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TECHNICAL REPORT

TR 6.2

FIBER REINFORCED POLYMER COMPOSITE MATERIALS
USED IN CIVIL ENGINEERING

ATLANTIC AREA
Transnational Programme
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NOTE:

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented.

PREFACE

The main subjects concerned in this TR were discussed and a general review was made inside the working group WG A6 – Smart & green structural and repair materials. The WG was created in the DURATINET project with the aim to stimulate the creation of a new cluster on smart and green structures and to promote the use of new construction materials environmental friendly and with improved performance and/or durability.

This TR is one of a series of review documents, concerning smart & green structural and repair materials theme, which summarizes the current knowledge on the applicability of Fibre-reinforced polymer composite materials in concrete.

Fibre-reinforced polymer composite materials (FRP) is a class of materials which presents an immense potential for use in Civil Engineering, both for rehabilitation of existing structures and for the construction of new facilities.

Competition in the Civil Engineering market typically dictates high-volume low-cost materials with extended service-life and minimum maintenance. To attain these goals, composites for construction differ from mainstream aerospace composites in material constituents and manufacturing techniques.

The objective of this TR is to present the status of this “new” class of construction material. Rather than presenting an overview of FRP materials, in general, emphasis is given to their application in Civil Engineering.

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1 Introduction

Fibre-reinforced polymer composite materials (FRP) have hitherto been utilised predominantly in the aerospace and military industries, but for the last three decades there has been a growing awareness amongst civil engineers of the importance of the unique mechanical and in-service properties of these materials together with their customised fabrication techniques. In fact, this class of materials presents an immense potential for use in Civil Engineering, both for rehabilitation of existing structures and for the construction of new facilities [1].

Competition in the Civil Engineering market typically dictates high-volume low-cost materials with extended service-life and minimum maintenance. To attain these goals, composites for construction differ from mainstream aerospace composites in material constituents and manufacturing techniques[2].

The objective of this text is to present the status of this “new” class of construction material. Rather than presenting an overview of FRP materials, in general, emphasis is given to their application in Civil Engineering.

2 Fibre reinforced polymer composite materials

2.1 Composition

FRP is a general term used to describe a wide range of products made up of a combination of fibres in a polymer matrix. Their mechanical and physical properties are clearly controlled by their constituent properties and by the micro-structural configuration. While the fibres are mainly responsible for strength and stiffness properties, the polymeric matrix contributes to load transfer and provides environmental protection. In addition, fillers are used to reduce the cost and sometimes to improve performance, imparting benefits as shrinkage control, surface smoothness and crack resistance. Additives and modifiers ingredients can expand the usefulness of the polymeric matrix, enhance their processability or extend composite durability (*Fig 1*).

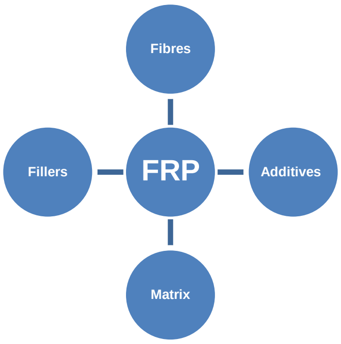

Fig.1. FRP components

The reinforcing of a low modulus polymeric matrix with high strength and modulus fibres utilizes the viscoelastic displacement of the matrix under stress to transfer the load to the fibre; this result in a high strength, high modulus composite material. The aim of the combination is to produce a two phase material in which the primary phase, that determines stiffness, is in the form of fibres and is well dispersed and bonded and protected by a weak secondary phase, the polymeric matrix [3].

2.1.1 Fibres

The four main fibres use in the construction industry are: (i) glass, (ii) carbon, (iii) aramid and (iv) basalt. Generally, fibres can be used in different ways, with the performance changing for each [4]:

- the highest performance in terms of strength and stiffness in one direction comes from uni-directional composites, when fibres are parallel and give their maximum possible performance in this single direction;
- by arranging the fibres in a weave or mat, strength can be gained in more directions, although the limit strength is reduced.
- by chopping the fibres into short lengths and arranging them randomly, equal strength is achieved in all directions. This is generally the cheapest technique, used for the least structurally demanding cases.

