.8
52	Green Hill Park Pedestrian Bridge	Roanoke	USA, Virginia		beams	21.3	2.4

Table A2. Cont.

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
53	Lake Fairfax	Fairfax	USA, Virginia		beams	16.8	1.8
54	Bovi Meadows—Olympic National Park	Port Angeles	USA, Washington		beams	22.9	1.8
55	Promised Land State Park	Greentown	USA, Pennsylvania		beams	18.3	1.2
56	Royal Mills River Walk	Warwick	USA, Rhode Island		beams	22.6	1.8
57	Guanyinqiao Bridge	Chongqing	China	1988	deck	157.0	4.6
58	A19 Tees Viaduct	Middlesborough	UK	1988	deck	Not given	Not given
59	Jiangyou Bridge	Jiangyou	China	1990	deck	Not given	Not given
60	Panzhuhua Bridge	Panzhuhua	China	1992	deck	24.1	3.0
61	Bromley South Bridge	Kent	UK	1992	deck	210.0	Not given
62	Chuanmian Bridge	Chengdu	China	1993	deck	10.7	5.2
63	Xiangyang Bridge	Chengdu	China	1993	deck	50.0	4.0
64	Parson's Bridge	Dyfed	UK	1995	deck	17.7	3.0
65	LaSalle Street Pedestrian Walkway	Chicago	USA, Illinois	1995	deck	67.1	3.7
66	Second Severn Bridge	Bristol	UK	1996	deck	29.4	9.1
67	Rogiet Bridge	Gwent	UK	1996	deck		
68	UCSD Road Test Panels	San Diego	USA, California	1996	deck	4.6	2.4
69	No-Name Creek Bridge	Russell	USA, Kansas	1996	deck	7.3	8.2
70	Staffordshire Highbridge	Staffordshire	UK	1997	deck	45.1	3.0
71	Magazine Ditch Bridge (Del Memorial Bridge)	New Castle	USA, Delaware	1997	deck	21.3	6.1
72	EXPO Bridge	Lisbon	Portugal	1998	deck	30.0	Not given
73	Rowser Farm Bridge	Bedford	USA, Pennsylvania	1998	deck	4.9	3.7
74	Wilson's Bridge	Chester	USA, Pennsylvania	1998	deck	19.8	4.9
75	Greensbranch Pedestrian Bridge	Smyrna	USA, Delaware	1999	deck	9.8	1.8
76	Levisa Fork of the Big Sandy River Footbridge	Johnson	USA, Kentucky	1999	deck	12.8	1.2
77	Salem Ave Bridge (State Rt 49)	Dayton	USA, Ohio	1999	deck	51.2	15.2
78	Sedlitz & Senftenberg Bridge	Sedlitz & Senftenberg	Germany	2000	deck	20.1	2.4
79	Milbridge Municipal Pier	Milbridge	USA, Maine	2000	deck	53.3	4.9
80	Wheatley Road	Cecil	USA, Maryland	2000	deck	10.4	7.3
81	Market Street Bridge [118]	Wheeling	USA, West Virginia	2000	deck	57.9	17.1
82	Buehl-Balzhofen Bridge		Germany	2001	deck	11.9	Not given
83	Stelzer Road Bridge	Columbus	USA, Ohio	2001	deck	118.0	10.7
84	Katy Truss Bridge [118]	Marion	USA, West Virginia	2001	deck	27.4	4.3
85	Towoomba Bridge	Towoomba	Australia	2002	deck	10.0	5.5
86	Klipphausen Bridge	Klipphausen	Germany	2002	deck	Not given	Not given
87	Benten Bridge	Fukushima	Japan	2002	deck	60.0	3.0
88	O'Fallon Park Bridge	Denver	USA, Colorado	2002	deck	30.5	6.7
89	West Mill Bridge [119]	Highworth	Oxfordshire, UK	2002	deck	7.5	4.0
90	Schwerin-Neumühle Bridge	Schwerin	Germany	2003	deck	45.0	2.5
91	Ribble Way Footbridge	Lancashire	UK	2003	deck	131.1	3.0

Table A2. Cont.

