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FRP REINFORCEMENT FOR CONCRETE STRUCTURES: STATE-OF-THE-ART REVIEW OF APPLICATION AND DESIGN

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Abstract. Fiber reinforced polymers (FRPs) are considered to be a promising alternative to steel reinforcement, especially in concrete structures subjected to an aggressive environment or to the effects of electromagnetic fields. Although attempts to develop effective reinforcement have been followed, the application of FRPs remains limited by the solution to simple structural problems that mainly appear due to the absence of design codes, significant variation in the material properties of FRP composites and limited knowledge gained by engineers as regards the application aspects of FRP composites and structural mechanics of concrete elements reinforced with FRPs. To fill the latter gap, the current state-of-the-art report is dedicated to present recent achievements in FRPs applying practice to a broad engineers' community. The report also revises the manufacturing process, material properties, the application area and design peculiarities of concrete elements reinforced with FRP composites. Along the focus on internal reinforcement, the paper overviews recent practices of applying FRP reinforced concrete (RC) elements in structural engineering. The review highlights the main problems restricting the application of FRPs in building industry and reveals the problematic issues (related to the material properties of the FRP) important for designing RC following the formulation of targets for further research.

Keywords: fiber reinforced polymers, FRP bars, reinforcement, material properties, application.

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Introduction

Steel and concrete are the principal materials of the industry of up-to-date construction. Nevertheless, there are applications that require an alternative material to be used. Fiber reinforced polymers (FRPs) are considered to be a promising alternative to steel reinforcement, especially in concrete structures subjected to an aggressive environment or to the effects of electromagnetic fields (Alsayed *et al.* 2000). Numerous concrete structures such as bridges, dams and off-shore structures are exposed to de-icing salts, combinations of temperature, moisture and chlorides that reduce the alkalinity of concrete and result in the corrosion of steel reinforcement.

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At present, almost a half of the budget of construction industry is spent on the repair and reconstruction of the existing buildings (Cigna *et al.* 2003). In order to cope with corrosion problems, engineers have turned to alternative metallic reinforcement such as epoxy-coated steel bars, cathodic protection and increased thickness of concrete cover. While adequate in certain situations, such methods may still be unable to entirely eliminate the problems of steel corrosion (ACI 440 2006). Therefore, due to a non-corrosive nature, higher strength and lower unit weight of FRPs relative to conventional steel reinforcement as well as the use of FRP materials in an adverse environment is gaining recognition.

Different kinds of materials are used for producing FRP reinforcement. Carbon fiber reinforced polymers (CFRP) have the best mechanical properties (amongst other FRP composites), but materials for its production are hardly accessible. In terms of mechanical properties and production complexity, basalt (BFRP) and aramid (AFRP) bars are somewhere in the middle, but they are seldom used in practice. The bars of glass fiber reinforced polymers (GFRP) are the most popular among other FRP types due to the combination of relatively low-cost with environmental resistance to structural fibres. With high durability, GFRP bars have tensile strength up to 5–6 times higher than structural steel. However, a low elastic modulus of polymer composites (in respect to steel) generally leads to the increased deformations of GFRP reinforced elements. Thus, serviceability limit state often becomes the governing criterion in the design of such elements. A number of techniques have been proposed for predicting deformational response of FRP reinforced concrete (RC) elements (Faza, GangaRao 1992; Bischoff 2007), though a lack of experimental data is still evident.

Moreover, various types of surface coatings are used for producing composite bars. The surface treatment determines the quality of a bond between the bars and concrete matrix. A complex, uneven and rough shape of the bars ensures good bond properties; however, such surface treatment may result in more complex manufacturing processes. There is still no global consensus on the most effective shape of FRP bars. The standardization of the shape would allow a more extensive use of FRP reinforcement in construction.

Over the past decades, external bonding of FRP plates or sheets has been widely used for strengthening RC structures. Due to high tensile strength and low weight (comparing to conventional steel), FRPs have become an ideal material for use in construction industry. Another advantage of FRP over steel as external reinforcement is easy handling; hence, minimal time and labour are required to implement them.

