Chapter 6

STRUCTURAL INTERVANTIONS WITH COMPOSITE MATERIALS

6.1 Introduction: Applications and general characteristics

The rapid progress made in the technology of building materials in recent years has resulted in the development of a range of new products that can be used in many applications of Civil Engineering, where the exclusive use of conventional materials fail to provide a satisfactory solution . Among these products a significant position is held by composites of fiber reinforced polymer (fiber reinforced polymer composites). They count of 'fabric' of fiber reinforced polymer impregnated with special epoxy resins. The 'fabric' is placed on the surfaces of structural membersproviding additional reinforcement. Mainly due to the persistence in electrochemical corrosion and high strength to weight rationing of they provide is a very good option to solve problems related to repair and strengthen structures.

During the last fifteen years researchers from around the world have developed many applications of composite materials of fiber reinforced polymers* for reinforcing structures for static and seismic loads concrete structures, (Figure 6.1) unreinforced masonry and steel structures etc. The efforts of these researchers have led an impressive evolution of the method for strengthening structures with composite materials. The first large-scale applications has been performed at the beginning of last decade.

The first widespread application of composite materials has been the strengthening two thousand bridge abutments in Yolo west of Sacramento, the capital of California in the middle of **decade very**

---

* For simplicity, the composite materials of fiber reinforced polymers will be reported later in this chapter simply as composites.

fard. Their use was extended to all types of technical projects in both the U.S. and many other countries in the Americas, Europe and Asia (Figure 6.2). It is characteristic that in Japan, a country with very high seismic hazard, the use of composite materials of fiber reinforced polymers dramatically increased in the period 1992-1995 and particularly after the earthquake Hyogoken-Nangu in 1995 at 500%. In Greece, civil engineering applications are mentioned by early 1990 (Chalcis)

.

Figure 6.1 Column with Aid FRP underground car park Dublin, Ireland

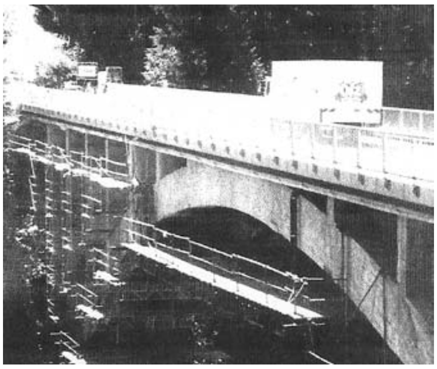


Figure 6.2.: Strengthen composite bridge materials in the Austrian Alps

.

The basic principles for the design of jackets composite materials are consistent with the concepts of metal jacketing. Compared with the use of metal plates for reinforcement of structural elements, the alternative application of fiber reinforced polymers has significant advantages such as excellent strength to weight properties, the availability of material in relatively unlimited length, the comparatively easier installation and resistance to corrosion. These advantages make composites a very attractive alternative.

Generally, the application of these materials has resulted in an increase or rather the modification of bending, shear and axial resistance of the member. External strengthening with fiber reinforced polymers are suitable for many applications. Typical uses are:

- Increase of the carrying capacity. As an example, one can mention the strengthening of a parkong structure in Munich and Dublin, Ireland as well as industrial buildings in the town of Zug, in Switzerland.
- Passive confinement to optimize the capacity to resist seismic loads. Typical applications are the strengthening of the bridge Osaky in South Korea and the viaduct Belo Horizonte in Sao Paulo, Brazil.
- *Greek Control and patching of the cracks*.Composite materials have been used to the repair and strengthen of listed buildings, monuments and archaeological and historical buildings that have developed cracks and other types of damages. Examples include the strengthening of the dome of the historic cathedral in British Columbia, Canada

Despite the high expectations that have grown, use of composite materials of fiber reinforced polymers have a relatively brief history. Consequently, the decision on the repair and strengthening of structures with fiber reinforced polymers must be taken with extreme caution and considered together after all other options. Use of fiber reinforced polymer should generally be avoided in the following cases:

- The state of the sub-surface on which to apply the composite material is unknown or has suffered significant impairment of resistance..
- There is ongoing significant corrosion of steel reinforcement..
- No sufficient steel reinforcement to ensure duchile behavior of the member to be strengthened.

The main advantages of using composites for the repair and strengthening of structures compared to traditional methods of repair and reinforcement using conventional materials are:

- A Little preparation on site. Evacuation is not necessary and disturbance to users is minimal. The preparation of the support members is small and short.
- The application of composite materials is simple.
- The dimensions of the supported member remain essentially unchanged, due to the small thickness of the composite materials.

- Placement of composite materials is possible even in cases where there is a limitation of working space (eg columns in a partition wall).
- The weight of the composite material is small and its installation does not require special or heavy equipment
- The composites can be coated and colored according to the aesthetic requirements of the project.
- The architectural characteristics of structures remain practically unchanged.
- The cost of composite materials is similar to traditional methods of repair and strengthening.

Finally it is worth mentioning that the engineers who choose to use fiber reinforced polymers structurals strengthening face a big challenge. This is primarily to the fact that the technology is not widely known in the technical world in comparison with the corresponding conventional technology of repair using steel and concrete. For this reason this chapter is rather extensive in order to clarify several, concepts associated with the use of composite materials.

