1. General

1.1 Introduction

The issue of upgrading existing concrete structures when they do not satisfy prescribed performance requirements has become one of great importance over the past two decades or so.Deterioration of bridge decks,beams,girders and columns,buildings,parking structures and others may be attributed to ageing,environmentally induced degradation, poor initial design and/or construction,lack of maintenance and to accidental events such as earthquakes.Infrastructure's increasing decay is occasionally combined with the need for upgrading so that structures can meet more stringent design requirements(e.g. increased traffic volumes in bridges exceeding the initial design loads),hence the topic of civil engineering infrastructure renewal has received considerable attention over the past years throughout the world.At the same time,seismic retrofitting has become at least equally important,especially in areas of high seismic risk.

1.2 Externally applied reinforcement(EAR)

Developments related to materials,methods and techniques for strengthening and seismic retrofitting have been enormous over the past two decades or so.One of today's state-of-the-art techniques is based on external bonding of fibre reinforced polymer (FRP) composites,which are increasingly used by structural engineers for rehabilitation of existing structures.FRPs for strengthening of civil engineering structures are available today mainly in the form of:

- Thin unidirectional strips,with thickness in the order of 1 mm,typically made by pultrusion
- Flexible sheets or fabrics,made of fibres in one or at least two different directions,respectively;these are typically impregnated in-situ or,rarely,pre-impregnated with resin
- Rods,with diameter in the order of a few mm,made by pultrusion

For comparison with steel reinforcement,typical stress-strain diagrams for unidirectional composites under short-term monotonic loading are given in Fig.1-1.Note that the tensile stress-strain lines are indicative,as FRP materials exist in different variants.

This chapter was mainly authored by Triantafillou.

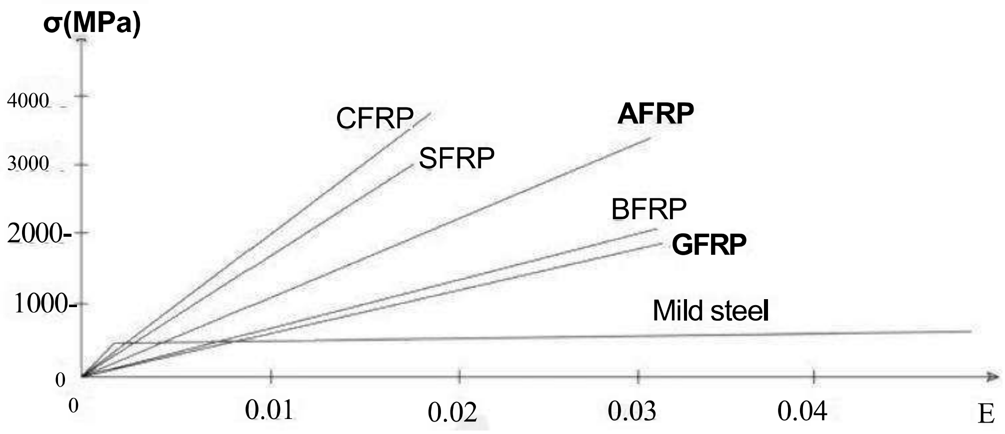

Fig.1-1 Uniaxial tension stress-strain diagrams for different unidirectional FRPs and steel.CFRP=carbon FRP,GFRP=glass FRP,AFRP=aramid FRP,BFRP=basalt FRP,SFRP=steel FRP

