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USE OF FRP REBARS IN REINFORCED CONCRETE STRUCTURES: AN OVERVIEW OF THE 2021 FRENCH GUIDELINE FROM AFGC

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ABSTRACT

In 2018, the French Association for Civil Engineering (AFGC) formed a dedicated working group to focus on the application of Fiber-Reinforced Polymer (FRP) bars for the internal reinforcement of concrete structures. The primary objective was to establish French recommendations by conducting a comprehensive review of existing standards and knowledge in the field. A technical report gathering those recommendations (in French) was released in 2021 and is currently undergoing translation into English. This report comprises six chapters covering various aspects, including the characterization of FRP reinforcing bars (rebars), their durability and temperature behaviors, as well as design recommendations for ultimate and serviceability limit states, encompassing flexure, shear, punching shear, fatigue, and pile reinforcement. Additionally, several case studies are presented in the Appendix.

KEYWORDS
FRP rebar; Reinforced concrete structures; Recommendations; Design rules; Mechanical and durability characterization; Quality control.

INTRODUCTION

Fiber-Reinforced Polymer (FRP) reinforcing bars (rebars), which involve the combination of continuous high performance fibers and organic matrices, present distinct benefits over conventional options such as carbon or stainless steel rebars: they are lightweight and corosion resistant, exhibit outstanding mechanical properties, and are most often non-conductive and non-magnetic. Numerous research studies, preliminary recommendations and design standards exist at both the European level (CNR-DT 203, 2006; Fib, 2007) and the international level (CSA S806-12, 2012; ACI 440.1R-15, 2014; AASHTO, 2018; ACI 440-11, 2022) regarding the utilization of these FRP rebars in reinforced concrete (RC) structures. European normalization commissions are actively involved in integrating these reinforcements into the ongoing revision of Eurocode 2. However, it is worth noting that in France, there is currently no established reference framework to guide engineering firms and project owners in incorporating FRP reinforcement into their projects. Several years ago, the French Association of Civil Engineering (AFGC) established a dedicated working group to address this matter and develop national-level recommendations. This group comprises various stakeholders, including academics, research centers, companies, project owners, engineering and inspection firms, certification bodies, and composite reinforcement manufacturers. In December 2021, the initial version of these recommendations was completed and made available. Currently, efforts are underway to translate the recommendations into English. This guide covers a range of important topics including the characterization of composite reinforcements, their durability and response to temperature variations. It also provides guidance on the design of reinforced concrete (RC) structures utilizing internal composite reinforcements, as well as information on quality control and on-site implementation, along with valuable feedback. Additionally, the guide incorporates case studies from various producers and includes several design examples that showcase the maturity of the technique. The present article aims to provide an overview of the key aspects covered in the guide. Readers are encouraged to refer to the final document (AFGC, 2021) for further information.

CHARACTERIZATION OF PHYSICAL AND MECHANICAL PROPERTIES OF FRP REBARS

The AFGC guide focuses on the use of pultruded FRP reinforcements, consisting of long fibers embedded in an organic matrix. Ensuring proper identification and traceability of the component materials is crucial.

Four main types of fibers are commonly used, namely carbon (CFRP), aramid (AFRP), glass (GFRP), and basalt (BFRP), each with different grades and corresponding properties that significantly impact the final mechanical properties of the reinforcements (see Fig. 1). The choice of fiber, along with its sizing, also influences the reinforcement's durability.

The matrix plays a vital role in facilitating force transfer between the fibers, ensuring homogeneous stress distribution throughout the reinforcement section, and providing protection against external environments. The matrices used are predominantly organic and can be categorized into two main polymer families: thermosetting (currently the most commonly used) and thermoplastic polymers. While thermoplastic matrices offer malleability at high temperatures, their application in FRP manufacturing is more challenging, and there is limited feedback on their performance.

To enhance the bond between FRP reinforcement and concrete, various techniques can be employed, including sand coating, machining, helical fiber addition, and combined treatments. It is essential to use sand coating compatible with the cementitious environment.

