CHAPTER 2

MATERIALS AND TECHNIQUES

This chapter provides general information on FRP materials used in concrete and/or masonry strengthening and on the basic technique for their application.

2.1 Materials

2.1.1 General

The selection of materials for different strengthening systems is a critical process. Every system is unique in the sense that the fibers and the binder components are designed to work together. This implies that a binder for one strengthening system will not automatically work properly for another. Furthermore, a binder for the fibers will not necessarily provide a good bond to concrete or masonry. Hence, only systems that have been tested extensively on reinforced concrete or masonry structures should be used in strengthening with composites. Today there are several types of composite material strengthening systems, which are summarised below:

- Wet lay-up systems
- Systems based on prefabricated elements
- Special systems, e.g. automated wrapping, prestressing, near-surface mounted bars, mechanically attached laminates, inorganic binder composites etc.

These systems correspond to several manufacturers and suppliers, and are based on different configurations, types of fibers, adhesives, etc. In the following sections the three main components, namely **adhesives**, **matrices** and **fibers** of a **composite material** strengthening system will be discussed briefly.

2.1.2 Fibers

Fibers have a diameter in the order of 5-25 μm and constitute the primary load-carrying elements (parallel to their axis) in a composite material system. Main properties of the fibers are the high tensile strength and the linear elastic behavior to failure (Fig. 2.1). Basic properties of the most common fibers used in FRP strengthening systems are given in Table 2.1 (Feldman 1989, Kim 1995). It should be noted that properties listed in this table correspond to monotonic loading and do not account for environmental degradation and/or sustained loading effects (see Chapter 10).

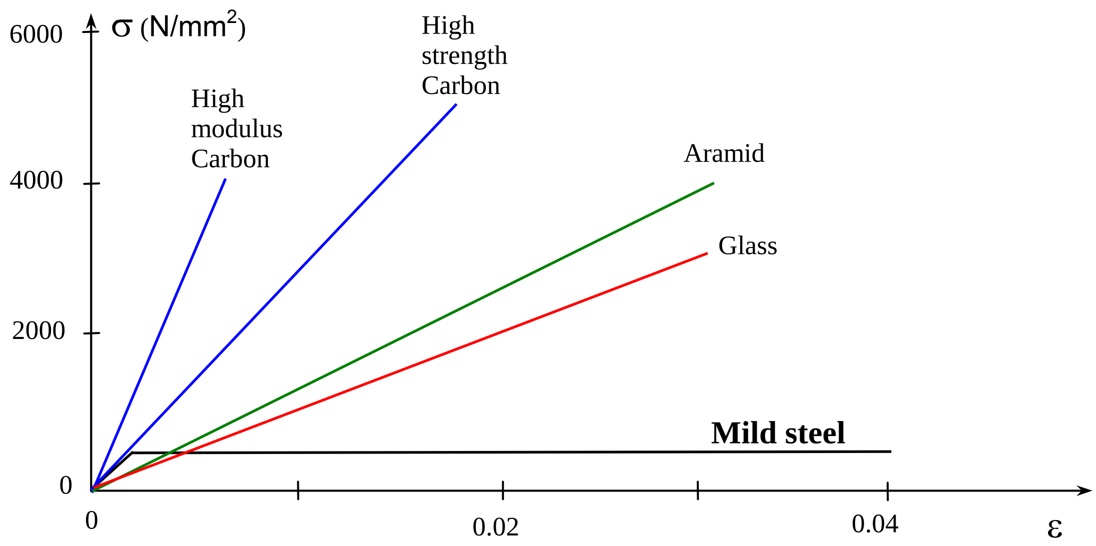


Fig. 2.1 Typical uniaxial tension stress-strain diagrams for different fibers and comparison with steel.

Table 2.1 Typical properties of fibers (Feldman 1989, Kim 1995).

Material	Elastic modulus (kN/mm^2)	Tensile strength (N/mm^2)	Ultimate tensile strain (%)
Carbon			
High strength	215-235	3500-4800	1.4-2.0
Ultra high strength	215-235	3500-6000	1.5-2.3
High modulus	350-500	2500-3100	0.5-0.9
Ultra high modulus	500-700	2100-2400	0.2-0.4
Glass			
E	70-75	1900-3000	3.0-4.5
AR	70-75	1900-3000	3.0-4.5
S	85-90	3500-4800	4.5-5.5
Aramid			
Low modulus	70-80	3500-4100	4.3-5.0
High modulus	115-130	3500-4000	2.5-3.5

Carbon fibers are normally either based on pitch or PAN, as raw material. Pitch fibers are fabricated by using refined petroleum or coal pitch that is passed through a thin nozzle and stabilized by heating. PAN fibers are made of polyacrylonitrile that is carbonized through burning. The pitch base carbon fibers offer general purpose and high strength/elasticity materials. The PAN-type carbon fibers yield high strength materials and high elasticity materials. The density of carbon fibers is 1800-1900 kg/m^3. **Glass** fibers for continuous fiber reinforcement are classified into three types: E-glass fibers, S-glass and alkali resistant AR-glass fibers. E-glass fibers, which contain high amounts of boric acid and aluminate, are disadvantageous in having low alkali resistance. S-glass fibers are stronger and stiffer than E-glass, but still not resistant to alkali. To prevent glass fiber from being eroded by cement-alkali, a considerable amount of zircon is added to produce alkali resistance glass fibers; such fibers have mechanical properties similar to E-glass. An important aspect of glass fibers is their low cost. The density of glass fibers is 2300-2500 kg/m^3. **Aramid** fibers were first introduced in 1971, and today are produced by several manufacturers under various brand names (Kevlar, Twaron, Technora). The structure of aramid fiber is anisotropic and gives higher strength and modulus in the fiber longitudinal direction. Aramid fibers respond elastically in tension but they exhibit non-linear and ductile behavior under compression; they also exhibit good toughness, damage tolerance and fatigue characteristics. The density of aramid fibers is 1450 kg/m^3.

