Opportunities for pultruded composites in infrastructure

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Corrosion presents an immense challenge in the infrastructure sector. Maintaining, rehabilitating, replacing and upgrading ageing, deteriorating structures is a growing burden worldwide, with significant economic and environmental impacts. Governments, infrastructure owners, designers and users need new construction technologies which deliver more durable, more sustainable and more economic solutions. Lightweight, corrosion-resistant composite materials could provide an answer – faster installation combined with longer asset life and minimal maintenance can deliver lower life cycle costs, and a lower carbon footprint, than steel, concrete and wood structures, particularly for applications in aggressive environments. Ideally suited to countless construction applications, pultruded composites are already making a proven difference in two crucial sectors of the infrastructure market – rebar for reinforcing concrete, and bridge building.

The cost of corrosion

Ageing infrastructure is a global problem with huge numbers of bridges and other critical structures in urgent need of rehabilitation, replacement or upgrading in many countries around the world. According to a 2021 report from the American Road and Transportation Builders Association (ARTBA)[1], more than 45,000 of the nation’s 618,000 bridges are classified as structurally deficient and the cost to repair or replace them is estimated at US$41.8 billion. Much of the European Union’s dense transport infrastructure, built after World War II, is straining under ever-increasing traffic load and intensity. Most transport bridges built post-war, many relying on reinforced concrete, had a design life of 50-100 years and the safety of many is now in question. A UK study[2] released in January 2021 found that local authorities in England, Scotland and Wales identified 3,105 bridges (structures over 1.5 m in span) as being substandard (unable to carry the heaviest vehicles now seen on the roads). Budget restrictions mean that only 392 are expected to have the necessary work carried out to take them back up to full carrying capacity within the next five years. The estimated cost to bring all the substandard bridges back up to perfect condition is £985 million, and the one-time cost to clear the maintenance backlog on all 71,656 bridges is £5.54 billion.

The collapse of the Morandi Bridge in Genova in 2018, with the loss of more than 40 lives, led to wide-ranging discussions about the condition of Europe’s infrastructure. Material degradation due to corrosion and underfunded maintenance activities were highlighted as key areas for concern, and the need for effective, proactive maintenance recognised.[3] But budgets are limited. The economic crisis in 2008 led to huge spending cuts; in many countries maintenance and rehabilitation activities have been deferred, and the maintenance backlog is growing considerably. This problem could be exacerbated if the Covid-19 pandemic leads to further spending cuts.

Corrosion is also extremely costly for the environment, resulting in the utilisation of more resources over a structure's lifetime. Optimising an asset's life cycle and minimising maintenance requirements play an important part in sustainable design. As the shift to a circular economy continues to gain pace worldwide, life cycle assessments (LCAs) to determine the environmental impacts of any project are becoming ever more important from the user, owner and regulator perspective.

The ongoing challenge of corrosion control forms part of a wider focus on life cycle costing (LCC) in the construction industry. This is increasingly driving the search for the next-generation of construction materials that provide resilient, safe and reliable infrastructure capable of long, maintenance-free service lives; that are easier to work with and faster to install; and that offer superior mechanical performance and greater design freedom. Considering total life cycle costs can help bridge engineers and owners to deliver significant cost efficiencies over the lifespan of a structure, rather than an approach focusing purely on the initial upfront cost**.** The increased use of LCC in infrastructure design and planning is highlighting the potential for polymer composite materials to provide corrosion-free, long-lasting solutions with superior structural performance which are fast to install and extend asset life**.** There is a growing body of evidence that composite materials can offer a reduced total cost of ownership for infrastructure owners, particularly in aggressive environments where steel, concrete and wood quickly succumb to corrosion. Alongside this, LCAs are demonstrating their potential benefits over conventional construction materials from an environmental point of view.

Strong, lightweight and durable, pultruded composite components are already to be found in countless building, construction and infrastructure applications. The pultrusion process is a cost-efficient method for the high-volume manufacture of rods, tubes and profiles of various shapes and sizes. In the infrastructure market, two significant and growing sectors where pultruded composites offer strong potential are bridge building and rebar for concrete reinforcement.