However, an engineer should be aware of the reliability of the applied strengthening technique. Frequently concrete cover separation or plate as well as interfacial debonding become the failure modes of FRP strengthening (Smith, Teng 2002; Oehlers *et al.* 2003). The behaviour of the interface between the FRP and concrete is the key factor controlling debonding failure in FRP-strengthened RC structures (Lu *et al.* 2005).

Although attempts to increase the effectiveness of FRP reinforcement have been followed, its application remains limited by the solution to simple structural problems. This might be related to the absence of design codes, significant variation in the material properties of FRP composites and limited knowledge gained by engineers on the application and structural aspects of FRP composites. The current state-of-art report is dedicated to fill the latter gap. The manuscript revises the manufacturing process, material properties, the application area and design peculiarities of concrete elements reinforced with FRP composites. Along the focus on internal reinforcement, the paper overviews recent practices of applying the FRP reinforced concrete (RC) element in structural engineering and formulates the main problems that restrict the application of FRPs in building industry. The review reveals problematic issues (related to the material properties of FRP) important for designing RC following the formulation of targets for further research.

1. FRP materials, properties and types of manufacturing

FRP composites are made from fiber, resin, interface, fillers and additives. The fibres of higher deformation modulus contribute to the mechanical strength of the FRP, whereas resin helps with transferring or distributing stress from one fiber to another to protect the fiber against environmental and mechanical damage. The interface between the fiber and matrix is known to significantly affect the performance of FRP composites. In addition to these three basic components (fibres, resins and interface), fillers serve to reduce cost and shrinkage. Additives assist in improving the mechanical and physical properties as well as the workability of composites.

The main part of FRP reinforcement is fibres. Table 1 presents the physical and mechanical properties of various kinds of fibres. There are four main materials used for producing fibres dominating in civil engineering industry: glass, carbon, aramid and basalt:

- Glass fiber reinforced polymers (GFRP). Relatively low cost comparing to other kinds of FRPs makes glass fibres the most commonly used in construction industry. However, a relatively low deformation modulus, low humidity and alkaline resistance as well as low long-term strength due to stress rupture are the main disadvantages of GFRP. In case of demand of better alkaline resistance, the so-called AR glass FRP is being used.
- Carbon fiber reinforced polymers (CFRP). These fibres have high deformation modulus and fatigue strength as well as do not absorb water. Though, a comparatively high energy requirement for the production of carbon fibres leading to high costs is one of the major disadvantages. Furthermore, their drawbacks include anisotropy (reduced radial strength) as well as potential galvanic corrosion in direct contact with steel (Carolin 2003).
- Aramid fiber reinforced polymers (AFRP). These fibres have high static and impact strengths. Nevertheless, their use is limited by reduced long-term strength (stress rupture) as well as sensitivity to UV radiation. Another drawback of aramid fibres is that they are difficult for cutting and processing (Tuakta 2005).
- Basalt fiber reinforced polymers (BFRP). Such fibres have excellent resistance to high temperatures and high tensile strength as well as good durability. Other advantages are high resistance to acids, superior electro-magnetic properties, resistance to corrosion, resistance to radiation and UV light and good resistance to vibration (Banibayat 2011).

Depending on the type of the FRP, the fibres combined with a matrix consisting of resins, fillers and additives are utilized for producing bars or sheets. Resins are the basic components of the matrix. There are two major types of resins: thermoplastic and thermosetting polymers. The latter are the most popular for producing FRP elements. Unlike thermoplastic polymers, once thermosetting polymers are cured, they cannot be reheated or reformed. Thermosets are usually brittle in nature, but offer high rigidity, thermal and dimensional stability, higher electrical, chemical and solvent

