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ADVISORY COMMITTEE
ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION

Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars



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1 FOREWORD

The present document adds to the series of documents recently issued by the CNR on the structural use of fiber-reinforced polymer (FRP) composites, started with the publication of CNR-DT 200/2004. The documents published refer to the use of externally bonded systems for strengthening concrete and masonry structures (CNR-DT 200/2004), timber structures (CNR-DT 201/2005) and structural steel (CNR-DT 202/2005). The subject of the present document is the use of FRP bars as internal reinforcement in concrete structures.

The use of fiber-reinforced polymer composites, in substitution for steel, for concrete structural elements is a widespread practice in many countries. The peculiar characteristic of FRP materials of not being susceptible to corrosion phenomena makes their use particularly suitable in different situations.

Several international guidelines are currently available supporting the design, construction and control of such structures.

From a theoretical perspective, there are no conceptual differences in relation to the classical theory of steel reinforced concrete elements. What does need to be taken into account, is the different mechanical behavior of FRP material, whose constitutive law is fundamentally linear elastic up to failure.

There are five guidelines currently available in English, listed from the most recently issued to the most dated: the document issued by the *fib* (Task Group 9.3, 2005); the *American Concrete Institute* (ACI 440.1R-03, 2003); the two documents published in Canada (CAN/CSA-S6-02, 2002 for buildings, and CAN/CSA-S6-00, 2000 for bridges) and the Japanese document (JSCE, 1997).

A complete reference to these documents can be found in the following:

- *fib*, 2005, “FRP Reinforcement for reinforced concrete Structures”, Task Group 9.3 (*Fiber Reinforced Polymer*) Reinforcement for Concrete Structures, Lausanne, Switzerland.
- ACI 440.1R-03, 2003, “Guide for the Design and Construction of Concrete Reinforced with FRP Bars”, *American Concrete Institute*, Farmington Hills, MI, USA.
- CAN/CSA-S6-02, 2002, “Design and Construction of Building Components with Fiber-Reinforced Polymers,” CAN/CSA S806-02, Canadian Standards Association, Rexdale, Canada.
- CAN/CSA-S6-00, 2000, “Canadian High Bridge Design Code,” Clause 16.8.6, Canadian Standard Association (CSA) International, Toronto, Ontario, Canada.
- Japan Society of Civil Engineers (JSCE), 1997, “Recommendation for Design and construction of Concrete Structures Using Continuous Fiber Reinforcing Materials”, *Concrete Engineering Series* No. 23, Tokyo, Japan.

All the aforementioned documents are written using the semi-probabilistic approach for both ultimate (ULS) and serviceability (SLS) limit states.

There are several reasons that make the use of FRP bars preferable to conventional steel ones.

As above mentioned, these innovative bars are not susceptible to corrosion which makes them suitable for marine structures as well as structures exposed to harsh environments. Furthermore, glass FRP composites (GFRP) are nonconductive and therefore can be used effectively when stray currents are an issue, as in the case of structures serving rail transportation (railway or subway lines), either outdoor or in tunnels. Even bridge decks used as railway overpasses can be affected by the same phenomenon.

In the building industry, the use of this new technology can be adopted for the construction of building slabs for civil or industrial use.

The reasons that lead to choosing FRP in this case can be related not only to durability issues, but also to the possibility of taking advantage of specific properties of composite materials, such as

magnetic transparency. The latter is of fundamental importance in the construction of hospital rooms to avoid interference where Magnetic Resonance Imager (MRI) units are located.

There are further attractive and promising uses of composites materials in the building of temporary structures and tunnel coverings.

It is important that the designer be informed about both the benefits and the drawbacks of composite materials to take full advantage of the former and properly reduce the latter. This target is particularly important in order to ensure a satisfactory service life of the designed structures. In this document the most considerable aspects related to this issue will be highlighted, both in terms of design as well as construction requirements.

For a wider and more exhaustive presentation of the constitutive and rheological properties of FRP, the reader should refer to the technical document CNR-DT 200/2004 as well as specialised textbooks available.

The purpose of this guide is to provide an advisory document for the design, construction and control of concrete structures reinforced with FRP bars. The approach followed is that of the limit states semi-probabilistic method, while the format adopted is that of 'principles' and 'practical rules' in compliance with the classical style of Eurocodes.

A guideline, by its nature, is not a binding regulation, but merely represents an aid for practitioners interested in the field of composites. Nevertheless, the responsibility of the operated choices remains with the designer.

Within the seismic field, the methods assuming plastic redistribution capability are not applicable, since the mechanical behavior of concrete elements reinforced with FRP bars is essentially elastic.

Consequently, the nearly complete lack of ductility displayed by FRP reinforced concrete structures shall be taken into account.

In the case of primary structural elements subjected to seismic actions, the design spectrum shall be derived from the elastic spectrum by setting the structural factor to an appropriate value to account for the elastic behavior shown by an element reinforced with FRP bars.

This Technical Document has been prepared by a Task Group whose members are:

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1.1 PUBLIC HEARING

After its publication, this document CNR-DT 203/2006 was subject to a public hearing. Following the public hearing, some modifications and/or integrations have been made to the document including corrections of typos, additions of subjects that had not been dealt with in the original version, and elimination of others deemed not to be relevant.

This Technical Document has been approved as a final version on 18/06/2007, including the modifications derived from the public hearing, by the “Advisory Committee on Technical Recommendation for Construction”, whose members are:

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2 INTRODUCTION

(1) The subject of this document regards structures reinforced with non-prestressed FRP bars. Nevertheless, the possibility that elements of such structures have traditional steel reinforcement is also accounted for.

(2) Principles and practical rules included in this document can not be used for prestressed structures using FRP tendons.

Such applications, however, have already been developed in several countries and need specific guidance, depending mainly on both pre-stressing technology and selected anchoring device, as well as on materials properties, particularly with reference to long term effects under high stress conditions.

2.1 SYMBOLS

General notations

$(.)_c$	value of quantity (.) for concrete
$(.)_d$	design value of quantity (.)
$(.)_f$	value of quantity (.) for FRP composite
$(.)_k$	characteristic value of quantity (.)
$(.)_R$	value of quantity (.) as resistance
$(.)_S$	value of quantity (.) as demand

Uppercase Roman letters

A_b	equivalent area of FRP bar
A_c	area of concrete cross section, net of steel reinforcement
A_f	area of FRP reinforcement
A_{fw}	area of FRP shear reinforcement within spacing s
A_p	equivalent area of FRP specimen
E_c	Young's modulus of elasticity of concrete
E_f	Young's modulus of elasticity of FRP reinforcement
E_s	Young's modulus of elasticity of steel reinforcement
M_{Rd}	flexural capacity of FRP reinforced element
M_{Sd}	factored moment
R_{ck}	characteristic cubic compressive strength of concrete
T_g	glass transition temperature of resin
V_{Rd}	shear capacity of FRP reinforced element
$V_{Rd,ct}$	concrete contribution to the shear capacity
$V_{Rd,f}$	FRP contribution to the shear capacity
$V_{Rd,max}$	maximum concrete contribution to the shear capacity
V_{Sd}	factored shear force

Lowercase Roman letters

b	width of the section
d	distance from extreme compression fiber to centroid of tension reinforcement
d_b	equivalent diameter of FRP bar
f_c	(cylindrical) concrete compressive strength
f_{cd}	design compressive strength of concrete

f_{ck}	characteristic compressive strength of concrete
f_{ctd}	design tensile strength of concrete
f_{fd}	design tensile strength of FRP reinforcement
f_{fk}	characteristic tensile strength of FRP reinforcement
h	section depth
s	FRP stirrups spacing
x	distance from extreme compression fiber to neutral axis

Lowercase Greek letters

γ_m	partial factor for materials
γ_{Rd}	partial factor for resistance models
ε_c	concrete strain of compression fiber
ε_{cu}	ultimate strain of concrete in compression
ε_f	strain of FRP reinforcement
ε_{fd}	design strain of FRP reinforcement
ε_{fk}	characteristic rupture strain of FRP reinforcement
ρ_l	flexural FRP reinforcement ratio
σ_c	stress in the concrete
σ_f	stress in the FRP reinforcement
τ_{Rd}	design shear stress

3 MATERIALS

- (1) FRP composite materials considered in this document are limited to bars and grids manufactured using thermosetting resins and glass, carbon or aramid fibers.
- (2)P The mechanical properties of such materials depend mainly on both matrix and fibers type, as well as on their volume fraction.
- (3) Based on the experience and knowledge acquired, this guide is restricted to the use of bars and grids made of fiber reinforced material using thermosetting resin with a fiber volume fraction greater than 50%.
- (4)P Bond properties of FRP bars to concrete are influenced mainly by the manufacturing process as well as the characteristics of the bar surface.
- (5) In addition to the parameters characterizing the bars, the bond properties of the grids also depend on the way the grid elements are interconnected.