What is pultrusion?

Pultrusion is a continuous process for producing linear fibre reinforced plastic (FRP) (composite) profiles with a uniform cross-section. In the pultrusion machine the reinforcing fibres are impregnated with resin and pulled through a heated die where curing takes place. The finished profiles are cut to length at the end of the line and can then be stored and used as structural units when required. The pultrusion operation can be readily automated, allowing for low labour involvement, and is therefore a fast, efficient way of producing high performance composite parts.

Pultrusion offers the designer major freedom regarding the geometry, properties and design of the finished profile. Both solid and hollow profiles can be manufactured, in simple and complex cross-sectional shapes, including tubes, rods, I-beams, T-, U- and Z-profiles. An immense variety of profile shapes is possible.

Since pultrusion allows for extremely high fibre loading and accurately controlled resin content pultruded parts have excellent structural properties and are produced at a consistently high quality. A range of reinforcing fibres, and formats, can be used, including glass and carbon fibre, with a variety of thermoset matrix resins such as polyester, epoxy and vinyl ester, as well as thermoplastics. Reinforcement, resin and additives can be combined in innumerable ways to ensure that the finished profile provides the optimum combination of properties required for a specific application.

Almost any profile cross-section can be manufactured within the following parameters:

- maximum length: 12 m (determined by transportation limits);
- maximum width: 1350 mm/900 mm (depending on the flammability rating);
- wall thickness: from 1.5 mm to a maximum of 60 mm, and typically 3-3.5 mm;
- undercuts and different wall thicknesses are possible;
- radii between 0.5 mm and 2 mm are required.

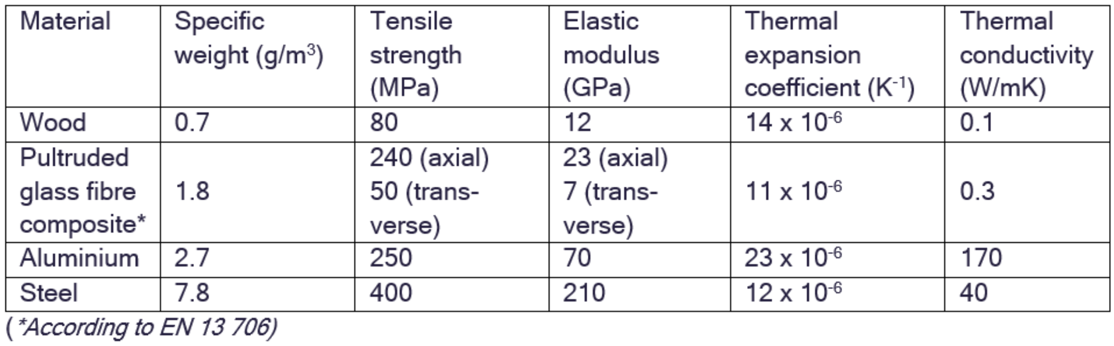
Pultruded profiles are pigmented throughout the thickness of the part and can be made in virtually any colour. Surfacing veils may be employed to create special appearances such as wood grain, marble and granite. Profiles can also be painted, cut and drilled using conventional hardened tools and connected using bolts, screws, rivets or adhesives. A durable UV-resistant coating is typically applied to profiles intended for outdoor use.

Several standards have been developed covering the design, fabrication and installation of pultruded profiles. These include the Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fibre Reinforced Polymer (FRP) Structures developed by the American Composites Manufacturers Association (ACMA) and the American Society of Civil Engineers (ASCE), and European Standard EN 13 706, which specifies minimum requirements for the quality, tolerances, strength, stiffness and surface of structural profiles. Other codes currently in use are the Eurocomp Design Guide and the CUR96 in the Netherlands. Work towards new European technical specifications for the design and verification of composite structures used in buildings, bridges and construction works is currently being conducted by Working Group WG4 'Fibre Reinforced Polymers' under the European Committee for Standardisation (CEN) Technical Committee 250 (CEN/TC250).