Table 1. Physical and mechanical properties of different FRPs

Type of FRP	Density	Tensile strength	Deformation modulus	Elongation	Coefficient of thermal expansion	Poisson's ratio
	kg/m^3	MPa	GPa	%	10^{-6}/°C	
Electrical-resistant *E*-glass	2500	3450	72.4	2.4	5.0	0.22
High-strength *S*-glass	2500	4580	85.5	3.3	2.9	0.22
Alkali-resistant *AR*-glass	2270	1800–3500	70–76	2.0–3.0	n/a	n/a
Carbon	1700	3700	250	1.2	−0.6 up to −0.2	0.20
Carbon (high-modulus)	1950	2500–4000	350–800	0.5	−1.2 up to −0.1	0.20
Carbon (high-strength)	1750	4800	240	1.1	−0.6 up to −0.2	0.20
Aramid (Kevlar 29)	1440	2760	62	4.4	−2.0 longitudinal 59 radial	0.35
Aramid (Kevlar 49)	1440	3620	124	2.2	−2.0 longitudinal 59 radial	0.35
Aramid (Kevlar 149)	1440	3450	175	1.4	−2.0 longitudinal 59 radial	0.35
Aramid (Technora H)	1390	3000	70	4.4	−2.0 longitudinal 59 radial	0.35
Aramid (SVM)	1430	3800–4200	130	3.5	n/a	n/a
Bazalt (Albarrie)	2800	4840	89	3.1	8.0	n/a

resistance. Table 2 gives the physical and mechanical properties of the most widely used thermosets.

These are the following processes used for producing FRP structural elements (Hoffard, Malvar 2005; Banibayat 2011):

- Pultrusion involves pulling rolls of a material through a series of tooling devices, resin baths and heated dies to merge, shape and cure the resulting composite into a solid part. Pultrusion produces continuous lengths of structural shapes with constant cross-sections.
- Hand lay-up/contact moulding is used for fabricating face skin over a panel core. Resin is manually applied to the core. The assembly of pre-cured face sheets is then placed on the top of a wet corrugated sheet of the core to produce a sandwich panel. The hand lay-up method lends itself to composite fabrication and repair in the field.
- Vacuum assisted resin transfer moulding (VARTM) uses a vacuum to infuse resin into reinforcement fibres or fabrics that are placed in an evacuated mold. The mixture is allowed to cure under the vacuum. The main advantage of VARTM over pultrusion is the unlimited size and geometry possibilities of the components.
- The automated wet lay-up manufacturing process essentially consists of laying up the fibres impregnated with polymeric resin such that it yields usable composite bars when cured. FRP bars are made using a programmable arm with controlled movement in three orthogonal directions to manufacture the desired lengths to the required shape. The cost of producing FRP bars employing this method is believed to be reduced because the production method is simple and designed to reduce human involvement.

Table 2. Physical and mechanical properties of polyester, epoxy and vinyl-ester resins

Properties	Thermosetting resins		
	Polyesters	Epoxy	Vinyl-ester
Density, kg/m^3	1200–1400	1200–1400	1150–1350
Tensile strength, MPa	34.5–104	55–130	73–81
Deformation modulus, GPa	2.1–3.45	2.75–4.10	3.0–3.5
Poisson's ratio	0.35–0.39	0.38–0.40	0.36–0.39
Coefficient of thermal expansion, 10^{-6}/°C	55–100	45–65	50–75
Saturation, %	0.15–0.6	0.08–0.15	0.14–1.30

In addition to the already mentioned properties of the FRP, it is essential to secure sufficient bond strength between the reinforcement and structural elements. Depending on the application, FRP reinforcement can be categorized into two main groups: internal and external. Internal reinforcement is usually manufactured in the shape of the bars. As shown in Fig. 1, the core of the bars is made of fibres and resin and the surface might be deformed or sand-coated. The technology of surface coating is very important for bonding properties. Sand-coated surfaces often do not assure sufficient bond quality that leads to the slip of reinforcement in concrete. Therefore, the deformed surface is more prominent for structural application. Recent investigations by the authors (Gribniak *et al.* 2013; Timinskas *et al.* 2013) have revealed that grooved surface (for instance, *Schöck ComBAR*) reinforcement is characterized by the high quality (strength) of the bond. It could be explained by a well-balanced shape of the surface of the bar: the shear strength of concrete in the grooves is proportional to bar surface-to-core connection strength (Fig. 2).

Unlike internal reinforcement utilized in the production of new structures where bond quality mostly depends on the surface production technology external reinforcement is generally used for strengthening the existing structural elements. Gluing FRP sheets or strips (Fig. 3) onto damaged elements result in inadequate bond strength.