2.1.3 Matrix

The matrix for a structural composite material is typically a polymer, of thermosetting type or of thermoplastic type, with the first being the most common one. Recent developments have resulted in matrices based on inorganic materials (e.g. cement-based). The function of the matrix is to protect the fibers against abrasion or environmental corrosion, to bind the fibers together and to distribute the load. The matrix has a strong influence on several mechanical properties of the composite, such as the transverse modulus and strength, the shear properties and the properties in compression. Physical and chemical characteristics of the matrix such as melting or curing temperature, viscosity and reactivity with fibers influence the choice of the fabrication process. Hence, proper selection of the matrix material for a composite system requires that all these factors be taken into account.

Epoxy resins, polyester, vinylester and phenolics are the most common polymeric matrix materials used with high-performance reinforcing fibers. They are thermosetting polymers with good processibility and good chemical resistance. Epoxies have, in general, better mechanical properties than polyesters and vinylesters, and outstanding durability, whereas polyesters and vinylesters are cheaper. Phenolics have a better behavior at high temperatures. Recently, polymer-modified cement-based mortars have also become available in some applications. It is expected that these mortars will be used more and more in the near future.

2.1.4 Composite materials

Advanced composites as strengthening materials consist of a large number of small, continuous, directionalized, non-metallic fibers with advanced characteristics, bundled in the matrix (Fig. 2.2). Depending on the type of fiber they are referred to as CFRP (carbon fiber based), GFRP (glass fiber based) or AFRP (aramid fiber based); when different types of fibers are used, the material is called “hybrid”. Typically, the volume fraction of fibers in advanced composites equals about 50-70% for strips and about 25-35% for sheets. Given also that the elastic modulus of fibers is much higher than that of the matrix, it becomes clear that the fibers are the principal stress bearing components, while the matrix transfers stresses among fibers and protects them. Different techniques are used for manufacturing (e.g. pultrusion, hand lay-up), detailed descriptions of which are outside the scope of this document. As externally bonded reinforcement for the strengthening of structures, advanced composite materials are made available in various forms, which are described in Section 2.2.

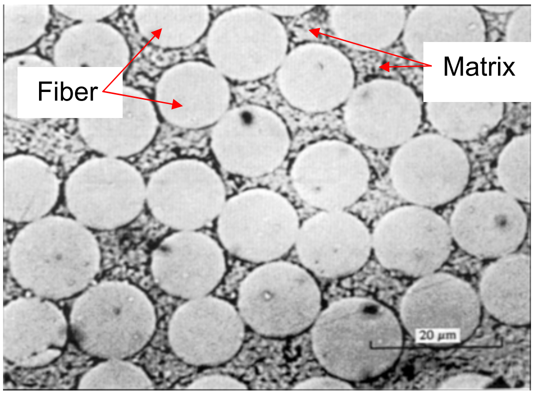


Fig. 2.2 Magnified cross section of a composite material with unidirectional fibers.

Basic mechanical properties of composites may be estimated if the properties of the constituent materials (fibers, matrix) and their volume fractions are known. Details about the micromechanics of composite materials are not considered here. However, for the simple – yet quite common - case of unidirectional fibers, one may apply the “rule of mixtures” simplification as follows:

$$E_f \approx E_{fib} V_{fib} + E_m V_m \tag{2.1}$$

$$f_f \approx f_{fib} V_{fib} + f_m V_m \tag{2.2}$$

where:

- E_f = elastic modulus of fiber-reinforced material in fiber direction
- E_{fib} = elastic modulus of fibers
- E_m = elastic modulus of matrix

V_{fib} = volume fraction of fibers

V_m = volume fraction of matrix = $1 - V_{fib}$

f_f = tensile strength of fiber-reinforced material in fiber direction

f_{fib} = tensile strength of fibers

f_m = tensile strength of matrix

At this point we should note that since $E_{fib}/E_m >> 1$ and $f_{fib}/f_m >> 1$, the above equations are approximately valid even if the second terms in the right parts are omitted.

In case of prefabricated strips the material properties based on the total cross-sectional area can be used in calculations and are usually supplied by the manufacturer. In case of in-situ resin impregnated systems, however, the final composite material thickness and with that the fiber volume fraction is uncertain and may vary. For this reason the properties of the total system (fibers and matrix) and the actual thickness should be provided based on experimental testing. Note that manufacturers sometimes supply the material properties for the bare fibers. In this case a property reduction factor r_1 should apply, to be provided by the supplier of the strengthening system. The above is better explained in the following example.