Fig 2 shows examples of configuration of different types of fibres used to reinforced polymers, with application in Civil Engineering [5]:

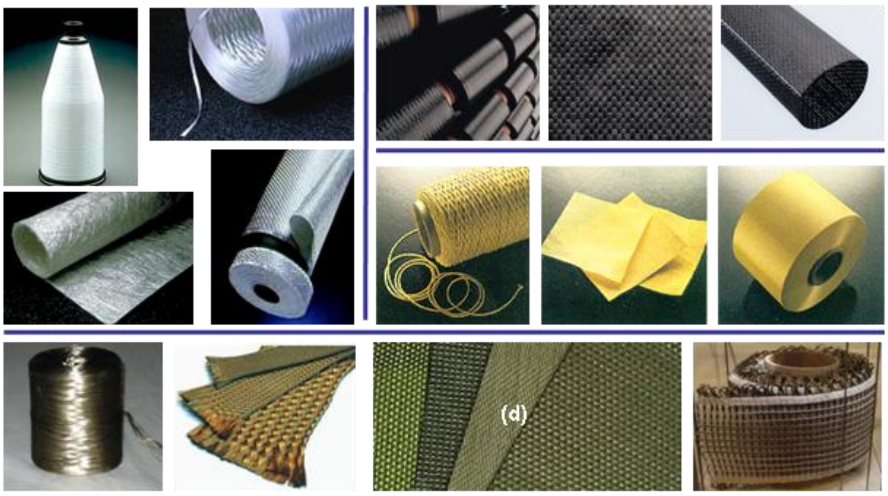

Fig 1. Fibre types in distinct configurations: (a) glass; (b) carbon; (c) aramid; (d) basalt

The most suitable of these fibres for a particular structural application depends primarily upon the mechanical requirements, as strength, stiffness, the environmental requests and allowable budget.

- Glass fibres are used for the majority of composite application because they are cheaper than the others. There are different forms known by names like E-glass (the most frequently used), S-glass (is a stringer and stiffer fibre with a greater corrosion resistance), R-glass (is a higher tensile strength and modulus and greater resistance to fatigue and aging) and AR-glass (an alkali-resistant glass used to reinforced concrete). The main characteristics of glass fibres are their high tensile strengths and moderate elastic modulus. Glass fibres are, also, excellent thermal and electrical insulators. Glass fibres are particularly sensitive to moisture, especially in the presence of salts and elevated alkalinity, and need to be well protected by the resin systems used in the FRP. Glass fibres are also susceptible to creep rupture and lose strength under sustained stresses.
- Carbon fibres, manufactured by the controlled carbonization of organic precursor, are produced in many grades. Carbon fibres cost currently significantly more than glass fibres. Their main characteristics are the high tensile strengths and elastic modulus and their very low density and thermal coefficient. The characteristic of each type of carbon fibre is often indicated in their commercial designation by codes as HS (high strength), HM (high modulus) or UHM (ultra high modulus). Carbon fibres are very durable and perform very well in hot and moist environments and when subjected to fatigue loads. They do not absorb moisture.
- Aramid fibres are polymeric fibres, where molecular chains are aligned and made rigid by means of aromatic rings linked by hydrogen bridges. Their main characteristics are high strength, impact resistance due to their energy absorbing properties, moderate modulus and low density. The fibres, themselves, are susceptible to degradation from ultraviolet light and moisture but exhibit resistance to acids and alkalis.
- Basalt fibres are materials obtained by melting crushed volcanic lava deposits. Basalt fibres have better physical and mechanical properties than glass fibres, but are significantly cheaper than carbon fibres. Their main advantages are fire resistance, significant capability of acoustic insulation and immunity to chemical environments.

Other fibres that are now in the development phase for use if FRP products for structural engineering include ultrahigh-molecular-weight polyethylene fibres and polyvinyl alcohol fibres. Natural fibres, such as sisal, flax and bamboo, have been used only in experimental applications to produce FRP products. However, it is expected that they will become more important in the construction industry due to their sustainability and recyclability [6].

Table 1 illustrates typical properties of the different types of fibres, showing their strength, stiffness and density.

Table 1. Range of properties for fibres for FRP composites

Fiber type	Density	Tensile strength (GPa)	Elastic modulus (GPa)
Glass	2.46 - 2.58	2.4 - 3.5	72 - 87
Carbon	1.74 - 2.20	2.1 - 5.5	200 - 500
Aramid	1.39 - 1.47	3.1 - 3.6	58 - 130
Basalt	2.65 - 2.80	4.2 - 4.8	89 - 110

According to Halliwell [7], the functional requirements of fibres in a composite are:

(i) high modulus of elasticity to give stiffness;
(ii) high ultimate strength;
(iii) low variation of strength between individual fibres;
(iv) stability during handling;
(v) uniform diameter.

