# Advanced Composites in Civil Engineering in Europe

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## Summary

Composite materials have been considered for use in structures in Europe for many years. The materials used for structures are all characterised by low creep, as would be expected when the structures must resist significant permanent loads. For most applications, the higher stiffness fibres, i.e. carbon, aramid, glass and polyester, are used. Unfortunately, the high strength comes at the expense of high cost, and mistakes have been made in attempting to find one-for-one substitutes for steel on a material-cost basis [1]. The successful applications have all made use of other properties of the materials, not least of which are the light weight and consequent ease of handling.

## Glass Fibre Rods for Prestressing

In 1978, a prestressing system (termed Polystal [2]) was developed using glass fibres pultruded with resin to form a round rod. Much research was carried out to determine the system's properties, including quantification of the stress-rupture phenomenon. An anchorage was developed using a resin cast around bundles of pultrusions inside a steel tube. This steel tube provided confinement and could be used as a mechanical fastening.

A number of bridges were built using these tendons: a simple footbridge was followed by a two-span continuous structure with internal tendons, both in Düsseldorf. Both are believed to have had considerable amounts of untensioned reinforcement and were designed as partially prestressed. These examples were followed by a bridge in Berlin with external tendons, and by others elsewhere in Germany and in Austria. Despite the technical success of the system it has not proved a commercial success, and production of the tendons has been discontinued.

## Aramid Rods for Prestressing

In the early 1980s research began in the Netherlands into the use of aramid fibres for prestressing in the form of pultrusions, both as flat strips and as round bars, under the name Arapree [3].

The surface of the bars can be indented or coated with sand to improve the bond. As with the Polystal tendons, it is difficult to provide long-term anchorages for permanent loads, since the force has to be transferred through the resin, which is susceptible to creep and temperature effects. However, anchoring systems have been developed that are adequate for short-term loadings. These rods are ideally suited for use as pretensioning tendons in precast concrete.

The system has been used to build a variety of structures in Europe and Japan. These range from non-structural components, such as noise barriers and fish-weir planks, to housing components and principal elements of quayside developments. The system has also been used in cantilever support brackets on a highway scheme in Barcelona.

During early trials, some problems were noted with the transverse expansion of the tendons due to thermal effects [4]. Cracking of the concrete along the line of the tendon was noted when the tendons were close to the surface. This was overcome by coating the tendon with a resin that contains microscopic air bubbles.

## Carbon Fibre Bonded Plates

The use of carbon fibre for structural applications was first studied at the Swiss Federal Testing Laboratories (EMPA) [5]. One of the first applications considered, which has proved commercially successful, was the use of carbon fibre plates as bonded external reinforcement. These are usually used to repair a defective structure, to allow for increases in the applied load, or to allow modification of the struc-

ture for changes in use [5]. It was recognised early in the work that carbon fibre is not economic when viewed on the basis of the material cost. However, it pays for itself because of the reduced time required on site and the considerable reduction in falsework compared with the use of steel plates. The carbon plates are much thinner than the steel equivalents, which allows lap joints to be made between different elements. The reduced eccentricity of the plate also reduces the tendency for peeling failure.

The amount of carbon fibre used is very small, with a negligible effect on the stiffness of the parent structure if the structure is intact. The fibres come into their own when the conventional reinforcement yields; large strains are induced in the carbon with corresponding stresses.

Various structures have been repaired using this system. The first application was on the Ibach Bridge in Lucerne, Switzerland, where steel tendons had been severed when the bridge was drilled to support a sign gantry. Other applications include the discrete strengthening of an old timber bridge to allow it to carry modern traffic, and various applications to buildings. Many of these applications involved alterations to existing structures where new holes were required, e.g. in floors to receive lift shafts, or in chimneys to allow the addition of new flues.

There are now many applications [6], and the technology is clearly reaching commercial maturity. Some systems use relatively thick pultrusions that are glued onto a prepared surface; others use a thinner system that can follow



*Fig. 1: Bonded plates on test beams*

surface undulations [7]. Many of the commercial systems, such as that developed under the Robust programme in the UK, began as collaborative research projects. The Robust team repaired and tested a number of structures, including several beams removed from the Botley Road flyover, near Oxford, UK, which had severely corroded post-tensioning tendons *(Fig. 1)*.