The reasons why composites are increasingly used as strengthening and seismic retrofitting materials for existing structures,including reinforced concrete(RC)members,may be summarised as follows:immunity to corrosion;low weight(about 14 of steel),resulting in easier application in confined space,elimination of the need for scaffolding and reduction in labour costs;very high tensile strength (both static and long-term,for certain types ofFRP materials);stiffness which may be tailored to the design requirements;large deformation capacity;easy and rapid application,minimising disruption of occupancy;and practically unlimited availability in FRP sizes and FRP geometry and dimensions.Composites suffer from certain disadvantages too,which are not to be neglected by engineers:contrary to steel,which is an elastoplastic material,composites in general are linear elastic to failure(although the latter occurs at large strains)without any significant yielding or plastic deformation,leading to reduced ductility.Additionally,the cost of materials on a weight basis is several times higher than that for steel (but when cost comparisons are made on a strength basis,they become less unfavourable).Moreover,some FRP materials,e.g.carbon and aramid,have different thermal expansion coefficients from concrete.Finally,their exposure to high temperatures(e.g.in the case of fire)may cause premature degradation and collapse (some epoxy resins start softening at about 50-80°C).Hence FRP materials should not be thought of blindly as a replacement of steel(or other materials)in structural intervention applications.Instead,the advantages offered by them should be evaluated against potential drawbacks and final decisions regarding their use should be based on consideration of several factors,including not only mechanical performance aspects,but also constructability and long-term durability.

1.3 Applications ofEAR

Composites have been used as strengthening materials of reinforced concrete members (such as beams,slabs,columns,shear walls etc.)in many thousands of applications worldwide,where conventional strengthening techniques may be problematic.For instance, one of the popular techniques for upgrading RC members has traditionally involved the use of steel plates epoxy-bonded to the external surfaces(e.g.tension zones)of beams and slabs.This technique is simple and effective as far as both cost and mechanical performance is concerned,but suffers from several disadvantagesl:corrosion of the steel plates resulting in bond deterioration; difficulty in manipulating heavy steel plates in tight construction sites; need for scaffolding; and limitation in available plate lengths (which are required in case of flexural strengthening of long girders), resulting in the need for joints. Replacing the steel plates with FRP strips (Fig. 1-2a) provides satisfactory solutions to the problems described above. Another common technique for the strengthening of RC structures (mainly in seismic applications) involves the construction of reinforced concrete jackets (either cast in-place or shotcrete) around existing members. Jacketing is clearly quite effective as far as strength, stiffness and ductility is concerned, but it increases member cross sections considerably, it is labour intensive, it often causes disruption of occupancy and it provides RC members, in many cases, with undesirable weight and stiffness increase. Jackets may also be made of steel; but in this case protection from corrosion is a major issue. Conventional jackets may be replaced with FRP sheets or fabrics wrapped around RC members (Fig. 1-2b-d), thus providing substantial increase in axial, shear and torsional