Example 2.1

Material supplier X provides unidirectional carbon sheets, with a weight of 260 g/m^2. Fiber properties are as follows: E_{fib} = 230 kN/mm^2, f_{fib} = 3500 N/mm^2. The nominal thickness of the sheet, t_{fib}, is calculated based on the fiber material density, say ρ_{fib} = 2000 kg/m^3, as follows: ρ_{fib}: $\rho_{fib} \mathrm{x}\, t_{fib}$ = 260, hence t_{fib} = 0.13 mm. We assume that after resin impregnation, the composite material reaches a thickness of 0.3 mm, implying a volumetric fraction of fibers equal to V_{fib} = 0.13/0.3 = 43%. If the tensile strength and the elastic modulus of the composite material were measured experimentally, the results would be lower than 0.43x230 GPa and 0.43x3500 N/mm^2, respectively, say by 10% (hence r_1 = 0.9): 89 kN/mm^2 και 1355 N/mm^2. Therefore, the composite material properties to be used in calculations should be one of the following:

(a) E_f = 89 GPa, f_f = 1355 N/mm^2, t_f = 0.3 mm, or

(b) E_f = **0.9**x230 GPa, f_f = **0.9**x3500 N/mm^2, t_f = 0.13 mm.

In a real application the amount of impregnating resin could, in general, be different from that suggested by the supplier, hence the real thickness of the composite will not be equal to 0.3 mm. But what is of interest in the calculations is typically the product $E_f\, t_f$ or, sometimes, the product $f_f\, t_f$, hence the above two solutions (a) and (b) are **equivalent**. The advantage of solution (a) is that the properties provided by the supplier are quite close to those expected in-situ and the disadvantage is that those properties are "hypothetical". On the other hand, the advantage of solution (b) is that the material provided by the supplier is accompanied by a set of properties, which could be combined with the proper reduction factor (0.9 in this example) to yield the properties of the in-situ applied composite.

2.1.5 Adhesives

The purpose of the adhesive is to provide a shear load path between the substrate (concrete or masonry) and the composite material, so that full composite action may develop. The most common type of structural adhesives is epoxy, which is the result of mixing an epoxy resin (polymer) with a hardener. Other types of adhesives may be based on inorganic materials (mainly cement-based). Depending on the application demands, the adhesive may contain fillers, softening inclusions, toughening additives and others.

When using **epoxy** adhesives there are two different time concepts that need to be taken into consideration. The first is the **pot life** and the second is the **open time**. Pot life represents the time one can work with the adhesive after mixing the resin and the hardener before it starts to harden in the mixture vessel; for an epoxy adhesive, it may vary between a few seconds up to several years. Open time is the time that one can have at his/her disposal after the adhesive has been applied to the adherents and before they are joined together.

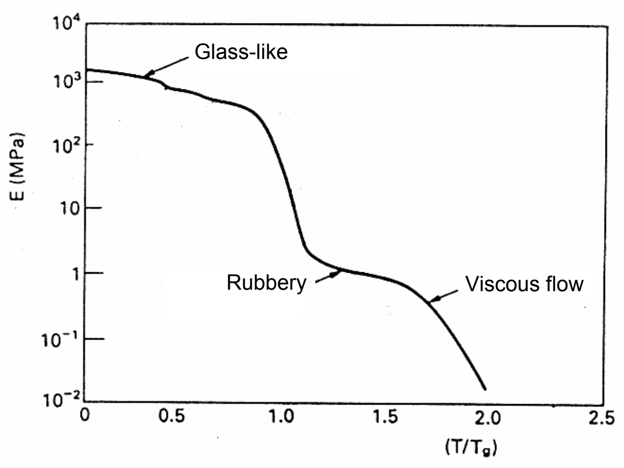


Fig. 2.3 Effect of temperature on elastic modulus of polymers (Triantafillou 2004).

Another important parameter to consider is the **glass transition temperature**, T_g. Most synthetic adhesives are based on polymeric materials, and as such they exhibit properties that are characteristic for polymers. Polymers change from relatively hard, elastic, glass-like to relatively rubbery materials at a certain temperature (Fig. 2.3). This temperature level is defined as glass transition temperature, and is different for different polymers.

Typical properties for cold cured epoxy adhesives used in civil engineering applications are given in Table 2.2 (*fib* 2001). For the sake of comparison, the same table provides information for concrete and mild steel too.

Table 2.2 Typical properties of epoxy resins and comparison with concrete and steel (*fib* 2001).

Property (at 20 °C)	Epoxy adhesive	Concrete	Mild steel
Density (kg/m^3)	1100 – 1700	2350	7800
Elastic modulus (kN/mm^2)	0.5 - 20	20 - 50	205
Shear modulus (kN/mm^2)	0.2 – 8	8 - 21	80
Poisson´s ratio	0.3 – 0.4	0.2	0.3
Tensile strength (N/mm^2)	9 - 30	1 - 4	200 - 600
Shear strength (N/mm^2)	10 - 30	2 - 5	200 - 600
Compressive strength (N/mm^2)	55 - 110	25 - 150	200 - 600
Tensile strain at break (%)	0.5-5	0.015	25
Approximate fracture energy (Jm^{-2})	200-1000	100	10^5-10^6
Coefficient of thermal expansion (10^{-6}/°C)	25 - 100	11 - 13	10 - 15
Water absorption: 7 days - 25 °C (% w/w)	0.1-3	5	0
Glass transition temperature (°C)	50 - 80	---	---

Alternative materials to epoxies may be of the **inorganic binder** type. These materials are based on cement in combination with other binders (e.g. fly ash, silica fume, metakaolin), additives (e.g. polymers) and fine aggregates. In this case the adhesive also plays the role of the matrix in the composite material, hence it must be designed such that compatibility with the fibers (textiles) will be maximized. General requirements for inorganic binders are high shear (that is tensile) strength, suitable consistency, low shrinkage and creep and good workability.