The applicability and efficiency of strengthening with FRP composites depend mainly on the material and type of the member to be strengthened. In general, the applications where accessibility conditions allow wrapping a member with FRP composites, such as FRP wrapping of RC columns, has no problem regarding a debonding issue (Buyukozturk *et al.* 2004). Considering the use of FRPs for external strengthening of the external reinforcement of other types of concrete elements, Xiong *et al.* (2007), Kim *et al.* (2008a, b), Skuturna *et al.* (2008), Diab *et al.* (2009), and Daugevičius *et al.* (2012) found that additional anchoring was essential in order to assure FRP-to-concrete bond strength.

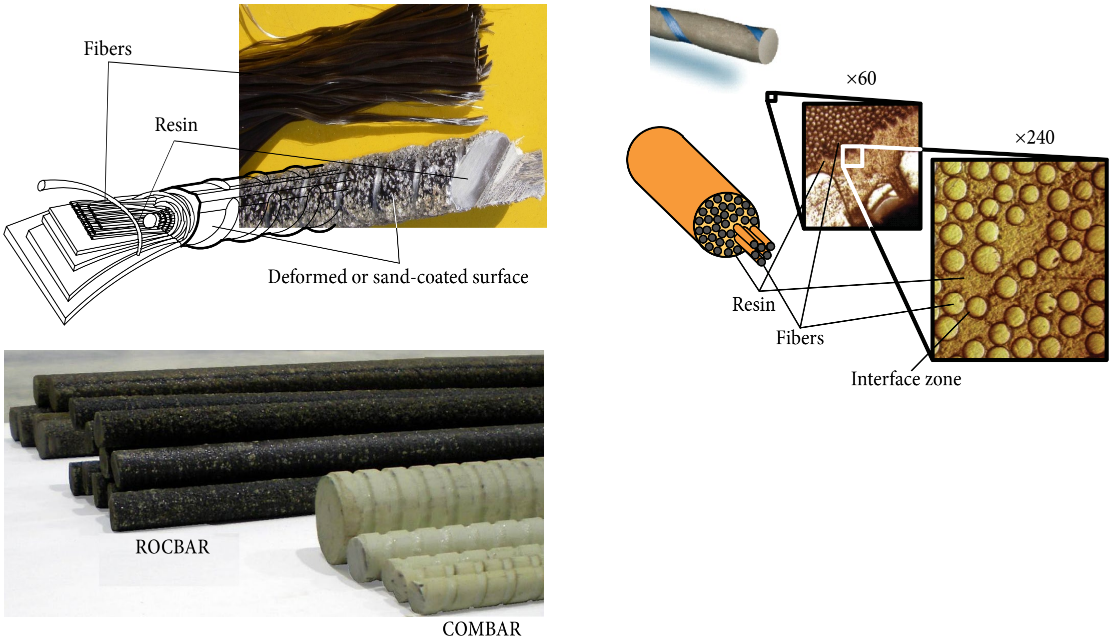

Fig. 1. The structure and coating of FRP bars

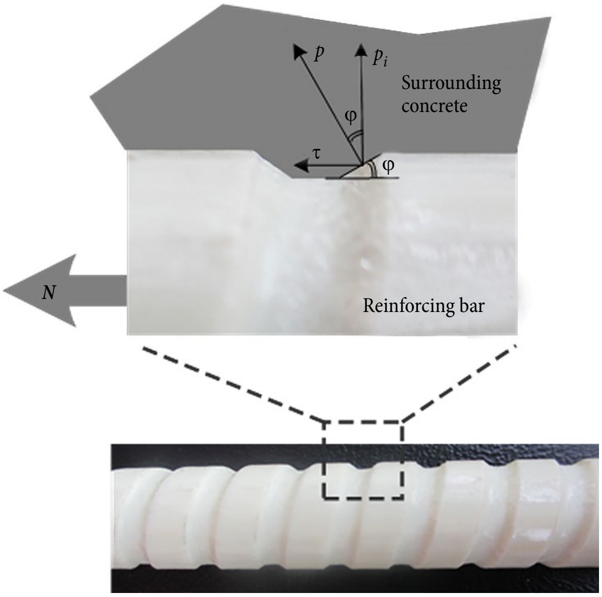

Fig. 2. Bond action of *Schöck ComBAR* reinforcement

Fig. 3. Carbon FRP sheet for external structural reinforcement (photo form http://www.fortecstabilization.com)

2. Structural applications

There is a huge variety of applications in which FRPs can be effectively used in structural engineering. FRP composites are applied both for new construction and strengthening or repairing the existing buildings. Generally, two main categories of FRP application can be defined: FRP bars, rods and tendons as an internal reinforcement as well as FRP sheets, wraps and laminates as an external reinforcement. This section outlines some of the most common uses of FRPs in civil infrastructure.