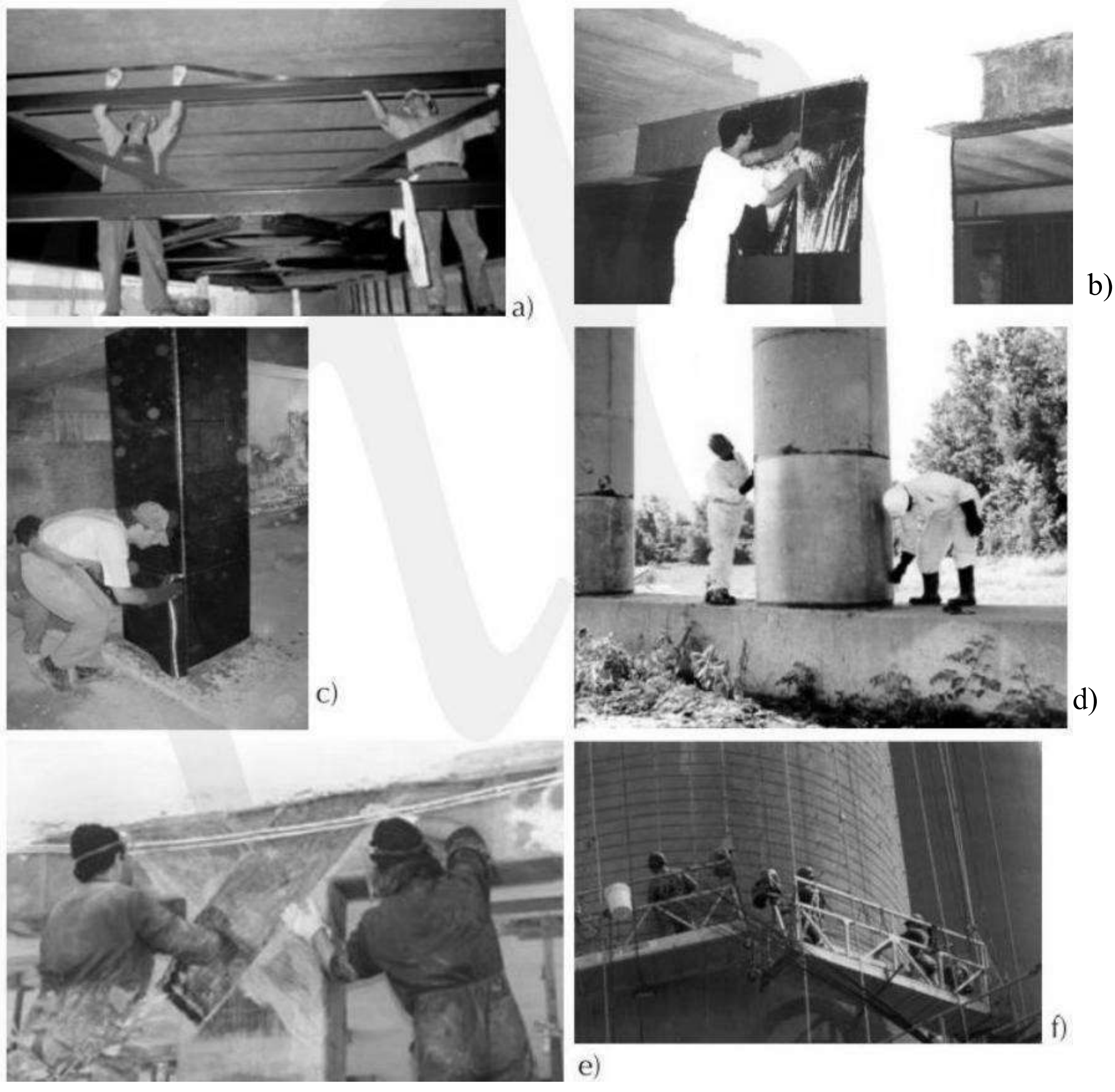

Fig. 1-2 Typical FRP applications as strengthening materials of RC structures: (a) flexural strengthening of slab with strips; (b) shear strengthening of beam; (c) shear strengthening and confinement of column; (d) local confinement of column; (e) shear strengthening of beam-column joint; (f) strengthening of silo using NSM rods

strength and in deformation capacity without significantly affecting the stiffness. The range of applicability of FRP in RC structures is constantly increasing: typical examples are those of beam-column joints strengthened in shear (Fig. 1-2e) and RC members strengthened in flexure or shear by bonding strips or rods into grooves cut in the cover region of the concrete [an application termed Near Surface Mounted (NSM) reinforcement, Fig. 1-2f]. Last, but not least, strengthening and/or seismic retrofitting of RC members may be achieved by the recently developed advanced composites made of steel fibres in combination with polymeric matrices (SFRP) or even with fibres in the form of textiles, in combination with inorganic mortars (Textile Reinforced Mortars-TRM).

1.4 EAR basic application forms

Externally applied reinforcement (EAR) for strengthening and retrofitting exists in different application forms. Often, EBR or externally bonded reinforcement has and is a commonly used terminology, which basically refers to the original and most often used application type of externally bonding steel plates or FRP strips to the surface. Yet, to take into consideration the differences in application forms which have appeared over the years, in this bulletin the abbreviation EAR or externally applied reinforcement is adopted. As such, EAR can refer to both bonded and unbonded applications, as well as different ways of adding the reinforcement to the concrete section, as outlined in Fig. 1-3. Note that in Fig. 1-3, EBR in the meaning of surface bonded reinforcement, is replaced with the abbreviation SBR. However, given the popular use of the abbreviation EBR when writing this document, the terms EBR and SBR are used interchangeably. More details on application forms are provided in Chapter 2.