2.1.2 Matrices

A polymer is an organic material composed of macro-molecules made from many repeats of the same unit called monomer. There are several different polymer matrices which can be utilized in FRP composites, but in construction industry only a relatively small number are actually used. According to their nature, there are two major types of polymers, which determine the methods of manufacturing and the properties of the composite: (i) thermoplastic and (ii) thermosetting. The first FRP were all based on thermosetting polymers and, besides the fact that thermoplastic have seen rapid growth in recent years, thermosetting is yet the most used in Civil Engineering applications[8].

Thermoplastic polymers are long chain molecules held together by relatively weak *Van der Waals* forces. These polymers can be amorphous, which implies a random structure with a high concentration of entanglement, or crystalline, with a high degree of molecular order [9]. The semi-crystalline polypropylene and nylon are especially popular as matrices.

Thermosetting polymers are usually made from liquid or semi-solid precursors which harden irreversibly; this chemical reaction is known as cure and on completion, the liquid resin is converted to a hard solid by chemical cross-linking which produces a tightly three-dimensional network of polymer chains. This family of polymers has an important virtue when used as matrices in FRP, which is the low viscosity of the precursor liquids, prior to cross-linking, that facilitates wetting of reinforcement fibres. The main polymers used in construction under this heading are:

- Unsaturated polyesters. Currently are the most widely used polymers in construction, as matrix of FRP. They are relatively low cost materials and are easy to process at an ambient temperature of cure. They can be formulated in hundreds of different ways to tailor their properties to different manufacturing process and can easily be filled and pigmented.

- Epoxies. In general epoxies have high specific strength and dimensional stability. They are particularly known by their adhesion ability to many substrates, and low shrinkage during the cure. A wide variety of formulations are available giving a broad spectrum of properties. They can be processed at both room and elevated temperatures. Epoxies have excellent environmental and chemical resistance, when compared with unsaturated polyester.
- Vinylesters. These polymers have similar mechanical and in-service properties to those of the epoxy resins and equivalent processing techniques to those of the unsaturated polyesters. Generally they have good wetting characteristics and possess resistance to strong acids and strong alkalis conditions. They can, also, be processed at both room and elevated temperatures.
- Phenolics. The most important characteristic of this family of polymers is there good flame retardant properties, low smoke generation and high heat resistance. For this reason, they are used when fire resistance is a requirement.

According to Hollaway and Head [3], the requirements for a good FRP matrix are the following:

(i) wet out the fibre and cure satisfactory in the required conditions;

(ii) bind together the fibres and protect their surfaces from abrasion and environmental ageing;

(iii) disperse the fibres an separate them in order to avoid any catastrophic propagation of cracks;

(iv) transfer stresses to the fibres efficiently;

(v) be chemically and thermally compatible with fibres;

(vi) have appropriate fire resistance and limit smoke propagation;

(vii) provide good aesthetic finish (colour and surface).

2.2 Fabrication

A wide range of processing methods is available for FRP composites, although there are differences between the techniques available for thermosetting and thermoplastic, due to their intrinsic different properties. One of the most important aspects of the manufacture of FRP composites is that the structural material and the product are formed simultaneously in a single process. FRP composites may be built “in situ” from the raw materials, as in the hand lay-up methods, or they may be shaping semi-finished or finished products.

Table 2 presents the commonly used process for fabrication of FRP composites applied in Civil Engineering, their principles and typical applications [4].

2.3 Properties

The attractiveness of FRP as construction materials derives from a set of advantages gleaned from the ability of this type of material through the synergistic combination of fibres in a polymeric matrix. Wherein, the fibre reinforcement brings load in designed direction taking benefit of anisotropy, and the resin acts as a medium to transfer stresses between adjoining fibres through adhesion in fibre-matrix interface.

The properties of FRP composites depend on the following aspects:

(i) nature and properties of the constituents (fibres, matrix, additives and fillers);

(ii) relative proportion of fibre/matrix;

(iii) fibre reinforcement configuration (particullarly, orientation);

(iv) methods of manufacture.

The influence of such aspects can be observed on typical material properties of different FRP composites shown in Table 3.

The choice of the FRP components, fibre/matrix proportion, fibre reinforcement configuration, and method of manufacture should be made on the basis of the structural application, environmental conditions, lifetime requirements and manufacturing process aspects.