FRP reinforcing bars comprising FRP grids have been extensively used as an internal reinforcement for a number of concrete structures, including bridges, tunnels, underground precast chambers and highway pavements. FRP grids are often applied as a lightweight reinforcement in curtain walls where lower requirements for concrete cover results in thinner and lighter facade panels. Due to their excellent resistance for corrosion, the internal FRP reinforcement has been widely employed in marine structures and systems for slope protection and stability. Moreover, FRP composites are characterized by having inertness for electric-magnetic inductivity, thus, are utilized for producing maglev rails.

Another high promising potential use of FRP materials is to fabricate specific structural components entirely out of the FRP, such as bridge decks, girders, etc. or to use prefabricated FRP stay-in-place reinforcement panels for the construction of the decks of concrete bridges (Fig. 4). The replacement of conventional concrete bridge decks with FRP composite bridge decks suggests a viable solution to the rehabilitation of the existing bridges. The benefits of FRP replacement decks embrace low weight (increasing the live load capacity of the bridge structure), increased durability (highly resistant to corrosion and fatigue), lower or competitive life-cycle cost and rapid bridge construction using large prefabricated FRP reinforcements.

FRP materials are becoming increasingly popular for repairing and strengthening concrete structures. In the interest of the increased flexural strength and rehabilitation of RC elements, the technique of near surface mounted (NSM) FRP rods are used. Moreover, FRP plates or sheets are bonded to the exterior of RC members following the wet lay-up procedure that helps in increasing their bending or shear capacity (Fig. 5).

In order to increase the strength and ductility of RC columns, FRP sheets (wraps) can be applied as a confining reinforcement applied around them. Another FRP application as an external reinforcement is concrete filled FRP tubes. Furthermore, the FRP outer shell protects the concrete core from exposure to harsh environmental conditions and provides confinement to concrete thereby increasing the strength and ductility of the pile. Summarizing the major FRP application options, the utilization of FRP is classified in Table 3.

In spite of extensive attempts to apply FRP reinforcement in civil engineering, there are some aspects limiting this process. The two main reasons are as follows:

- The design guides to FRP reinforced concrete elements in the USA, Canada, Japan and Italy have been provided, though, no design codes for FRP reinforcement have been developed. Due to the absence of design codes, in most cases, the responsibility of structural safety and serviceability fully lies on the designer.
- There are not enough reliable experimental data on the long-term degradation of the mechanical properties of FRP materials. Therefore, common design practice is based on the increased values of safety factors leading to higher costs of the elements with FRP reinforcement and making such constructions economically inefficient.

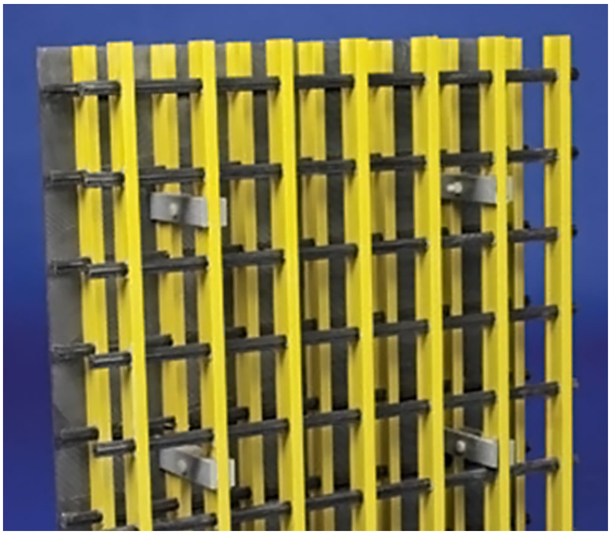

Fig. 4. Fiberglass grid form for bridge decks (photo from http://www.gefinc.com)

