# KEYNOTE PAPER

# NEXT GENERATION FOOTBRIDGES IN FRP COMPOSITES

**David KENDALL**
Structural Engineer
Optima Projects Ltd,
Lymington, UK
david.kendall@optima-projects.com

## Summary

Composite materials were used to create some of the first man-made buildings, using combinations of mud and straw. Polymers were developed to replace the mud and the straw has been superseded with very high-strength engineered fibres made from glass or carbon to create modern day Fibre Reinforced Polymer (FRP) Composites. These materials have revolutionised aircraft construction and motorsport and are now being used in mainstream family car primary structures.

Industries such as boat-building and wind energy have demonstrated the ability of the composites industry to manufacture very large structures in excess of 100m in length that are highly loaded, durable and cost-effective.

The mechanical properties of FRP Composites are attractive for bridge structures due to their low weight and high specific properties, which can create very lightweight bridge structures, sometimes as low as 10% of the weight of a traditional steel structure. For certain spans the reduction in weight and increase in natural frequency may remove the need for expensive tuned mass dampers on a structure, thereby reducing the overall cost. In other cases the lightweight structure may result in greater dynamic response and may require mitigation measures to control either pedestrian or wind induced vibration.

FRP materials are inherently very durable and maintenance is generally limited to normal inspections, cleaning and maintenance of aesthetic coatings or wear layers on decks. With careful selection of finishes, FRP footbridges could be produced with much lower through-life costs and maintenance demands, also reducing disruption due to major maintenance events occupying infrastructure below the bridge.

The aesthetic possibilities with FRP footbridges have yet to be fully explored but will open up new and exciting possibilities for geometric forms and potential for greater structural optimisation. The ability for produce lightweight carbon fibre footbridges spanning in excess of 300m as a single clear span is demonstrated in the paper and opens the door for a new era of footbridge design and construction.

We expect to see much greater use of FRP in footbridges, ranging from small functional bridges over railways, possibly produced in large numbers based on modular designs, through to large structures spanning several hundred metres and providing dramatic landmark features.

**Keywords**: aesthetics; carbon fibre; dynamics; structural concepts; new materials; fibre reinforced polymer composites; FRP; lightweight footbridges; long-span footbridges.

## 1. Introduction

The use of “composite” materials in construction can be traced back to the 1500s BC when early Egyptians used a mixture of mud and straw to create strong and durable buildings. Later, in 1200 AD, the Mongols invented the first composite bow. Using a combination of wood, bone, and “animal glue”, bows were pressed and wrapped with birch bark. Composite Mongolian bows provided Genghis Khan with military dominance, and because of the composite technology, this weapon was the most powerful weapon on earth until the invention of gunpowder.

The modern composites era started with the development of polymers in the early 1900s to replace glues and resins derived from animals or plants, although it was soon found that these did not poses sufficient strength for structural applications. Reinforcement was required and in 1935 fibreglass was introduced and combined with polymers to start the development of Fibre Reinforced Polymer (FRP) materials.

Many of the significant material advances have been made during times of war and World War II pushed the development of FRP composites due to the need for lighter materials within aircraft and other structures. However, following the war the emerging composites industry needed to find peacetime applications for their new materials and boat building was an obvious example and FRP composites have become a dominant material in many forms of boat construction for leisure, commercial and military applications.

*Fig. 1 – “Bluefin” Catamaran built in 1958 and still in use today*

*Fig. 2 – FRP structures used for workboat applications for wind farms (Ctruk Boats)*

The 1960s saw the invention of carbon fibre and in the coming decades truly advanced FRP composites were developed for major structural applications. Carbon fibre epoxy composites (CFRP) are now the favoured construction material for aircraft structures for both military and civil applications.

*Fig. 3 – Lockheed Martin F-35 Lightning II Military Aircraft*


*Fig. 4 – Airbus A380 civil aircraft*

It did not take long for other industries to see the benefits that lightweight composite materials can offer and in particular areas such as motorsport have benefited significantly from the weight-saving possibilities offered by carbon fibre composites. Mainstream automotive is now also adopting CFRP for example in the new BMW i3 family hybrid car with a full CFRP body shell.


