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Use of FRP rebars in reinforced concrete structures: overview of the French AFGC guidelines

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ABSTRACT

In 2018, the French Civil Engineering Association established a dedicated working group focused on the utilization of Fiber-Reinforced Polymer (FRP) bars for internal concrete reinforcement. The group's objective was to formulate French recommendations by scrutinizing existing standards and knowledge in the field. A technical report was published in 2021, followed by the release of an English version in 2023. Comprising six chapters, this report covers the characterization methods of FRP bars, their durability and temperature behavior, in addition to providing design recommendations for ultimate and serviceability limit states (encompassing bending, shear, punching shear, fatigue and creep). The present technical note highlights key aspects of the AFGC guide which is currently serving as a reference document for design offices and construction companies in France.

INTRODUCTION

Fiber-Reinforced Polymer (FRP) reinforcing bars (rebars), which combine continuous high-performance fibers with organic matrices, offer notable advantages over traditional options like carbon or stainless steel rebars. They are lightweight, corrosion resistant, possess excellent mechanical properties, and are often non-conductive and non-magnetic. Extensive research studies and preliminary recommendations are already available at the European ([CNR-DT203 2006](#)) ([FIB 2007](#)) and international levels ([CSA-S806-12 2012](#)) ([ACI440.1R-15 2014](#)) ([AASHTO 2018](#)) ([ACI440-11 2022](#)) regarding their application in reinforced concrete (RC) structures. The European Normalization Commissions are actively incorporating these FRP reinforcements into the ongoing revision of Eurocode 2.

Recognizing the significance of FRP rebars, the French Civil Engineering Association (AFGC) established a working group to develop national-level recommendations, engaging stakeholders such as academics, research centers, companies, project owners, and manufacturers. The French version of the recommendations was completed in 2021 and the document was made available in English in 2023.

CHARACTERIZATION OF PHYSICAL AND MECHANICAL PROPERTIES OF FRP REBARS

Current literature primarily focuses on four types of FRP rebars distinguished by the fibers used: carbon (CFRP), aramid (AFRP), glass (GFRP), and basalt (BFRP). The prevailing matrices employed are typically vinylester or epoxy. Various techniques have also been explored to improve the bond between FRP reinforcement and concrete, encompassing sand coating, machining, the incorporation of helical fibers, and combined treatments.

In this context, the initial chapter of the AFGC guide provides comprehensive methods and recommendations for characterizing diverse aspects of FRP rebars, including density, effective

section, microstructural parameters, thermal behavior parameters and mechanical properties, as well as assembly properties. The chapter also addresses experimental protocols for assessing crucial factors such as the fiber mass fraction, porosity, water absorption and thermal expansion coefficients of the FRP rebars, as well as the glass transition temperature and degree of cure of the thermosetting matrix. Bond properties at FRP/concrete interfaces and anchorage systems are also examined in this section.

The AFGC guide was formulated to harmonize North American final properties—including minimum and maximum cross sections, modulus of elasticity, tensile strength, and minimum bending radius—with the dimensions (diameters of rebars) prevalent in the French market. Table 1 outlines key material properties, recommended determination methods, and proposed specifications. European standards are used whenever available. Additionally, the guide offers comprehensive instructions for conducting experimental investigations.

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

Characteristic/property	Symbol	Standard method	AFGC specification
<i>Microstructural parameters</i>			
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
<i>Other physical parameters</i>			
Density		NF EN ISO 1183-1: 2019 (Method A)	
Effective section	$A_{PRF, eff}$	ISO 10406-1: 2015 (Chap. 5)	AFGC, 2021
<i>Parameters related to the thermal behavior</i>			
Coefficients of thermal expansion	α_T and α_L	ISO 10406-1: 2015 (Chap. 15)	$\alpha_T < 40 \cdot 10^{-6}$
Glass transition temperature	T_g	NF EN ISO 11 357-2: 2020	$T_g > 100^\circ\text{C}$
Degree of cure or Cure ratio	$C\%$	ISO 14322: 2018	$C\% > 95\%$
<i>Parameter specific to thermoplastic FRPs</i>			
Melting temperature	T_m	NF EN ISO 11357-3: 2018	
<i>Mechanical properties of FRP rebars</i>			
Tensile properties	$f_{PRF,k}$, E_{PRF}	ISO 10406-1: 2015 (Chap. 6)	$E_{PRF} \geq 45 \text{ GPa}$ (GFRP and BFRP) $E_{PRF} \geq 70 \text{ GPa}$ (AFRP) $E_{PRF} \geq 120 \text{ GPa}$ (CFRP) For $f_{PRF,k}$ see (AFGC, 2021)
Compression properties		ASTM D695-15	
Transverse shear strength	τ_s	ISO 10406-1: 2015 (Chap. 13)	$\tau_s \geq 130 \text{ MPa}$
Interlaminar shear strength	τ_i	ASTM D4475-02: 2016	
Flexural properties		NF ISO 3597-2: 2004	
<i>Characteristics of assemblies</i>			
Average bond strength at the concrete/FRP interface	τ_b	ISO 10406-1: 2015 (Chap. 7)	$\tau \geq 7.6 \text{ MPa}$