3.1 MANUFACTURING TECHNIQUES

- (1) The main manufacturing techniques of FRP bars and grids as well as the most popular typologies available on the market are reported in Appendix A.

3.2 CHARACTERISTICS OF FRP BARS

- (1)P The determination of both the geometrical and mechanical properties of FRP bars requires the use of specific procedures.

3.2.1 Geometrical properties

- (1)P In relation to the considerable variety of bars available on the market, also in terms of cross section geometry, it is suitable referring to an equivalent (or nominal) circular cross section, with both the diameter and area being defined properly.
- (2) One of the procedures for the evaluation of equivalent diameter and area is described in Appendix B.

3.2.2 Strength and Young's modulus of elasticity for tensile stress in the longitudinal direction (bar axis)

- (1)P Similar to pre-formed composites, FRP bars are characterized by a unidirectional array of fibers, generally having a volume fraction ranging between 50% and 70%.
Only for small diameter bars, this circumstance allows using the rule of mixtures to determine the proper values of the mechanical properties such as stiffness and strength.
However, the derived values represent only an estimation of the real values, which are often approximated to excess. In fact, these values do not take into account the influence of further significant parameters, such as the bond between the fibers and matrix, the presence of manufacturing defects and voids, as well as fiber misalignment.
- (2)P In order to evaluate the mechanical properties of the FRP bars, consideration shall be given to suitable experimental tests to obtain significant statistic values. Values provided by manufacturers shall be derived according to the principles described in Section 3.5.

(3) There are two approaches to evaluate the strength and Young’s modulus of elasticity for tensile stress in the longitudinal direction. The first is based on pure tensile tests, while the second on flexural tests carried out on bar specimens embedded in concrete beams. Although the latter generally gives higher strength values, the direct test is usually preferred from a practical standpoint. Further information is reported in Appendix B.

(4) Strength and stiffness values provided by the manufacturer shall refer to the bar equivalent area.

(5) All types of FRP bars can be used provided that the characteristic strength is not lower than 400 MPa, and the average value of the Young’s modulus of elasticity in the longitudinal direction is not lower than 100 GPa for carbon FRP bars, 35 GPa for glass FRP bars, and 65 GPa for aramid bars.

3.2.3 Coefficients of thermal expansion

(1)P The coefficients of thermal expansion of FRP bars in both longitudinal, α_l , and transversal, α_t , directions, are strictly related to those of the single phases (matrix and fibers) of the composite material.

In particular, as the volume fraction of the fibers increases, the value of α_l approaches that of the fibers; for lower volume fraction, α_l can be approximated to the coefficient of thermal expansion of the matrix.

For more in-depth indications on thermal properties of the single phase refer to the technical document CNR-DT 200/2004.

(2) Typical values of the coefficient of thermal expansion in the longitudinal and transversal directions, α_l and α_t , respectively, of composite bars with a fibers volume fraction ranging between 50% and 70%, are reported in Table 3-1.

Table 3-1 – Coefficients of thermal expansion

Bar	α_l [10 ⁻⁶ °C ⁻¹]	α_t [10 ⁻⁶ °C ⁻¹]
AFRP	-6.0 ÷ -2.0	60.0 ÷ 80.0
CFRP	-2.0 ÷ 0.0	23.0 ÷ 32.0
GFRP	6.0 ÷ 10.0	21.0 ÷ 23.0

(3)P Higher values of the transversal coefficients of thermal expansion, combined with the Poisson’s effect in the case of compressed reinforcements, can be responsible for circumferential tensile stresses that allow the formation of cracks in the radial direction (Figure 3-1).

These cracks may endanger the concrete-FRP bond with undesirable consequences on the structural behavior both under service and ultimate conditions.

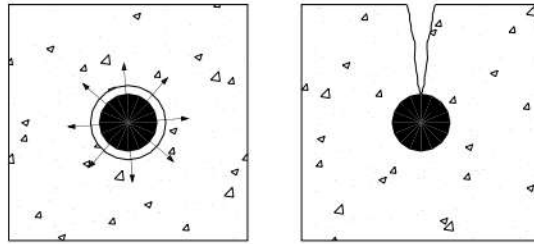


Figure 3-1– Crack induced by circumferential stresses

(4) In order to avoid the formation of such cracks either due to the FRP bar transversal expansion or slippage given by transversal shrinkage, a proper value of the concrete cover shall be considered (Section 4.11).

3.2.4 Static fatigue

(1)P FRPs are susceptible to static fatigue phenomenon (“creep rupture”), which is a progressive reduction of strength under long term loads.

Such phenomenon is also highly influenced by environmental factors, such as temperature and moisture.

(2) In order to reduce creep effects and avoid creep rupture of the FRP bars, the stress under service loads shall be controlled (Section 4.6.2).

3.2.5 Bar-concrete bond

(1)P The bond between the FRP bar and the surrounding concrete is ensured by propagation of stresses whose values depend on bar geometry, chemical and physical characteristics of its surface as well as concrete compressive strength. The latter parameter is less important for FRP bars than for steel bars.

(2) Bond characterization requires that a specific pull-out test is carried out on the bar specimens.

Bond characterization can be avoided provided that all the limitations for serviceability limit states prescribed hereafter are satisfied.

3.3 FRP GRIDS CHARACTERISTICS

(1) Geometrical and mechanical properties of grids can be derived using the same procedures shown for bars.

(2) In particular, unless more specific analyses are conducted, bond properties of FRP grids may be linked to those of the constituent bars.

3.4 TECHNICAL DATA SHEET FOR FRP BARS

(1) Manufacturers are required to provide material data sheets for the FRP bars. The structure of a material data sheet is reported in Appendix C.

3.5 CERTIFICATION AND FACTORY PRODUCTION CONTROL

(1)P FRP bars used as reinforcement in concrete structures shall undergo inspections in order to ensure a satisfactory level of both the mechanical and physical properties.

The following is required:

- The Factory Production Control (FPC) shall relate to the geometrical, mechanical (stiffness and strength) and physical properties of the FRP bars as discussed in the following Sections.
- The bar manufacturer shall use basic materials (fiber and resin) certified by their supplier.

(2)P The sampling as well as the tests on the product samples shall be regularly carried out on the manufacturing plant. Both the mechanical and physical qualification tests shall be carried out by a certified laboratory provided with the necessary equipment and experience in the characterization of composite materials. If the factory laboratory is either not available or not certified, the qualification tests shall be carried out by an external laboratory certified in the characterization of composite materials.

The mechanical characteristics, reported in the technical data sheets of the products, shall be obtained through a statistical analysis, including the characteristic values, percentile, sample mean, sample standard deviations, confidence intervals, and the number of samples tested. Suitable partial factors of the semi-probabilistic method should be employed on the characteristic evaluated values.

(3) Test methods for characterising the FRP bar mechanical properties bars are reported in Appendix C. For further requirements, international specific standards (*e.g.*, ACI, ISO and ASTM standards) are available.

3.6 ACCEPTANCE

(1) The following operators shall take part in the acceptance process of the FRP bars:

- Manufacturer;
- Designer;
- Contractor;
- Construction manager;
- Test laboratories;
- Inspector.

The tasks and responsibilities of these professionals are reported in Appendix D.

4 BASIS OF DESIGN

(1)P The design of concrete structures reinforced with FRP bars shall satisfy strength and serviceability requirements.

(2)P The design of concrete structures shall not rely upon strength and stiffness contributions provided by the compressed FRP bars.

(3)P Special care is required in the case of structural analysis, where the almost complete lack of ductility of the FRP reinforced concrete structures shall be taken into account. More specifically, the analyses assuming either the elastic or elastic-plastic redistribution capability are not applicable.

(4)P Specific fire resistance analyses of the structural element shall be performed according to current fire regulations, taking into account the value of the glass transition temperature, T_g . Some structural typologies, such as bridge decks and more generally those less susceptible to fire problems, do not require a specific fire verifications.

(5) The use of bent bars is allowed in compliance with Section 4.11.

4.1 BASIC REQUIREMENTS

(1)P Basic requirements related to the design of FRP reinforced concrete structures can be considered fulfilled when:

- Suitable materials are chosen;
- A careful choice of construction details is ensured;
- Controlling procedures for design, manufacturing, construction and use are defined.