.

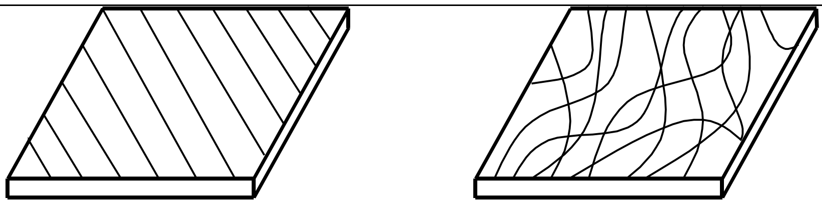
6.2 Categories composites

- With the wider use of the term, are developed by combining two or more materials composite materials. The composites of fiber reinforced polymers, on which mainly focuses this chapter, are constituent elements of high-strength fibers and high modulus in a thick toughened matrix. In this form, both the fiber and the matrix retain their physical and chemical properties, while generating a combination of properties that can not be achieved by any of the constituents when acting alone. Bonding of oriented fibers on the softer matrix material results in a fiber-reinforced polymer composite material with superior properties along the fiber direction. Depending on the combination of materials, composite materials can be divided into three categories

- fiber composite materials (fibrous composites) consisting of fiber impregnated resin or not.
- Composite materials layers (laminated composites) consisting of layers of different materials.
- Composite materials particles (particulate composites) consisting of particles of various materials in a body.

Based on the direction of the fibers are two general categories of fiber composites

- Oriented (directional), whose fibers are continuous and all have the same direction (Figure 6.3a).
- Non-directional (random), whose fibers are randomly placed in the composite material (Figure 6.3v).

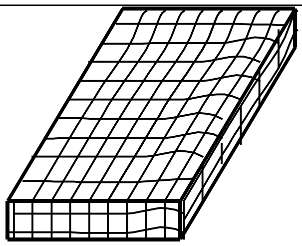


ό(a) composite Oriented *ό(b) Non-oriented composite*

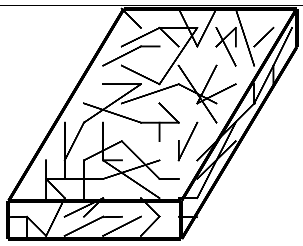
Figure 6.3.: General types of fibrous composites

In composites, fibres, are placed in different ways depending on the needs of each application. Depending on the placement method and the fiber combination in the compote, the composite, can be classified into the following four categories: :

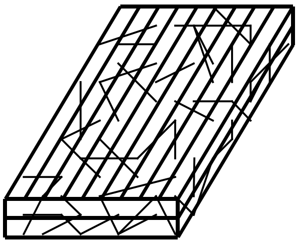
- Woven fiber, which form a continuous body without the individual layers. This way to detachment (Figure 6.4a). But their resistance is reduced because of high stress concentration, and use a high percentage of resin.
- Chopped fiber, which contain short fibers dispersed in the resin (Figure 6.4v). The mechanical strength is generally lower than those with continious fiber.
- Hybrid, which consist of either continuous or discontinuous fibers (Figure 6.4g) or more than one type of fiber (eg glass and graphite). They are used when the composite fiber does not have by iself the desired properties.
- Continuous fiber, in which strength layers of continuous fiber-resin are placed in the desired direction and form a body (Figure 6.4d). They excibit great, but separation between layers is possible.



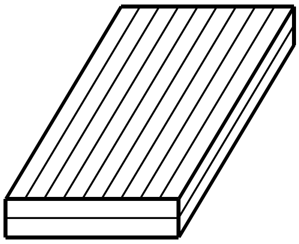
(α) Σύνθετο υλικό πλεκτών ινών.



(β) Σύνθετο υλικό ασυνεχών ινών.



(γ) Υβριδικό σύνθετο υλικό.



(δ) Σύνθετο υλικό συνεχών ινών.

Σχήμα 6.4.: *Τύποι σύνθετων υλικών ινών.*

The composites of fiber reinforced polymers are used to repair and strengthen structures that mainly belong to the category of oriented continuous fiber composites (directional continuous fibrous composites). Due to the orientation of the fibers, the composite material of the type is anisotropic excibiting a behaviour similar to reinforced concrete. The anisotropic behavior allows the designer orient the layers of the composite material in order to strengthen the structural member in the direction of the anticipated higher stresses primarily transfer the load.

6.3 Properties of composite materials of fiber reinforced polymers

As mentioned above, typical properties of composites include low specific weight, high strength to weight ratio and high modulus of elasticity to weight ratio. Also, most composites of fiber reinforced polymers are highly resistant to electrochemical corrosion. Another feature of composite materials of fiber reinforced polymer is an almost linear stress-strain relation up to failure. Although the materials that compose the matrix are capable of plastic deformation, the fibers generally behave only elastically. But since the behavior of the composite material is mainly determined by the behavior of the fibers, which very rarely fiber reinforced polymers used for repair and strengthen structures. Unlikely, fracture is the typical type of failure of a composite material ultimate stress conditions.

The three most common types of fibers used in fiber reinforced polymer composites are fiberglass, carbon fiber and the fiber polyaramidis.