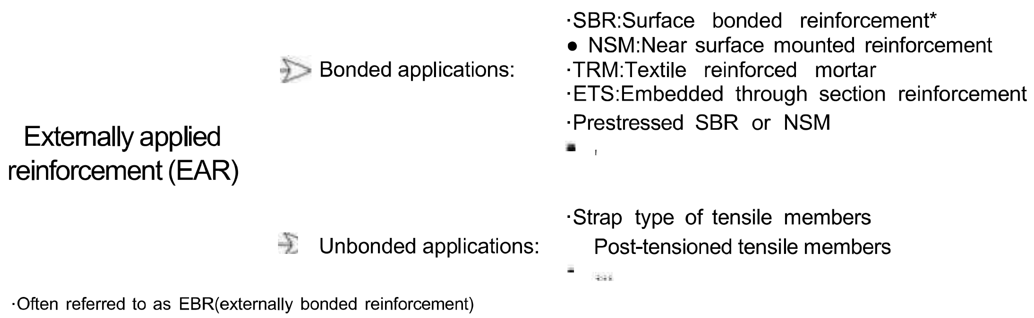

Fig. 1-3 EAR basic application forms

1.5 Aim and content of this report

This report deals mainly with the design of RC members strengthened with externally applied composite materials. Other aspects, such as currently available materials, durability, proper execution techniques are described too. The report focuses on strengthening and seismic retrofitting with fibre reinforced polymers, in the form of either externally (more specific surface) bonded reinforcement (EBR or SBR) or near surface mounted (NSM) reinforcement. The report is structured in such a way so that separate chapters deal with different topics. Chapter 2 provides a general description of materials and techniques related to the application of composites as external reinforcement of concrete members. Chapter 3 is devoted to the basis for the design of strengthened and/or seismically

2.Materials,systems and techniques

This chapter provides general information on fibre reinforced materials used in concrete strengthening and seismic retrofitting,on systems and techniques for their application, and on recently developed advanced methods of externally applied reinforcement(EAR) applications in concrete structures.Further details are also provided in Chapter 10 on “Practical Execution and Quality Control”.

2.1 Materials for EAR strengthening

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 fibres 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 fibres will not necessarily provide a good bond to concrete.Therefore,only systems that have been tested and applied at full scale on reinforced concrete structures should be used in EAR strengthening.

Today there are several types of EAR strengthening systems,which are summarised below:

-Surface bonded reinforcement,making use of cured in-situ FRP systems.

-Surface bonded reinforcement,making use of FRP systems based on prefabricated elements(pre-cured FRP systems).

-Subsequent or special systems,originating from the basic surface bonded systems, e.g.near-surface mounted bars,prestressing,mechanically attached laminates, automated wrapping,etc.

These systems correspond to several manufacturers and suppliers,and are based on different configurations,types of fibres,adhesives,etc.Also,the suitability of each system depends on the type of structure to be strengthened.For example,prefabricated strips are generally best suited for plane and straight surfaces,whereas sheets or fabrics are more flexible and can be used on plane as well as on convex surfaces.Near-surface mounted bars can be preferable for improved bond conditions between EAR and concrete and/ or if the EAR should be better protected.Automated wrapping can be an option in cases when many similar columns need to be strengthened at the same site.Practical execution and application conditions,for example cleanliness and temperature,are very important in achieving a good bond.Only a well prepared and clean surface will provide an adequate bond.The adhesives undergo a chemical process during hardening that needs a temperature above 5℃ to start.If the temperature drops,the hardening process becomes slow.Specialised resins for application at low or elevated temperatures are available from some manufacturers.

In the following sections the three main components,namely adhesives,matrices and fibres of an EAR strengthening material system willbe discussed briefly.

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2.1.2 Fibres

A great majority of materials are stronger and stiffer in a fibrous form than as a bulk material. A high fibre aspect ratio (length/diameter ratio) permits an effective transfer of load from the matrix materials to the fibres, thus enabling full advantage of the properties of the fibres to be taken. Therefore, fibres are effective and attractive reinforcement materials. Fibres can be manufactured in continuous or discontinuous (chopped) form, but here only continuous fibres are considered. Such fibres have a diameter in the order of 5-20μm, and can be manufactured as unidirectional or multi-directional reinforcement, sometimes in the form of textiles (e.g. in the case of inorganic binders). The fibres used for strengthening all exhibit a practically linear elastic behaviour up to failure and do not have a pronounced yield plateau as for steel.