4.2 STRUCTURE SERVICE LIFE

(1)P For the purposes of FRP design of reinforced concrete structural elements, the conventional service life and the corresponding levels of the design loads according to the current building code shall be considered.

(2)P If FRP bars are used for the construction of temporary reinforced concrete structures, the design loads and the safety assessment shall be adjusted to the structure service life (less than one year), according to specific current regulations.

4.3 DURABILITY REQUIREMENTS

(1)P The structure shall be designed by taking into account both the environmental conditions as well as the maintenance program.

(2) In order to ensure proper durability, the following should be considered:

- The intended or foreseeable use;
- The expected environmental conditions;
- The composition, properties and performance of the materials employed.

(3)P Special design problems (environmental actions, loading modes, etc.) shall be identified at the first stage of design in order to evaluate their relevance to the durability of the FRP reinforcement.

4.4 REINFORCEMENT: GENERAL PRINCIPLES

4.4.1 Introduction

(1)P Design of FRP reinforced concrete members shall be performed at both the ultimate and service limit states, as defined by the current building code.

(2) Verification of one limit state may be omitted provided that sufficient information are available to prove that it is satisfied by another one.

(3)P The following inequality shall always be met:

$$E_d \leq R_d, \quad (4.1)$$

where E_d and R_d are the factored design values of the demand and the corresponding factored capacity, respectively, within the limit state being considered.

(4) The design values are obtained from the characteristic values through suitable partial factors, to be chosen according to the current building code, or indicated in this document with reference to specific issues dealt herewith.

4.4.2 Design loads

(1) Design loads shall be chosen according to the current building code.

4.4.3 Material properties

(1)P The properties of the FRP bars shall be determined through standardized laboratory tests, such as those indicated in the present document.

(2) Strength and strain properties of the FRP bars are quantified by the corresponding characteristic values. Only the stiffness parameters (Young's modulus of elasticity) are evaluated through the corresponding average values.

(3) The design value, X_d , of the generic strength and/or strain property of a material, in particular of a FRP bar, can be expressed as follows:

$$X_d = \eta \frac{X_k}{\gamma_m}, \quad (4.2)$$

where X_k is the characteristic value of the property being considered, η is a conversion factor accounting for special design problems, and γ_m is the material partial factor.

(4) The conversion factor η is obtained by multiplying the environmental conversion factor, η_a , by the conversion factor due to long-term effects, η_l . Possible values to be assigned to such factors are reported in Table 4-1 and Table 4-2, respectively. Values obtained from experimental tests can be assigned when available. Such values are obtained by testing FRP bars to a constant stress equal

to the maximum stress at service for environmental conditions similar to that encountered by the structure in its life and by evaluating the bar residual strength over time in compliance with the standard ISO TC 71/SC 6 N.

4.4.4 Design capacity

(1) The design strength, R_d can be expressed as follows:

$$R_d = \frac{1}{\gamma_{Rd}} R\{X_{d,i}; a_{d,i}\}, \quad (4.3)$$

where $R\{\cdot\}$ is a function depending upon the specific mechanical model considered (e.g. flexure, shear) and γ_{Rd} is a partial factor covering uncertainties in the capacity model; unless otherwise specified, such factor shall be set equal to 1. The arguments of the function $R\{\cdot\}$ are typically the mechanical and geometrical parameters, whose design and nominal values are $X_{d,i}$ and $a_{d,i}$, respectively.

4.5 PARTIAL FACTORS

4.5.1 Material partial factors γ_m

- (1) For ultimate limit states, the partial factor γ_m for FRP bars, denoted by γ_f , shall be set equal to 1.5.
- (2) For serviceability limit states, the value to be assigned to the partial factor is $\gamma_f = 1$.
- (3) The partial factor prescribed by the current building code shall be assigned for concrete.

4.6 SPECIAL DESIGN PROBLEMS AND RELEVANT CONVERSION FACTORS

(1) Reference values to be assigned to the conversion factor η that affect durability and behaviour of FRP reinforced concrete members are reported in the next sections.

4.6.1 Environmental conversion factor η_a

- (1)P The mechanical properties (e.g. tensile strength, ultimate strain, and Young's modulus of elasticity) of FRP bars degrade under specific environmental conditions such as alkaline environment and moisture (water and salt added to water).
- (2) Effects of the alkaline environment. The water contained in concrete pores may be responsible for the degradation of the polymeric matrix. The damage to the polymeric matrix due to the alkali attack is typically more dangerous than that due to moisture.
- (3) Effects of moisture (water and salt added to water). The main effects of moisture absorption concern the matrix and are: plasticization, reduction of glass transition temperature, strength reduction, and stiffness reduction (less pronounced). The absorption of moisture depends on the types of polymeric matrix, the matrix-fiber interface, as well as the composition and quality of the bars.

(4) Table 4-1 shows the values to be assigned to the environmental conversion factor η_a for different types of FRP and exposure conditions.

Table 4-1 – Environmental conversion factor η_a for different exposure conditions of the structure and different fiber types.

Exposure conditions	Type of fiber / matrix*	η_a
Concrete not-exposed to moisture	Carbon / Vinylester or epoxy	1.0
	Glass / Vinylesters or epoxy	0.8
	Aramid / Vinylesters or epoxy	0.9
Concrete exposed to moisture	Carbon / Vinylesters or epoxy	0.9
	Glass / Vinylesters or epoxy	0.7
	Aramid / Vinylesters or epoxy	0.8

* The use of a polyester matrix is allowed only for temporary structures.

(5) If FRP bars are used for temporary structures (service life less than one year), the environmental conversion factor η_a can be assumed equal to 1.00.

4.6.2 Loading modes and conversion factors for long-term effects η_l

(1)P The mechanical properties (e.g. tensile strength, ultimate strain, and Young’s modulus of elasticity) of FRP bar degrade due to creep, relaxation, and fatigue.

(2) Effects of static fatigue, creep and relaxation. In FRP bars static fatigue, creep and relaxation depend on the properties of the resin and fibers. Typically thermosetting resins (vinyl esters, epoxy and phenolic resins) are less viscous than thermo-plastic resins (polypropylenes, nylon, polycarbonates, etc.). Since the presence of fibers lowers the resin creep, such phenomena are more pronounced when the load is applied transversally to the fibers or when the composite has a low volume ratio of fibers.

Static fatigue can be reduced by ensuring low serviceability stresses. Carbon FRP-based systems are the least prone to failure due to static fatigue, while aramid FRP-based systems are moderately prone, and fiberglass-based systems are the most susceptible.

Carbon and glass fibers exhibit low relaxation (3%), whereas aramid fibers exhibit larger values.

(3) Fatigue effects. The performance of FRP bars under fatigue conditions is typically good. Glass fibers are the most susceptible to this phenomenon.

(4) In order to avoid failure of FRP reinforcement under both continuous stress, and/or cyclic loading, the values that can be assigned to the conversion factor η_l are reported in Table 4-2.

Table 4-2 – Conversion factor for long-term effects η_l for different types of FRP.

Loading mode	Type of fiber / matrix	η_l	η_l
		(SLS)	(ULS)
Quasi-permanent and/or cyclic (creep, relaxation and fatigue)	Glass / Vinylesters or epoxy	0.30	1.00
	Aramid / Vinylesters or epoxy	0.50	1.00
	Carbon / Vinylesters or epoxy	0.90	1.00

4.7 FLEXURE

4.7.1 Introduction

(1) The case of uniaxial bending, e.g. when the loading axis coincides with a symmetry axis of the reinforced element cross section, is examined.

4.7.2 Analysis of the behaviour for ultimate limit state

4.7.2.1 Design basis

(1)P Design at ultimate limit state requires that the factored ultimate moment M_{Sd} and the flexural capacity M_{Rd} of the FRP reinforced concrete element satisfy the following inequality:

$$M_{Sd} \leq M_{Rd}. \quad (4.4)$$

(2)P The ultimate limit state analysis for FRP reinforced concrete sections relies on the following fundamental hypotheses:

- Cross-beam sections remain plane after deflection up to failure;
- Perfect bond exists between the FRP and concrete;
- Concrete does not react in tension;
- Contribution in compression of the FRP bars to the flexural capacity is neglected;
- Constitutive laws for concrete are accounted for according to the current building code;
- FRP is considered a linear-elastic material up to failure.