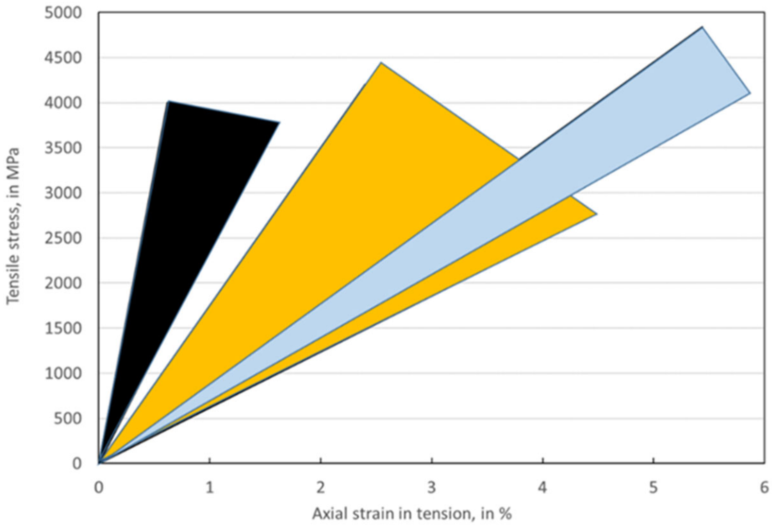

Figure 1: Tensile behavior range of the most common types of fibers used in FRP reinforcing bars (black : carbon, orange : aramid, blue : glass or basalt).

There are various manufacturing processes for composite materials, but when it comes to FRP rebars for internal reinforcement of concrete, a highly suitable and widely adopted method involves pultrusion. In this process, a bundle of fibers is pulled through a series of stages known as a "pultrusion" chain. The fibers undergo successive steps, including passing through resin baths, through a die to shape the desired section geometry, and through ovens for the polymerization (crosslinking) of the thermosetting resin. This continuous process enables the production of straight reinforcements.

As part of the pultrusion process, manufacturers apply surface treatments to improve the adhesion between FRP rebars and concrete. Figure 2 provides an overview of the surface preparations commonly used in this procedure.

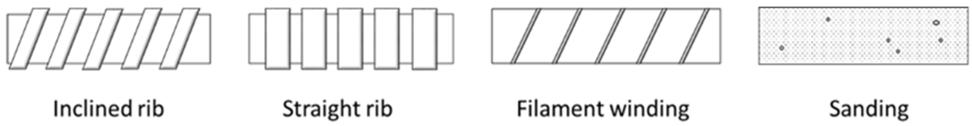

Figure 2: Examples of surface finishes commonly found on commercial-grade FRP rebars.

It's important to note that pultrusion is not suitable for the production of curved FRP rebars or reinforcements with specific anchorages. In such cases, different manufacturing processes are used. Typically, the fibers are placed on steel molds with the desired shape after passing through resin baths and dies. Subsequently, these molds are placed in ovens to initiate polymerization and achieve the final geometries of the rebars.

The first chapter of the AFGC guide focuses on the characterization of FRP reinforcements and provides a comprehensive set of methods and recommendations (test protocols, performance threshold values, etc.) covering the following parameters:

- **microstructural parameters:** mass fraction of fibers or fiber content, porosity or void content, water absorption;
- **other physical parameters:** density, effective section;
- **thermal behavior parameters:** thermal expansion coefficients (longitudinal and transverse), glass transition temperature (Tg) and degree of cure of the polymer matrix;
- **mechanical properties of the FRP reinforcements:** tensile and compressive characteristics, transverse and interlaminar shear strength, bending strength;
- **assembly properties:** bond properties at FRP/concrete interfaces, strength of couplers and anchorage systems (button-ended reinforcement or bent bar).

Considerable effort has been made to adapt North-American recommendations on final properties (minimum and maximum cross-sections; mechanical tensile properties: elastic modulus and tensile strength; minimum bending radius) to suit the diameters commonly encountered in the French market. Additionally, the guide provides detailed guidelines on how experimental investigations should be conducted.
Table 1 presents a list of the main characteristics discussed in the AFGC guide, along with the recommended determination methods and threshold values. European standards were adopted whenever available. For further details regarding specific threshold values, such as the minimum tensile strengths for straight and bent bars that vary according to the diameter, readers are encouraged to consult the AFGC guide (AFGC, 2021).