There is extensive research into the adhesives that are required [8], their durability, and the novel failure mechanisms that can occur, such as peeling of the laminate from the surface.

Experiments have been carried out into the use of carbon fibre strips to reinforce masonry structures to resist earthquakes [9]. Subsequently, such strips have been applied to the domes of ancient churches in Italy [10] and Greece [11] that were thought to be susceptible to earthquake damage.

Development continues in this field, particularly with systems that will allow the plates to be prestressed at the time they are bonded to the structure [12]. Stressing of plates that are to lie flush with the concrete surface is very awkward, since the stressing system has to be essentially one-sided. It must also maintain the prestress for long enough to allow the adhesive to reach its full strength, or additional end-fixing needs to be provided. While such experiments in laboratories are successful, the practical application on site remains a problem.

Another area that is attracting considerable interest, but causes significant problems, is reinforcement against shear [13, 14]. The problem is one of achieving adequate bond at the ends of the fibres. In a typical beam-and-slab bridge configuration, the carbon fibre sheets can be wrapped around the bottom of the beam, but at the top of the beam it is difficult to anchor the material near the compression zone because of the slab. A variety of mechanisms are being investigated to overcome this problem [15], but it remains to be seen whether shear reinforcement will achieve the same success as passive flexural reinforcement.

## Carbon Fibre Cables for Stays and Prestressing Tendons

Carbon fibre stay cables, usually made from multiple pultrusions, are being used increasingly. This has required the development of anchorage systems that allow multiple rods to be anchored into the same block. To avoid problems of stress concentrations where the rod enters the anchorage, the shape of the block is carefully controlled and the fixing resin is added in layers, each with a different stiffness [16]. The softest resin is placed where the rods enter the terminal, with stiffer resins to the back. A variety of other anchoring systems have been developed, all aimed at easing stress concentrations [17].

The Storchen Bridge in Wintherthur, Switzerland, with a total length of 124 m has two of its 24 cables made from carbon fibres [18]. Similar cables have been used to prestress the lower chord of a tubular steel footbridge near Lucerne, Switzerland. Box Lane Bridge in Stoke-on-Trent, UK, has carbon fibre cables [19], as does an 80-m-long bridge over a railway yard in Herning, Denmark [20]. The latter bridge, believed to be the largest constructed with carbon-fibre-reinforced polymer (CFRP) cables, carries a walkway and emergency vehicles. It has 16 stay cables in two planes anchored to a central pylon. In addition, part of the deck is prestressed with CFRP tendons.

CFRP cables, and the aramid ropes described below, offer the possibility of extremely large spans for suspension and cable-stayed bridges, which are presently limited by the weight of the cables. Spans of up to 10 km are possible when considering static conditions [21, 22], but the actual limit on this type of structure is almost certain to be aerodynamic stability [23].

## Composite Bars as Reinforcement

Despite the low stiffness and lack of ductility, there is a requirement for a non-corroding reinforcing bar. Structures with this type of reinforcement are likely to be governed by stiffness, rather than by strength.

A consortium was formed to investigate the use of FRP as reinforcement for concrete and has carried out extensive investigations of the durability of FRP rods [24]. These investigations involved the production of pultrusions with various fibres as the main tension reinforcement. Subsequently, design guidance for reinforced concrete has been produced [25].

Fidgett footbridge was the first concrete footbridge in the UK to be fully reinforced with glass-FRP (GFRP) rods. Vibrating wire strain gauges and thermistors were cast into the concrete and fibre optic sensors fitted to the slab to allow long-term monitoring of the bridge. The bridge was also fitted with GFRP handrails.

Meanwhile, further significant work has been carried out on reinforcement, most notably in France [26], and FRP composites can be used as combined permanent shuttering and tensile reinforcement [27].