At the end of their service life pultruded profiles can be recycled. A grinding process results in a by-product that can be used as a filler in building materials such as concrete and asphalt, or reused in the pultrusion process as a filler in the matrix resin. An important advance in Europe involves the recycling of glass fibre-based composite regrind through coprocessing in cement kilns. This route is becoming increasingly popular since it is highly cost effective, helps to improve the ecological footprint of cement manufacturing and is compliant with the European Waste Framework Directive (WFD) 2008/98/EC. The composite regrind used for co-processing in cement kilns is both an alternative fuel and raw material (AFR). When combined with other feedstock materials into an input stream with consistent composition and caloric value the inorganic fraction acts as valuable raw material, while the organic fraction acts as efficient fuel for the calcination process.

The composites advantage

Pultruded glass fibre composites offer a combination of properties not available with the traditional building materials of steel, aluminium, concrete and wood.



Material	Specific weight (g/m^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Thermal expansion coefficient (K^{-1})	Thermal conductivity (W/mK)
Wood	0.7	80	12	14×10^{-6}	0.1
Pultruded glass fibre composite*	1.8	240 (axial) 50 (trans-verse)	23 (axial) 7 (trans-verse)	11×10^{-6}	0.3
Aluminium	2.7	250	70	23×10^{-6}	170
Steel	7.8	400	210	12×10^{-6}	40

(*According to EN 13 706)*

Table 1: Property comparison

Lightweight: Pultruded profiles are 80% lighter than steel and approximately 30% the weight of aluminium. They are therefore easily transported, handled and installed, resulting in lower costs. Complete structures can often be pre-assembled and shipped to the job site ready for fast installation.

High strength: Glass fibre composites have excellent mechanical properties, delivering higher strength than steel and aluminium on a kg-for-kg basis. Composites are anisotropic materials and pultruded profiles deliver their highest strength values in the lengthwise (axial) direction. By varying the orientation and format of the reinforcements it is possible to optimise the required strength or stiffness in the direction in which these properties are required. Considerable design freedom can be gained by the capability of adding extra strength in highly stressed areas.

Parts consolidation: With composite materials a designer is able to integrate various separate parts and functions into one profile and can create complicated shapes which are not possible with other materials. This reduces the number of fabricated parts and as there are less parts to join together, installation is simplified. Single composite parts can replace complex assemblies of multiple parts that are produced with traditional materials such as wood, steel or aluminium.

Corrosion resistance: Glass fibre composite is stable, inert and impervious to moisture and a broad range of chemical elements. Pultruded products will not rot or rust and require minimal maintenance compared with traditional building materials. Composites are the material of choice for outdoor exposure, especially coastal areas subject to airborne and waterborne salt agents.

Durability: Composite structures have a long life span. Many well-designed composite structures are still in use after 50 years of service. Coupled with their low maintenance requirements, this longevity is a key benefit.

Fire safety: Composite formulations have been developed to satisfy stringent fire safety regulations. Advances in resin and additive technologies continue to improve fire, smoke and toxicity (FST) performance of composite structures.

Thermal insulation: Glass fibre composite has a low thermal conductivity. This is a significant advantage for applications where energy loss must be minimised, such as window and door systems and heating ducts.

Dimensional stability: Glass fibre composite has a low coefficient of thermal expansion and pultruded profiles will not expand, shrink or warp.

High and low temperature capabilities: Glass fibre profiles maintain excellent mechanical properties at elevated and extremely low temperatures (down to -50°C).

Electrical insulator: Glass fibre profiles are electrically non-conductive and ideal for components in current carrying applications. This is a valuable safety benefit in utility poles, for example, where metal structures need to be earthed.

