FRP COMPOSITES FOR STRUCTURAL ENGINEERING APPLICATIONS

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Summary

The use of composite materials as strengthening means for structural elements, in both reinforced concrete and masonry, is nowadays current practice worldwide, especially in seismic zones, either for retrofitting insufficiently designed buildings or for rapid after-quake intervention measures. Composite materials used in structural engineering applications are in general fiber reinforced polymers, widely known with the acronym FRP. Many socuments providing guidelines and codes have been developed, and they include the most advanced concepts in FRP-strengthening. This chapter refers to one

such document, the Italian CNR DT-200/2004, and deals with all the aspects relevant to a correct design process, starting from the main properties of the constituent materials, to the main strengthening schemes and the equations for strengthening.

1. General

1.1 Objectives

Although Earthquake Engineering does not have a long history, the urgency of a theoretical development and the relevance of the availability of guidance documents, are achievements of the last few years. If one considers the even shorter history of composites in construction, which naturally lend themselves as effective strengthening materials for such situations, the effort of the last ten years aiming at developing specialized normative actions appears more than justified.

Worldwide, the number of existing buildings that were designed and built without considering seismic impacts, and/or did not follow appropriate design rules, and are consequently at high risk, is far greater than the number of new and correctly conceived and appropriately designed buildings. By common sense, one can easily envisage that in the next decade the research in the field of earthquake engineering will necessarily redirect its focus towards the development of approaches for effectively strengthening the existing structures at risk.

It is worth noting the great differences that exist between the development of methods for the design of new structures, an area in which earthquake engineering has achieved substantial progress and harmonized and consolidated approaches, and the development of methods for the retrofitting of the existing building stock.

While for the design of new structures procedures are available for proportioning the relative strength of structural elements so as to control the overall behavior, existing structures are often penalized by mistakes, both in the structural conception and, mostly, in the detailing of the elements. Discovering these mistakes and determining the way they should be fixed is a process completely original and different from the one required for the design of new structures.

Even more complex is the task of redirecting the structure towards a safe behavior by means of strengthening measures, especially if these are made from FRP, applicable only locally on deficient elements. In both cases, the task does not consist in checking compliance with some normative prescriptions, which would seldom be satisfied, but in a performance assessment of the structure exploiting its own resources, with and without additional strengthening materials.

Starting from the above described problem, the first studies in the field have started in the beginning of the 1990s, with the distinction in the two main fields of FRP research, namely, strengthening of reinforced concrete and strengthening of masonry. Researchers strived at finding new solutions for increasing the safety of existing constructions, that could compete with the more developed and usual techniques, such as, mortar injections, concrete jacketing, steel tying and plating, base isolation, integrative bracings (dissipative or not).

1.2. Strengthening Concepts

Strengthening takes place once the requirement to assess a particular building has been established. The conditions under which seismic assessment of individual buildings – possibly leading to retrofitting – are required are addressed in the recently issued Italian seismic code. Here a distinction is needed between "active" and "passive" seismic assessment and retrofitting programs, as for example introduced in Eurocode 8 - Part 3 (EN 1998-3). An "active" program requires owners of certain categories of buildings to meet specific deadlines for the completion – of the seismic assessment and – depending on its outcome – of the retrofitting. The categories of buildings selected to be targeted may depend on seismicity and ground conditions, importance class and occupancy and perceived vulnerability of the building (as influenced by type of material and construction, number of stories, age of the building with respect to dates of older code enforcement, etc.). A "passive" program associates seismic assessment – possibly leading to retrofitting – with other events or activities related to the use of the building and its continuity, such as a change in use that increases occupancy or importance class, remodeling above certain limits (as a percentage of the building area or of the total building value), repair of damage after an earthquake, etc.