## Aramid Rope Systems

Fibres have also entered the structural engineering field from the rope industry. The Parafil system was developed in the 1970s for mooring offshore platforms and providing stays to large radio antennae [28]. With the advent of long man-made fibres of high strength and stiffness, the necessity for braiding or laying of ropes is removed. The two most common fibres for use with these systems are polyesters and aramids. The parallel filaments are placed within an extruded thermoplastic sheath, which gives the rope structure and protects the fibres from ultraviolet light.

Fundamental to the system is the termination *(Fig. 2)*, consisting of an external conically tapered barrel and an internal carefully shaped spike [29]. As the rope and spike are drawn into the barrel, a radial stress is set up which generates a frictional force on the fibres. With careful design of the shape of the spike, the system can be arranged to give a very uniform transfer of force into the fibres, allowing the full strength of the rope to be utilised.

Various structural engineering applications of this system have been developed. Externally post-tensioned concrete is a logical use, where the chemical stability of the fibres means that they can be left exposed. The cooling towers on Thorpe Marsh Electricity Generating Station, UK, had devel-
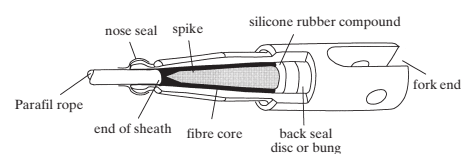


*Fig. 2: Termination system for parallel-lay rope*

Fig. 3: Tring Footbridge: prestressed masonry



Fig. 4: Fibre ropes used to support tramway cables in the absence of insulators

oped major cracks that were repaired by resin injection of the cracks and prestressing with external Parafil cables [30]. The principal cost saving over steel cables was the reduction in access costs due to the light weight.

The Parafil system has been applied to prestressed masonry [31] at Tring, UK, where a brick footbridge was constructed over a stream in a country park *(Fig. 3)*. The deck was built vertically as four linked tubes, such that the stronger (bedding) joints were horizontal and the weaker (perpend) joints were vertical. Parafil cables were then inserted into the vertical tubes and prestressed, after which the deck was rotated to the horizontal.

The Oppegaard footbridge in Norway is in essence a tied arch, with Parafil rope providing the tension tie [32]. The bridge crosses a small stream on a golf course. The beams are reinforced with GFRP straight rods with thermoplastic GFRP shear links.

The ropes offer high strength, high stiffness and light weight, and are therefore ideal for use as stay cables [33]. Their light weight simplifies installation and their good fatigue properties mean that a higher proportion of the strength can be used to resist the variable live load.

Electrically insulating stay cables are required in a number of applications. Radio antennae require staying but also require electrical insulation, so the higher cost of the rope can be offset against the elimination of insulators. In the case of transmitting antennae, high currents can be induced by the radio waves and the cables can also resist these effects. Electrical insula-

tion is also required to support the overhead catenary on railway and tramway systems. The use of an electrically insulating headwire means that no insulators are required, thus simplifying construction, reducing overhead weight, and reducing visual intrusion *(Fig. 4)*.

Similar ropes were also used as stay cables on a telecommunications tower in Barcelona [34], where steel cables would have caused electrical interference problems.

## FRP as Reinforcement

### Bond of Reinforcement

With steel reinforcement in concrete it is assumed that a high level of bond between the steel and the concrete is a good thing. If the strain in the tendon becomes high at a crack, the steel will yield and no stress concentration can occur. However, with composites,



Fig. 5: Inferred bond stresses for three types of tendon [35]

which are linearly elastic and have no plastic plateau, it has been demonstrated that both high moment capacity and high rotation capacity can be achieved by partially bonding the reinforcement to the concrete. The different bond characteristics of composites are currently the subject of extensive research [35–37], since FRP composites have very different bond characteristics, both from steel and from each other, depending on the surface texture *(Fig. 5)*.

### Column Reinforcement

Relatively little work has been performed in Europe wrapping columns to resist seismic loads. A significant amount of work has however been carried out in Germany and elsewhere providing additional reinforcement to columns that have corroded at the base, usually due to de-icing salts on the highway [38]. In the UK an extensive program of column strengthening to resist higher impact loads is about to begin [39].