*Fig. 5 – Motorsport is now a major user of composite materials*

During recent decades new industries have also evolved such as renewable energy involving wind, wave and tidal power and devices for all energy sources are utilising FRP composites. The wind power industry is the most mature renewable sector and highly developed blades now exist up to 85m in length, manufactured in a single piece. It will not be long before we see blades in excess of 100m, which are currently in development and it is not yet clear how much larger they will become or what the optimum size will be.

*Fig. 6 – FRP wind turbines*

*Fig. 7 – Transportation of 83.5m long turbine blade*

New industries have had the benefit of developing without too many preconceptions of how things should be done or what materials should be used. More traditional industries, such as Civil Engineering and bridge-building have a certain tradition of building in “conventional” materials such as steel and concrete and traditional bridge engineers will consider a “composite” bridge to be a concrete deck on steel beams! There are varying degrees of resistance to change in all industries and this is no different in bridge-building. In certain sectors of bridge-building and in some countries we see considerable resistance to change, whilst in others we see a desire for innovation and use of FRP composites for primary structures of all types of bridges including foot, cycle, vehicle and to some extent even for rail bridges, which has traditionally been the most conservative sector of the market.

These changes are partly being pulled through by Clients who desire more durable structures with lower through-life costs and there is also a push from the composites industry looking for new applications for their materials. In the middle are the Designers, Engineers and Contractors who have to deliver such projects and a lack of awareness and understanding of FRP materials is limiting the rate of development and growth. Some countries have been much quicker to develop the use of FRP, in particular The Netherlands, which now has a substantial number of FRP bridges in use and several manufacturers in the supply chain able to service the demand. There have been contracts let in The Netherlands for very large numbers of FRP bridges in a single contract, which has shown significant economies of scale and enabled more efficient manufacturing techniques to be implemented. In many other counties FRP bridge applications have been in small numbers, often for specialist projects, but we expect this to change in coming years as the use of FRP matures and becomes more widely accepted.

Footbridges are an area of bridge-building that has often been more innovative with architectural designs and use of alternative materials and is therefore a large potential market for FRP composites.

As we see from this introduction the use of FRP Composites in structural applications is not new, the materials are well understood by specialists within the composites industry and indeed they are not new in footbridge construction.

In 1992 the Aberfeldy footbridge was constructed in Scotland including 18m high masts and the 112m long deck with a 63m central span all constructed from pultruded FRP composites. The design was developed by students from Dundee University under the guidance of Peter Head from Maunsell. This was a highly innovative project and still remains one of the largest FRP footbridge built to date. The Designers were probably at least a decade or two ahead of the mass-market acceptance for FRP bridges, but it is good to see that the pultruded profiles used in the Aberfeldy Bridge are now readily available as a standard structural component and have more recently been used in several other footbridges.

*Fig. 8 – Aberfeldy Footbridge*

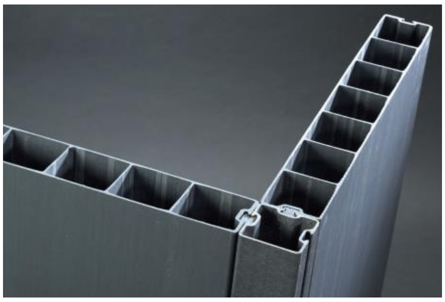

*Fig. 9 – Composolite® pultruded panels used in the Aberfeldy Footbridge (Strongwell, USA)*

## 2. FRP Materials

FRP materials consist of high-strength fibres, most commonly E-Glass (GFRP), carbon (CFRP) or aramid (AFRP) fibres combined with a polymer matrix, most frequently polyester, vinylester or epoxy resin. There are also uses of natural fibres such as hemp, jute, flax, bamboo etc and bio-derived resins from plant oils. Some of these natural composite materials are also able to make use of fibre sources from other industries, which are currently going to waste, so possess extremely good ecological credentials. There are also applications involving specialist resins such as phenolics providing extremely good fire, smoke and toxicity properties and applicable, for example, in underground or internal transport applications.