Of three types of fibres used in FRP reinforcement the one with the greatest tensile strength is aramid, with carbon and glass offering similar strength (*Table 1*). Glass fibre is significantly weaker than the others and is not suitable for applications where high tensile loads are expected. When specific stiffness is required, carbon fibre out-performs the others.

Table 1. Fabrication processes of FRP composites

Pultrusion	Tightly packed tows of fibres, impregnated with polymer, are pulled through a shaped heated die to form aligned, continuous sections geometry. Solid and hallow profile section may be produced with a high fibre content and high degree of fibre alignment. Off-axis fibres may also be introduced, if required. Pultruded shapes and concrete reinforcing bars and tendons; I beams and other sections.
Filament winding	The process involves winding fibres over a mandrel which rotates while a moving carriage laying down the reinforcement in the desired pattern. The orientation of the fibres can also be carefully controlled so that successive layers are plies or oriented differently from the previous layer. Cylindrically symmetric structures such as hollow tanks and vessels. The process of wrapping in retrofit strengthening is an adaptation of the process.
Compression and transfer moulding of compounds	Compression moulding of thermosetting moulding compounds in form of dough with chopped glass fibres (DMC) or sheets with longer fibres (SMC). Simple or complex decorative panels.
Matched-die moulding and autoclave	Large panels and relatively complex open structural shapes are constructed by hot-pressing sheets of pre-impregnated fibres or cloths between flat or shaped platens, or by pressure autoclaving to consolidate a stack of prepreg sheets against a heated, shaped die. Composite reinforced with chopped-strand mat or continuous-filament mat reinforcements may also be press-laminated. Laminates and retrofit strengthening sheets.
Continuous sheet production	Chopped strand mat or chopped strands are impregnated with resin and sandwiched between two layers of film on a moving belt. The sandwich passes through guides that form the corrugated or other desired profile. Corrugated plates.
Resin-transfer moulding and vacuum-assisted resin transfer moulding	Pre-catalysed resin is pumped under low pressure into a fibre preform, which is contained in a closed and often heated die. The preform may be made of any kind of reinforcement, but usually consists of woven cloths or continuous-fibres mats. Structural components with varying shapes and degrees of anisotropy/orthotropy, e.g. cladding and roofing panels, shell structures and bridge decks.
Contact moulding by hand lay-up or spray-up	Open mould methods, where fibre continuous strand mat and/or other fabrics such as woven roving are placed manually in the mould and each ply is impregnated with brushes and rollers. The product must also be built by spraying through a gun which simultaneously delivers short fibre and pre-catalysed resin. Fabrication one-off structures, small number of large components.

Tensile experimental curves for unsaturated polyester offers an elongation at break of about 3 %; vinylester and epoxies have greater elongations of 4.5 % and 8 %, respectively.

Table 2. Typical mechanical properties of unidirectional FRP composites

Fibre type	Fibre content	Tensile strength (MPa)	Tensile modulus (GPa)	Shear strength (MPa)
Glass	0.55 - 0.65	600 - 1200	35 - 50	4 - 6
Carbon	0.57 - 0.60	600 - 1200	130 - 300	60 - 90
Aramid	0.60	1200 - 1400	76	60 - 83

2.4 Durability

FRP materials are increasingly being used in civil engineering applications such as reinforcing rods and tendons, wraps for seismic retrofit of columns, externally bonded reinforcement, composite bridge decks, and even hybrid and all composite structural systems. Since FRP are still relatively unknown to the infrastructure systems planner, there are heightened concerns related to the overall durability of these materials, especially as related to their capacity for sustained performance under harsh and changing environmental conditions under load [10][[i]].

Although FRP have been successfully used in the industrial, automotive, marine and aerospace sectors, there are critical differences in loading, environment and even the types of materials and processes used in these applications. Several evidences provides substantial reason to believe that if appropriately designed and fabricated, these materials can grant longer lifetimes and lower maintenance costs than equivalent structures fabricated from conventional materials [10].

FRP materials used in civil infrastructure are exposed to a variety of environments that may act individually or may be synergistic in nature. According a recent study undertaken to identify critical gaps in durability of composites to be used in civil infrastructure applications [11], seven factors were distinguish, namely:

(i) moisture/solution;

(ii) alkali;

(iii) thermal, including cycling and freeze-thaw;

(iv) creep and relaxation;

(v) fatigue;

(vi) ultraviolet radiation;

(vii) fire.