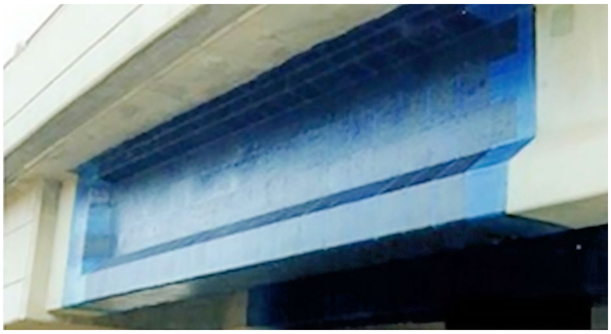

Fig. 5. Externally-bonded carbon FRP sheets for shear strengthening of a reinforced concrete bridge girder (photo from http://www.fhwa.dot.gov/everydaycounts/technology/bridges/pbeswebinartraining/s3_m9.cfm)

3. Peculiarities of structural application and design

Structural elements reinforced with FRPs may deteriorate due to environmental, physical or chemical conditions thus leading to the loss of strength and stiffness. The degree of damage and deterioration depends on a variety of factors such as the type and volume of fibres and resin matrix, the exposed environment and the manufacturing process (Malvar 1998).

Table 3. Application of internal and external FRP reinforcements

Internal			External		
Reference	Reinforcement	Application	Reference	Reinforcement	Application
Rizkalla *et al.* (1998)	One-dimensional (longitudinal) bars	Bridge deck slabs	Teng *et al.* (2007); Fam *et al.* (2003a, b)	FRP tubes (outer shells)	Precast piles, concrete-filled fender piles and columns
		Barrier walls	Shahawy *et al.* (1996a, b)	Sheets and pre-cured laminates	Flexural strengthening of slabs and beams
Cheng, Karbhari (2006); Rizkalla, Tadros (1994)	Strands and rods	Pre-stressed girders	Hutchinson *et al.* (2003); Teng *et al.* (2003)	FRP sheets	Shear strengthening of girders
Benmokrane *et al.* (2006, 2000); Lopez-Anido (1997)	Two-dimensional grids	Bridge deck slabs and deck systems	El-Hacha, Rizkalla (2004); De Lorenzis, Nanni (2002)	Near surface mounted (NSM) rods and bars	Repair of concrete bridge girders
Benmokrane (1999)		Underground structures, chambers	Ilki *et al.* (2008); Demers *et al.* (2003); Neale (2000); Seible *et al.* (1997)	Wrapping sheets, jackets	Seismic retrofit of columns and special structures
Rizkalla *et al.* (2006)	Shear stirrups	Pre-stressed girders			
Eddie *et al.* (2001)	Dowels	Highway pavements	Niroomandi *et al.* (2010); Engindeniz *et al.* (2005)	FRP sheets	Joint strengthening of RC structures
Keller (2003); Tezuka (1994); Mufti *et al.* (1991)	Prestressing tendons	Bridge cables, cable reinforcement			

Most composites exhibit long-term static strength that is significantly lower than short-term strength. For Polyester E-glass tendons, long-term static strength at 10,000 hours (about 1 year) has been reported to be 70% of short-term static strength (Wolff, Miesser 1989; Taerwe 1993). Sultan *et al.* (1995) report that the remaining strength of hand laid-up fibreglass after 10 to 15 years becomes 40% of short-term static strength. Slattery (1994) reports that long-term tests on fibreglass composites with epoxy resin showed a failure of about a half of the samples tested at the sustained stress of only 50% of ultimate after about 7 years. Some of the samples ruptured at levels as low as 33% of ultimate. According to Hawkins *et al.* (1996), E-glass composite wraps applied as confinement to circular highway columns failed in 3 years under sustained stress around 32% of the manufacturer's reported strength. For Kevlar fibres, 100-year sustained strength is around 60% of short-term strength (Taerwe 1993; Horn *et al.* 1977). Test data on carbon fibres show very few failures after several years and the sustained stress of 80% of the short-term ultimate value (Slattery 1994).