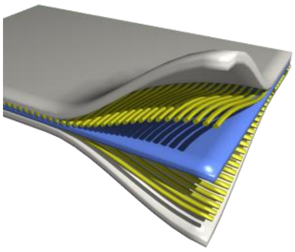

*Fig. 10 – Schematic illustration of FRP laminate*

## 3. FRP Mechanical Properties

FRP mechanical properties can vary significantly depending on the manufacturing process, fibre content and fibre direction. The illustrations below show some typical properties for unidirectional (UD) composites, where we have continuous fibres all in a single direction and are typical for infusion moulded or pultruded laminates with fibre volume fractions around 55%. This will be an optimum configuration if there are only uniaxial loads, although in most typical applications we will also have some reinforcement in other directions to handle transverse or shear loads. These properties are compared to conventional S275 structural steel.

As seen in Fig.11 the tensile strength of FRP compares very well to that of steel and even a glass fibre based unidirectional laminate will exceed the ultimate strength of steel. It should also be noted that the strength of some ultra-high modulus (UHM) carbon fibre laminates can be significantly less than "conventional" high-strength carbon fibre. The reduction in compressive strength can be even more significant for some UHM carbon fibre laminates, so they do need to be used with some care in strength critical areas.

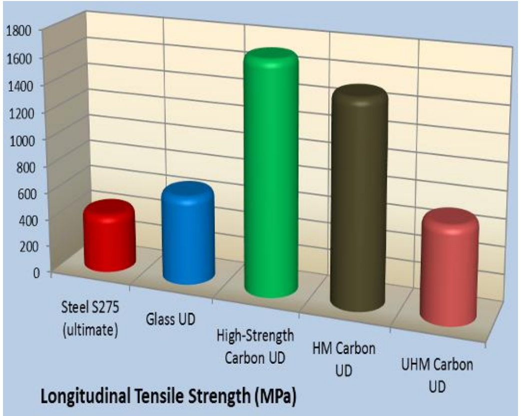


*Fig. 11 – Tensile Strength*

When we look at modulus as shown in Fig.12 the situation is very different. Glass fibre based laminates have considerably lower modulus than steel and even high-strength carbon fibre UD laminates only have a modulus of around 60% of steel. It is therefore common for FRP structures such as bridges to be stiffness driven in the design, rather than being strength critical. This has the advantage of usually exhibiting large reserves of strength in the structure and high resilience to fatigue loading and high damage tolerance.

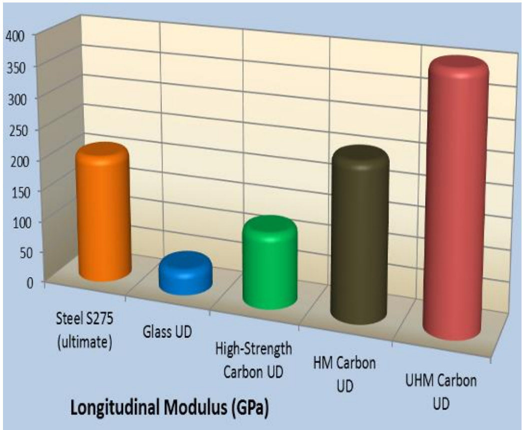


*Fig. 12 – Longitudinal Modulus*

However, it should also be noted that the reduction in modulus can lead to other considerations becoming critical such as buckling and vibration. Buckling issues can often be resolved through the use of sandwich structures for panels and skins and sometimes through geometric optimisation and the ability to create curved surfaces where the geometry will provide much greater stability.

Vibration induced by pedestrians and wind buffeting or vortex shedding can often become critical for footbridges in all materials and as spans increase it is not unusual to need to install devices to control or limit such vibrations, such as aerodynamic devices or tuned mass dampers.

