Design Guidelines for the Strengthening of Existing Structures with FRP in Italy

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Synopsis: A regulatory document was issued by the National Research Council (CNR) of Italy on the use of FRP for strengthening structures: 'Instructions for Design, Execution and Control of Strengthening Interventions by Means of Fibre-reinforced Composites' (2004). Emphasis is also given to specific requirements for seismic applications.

This document, described in more details in the paper, sets for the first time in Italy some standards for production, design and application of FRP for reinforced concrete and masonry constructions. It is also conceived with an informative and educational spirit, which is crucial for the dissemination, in the professional sphere, of the mechanical and technological knowledge needed for an aware and competent use of such materials.

The document is the result of a remarkable joint effort of almost all professors and researchers involved in this emerging and promising field, from 15 universities, of the technical managers of major production and application companies, and of the representatives of public and private companies that use FRP for strengthening artifacts. Thus, the resulting FRP code naturally incorporates the experience and knowledge gained in ten years of studies, researches and applications of FRP in Italy.

Keywords: design guidelines; fiber-reinforced polymers; masonry structures; reinforced concrete structures; seismic strengthening

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INTRODUCTION

The peculiar situation of Italy with regards to the preservation of existing constructions results from the combination of two aspects: a) seismic hazard over the whole of the national territory, recently refined by a new seismic zonation, with medium-high intensity over a large portion of it, the highest expected PGA being 0.35g for a 475 years return period, and b) extreme variety of the built environment, perhaps with no comparison in the entire world.

Construction typology in Italy encompasses examples reckoned as Country's (and world's) historical, architectural and cultural heritage – which include buildings of various function and importance, such as palaces, temples, churches, cloisters, theatres, thermae, memorials, city walls, castles, simple dwellings, civil engineering works as bridges harbours and aqueducts – dating back to more than 2000 years ago, throughout the ancient- middle- modern- and contemporary ages, down to those built in the 20th century. The former are largely made of masonry, although under this name again a great quantity of techniques and materials are indicated, from those using stone of various natures, squared or not, regularly placed or loose, or clay bricks of different quality, or combinations of them, and binders extremely different in nature, in application ways and in ageing conditions. Instead, the latter mainly consist of reinforced concrete constructions, if not uniform, at least more homogeneous. This has motivated the growth of two clearly distinct fields of research and application of fiber-reinforced polymers (FRP): one for (generally old) masonry and one for (relatively recent) reinforced concrete constructions. The first one is more peculiar, apart the complexity of the subject, as masonry constructions have less alternatives of strengthening means and have received less applications and studies.

It goes without saying that for the historical, cultural and architectural heritage, the issue of structural safety is only one aspect of the wider concepts of restoration, preservation and conservation. In this respect, it should be underlined that these concepts do not allow a systematic use of innovative materials, such as FRP, for strengthening purposes, unless it is demonstrated that they comply with the strict requirements regarding formal and material compatibility. These essential considerations have such complex and articulated implications that they would deserve deeper consideration that is beyond the scope of this paper.

With the distinction in the two above described main fields of research on FRP, namely, masonry and reinforced concrete, the first studies have started in the early 90's by some pioneering groups that were striving at finding new solutions for increasing the safety of existing constructions, that could compete with the more developed and usual ones of concrete jacketing, steel plating, base isolation, and dissipative bracings.

In the last ten years the interest has spread so widely and rapidly that now FRP has become one of the most active and prolific research fields throughout the country. The most important testimony of the intense activity in Italy in the field of FRP is the recently issued regulatory document CNR-DT 200/2004 [1]: 'Instructions for Design, Execution and Control of Strengthening Interventions by Means of Fibre-reinforced Composites' (2004), under the auspices of the Research National Council (CNR).

THE NEW FRP CODE IN ITALY

The CNR-DT 200/2004: 'Instructions for Design, Execution and Control of Strengthening Interventions by Means of Fibre-reinforced Composites' (2004) is composed of the following chapters:

- Materials (with Annex),
- Basic concepts of FRP strengthening and special problems,
- Strengthening of reinforced concrete and prestressed concrete structures,
- Strengthening of masonry structures.

Materials

The chapter on materials has a prevailing informative character and contains the fundamental information needed to obtain a basic knowledge of the composite materials, of their components (fibres, matrices, and adhesives) and of their physical and mechanical properties. It also includes an annex describing the most usual production techniques and some basic notions on the mechanical behavior of composites.