There are mainly four types of fibres that are used for strengthening of civil engineering structures, namely carbon, glass, aramid and basalt fibres. In some special circumstances steel fibres may also be used, although products with steel fibres are heavy and prone to corrosion. More recently, other fibres have also become of interest, such as natural fibres and PBO (poly phenylene bezobisoxazole, a relative new organic high-strength fibre). Especially for natural fibres, durability-related problems are yet to be addressed. It should be recognised that the physical and mechanical properties can vary for a given type of fibre as well as for the different fibre types. Basic mechanical properties of fibres commonly used in strengthening systems are summarised in Table 2-1. Note that values in this table are only indicative of static strength of unexposed fibres. Design values of the EAR systems should account both for the presence of matrix (see "rule of mixtures" in Section 2.1.4) and for possible reductions due to long-term loading, environmental exposure etc. (see amongst other Chapters 3 and 4).

Table 2-1 Typical properties of fibres

Material	Elastic modulus (GPa)	Tensile strength (MPa)	Ultimate tensile strain (%)
Carbon			
High strength	215-235	3500-4800	1.4-2.0
Ultra high strength	215-235	4800-6000	2.0-2.3
High modulus	350-500	2500-3100	0.5-0.9
Ultra high modulus	500-700	2100-2400	0.2-0.4
Glass			
E	70	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
Basalt	80-90	2500-3200	3.0-3.5
Steel	185	3070	1.7
Natural fibres			
Hemp	30-70	500-700	2.0-4.0
Flax	30-40	500-1500	2.5-3.5
Kenaf	30-50	500-900	1.5-2.0

Carbon fibres are normally either based on pitch or PAN, as raw material. Pitch fibres are fabricated by using refined petroleum or coal pitch that is passed through a thin nozzle and stabilised by heating. PAN fibres are made of polyacrylonitrile that is carbonised by different heat treatments. The diameter of pitch-type fibres measures approximately 9-18 μm and that of the PAN-type measures 5-8μm. The structure of this carbon fibre varies according to the orientation of the crystals; the higher the carbonation degree, the higher the orientation degree and stiffness, as a result of growing crystals. The pitch based carbon fibres offer general purpose and high strength/modulus materials. The PAN-type carbon fibres yield high strength and high modulus materials. Typical properties of various types of fibre materials are provided in Table 2-1[1,2,3,4].

Glass fibres for continuous fibre reinforcement are classified into three main types: E-glass fibres, S-glass and alkali resistant AR-glass fibres. E-glass fibres, which contain high amounts of boric acid and aluminate, are disadvantageous in having low alkali resistance. S-glass fibres are stronger and stiffer than E-glass, but still not resistant to alkali. To improve the alkali resistance of glass fibres from being eroded by cement-alkali, a considerable amount of zircon is added to produce alkali resistant glass fibres; such fibres have mechanical properties similar to E-glass. An important aspect of glass fibres is their low cost.

Aramid fibres were first introduced in 1971, and today are produced by only a few manufacturers. Similar as for the other fibres, the structure of aramid fibre is anisotropic and gives higher strength and modulus in the fibre longitudinal direction rather than in the cross direction. Yet, they exhibit more toughness because of their molecular structure. The diameter of aramid fibre is approximately 12μm. Aramid fibres respond elastically in tension but they exhibit non-linear and ductile behaviour under compression. They also exhibit good toughness, damage tolerance and fatigue characteristics. Aramid fibres can absorb up to about 7% water from ambient air humidity and may need to be dried prior to application if stored outside. If exposed to direct sunlight without protection against UV radiation, aramid fibres can lose up to 70% of their initial tensile strength.

Basalt fibres have been introduced in the field of strengthening with composites relatively recently. Basalt is a volcanic mineral (solidified magma), representing a silicate by its chemical origin, and basalt fibres are prepared by melt-spinning from basalt melt by a technology fundamentally similar to the production of glass fibres but with less energy requirements. Their mechanical properties are comparable to glass fibres with a slightly higher stiffness[5]. Reliable results of studies are limited at present regarding their long-term use and in direct exposure to alkaline environments.