Although the material modulus has reduced significantly, so has the mass and if we compare specific modulus (modulus / density) the situation looks different again as seen in Fig.13. Now we see the properties for glass UD based FRP being similar to steel and the carbon fibre properties being significantly better.

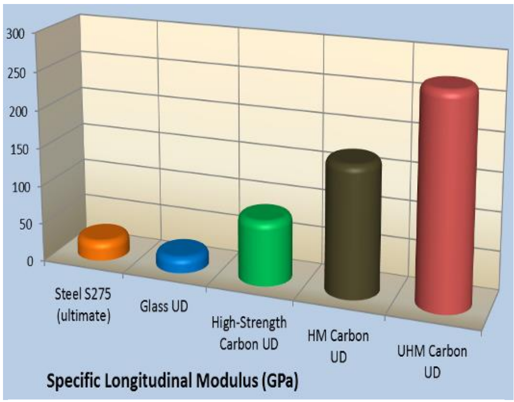


*Fig. 13 – Specific Longitudinal Modulus*

The high specific stiffness of FRP composites enables us to produce very light and stiff structures with much higher natural frequencies compared to other materials. It is sometimes therefore possible to mitigate potential vibration issues by designing an FRP structure with natural frequencies above those that are likely to be excited by pedestrians or the aerodynamic effects of the wind.

Furthermore, the ability to mould complex shapes and varying cross-sections can assist in reducing aerodynamic wind loads and minimising the effects of vortex shedding by having tapering sections that will not shed vortices at consistent frequencies along the length of the bridge.

However, care must be taken in the analysis of such lightweight structures, which may be an order of magnitude lighter than conventional bridges and if excited by either pedestrian or aerodynamic forces close to their natural frequency may exhibit unacceptably large responses. If this is the case, then conventional means such as fitting tuned mass dampers or other damping devices may be employed to limit such response.

### 3.1 Anisotropic Properties

The properties of FRP laminates can be highly anisotropic. The ability to tailor properties in different directions and in different areas of the structure, even mixing different fibre types in different locations to optimise the structure for the loading conditions can be very beneficial. This ability to design the material at the same time as designing the structure brings in considerable potential for structural optimisation, bringing cost and weight reductions, but does entail extra effort at the design stage.

Even taking a simple detail such as a panel stiffener as shown in Fig.14, we see how not only the geometry of the stiffener can be varied but also the laminate configuration, typically with +/-45° fibres in the webs to carry shear loads and UD fibres in the crown of the stiffener to carry bending loads. Both web and crown laminate may also be varied and optimised along the length of the stiffener to suit varying shear and bending loads.

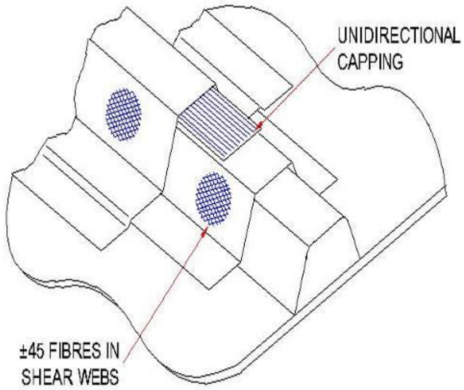


*Fig. 14 – Typical Panel Stiffener Detail*

### 3.2 Thermal Properties

Bridges will typically need to cater for thermal movements due to expansion or contraction with varying temperatures. Glass fibre based composites have coefficients of thermal expansion (CTE) typically similar to steel in order of magnitude, but varying depending on fibre content and direction. Carbon and aramid fibres are unusual in exhibiting a negative CTE. When combined with a matrix material to form a composite laminate and when off-axis reinforcement plies are considered the resulting laminate CTE can be very close to zero. This can be a significant benefit in reducing thermal movements and could open up some new possibilities for fixed abutment details omitting complex movement joints.