The most notable aspect is that a possible classification of composites usually adopted for structural strengthening is proposed, and some appropriate criteria for product qualification and acceptance are introduced. Moreover, the concept is introduced of FRP as a strengthening *system*, enforcing all applicators to sell fiber-reinforced material and bonding agent as a certified package.

It is widely recognised that the design of a FRP strengthening system is a critical process. The various components (fibers, resin and the support) have different mechanical properties and roles but must be selected and designed to work together in a unique system. Therefore the properties of the components, their interactions and the properties of the final FRP must be well known and defined. The chapter on materials provides both general information on the mechanical, physical and chemical properties of FRP materials and indications for the qualification of the components and the systems on use in the reinforcement of civil engineering structures.

Specific sections of the chapter are dedicated to the main components, namely the fibers and the textiles, the resin and the adhesives. For each of them the main properties are discussed and some examples of the technical data sheets that should be provided with the products are reported. For all the mechanical, physical and chemical properties that must be determined or verified, reference is made to the appropriate testing procedures and the relevant European and American standards. The terms and quantities that are commonly used in the textile or chemical fields and are not familiar to civil engineers are properly explained.

An informative section is dedicated to the different reinforcing systems. The main aim is to clarify that the material properties can be referred to the total cross-sectional area for the prefabricated strips. On the contrary when in-situ resin impregnated systems are used, the final FRP thickness varies with the amount of resin and cannot be known in advance. For this reason the calculations may be based on the properties of the bare fibers but a reduction factor should be included to account for the efficiency of the system and for other detrimental variables such as the textile architecture or possible misalignments of the fibers.

It is known that conventional materials used in the civil engineering field are covered by standard specifications that both ensure the properties of the materials and provide standard procedures for the tests. The CNR –DT 200 document suggests two levels of qualification for the FRP materials that imply a set of mechanical and physical tests for the definition of short-term or long-term material properties respectively. The complete systems are also classified in two categories. In both cases all the basic components of the FRP must be tested and certified while a series of tests on the complete system in full scale and with the proper substrate must be performed for class A systems. Certified systems of this class have the advantage of being subject to less severe safety factors.

Basic Concepts

It is stated that the design of the FRP strengthening intervention must meet with the requirements of strength, serviceability and durability. In case of fire, the strengthening resistance must be adequate to the prescribed exposure time. The design working life of the strengthened structure is taken equal to that of new structures. This implies that the design actions to be considered are those of the current design codes for new constructions.

The safety verifications are performed for both the serviceability and the ultimate limit states. The format is that of the partial factor method. The design properties of both the materials and the products are obtained from the characteristic values, divided by the appropriate partial factor.

A rather innovative point (following the indications of EN 1990) is that the design properties X_d of the existing materials in the structure to be strengthened are obtained as a function of the number of tests performed to acquire information on them:

$$X_{\mathrm{d}} = \frac{\eta}{\gamma_{\mathrm{m}}} \cdot m_{\mathrm{X}} \cdot (1 - k_{\mathrm{n}} \cdot V_{\mathrm{X}}) \,, \qquad (1)$$

where η is a conversion factor, lower than 1, accounting for special design problems (related to environmental conditions and long duration phenomena), γ_m is the material partial factor, m_X is the mean value of the property X resulting from the number n of tests, the value k_n is given as a function of the number n and the coefficient of variation

V_X is supposed known. The latter can be assumed equal to 0.10 for steel, to 0.20 for concrete and to 0.30 for masonry and timber.
The partial factor γ_m for FRP at the ultimate limit states (γ_f) is taken as 1.10 under quality control and as 1.25 in other situations. Similarly, the partial factor γ_m for delamination at the ultimate limit state ($\gamma_{f,d}$) is taken as 1.20 under quality control and as 1.50 in other situations.

The design capacity is given as:

$$R_d = \frac{1}{\gamma_{Rd}} \cdot R\left\{X_{d,i}; a_{d,i}\right\} , \tag{2}$$

where $R\{\cdot\}$ is the function describing the relevant mechanical model considered (e.g., flexure, shear, anchorage, etc.) and γ_{Rd} is a partial coefficient accounting for the uncertainties in the above capacity model (equal to 1.00 for flexure, 1.20 for shear and 1.10 for confinement). The function arguments are, in general, a set of mechanical and geometrical properties, of which $X_{d,i}$ and $a_{d,i}$ are the design value and the nominal value of the i-*th* quantity, respectively.