(3)P It is assumed that flexural failure takes place when one of the following conditions is met:

- The maximum concrete compressive strain ε_{cu} as defined by the current building code is reached.
- The maximum FRP tensile strain ε_{fd} is reached; ε_{fd} is computed from the characteristic tensile strain, ε_{fk} , as follows:

$$\varepsilon_{fd} = 0.9 \cdot \eta_a \cdot \frac{\varepsilon_{fk}}{\gamma_f}, \quad (4.5)$$

where the coefficient (0.9) accounts for the lower ultimate strain of specimens subjected to flexure as compared to specimens subjected to standard tensile tests, while η_a and γ_f are the defined in Table 4-1 and in Section 4.5.1, respectively.

4.7.2.2 Member flexural capacity

(1)P The evaluation of the member flexural capacity is carried out as indicated in Section 4.7.2.1.

(2) With reference to the illustrative scheme shown in Figure 4-1, two types of failure may be accounted for, depending upon whether the ultimate FRP strain (area 1) or the concrete ultimate compressive strain (area 2) is reached.

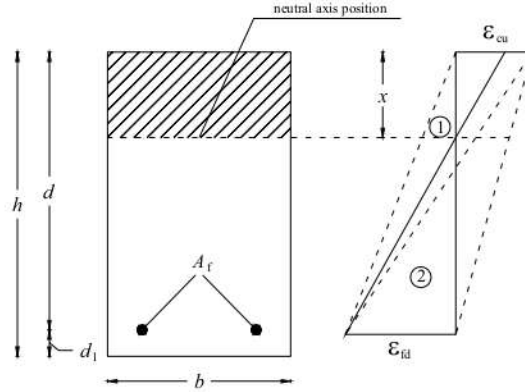


Figure 4-1 – Failure modes of FRP reinforced concrete section.

(3) Failure occurring in area 1 is attained by reaching the design strain in the FRP bars: any strain diagram corresponding to such failure mode has its fixed point at the limit value of ε_{fd} , defined by the relationship (4.5). For FRP bars arranged on multiple layers such value is referred to the centroid of the bar located farthest from the neutral axis.

From the hypothesis that a plane cross-beam section before loading remains plane after loading, the following relationship can be written:

- (concrete on compression side) $\varepsilon_c = \varepsilon_{fd} \cdot \frac{x}{(d-x)} \leq \varepsilon_{cu}$,
- (centroidal fiber of FRP bars) $\varepsilon_f = \varepsilon_{fd}$,

where ε_{cu} is the maximum concrete compressive strain and the remaining symbols are illustrated in Figure 4-1.

(4) Failure occurring in area 2 takes place due to concrete crushing, while the ultimate strain of FRP has not been attained yet: in this case the maximum concrete compressive strain ε_{cu} is reached, and the assumption of plane cross-beam section after deflection allows the calculation of the strain in the FRP bars as follows:

- (concrete on compression side) $\varepsilon_c = \varepsilon_{cu}$,
- (centroidal fiber of FRP bars) $\varepsilon_f = \varepsilon_{cu} \cdot \frac{d-x}{x} \leq \varepsilon_{fd}$,

where the symbols are illustrated in Figure 4-1.

(5) For both failure modes (neutral axis in area 1 or 2) the position x of the neutral axis is calculated based on the force equilibrium as follows:

$$N_c - N_f = 0, \quad (4.6)$$

where N_c and N_f represent compressive and tensile forces in concrete and FRP bars, respectively. The member flexural capacity M_{Rd} can be determined by summing the moments about the line of action of either the compressive or the tensile force.

- (6) Due to the FRP bars having linear elastic behaviour up to failure, their stress may be computed as the product of the pertaining strain by the FRP modulus of elasticity.
- (7) According to the current building code, design at ULS can be conducted by assuming a simplified distribution of the normal stresses for concrete (“stress block”), for elements whose failure is initiated either by the crushing of concrete or rupture of the FRP bars.

4.7.2.3 Minimum reinforcement

- (1) The amount of longitudinal FRP reinforcement in tension shall not be less than the minimum value that satisfies the following equation:

$$M_{Rd} = 1.5 \cdot M_{cr}, \quad (4.7)$$

where M_{cr} is the the cracking moment to be determined according to the current building code.

- (2) For elements that do not require shear reinforcement, sufficient longitudinal FRP reinforcement in tension shall be provided such that $\rho_l = A_f / (b \cdot d) \geq 0.01$.

4.7.3 Service limit state analysis

4.7.3.1 Design assumptions

- (1)P The present section deals with the most frequent service limit states, and particularly those relating to:

- Stress limitation (Section 4.7.3.2);
- Deflection control (Section 4.7.3.3);
- Cracking control (Section 4.7.3.4).

Other service limit states may be relevant in particular situations, even though they are not listed in this Document.

- (2)P The following items shall be checked at SLS:

- The stress level in all materials is properly limited in order to avoid FRP bars rupture under continuous stress as well as to mitigate creep phenomena in the concrete;
- Both deformations and deflections do not attain excessive values, so as to inhibit the normal use of the structure, induce damage to non supporting elements, and cause psychological disturbances to the users;
- Cracking phenomena are properly limited to not significantly affect the durability of the structures, their functionality, their aspect, and damage the integrity of the adhesive bond at the FRP-concrete interface.

- (3)P Safety checks at SLS can be carried out in the linear-elastic range, by taking into account both the behaviour of the uncracked or cracked transformed section. The stress in the materials can be evaluated by the superposition principle.

The design hypotheses are as follows:

- Linear elastic behaviour of materials;
- Plane cross-beam sections before loading remains plane after loading;

- Perfect bond exists between the concrete and FRP bars.

(4)P The first hypothesis implies the assumption of a constant Young's modulus of elasticity (in the direction of the beam axis) for each material; the second implies the linearity of the strain diagram; the third, coupled with the first, allows a proportionality ratio between the stress in the FRP reinforcement and that in a concrete fiber bonded to it ($\sigma_f/\sigma_c=E_f/E_c=n_f$).

Such ratio is called modular ratio of the FRP reinforcement with respect to concrete. It represents the stress diagram on FRP reinforced elements as a concrete transformed cross section, provided that the FRP is magnified by the coefficient n_f .

The value of n_f shall be set accounting for the evolution of creep for both short and long-term situations.

(5)P The position of the neutral axis and the moment of inertia of both uncracked and cracked transformed cross-beam sections shall be evaluated for safety checks at SLS.

(6)P In addition to applied loads, when computing stresses at SLS the effects of thermal variation, creep and shrinkage shall be accounted for.

4.7.3.2 Stress limitation

(1)P The stress in the FRP reinforcement at SLS under the quasi-permanent load shall satisfy the limitation $\sigma_f \leq f_{fd}$, f_{fd} being the FRP design stress at SLS computed by setting $\gamma_f = 1$ with the values of η reported in Section 4.6.

Stress in the concrete shall be limited according to the current building code.

4.7.3.3 Deflection control

(1)P Deflections exhibited by FRP reinforced structures shall comply with current building code requirements.

(2)P The adopted deflection model shall simulate the real behaviour of the structure. If deemed necessary, cracking shall be accounted for.

(3)P The adopted deflection model shall take into account the following:

- Appropriate concrete Young's modulus of elasticity depending upon concrete curing at the time of loading;
- Creep and shrinkage of concrete;
- Concrete stiffening between cracks;
- Thermal loads;
- Static and/or dynamic loads.

(4)P The superposition principle shall not be applied if deflections are computed using non-linear analysis.

(5) Deflection computation for FRP reinforced members can be performed by integration of the curvature diagram. Such diagram can be computed with non-linear analyses by taking into account both cracking and tension stiffening of concrete. Alternatively, simplified analyses are possible, similar to those used for traditional RC members. Experimental tests have shown that the model proposed by Eurocode 2 (EC2) when using traditional reinforced concrete members can be deemed

suitable for FRP reinforced concrete elements too. Therefore, the following EC2 equation to compute the deflection f can be considered:

$$f = f_1 \cdot \beta_1 \cdot \beta_2 \cdot \left(\frac{M_{cr}}{M_{max}} \right)^m + f_2 \cdot \left[1 - \beta_1 \cdot \beta_2 \cdot \left(\frac{M_{cr}}{M_{max}} \right)^m \right] \quad (4.8)$$

where:

- f_1 is the deflection of the uncracked section;
- f_2 is the deflection of the transformed cracked section;
- $\beta_1 = 0.5$ is a non-dimensional coefficient accounting for bond properties of FRP bars;
- β_2 is a non-dimensional coefficient accounting for the duration of loading (1.0 for short time loads, 0.5 for long time or cyclic loads);
- M_{max} is the maximum moment acting on the examined element;
- M_{cr} is the cracking moment calculated at the same cross section of M_{max} ;
- m is a coefficient to be set equal to 2.