3 Fibre reinforced polymer composite materials as a construction material

Some of the most important advantages of FRP composites over conventional construction materials are listed in *Table 4*.

Table 3. Advantages of FRP over conventional construction materials

High specific strength and stiffness	New design concepts (e.g. bridges with longer free s spans). Saving in the supporting and substructure elements. Enhancement of seismic resistance by weight saving. Increasing speed of assembly and reduction of time for time-critical projects (e.g. bridge repair).
Corrosion resistance	Unlike metals, FRP do not rust, making them attractive in applications where corrosion is a concern (marine waterfront structures, for example).
Non-magnetic properties	Steel members and reinforcements for concrete are often a problem in structures with electromagnetic interference sensitive electronic equipment.
Time saving	Large FRP composite parts can be pre-fabricated off-site and can be shipped to the construction site and installed, due to their light weight. Increase in overall construction efficiency and positive effects on planning and logistics.
Low maintenance requirements	Due to the corrosion resistance and enhanced environmental resistance, it is expected to require less maintenance, resulting in lower overall life-cycle costs. Ideal where access is difficult or expensive.
Tailored properties	It is possible to tailor properties to comply only in the directions required, improving efficiency and economy, when compared with solution with isotropic materials.
Freedom of shape and appearance	It is possible to fabricate shape and complex geometry. Can give a particular color or texture, particularly important in architectural applications.

Despite the considerable advantages there still exist significant challenges that must be overcome before FRP can be used as widely as conventional materials, such as concrete, steel or timber. The most important are listed in Table 5.

Table 4. Challenges in the adaptation of FRP as a construction material

High initial material costs	Probably, one of the major obstacles for using FRP materials in an extremely cost-competitive market. Cost analysis of FRP materials with respect to conventional construction materials should be based on a per unit performance, with proper consideration to weight reductions.
Need of familiarity with materials	Mechanical properties of FRP materials strongly depend on their constituents, fibre fraction and configuration. Failure mechanisms depend on microstructure and fibre architecture.
Perception of brittle material response	FRP do not show yield like steel.
Lack of knowledge on design	Design and fabrication must be considered at the same stage of the project.
Design guidelines not standardized	The intrinsic tailorability of FRP difficult the adoption of standardized design guidelines.
Uncertain durability	Lack of substantiated data related to the FRP long-term durability. Key durability concerns for fibre-reinforced composites in civil infrastructure have been identified as follows: a) moisture and chemical reagents; b) alkaline solutions; c) thermal effects; d) creep rupture; e) fatigue resistance; f) UV weathering; g) fire performance.
Environmental impact	In a very simple analysis it may be appear that FRP are not an ideal material, from an environmental perspective. However, with a holistic approach, the material are much more positive (for example, they are able to “save” an otherwise failing structure).
Fire	Careful design and the right choice of resins, additives and fillers can make FRP fire retardant. However, there is always a compromise to be made, and if fire resistance is absolutely critical, than FRP materials can often be the most cost-effective solution.

4 Application of FRP composites in Civil Engineering

Over the last decade there has been significant growth in the use of FRP composites as construction material in structural engineering. These materials have proven themselves to be valuable for use in the construction of new buildings and bridges and for the upgrading of existing structures [6].

Composites applications in infrastructure can be classified into the general areas of structural rehabilitation and new construction, as shown in Fig 3.

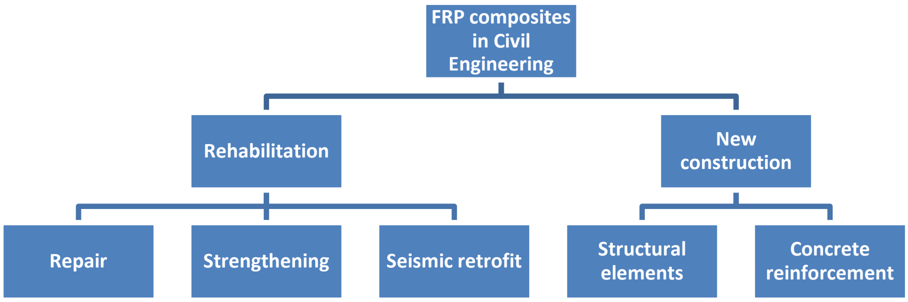

Fig 2. Classification of composite application in civil infrastructures

4.1 Rehabilitation

The repair and strengthening of deteriorated and damaged infrastructure has become one of the important challenges confronting the civil engineer worldwide. In many countries the rehabilitation of existing structures is fast growing especially in developed countries that completed most of their infrastructure in the first half of the last century. These structures are now in need of urgent repair and retrofit. There is, therefore, an urgent need for development of effective, durable and cost-efficient repair, strengthening and retrofit materials and methodologies [3].