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
92	Chief Joseph Dam Bridge	Bridgeport	USA, Washington	2003	deck	90.8	9.8
93	US 151 over SH 26	Fond de Lac	USA, Wisconsin	2003	deck	65.2	11.9
94	ApATeCh Pedestrian passage	Moscow	Russia	2005	deck	56.8	2.9
95	Mount Pleasant M6 Bridge	Lancashire	UK	2006	deck	Not given	Not given
96	Tangier Island Bridge	Tangier Island	USA, Virginia	2006	deck	Not given	Not given
97	Pedestrian bridge in recreation zone "Tsaritsyno Ponds"	Moscow	Russia	2007	deck	58.2	3.7
98	Standen Hey Overbridge	Clitheroe	Lancashire, UK	2007	deck	9.5	3.0
99	Wilcote footbridge [120,121]	Wilcote	Shropshire, UK	2007	deck	51.3	2.0
100	Friedberg Bridge over B3 Highway	Friedberg	Germany	2008	deck	27.0	Not given
101	Footbridge over road no. 11 n. Gadki	Gadki	Poland	2008	deck	260.0	Not given
102	Holländerbrücke [122]	Reinbeck	Germany	2009	deck	98.0	3.5
103	Belle Glade Bridge	Belle Glade	USA, Florida	2009	deck	Not given	Not given
104	Lafayette Bridge	Lafayette, Tippecanoe	USA, Indiana	2009	deck	Not given	Not given
105	Lunetten Footbridge	Utrecht	Netherlands	2010	deck	12.0	5.0
106	Redstone Arsenal Bridge	Redstone Arsenal	USA, Alabama	2010	deck	Not given	Not given
107	Fort Amherst Footbridge	Fort Amherst	UK	2011	deck	25.0	2.0
108	Moss Canal Bridge	Rochdale	UK	2011	deck	12.0	3.0
109	Purfleet Footbridge	King's Lynn	Norfolk, UK	2013	deck	10.0	2.0
110	River Chor Aqueduct	Chorley	Lancashire, UK	2014	aqueduct	38.0	2.0
111	Thornaby Footbridge	Thornaby-on-Tees	Stockton-on-Tees, UK	2014	deck	40.0	Not given
112	Mapledurham footbridge,	Mapledurham	Berkshire, UK	2015	deck	13.0	Not given
113	Sedlescombe Bridge	Sedlescombe	East Sussex, UK	2015	deck	8.0	1.35
114	Kiora Sluice Footbridge	Broxbourne	Hertfordshire, UK	2017	deck	21.0	1.5
115	Prince Street Footbridge	Bristol	UK	2017	deck	27.0	Not given
116	Kings Stormwater Channel Bridge	Indio / Riverside	USA, California	2000	deck, beam shells, piers shells	20.1	13.4
117	St. Francis Street Bridge	St. James	USA, Missouri	2000	deck, tendons	7.9	8.5
118	Bridge St Bridge over Rouge River	Southfield	USA, Michigan	2001	deck, tendons	60.4	9.1
119	Lunenschegasse Bridge	Dusseldorf	Germany	1980	tendons	6.4	6.1
120	Ulenbergstrasse Bridge	Dusseldorf	Germany	1986	tendons	46.9	14.9
121	Marienfelde Bridge	Berlin	Germany	1988	tendons	50.3	4.6
122	Shinmiya Bridge	Ishikawa	Japan	1988	tendons	6.1	7.0
123	Nakatsugawa Bridge	Chiba	Japan	1989	tendons	7.9	2.4
124	Bachigawa Minami Bridge	Fukuoka	Japan	1989	tendons	36.0	12.2
125	Notsch Bridge	Notsch, Karnnten	Austria	1990	tendons	43.9	11.9
126	Birdie Bridge	Ibaraki	Japan	1990	tendons	54.6	2.1

Table A2. Cont.

S.No	Name of Bridge	Location	Country/State	Year	Use of FRP	Length (m)	Width (m)
127	Talbus Bridge	Tochigi	Japan	1990	tendons	9.5	5.5
128	Oststrasse Bridge	Ludwigshafen	Germany	1991	tendons	81.7	11.3
129	Bridge #15 Hakui Kenmin Bicycle Route	Ishikawa	Japan	1991	tendons	10.7	4.3
130							
131	Access Road to Rapid City Cement Plant	Rapid City	USA, South Dakota	1991	tendons	9.1	5.2
132	Takahiko Pontoon Bridge	Ibaraki	Japan	1992	tendons	73.2	3.0
133	Amada Bridge	Ishikawa	Japan	1992	tendons	7.3	3.4
134	Hishinegawa Bridge/Hakui Kenmin Bicycle Route	Ishikawa	Japan	1992	tendons	14.0	12.2
135	Beddenton Trail Bridge/Central Street	Calgary	Canada, Alberta	1993	tendons	42.0	15.2
136	Yamanaka Bridge	Tochigi	Japan	1993	tendons	9.4	5.5
137	Slab Bridge	Mie	Japan	1995	tendons	10.7	3.7
138	Mukai Bridge	Ishikawa	Japan	1995	tendons	14.9	14.3
139	Seisho Bridge Bridge	Kanagawa	Japan	1996	tendons	10.7	3.7
140	Storchenbruecke	Winterthur	Switzerland	1996	tendons	123.7	6.1
141	Taylor Bridge	Headlingley	Canada, Manitoba	1997	tendons	132.0	17.0
142	Milbridge Bridge	Milbridge	USA, Maine	1997	tendons	4.9	7.3
143	Herning Stibro	Herning	Denmark	1999	tendons	79.9	3.0
144	Parker @I-225 Bridges	Denver	USA, Colorado	2000	tendons	10.7.	11.0
145	Ikeishima Island Bridge	Okinawa	Japan	2001	tendons	37.8	4.0
146	Route 141 over Willow Creek	Guthrie	USA, Iowa	2001	tendons	64.0.	7.9
147	Passerelle de Laroin	Laroin	France	2002	tendons	Not given	Not given
148	I-225 & SH83 Interchange	Aurora	USA, Colorado	2002	tendons	410.0	12.8

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