4.7.3.4 Crack control

(1)P At SLS, crack width shall be checked in order to guarantee a proper use of the structure as well as to protect the FRP reinforcement.

(2) It is recommended to consider only permanent loading for crack control.

(3)P Under no circumstances crack width of FRP reinforced structures shall be higher than 0.5 mm.

(4)P Experimental tests on FRP reinforced members (with the exception of smooth bars) showed the suitability of the relationships provided by the EC2 for computation of both distance between cracks and concrete stiffening.

The following equation can be used:

$$w_k = \beta \cdot s_{sm} \cdot \varepsilon_{fm}, \quad (4.9)$$

where:

- w_k is the characteristic crack width, in mm;
- β is a coefficient relating average crack width to the characteristic value, to be set equal to:
 - i) 1.7 for cracking due to loads;
 - ii) 1.7 for restrained cracking in cross sections with a minimum dimension (depth, width or thickness, whichever is the least) higher than 800 mm.

- iii) 1.3 for restrained cracking in cross sections with a minimum dimension (depth, width or thickness, whichever is the least) less than 300 mm.
- iv) a linearly interpolated value between 1.3 and 1.7 for restrained cracking in sections with a minimum dimension ranging between 300 mm and 800 mm.

- s_{fm} is the final average distance between cracks, in mm;

- ε_{fm} is the average strain accounting for tension stiffening, shrinkage, etc.

(5) The final average distance between cracks can be computed using the following equation:

$$s_{fm} = 50 + 0.25 \cdot k_1 \cdot k_2 \cdot \frac{d_b}{\rho_r}, \quad (4.10)$$

where:

- k_1 is a coefficient accounting for the bond properties of the FRP bars, to be set equal to 1.6;

- k_2 is a coefficient depending upon the strain diagram (0.5 for flexure, 1.0 for pure tension);

- d_b is the equivalent diameter of the FRP bars, in mm; if bars of different diameter are used, their average value can be considered;

- ρ_r is the effective reinforcement ratio, equal to $A_f / A_{c,eff}$, where $A_{c,eff}$ is the effective area in tension defined as the concrete area surrounding the tensile FRP reinforcement, having depth equal to 2.5 times the distance between tension fiber and bars centroid (EC2).

(6) ε_{fm} can be derived using the following equation:

$$\varepsilon_{fm} = \frac{\sigma_f}{E_f} \cdot \left[1 - \beta_1 \cdot \beta_2 \cdot \left(\frac{\sigma_{fr}}{\sigma_f} \right)^m \right], \quad (4.11)$$

where:

- σ_f is the reinforcement stress in tension of the cracked cross section;

- β_1 e β_2 are coefficients defined in Section 4.7.3.3;

- σ_{fr} is the reinforcement stress in tension of the cracked cross section when the first crack is observed;

- m is a coefficient to be set equal to 2.

(7) A specific bond characterization of FRP bars for the investigation of crack control is reported in Appendix E to determine both m and k_1 .

4.8 SHEAR

4.8.1 Introduction

- (1) This document refers to shear reinforcement made of FRP stirrups perpendicular to the axis of the element.
- (2)P Shear verifications of FRP reinforced concrete members shall be carried out at ULS only.

4.8.2 Basis for design

4.8.2.1 Members without shear reinforcement

- (1) Design of slabs, plates, or frames without stirrups is permitted provided that proper transversal distribution of loads is allowed.
- (2) Shear capacity of FRP reinforced members without stirrups can be evaluated as follows:

$$V_{Rd} = \min \{ V_{Rd,ct}, V_{Rd,max} \}, \quad (4.12)$$

where $V_{Rd,ct}$ represents the concrete contribution to shear capacity, and $V_{Rd,max}$ is the concrete contribution corresponding to shear failure due to crushing of the web, as reported by the current building code.

- (3) $V_{Rd,ct}$ can be computed as follows:

$$V_{Rd,ct} = 1.3 \cdot \left(\frac{E_f}{E_s} \right)^{1/2} \cdot \tau_{Rd} \cdot k \cdot (1.2 + 40 \rho_1) \cdot b \cdot d, \quad (4.13)$$

satisfying the limitation $1.3 \cdot \left(\frac{E_f}{E_s} \right)^{1/2} \leq 1$.

The following symbols have been introduced in the equation (4.13):

- E_f and E_s , which represent the Young's moduli of elasticity of the FRP and steel bars (N/mm^2), respectively;
- τ_{Rd} , which is defined the design shear stress (N/mm^2), defined as: $\tau_{Rd} = 0.25 f_{ctd}$;
- k , which represents a coefficient to be set equal to 1 for members where more than 50 % of the bottom reinforcement is interrupted; if this is not the case, k shall be assumed as $(1.6 - d) \geq 1$, where d is in m;
- the parameter $\rho_1 = A_f / (b \cdot d)$, which shall not be assumed larger than 0.02.

4.8.2.2 Elements with shear reinforcement

- (1) Shear capacity of FRP reinforced elements using FRP stirrups can be computed using the following equation:

$$V_{Rd} = \min \{ V_{Rd,ct} + V_{Rd,f}, V_{Rd,max} \},$$

where $V_{Rd,ct}$ and $V_{Rd,max}$ have been introduced in Section 4.8.2.1, and $V_{Rd,f}$ is the FRP contribution to the shear capacity, to be evaluated as defined hereafter.

(2) $V_{Rd,f}$ can be calculated as follows:

$$V_{Rd,f} = \frac{A_{fw} \cdot f_{fr} \cdot d}{s}, \quad (4.14)$$

where A_{fw} is the amount of FRP shear reinforcement within stirrups spacing s (sum of the area of single stirrup legs), and f_{fr} is the reduced tensile strength of the FRP reinforcement, defined as $f_{fd}/\gamma_{f,\phi}$.

The partial factor $\gamma_{f,\phi}$, which further reduces the design tensile strength of FRP reinforcement to account for the bending effect, shall be set equal to:

- 2 when no specific experimental tests are performed, provided that the bend radius is not less than six times the equivalent diameter, d_b ;
- the ratio of the straight FRP bar strength to the bent FRP design strength, in all other cases (see Section 4.11).

4.8.3 Minimum shear reinforcement

(1) Where shear reinforcement is required, the minimum area of shear reinforcement shall be computed as follows:

$$A_{fw,min} = 0.06 \cdot \sqrt{f_{ck}} \cdot \frac{b \cdot s}{0.004 \cdot E_f} \quad [\text{stresses in N/mm}^2], \quad (4.15)$$

but shall not be less than $(0.35 \cdot b \cdot s)/0.004 \cdot E_f$.

4.9 SECONDARY FRP REINFORCEMENT

(1) For slabs and other two-dimensional elements calculated using a one-way approach, only primary FRP reinforcement to be placed in the main direction can be calculated. Secondary FRP reinforcement of not less than 20% of the primary reinforcement shall be placed perpendicular to the primary reinforcement.

4.10 DEVELOPMENT LENGTH

(1) The development length of FRP reinforcement shall not be less than the following:

$$l_d = 0.1 \cdot \sigma_f \cdot d_b \quad [\text{forces in N, lengths in mm}], \quad (4.16)$$

nor 400 mm.

In Equation (4.16) σ_f and d_b are the stress of the FRP bar at the end anchorage cross section and the equivalent diameter bar, respectively.

The possibility of a suitable shifting of the bending moment diagram close to the support zone, where the shear forces may induce inclined cracking, shall be taken into account in the evaluation of stress σ_f .

(2) Anchoring and lap splice of smooth FRP bars in tension is not allowed. Anchoring and lap splice of smooth FRP bars in compression can be computed as twice the value provided by the equation (4.16).

4.11 CONSTRUCTION DETAILS

(1) In addition to Section 4 item (2)P, a minimum amount of FRP reinforcement equal to: 0.3 % of the concrete area for columns reinforced with carbon FRP bars; 1.5 % of the concrete area for columns reinforced with glass FRP bars; 0.8 % of the concrete area for columns reinforced with aramid FRP bars, shall be provided.

(2) To limit the stress concentration at the bent portion of the FRP bars, the radius of the bend shall not be less than $6d_b$.

The use of lower values of the bend radius is allowed provided that:

- The manufacturer performs experimental tests (ACI 440.3R-04) in order to determine the characteristic strength of the bent portion of the specimen;
- The value of partial factor $\gamma_{f,\phi}$ to use for computation of f_{fr} shall be derived according to item (2) of Section 4.8.2.2.