2.2 Strengthening systems

Different systems of externally bonded FRP reinforcement exist, related to the constituent materials, the form and the technique of the FRP strengthening. In general, these can be subdivided into “wet lay-up” (or “cured in-situ”) systems and “prefab” (or “pre-cured”) systems. In the following, an overview is given of the different forms of these systems (e.g. ACI 1996, *fib* 2001). Basic techniques for FRP strengthening are given in Section 2.3.

2.2.1 Wet lay-up systems

- Dry unidirectional fiber *sheet* (Fig. 2.4) and semi-unidirectional *fabric* (woven or knitted), where fibers run predominantly in one direction partially or fully covering the structural element. Installation on the substrate requires saturating resin usually after a primer has been applied. Two different processes can be used to apply the fabric:
  - the fabric can be applied directly into the resin which has been applied uniformly onto the substrate
  - the fabric can be impregnated with the resin in a saturator machine and then applied wet to the sealed substrate

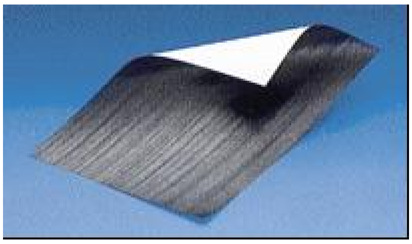


Fig. 2.4

- Dry multidirectional *fabric* (woven or knitted), Fig. 2.5, where fibers run in at least two directions (e.g. 0^{o} and 90^{o} or $\pm 45^{o}$ with respect to the member axis). Installation requires saturating resin. The fabric is applied using one of the two processes described above.

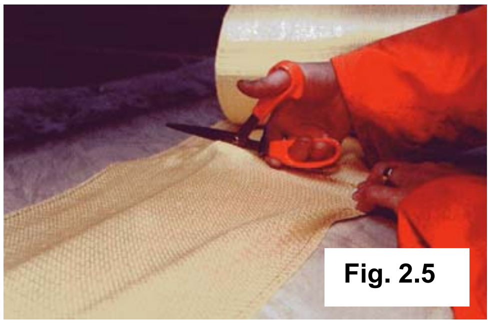


Fig. 2.5

- Resin pre-impregnated uncured unidirectional *sheet* or *fabric*, where fibers run predominantly in one direction. Installation may be done with or without additional resin.
- Resin pre-impregnated uncured multidirectional *sheet* or *fabric*, where fibers run predominantly in two directions. Installation may be done with or without additional resin.
- Dry fiber *tows* (untwisted bundles of continuous fibers) that are wound or otherwise mechanically placed onto the substrate. Resin is applied to the fiber during winding.
- Pre-impregnated fiber *tows* that are wound or otherwise mechanically placed onto the substrate. Product installation may be executed with or without additional resin.

2.2.2 Prefabricated elements

- Pre-manufactured cured straight *strips*, which are installed through the use of adhesives. They are typically in the form of thin ribbon strips or grids that may be delivered in a rolled coil. Normally strips are pultruded. In case they are laminated, also the term *laminate* instead of *strip* may be used. In the past few years special laminates have been developed with fibers in various directions (e.g. $\pm 45^{o}$, in addition to $0^{o}/90^{o}$), allowing their attachment on substrates through the use of mechanical fasteners (e.g. powder activated nails, bolt anchors), that is without any adhesive.

- Pre-manufactured cured straight *bars*, with circular of rectangular cross sections; these bars are mounted using epoxy adhesives or polymer-modified mortars in grooves near the surface of concrete or masonry substrates.
- Pre-manufactured cured shaped *shells*, *jackets* or *angles*, which are installed through the use of adhesives. They are typically factory-made curved or shaped elements or split shells that can be fitted around columns or other elements.

The suitability of each system depends on the type of structure that shall be strengthened. For example, prefabricated strips are generally best suited for plane and straight surfaces (e.g. bottom of beams and slabs), whereas sheets or fabrics are more flexible and can be used to plane as well as to convex surfaces (e.g. sides of beams, column wrapping).