(α) glass fibers. Fiberglass first appeared commercially in 1939. Produced mechanically by glass melts. The main feature of glass is that it has neither fully crystalline nor properties fluid. Depending on the type of application for which they were developed, there are six different types of fiberglass. Of these, two types that are used to repair and strengthen structures is the-E glass and the S-glass. Although, as shown in Table 6.1, the S-glass has a higher tensile strength and modulus of the E-glass because of its high cost has limited application in relation to the latter.

.

Table 6.1.: *Properties of E-glass and S-glass*

Type of glass fiber	**Tensible strength (MPa)**	**Modulus of elasticity (GPa)**	**Failur strain (%)**	**Densidy (gr/cm^3)**
ύαλος-E	2000 – 3000	70 – 75	3.0 – 4.5	2.54
ύαλος-S	3500 – 4800	85 – 90	4.5 – 5.5	2.48

Although the glass fibers, are resistant to most solvents, they react with some alkali and strong acids. Glass provides excellent thermal and electrical insulation. The sheets of glass are less resistant to fatigue the sheets the coal or polyaramidis, but more than most metals. Like coal, glass dies not excihib creep deformation of, but it is vulnerable to erosion. It should be noted that these properties are strongly influenced by environmental conditions as well as chosen matrix to produce the composite material.

(β) carbon fibers . Carbon fibers have been commercially available since late 50. The coal is produced from polyakrylonitrilio, tar (a by-product of oil refining) or rayon through pyrolysis at very high temperature (often up to 3000 ° C). Through pyrolysis cyanide and various hydrogen atoms are removed from the polycarbonate. The formed crystalline carbon sheets are intensified in order to orient parallel to the axis of the fiber. This way, crystals solidify at an optimal layout. Theoretically, carbon fibers can develop mechanical

properties excibiting tensible strength close to 100 GPa and modulus of elasticity1000 GPa. However, such high properties are generally not fully developed because of defects in the crystalline structure.

The carbon fibers that are commercially available have a tensile strength ranging from 2100 MPa to 6800 MPa with mean valuesin the range of around 3500 MPa and tensile modulus from 215 GPa to 700 GPa. The stram at break ranges from 0.2 to 2.5% depending on the type of yarn and manufacturing method.
The carbon fibers are chemically inert to most solvents, whether they acidic or alcoli. In addition, they have high resistance to high temperatures. The sheets of carbon fiber and epoxy resin are resistant to fatigue, creep and corrosion. Has high conductivity and can cause galvanic corrosion of metals in contact with it. For this reason, direct contact of steel or aluminum with carbon fiber should be avoided. It should be noted that the cost of carbon fiber, although still quite high compared with other types of fiber, has significantly declined in recent years.

•

(γ) Polyaramidis Fiber. The brand name of the first fiber polyaramidis marketed in the early 1970's is Kevlar. The use of fiber composites polyaramidis in construction works is limited compared to fiberglass and carbon fiber. Their main application is the construction of armor for impact loads.
Because the chemical structure of polymer, the fibers have a large modulus of elasticity and high density. Although some of the fibers of this category of elasticity mean have a tensile strength from 3500 έως 4100 MPa and modulus of about 175 GPa, which in exceptional cases can reach up to 210 GPa, the value of tensile strength is 3800 MPa, while the modulus ranges from 70 to 130 GPa. The elongation at break is between 2.5 and 5.0%.They also excibit for high resistance to fatigue and abrasion resistant to solvents, except strong acids and bases. Because they are hydrophilic, they show partial loss of strength in a hot environment with high humidity. The compressive strength is significantly lower than the corresponding tensile (about 20%), and yet, at a given stress they creep.
Besides the three main categories, that presented, have been other types of fibers used in several civil engineering applications include:

- graphite fibers, produced as carbon fibers by pyrolysis. The graphite fibers contain at least 99% of carbon, while the percentage of carbon of the carbon fibrs is less than 95%
- boron fibers: move the largest diameter (0.05-0.2 mm) compared with other fibers. Their strength and stiffness are greater than those of graphite fibers. .
- Silicon carbide Fiber: they have high resistance to oxidation and resistance to high temperatures.

6.3.1 Composite Materials Fibers

Resins are commonly used as matrices for the production of fiber composites. Resin is the binder between the fibers and simultaneously contributes to resistance and electrical insulation of the composite material. To develop a strong mechanical and chemical bonding between fibers and resin, it is necessary to develop a link between them. It should also be chemically compatible so that no side reactions take place between them. The resins of such type are at least an order of magnitude weaker than the fibers which are impreguated. They are more sensitive to heat and fire, and generally have greater sensitivity to chemical solvents, acids, alcali and water in relation to the fibers. All types of resins are excibit creep defomation compared with traditional building materials. Nevertheless, the fiber reinforced polymer composites could not be developed without the resins as they are transfering the load and distribute it to the fibers of each layer of the polymer. Thereby enabling the fiber-reinforced polymer to behave almost like a homogeneous material.
The long life characterizes the polymer matrices associated with the gradual change of their physical properties, which evolves over time and load. Prestressing composites can have very significant impact on the life of the matrix polymer. The creep rupture, a typical failure mode of fiber reinforced polymer, can the attributed to the ixodoplastic behavior of the polymer matrix rather than fiber.
These resins that are commonly used to produce composite materials for repairing and strengthening structures are epoxy, polyester and vinyl ester. The most important mechanical properties of these three classes of resins are shown in Table 6.2.