## 4. FRP Benefits for Footbridges

### 4.1 Lightweight

There are numerous potential benefits in using FRP for footbridge construction. The most obvious difference between FRP and traditional construction materials such as steel or concrete is the resulting weight of the structure, which for GFRP can typically be only 10-25% of the mass of an equivalent steel bridge and significantly less for CFRP. Such dramatic weight reduction makes the dead loads on the structure almost irrelevant compared to live and wind loading and also makes the structure significantly easier to transport and install. Bridge installation costs can often be high, especially for difficult to access sites and the significant weight reduction can allow smaller cranes, greater reach or use of alternative plant to lift the bridge into position as shown in Fig.15.

*Fig. 15 – Lifting of a lightweight FRP bridge (courtesy of Fibercore Europe)*

There have been several examples of FRP footbridges being delivered to remote sites using helicopters to deliver the complete pre-fabricated structure into position in a single lift. The reduction in Dead Load will also reduce load on foundations and supporting structures and can allow an increase in Live Load when existing bridges are replaced with lighter options onto existing abutments.

### 4.2 Pre-fabrication

The ability to pre-fabricate off-site very large structures can significantly reduce the amount of work on-site, reducing construction time, improving health & safety and reducing costs and disruption.

*Fig. 16 – Prefabricated FRP footbridge for Dawlish Train Station, UK (Optima Projects, TGP, Pipex)*

### 4.3 Durability

FRP materials are extremely durable, needing very little if any maintenance other than cleaning or maintenance of aesthetic coatings when the visual appearance is an important consideration or renewal of wear layers on decks. When a bridge is over major infrastructure such as railways or major roads, access to the underside of the bridge can be difficult and extremely expensive and also disruptive to transport systems below the bridge. The durability of FRP can offer significant through-life cost savings and reductions in future disruption.

### 4.4 Aesthetics

FRP will bring new possibilities to footbridge aesthetic designs, the possibilities of which have not yet been fully explored. The potential to manufacture complex shapes is clearly demonstrated in the boat-building industry and also in construction with complex buildings and sculptures as shown in Fig.17.

*Fig. 17 –FRP Sculpture (Stage One, 3XN Architects & Optima Projects)*

## 5. Manufacturing Methods

Manufacturing options are fundamentally split between pultrusion and moulding techniques with different benefits in each process.

### 5.1 Pultrusion

Pultrusion is a continuous process in which reinforcing fibres and fabrics are pulled through a heated mould to create prismatic linear shapes and profiles. This has the advantage of reduced labour content and semi-automated control of the process. This also enables "standard" profiles such as angles, channels, boxes and H beams to be produced and made available from stock with defined and verified properties to European standards [1]. This can ease the acceptance of FRP by Engineers who are accustomed to working with similar steel shapes, but will not always produce an optimum solution. Even for a standard straight beam profile it may be beneficial to consider alternative shapes such as the "double web beam" shown in Fig.18.

*Fig. 18 – Large Pultruded FRP Bridge Double-Web Beams (Strongwell, USA)*

Where FRP composites have been used extensively in other industries it has been shown many times that trying to replicate existing metallic solutions in FRP will not provide the most efficient solutions and to optimise a structure it will be beneficial to completely rethink the structural form to suit the material and potential manufacturing options.

Numerous footbridges have been fabricated using pultruded profiles such as the 18m footbridge at Dawlish Station, shown in Fig.19, which used a hybrid structure of pultruded profiles and deck panels and infused foam sandwich parapet panels [2].

*Fig. 19 – Dawlish FRP Footbridge, UK*

This coastline of the UK was subject to some of the most severe storms ever seen in the 2013/14 winter, destroying much of the railway and incurring severe damage to the station infrastructure at Dawlish.

The newly installed FRP footbridge was undamaged and testament to the fact that FRP structures can certainly be robust, not only against the winds that were in excess of 100mph, but also against sea spray and a battering from shingle picked up from the beach and spread across the railway.