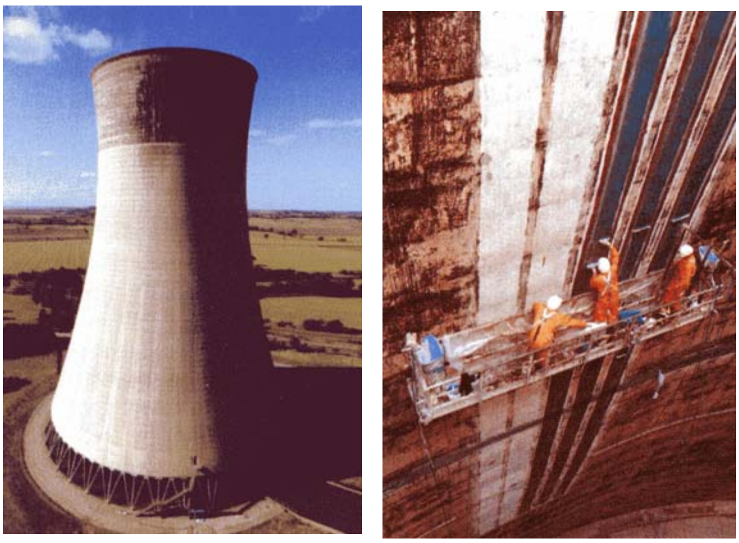
2.3 Basic strengthening technique

The basic FRP strengthening technique, which is most widely applied, involves the manual application of either wet lay-up (so-called hand lay-up) or prefabricated systems by means of cold cured adhesive bonding. Common in this technique is that the external reinforcement is bonded onto the concrete or masonry surface with the fibers as parallel as practically possible to the direction of principal tensile stresses. Typical applications of the hand lay-up and prefabricated systems are illustrated in Fig. 2.6.

Column wrapping using CFRP

Impregnation of fabric with epoxy resin

Application of pre-impregnated fabric



Strengthening of cooling tower with carbon fabrics

Preparation (levelling) of masonry substrates for the bonding of CFRP strips

Strengthening of vaults with CFRP strips

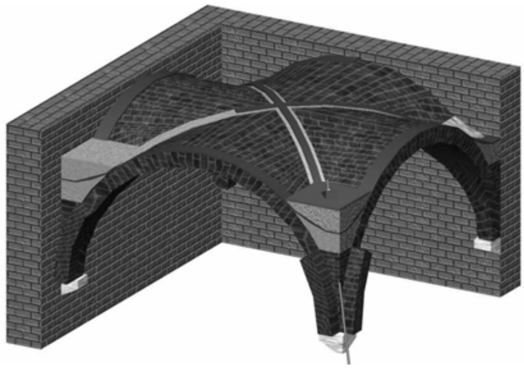


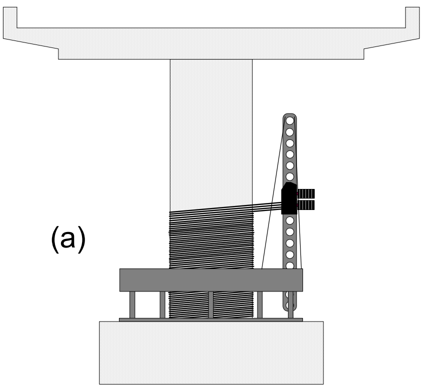
Fig. 2.6 Examples for the application of the basic FRP strengthening technique.

2.4 Special techniques

Apart from the basic technique there are a number of special techniques with rather limited applicability: *automated wrapping*, *prestressed FRP*, *in-situ fast curing using heating device*, *prefabricated shapes, near-surface-mounted bars*, *mechanical fastening, textile-reinforced mortar jacketing* etc. A brief description is given next.

2.4.1 Automated wrapping

(a)



(b)

Fig. 2.7 Automated RC column wrapping. (a) Schematic. (b) Photograph of robot-wrapper.

The strengthening technique through automated winding of tow or tape was first developed in Japan in the early 90s and a little later in the USA. The technique, illustrated in Fig. 2.7, involves continuous winding of wet fibers under a slight angle around columns or other structures (e.g. chimneys, as has been done in Japan) by means of a robot. Key advantage of the technique, apart from good quality control, is the rapid installation.

2.4.2 Prestressed FRP

In some cases it may be advantageous to bond the external FRP reinforcement onto the concrete surface in a prestressed state. Both laboratory and analytical research (e.g. Triantafillou et al. 1992, Deuring 1993) has shown that prestressing represents a significant contribution to the advancement of the FRP strengthening technique, offering several advantages: delay of cracking and limitation of crack widths, increased stiffness, increased flexural and shear resistance etc.). The main drawbacks of this technique are associated with the increased complexity and the higher cost, due to the need for special anchorage devices (e.g. Fig. 2.9).