An essential and innovative aspect is related to the safety verifications in the presence of fire. It is suggested that the load combination for exceptional situations, where E_d is the design value of the indirect thermal action due to fire, refers to the following situations:

- Exceptional event in the presence of strengthening (with E_d), in case the strengthening was designed for a predefined fire exposure time. In this case, the service actions of the frequent combination are to be considered. The elements capacity, appropriately reduced to account for the fire exposure time, should be computed with the partial coefficients relevant to the exceptional situations;
- After the exceptional event (without E_d), in the absence of strengthening. In this case, the service actions of the quasi-permanent combination are to be considered. The elements capacity, appropriately reduced to account for the fire exposure time, should be computed with the partial coefficients relevant to the service situations.

Reinforced Concrete Structures

Debonding **--** Two different collapse modes for debonding are considered: end debonding (mode I) and intermediate debonding for flexural cracking (mode II).

The optimal anchorage length of FRP strip (Figure 1) is given as (length units in mm):

$$l_e = \sqrt{\frac{E_f \cdot t_f}{2 \cdot f_{ctm}}} , \tag{3}$$

where E_f is the modulus of the FRP overlay in the fibers direction, t_f is the thickness of FRP and f_{ctm} is the concrete mean tensile strength.

The design debonding strength for end debonding (Mode I) is:

$$f_{fdd} = \frac{1}{\gamma_{f,d} \cdot \sqrt{\gamma_c}} \cdot \sqrt{\frac{2 \cdot E_f \cdot \Gamma_{Fk}}{t_f}} \quad , \tag{4}$$

$$\text{with } \Gamma_{Fk} = 0.03 \cdot k_b \cdot \sqrt{f_{ck} \cdot f_{ctm}} \quad \text{(forces in N, lengths in mm)} , \tag{5}$$

where Γ_{Fk} is the characteristic value of fracture energy of bond between concrete and FRP, k_b is a scale/covering coefficient ≥ 1, $\gamma_{f,d}$ is the delamination partial factor, and f_{ck} is the concrete characteristic strength.

The design debonding strain for intermediate debonding is:

$$\varepsilon_{fdd} = \frac{k_{cr} \cdot f_{fdd}}{E_f} , \tag{6}$$

where k_{cr} is a coefficient assumed equal to 3.0.

Flexure -- The flexural capacity is attained when either the concrete compressive strain reaches its ultimate value or when the FRP tensile strain reaches its ultimate value $\varepsilon_{fd} = \min(\eta_a \varepsilon_{fu}/\gamma_f, f_{fdd}/E_f)$ where the first value corresponds to failure and the second to the design debonding as previously defined. The flexural capacity is then given as (notation in Figure 2):

$$M_{Rd} = \frac{1}{\gamma_{Rd}} \cdot \left[\psi \cdot b \cdot x \cdot f_{cd} \cdot (d - \lambda \cdot x) + A_{s2} \cdot \sigma_{s2} \cdot (d - d_2) + A_f \cdot \sigma_f \cdot d_1 \right], \tag{7}$$

where the neutral axis x is found by solving:

$$0 = \psi \cdot b \cdot x \cdot f_{cd} + A_{s2} \cdot \sigma_{s2} - A_{s1} \cdot f_{yd} - A_f \cdot \sigma_f , \tag{8}$$

in which σ_{s2} is the stress in the superior compressed re-bars, σ_f is the tensile stress in the FRP reinforcement, f_{cd} is the concrete design strength, f_{yd} is the yield stress in the inferior re-bars, ψ and λ are non-dimensional coefficients representing the intensity and the position of the compressive concrete resultant, respectively. However, the strengthened capacity cannot be considered as greater than the 60% of initial capacity.

Flexure in the presence of axial force – The flexural capacity in the presence of an axial force N_{sd} can be evaluated by means of eqns. (7 and 8), substituting the first member of eqn. (8) by N_{sd}. Longitudinal fibers must be accurately confined in order to avoid their debonding as well as the spalling of the support material.