Excellent dielectric properties: Glass fibre composite profiles are almost ‘invisible’ to RF waves and have been used in telecommunications applications such as base stations and radomes for many years, where they offer minimal signal attenuation. Different fibres and resins can be combined to deliver a range of dielectric properties suitable for various end-use applications. Materials advances continue to target lower dielectric constants and loss tangents to enable better performance with higher frequency signals.

Rust-free rebar

Reinforced concrete is one of the most widely used construction materials. Whilst concrete is strong in compression, it is relatively weak under tension and steel rebar (reinforcing rod) is used to improve its tensile strength. The surface of rebar is generally ‘deformed’ (roughened by introducing ridges or other features) to enhance its bond with the concrete. Although steel rebar typically accounts for only a small percentage of the total amount of concrete, its corrosion is a primary cause of cracking and spalling of concrete structures, requiring costly maintenance procedures to ensure that structural integrity is not compromised. To protect the steel from corrosion a minimum depth of cover of concrete is specified, and corrosion inhibitors can be added to the concrete mix or applied to the cured concrete surface. Cathodic protection systems can also be employed. A further corrosion mitigation technique involves the use of epoxy-coated, galvanised or stainless steel rebar, which resist corrosion better than standard rebar but are more expensive and still corrode over time. Composite rebar offers a way to eliminate the expensive problem of corrosion almost completely and extend a structure’s service life.

Steel rebar is readily available and widely used in building and construction applications, but it is susceptible to corrosion. (Image courtesy of Hans Braxmeier/Pixabay.)

Pultruded composite rebar can be manufactured using various combinations of reinforcing fibre and polymer, resulting in different properties. To withstand the highly alkaline concrete environment, it is typically produced using a corrosion resistant glass fibre product. Carbon fibre and basalt fibre are employed to a lesser extent for certain applications. The reinforcing fibre is placed along the length of the bar for maximum strength. Vinyl ester resin is generally considered to handle combined moisture and alkalinity better than epoxy resin, but rebar durability is also dependent on factors such as the fibre sizing. Polyester resin is only used for temporary applications. Rebar producers have developed modified pultrusion processes allowing different surface finishing techniques (such as sand coating and helical grooving) to ensure a strong bond with the concrete. Pultruded rebar is available straight or bent, in a variety of standard shapes, diameters and lengths, and custom bars can be manufactured to meet specific requirements. Composite rebar is beige, but it can be coloured if required.

Pultruded rebar has a tensile strength twice that of steel rebar but at a quarter of the weight, making it much easier to transport, move and position and so quicker to install. It is highly resistant to impact and minor damage incurred during transport or installation will not affect its performance since it does not rely on a coating to protect it from corrosion. It does not require cathodic protection. Since composite rebar does not rust – even in the most challenging environments – less concrete cover is needed and maintenance requirements are minimal. These factors can add up to substantial cost savings over the structure's lifetime and contribute to a reduced environmental impact.

Composite rebar is ideally suited to a variety of applications where it offers clear-cut advantages over steel.

Corrosive environments: The greatest opportunities for pultruded rebar lie in infrastructure located in particularly aggressive environments, such as seawalls, docks, piers and other structures directly in contact with, or in close proximity to, seawater, where steel, reinforced concrete and wood are subject to costly monitoring and maintenance programmes. Corrosion resistance is also a key requirement for structures such as dams and bridges in contact with freshwater; chimneys, storage tanks and other concrete structures used in chemical and power plants, wastewater treatment facilities and further industrial sites where corrosive agents are present; as well as in transport infrastructure exposed to de-icing salts, such as bridge decks and car parks. Composite rebar has now been utilised for more than 30 years and a considerable body of research is available regarding its long-term durability in concrete.

Specialised applications: There are also a variety of applications which demand materials which are non-magnetic, RF-transparent, or electrical or thermal insulators, where steel rebar cannot be used. Glass fibre composite rebar can be used in hospital buildings housing sensitive magnetic resonance imaging (MRI) machines, for example, and it is ideal for temperature-sensitive applications such energy-efficient buildings and refrigerated warehouses.