### Reinforcement of Concrete Tubes

An extensive programme of work has been undertaken at Southampton, UK, on the use of concrete-filled FRP tubes. By making the tubes from composites produced by filament winding with a low lay angle, the tube itself has virtually no axial stiffness, so there is no reduction in the restraint caused by expansion of the tube [40]. Very significant enhancements of the columns' strength and strain capacities have been observed, not only with axial loads, but also with loads where there is a significant bending component.
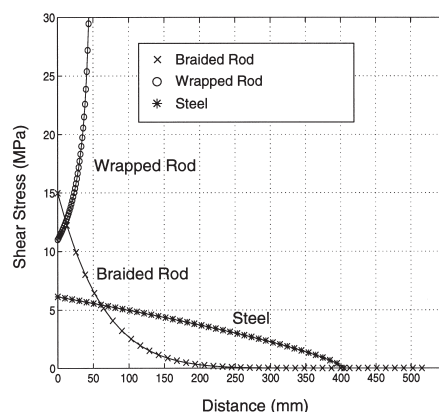
### Novel Forms of Reinforcement

The nature of the fibre reinforcement lends itself to novel forms. Pultrusions are difficult to bend into conventional reinforcement shapes without seriously weakening the element at the bend. So why not make use of the fibres' flexibility to form the links before adding resin to stiffen the material? Research is underway in Germany into the use of a variety of textile processes, including the double-layer and Raschel knitting techniques *(Fig. 6)*, which produce three-dimensional structures [41, 42].
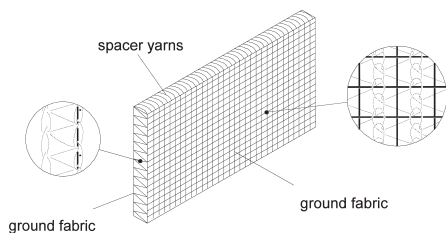


*Fig. 6: Double-knit textile reinforcement* [42]

### Reinforcement of Wood

Timber structures can also be reinforced by means of composites, in a variety of ways. A project is being carried out in Bath, UK, to reinforce joints between timber components by means of composite inserts [43], and at least one timber bridge in Russia has been prestressed with GFRP [44].

## Fully Composite Structures

Structures made entirely from composites need to be thought about from a completely fresh viewpoint. The production processes are different from conventional structures, and the governing material properties are unfamiliar to many engineers. The two most sensible production techniques, pultrusion and filament winding, yield products with considerable anisotropy in their properties. This results in considerable difficulties in making joints. Drilling for bolts tends to sever the load-carrying fibres, and the lack of isotropy precludes other load paths [45]. Welding is impossible, and although adhesives can be used, the design of efficient and durable adhesive joints is not trivial.

It was recognised by a UK consulting engineering firm that composite materials are most easily fabricated in the form of pultrusions, which inevitably means that the strengthening fibres are aligned axially, except when woven tapes are used. Pultrusions require dies, which are expensive and must be reused to be economic, which means a standard cross-section (although not necessarily standard reinforcement). A jointing system was thus required that allowed components to be assembled into fabrications. The result was the "toggle joint", where the main elements have grooves that are fabricated as part of the pultrusion process, including additional reinforcement. Two such elements can then be glued together, with an FRP toggle bar introduced to hold the elements together until the adhesive is set [46].

To promote acceptance of the new techniques by the civil engineering community, documents were produced using the same principles as existing codes. This required the development of testing regimes so that quality assurance principles could be applied [47].

The first major application of the system was to provide a bridge enclosure for the A19 viaduct in Middlesborough, UK [48]. This large viaduct, carrying a major highway over the River Tees, had steel plate girders and a concrete deck. It had developed serious corrosion problems, and access was very difficult. The requirement was thus to provide an enclosure that would protect the steel from atmospheric pollution and provide access for maintenance in the future. The resulting design provided a GFRP floor system made from planks, joined together by the toggle system, which also incorporated hangers from the existing bridge. This structure was ideal as a first application of the technology: it was justified in terms of cost, and was large enough to be taken seriously. Once the investment had been made in the production process and its quality control, subsequent applications were made easier.