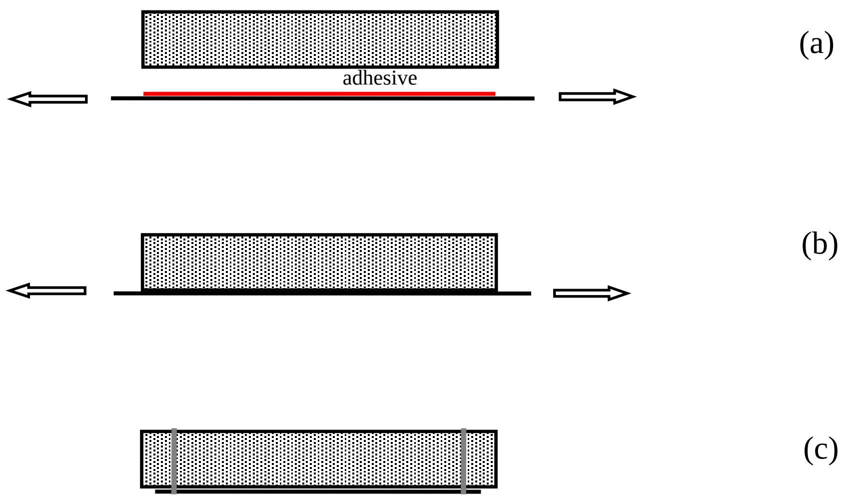
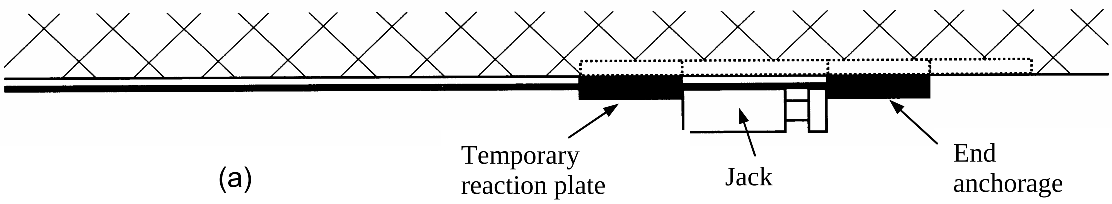
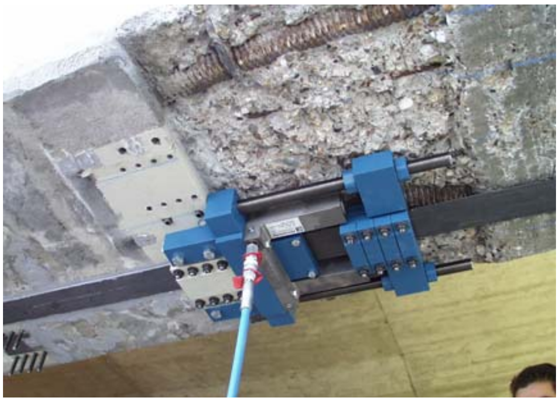


Fig. 2.8 Strengthening with prestressed FRP strips: (a) prestressing; (b) bonding; (c) end anchorage and FRP release upon hardening of the adhesive.





(b)

Fig. 2.9 (a) Schematic illustration and (b) photograph of FRP anchorages.

Prestressing can also be applied to column jackets (active confinement), e.g. by pretensioning the fiber bundles during winding or with unstressed jackets by making use of expansive mortar or injection of mortar or epoxy under pressure (Fig. 2.10).

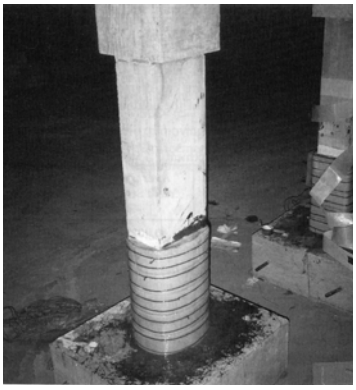
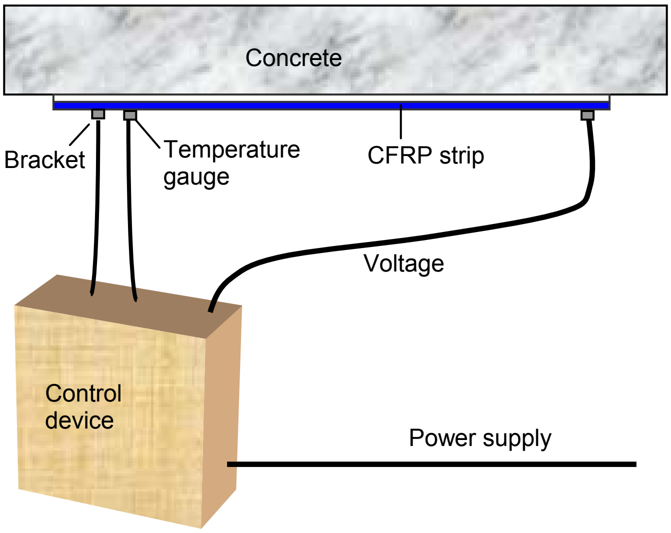


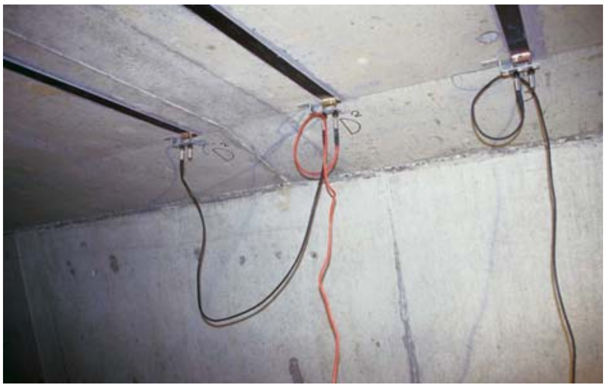
Fig. 2.10 Elliptical jacket filled with expansive mortar at the base of a reinforced concrete column.

2.4.3 In-situ fast curing using heating device

Instead of cold curing of the bond interface (curing of the two-component epoxy adhesive under environmental temperature), heating devices can be used. In this way it is possible to reduce curing time, to allow bonding in regions where temperatures are too low to allow cold curing, to apply the technique in winter time, to work with prepreg FRP types, etc. Different systems for heating can be used, such as electrical heaters, IR (infrared) heating systems and heating blankets. For CFRP the system illustrated in Fig. 2.11 is also possible. This system takes advantage of the electrical conductivity of carbon fibers and uses a special heating device to pass an electric current through CFRP strips during the strengthening process. The control unit allows the desired curing temperature to be maintained within a narrow range. Controlled fast curing enables not only rapid application of the strengthening technique (e.g. full curing at 70 ^{o}C may be achieved in 3 hours) but also increases the glass transition temperature of the adhesive.