Corrosion is a constant concern for the Florida Department of Transportation (FDOT). High humidity, high temperatures, high water tables and high exposure to salt water mean maintenance of steel or steel-reinforced concrete bridge structures can become very expensive. In response, FDOT has been investigating materials and design advances that reduce costs across the lifetime of a bridge. The Halls River Bridge in Homasassa Springs was used to test a variety of new technologies that address maintenance and longevity issues. The project involved the replacement of a deteriorated 180-ft-long bridge built in 1954 and served as a showcase for new composite technologies, including pultruded rebar. (Pictures courtesy of FDOT.)

Temporary applications: For permanent structures, the high tensile strength of composite rebar makes it particularly suited to flexural applications. However, its low shear strength is beneficial in temporary applications where the concrete structure must be easily demolished after use. One temporary application for pultruded rebar which is now widely used is the ‘soft-eye’ tunnelling technique, which allows for safer, more economic operations.

Soft-eye cuts the costs of tunnelling

Tunnel boring machines (TBMs) are widely used today to excavate tunnels for underground railways and other infrastructure. One challenge of this technique relates to drilling through the reinforced concrete retaining walls (diaphragm walls or pile walls) of the TBM launch and recovery shafts, as well as the subway stations and shafts along the tunnel’s route. These walls are often built to great depths and they need to be thick and reinforced with large amounts of steel rebar in order to withstand high loads. However, steel rebar can damage the TBM’s cutting tools and so the concrete wall must be broken down, and the reinforcement cut, manually. This expensive and time-consuming procedure is also hazardous for the workers on site.

The 'soft-eye' method involves substituting the steel with composite rebar in the section of wall the TBM must break through. Frequently, a section of the wall corresponding to the dimensions of the TBM shield is reinforced with composite rebar, leaving the upper and the lower sections reinforced with steel rebar. The two steel sections are then connected to the composite section. Since composite rebar has a high tensile strength but low shear strength, the TBM can bore through this composite-reinforced section of wall – the so-called 'soft-eye' – easily, without any damage to its cutting tools. As well as significantly speeding up the excavation schedule and eliminating risky manual operations, lightweight pultruded rebar also allows for easier installation than steel. All these factors can add up to substantial project cost savings.

Installation of a soft-eye structure during the construction of a metro line in Bucharest.

The soft-eye technique has become a popular for tunnelling of subway lines in Europe and other parts of the world, and for the reinforcement of piles and complex concrete structures. Although intended as a temporary solution, a soft-eye made from corrosion resistant pultruded rebar can remain in place and become part of a permanent structure for its lifetime.

The global steel rebar market is substantial and continues to grow in line with increased building and construction activities around the world. Whilst steel rebar is estimated to account for 97% or more of the market, the uptake of corrosion-resistant solutions is increasing. One study[4] forecasts that the composite rebar market will experience a CAGR of 4.6% over the 2020-2025 period to reach a value of US$802 million by 2025, with North America accounting for the majority of activity. Continuing adoption of pultruded rebar is dependent on several factors, including comprehensive, approved design and application guidance on the correct use of pultruded rebar in concrete reinforcement, and greater cost competitiveness with steel rebar.

Since pultruded rebar is not a direct replacement for steel, numerous standards and design and application guides have been developed in North America, Europe and Asia over recent years to specifically address its use in the construction of concrete structures. Ongoing work on product certifications, approvals, and harmonising different international and national standards, will serve to increase the construction industry's confidence in composite rebar. The production of bends, for example, is one important area where composite rebar differs from steel. For a typical project, roughly 30% of the rebar is bent bar. Steel rebar can be bent and welded on site to create reinforcement cages; composite rebar cannot. Bent composite rebar is produced to specification in the factory and delivered to the construction site. Efforts in the pultrusion industry are aimed at providing improved solutions for bending and connection of bars. Thermoplastic rebar, which can be thermoformed, is one approach under investigation.