Shear and Torsion -- Shear strengthening configurations can be in the form of side bonded, U-jacketed and wrapped FRP strips/sheets. The design shear strength of the strengthened element is given as:

$$V_{Rd} = \min\left\{ V_{Rd,ct} + V_{Rd,s} + V_{Rd,f}, V_{Rd,max} \right\}, \tag{9}$$

where $V_{Rd,ct}$, $V_{Rd,s}$ and $V_{Rd,f}$ are the concrete, transverse steel and FRP contribution, respectively, while $V_{Rd,max}$ is the shear producing collapse in the compressed diagonal concrete strut.

The FRP contribution to the overall strength is given based on the chosen strengthening configuration. For side bonding (see Figure 3 for notation):

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} \cdot \min\left\{0.9 \cdot d, h_w\right\} \cdot f_{fed} \cdot 2 \cdot t_f \cdot \frac{\sin\beta}{\sin\theta} \cdot \frac{w_f}{p_f}, \tag{10}$$

where the partial safety factor γ_{Rd} is equal to 1.20, while for U-jacketing and wrapping:

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} \cdot 0.9 \cdot d \cdot f_{fed} \cdot 2 \cdot t_f \cdot (\cot\theta + \cot\beta) \cdot \frac{w_f}{p_f}, \tag{11}$$

where f_{fed}, termed effective debonding strength, is given, in the case of side bonding, as:

$$f_{fed} = f_{fdd} \cdot \frac{z_{rid,eq}}{\min\left\{0.9 \cdot d, h_w\right\}} \cdot \left(1 - 0.6 \cdot \sqrt{\frac{l_{eq}}{z_{rid,eq}}}\right)^2, \tag{12}$$

with:

$$z_{rid,eq} = z_{rid} + l_{eq}, \quad z_{rid} = \min\left\{0.9 \cdot d, h_w\right\} - l_e \cdot \sin\beta, \quad l_{eq} = \frac{s_f}{f_{fdd} / E_f} \cdot \sin\beta, \tag{13}$$

where l_e is the optimal anchorage length given in (3), s_f is the ultimate delamination slip assumed as 0.2 mm and E_f is the elastic modulus of FRP reinforcement in the fiber direction.

In the case of U-jacketing and wrapping, respectively, it is given by:

$$f_{fed} = f_{fdd} \cdot \left[1 - \frac{1}{3} \cdot \frac{l_e \cdot \sin\beta}{\min\left\{0.9 \cdot d, h_w\right\}}\right], \tag{14}$$

$$f_{\text{fed}} = f_{\text{fdd}} \cdot \left[1 - \frac{1}{6} \cdot \frac{l_{\text{e}} \cdot \sin\beta}{\min\{0.9 \cdot d, h_{\text{w}}\}} \right] + \frac{1}{2} (\phi_{\text{R}} \cdot f_{\text{fd}} - f_{\text{fdd}}) \cdot \left[1 - \frac{l_{\text{e}} \cdot \sin\beta}{\min\{0.9 \cdot d, h_{\text{w}}\}} \right], \quad (15)$$

where f_{fd} is the FRP design strength, and:

$$\phi_{\text{R}} = 0.2 + 1.6 \cdot \frac{r_{\text{c}}}{b_{\text{w}}}, \qquad 0 \le \frac{r_{\text{c}}}{b_{\text{w}}} \le 0.5, \quad (16)$$

is a coefficient depending on the rounding radius R with respect to the beam web width b_{w}.

With regards to strengthening in torsion, this is obtained through the application of wrapping strips/sheets at an angle of 90° to the element axis. The design torsional strength of the strengthened element is given as:

$$T_{\text{Rd}} = \min\left\{ T_{\text{Rd,s}} + T_{\text{Rd,f}}, T_{\text{Rd,max}} \right\}, \quad (17)$$

where $T_{\text{Rd,s}}$ and $T_{\text{Rd,f}}$ are the transverse steel and FRP contribution, respectively, while $T_{\text{Rd,max}}$ is the torque producing collapse in the compressed diagonal concrete strut. The FRP contribution to the torsional strength is given as:

$$T_{\text{Rd,f}} = \frac{1}{\gamma_{\text{Rd}}} \cdot 2 \cdot f_{\text{fed}} \cdot t_{\text{f}} \cdot b \cdot h \cdot \frac{w_{\text{f}}}{p_{\text{f}}} \cdot \cot\theta, \quad (18)$$

where f_{fed} is given by (14) and γ_{Rd} is equal to 1.20.