*Fig. 20 – Dawlish FRP Footbridge during severe storms of 2014*

Whilst the use of standard pultrusions can be beneficial for small projects to avoid the cost of new tooling and setup times, this does limit the ability to optimise the structure and may involve the assembly of several components. In a recent development it has been demonstrated that efficiencies can be obtained by designing specialist pultrusions to manufacture bridge girders as shown in Fig.21. In this girder/parapet section the top and bottom of the girder are formed from a single bespoke pultrusion containing a female slot into which a pultruded or moulded FRP plate can be bonded to form the web of the girder. This system enables a variable height girder to be produced and also cambered sections.

*Fig. 21 – Pultruded Variable Height Girder (Dura Composites (Patent applied for) & Optima Projects)*

Some the disadvantages of pultrusion include;

- limited part cross-section size, although any length can be potentially manufactured
- only straight sections can be manufactured
- laminate reinforcement is constant along the section so there is limited ability to optimise the laminate for varying loading along the section.

### 5.2 Moulding

A wide selection of different moulding technologies are available such as contact moulding (hand layup), infusion, wet-preg and pre-preg moulding, offering various advantages, mechanical properties and process controls.

Moulding has the following advantages;

- Ability to manufacture very large parts minimising need for joints.
- Virtually any shape can be manufactured including complex 3D forms providing the ability to manufacture unique aesthetic designs.
- Very lightweight structures can be produced including sandwich structures.
- Laminate reinforcement may be constantly varied and optimised throughout the structure.

*Fig. 22 – Bradkirk FRP Footbridge, UK (Birse Rail & Optima Projects)*

The main disadvantage of moulding for one-off bespoke projects can be the time and cost of creating new tooling, although there are also techniques available to enable one-off mouldings to be produced in temporary low-cost moulds or even without any moulds by laminating over shaped structural internal cores.

Moulded FRP may be used for small and large footbridges and for both one-off projects and mass-produced bridges. The Bradkirk footbridge shown in Fig.22 has been designed with the potential for mass-production in mind, using moulds that can be adjusted in length and width to produce a variety of different footbridges. This is an extremely lightweight design, with a single 12m span weighing less than 1.5 tonnes. The staircase sections were produced from the same main mould as the primary span, thereby minimising tooling costs.

The ability to mould complex and aesthetically interesting forms is demonstrated well in the Foryd Harbour Footbridge recently built in the UK and shown in Fig.23. As this is a lifting bridge the weight saving through the use of FRP is particularly beneficial.

*Fig. 23 – Foryd Harbour FRP Footbridge, UK (AM Structures & Gurit)*

The lightweight moulded FRP structure of the bridge does not only help during installation, but also for handling within the factory as shown in Fig.24, enabling the use of smaller, lower cost and more compact handling equipment.


*Fig. 24 – Easy handling of lightweight 30m section of Foryd Harbour FRP Footbridge, (AM Structures)*

## 6. Ooypoort Footbridge

In early 2014 the composite pedestrian bridge "Ooypoort" was opened and with a span of 56 metres, is one the largest single span FRP composite footbridges built to date. The bridge connects the city of Nijmegen to the Ooijpolder, a nature reserve located on the banks of river Waal. The structure of the bridge consists purely of glass fibre FRP moulded by resin infusion in 3 large sections, which were joined on-site with resin infused laminate joints to create a continuous structure.

One of the design criteria was that house boats should be able to pass underneath the bridge and to avoid the cost of an opening bridge a tall arch structure has been produced as shown in Fig.25. The bridge has been created by Meerdink Bruggen (main contractor), Olaf Gipser (architect), Delft Infra Composites (production) and Lightweight Structures BV (structural engineering) and was commissioned by the City of Nijmegen.

*Fig. 25 – Ooypoort FRP Footbridge*

The big advantage of using composites for this bridge is not only the low structural weight, but also the durability and the low maintenance costs.