(a)



(b)

Fig. 2.11 Fast curing using heating device: (a) Schematic, (b) Photograph of end brackets.

2.4.4 Prefabricated shapes

Prefab type of composite material systems are mostly applied in the form of straight strips. However, these prefab systems can also be produced in other forms, depending on the foreseen application. By shaping them, prefab systems can be employed in applications where normally the more flexible wet lay-up systems are used. For shear strengthening of beams, pre-manufactured angles (about 1 mm thick and 50-100 mm wide) can be used as shown in Fig. 2.12a-c. Figure 2.12d-e shows prefab shells or jackets which can be used for the confinement of circular and rectangular columns. In this case, the shells should be fabricated with sufficiently small tolerances.

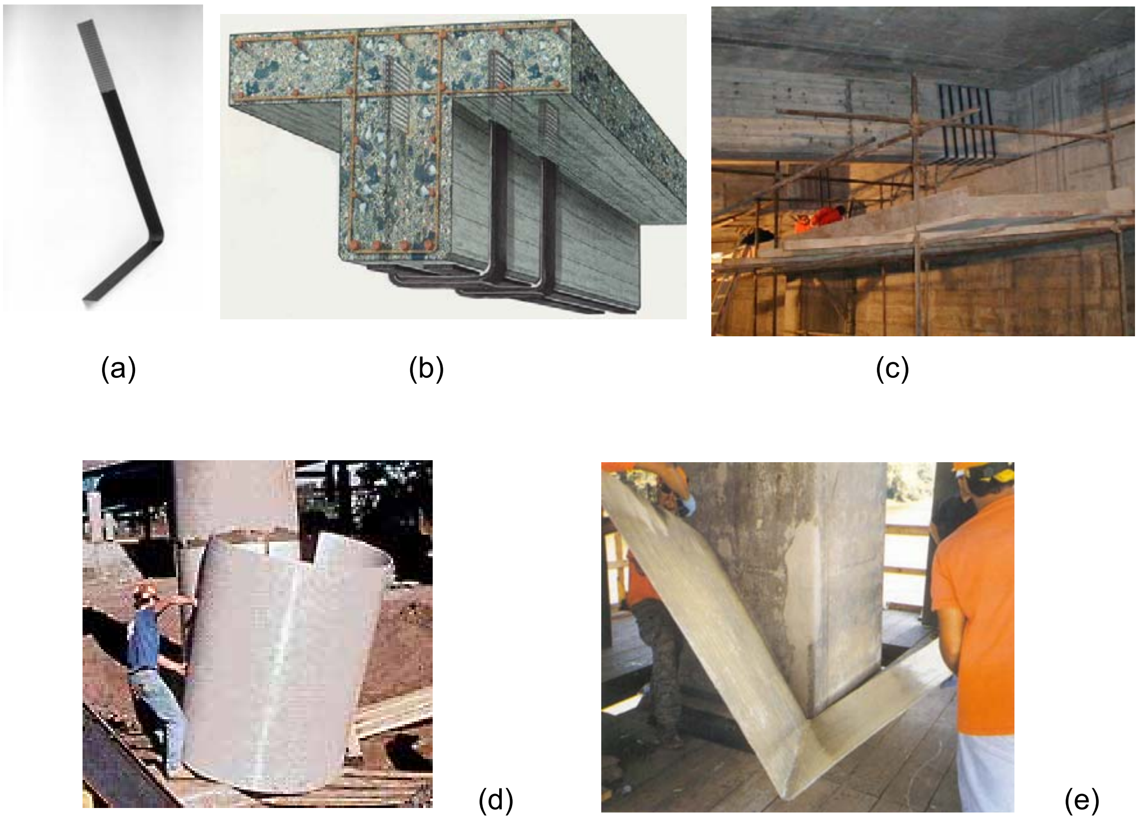
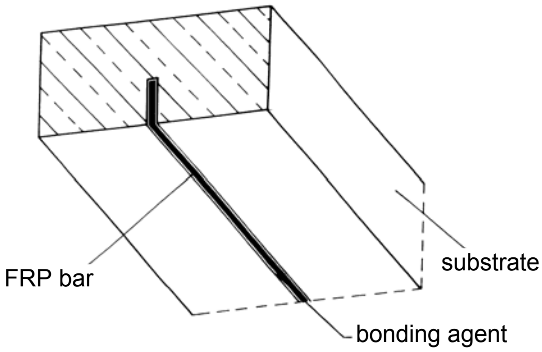


Fig. 2.12 Examples of prefab shapes for strengthening. (a) Angle, (b)-(c) application of angles in shear strengthening of beams, (d) shell-shaped jacket, (e) jacket applied in pieces to rectangular column.

2.4.5 Near-surface mounted reinforcement

The use of FRP bars bonded using epoxy resin or special mortars into slits or grooves near the surface of concrete or masonry (Fig. 2.13, 2.14) typically aims at increasing the flexural resistance of RC members or the in-plane shear resistance of unreinforced masonry. Main advantages of this technique are the improved bond characteristics of FRP as well as their better protection against demolition, weathering etc.