Table 1: List of the main characteristics and specifications reported in the guide (AFGC, 2021)

Characteristic/property	Symbol	Standard method	AFGC specification
Microstructural parameters			
Mass fraction of fiber or fiber content	M_f	ISO 14127: 2008 (CFRP) NF EN ISO 1172: 1999 (GFRP and BFRP)	M_f > 50%
Porosity or void content		ISO 14127: 2008	
Water absorption		NF EN ISO 62: 2008 (method 1 at 50°C)	< 1% at saturation
Other physical parameters			
Density		NF EN ISO 1183-1: 2019 (Method A)	
Effective section	$A_{PRF,\ eff}$	ISO 10406-1: 2015 (Chap. 5)	cf (AFGC, 2021)
Parameters related to the thermal behavior			

Coefficients of thermal expansion	α_T and α_L	ISO 10406-1: 2015 (Chap. 15)	$\alpha_T < 40\ 10^{-6}$
Glass transition temperature	T_g	NF EN ISO 11 357-2: 2020	$T_g > 100°C$
Degree of cure or Cure ratio	$C_{\%}$	ISO 14322: 2018	$C_{\%} > 95\%$
Parameter specific to thermoplastic FRPs			
Melting temperature	T_m	NF EN ISO 11357-3: 2018	
Mechanical properties of FRP rebars			
Tensile properties	$f_{PRF,k}$, E_{PRF}	ISO 10406-1: 2015 (Chap. 6)	$E_{PRF} \geq 45\ GPa$ (GFRP and BFRP) $E_{PRF} \geq 70\ GPa$ (AFRP) $E_{PRF} \geq 120\ GPa$ (CFRP) For $f_{PRF,k}$, cf (AFGC, 2021)
Compression properties		ASTM D695-15	
Transverse shear strength	τ_s	ISO 10406-1: 2015 (Chap. 13)	$\tau_s \geq 130\ MPa$
Interlaminar shear strength	τ_i	ASTM D4475-02: 2016	
Flexural properties		NF ISO 3597-2: 2004	
Characteristics of assemblies			
Strength of the concrete/FRP interface	τ_b	ISO 10406-1: 2015 (Chap. 7)	$\tau \geq 7.6\ MPa$
Strength of connectors		ISO 10406-1: 2015 (Chap. 8)	
Strength of FRP bars with anchor heads		ISO 10406-1: 2015 (Chap. 8)	
Strength of curved FRP bars		CSA S807-19 Appendix E	cf (AFGC, 2021)

DURABILITY, TEMPERATURE BEHAVIOR AND FIRE RESISTANCE OF FRP REBARS

Durability of FRP rebars

In general, FRP materials can experience alterations in the microstructure of the matrix, fibers, or fiber/matrix interface when exposed to external aggressive agents. These alterations can result in significant loss of mechanical performance. Additionally, medium- and long-term mechanical stresses, such as creep and fatigue, can cause damage and impact the durability of FRPs (Figure 3).

Numerous laboratory studies have focused on evaluating the durability of Glass-FRP (GFRP) bars, considered as the most economically viable material. These studies often involve accelerated aging tests, including immersion in alkaline environments that simulate the condition of early age concrete and its potential aggressiveness towards glass fibers. The findings from these studies have contributed to the development of evaluation and qualification procedures for assessing the durability of FRP reinforcements. Efforts have also been made to establish correlations between laboratory results and actual on-site aging conditions. Despite significant progress in this area (better representation of the alkaline concrete environment, consideration of creep load effects during aging), challenges still remain in proposing reliable predictive approaches for on-site degradation kinetics of FRP reinforcements. Further research is also necessary to enhance the understanding of the durability of the FRP/concrete interface.