<u>Confinement</u> **--** This aims both at increasing the ultimate strength in elements under axial load, and the ductility in FRP-confined elements under axial load and flexure. In case of elements with circular cross-section of diameter D, the confined/unconfined concrete strength ratio is:

$$\frac{f_{\text{ccd}}}{f_{\text{cd}}} = 1 + 2.6 \cdot \left(\frac{f_{\text{l,eff}}}{f_{\text{cd}}} \right)^{2/3}, \quad (19)$$

that depends on the effective confinement pressure exerted by the FRP sheet, given as:

$$f_{\text{l,eff}} = k_{\text{eff}} \cdot f_{\text{l}}, \quad (20)$$

where k_{eff} is an effectiveness coefficient (≤ 1), equal to the ratio between the volume of confined concrete $V_{\text{c,eff}}$ and the total volume of concrete element V_c.

The confinement pressure is:

$$f_l = \frac{1}{2} \cdot \rho_f \cdot E_f \cdot \varepsilon_{fd,rid} , \tag{21}$$

$$\varepsilon_{fd,rid} = \min\{\eta_a \cdot \varepsilon_{fk} / \gamma_f ;\ 0.004\} , \tag{22}$$

where η_a is the conversion factor related to environmental conditions, γ_f is the confinement partial safety factor equal to 1.10 and $\varepsilon_{fd,rid} = 0.004$ is the FRP conventional ultimate strain, corresponding to an unacceptable degradation of concrete. The geometrical percentage of reinforcement for circular section is:

$$\rho_f = \frac{4 \cdot t_f \cdot b_f}{D \cdot p_f} , \tag{23}$$

where t_f and b_f are the thickness and the height of FRP strips, p_f is the distance of the strips and D the diameter of circular section (Figure 4).
In the case of continuous wrapping, ρ_f is equal to:

$$\rho_f = \frac{4 \cdot t_f}{D} . \tag{24}$$

However, the strengthened capacity cannot be considered as greater than the 60% of the initial capacity.

For the case of rectangular sections with dimensions $b \times d$, with corners rounded with a radius $r_c \geq 20$ mm, the geometrical percentage of reinforcement can be computed by:

$$\rho_f = \frac{4 \cdot t_f \cdot b_f}{\max\{b, d\} \cdot p_f} . \tag{25}$$

In the case of continuous wrapping, ρ_f is equal to:

$$\rho_f = \frac{4 \cdot t_f}{\max\{b, d\}} . \tag{26}$$

With regards to the ductility increase, the sectional ultimate curvature can be evaluated, in a simplified way, by adopting the classical parabola-rectangle law for concrete (Figure 5), with the ultimate concrete strain given by:

$$\varepsilon_{ccu} = 0.0035 + 0.015 \cdot \sqrt{\frac{f_{l,eff}}{f_{cd}}} . \tag{27}$$

Masonry Structures

The application of FRP on masonry walls has the primary aim of increasing their strength and, secondarily, of increasing their collapse displacements. The objectives of FRP strengthening in masonry structures are: a) transmission of stresses either within the structural elements or between adjacent elements, b) connection between elements, c) in-plane stiffening of slabs, d) limitation of cracks width, e) confinement of columns in order to increase their strength. It is again underlined that the choice of the strengthening FRP material should avoid any incompatibility, both physical and chemical, with the existing masonry.

The strengthening intervention can include: a) increase of strength in walls, arches or vaults, b) confinement of columns, c) reducing the thrust of thrusting elements, d) transformation of non structural elements into structural elements, e) stiffening of horizontal slabs, f) application of chains in the building at the slabs and roof levels.

The masonry walls can be FRP-strengthened to prevent the out-of-plane collapse modes due to: overturning, vertical flexure, and horizontal flexure (Figure 6).

In these cases, the design of the FRP strengthening is performed through simple equilibrium between the acting forces and the resisting force of FRP strips located on top of the wall to restrain its rotation.