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	AFGC, 2021

DURABILITY, TEMPERATURE BEHAVIOR AND FIRE RESISTANCE OF FRP REBARS

The second chapter of the AFGC guide deals with the durability assessment of FRP rebars, highlighting the effects of external aggressive agents (moisture, alkalinity, etc.) and mechanical stresses (creep, fatigue, etc.) on their long-term performance. Overall, field investigations documented in the literature cover FRP-reinforced structures exposed for up to 20 years, revealing no significant damage to the FRP rebars. In contrast, accelerated aging tests conducted through immersion in alkaline environments reveal more adverse effects, yet they may not accurately reflect real-world service conditions.

In this context, the guide provides recommendations on test protocols and performance limits for fatigue, creep, and alkali resistance.

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 sustained load)	CSA S806-12 Annex M	Residual tensile strength > 60% $f_{PRF,k}$;

The rise in temperature significantly impacts the tensile properties of FRP rebars compared to their steel counterparts. However, temperature-induced alterations in tensile properties vary based on factors such as constituent material properties and the manufacturing process. While limited studies have explored the effect of temperature on FRP/concrete bond properties, observations suggest that interface properties decline more with temperature than the tensile properties of the FRP itself. As per (AFGC 2023) guidelines, it is advised to maintain maximum service temperatures 20°C below the characteristic T_g of the FRP rebars. In terms of fire design, it is recommended to adopt comparable approaches to those employed for steel RC structures, as detailed in (ACI440.1R-15 2014). The critical temperature is defined as the temperature at which the tensile strength of the FRP decreases by 50 %. Anchorage zones must be located in areas of low fire risk.

DESIGN OF CONCRETE STRUCTURES REINFORCED WITH FRP REBARS

The third chapter of the guide provides a comprehensive set of design methods for safely incorporating FRP reinforcement into concrete structures, covering various static loading and fatigue conditions, including bending, shear, compression, and combined loading.

The guide's recommendations are based on the current version of Eurocode 2, with specific adaptations for FRP reinforcements, taking into account various existing guidelines, including (CSA-S806-12 2012), (AASHTO 2018), (CNR-DT203 2006), and (ACI440.1R-15 2014). The guide

discusses the limitations of considering plastic redistribution and compression reinforcements in the design of structures reinforced with FRP bars. It recommends excluding these scenarios in limit state design. In Ultimate Limit State (ULS) design, the design value of the tensile strength $f_{FRP,d}$ is derived from the characteristic value $f_{FRP,k}$, incorporating the partial safety factor γ_{FRP} and the environmental factor α_{FRP} as per equation (1). The prescribed values for the partial safety factor and the environmental factor are outlined in table 3. When addressing the Serviceability Limit State (SLS), it is essential to validate deflection, maximum crack width, and maximum stress values using the same criteria applied to steel rebars. Table 4 provides recommended ultimate values for these parameters.

$$f_{FRP,d} = \alpha_{FRP} \cdot \frac{f_{FRP,k}}{\gamma_{FRP}} \tag{Eq. 1}$$

Table 3: Values of the environmental factor α_{FRP} and the partial safety factor γ_{FRP} (AFGC, 2021)

Exposure class	Fiber type	α_{FRP}		γ_{FRP}
X0	Carbon	1	Persistent situations	1.3
	Aramid, Glass, Basalt	0.9		Accidental situations
XC, XD, XS, XF, XA	Carbon	0.9		
	Aramid, Glass, Basalt	0.8		

Table 4: Maximum stress and crack opening values at serviceability limit states (AFGC, 2021)

	Fibre type	Maximum stress	Exposure class	Maximum crack width
Quasi-permanent SLS	Carbon	$0.6 f_{FRP,k}$	X0	0.7
	Aramid	$0.4 f_{FRP,k}$	XC, XD, XS, XF, XA	0.5
	Glass, Basalt	$0.25 f_{FRP,k}$		
Characteristic SLS	Carbon	$0.7 f_{FRP,k}$		
	Aramid	$0.55 f_{FRP,k}$		
	Glass, Basalt	$0.55 f_{FRP,k}$		

The guide illustrates three design examples, including a double-span T-beam (Figure 1), a retaining wall, and an above-ground parking column. It emphasizes that in concrete structures reinforced with FRP bars, serviceability limit states, such as crack opening and deflection, play a crucial role. This contrasts with steel rebars, where design considerations are primarily governed by ultimate limit states.