(3) According to Section 3.2.3 item (4) the concrete cover d_s shall be determined as recommended in the current building code for traditional steel reinforced concrete structures. In addition, d_s shall satisfy the following limitations:

$$d_s \geq \begin{cases} 25 \text{ mm (two-ways slabs)} \\ 30 \text{ mm (one-ways slabs)} \\ 35 \text{ mm (columns)} \end{cases} \quad (4.17)$$

The threshold d_s shall be increased by 20% for concrete with $R_{ck} < 25 \text{ N/mm}^2$.

(4) FRP reinforced concrete beams shall have at least three stirrups per meter and in no case shall be $s \geq 0.8 d$ (s = stirrup spacing).

At connections of principal framing elements (such as beams and columns) and at the location of concentrated loads, for a distance equal to the effective depth of the cross section, stirrup spacing shall not exceed the least among the following:

- $d/4$,
- 12 times the minimum equivalent diameter of longitudinal FRP reinforcement;
- 15 cm.

(5) Spacing of shear reinforcement in columns shall not exceed 15 times the minimum FRP bar diameter used in the longitudinal direction, nor 25 cm.

Stirrups spacing shall be decreased at column edges for a length not less than the following:

- the larger dimension of the cross section;

- $1/6$ of net column height ($1/3$ of net column height for isostatic columns);
- 45 cm.

Along column edges the distance between stirrups shall not exceed the lesser between the following:

- $1/6$ of minimum dimension of the cross section;
- 15 cm.

5 APPENDIX A (MANUFACTURING TECHNIQUES OF FRP BARS AND GRIDS)

5.1 FRP BARS

FRP bars are available on the market as reinforcement for concrete structures (Figure 5-1). They are made of glass fibers (GFRP), carbon fibers (CFRP) or aramid fibers (AFRP), embedded in thermoset or thermoplastic resins. The use of the last ones is not included in the present document. In this guide, the main characteristics of resins are reported, whereas fibers characteristics are detailed in the technical document CNR-DT 200/2004.

FRP bars properties, such as high temperature performances, corrosion resistance, dielectric properties, flammability and thermal conductivity are mainly derived from the properties of their components.

Unsaturated polyester resins

The basic components of unsaturated polyester resins are made of orthophthalic acids, isophthalic acids or anhydrides, mixed with maleic anhydride and different glycols. Polyester resins shall have gelling and quick hardening capability. Resins with a viscosity of 100 mPas are used in pultrusion. Monomers with larger viscosity and lower reactivity can be mixed with styrene to aid the manufacturing process. Styrene level shall be such that proper reticulation without styrene residuals will occur in the composite.

Polyester resins exhibit good resistance to corrosion with respect to aliphatic hydrocarbons, water, and acid environment. They do not exhibit good resistance to aromatic hydrocarbons, ketones and concentrated acids and alkali. Highly unsaturated polyester chains can cause shrinkage up to 7% during the curing process. This can be reduced by using fillers or additives. Polyester resins show good electrical insulation and fire resistance, with bromide process or additives reducing even further flammability and smoke development.

Vinyl ester resins

Vinyl ester resins show better resistance to both corrosion and penetration of moisture, and they have good mechanical properties at elevated temperatures. They also have good resistance to interlaminar shear and impact. Their chemical structure promotes reactions at the edges of polymeric chains rather than along the chain itself, thus resulting in a stiffer internal framework. This implies lower connection density and resistance to higher temperatures.

Epoxy resins

Epoxy resins show good resistance to both moisture and chemical agents and they have good adhesive properties. They are used mainly due to their good mechanical properties, excellent electric properties, corrosion resistance and performances at elevated temperatures, up to 150°C. Epoxy resins show higher flexure and shear capacity than polyester and vinyl ester resins. They need longer curing time, therefore affecting the efficiency of the pultrusion process.

Thermoplastic resins

Composite bars using thermoplastic resins are currently being studied as they can be bent through thermal treatment even after the manufacturing process. Such resins have the capability of flowing after heating at a temperature higher than the glass transition temperature for amorphous materials, and higher than the melting temperature for semi-crystalline materials. The shape of each component may be modified by simply heating the material at a suitable temperature (hot forming).

Thermoplastic resins are generally tougher, more impact resistant and more ductile than thermosetting resins. Some resins may be characterised by higher operating temperatures and better resistance to moisture and environmental factors.

Other resin types

Other resin types are available on the market for specific applications. For example methyl methacrylate resins show excellent mechanical characteristics, low viscosity, quick reaction times, excellent resistance to fire and environmental factors.

Finally, phenolics are used due to their high resistance to both temperature and fire as well as low smoke development.

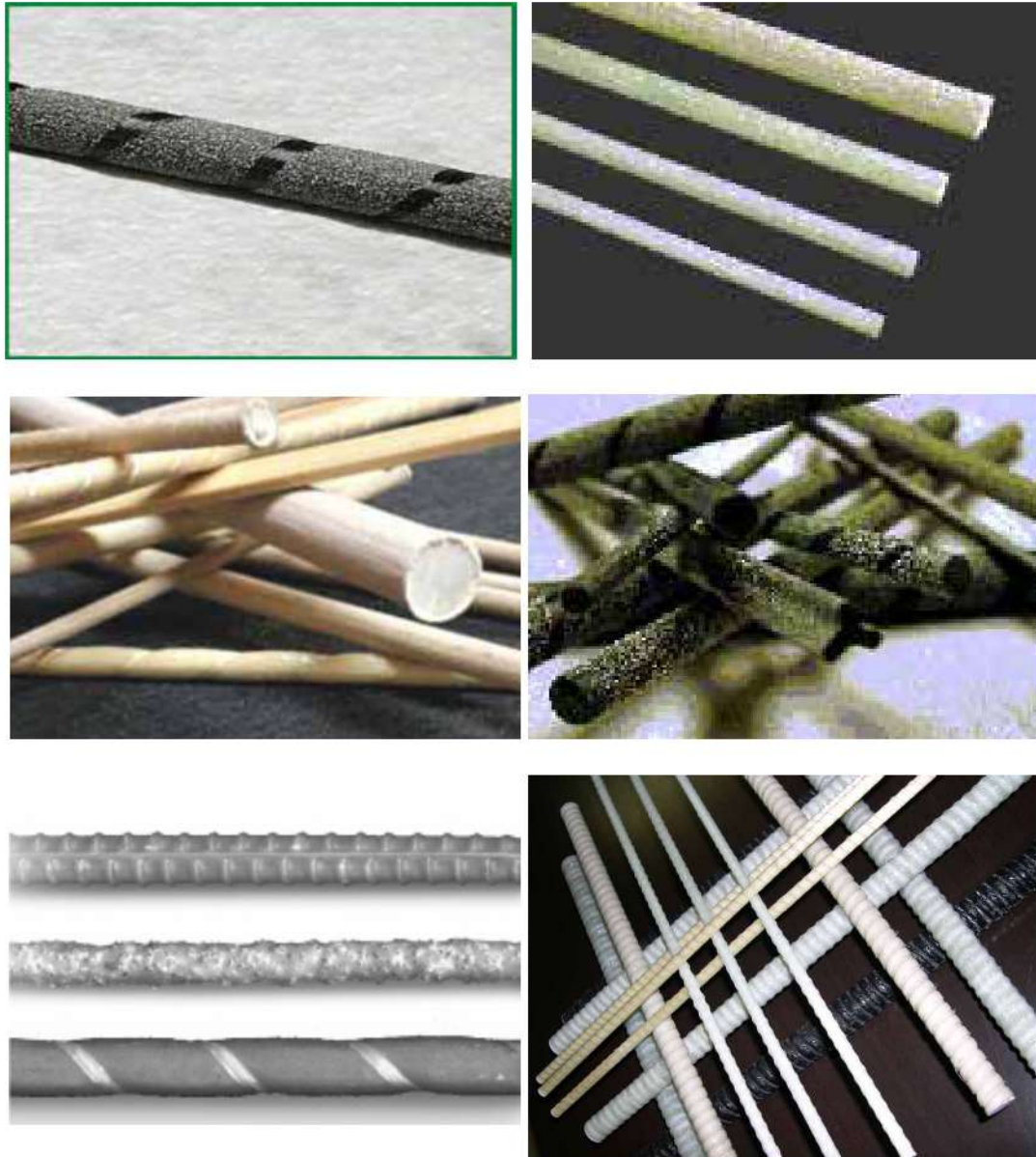


Figure 5-1 – FRP bars available on the market.