The rebar market also demands high volume and low prices, and the higher initial cost of composite rebar has traditionally been a major barrier to its more widespread adoption. Whilst the purchase and installation cost of rebar for a particular project is dependent on many factors, currently the use of pultruded rebar is generally only justified in the face of specific needs that cannot be answered by steel rebar: permanent infrastructure located in particularly aggressive environments; in applications where steel cannot be used; or in temporary structures where ease of demolition is a key requirement. However, composite rebar technology has advanced significantly over the last decade, and developments in materials and more efficient pultrusion processes with greater productivity are making it increasingly competitive with steel. The scaling up of production volumes and more competition in the market resulting from greater use of pultruded rebar can also be expected to improve its affordability. More importantly, the long-term economic and environmental benefits of pultruded rebar will become greater drivers for its use as designers and asset owners look beyond initial costs to assessments focusing on the total cost of ownership and sustainability of infrastructure projects.

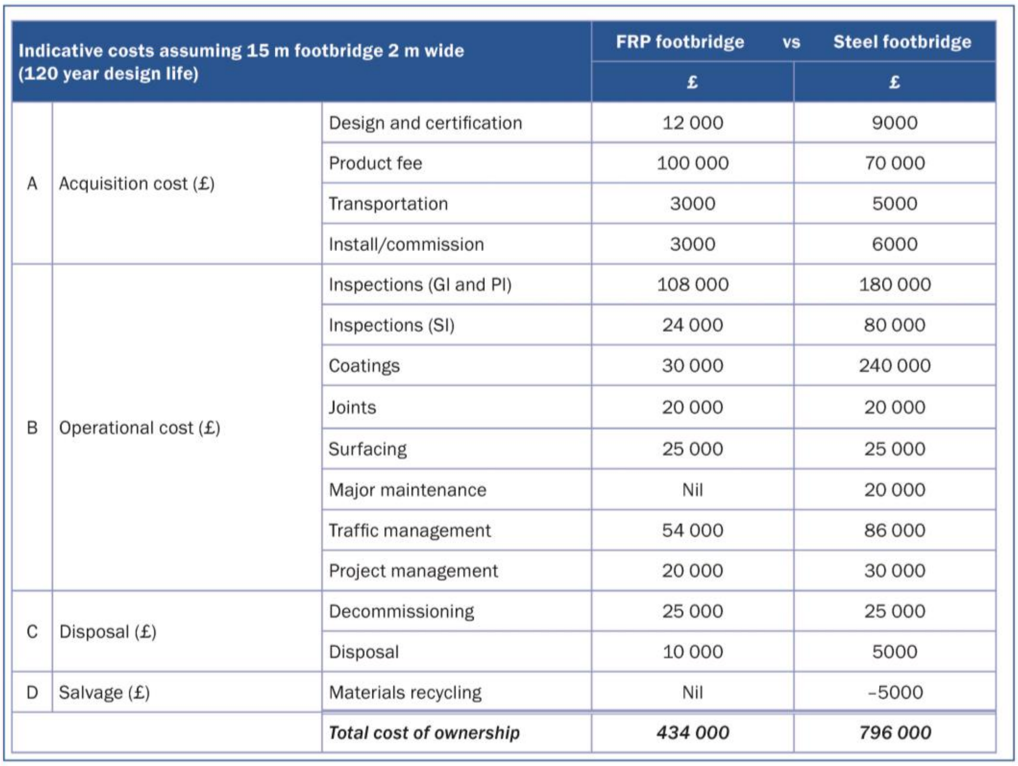
Better bridges

The first bridges employing polymer composite materials were installed in the early 1980s as researchers, designers and engineers sought to develop novel construction technologies providing improved performance, design flexibility and sustainability at lower cost. Over the past 20 years the use of composites in bridge design has increased considerably, both in renovation projects such as replacement decks, as well as in new builds where the design possibilities of composites can be fully exploited.