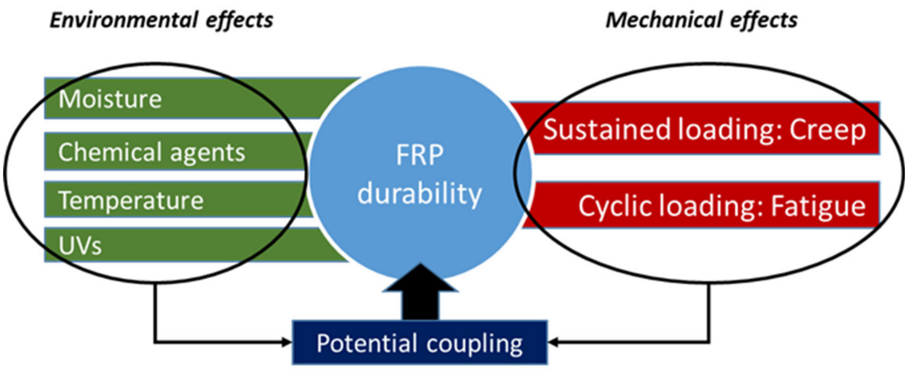

Figure 3: Synergistic effects of environmental and mechanical factors, based on (ISIS, 2007).

We now have approximately twenty years of experience with the in-situ aging of FRP rebars in concrete structures that are in service. The feedback obtained from these real-life conditions demonstrates that natural aging conditions are much less aggressive compared to accelerated laboratory aging. This emphasizes the conservative nature of the North American standards, which served as a basis for the development of the AFGC guide. Additionally, the quality of reinforcement has improved significantly since the first applications in North America. As a result, it is likely that some environmental partial safety coefficients can be revised after new investigations on longer aging periods are carried out.

In this context, the second chapter of the AFGC guide focuses on a range of characterization methods specifically dedicated to the durability assessment of FRP rebars. This chapter also provides recommendations, including test protocols and performance threshold values, in relation to fatigue, creep, and alkali resistance. Table 2 presents a compilation of the recommended experimental methods and key specifications.

Table 2: Main durability characteristics and specifications discussed in the guide (AFGC, 2021)

Characteristic/property	Standard method	AFGC specification
Fatigue strength	ISO 10406-1: 2015 (Chap. 10)	> 35% $f_{PRF,k}$ (GFRP and BFRP) ; > 45% $f_{PRF,k}$ (AFRP) ; > 75% $f_{PRF,k}$ (CFRP) ;
Creep rupture strength (in tension)	ISO 10406-1: 2015 (Chap. 12)	> 35% $f_{PRF,k}$ (GFRP and BFRP) ; > 45% $f_{PRF,k}$ (AFRP) ; > 75% $f_{PRF,k}$ (CFRP) ;
Alkali resistance in high pH solution (without load)	ISO 10406-1: 2015 (Chap. 11)	Residual tensile strength > 80% $f_{PRF,k}$; Residual interlaminar shear strength > 80% τ_i ;
Alkali resistance in high pH solution (with load)	CSA S806-12 Annex M	Residual tensile strength > 60% $f_{PRF,k}$;

Temperature behavior and fire resistance of FRP rebars

As temperature increases, FRP rebars experience a more significant decrease in their tensile mechanical properties (elastic modulus and tensile strength) compared to steel rebars. Experimental curves depicting these decreasing trends are presented in (Bisby, 2003) (Figure 4) for CFRP, AFRP, and GFRP. It should be noted that these evolutions are influenced by various factors, including the component materials (fiber and matrix type), fabrication process, and other variables. Hence, it is crucial to characterize the property evolutions over a wide temperature range for each new FRP rebar introduced to the market. Typically, the tensile strength of FRP rebars is divided by a factor of two (with respect to the reference strength at 20°C) at temperatures of around 325-350°C for CFRPs and 250-280°C for

GFRPs (Wang et al., 2005; Bisby et al., 2007). It is important to note that these temperatures are well above the glass transition temperature (Tg) of the polymer matrix. Furthermore, it appears that CFRP rebars have better fire resistance than GFRP rebars.

Limited studies have examined the impact of temperature on the FRP/concrete interface. However, it has been observed that the interfacial properties exhibit a more pronounced decrease with temperature compared to the tensile properties of the FRP itself. For instance, Solyom et al. (2020) conducted pull-out tests at different temperatures and demonstrated that the bond strength decreased by 30% near the glass transition temperature (Tg) of GFRPs, and even by 90% around 300°C (Figure 4). It is important to note that these results are influenced by factors such as the type of rebar, fabrication process, surface treatment, and concrete formulation.
Therefore, it is essential to specify a maximum service temperature when designing concrete reinforced with FRP rebars. AFGC (2021) recommends maximum service temperatures 20°C lower than the characteristic Tg of the FRP rebars, in agreement with (CSA S6-14, 2014).