With regards to the in-plane collapse modes, these are due to flexure or shear. The wall shear strength is given by the sum of the masonry and the FRP shear strengths:

$$V_{\mathrm{Rd}} = \min\left\{ V_{\mathrm{Rd,m}} + V_{\mathrm{Rd,f}}, V_{\mathrm{Rd,max}} \right\}. \tag{28}$$

When the FRP strips are parallel to mortar joints the expression of $V_{\mathrm{Rd,m}}$ and $V_{\mathrm{Rd,f}}$ are given by:

$$V_{\mathrm{Rd,m}} = \frac{1}{\gamma_{\mathrm{Rd}}} \cdot d \cdot t \cdot f_{\mathrm{vd}}, \tag{29a}$$

$$V_{\mathrm{Rd,f}} = \frac{1}{\gamma_{\mathrm{Rd}}} \cdot \frac{0.6 \cdot d \cdot A_{\mathrm{fw}} \cdot f_{\mathrm{fd}}}{p_{\mathrm{f}}}, \tag{29b}$$

where γ_{Rd} = partial safety factor (in this case 1.20), d = steel depth (if any), t = wall thickness, f_{vd} = design shear strength of masonry, A_{fw} = FRP strip area, p_{f} = FRP strip spacing and f_{fd} = FRP design strength.

In the same case, the expression of $V_{\mathrm{Rd,max}}$ is given by:

$$V_{\mathrm{Rd,max}} = 0.3 \cdot f_{\mathrm{md}}^{\mathrm{h}} \cdot t \cdot d, \tag{30}$$

where $f_{\mathrm{md}}^{\mathrm{h}}$ is the masonry compressive resistance in the horizontal direction, it is parallel to the mortar joints.

When strengthening elements with either single (barrel vaults, in Figure 7) or double (groin and cross vaults, in Figure 8) curvature, the FRP strips should contrast the relative rotation at the hinge zones that develop where the limited tensile strength of masonry is attained. Thus, application of FRP strips over the outer (inner) surface of the vault thickness can prevent the formation of hinges on the opposite inner (outer) surface.

The FRP strengthening of arches includes two possible structural schemes: a) arch on fixed restraints, and b) arch supported by columns. The aim is to avoid the formation of four hinges, which would imply collapse. The FRP-strengthening is applied on either (preferably) the outer or the inner surface, in the form of fabrics that adapt better to a curved shape than prefab strips.

The FRP strengthening of domes should increase the capacity of both the membrane and the flexural regimes. For the former, FRP strips should be applied circumferentially around the dome base (Figure 9) , while for the latter, FRP strips should be applied along the meridians.

The load bearing capacity of masonry columns can be increased by confining them through FRP. The confining system can consists in an external overlay and/or in internal bars. The confined strength (which cannot be taken as greater than 1.5 the initial strength) can be computed as:

$$f_{\mathrm{mcd}} = f_{\mathrm{md}} + k' \cdot f_{\mathrm{l,eff}} , \tag{31}$$

where f_{md} is the initial masonry strength and k' is an effectiveness coefficient that can be assumed equal to:

$$k' = \frac{g_{\mathrm{m}}}{1000} , \tag{32}$$

where g_{m} (kg/m^3) is the mass density of masonry, when there isn't specific experimental evaluations.

The effective confining pressure $f_{\mathrm{l,eff}}$ is evaluated as:

$$f_{\mathrm{l,eff}} = k_{\mathrm{eff}} \cdot f_{\mathrm{l}} = k_{\mathrm{H}} \cdot k_{\mathrm{V}} \cdot f_{\mathrm{l}} , \tag{33}$$

with $f_{\mathrm{l}} = \frac{1}{2} \cdot (\rho_{\mathrm{f}} \cdot E_{\mathrm{f}} + 2 \cdot \rho_{\mathrm{b}} \cdot E_{\mathrm{b}}) \cdot \varepsilon_{\mathrm{fd,rid}} ,$ (34)

where E_f is the modulus of the FRP external overlay in the fibers direction, E_b is the longitudinal elastic modulus of the FRP internal bars, $\varepsilon_{f,rid} = 0.004$, ρ_f and ρ_b are the FRP external overlay and the FRP internal bars ratios, respectively.

FRP Strengthening in Seismic Zones

The above described chapters on strengthening also contain specific indications regarding constructions in seismic zones. These follow the approach of the most recent Italian and International codes, with regards to: assessment techniques, safety requirements (limit states), seismic protection levels, analysis methods, and verification criteria (distinction between ductile and brittle elements).