A composite bridge can deliver the same performance as a steel structure with a weight saving of 50% or more. Even greater weight savings can be realised against concrete designs. This enables more streamlined bridge designs which require less substantial supporting structures and foundations and are much faster to install. Large steel and concrete bridge elements are expensive to transport and require heavy-duty lifting equipment to move and position. It generally takes several days to assemble a precast concrete bridge on site, and much longer to pour and cure a cast-in-place concrete deck. Lightweight composite parts are easier to transport and handle, making installation simpler and reducing labour and equipment requirements. Modular structures with reduced part count can be prefabricated offsite to reduce onsite construction time – a composite bridge or deck can be lifted into place by crane overnight. Faster installation means much less disruption to users and lower costs for owners and operators of busy road and rail infrastructure. Glass fibre composites also offer safety benefits over steel. Hot works such as welding are not needed, reducing fire risks, and as they do not conduct electricity composites can be safely used near rail and electrical equipment.

Since composite bridge structures are highly resistant to moisture, chemicals, harsh weather conditions and extreme temperatures, they do not require regular re-painting to protect them from corrosion like steel and wood. Concrete structures can deteriorate rapidly in corrosive environments and require maintenance to repair spalling and seal cracks. Bridges constructed from steel, reinforced concrete and wood can start to fail in as little as 15 years after initial installation. Composite bridges are being designed to provide a service life of 75 years or more.

Considering all the costs that occur over a bridge's lifetime, composite materials can deliver substantial savings over conventional construction materials, particularly in challenging corrosive environments. A design guide developed in the UK[5] presents a theoretical example based on a 15 m footbridge, 2 m wide, with a 120-year design life. The total cost of ownership (TCO) – covering acquisition, operational, disposal and salvage costs – of a composite bridge was estimated at £434,000, whereas the TCO for a steel bridge amounted to £796,000. The initial cost of the composite footbridge was higher, but life cycle maintenance and management costs were lower. The cost of coatings and inspections were substantial factors for the steel bridge.



Indicative costs assuming 15 m footbridge 2 m wide (120 year design life)			**FRP footbridge**	**vs Steel footbridge**
			£	**£**
A	Acquisition cost (£)	Design and certification	12 000	9000
		Product fee	100 000	70 000
		Transportation	3000	5000
		Install/commission	3000	6000
B	Operational cost (£)	Inspections (GI and PI)	108 000	180 000
		Inspections (SI)	24 000	80 000
		Coatings	30 000	240 000
		Joints	20 000	20 000
		Surfacing	25 000	25 000
		Major maintenance	Nil	20 000
		Traffic management	54 000	86 000
		Project management	20 000	30 000
C	Disposal (£)	Decommissioning	25 000	25 000
		Disposal	10 000	5000
D	Salvage (£)	Materials recycling	Nil	-5000
		Total cost of ownership	***434 000***	***796 000***

Table 2: A theoretical comparison of the total cost of ownership of a composite footbridge and a steel footbridge. (Source: Fibre Reinforced Polymer Bridges – Guidance for Designers (2018) C779, CIRIA, www.ciria.org.)

In terms of environment impact, composites also offer a route to reducing the carbon footprint of bridge structures. Key factors beneficial for sustainability include faster installation with reduced impacts from road and rail line closures, and lower through-life maintenance-related activities.

Pultruded profiles are an increasingly popular and versatile option for bridge construction –for rehabilitation of ageing structures, in upgrading projects, and in new builds. Pultruded profiles can be used for the main load-bearing structure or in components such as decks. As a controlled, repeatable manufacturing process, pultrusion enables the production of profiles with consistent mechanical properties and cross-sections. It possible to manufacture a wide range of solid and hollow profiles which can be employed as beams, decking panels, trusses, bridge enclosure systems, parapets, ramps, arches, grating systems, handrails etc. Curved profiles are also possible. Smaller bridges and decks can be supplied in 'kit' form or fully assembled and in some cases weigh so little that they can be handled manually. Glass fibre reinforced polyester and glass fibre reinforced vinyl ester materials are typically used, although carbon fibre is sometimes employed to reinforce specific areas, such as the substructure. A pultruded composite bridge requires less design input than an infused composite structure for short-to-medium spans.