Regarding fire design, similar approaches to those adopted for steel RC structures can be applied, as outlined in (ACI 440.1R-15, 2014). The Eurocode 2 approach defines the critical temperature as the temperature at which the FRP's tensile strength decreases by 50%. Additionally, it is essential to ensure that anchorage zones are located in areas with low risks of fire exposure.

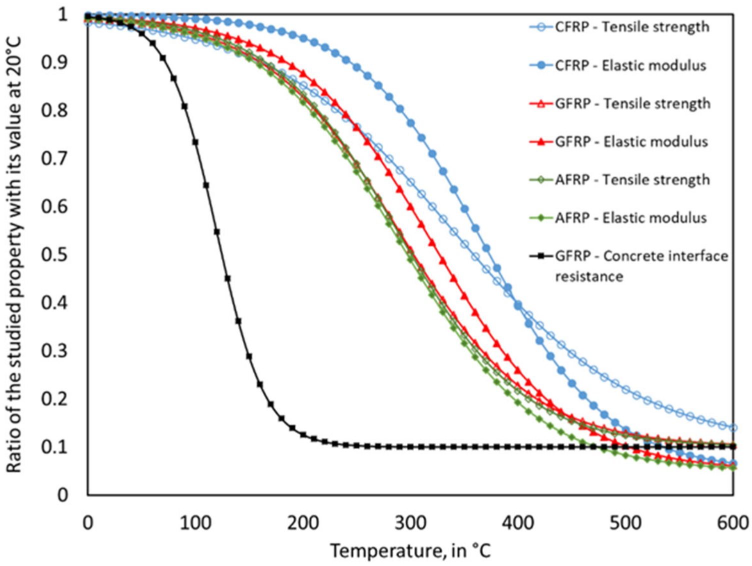

Figure 4: Variations in tensile properties of CFRP, AFRP, and GFRP rebars, as well as changes in GFRP/concrete bond strength with temperature, according to (Bisby, 2003) (Solyom et al., 2020).

DESIGN OF CONCRETE STRUCTURES REINFORCED WITH FRP REBARS

The third chapter of the guide presents a comprehensive set of design methods covering various aspects, including:

- the determination of an appropriate cover thickness for the reinforcement;
- the establishment of safety coefficients for calculating strength design values, including partial safety factors that vary depending on the type of loading and environmental factors based on exposure class and fiber type;
- justifications in bending, considering both ultimate and serviceability limit states with regards to stresses, deflections, and crack openings;
- justifications with respect to shear forces;
- reinforcement design for columns subjected to simple compression or combined bending;
- verification of slab resistance against punching shear;
- verifications with respect to fatigue;

- specific constructive provisions for each type of loading, such as reinforcement ratios, rebar spacing, diameters,…;
- general recommendations for anchorage length and lap length.

These design methods provide guidance for incorporating FRP reinforcement effectively and safely in RC structures.

The recommendations provided in each section of the guide are based on the general methodology outlined in Eurocode 2, with adaptations specifically tailored to the use of FRP reinforcements. These adaptations take into account guidelines from various sources, including (CSA S806-12, 2012), (CSA S6-14, 2014), (AASHTO, 2018), (CNR DT 203, 2006), and (ACI 440.1R-15, 2014). It is important to note that due to the brittle elastic behavior of FRP reinforcements, it is not recommended to consider plastic redistribution within the structure. Additionally, the contribution of compression reinforcements can be neglected in the design justifications for limit states.
The guide includes three comprehensive design examples that are developed with detailed design considerations. These examples cover a simply supported T-beam (Figure 5), a retaining wall, and an above-ground parking column. An important observation, supported by existing literature, is that for the first two cases, the serviceability limit states tend to be critical in concrete structures reinforced with FRP bars. These serviceability limit states commonly involve considerations such as crack opening and deflection. This differs from structures reinforced with steel, where the ultimate limit states usually govern the design considerations.