.

(α) Epoxy Resinsς. The epoxy resins are generally considered the best matrix for use in fiber reinforced polymers because of their high resistance, adhesive characteristics, resistance to fatigue and corrosion, as well as low shrinkage presented under curing. As with other types of resins, the

properties of epoxy resin vary considerably depending on the resin base and the chemicals used for their production.
The rate of viscosity of epoxy resins is generally higher than the rate of either polyester and vinyl resins. They also need more time to fully develop their mechanical properties and a higher cost than the other two types of resins.

Table 6.2.: *Resin Properties*

Type of resin	Flexural Strength (MPa)	Modulus of Elasticity (GPa)	Deformation of failure (%)	Density (gr/cm^3)
Epoxy	55 – 130	2.0 – 4.5	4.0 – 14.0	1.20 – 1.30
Polyesteric	35 – 104	2.1 – 4.1	< 5.0	1.10 – 1.46
Vinylester	73 – 81	3.0 – 3.6	3.5 – 5.5	1.12 – 1.32

(β) Polyester Resins. These resins are the bulk of the polymers used in the composites industry. These unsaturated polyesters are produced by the reaction of glycol or dibasic acids or anydrides. Because of the wide variety of components, the properties of polyester resins can vary widely. The chemical reaction by which polyester resins are produces is significantly exothermic. For this reason great care is required to use the proper amount of mass of the reactants. If the mass is a large, the polyester sheet can ignite or fragment. However, when the mass is small, the heat released is insufficient to complete the reaction.
The polyesters have moderate resistance to solvents and acids, while they are vulnerable to water and high temperature. They are generally less resistant to fatigue compared to epoxy and vinyl ester resins. The deformation at break is typically of the order of 1%. However, the main drawback of polyester resins for their application to buildings is the unpleasant smell attributed their chemical composition.

(γ) Ester vinyl resins. These hybrid resins are produced by a chain reaction of epoxy polymer with acrylic or methacrylic compounds. Because of the presence of the epoxy polymer, ester vinyl resins are more flexible, tougher, more resistant to fatigue and less chemically active than polyester resins. The Hydroxy compounds in the epoxy polymer form hydrogen bonds with corresponding groups on the surface of glass fiber. Thereby, significantly improving the bond between the fibers and the resin, though not to the deyrec of bond development of epoxy resins. This is mainly attributed to the large volume loss of the vinyl resins during shrinking.

In contrast, ester vinyl resins excibit both high strength and resistance to fatigue as the epoxy. Because of their chemical composition, there are also characterized by the same problem of odor as polyester resins. The shrinkage is generally in the range of 5 to 10%. Their cost is generally between the cost of epoxy and polyester resins.

6.3.2 Composite Material Properties

The properties of composite material combination of the properties of the individual components of the materials, i.e., fiber and resin. Table 6.3 shows the tensile strength, modulus of elasticity and thickness of one layer of the two most common types of fiber reinforced polymers used to strengthen structural elements. These properties result by combining or glass fiber and epoxy resin or carbon fiber and epoxy resin.

Table 6.3 *Representative properties of fibers and resins of FRPs*

Type of Fiber	**Flexural Strength (MPa)**	**Modulus of Elasticity (GPa)**	**Thickness of fiber layer (mm)**
Υαλονήματα και εποξική ρητίνη	1800 – 4300	65 – 80	0.30 – 1.30
Ανθρακονήματα υψηλής αντοχής και εποξική ρητίνη	2200 – 4300	200 – 450	0.12 – 0.60

Available to the engineer are also in the form of narrow plates and thickness of 2 and half mm prefabricated composite materials with carbon fibers which are stuck to the concrete by resin. Used primarily to support slabs and beams. In the case of beams, use of such narrow plates restricted to narrow beams with a width in the range of 10 cm.

6.4 Micromachining composites

As mentioned before, the characteristics and properties of a composite material results from the properties of the fiber lamina and resin. From the perspective of micromechanics in order to determine the properties of the composite material one should know the percentage by which each material in the final product.
The Law of Composition (Rule of Mixtures) uses participation rates of fiber and resin in the final product to predict the mechanical properties of composite materials. The law of composition is described by the following

relations:

$$v_f + v_m + v_u = 1 \tag{6.1}$$

$$w_f + w_m = 1 \tag{6.2}$$

$$\rho_c = \rho_f\ v_f + \rho_m\ v_m \tag{6.3}$$

where vf, vm and vu is the volume ratio of fibers, resin and voids, respectively and is equal to vi = Vi / V, where V is the total volume of the composite material and Vi with i = f, m, u is the voids volume of the fibers, resin and gaps, respectively. Also, w_f and w_m is the weight ratio of fibers and resin and is equal to wi = Wi / W, where W is the total weight of the composite material and Wi with i = f, m is the weight of the corresponding component. Finally, if ρ_m and ρ_c is the density of fibers, resin, and the overall composite, respectively.
Also, the relationship between the modulus of elasticity of the composite material with the modulus of the fiber E_f and the modulus of the matrix E_m is the following:

$$E = E_f\, v_f + E_m\, v_m \tag{6.4}$$

The tensile strength of the composite material is primaly dependent on the tensile strength of the fibers, since their strength is an order of magnitude higher than that of the matrix. In practice, failure of the fiber results in failure of the composite material.
If s, s_f, and s_{mf} is the tensile strength of the composite, the tensile strength of the fiber and the matrix tensile stress at failure of the fiber, respectively, then,

$$s = s_f\ v_f + s_{mf}\ (1 - v_f) \tag{6.5}$$

Application. In order to demonstrate the application of these relations, consider a carbon - epoxy resin FRP with dimensions 2.54 cm x 2.54 cm x 0.30 cm, that weighs 2.980 gr. The densities of carbn and the resin is r_f = 1.9 gr/cm3 and r_m = 1.2 gr/cm, respectively. Disolving the resin with acid, the remaining is fibers weigh 1.863 gr. Calculate the volume rations of fiber v_f resin v_m resin and voids v_u.

The density of the composite material is

$$\rho_c = W/V = 2.98 / (2.54\times2.54\times0.3) = 1.54 \text{ gr/cm}^3$$

Thus, according to relations (6.1) and (6.2) the volume ratio of voids, v_u is

$$v_u = 1 - (v_f + v_m) = 1 - [W_f / \rho_f + (W - W_f)/ \rho_m] / V =$$
$$= 1 - [1.863/1.9 + (2.98 - 1.863)/1.2] / (2.54\times2.54\times0.3) =$$
$$= 0.012 = 1.2\%$$

Therefore, $v_f + v_m = 0.988$, thus, the relations hip (6.3) gives

$$\rho_c = \rho_f\, v_f + \rho_m\, v_m \Rightarrow$$
$$\Rightarrow 1.54 = 1.9\, v_f + 1.2\,(0.988 - v_f) \Rightarrow$$
$$\Rightarrow v_f = 50.6\%$$

In summary the result is

$$v_f = 50.6\%\ ,\ v_m = 48.2\%\ ,\ v_u = 1.2\%$$

EuRoCODE 8 Part 3 1998-3: 2005

condition is necessary for the jacket to be able to control the width of internal cracks and to ensure the integrity of the concrete, thus allowing the original shear resisting mechanism to continue to operate.

(2) If only 50% of the steel yield strength of the jacket is used, the expression for the additional shear V_j carried by the jacket is:

$$V_j = 0{,}5\frac{2t_j b}{s} f_{yj,d} \frac{1}{\cos\alpha} \qquad \text{(A.21)}$$

where:

t_j is the thickness of the steel straps,

b is the width of the steel straps, and

s is the spacing of the steel straps ($b/s = 1$, in case of continuous steel plates), and

$f_{yj,d}$ is the design yield strength of the steel of the jacket, equal to its nominal strength divided by the partial factor for structural steel in accordance with EN1998-1: 2004, **6.1.3(1)**P.

A.4.3.3 Clamping of lap-splices

(1) Steel jackets can provide effective clamping in the regions of lap-splices, to improve cyclic deformation capacity. For this result to be obtained the following is necessary:

- the length of the jacket exceeds by no less than 50% the length of the splice region,
- the jacket is pressured against the faces of the column by at least two rows of bolts on each side normal to the direction of loading,
- when splicing occurs at the base of the column, the rows of bolts should be located one at the top of the splice region and another at 1/3 of that region, starting from the base.

A.4.4 FRP plating and wrapping

A.4.4.1 Introduction

(1) The main uses of externally bonded FRP (fibre-reinforced polymers) in seismic retrofitting of existing reinforced concrete elements are as follows:

- Enhancement of the shear capacity of columns and walls, by applying externally bonded FRP with the fibers in the hoop direction,
- Enhancement of the available ductility at member ends, through added confinement in the form of FRP jackets, with the fibres oriented along the perimeter,
- Prevention of lap splice failure, through increased lap confinement again with the fibers along the perimeter.

(2) The effect of FRP plating and wrapping of members on the flexural resistance of the end section and on the value of the chord rotation at yielding, θ_y, may be neglected

(θ_y may be computed in accordance with **A.3.2.4(2)** to **(4)**, with $l_{oy,min}$ taken equal to $0,2d_{bL}f_{yL}/\sqrt{f_c}$, in **A.3.2.4(4)**).

A.4.4.2 Shear strength

(1) Shear capacity of brittle components can be enhanced in beams, columns or shear walls through the application of FRP strips or sheets. These may be applied either by fully wrapping the element, or by bonding them to the sides and the soffit of the beam (U-shaped strip or sheet), or by bonding them to the sides only.

(2) The total shear capacity, as controlled by the stirrups and the FRP, is evaluated as the sum of one contribution from the existing concrete member, evaluated in accordance with EN 1998-1: 2004 and another contribution, V_f, from the FRP.