*Fig. 26 – Ooypoort FRP Footbridge*

*Fig. 27 – Ooypoort Footbridge Assembly*

## 7. Future Developments

### 7.1 Architectural Designs & Structural Solutions

It is expected that as awareness and knowledge of FRP materials becomes more widespread amongst Architects and Engineers, that we will see continual development of applications of FRP footbridges with some new and novel aesthetic designs and also refinement of structural solutions leading to greater efficiency and optimisation leading to more affordable solutions.

Fig.28 shows a beautiful footbridge concept developed some years ago but unfortunately never built. There have been numerous concept designs for FRP applications that have not always been built, possibly being rather ahead of their time in terms of market acceptance and maturity within the supply chain. This is expected to be less of an obstacle in the future as there are now numerous examples that have been in service for several years and a capable supply chain.

*Fig. 28 – Hybrid FRP/Concrete Footbridge Design developed by Flint & Neill and Wilkinson Eyre*

### 7.2 Cycle Networks

With similar challenges and structural requirements to footbridges, elevated cycleways could revolutionise the ability to cycle efficiently and safely around congested cities. The SkyCycle scheme shown in Fig.29 proposes 220km of cycleway elevated above the existing rail network in and around central London. Whilst this makes very good use of space already used by the railways, it will be important for the new structure to be durable and low-maintenance so as not to impact on the availability of the rail network. With the use of overhead power lines on much of the railway, the ability to make GFRP composite structures that are both durable and electrically non-conductive could be hugely beneficial to such a scheme.

*Fig. 29 – SkyCycle proposed by Exterior Architecture Ltd - Foster + Partners - Space Syntax*

### 7.3 Long-span FRP footbridges

The advantages of saving weight demonstrated on small and medium scale FRP footbridges are expected to be considerably increased as we move onto long-span footbridges. As spans increase the dead load of the structure becomes significant and in many areas it can be expensive or impractical to provide supports to the ground in the most advantageous locations for the superstructure of the bridge. This may be the case over rivers, where piers in the river can be extremely expensive, or over major infrastructure such as railways or major roads, where there may be insufficient space for piers, or if built may be extremely expensive due to additional impact protection required. Therefore the ability to span greater distances, for example in the range 100-300m or more, with lightweight FRP materials could be very advantageous.

Such long spans have frequently been provided with cable-stayed bridges utilising steel masts, cables and deck structures and many beautiful examples exist around the world, often forming striking landmark features. Many of these structures will incur some considerable maintenance costs during their lives and it is considered that there may be a market opportunity for some simpler, cleaner, more durable and more cost-effective designs based around FRP structures. Utilising ultra-lightweight CFRP it has been shown that it is feasible, both technically and commercially to span such distances with monocoque structures without the need for masts and supporting cables [3 & 4].

FRP composites will provide unique opportunities to create new sculptural aesthetics in landmark bridges and this opportunity is yet to be fully explored or developed.

The author started development work on long-span CFRP bridges in 2004 and has developed several concept designs ranging from 260 to 330m clear span, similar in overall length to the Millennium Bridge in London over the River Thames, but without the need for piers in the river [3 & 4].

Structural analysis has demonstrated the technical feasibility of such concepts and preliminary cost estimates indicate that total construction costs will be similar in magnitude to other landmark bridges of similar overall length.

The aesthetic possibilities are considerable and will be influenced by site context on individual projects. At the present time the intention of this work has been to demonstrate the viability of the concept and give an insight into some of the aesthetic possibilities. Some early design concepts are shown in Figs. 30 and 31 with a relatively simple CFRP monocoque shell structure in which the outer skin forms the primary structure.