The Aberfeldy Footbridge *(Fig. 7)* in the UK has been extensively reported in the literature [49]. It joins two halves of a golf course on either side of the River Tay. The main structure consists of a cable-stayed GFRP deck, suspended by Parafil aramid ropes from GFRP towers. Although originally designed only for pedestrians, it has recently been strengthened locally by the addition at some highly stressed locations of CFRP in order to deal with golfers' motorised "buggies". There have been some concerns expressed about the flexibility of GFRP structures due to the low Young's modulus of glass, which can result in unacceptably low natural frequencies [50]. The very light weight allowed mass to be added locally to the structure (by filling some of the tubes with concrete) so that the flexural and torsional natural frequencies could be separated.

The light weight of composites offers advantages when moveable bridges are required, since significant savings



*Fig. 7: Aberfeldy Bridge*

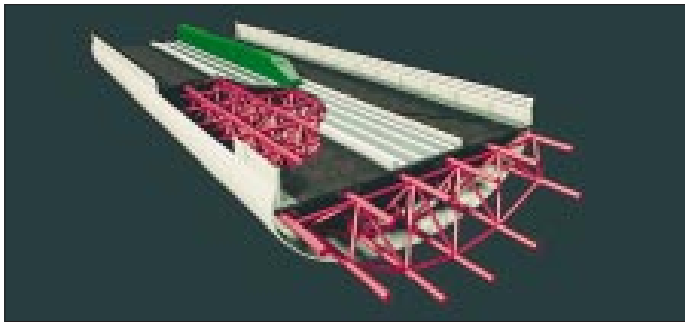

*Fig. 8: Bonds Mill Lifting Bridge*

Fig. 9: The SPACES system



Fig. 10: Site office/Visitor's Centre at Severn Crossing

in the machinery can be realised. Bonds Mill Lifting Bridge *(Fig. 8)* near Gloucester, UK, provides access for heavy trucks to an industrial estate, across a recently reopened canal. The deck is made from GFRP pultrusions, similar to those used in Aberfeldy. The upper layer of cells is filled with structural grade foam to resist local bending under wheel loads. The whole structure can be lifted by means of a pair of hydraulic jacks [51].

The GFRP system has now been integrated into the SPACES concept, where an automatically fabricated tubular truss structure has an external cladding of GFRP units *(Fig. 9)* [52]. The most significant innovation is the ability to add shear connections between the two systems so that they can act as a single integral unit. The contribution of the GFRP to the flexural capacity is relatively modest, as would be expected due to its low stiffness, but it has a significant effect on the torsional stiffness because it forms a box.

The GFRP modular idea does not stop with bridges. The Egan Report [53] identified modularity in building structures as a significant new technology. Modular buildings received a bad name after some unfortunate experiences with modular concrete flat-pack systems in the 1960s. These problems centred around the difficulties in making the joints between the panels strong, robust and watertight. With composites, however, the joint detail is the starting point of the design and is fundamental to its success. The engineer's site facilities for the Second Severn Crossing were built using this system, and these have now been turned into a Visitor's Centre *(Fig. 10)*. This is seen as a prototype for an extensive range of buildings.

Elsewhere in Europe, other systems have been used to fabricate lightweight bridges. In Switzerland, a two-span girder bridge at Pontresina has been fabricated from standard pultrusions. In one span the joints are made by bolting, in the other the joints used adhesives [54]. This bridge is unique in that it was designed to be removed each year before the snows melt, and then reinstalled once the danger of flooding has passed. The light weight was thus a significant factor in the design, and the two 12.5-m spans were lifted into place by helicopter.

In Denmark, the Kolding Bridge carries a footway across electrified railway lines [55]. The bridge is made from lattice girders, and is 38 m long with a central tower supporting GFRP stay cables.

## Composites in the Marine Industry

The use of GFRP for dinghies and yachts was one of the material's earliest applications, since it offers greater durability than wood. It was thus logical for the UK Royal Navy to consider FRP for use in its Minehunters. These vessels had traditionally been made from wood to reduce the magnetic signature when working near mines. Innovations include detailing of joints between hull and bulkheads, where fibres cannot be taken around corners, and the use of large FRP fabrications for the engine mountings. The use of metals is minimised, with special details to join the fibreglass of the hull and superstructure to the metallic elements of the equipment [56]. Special details have also been developed to carry high point forces, such as at the engine mounts, and at the armament mounting positions.