(3) The total shear capacity may not be taken greater than the maximum shear resistance of the concrete member, $V_{R,max}$, as controlled by diagonal compression in the web. The value of $V_{R,max}$ may be calculated in accordance with EN1 992-1-1: 2004. For concrete walls and for columns with shear span ratio, L_V/h, less or equal to 2, the value of $V_{R,max}$ is the minimum of the value in accordance with EN 1992-1-1: 2004 and of the value calculated from **A.3.3.1(2)** and **A.3.3.1(3)**, respectively, under inelastic cyclic loading.

(4) For members with rectangular section, the FRP contribution to shear capacity may be evaluated as:

– for full wrapping with FRP, or for U-shaped FRP strips or sheets,

$$V_{Rd,f} = 0{,}9d \cdot f_{fdd,e} \cdot 2 \cdot t_f \cdot \left(\frac{w_f}{s_f}\right)^2 \cdot (\cot\theta + \cot\beta) \cdot \sin\beta \tag{A.22}$$

– for side bonded FRP strips or sheets as:

$$V_{Rd,f} = 0{,}9d \cdot f_{fdd,e} \cdot 2 \cdot t_f \cdot \frac{\sin\beta}{\sin\theta} \cdot \frac{w_f}{s_f} \tag{A.23}$$

where:

d is the effective depth,

θ is the strut inclination angle,

$f_{fdd,e}$ is the design FRP effective debonding strength, which depends on the strengthening configuration in accordance with **(5)** for fully wrapped FRP, or **(6)** for U-shaped FRP, or **(7)** for side bonded FRP,

t_f is the thickness of the FRP strip, sheet or fabric (on single side),

β is the angle between the (strong) fibre direction in the FRP strip, sheet or fabric and the axis of the member,

w_f is the width of the FRP strip or sheet, measured orthogonally to the (strong) direction of the fibres (for sheets: $w_f = \min(0{,}9d, h_w) \cdot \sin(\theta + \beta)/\sin\theta$) and

s_f is the spacing of FRP strips (= w_f for sheets), measured orthogonally to the (strong) fibre direction.

(5) For fully wrapped (i.e., closed) or properly anchored (in the compression zone) jackets, the design FRP effective debonding strength may be taken in expressions (A.22), (A.23) as:

$$f_{\mathrm{fdd,e,W}} = f_{\mathrm{fdd}} \cdot \left[1 - k\frac{L_{\mathrm{e}}\sin\beta}{2z}\right] + \frac{1}{2}\left(f_{\mathrm{fu,W}}(R) - f_{\mathrm{fdd}}\right) \cdot \left[1 - \frac{L_{\mathrm{e}}\sin\beta}{z}\right] \qquad \text{(A.24)}$$

where:

$z = 0{,}9d$ is the internal lever arm,

$k = \left(1 - \frac{2}{\pi}\right)$, and:

$$f_{\mathrm{fdd}} = \frac{1}{\gamma_{\mathrm{fd}}}\sqrt{0{,}6\frac{E_{\mathrm{f}}\, f_{\mathrm{ctm}}\, k_{\mathrm{b}}}{t_{\mathrm{f}}}} \qquad \text{(units: N, mm)} \qquad \text{(A.25)}$$

is the design debonding strength, with:

γ_{fd} the partial factor for FRP debonding,

NOTE The value ascribed to γ_{fd} for use in a country can be found in its National Annex. The recommended value is γ_{fd}=1,5.

E_{f} the FRP sheets/plates modulus,

f_{ctm} the concrete mean tensile strength,

$k_{\mathrm{b}} = \sqrt{1{,}5 \cdot (2 - w_{\mathrm{f}}/s_{\mathrm{f}})/(1 + w_{\mathrm{f}}/100\ \mathrm{mm})}$ the covering coefficient,

in which:

w_{f}, s_{f}, t_{f} are as defined in **(4)** and

$f_{\mathrm{fu,W}}(R)$ is the ultimate strength of the FRP strip or sheet wrapped around the corner with a radius R, given by:

$$f_{\mathrm{fu,W}}(R) = f_{\mathrm{fdd}} + \langle \eta_{\mathrm{R}} \cdot f_{\mathrm{fu}} - f_{\mathrm{fdd}} \rangle \qquad \text{(A.26)}$$

where the term in $\langle\cdot\rangle$ should be taken only if positive and where the coefficient η_{R} depends on the rounding radius R and the beam width b_{w} as:

$$\eta_{\mathrm{R}} = 0{,}2 + 1{,}6\frac{R}{b_{\mathrm{w}}} \qquad 0 \le \frac{R}{b_{\mathrm{w}}} \le 0{,}5 \qquad \text{(A.27)}$$

L_{e} is the effective bond length:

$$L_{\mathrm{e}} = \sqrt{\frac{E_{\mathrm{f}} \cdot t_{\mathrm{f}}}{\sqrt{4 \cdot \tau_{\max}}}} \qquad \text{(units: N, mm)} \qquad \text{(A.28)}$$

MPa, mm

with:

$\tau_{\max} = 1{,}8 f_{\mathrm{ctm}} k_{\mathrm{b}}$ = maximum bond strength.