Tests on the aramid bar showed sustained to the short-term strength ratios of 75%, 70%, 60% and 50% for exposure to 20 °C air and 20 °C, 40 °C and 60 °C alkaline environments respectively (at 10,000 hours) (Scheibe, Rostasy 1995). The estimated 100-year sustained strength of an aramid rod decreased from 60% in air to 50% of short-term strength in an alkaline environment (Horn *et al.* 1977; Gerritse 1992; Gerritse, Den Uijl 1995). Dolan *et al.* (1997) found the long-term strength (at 5500 hours and for GFRP tendons embedded in concrete) of about 55% of the short-term value.

Attention should be paid to protect FRP materials, particularly glass and aramid bars, from the alkali environment in concrete. In case of CFRP, a decrease in strength and stiffness might reach about 20% (Takewaka, Khin 1996) while the type of glass fibres, resin and the manufacturing process may lower tensile capacity even in the range of 25–100% (Rostasy 1997). In addition to that, according to Nkurunziza *et al.* (2005), the reduction of strength due to alkali can be influenced by a high temperature and stress level. Another report states that a reduction in the tensile strength of 41% was observed after alkali exposure for 42 days at a temperature of 60 °C (Micelli, Nanni 2004). Regarding AFRP, the tensile strength and stiffness of AFRP rods in elevated temperature alkaline solutions either with or without tensile stress have been reported to decrease between 10–50% and 0–20% of the initial values respectively (Takewaka, Khin 1996; Rostasy 1997; Sen *et al.* 1998). Protection from the alkali environment may be assured at the manufacturing stage of FRP by using proper coating materials. However, the coated surface may be damaged under construction. Moreover, fibres are deteriorated due to chemical attack through the uncovered (by cutting) endings of the bars. Thus, the construction of the elements with GFRP or AFRP bars requires increased accuracy.

A relatively low modulus of elasticity (comparing to steel) is characteristic of the most of FRP bars (Fig. 6). This leads to smaller structural rigidity provided by these bars in respect to RC elements. Moreover, the deformation modulus might significantly decrease in time. According to Arockiasamy *et al.* (2000), an increase in deflections over the instantaneous values for a period of 470 and 610 days is up to 115% and 125% respectively.

Structural elements with FRP reinforcement with a low modulus of elasticity may not meet serviceability (limitation of strain and deflection) requirements. In order to solve this problem, the design of FRP reinforced elements often is based on the condition of relative stiffness $n_f \times \rho$ (FRP bar-to-concrete deformation modulus ratio multiplied by longitudinal reinforcement ratio) equivalent to conventionally (with steel bars) reinforced elements (Baena *et al.* 2012). As can be observed from Fig. 6, such a design, depending on the type of FRP reinforcement, may lead to 2–3 times increased cross-area of FRP bars. Consequently, this increases the cost of the structural element.

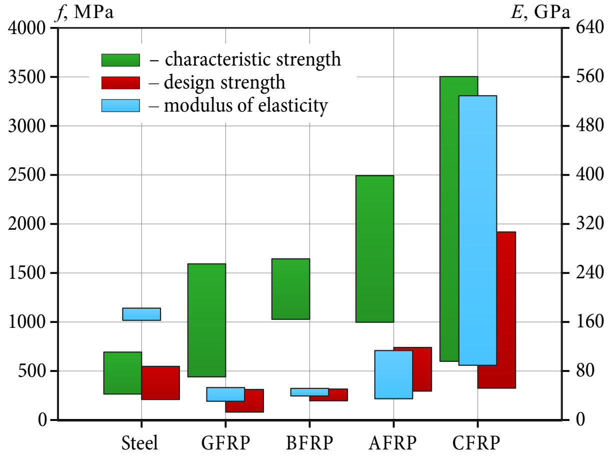

Fig. 6. Comparison of characteristic and design tensile strength and elasticity modulus of different types of reinforcement (Timinskas *et al.* 2013)

The effect of ultraviolet (UV) radiation is another aspect that is of vital importance for applying FRP composites as an external reinforcement (Bank *et al.* 1995; Odagiri *et al.* 1997). Aramids are most vulnerable to UV attack. A thin Kevlar 29 fabric exposed to Florida sun for 5 weeks lost 49% of its strength (DuPont 1992). Tests on FRP materials exposed to UV rays carried out by Kato *et al.* (1997) and Tomosawa *et al.* (1998) have shown AFRP rods having around 13% reduction in tensile strength after 2500 h of exposure, and GFRP rods experiencing 8% reduction after 500 h (no reduction thereafter). Glass and particularly carbon FRPs are less sensitive to the effects of UV radiation, though the majority of resins will be affected by UV. To prevent the effect of UV radiation, structural measures or material modifications (extra matrix additives, pigmented gel coatings, painting) are used.