Generically, FRP composites can be utilized for structural rehabilitation in the following situations [12]:

- Deficiencies at the design stage, including: design errors, inadequate factors of safety, use of inferior class materials and poor construction quality.
- Change of use, in service, namely, increased safety requirements (upgrading of structural design standards), modernisation that causes redistribution of stresses and increase of the applied load.
- Ageing of materials that compromise the load capacity of the structure: for example concrete degradation in hostile marine or industrial environments.
- Accidents, as fire or seismic events.

There are two possible alternatives to restore a deficient structure to the required standard; these are complete or partial demolition and rebuild, or beginning of a programme of strengthening [13].

Within the scope of rehabilitation of concrete structures, it is essential that differentiation is made between repair, strengthening and retrofit terms which are often erroneously used interchangeably [3]:

- in “repairing” a structure, the FRP composite is used to fix a structural or functional deficiency such as a crack or a severally degraded structural component.
- the “strengthening” of structures is specific to those cases wherein the addition or application of the FRP composite would enhance the existing designed performance level.
- the term “retrofit” is used to relate to the seismic upgrades of facilities.

4.1.1 Repair and strengthening

Repair is necessary when the original structure has deteriorated, damage in service or was not constructed according the required design. In many cases, a repair programme may include strengthening to add a level of safety to the repaired structure and to account for uncertainty in the rehabilitation project.

Repair with FRP composites has been used successfully on concrete, timber, metal and masonry structures. The predominant role of concrete as a structural construction material stimulated the application of FRP composite in repairing of concrete structures, namely, bridges and large structural elements [14][15].

The basic FRP strengthening technique, which is most widely applied, involves the manual application of either wet lay-up (Fig 4) or prefabricated systems (Fig 5) by means of cold cured adhesive bonding. Common in this techniques is that the external reinforcement is bonded onto the concrete surface with the fibres as parallel as practically possible to the direction of principal tensile stresses. Besides the basic techniques, several special techniques have been developed, namely the automated wet lay-up wrapping (of columns or chimneys, for example), use of pre-stressed FRP (to close open cracks in bridge decks, for example) [16]. Near-surface mounted (NSM) technique may also be thought as a special method of reinforcement of concrete structures. In the NSM method, grooves are first cut into the concrete cover and the FRP reinforcement, usually a laminate strip, is bonded therein with appropriate groove filler, typically epoxy paste or cement grout.

Fig 3. Wet lay-up of FRP sheets

Fig 4.Application of FRP strips

4.1.2 Seismic retrofit

The problem of structural deficiency of existing constructions is especially acute in seismic regions, as, even there, seismic design of structures is relatively recent. The enhancement of confinement in structurally deficient concrete columns in seismically active regions of the world has proven to be one of the most significant applications of FRP materials in infrastructure applications [17].

Seismic retrofit of reinforced concrete structures, namely bridges, using conventional steel techniques, whilst effective, has been found to be time consuming, cause significant traffic disruption, rely on field welding and is susceptible to corrosion. Additionally, many of the methods increase the stiffness and strength capacity of the columns putting adjacent structural elements at risk from higher transmitted seismic forces. The use of FRP composites in this application (Fig 6), not only provides a means of confinement, without the associated increase in stiffness, but also enables the rapid fabrication of cost effective and durable jackets with little traffic interference.

Fig 5. Seismic retrofitting of a bridge with FRP composites

4.2 New constructions

FRP composites, today, are used in a variety of applications, ranging from replacements for steel rebar and tendons used conventionally as tensile reinforcement in concrete, jackets for retrofit of columns, and externally bonded reinforcement for the rehabilitation of deteriorating structural systems. Additionally, FRP composite are use in “all composite” structures such as building frames and bridge decks and are being increasingly adopted for fabrication of structural elements to be used in conjugation with the traditional construction materials.

4.2.1 Seismic retrofit

One of the most popular area of FRP composite, as construction material of structural elements, is in the form of high-quality constant cross section FRP profile shapes. *Fig 7* shows examples of products commercially available.