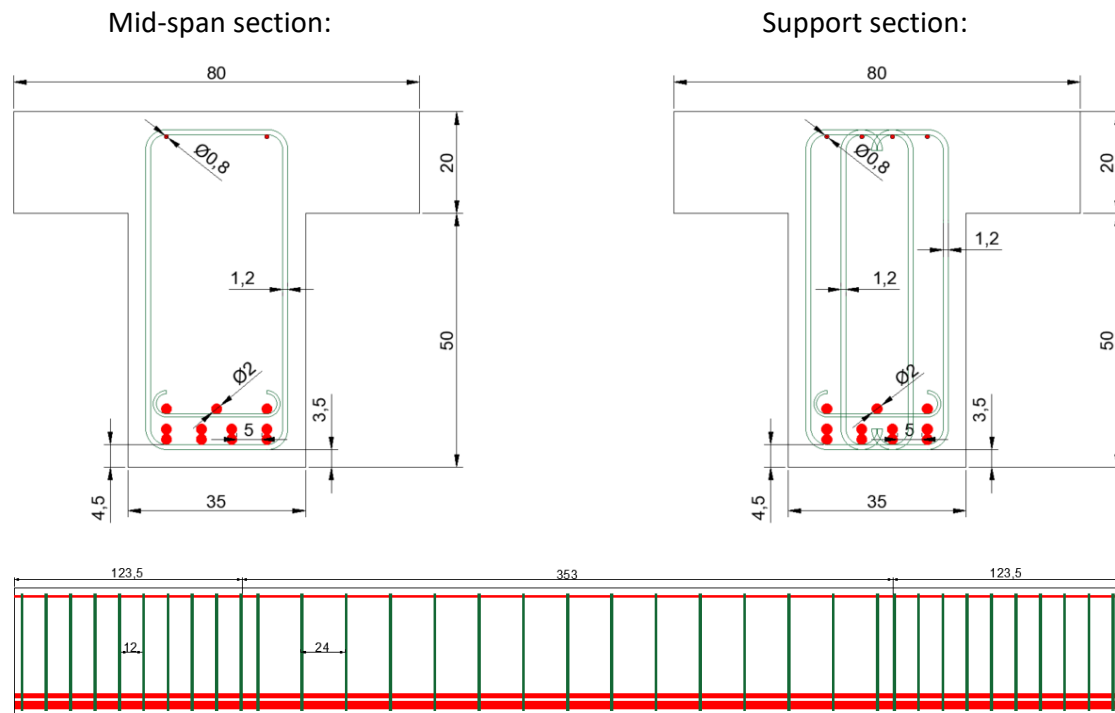


Figure 1: Configuration of longitudinal and transverse FRP reinforcements (shear force) in a T-beam: Arrangements at mid-span and on support, extracted from the example of (AFGC, 2021).

QUALITY CONTROL AND ON-SITE APPLICATION

France currently lacks a regulatory framework for certifying FRP reinforcements or for affixing CE or NF markings, posing challenges to the broader acceptance and advancement of FRP rebar technology. Nevertheless, the guide aligns with European quality control practices for construction products. This approach involves an initial assessment of essential characteristics through testing conducted under the supervision of an external assessment body. It also encompasses ongoing evaluation and verification through a comprehensive control program. This program delineates the manufacturer's responsibilities, including internal factory production control, and tasks assigned to an external control body, such as periodic audits and sample testing. Additionally, the guide offers comprehensive guidance on the storage, handling, and on-site implementation of FRP reinforcement. This ensures adherence to best practices throughout its life cycle, thereby promoting the reliable and effective utilization of FRPs in construction projects.

CONCLUSION

The developed guide (AFGC 2023) aims to assist engineers and offices engaged in the design and verification of concrete structures reinforced with FRP rebars. While the guide offers valuable recommendations, it does not have normative authority. It is important to acknowledge that standards concerning design and certification, including CE marking, are currently under development in Europe. Consequently, the AFGC guide may undergo revisions to align with the evolving European standards.

To enhance the recommendations outlined in the AFGC guide, it is essential to undertake further research in various areas related to FRP internal reinforcements. Key areas demanding additional investigations include comprehensive studies on the environmental and

mechanical durability of these FRP reinforcements, covering aspects like creep, fatigue, durability in alkaline environments, and combined effects. This aims to refine the proposed safety factors and validate the adequacy of the evaluation methods.

Research should also delve into the fire and post-fire behavior of FRP reinforcements, along with the development of couplers and anchoring systems tailored for diverse geometries.

In relation to the design of concrete structures reinforced with FRP rebars, it is recommended to conduct additional studies on their behavior under shear force. This should include examinations of straight reinforcements, bent reinforcements, and systems with anchor heads, as well as analyses of punching behavior. Furthermore, there is a need for research on the behavior of FRP reinforcements in compression zones to enhance bending recommendations. Exploration into the utilization of hybrid reinforcement (combining FRP and steel) and further investigations into seismic behavior are also necessary.

Data Availability Statement

The English version of the guide can be downloaded free of charge from the AFGC website: <https://www.afgc.asso.fr/publication/recommendations-for-the-use-of-frp-fibre-reinforced-polymer-rebars-for-reinforced-concrete-structures>

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