A growing number of projects worldwide are demonstrating the successful adoption of pultruded composites, particularly in simple small-to-medium span pedestrian and cycle bridges, where prefabricated modules enable extremely quick construction, and in replacement bridge decks. Decks are typically the least durable part of a bridge, and their replacement and repair can account for the major portion of bridge maintenance costs. For basic decks with constant cross-section, pultruded 'planks,' or panels comprising several profiles bonded together, can be fixed between supporting elements such a steel beams by bonding or bolting. Features such as curbs, drainage systems and anti-slip surfaces can be moulded into prefabricated decking systems, speeding up installation times considerably. Decks can be supplied in various colours, and even designed to imitate wood decking if required. They can be fitted with panels and railings designed to blend in with the surroundings.

Composite decks are a particularly cost-effective solution where resistance to corrosion is the key requirement – for bridges located in coastal locations, for instance, or on roads where de-icing salts are regularly applied. Lightweight composite decking is also ideal for bascule, swing and other movable bridges, to minimise energy use. In renovation projects, such as the replacement of deteriorated steel or concrete decks on ageing steel truss bridges, the lightweight composite decking minimises stress on the supporting structure. And in cases where the load on an existing bridge's substructure is approaching its maximum, a lightweight composite deck could, for example, be added to provide new pedestrian or cycle paths. Composite decking also offers a lightweight solution for bridges in remote locations or environmentally-sensitive areas where heavy-duty lifting equipment cannot be used, or where fast installation is essential.

Composite bridge design is continuing to evolve. In future, modular bridge design solutions are expected to become more popular, and efforts are underway to scale up composite designs for larger spans and production volumes for larger series. It is relatively easy to integrate sensors into composites structures to enable structural health monitoring or even to create ‘smart’ bridges which could, for example, monitor environmental conditions such as air quality. Composite material innovations will continue to emerge, in both resins and fibres, and it is expected that lower cost carbon fibre (including recycled carbon fibre) will become more widely available. The use of renewable composite materials, such as bio-based polymers and natural fibres, is already being trialled in numerous bridge projects as a way to further improve sustainability.

The way ahead

Standardisation initiatives to allow structural engineers to use pultruded products with confidence will be crucial to facilitating their further adoption in bridge building and other structural applications. In Europe, historically many design guides have been issued for composites in different countries. For pultruded composites, *EN 13706: Reinforced plastics composites – Specifications for pultruded profiles*, published in 2002, has been widely accepted. This specifies minimum requirements for a number of properties, but a more comprehensive approach is required for engineers to have confidence in designing safe structures with composites. Progress towards this is underway as part of an ongoing revision of the Eurocodes. This series of European Standards, written in the 1990s, provides a common approach for the design of buildings and other civil engineering works and includes codes relating to concrete, steel and other construction materials. Composites were not included the first editions of the Eurocodes but work towards a code specifically for composites is currently being conducted by Working Group WG4 'Fibre Reinforced Polymers' under the European Committee for Standardisation (CEN) Technical Committee 250 (CEN/TC 250). It has been provisionally designated as *Pr EN 19101 Eurocode 11: Design of fibre-polymer composite structures*. The final draft, and a comprehensive background document providing test data to support the accuracy of design formulae, has been completed ready for submission to TC 250. If approved on schedule in 2021/22, there will be two years of testing before the final approval stage in 2023/24. The new Eurocode will put composite materials on the same level as conventional construction materials and enable the design of large structures capable of safe, reliable service for up to 100 years.

Wider awareness and validation of the benefits composite materials can offer based on several decades of field infrastructure applications, combined with authoritative design guidelines and standards, and a growing focus on through-life costing and sustainability are building a strong case for further adoption of composites in future infrastructure. Ongoing LCC and LCA studies will play a key role in identifying the optimal economic and environmental solution for each project.

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