The choice of the Limit States to be checked, as well as the return periods of the seismic action ascribed to the various Limit States, depends on the program for assessment and retrofitting. The relevant requirements are less stringent in "active" programs than in "passive" ones; for example, in "passive" programs triggered by remodeling, the relevant requirements usually gradate with the extent and cost of the remodeling work undertaken. 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 former is more peculiar, apart from the complexity of the subject, as for the case of masonry structures, this research has less alternatives of strengthening means and has received less applications and studies.

It is evident that for the historical, cultural and architectural heritage, the issue of structural safety is only one aspect included in the broader needs of restoration, preservation and conservation up to now. 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 one can demonstrate that they comply with the basic principles of restoration related with formal and materials compatibility, reversibility and authenticity.

These essential considerations have so complex and articulated implications that they deserve deeper considerations discussed in the final section, where an attempt is made to describe the philosophical and methodological bases of preservation of historical construction and the constraints posed to the use of FRP in this field.

2. Materials

Continuous fiber-reinforced materials with polymeric matrix (FRP) can be considered as composite, heterogeneous, and anisotropic materials with a prevalent linear elastic behavior up to failure. They are widely used for strengthening of civil structures. There are many advantages of using FRPs: lightweight, good mechanical properties, corrosion-resistance, etc. Composites for structural strengthening are available in several geometries from laminates used for strengthening of members with regular surface to bi-directional fabrics easily adaptable to the shape of the member to be strengthened. Composites are also suitable for applications where the aesthetics of the original structures needs to be preserved (buildings of historic or artistic interest) or where strengthening with traditional techniques can not be effectively employed.

This chapter includes the basic information on composite materials, their constituents (fiber, matrix, and adhesive), and their physical and mechanical properties. Such information is necessary to know the pros and cons of fiber-reinforced composite materials to make use of their advantages and mitigate, if possible, their disadvantages. This is of particular relevance to ensure durability of FRP strengthening applications where traditional materials such as concrete or masonry are coupled with high technology materials.

2.1. Characteristics of Composites

Composite materials exhibit the following characteristics:

- They are made of two or more materials (phases) of different nature and “macroscopically” distinguishable.
- At least two phases have physical and mechanical properties quite different from each other, so as to provide FRP material with different properties than those of its constituents.

Fiber-reinforced composites with polymeric matrix satisfy both of the above characteristics. In fact, they are made out of both organic polymeric matrix and reinforcing fibers, whose main characteristics are summarized in Table 1. As it can be seen, carbon fibers may exhibit values of Young’s modulus of elasticity much larger than those of typical construction materials. Therefore, they are more effective from a structural point of view. Potential problems with other materials used as support need to be carefully evaluated by designers and practitioners.

The matrix may be considered as an isotropic material, while the reinforcing phase, with the exception of glass fiber, is an anisotropic material (different properties in different directions). The defining characteristics of FRP materials are as follows:

- Geometry: shape and dimensions.
- Fiber orientation: the orientation with respect to the symmetry axes of the material; when random, the composite characteristics are similar to an isotropic material (“quasi-isotropic”). In all other cases the composite can be considered as an anisotropic material.
- Fiber concentration: volume fraction, distribution (dispersion).

Therefore, composites are in most cases non-homogeneous and anisotropic materials.

	Young's modulus E	Tensile strength σ_r	Strain at failure ε_r	Coefficient of thermal expansion α	Density ρ
	[GPa]	[MPa]	[%]	[10^{-6} °C^{-1}]	[g/cm^3]
E-glass	70 – 80	2000 – 3500	3.5 – 4.5	5 – 5.4	2.5 – 2.6
S-glass	85 – 90	3500 – 4800	4.5 – 5.5	1.6 – 2.9	2.46 – 2.49
Carbon (high modulus)	390 – 760	2400 – 3400	0.5 – 0.8	-1.45	1.85 – 1.9
Carbon (high strength)	240 – 280	4100 – 5100	1.6 – 1.73	-0.6 – -0.9	1.75
Aramid	62 – 180	3600 – 3800	1.9 – 5.5	-2	1.44 – 1.47
Polymeric matrix	2.7 – 3.6	40 – 82	1.4 – 5.2	30 – 54	1.10 – 1.25
Steel	206	250 – 400 (yield) 350 – 600 (failure)	20 – 30	10.4	7.8