FRP pultruded structures profiles have been used in a significant number of structures to date, including pedestrian bridges, vehicular bridges, building frames, cooling towers, walkways and platforms, etc.

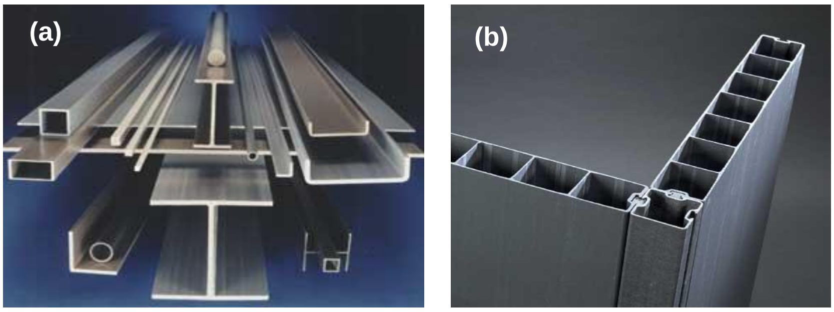

Fig 6 . (a) Examples of FRP pultruded profiles; (b) FRP unit building block system

In the 1990s a significant efforts was undertaken by FRP manufacturers to develop FRP bridge deck systems that could be used on conventional steel or concrete girders. In fact, there are now an increasing number of field applications of FRP bridge decks systems (*Fig 8*), driven by needs of lighter weight and more durable systems to offset increasing costs of maintenance of conventional structural concrete in areas of harsh climatic conditions, or where there is a need for upgrading of structures to meet new code requirements without access to new construction.

Fig 7. Example of a FRP bridge deck system

4.2.2 Concrete reinforcement

The predominant role of concrete as a construction material and the problems associated with corrosion of steel reinforcement stimulated the development of fibre composites for internal [18][19] and external [16][20] reinforcement of concrete and pre-stressing cables and tendons [21].

<u>FRP bars, rods and grids</u>

The use of FRP reinforcing bars and grids for concrete is a growing segment of the application of FRP composites in structural engineering for new construction [19]. For an effective reinforcing action, it is necessary to develop bond strength between FRP and concrete. This is attained in FRP rod by having various types of deformation systems, including exterior wound fibres, sand coatings and separately formed deformations (Fig. 9).

Fig 8. Examples of glass and carbon FRP bars and rods

FRP reinforcing bars and grids for concrete with both glass and carbon fibres are produced by a number of companies in USA, Asia and Europe [22]. Their use has become recurrently and is no longer confined to demonstration project as in the past. Applications have become routine for certain specialised environments, namely in bridge decks an in underground tunnels (Fig 10).

Fig. 10. Application of FRP as concrete reinforcement in new structures: (a) bridge deck; (b) underground tunnel

The use of FRP in concrete for anti-corrosion purposes is expected to find applications in structures in or near marine environments, in or near the ground, in chemical and other industrial plants, in places where good quality concrete cannot be achieved and in thin structural elements. The magnetic neutrality of FRP makes them also an ideal reinforcement solution for concrete in specific areas as railway magnetic levitation systems, telecommunications stations and hospital building where magnetic resonance imaging equipment is used.

<u>FRP cables for pre-stressing and post-stressing applications</u>

Composite cable applications in the infrastructure are used in the construction of suspension and stay cables for bridges, pre-stressed tendons for various concrete structures and external reinforcements for structural beams. All these applications require materials that incorporate high tensile strength and, in addition, require characteristics such as corrosion resistance and light weight [23].

Corrosion of steel pre-stressing tendons can lead to the concrete degradation and the deterioration of structural integrity. In cable-stay applications, both corrosion and fatigue make the replacement of conventional cables a significant life cost. FRP composites have good corrosion, durability and fatigue characteristics and therefore the utilisation of these materials does make good engineering sense. The initial cost of the cables is higher than their competitors but this must be weighed against reduced transportation and handling costs, reduced maintenance and the anticipated longer useful life for individual stay cables and for concrete structures pre-stressed with FRP composite cables.

FRP cables are unidirectional reinforced structural elements made from glass, aramid or carbon fibres embedded in the polymer matrix. Different shapes exists, such as bars, cables, rectangular strips and braided reinforcement.

Carbon fibre and aramid cables are used for pre-tension and post-tension concrete, however glass fibre cables are not recommended for pre-tension due the low resistance to alkaline environments.

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