Composite systems have now been developed to provide impact and fire protection systems for offshore applications, including use in helicopter decks, pipeline support systems, and valve enclosures. On the Troll platform, about 180 t of GFRP composites were used for primary structures, while a number of riser support structures, each about 4 t in weight, have also been installed.

On the Beryl B platform, a major programme has been carried out to strengthen walls to resist blast in the production areas and to prevent damage to the crew areas. Much of this work was carried out with carbon fibre pre-pregs, which are relatively flexible and thus could be fitted into the cluttered machinery space. These were bonded to the structure and cured *in situ*. Some of these elements were very large, extending over several floors, and designed to resist substantial blast loading.

## Composites in the Railway Industry

The railway industry offers considerable scope for the structural use of composites. There have been several applications of composites in the railway vehicles themselves. The fairings at the front of trains are frequently made from GFRP; these are not merely wind deflectors but also provide significant impact resistance. There have also been innovations in the fabrication of railway vehicles [57], with complete vehicle bodies being formed by filament winding with carbon fibres.

The variety of railway infrastructure raises many challenges and opportunities for the composites industry. Recent concrete structures can be reinforced by means of plate bonding, as was carried out in Sweden when some railway bridges were strengthened to deal with higher wheel loads. However, many of the older railway structures are made of cast or wrought iron, and many of these are in need of repair or strengthening. When the surface to

be reinforced is relatively flat, plate bonding can be used, as was done on a number of cast iron bridges for the London Underground, UK. A more attractive option would be to prestress the carbon fibre in order to improve the stress distribution in the cast iron, often with a view to reducing the compressive stresses in the opposite face.

Other problems exist on railways with riveted structures, where the presence of the rivets prevents the use of bonded plates, but for which the aramid rope systems are likely to be suited. Several groups are actively looking at methods of reinforcing cast or wrought iron arches, where the curvature causes some interesting effects.

It is estimated that the capital cost of the composite materials in some of these applications may be up to ten times that of conventional materials. However, when working in the restricted space of the railway tunnels and with overnight track possessions lasting as little as 4 hours, the ease of handling of composites far outweighs the higher material cost.

## Composites in Ground Engineering

Fibres are used extensively in the soil-reinforcement industry [58]. Polyester-based soil reinforcement has been a commercial product for many years, competing successfully against steel alternatives [59]. The polyester fibres are contained within a polyethylene sheath and are supplied in the form of flat strip (Paraweb). It is competitive in price, much easier to install, and much more durable. It has been used in a number of applications, including examples where the wall is in the tidal range *(Fig. 11)*, leading to alternate wetting and drying.

Other composite applications include soil nailing using GFRP, which is being pioneered in Germany, and the use of composite ground anchors in Paris,

*Fig. 11: Wall in tidal zone reinforced with polyester strips*

used as temporary supports for the basement of a multi-storey building. The composite anchors were placed where the ground was later going to be excavated by tunnel boring machines; steel anchors would have caused serious disruption to the cutting head of the machine.

## Commercial Factors and the Future

The use of CFRP as externally bonded passive flexural reinforcement is a commercial success, due to the light weight of the material and the consequential savings in construction time. Similarly, the use of GFRP composites for complete structures is proving to be economic when there are access difficulties for building conventional heavy structures. The use of polyesters as soil reinforcement is also commercially successful, due to their resistance to corrosion in potentially aggressive soil conditions.

Other applications have not yet taken off commercially. There is some scope for the use of composite reinforcement, but only in areas where rapid corrosion of steel is to be expected and only when deflections are not the limiting factor. Post-tensioned concrete with external cables should be economic provided that whole-life costs and proper alternative designs are evaluated. Internal pre-tensioning tendons are unlikely to be economic, primarily because there are few problems with steel tendons, unless some form of automated production process can be developed that uses machines to fabricate the shear reinforcement.

What remains to the industry, at the moment, is niche applications, where novel solutions are found to existing problems by making use of the combination of properties that composites possess. The successful applications all make use of more than one benefit of using composites, which makes the cost problem less acute.

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