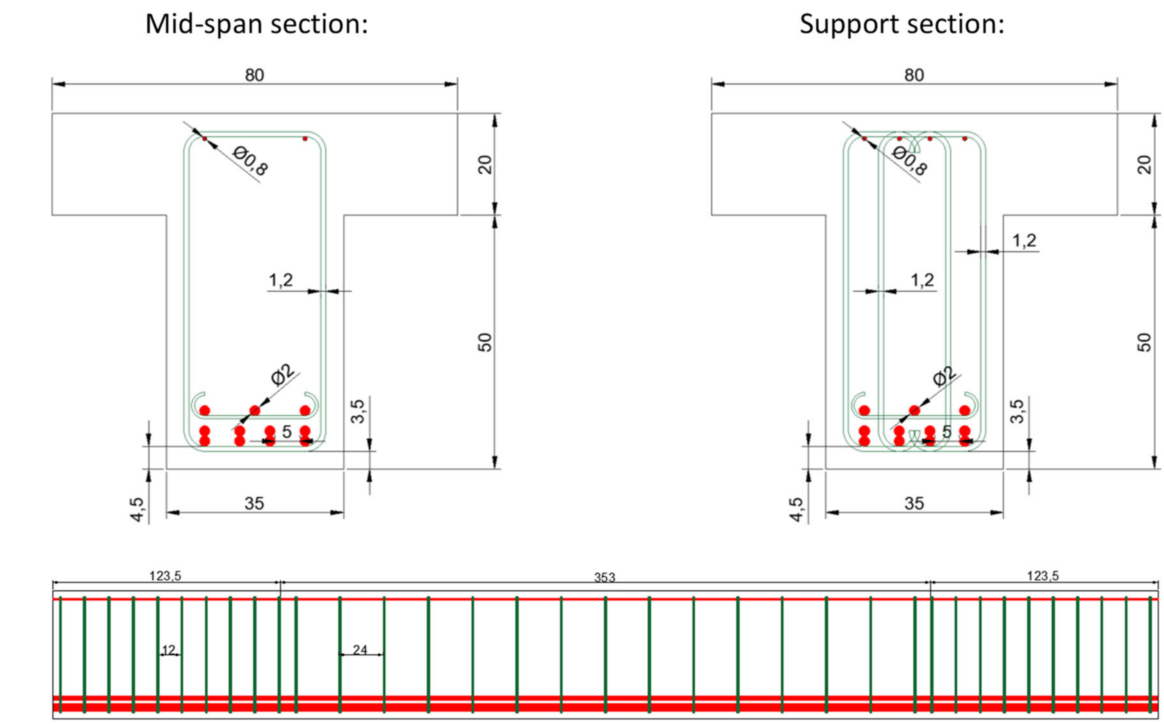

Figure 5: Arrangement of longitudinal and transverse FRP reinforcements (shear force) in the T section of the beam studied at mid-span and on support, extracted from the example of (AFGC, 2021).

QUALITY CONTROL AND ON-SITE APPLICATION

Currently in France, there is no established regulatory framework for certifying FRP reinforcement or affixing a CE or NF marking, similar to the case of steel reinforcements that are certified under AFCAB (independent body for certification). This limitation hinders the broader adoption and development of FRP rebar technology. Nevertheless, the recommendations presented in the guide align with the quality control practices followed in Europe for construction products, as outlined in the EU Construction Products Regulation No. 305/2011 (CPR) (EU, 2011).

The approach proposed in the guide involves:

- initial evaluation of the essential characteristics of the FRP reinforcement, where performance levels associated with each essential characteristic are determined. This evaluation is typically conducted through testing, under the responsibility of an external assessment body;
- ongoing evaluation and verification of performance consistency through the implementation of a control program. This control program outlines the responsibilities of the producer in terms of internal factory production control, as well as the tasks assigned to an external control body, including periodic audits and sample testing.

The guide's final chapter provides recommendations for internal or third-party evaluation programs, encompassing aspects such as defining production lots, identifying characteristics to be determined, specifying evaluation methods, determining the number of samples and testing frequency.

Additionally, the guide offers guidance on storage, handling, and on-site implementation of FRP reinforcement. These recommendations aim to ensure proper practices are followed throughout the lifecycle of FRP reinforcement, promoting its reliable and effective use in construction projects.