Manufacturing processes of FRP bars

FRP bars exhibit anisotropic behaviour and may have different cross sections (rectangular, circular). They are mainly produced by pultrusion (see technical document CNR-DT 200/2004), twisting or weaving of transversal fiber filaments around the cross section is usually performed for production of different systems to ensure a better bond between the FRP bar and concrete. Such bond

properties are typically made by helical-wrapping of fiber filaments around the cross section, frosting of bar surfaces or pure resin molding.

Wrapping of transversal fiber filaments around the cross section is very significant for the shear behavior of the FRP bars, which show a low resistance to interlaminar shear mainly governed by the polymeric matrix. Filaments are applied after the pultrusion process. An alternative technology using layers of *mat* (fabric made of short fibers randomly oriented) allows transversally reinforcing the bar during the pultrusion process.

In relation to steel reinforcement, FRP bars show limited applicability due to the bending difficulties when producing either stirrups or shaped pieces. Such elements can be manufactured through molding in specific machineries, but only limited shapes and dimensions can be performed at higher cost. FRP bars are currently used as straight bars or grids to build slabs, walls and diaphragms. The use of thermoplastic resins is likely to solve the aforementioned drawbacks, making FRP bars competitive with metallic bars.

Factors such as volume and fibers orientation, fibers and resins nature, dimensional effects and quality control during manufacturing play an important role in determining the properties of FRP bars.

5.2 FRP GRIDS

FRP grids are characterised by specific physical and mechanical properties: lightness, high strength and corrosion resistance.

These grids are generally adopted, either in place of or in addition to traditional reinforcement (steel bars and welded grids) for the construction of reinforced concrete elements.

A further advantage of the use of FRP grids over steel ones is represented by the possibility of being positioned closer to structural element extrados, since there is no need for a concrete cover against corrosion phenomena.

The use of FRP grids in structural elements may reduce the concrete cracking.

FRP grids are supplied on market in rolls and are characterised by fixed grid spacing and its cross sectional area.

6 APPENDIX B (TEST METHODS FOR CHARACTERISING FRP BARS)

This Appendix includes the test methods for determining the geometric and mechanical properties of FRP bars, as proposed by the ACI Committee 440 in the document entitled “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures” (2004).

6.1 METHOD FOR CALCULATING THE GEOMETRIC PROPERTIES

The following test method described is intended to determine the equivalent cross sectional area of an FRP bar.

At least five bar specimens, approximately 200 mm long, shall be used. The specimens shall be conditioned prior to test in accordance to procedure A of ASTM D 618 standard.

This procedure requires that the specimen bars with a diameter of approximately 7 mm or less are conditioned for 40 hours at 23°C with 50% relative humidity whereas those bars with a diameter greater than 7 mm shall be conditioned for 88 hours under the same conditions.

The tests shall be carried out under standard environmental conditions (at 23±3 °C and 50±10 % relative humidity) with the specimens being kept in the test environment for at least 24 hours prior to testing.

The tests consists of immersing the specimen bars in a graduated cylinder filled with either water, or ethanol if air bubbles are present on the specimen surface, and then once the bars are fully immersed, measuring the volume increase of the liquid.

The cylinder used shall be of an appropriate height in order to contain the whole bar as well as ensure that there will be no overflow once the specimen is immersed. It shall also be graduated with a maximum gradient of 10 ml.

In order to determine the equivalent cross sectional area of the tested specimen, A_p , its average length, l_p , shall be determined. The latter is assumed to be equal to the average value of the three specimen lengths, measured rotating the bar by 120° for each measure. The measurement shall be carried out using callipers with a precision of 0.025 mm.

Once the average length of the single specimen, l_p , has been calculated, its equivalent cross sectional area can be evaluated using the following expression:

$$A_p = \frac{V_1 - V_0}{l_p}, \quad (6.1)$$

where V_0 and V_1 are the volume in the cylinder before and after immersing the bar, respectively.

Once all the equivalent cross sectional areas of the specimens have been determined, the average value of these quantities, A_b , which characterises the geometry of the bar, may be evaluated. The corresponding diameter is indicated using d_b .

6.2 METHOD FOR CALCULATING THE MECHANICAL PROPERTIES

This section describes the test method intended to determine the mechanical properties of a composite bar. The test conditions are the same for the aforementioned test, with standard environmental conditions (at 23±3 °C and 50±10 % relative humidity). At least five FRP specimen bars are also required for this test, conditioned according to procedure A of the ASTM 618 (see Section 6.1). The bars must be kept in the test environment for at least 24 hours prior to testing.

The length of the specimens to be tested, l_p , shall be in compliance with the following requirements:

$$l_p \geq 100 + 2 \cdot l_a \quad [\text{length in mm}],$$

$$l_p \geq 40 \cdot d_b + 2 \cdot l_a, \quad (6.2)$$

considering that l_a and d_b , are the length of the anchorage and the bar diameter, respectively, with the latter being calculated according to Section 6.1.

The geometry of anchorage systems and, in particular, their length, l_a , shall ensure that specimen rupture occurs outside the anchorage zone, whose length is equal to, $l_p - 2 l_a$.

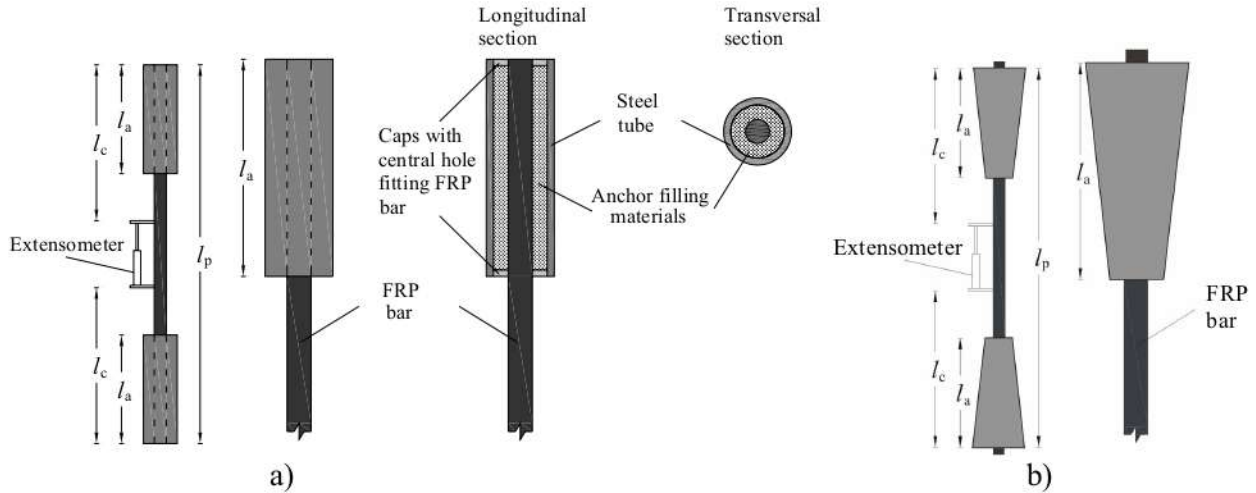


Figure 6-1 – Examples of anchorage devices: a) by using steel tubes; b) by making cone ends of bar.

The mechanical properties of bars are determined by carrying out a tensile test, conducted in load control, strain control or displacement control. The minimum resolution of the testing machine shall be of 100 N for load, 0.01‰ for strain and 0.001 mm for displacement. The rate of load or strain or displacement shall be constant during the test as well as be such that the specimen fails in 1 to 10 minutes.

The bar strain shall be measured during the test in correspondence of the mid-span cross section by using either strain gauges or extensometers.

The extensometers accuracy shall be not less than 0.02‰ of the gauge length, and it shall not be less than 8 times the specimen diameter ($8 d_b$). In reference to Figure 6-1, therefore the following inequality shall be satisfied: $l_c \geq l_a + 8 d_b$.

At the end of the test, the load-strain curve may be obtained from which the tensile strength, $f_{fu,p}$, may be calculated through the following expression:

$$f_{fu,p} = F_{fu,p} / A_b, \quad (6.3)$$

where $F_{fu,p}$ and A_b represent the recorded ultimate load and the cross sectional area of the bar, respectively. The latter is calculated according to Section 6.1.