(a)

(b)

Fig. 2.13 Use of FRP strips inside slits: (a) Schematic illustration, (b) photograph.

2.4.6 Mechanically-fastened FRP

A method has been developed in the past few years (e.g. Lamanna et al. 2001) where the strengthening strips are entirely mechanically attached to the concrete surface using multiple small, distributed powder actuated fasteners, sometimes in combination with anchor bolts at the strip ends, without any bonding (Fig. 2.14). This system requires simple hand tools, lightweight materials and minimally trained labor. Unlike the conventional method of adhesively bonding FRP strips to the concrete surface, this strengthening technique does not require significant surface preparation and allows for immediate use of the strengthened structure.

(a)

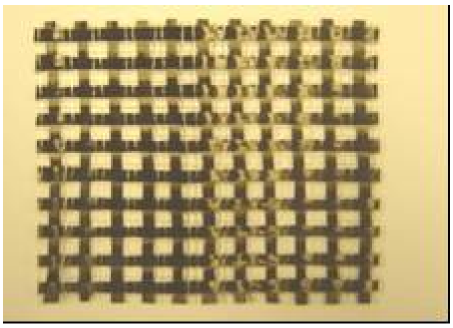
(b)

Fig. 2.14 (a) Mechanically-fastened FRP. (b) Detail of end anchorage with a combination of anchors and powder actuated nails.

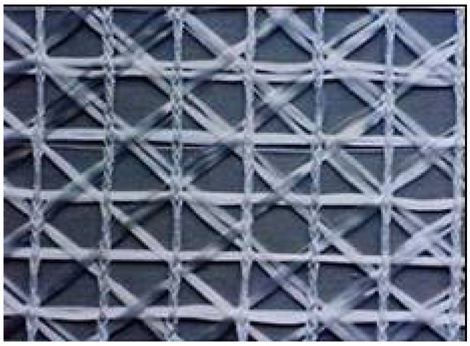
RC elements strengthened with the conventional method (of adhesively bonding FRP strips) exhibit a tendency to fail in a brittle fashion, with a sudden debonding of the strip. However, suitably designed mechanically fastened strips enable a more ductile failure, due to the partial shear connection at the strip concrete-interface as a result of strip compression failure at the points of contact with the fasteners, possibly combined with fastener pull-out and/or bending. One of the key requirements for this desirable failure mechanism to be activated is the proper design of strips with fibers in many directions, so that sudden shearing type of failures in the strips may be avoided.

2.4.7 Application of textile-reinforced mortar (TRM) jacketing

Despite its great advantages over other conventional techniques in a variety of applications, the FRP strengthening technique suffers from some problems associated with the epoxy resins, including the problematic behavior at high temperatures and the relatively high cost. One possible solution to alleviate these problems would be the mere replacement of resins with inorganic binders. However, as a consequence of the granularity of the mortar, penetration and impregnation of conventional fiber sheets is very difficult to achieve; also, mortars cannot wet individual fibers, unlike resins. Bond conditions in cementitious composites could be improved and fiber-matrix interactions could be made tighter when continuous fiber sheets are replaced by textiles. These materials comprise fabric meshes made of long woven, knitted or even unwoven fiber rovings in at least two (typically orthogonal) directions (Fig. 2.15).



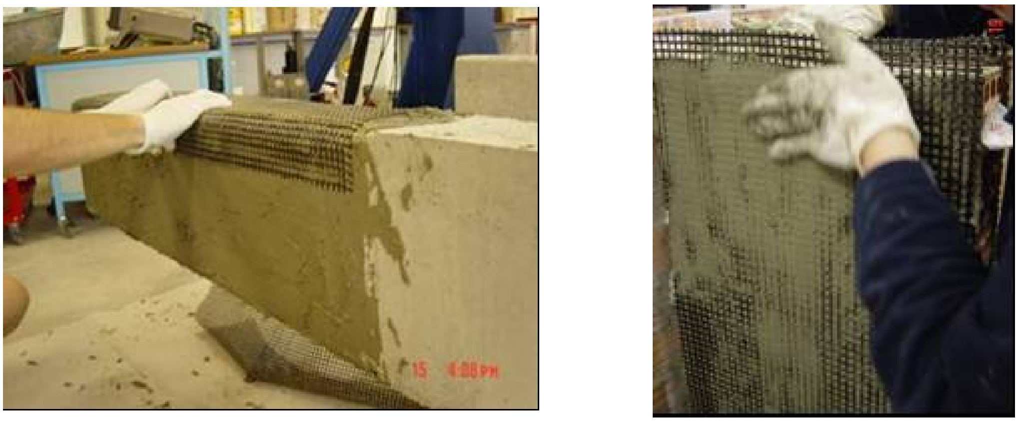
(a)



(b)

Fig. 2.15 (a) Bidirectional carbon fiber and (b) multidirectional glass fiber textiles.

The density, that is the quantity and the spacing, of rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the textile and the degree of penetration of the mortar matrix through the mesh. The combination of textiles with mortars has led to the development of the so-called TRM-strengthening technique (Fig. 2.16), which appears exctremely promising for jacketing of RC members (Triantafillou et al. 2006, Triantafillou and Papanicolaou 2006) as well as for strengthening of unreinforced masonry.



(a) (b)

Fig. 2.16 Textile-reinforced mortar (TRM) jacketing.