CONCLUSIONS

The purpose of the developed guide (AFGC, 2021), as briefly introduced here, is to provide support to engineers and design offices involved in the design and verification of concrete structures reinforced with FRP rebars. At this stage, the guide offers recommendations and does not have any normative intent. However, it should be noted that in Europe, standards are being developed regarding the design and certification aspects, including CE marking. Therefore, the AFGC guide may undergo revisions based on the progress of ongoing European standards and associated techniques.

Furthermore, efforts are underway to assess the environmental impact of FRP reinforcements. An overview of this subject is presented at the end of the guide and summarized in Table 3. It is interesting to note that GFRP and BFRP reinforcement have a lower impact on global warming than do CFRP and AFRP reinforcement. Additionally, the choice of matrix material significantly influences the overall environmental impact of these reinforcements. While the impact of GFRP reinforcements per unit of mass is higher than that of steel reinforcements, it is important to consider that the density of FRP reinforcements is much lower than that of steel reinforcements, as shown in Table 4. On the other hand, when considering impact per unit of volume, GFRP and BFRP exhibit lower environmental impacts than steel. Similar findings have been confirmed in (Seacon, 2015) for various environmental impacts, such as global warming, acidification, photochemical oxidation potential, and eutrophication. However, further studies are needed to validate the databases used and enable comparisons at the scale of global projects, considering that the reinforcement ratio strongly depends on the component materials of the FRP rebar.

Table 3: Literature review on CO_2 emission and potential for soils and water acidification associated with various materials

Material	References	Impact on global warming	Soils and water acidification potential
Steel	(Inman et al., 2016), (Stoiber et al., 2020), (Perier et al., 2013)	0.8-2.8 (kgCO_2eq/kg)	16.7-27.3 (MJ/kg)

Concrete	(Stoiber et al., 2020), (Perier et al., 2013)	232-431 ($kgCO_2eq/m^3$)	845-1567 (MJ/m^3)
Carbon fiber	(Stoiber et al., 2020), (Perier et al., 2013), (Duflou et al., 2012)	11.4-31 ($kgCO_2eq/kg$)	265-704 (MJ/kg)
Aramid fiber	(Barker et al., 2016)	19.7 ($kgCO_2eq/kg$)	-
Glass fiber	(Duflou et al., 2012)	2.6 ($kgCO_2eq/kg$)	45 (MJ/kg)
Epoxy resin	(Inman et al., 2016), (Stoiber et al., 2020), (Duflou et al., 2012)	4.7-8.6 ($kgCO_2eq/kg$)	76-137 (MJ/kg)
GFRP	(Perier et al., 2013), (Barker et al., 2016)	2.6-4.8 ($kgCO_2eq/kg$)	-
BFRP	(Inman et al., 2016)	2.6 ($kgCO_2eq/kg$)	-
CFRP	(Stoiber et al., 2020), (Barker et al., 2016)	18.4-31 ($kgCO_2eq/kg$)	281-301 (MJ/kg)

Table 4: FRP rebar's densities [kg/m^3] *(Fib, 2007) ** (Brozda et al., 2017)

FRP	CFRP *	AFRP *	GFRP *	BFRP **	Steel *
Density	1430-1670	1300-1450	1730-1760	1990-2260	7850

In order to enhance the recommendations provided in the AFGC guide, it is crucial to conduct further research in various areas related to FRP reinforcements. The identified areas requiring additional investigation include, but are not limited to:

- additional studies on the environmental and mechanical durability of these FRP reinforcements, including creep, fatigue, durability in alkaline environments, and combined effects, are necessary to refine the proposed safety coefficients and verify the adequacy of the evaluation methods;
- research on the fire behavior and post-fire behavior of these reinforcements is required;
- the development of couplers and anchoring systems for all geometries is needed

With respect to the design of concrete structures reinforced with FRP rebars, the following additional studies are recommended:

- more research on the behavior under shear force, including straight reinforcements, bent reinforcements, and systems with anchoring heads, as well as punching shear effects;
- studies on the behavior of FRP reinforcements in compression zones to improve recommendations in flexure;
- investigation of the use of mixed reinforcement (FRP and steel);
- work on the seismic behavior of these structures to study dissipation mechanisms and their reversibility.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to the work presented in this paper.

DATA AVAILABILITY

The complete data on which this paper is based can be found in (AFGC, 2021).

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