Table 1. Comparison between properties of fibers, resin, and steel (typical values)

To summarize FRP properties, it is convenient to recognize fiber-reinforced composites in two categories, regardless of their production technology:

- Single-layer (lamina)
- Multi-layer (laminates)

Laminates are materials composed of stacked layers (the lamina) whose thickness is usually of some tenths of a millimeter. In the simplest case, fibers are embedded only in the lamina's plane (there are no fibers arranged orthogonally to that plane).

Composite materials can be stronger and stiffer (carbon FRP) than traditional construction materials. As a result, composites may become very attractive when the weight of the structure becomes an issue. FRP tensile strength and Young's modulus of elasticity can be up to four and two times that of traditional materials, respectively. This means that a composite material structure may weigh nearly half of a traditional construction material structure of equal stiffness.

Structural failures of FRP composites are often due to lack of bond between matrix and fibers. Therefore, the FRP material manufacturer should take special care in choosing the most appropriate component to use to promote the bond.

2.2. Fibers and Matrices Used in Composites

The most common fibers used in composites are glass, carbon, and aramid. Their unique unidimensional geometry, in addition to being particularly suitable for the realization of composites, provides FRP laminates with stiffness and strength higher than those of three-dimensional FRP shapes. This is due to the lower density of defects of mono-dimensional configurations as opposed to that of three-dimensional members.

Thermoset resins are the most commonly used matrices for production of FRP materials. They are usually available in a partially polymerized state with fluid or pasty consistency at room temperature. When mixed with a proper reagent, they polymerize to become a solid, vitreous material. The reaction can be accelerated by adjusting the temperature. Thermoset resin have several advantages, including low viscosity that allows for a relative easy fiber impregnation, good adhesive properties, room temperature polymerization characteristics, good resistance to chemical agents, absence of melting temperature, etc. Disadvantages are limited range of operating temperatures, with the upper bound limit given by the glass transition temperature, poor toughness with respect to fracture ("brittle" behavior), and sensitivity to moisture during field applications. The most common thermosetting resins for civil engineering are the epoxy resin. Polyester or vinylester resins are also used. Considering that the material is mixed directly at the construction site and obtains its final structural characteristics through a chemical reaction, it should always be handled by specialized personnel.

2.3. FRP Strengthening Systems

FRP systems suitable for external strengthening of structures may be classified as follows:

- **Pre-cured systems**: Manufactured in various shapes by pultrusion or lamination, pre-cured systems are directly bonded to the structural member to be strengthened.
- **Wet lay-up systems**: Manufactured with fibers lying in one or more directions as FRP sheets or fabrics and impregnated with resin at the job site to the support.
- **Prepreg (pre-impregnated) systems**: Manufactured with unidirectional or multidirectional fiber sheets or fabrics pre-impregnated at the manufacturing plant with partially polymerized resin. They may be bonded to the member to be strengthened with (or without) the use of additional resins.

2.4. Mechanical Properties of FRP Strengthening Systems

In FRP materials, fibers provide both loading carrying capacity and stiffness to the composite while the matrix is necessary to ensure sharing of the load among fibers and to protect the fibers themselves from the environment. Most FRP materials are made of fibers with high strength and stiffness, while their strain at failure is lower than that of the matrix.

Figure 1 shows the stress-strain relationship for fiber, matrix, and the resulting FRP material. The resulting FRP material has lower stiffness than fibers and fails at the same strain, $\varepsilon_{\mathrm{f,max}}$, of the fibers themselves. In fact, beyond such ultimate strain, load sharing from fibers to the matrix is prevented.