(6) For U-shaped (i.e., open) jackets, the design FRP effective debonding strength may be taken in expressions (A.22) and (A.23) as:

$$f_{\mathrm{fdd,e,U}} = f_{\mathrm{fdd}} \cdot \left[1 - k\frac{L_{\mathrm{e}} \sin\beta}{z}\right] \tag{A.29}$$

where all variables are as defined in **(5)**.

(7) For side-bonded sheets/strips, the design FRP effective debonding strength may be taken in expressions (A.22), (A.23) as:

$$f_{\mathrm{fdd,e,S}} = f_{\mathrm{fdd}} \cdot \frac{z_{\mathrm{rid,eq}}}{z} \cdot \left(1 - \sqrt{k\frac{L_{\mathrm{eq}}}{z_{\mathrm{rid,eq}}}}\right)^2 \tag{A.30}$$

where:

$$z_{\mathrm{rid,eq}} = z_{\mathrm{rid}} + L_{\mathrm{eq}}, \quad z_{\mathrm{rid}} = z - L_{\mathrm{e}} \cdot \sin\beta, \quad L_{\mathrm{eq}} = \frac{u_1}{\varepsilon_{\mathrm{fdd}}} \cdot \sin\beta \tag{A.31}$$

with:

$\varepsilon_{\mathrm{fdd}} = f_{\mathrm{fdd}}/E_{\mathrm{f}}$, and

$u_1 = k_{\mathrm{b}}/3$.

(8) For members with circular section having diameter D, the FRP contribution is evaluated as:

$$V_{\mathrm{f}} = 0{,}5\ A_{\mathrm{c}} \cdot \rho_{\mathrm{f}} \cdot E_{\mathrm{f}} \cdot \varepsilon_{\mathrm{f,ed}} \tag{A.32}$$

where:

A_{c} is the column cross-section area,

ρ_{f} is equal to 4 t_{f}/D is the volumetric ratio of the FRP, and

$\varepsilon_{\mathrm{f,ed}} = 0{,}004$.

(9) In members with their plastic hinge region fully wrapped in an FRP jacket over a length at least equal to the member depth h, the cyclic shear resistance, V_{R}, may be taken to decrease with the plastic part of the chord rotation ductility demand at the member end: $\mu_{\Delta}^{\mathrm{pl}} = \mu_{\Delta}$-1, in accordance with expression (A.12), adding to V_{w} (i.e. to the contribution of transverse reinforcement to shear resistance) that of the FRP jacket. The contribution of the FRP jacket to V_{w} may be computed assuming that the FRP stress reaches the design value of the FRP ultimate strength, $f_{\mathrm{u,fd}}$, at the extreme tension fibres and reduces linearly to zero over the effective depth d:

$$V_{\mathrm{w,f}} = 0{,}5\rho_{\mathrm{f}} b_{\mathrm{w}} z f_{\mathrm{u,fd}} \tag{A.33}$$

where:

ρ_{f} equal to $2t_{\mathrm{f}}/b_{\mathrm{w}}$ is the geometric ratio of the FRP,

z is the length of the internal lever arm, taken equal to d, and

$f_{\mathrm{u,fd}}$ is the design value of the FRP ultimate strength, equal to the FRP ultimate strength, $f_{u,f}$ divided by the partial factor γ_{fd} of the FRP,

NOTE The value ascribed to γ_{fd} for use in a country can be found in its National Annex. The recommended value is γ_{fd}=1,5.

A.4.4.3 Confinement action

(1) The enhancement of deformation capacity is achieved through concrete confinement by means of FRP jackets. These are applied around the element to be strengthened in the potential plastic hinge region.

(2) The necessary amount of confinement pressure to be applied depends on the ratio $I_\chi = \mu_{\phi,tar}/\mu_{\phi,ava}$, between the target curvature ductility $\mu_{\phi,tar}$ and the available curvature ductility $\mu_{\phi,ava}$, and may be evaluated as:

$$f_l = 0{,}4 \; I_\chi^2 \frac{f_c \cdot \varepsilon_{cu}^2}{\varepsilon_{ju}^{1,5}} \tag{A.34}$$

where:

f_c is the concrete strength, defined as for expression (A.1),

ε_{cu} is the concrete ultimate strain, and

ε_{ju} is the adopted FRP jacket ultimate strain, which is lower than the ultimate strain of FRP, ε_{fu}.

(3) For the case of circular cross-sections wrapped with continuous sheets (not in strips), the confinement pressure applied by the FRP sheet is equal to $f_l = 1/2\rho_f E_f \varepsilon_{ju}$, with E_f being the FRP elastic modulus and ρ_f the geometric ratio of the FRP jacket related to its thickness as: $t_f = \rho_f D/4$, where D is the diameter of the jacket around the circular cross-section.

(4) For the case of rectangular cross-sections in which the corners have been rounded to allow wrapping the FRP around them (see Figure A.1), the confinement pressure applied by the FRP sheet is evaluated as: $f'_l = k_s f_l$, with $k_s = 2R_c/D$ and $f_l = 2 E_f \varepsilon_{ju} t_f /D$, where D is the larger section width.

(5) For the case of wrapping applied through strips with spacing s_f, the confinement pressure applied by the FRP sheet is evaluated as: $f'_l = k_g f_l$, with $k_g = (1 - s_f /2D)^2$.