The tensile Young's modulus of elasticity, $E_{f,p}$, shall be taken either as a linear regression of the data points from 20 to 50% of the tensile strength of the bar, or alternatively by using the simplified formula:

$$E_{f,p} = \frac{F_1 - F_2}{(\varepsilon_1 - \varepsilon_2) \cdot A_b}, \quad (6.4)$$

where F_1 and ε_1 are the load and corresponding strain, respectively, at approximately 50% of the ultimate tensile capacity, while F_2 and ε_2 , are the load and corresponding strain, respectively, at approximately 20% of the ultimate tensile capacity.

The ultimate strain of the specimen bars, $\varepsilon_{fu,p}$, shall be calculated with the following expression:

$$\varepsilon_{fu,p} = \frac{F_{fu,p}}{E_{fp} \cdot A_b} \quad (6.5)$$

Once the mechanical properties of the specimens have been determined, the characteristic values of these properties of the FRP bar may be determined according to Section 4.4.3.

7 APPENDIX C

7.1 TECHNICAL DATA SHEET FOR FRP BARS

(1) An example of a standard technical data sheet for FRP bars is proposed in the following section. It presents analogies with the data sheet proposed in the CNR-DT 200/2004 document for pre-cured systems used in external strengthening of existing structures. Technical data sheets of FRP bars available on the market can also include other information or report only a portion of those here indicated. The proposed structure is exhaustive regarding the type and amount of information given.

TECHNICAL DATA SHEET: FRP bars for reinforced concrete structures

THE MANUFACTURER SHALL REPORT THE STATISTICAL VALUES NEEDED FOR THE EVALUATION OF THE CHARACTERISTIC STRENGTHS (E.G. SAMPLE MEAN, STANDARD DEVIATION, POPULATION, PERCENTILE, CONFIDENCE INTERVAL).

Description

Commercial name, type of fiber, type of resin, manufacturing technology and any other information deemed useful

Geometrical and physical properties

Property		Measurement unit	Test method Reference standard	Note
bar cross section geometry			Appendix B	
bar equivalent area		mm ²	Appendix B	
bar equivalent perimeter		mm	Appendix B	(1)
color				
density	fiber	g/cm ³	ISO 1183-1:2004(E)	(2)
	matrix	g/cm ³		
fiber content	weight	%	ISO 11667:1997(E)	
	volume	%		
glass transition temperature of resin(T _g)		°C	ISO 11357-2:1999(E) (DSC) ISO11359-2:1999(E) (TMA) ASTM E1640 (DMA)	
maximum operating temperature		°C		
electrical conductivity		S/m		

(1) Value to be used in case of non-circular bars to determine the anchorage length.

(2) Value to be used to determine the fiber weight fraction when only the volume fraction is known or vice versa.

Properties

Property		Measurement unit	Test method Reference standard	Note
Tensile modulus of elasticity		GPa	Appendix B / ISO 527-4,5:1997(E)	
tensile strength (average and characteristic value)		MPa	Appendix B / ISO 527-4,5:1997(E)	
strain at failure		%	Appendix B / ISO 527-4,5:1997(E)	
creep			ISO 899-1:2003(E)	(3) %

relaxation (bars, cables)			(4)
bond: tangential stress (bars, cables)		pull-out test	(4)

(3) The ISO 899-1:2003(E) standard is the general reference standard for creep behaviour of FRP materials, while the ISO standard (TC71/SC6N) “Non-conventional strengthening of concrete - Test methods-Part 1: Fiber strengthened polymer (FRP) bars and grids” is under way for reinforcing FRP bars and prestressed grids, where a specific test is proposed for FRP bars (“Test Method for creep failure”). As an alternative, there is a test proposed in the document ACI 440.3R-04 “Guide Test Methods for Fiber-reinforced Polymers for Reinforcing or Strengthening Concrete Structures” named “Test Method for creep rupture of FRP bars”.

(4) In the ISO standard (TC71/SC6N) concerning FRP bars and grids the following two tests are proposed: “Test method for bond strength by pull-out testing” for bond, and “Test Method for long-term relaxation” for relaxation. Similar tests are included in the ACI 440.3R-04 document.

Storage Conditions

Description

Safety and handling

Description

8 APPENDIX D

8.1 SELECTION AND TESTING OF FRP BARS: TASKS AND RESPONSIBILITIES OF PROFESSIONALS

Manufacturers:

- Production of FRP bars as well as that of single phase (fibers and matrix) shall be subjected to a quality control program including fibers, matrices, adhesives, pre-cured composites and other constituents.
- Manufacturers shall provide test certificates for each production lot in compliance with their published literature.
- Whenever possible, each production lot shall be marked to ensure traceability. If this is not the case, each lot shall be accompanied by labels or tags reporting all the information needed for their traceability.

Designer:

- Designers shall clearly state the quality and characteristics (geometrical, mechanical, and physical) of FRP bars, specifying, if necessary, the minimum acceptance requirements.
- Designers shall specify the acceptance criteria for FRP bars, informing the construction manager of the samples to be taken and the tests to be carried out. For example, depending on the relevance of the application, designers could suggest to carry out some tests to check some or all of the mechanical and physical characteristics reported by the manufacturer in the technical data sheets.

Contractor/subcontractors:

- Shall obtain the FRP bars indicated by the designer through suppliers/manufacturers who guarantee the quality of their products.
- Shall make sure that the products are accompanied by suitable technical data sheets, reporting both mechanical and physical characteristics, and possibly by laboratory test certificates.
- Shall make sure that the products comply with the provisions indicated by the designer; if the material with the indicated requirements is not available, they shall agree with the designer upon viable alternatives.

Construction manager:

- Shall make decisions as to the acceptance of products.
- Shall check the compliance of the material with the designer's provisions.
- Shall check the origin of the supplied material. FRP bars are typically marked by the manufacturer for their identification or they have labels or tags with the necessary information for their traceability.
- Shall check the mechanical and physical characteristics of products using the test certificates provided by the manufacturer.
- Based upon the importance of the application, it may require experimental tests to evaluate both quality of materials and compliance with the values provided by the manufacturer. Such tests shall be carried out in laboratories of proven experience that are appropriately equipped to characterize FRP materials. Acceptance criteria may be based on the maximum acceptable deviation of results from the values obtained during production. In such a case, it is necessary to ensure that the test procedures are the same. In some cases, tests may be required to evaluate both mechanical and physical properties of un-conditioned and conditioned specimens to take into account temperature and moisture variation.

Test laboratories:

- Shall demonstrate experience in the experimental characterization of FRP materials.
- Shall be equipped with appropriate measurement devices and tests instrumentation.
- Shall carry out the experimental tests according to the procedures indicated in the specific standards for FRP bars.
- Shall provide detailed test reports on test instrumentation and results.
- Shall own a quality manual and carry out experimental activities according to EN-ISO17025 “General requirements for the competence of testing and calibration laboratories”.

Inspector:

- Check the quality of the materials to be in compliance with the manufacturer specifications.
- Verify that all materials used have been accepted by the construction manager.
- Check the results of experimental tests required by the construction manager, if available.

9 APPENDIX E (CALCULATING DEFLECTIONS AND CRACK WIDTHS FOR FLEXURAL ELEMENTS OF CONCRETE REINFORCED WITH FRP BARS)

This section describes the procedure to be used by the manufacturer to determine through appropriate tests the FRP bar-concrete adherence in order to accurately evaluate deflections and crack widths, as previously set out in Sections 4.7.3.3 and 4.7.3.4.

Deflections can be calculated using the following formula:

$$f = f_1 \cdot \left(\frac{M_{cr}}{M_{max}} \right)^m + f_2 \cdot \left[1 - \left(\frac{M_{cr}}{M_{max}} \right)^m \right], \quad (7.1)$$

with the quantities already having been defined in Section 4.7.3.3.

On the basis of a population of at least five elements of concrete reinforced with FRP bars, that shall be subjected to four-points bending test, deflections and crack width are measured for fixed load values, ensuring that for a single test at least five acquisitions are made over time intervals between 20% and 60% of the ultimate load.

The same load values are used to calculate the theoretical deflections starting from Equation (7.1).

The exponent, m , is determined on the basis of the comparison between the analytical and experimental results, using an appropriate statistical analysis (i.e one based on the maximum likelihood method).

Upon determining this value, the experimental values of the crack widths for the tested specimens are then compared with the corresponding theoretical values, computed according to Equation (4.9) and assuming the m value obtained for the previously mentioned procedure assigned to it as well as to the coefficients β_1 and β_2 the unitary value.

The coefficient, k_1 , as obtained from Equation (4.10), is determined through an appropriate statistical analysis, not exceeding the following limitation $k_1 \geq 0.8$.

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