Design recommendations for FRP reinforced concrete elements exist in the USA (ACI 440 2006), Canada (CSA 2010, 2012), Japan (JSCE 1997) and Italy (CNR 2007). The International Federation for Structural Concrete developed a technical report considering the application of FRP reinforcement in RC structures (FIB 2007). However, there are no design codes for such type of the reinforcement. The current European (CEN 2004), American (ACI 318 2011) and Russian (NIIZhB 2006) design codes of structural concrete are adapted to the elements reinforced with steel bars, but, may be inadequate for designing structures with composite bars.

As noted before, the lack of reliable experimental data results in the increased values of safety factors. According to ACI 440 recommendations, in order to ensure the serviceability limit state of the existing structures, a characteristic value of the tensile strength of GFRP, AFRP and CFRP has to be reduced by 80%, 70% and 45% respectively. Following the report (Schöck 2006), despite the high (well above 1000 MPa) short-term tensile strength of *ComBAR* bars, a reduction in the strength value is recommended to be 435 MPa for design purposes. For the deformation analysis of FRP RC elements, the Italian design guide (CNR 2007) applies empirical expressions from the Eurocode 2 (CEN 2004) with a multiplier that simply increases the deformations of a cracked element twofold. However, recent investigations by the authors (Gribniak *et al.* 2013) have revealed that such methodology is too rough, as deformations mainly depend on the bond properties of FRP bars embedded in concrete. Similar results were obtained by Miàs *et al.* (2013b) who investigated long-term deflections of FRP RC elements. However, it is important to note that a long-term deflection increment depended on the longitudinal reinforcement ratio growing with the increased cross-section of FRP reinforcement (Miàs *et al.* 2013a).

In fact, the design of concrete elements reinforced with FRP bars should be based on the experimental results of structural stiffness and bond properties between FRP bars and concrete. This problem can be solved by developing a standard shape of FRP bars and anchoring measures for the external reinforcement. The standardization of the shape would allow a more extensive use of FRP reinforcement in construction industry. However, having in mind that the development of the shape of steel bars took over 100 years, it is believed that the uniform methodology for FRP reinforcement would be developed in the middle of this century.

Conclusions

On the basis of the performed extensive analysis of literature sources, it can be concluded that for designing FRP RC elements, the main attention should be paid to the following factors:

1. *Long-term degradation of mechanical properties*. Depending on the type of FRP reinforcement, long-term strength might decrease two-three times (in respect to the short-term value). The maximum decrement of strength is related to GFRP; however, other fibres also are vulnerable for the time effect. Moreover, creep is characteristic for most of the polymer resins applied in FRP. Therefore, a designer should be aware of the increment of deformations in time of concrete elements with FRP reinforcement.
2. *Proper selection of FRP material under severe environmental conditions*. Most of the materials used for producing FRP are not resistant to specific environmental actions. For instance, glass fibres are not alkali-resistant; UV radiation is harmful to the mechanical properties of most of polymer resins. An adequate (in respect of the current environmental actions) selection of FRP materials would improve the exploitation properties of concrete structures.
3. *Bond properties as the governing criteria for deformational analysis*. In most cases, the design of FRP RC elements is based on the application of the increased values of safety factors. However, recent investigations by the authors have revealed that such methodology is too rough as deformations mainly depend on the bond properties of FRP composites. Thus, it can be stated that, in order to increase the effectiveness of applying structural composites, design practice has to be based on experimental tests referring to the bond properties of particular FRP materials.

The review has revealed that further research should aim at:

- experimental investigation into long-term mechanical processes taking place in concrete elements with FRP reinforcement;
- development of the standard shape of internal FRP bars and anchoring measures for external reinforcement;
- development of design procedures for the application of unified internal and external reinforcements.

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