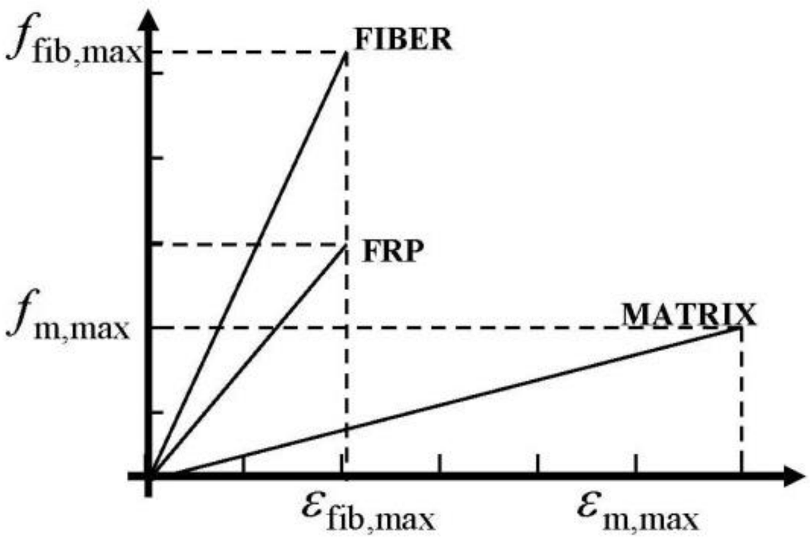

Figure 1. Stress-strain relationship of fibers, matrix and FRP.

Table 2 summarizes mechanical properties of a pre-cured laminate compared to the average values of the corresponding fibers. The values of Young modulus of elasticity, E_f, and ultimate strength at failure, f_f, of the laminate are lower than those of the fiber itself, while the ultimate tensile strain is of the same order of magnitude for both materials.

Pre-cured systems	**Modulus of elasticity [GPa]**		**Ultimate strength [MPa]**		**Ultimate strain [%]**	
	FRP E_f	**Fiber** E_{fib}	**FRP** f_f	**Fiber** f_{fib}	**FRP** ε_{fu}	**Fiber** $\varepsilon_{fib,u}$
CFRP (low modulus)	160	210-230	2800	3500-4800	1.6	1.4-2.0
CFRP (high modulus)	300	350-500	1500	2500-3100	0.5	0.4-0.9

Table 2. Comparison between mechanical properties of a pre-cured laminate and fibers

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[This document contains details for the design and construction methodology for strengthening of structures using fiber-reinforced composites].

Biographical Sketch

Giorgio Monti graduated in engineering in 1986 at the University of Roma La Sapienza; he obtained a Master of Science at the University of California at Berkeley in 1993, and a PhD at the University of Roma La Sapienza in 1994. Since 2001 he has been Full Professor at the University of Roma La Sapienza. His scientific activity addresses the topics of: modeling and analysis of reinforced concrete structures under seismic excitation, assessment of existing structures, strengthening techniques for structures with innovative materials (FRP), strategies for the preservation of historical city centers, and reliability analysis of structures and infrastructures in seismic zones. In these fields he has produced more than 180 papers. He is an active member of national and international committees for the development of normative document on seismic design, and assessment and rehabilitation of buildings and bridges, by means of innovative techniques. He has coordinated a 3-year Italian National Project on the Seismic Assessment of Existing Reinforced Concrete Buildings. He has taken part to scientific exchanges with Institutions in Europe, China, the USA, and Australia. He is the coordinator since 2008 of Working Group 4.4: “Computer-Based Modelling and Design” of *fib* Commission 4 ‘Modelling of Structural Behaviour and Design’. He has substantially contributed to the writing of EN1998 Part 3: “Assessment and retrofitting of Buildings”. He participated in the Commission that issued the new Italian Seismic Code and he is in the Coordinating Group that produced the new Italian set of codes on the use of Fiber Reinforced Polymers. He is currently member of the Commission 8 of the Structural Engineering Committee of UNI.