Reinforced Concrete Buildings **--** FRP strengthening is regarded as a selective intervention technique aiming at: a) increasing the flexural and shear capacity of deficient members, b) increasing the ductility (or the chord rotation capacity) of critical zones through confinement, c) improving the performance of lap splice zones through confinement, d) prevent longitudinal steel bars buckling through confinement, and e) increase the tensile strength in partially confined beam-column joints through application of diagonal strips.

A relevant innovation concerns the definition of the inspiring principles of the intervention strategies: a) all brittle collapse mechanism should be eliminated, b) all "soft story" collapse mechanism should be eliminated, and c) the global deformation capacity of the structure should be enhanced, either: c1) by increasing the ductility of the potential plastic hinge zones without changing their position, or c2) by relocating the potential plastic hinge zones by applying capacity design criteria. In this latter case, the columns should be flexure-strengthened with the aim of transforming the frame structure into a high dissipation mechanism with strong columns and weak beams.
Failure of brittle mechanisms such as shear, lap splicing, bar buckling, and joint shear should be avoided. For shear, the same criteria apply as for the non-seismic case, with the exception that side bonding is not allowed and FRP strips/sheets should only be applied orthogonal to the element axis. For lap splices of length L_s, adequate FRP confinement should be provided, having thickness:

$$t_f = \frac{\max\{b,d\}}{2 \cdot E_f} \cdot \left(1000 \cdot \frac{f_l}{k_H} - E_S\right), \qquad (35)$$

where E_s = steel modulus, and f_l = confinement pressure:

$$f_l = \frac{A_s \cdot f_y}{\left[\frac{u_e}{2 \cdot n} + 2 \cdot (d_b + c)\right] \cdot L_s}, \qquad (36)$$

where u_e= perimeter of the cross section inscribed in the longitudinal bars, of which n are spliced, and c = concrete cover. For bar buckling, adequate FRP confinement should be provided, having thickness:

$$t_f = \frac{10 \cdot n \cdot \max\{b, d\}}{E_f}, \tag{37}$$

where n = total number of longitudinal bars under potential buckling.

Masonry Buildings -- Starting from the same principles as for RC buildings, when FRP-strengthening a masonry building one should also consider that: a) masonry walls inadequate to resist vertical and horizontal actions should be strengthened or rebuilt, b) orthogonal and corner walls should be adequately connected, c) slab/wall and roof/wall connections should be ensured, d) thrusts from roofs, arches and vaults should be counter-reacted by appropriate structural elements, e) slabs should be in-plane stiffened, f) vulnerable elements that cannot be strengthened should be eliminated, g) irregularity of buildings cannot be corrected by FRP applications, h) local ductility increase should be pursued whenever possible, and i) the application of local FRP strengthening should not reduce the overall structural ductility.

Quality Control

A series of *in situ* checks and operations are specified in order to validate the quality level of the applications of composite materials: check and preparation of the substrate, evaluation of the substrate degradation, removal and reconstruction of the substrate with possible treatment of steel bars.

A series of requirements for a correct application are also given with regards to: humidity conditions, environmental and substrate temperature, construction details and rules. The quality control of the application is then based on semi-destructive and non-destructive tests.

CONCLUSIONS

The peculiarity of Italy, highly seismic and endowed with a built environment unique in the world, extremely various and rich of cultural value, renders all research in this field a continuous and challenging task.

This nationwide effort has resulted in a first regulatory document (CNR-DT 200/2004), that was conceived both for regulating a rapidly growing professional and technical market, as well as for an informative and educational purpose. The document is deemed of great importance for the dissemination, in the professional sphere, of the physical and technological knowledge necessary to conscious and competent use of FRP in strengthening.

A version in English of the document is under preparation and will be available in summer 2005.

REFERENCES

[1] CNR-DT 200/2004: 'Instructions for Design, Execution and Control of Strengthening Interventions by Means of Fibre-reinforced Composites' (2004)

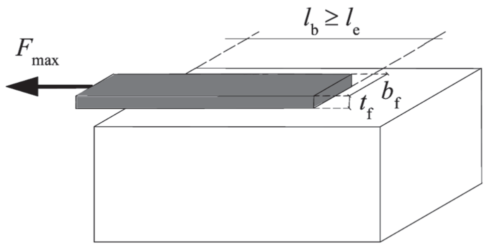

Figure 1 - Notation for anchorages.