(6) For members of rectangular section with corners rounded as in Figure A.1, an alternative to **(2)** and **(4)** is to calculate the total chord rotation capacity or its plastic part through expressions (A.1) or (A.3), respectively, with the exponent of the term due to confinement (i.e. the power of 25 before the last term in expressions (A.1) and (A.3)) increased by $\alpha \rho_f f_{f,e}$, with:

(a) $\rho_f = 2t_f/b_w$, the FRP ratio parallel to the loading direction,

(b) $f_{f,e}$, an effective stress given by the following expression:

$$f_{\mathrm{f,e}} = \min\left(f_{\mathrm{u,f}}, \varepsilon_{\mathrm{u,f}} E_{\mathrm{f}}\right)\left(1 - 0{,}7\min\left(f_{\mathrm{u,f}}, \varepsilon_{\mathrm{u,f}} E_{\mathrm{f}}\right)\frac{\rho_{\mathrm{f}}}{f_{\mathrm{c}}}\right) \tag{A.35}$$

where $f_{\mathrm{u,f}}$ and E_{f} are the strength and Elastic modulus of the FRP and $\varepsilon_{\mathrm{u,f}}$ a limit strain, equal to 0,015 for CFRP (carbon-fibre-reinforced polymer) or AFRP (aramid-fibre-reinforced polymer) and to 0,02 for GFRP (Glass-fibre-reinforced polymer); and

(c) α, the confinement effectiveness factor given by:

$$\alpha = 1 - \frac{(b-2R)^2 + (h-2R)^2}{3bh} \tag{A.36}$$

where R is the radius of the rounded corner of the section and b, h the full cross-sectional dimensions (see Figure A.1).

(7) Paragraph **(6)** applies to members with continuous deformed (high bond) or smooth (plain) longitudinal bars, with or without detailing for earthquake resistance, provided that the end region is wrapped with FRP up to a distance from the end section which is enough to ensure that the yield moment M_{y} in the unwrapped part will not be exceeded before the flexural overstrength $\gamma_{\mathrm{Rd}}M_{\mathrm{y}}$ is reached at the end section. To account for the increase of the flexural strength of the end section due to confinement by the FRP, γ_{Rd} should be at least equal to 1,3.

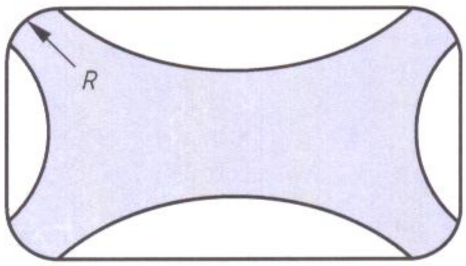


Figure A.1. Effectively confined area in an FRP-wrapped section.

A.4.4.4 Clamping of lap-splices

(1) Slippage of lap-splices can be prevented by applying a lateral pressure σ_{l} through FRP jackets. For circular columns, having diameter D, the necessary thickness may be estimated as:

$$t_{\mathrm{f}} = \frac{D(\sigma_{\mathrm{l}} - \sigma_{\mathrm{sw}})}{2E_{\mathrm{f}} \cdot 0{,}001} \tag{A.37}$$

where σ_{sw} is the clamping stress due to the stirrups at a strain of 0,001 (σ_{sw}=0,001$\rho_{\mathrm{w}}E_{\mathrm{s}}$), or the active pressure from the grouting between the FRP and the column, if provided, while σ_{l} represents the clamping stress over the lap-splice length L_{s}, as given by:

$$\sigma_l = \frac{A_s f_{yL}}{\left[\frac{p}{2n} + 2(d_{bL} + c)\right]L_s} \tag{A.38}$$

where:

A_s is the area of each spliced longitudinal bar,

f_{yL} is the yield strength of longitudinal steel reinforcement, taken equal to the mean value obtained from *in-situ* tests and from the additional sources of information, appropriately multiplied by the confidence factor, CF, given in Table 3.1 for the appropriate knowledge level (see **2.2.1(5)**P),

p is the perimeter line in the column cross-section along the inside of longitudinal steel,

n is the number of spliced bars along p,

d_{bL} is the (largest) diameter of longitudinal steel bars, and

c is the concrete cover thickness.

(2) For rectangular columns, the expressions above may be used by replacing D by b_w, the section width, and by reducing the effectiveness of FRP jacketing by means of the coefficient in **A.4.4.3(4)**.

(3) For members of rectangular section with longitudinal bars lapped over a length l_o starting from the end section of the member, an alternative to **(1)** and **(2)** for the calculation of the effect of FRP wrapping over a length exceeding by no less than 25% the length of the lapping, is to apply **A.3.2.2(4)**:

a) taking into account in expression (A.3) confinement only due to transverse bars (exponent of the power of 25 before the last term), and

b) calculating $l_{ou,min}$ as: $l_{ou,min} = d_{bL} f_{yL} / [(1{,}05 + 14{,}5 \alpha_{l,f} \rho_f f_{f,e} / f_c) \sqrt{f_c}]$ on the basis of the FRP alone, with $\alpha_{l,f} = 4/n_{tot}$ and ρ_f, $f_{f,e}$, n_{tot} as defined in **A.4.4.3(6)** for the FRP.