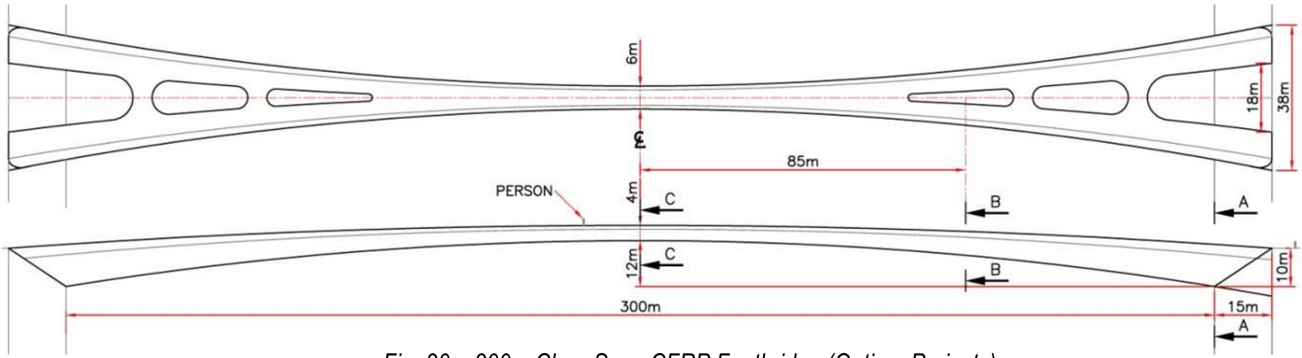


*Fig. 30 – 300m Clear Span CFRP Footbridge (Optima Projects)*

*Fig. 31 – 300m Clear Span CFRP Footbridge Visualisation (Optima Projects)*

The initial design concepts are being extended into more three-dimensional forms as shown in Fig.32, with a much higher arched structure supporting a high level central walkway. This could also be developed further into a dramatic, sculptural and aesthetic architectural design, providing a more dramatic user experience with high-level views from the bridge and greater clearance below, which may be required in some locations. The high-level walkway will be accessed by long ramps, stairs or lifts or in some locations may link into existing high-level embankments.

Structural analysis has demonstrated the potential efficiency of this concept producing a much stiffer structure with a similar material content to the previous designs.

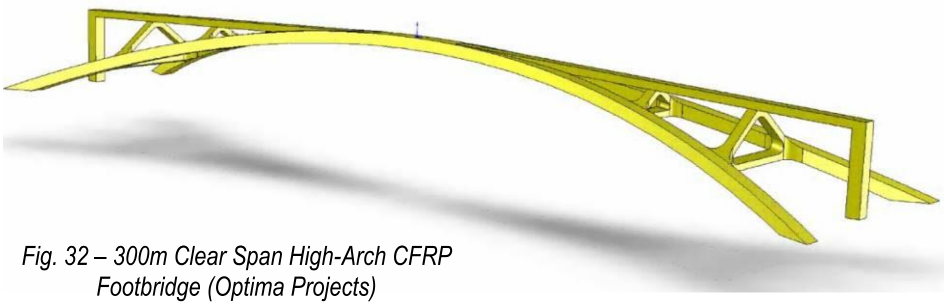

*Fig. 32 – 300m Clear Span High-Arch CFRP Footbridge (Optima Projects)*

## 8. Conclusions

FRP composite materials are certainly not new and have been proven and accepted for numerous structural applications including footbridges.

They can be a cost effective solution for manufacturing both small and very large footbridges and will provide a significant weight saving over conventional materials such as steel or concrete, better durability and architectural freedom to produce some unique designs. It has been demonstrated that very long clear spans can be achieved, removing the need for intermediate supporting piers, minimising the impact on land or infrastructure below the bridge and reducing construction costs and time on site.

It is also feasible to produce smaller scale mass-produced bridges and as volumes increase so production efficiencies will allow significant cost reductions for future applications.

## 9. References

[1] EN 13706 – Reinforced plastics composites – Specifications for pultruded profiles.

[2] KENDALL D, SMITH I, GOUGH W, “Dawlish FRP Footbridge” *NGCC FRP Bridges Conference,* UK 2012.

[3] KENDALL D, “Large Span FRP Composite Bridges” *Bridge Engineering Conference,* Rotterdam, June 2006.

[4] KENDALL D, “FIBRE REINFORCED POLYMER FOOTBRIDGES SPANNING 300m” *Footbridges 2014 Conference,* London, July 2014.