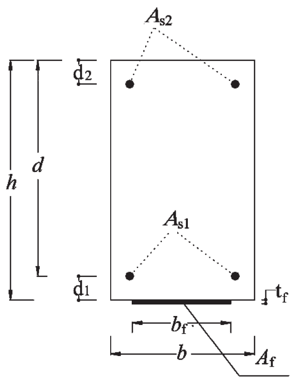

Figure 2 - Notation for flexural strengthening.

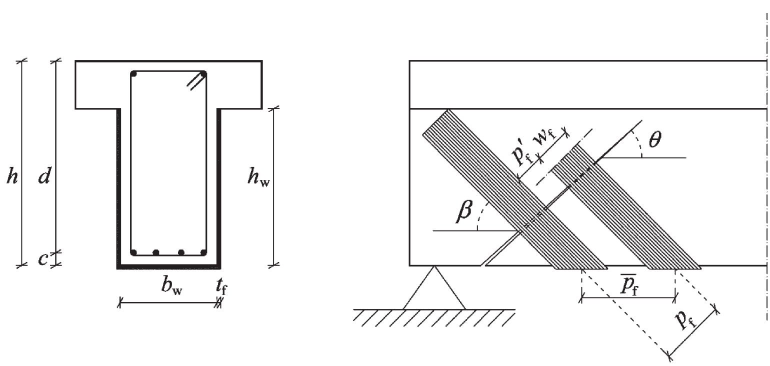

Figure 3 - Notation for shear strengthening (in lack of specific evaluation, it can assume $q = 45°$).

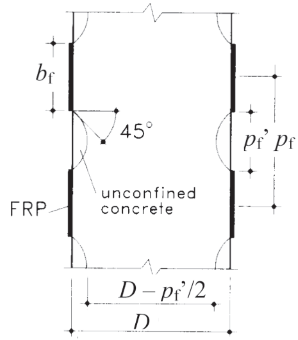

Figure 4 - Notation for confinement (column vertical section).

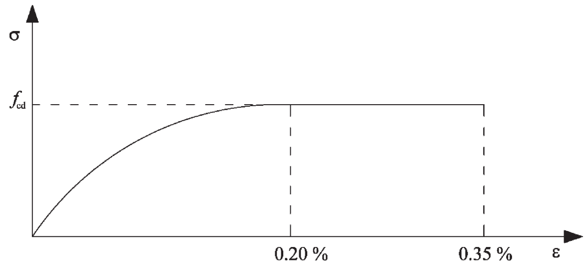

Figure 5 – Parabola-rectangle law (f_{cd} = concrete design strength).

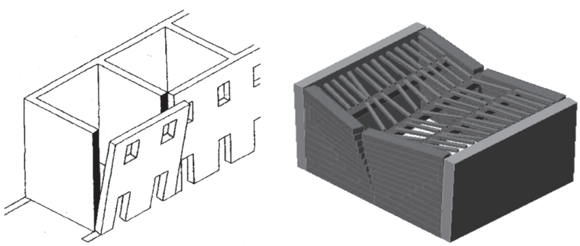

Figure 6 - Collapse modes of masonry walls: overturning (left) and horizontal flexure (right).

Figure 7 - FRP strengthening of a masonry barrel vault.

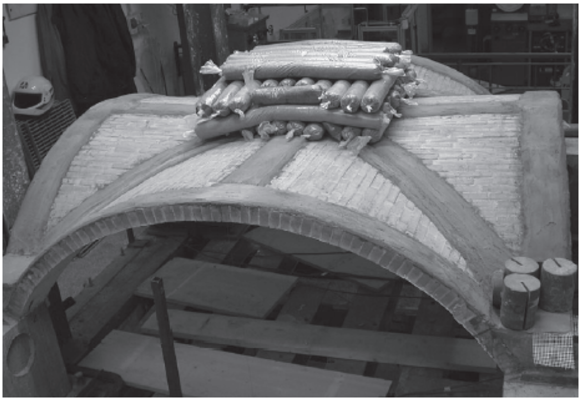

Figure 8 - FRP strengthening of a masonry cross vault.

Figure 9 - FRP strengthening of a masonry dome.