High strength **steel** wires with diameter equal to a fraction of a millimetre have also been introduced as fibres in strengthening systems with polymeric matrices[6,7] and the respective composite material is typically named steel fibre reinforced polymer (SFRP), sometimes also referred to as steel cord reinforced polymer. These steel wires, which can be bundled into cords, typically have a protective layer of zinc or brass coating to protect them from corrosion. One of the interesting features of these materials is their linear elastic response all the way to failure.

Natural fibres have been recently introduced in strengthening systems with both organic and inorganic matrices. The relevant scientific literature includes a large variety of fibres, whose mechanical and physical properties are significantly variable. Those most applied in strengthening systems are the vegetal fibres, including hemp, flax and kenaf. The tensile strength of these fibres can vary between about 500 MPa to 1500 MPa, whereas their elastic modulus varies between 30 GPa to 70 GPa[8]. However, mechanical and physical properties of natural fibres are strongly influenced by their geographic origin as well as by the processes the fibres are subjected to during the transformation activities. The diameter of the fibres is also largely variable and natural fibres are typically intertwined to form small chords that are used to prepare sheets, fabrics or grids. Natural fibres are typically affected by a microstructural shear-lag mechanism that causes a reduction of the tensile strength and the elastic modulus, as the diameter of the chords increases[9]. Physical and mechanical interaction with matrices needs to be also considered, since the bonding mechanisms between the fibres and the matrices as well as the fibre durability can vary with the fibre and the matrix typologies. Thus, the mechanical properties of these systems need to be carefully determined, based on mechanical tests to be carried out on each specific strengthening system.

2.1.3 Matrices

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. Alternatively, the matrix can be based on inorganic materials, such as cementitious mortars. The function of the matrix is to protect the fibres against abrasion or environmental corrosion, to bind the fibres 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 fibres 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[10].

Epoxy resins, polyester and vinylester are the most common polymeric matrix materials used with high-performance reinforcing fibres. 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. Polymer-modified cement-based mortars are the most common inorganic matrix materials combined with high-performance fibres, typically in the form of textiles.

2.1.4 FRP materials

FRP materials for EAR typically consist of a large number of continuous, directionalised fibres with advanced characteristics, bundled in a polymeric (resin) matrix. Depending on the type of fibre they are referred to as CFRP (carbon fibre based), GFRP (glass fibre based), AFRP (aramid fibre based), BFRP (basalt fibre based) and SFRP (steel fibre based). When different types of fibres are used, the material is called "hybrid". Typically, the volume fraction of fibres in FRP systems equals about 50-70% for strips and about 25-50% for sheets or fabrics. Hence fibres are the principal stress bearing components, while the matrix transfers stresses among fibres 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 Bulletin. As externally bonded reinforcement for the strengthening and/or seismic retrofitting of structures, FRP materials are made available in various forms which are described in Section 2.2.

Basic mechanical properties of FRP materials may be estimated if the properties of the constituent materials (fibres, matrix) and their volume fractions are known. For the simple-yet quite common-case of unidirectional fibres, one may apply the "rule of mixtures" simplification as follows:

$$E_f = E_{fib} \cdot V_{fib} + E_m \cdot V_m \quad (2\text{–}1)$$

$$f_f \approx f_{fib} \cdot V_{fib} + f_m \cdot V_m \quad (2\text{–}2)$$

where E,=elastic modulus of FRP in fibre direction,E=elastic modulus of fibres, E_m = elastic modulus of matrix,Vb=volume fraction of fibres, V_m = volume fraction of matrix,f,=tensile strength of FRP in fibre direction,fi=tensile strength of fibres and fm=tensile strength of matrix.Note that in the above equations $V_{fib} + V_m = 1$.

As the rule of mixtures is an [unconservative,especially in the case of Eq.(2-2)] approximation of the micro-mechanical behaviour of fibre composites,a more accurate prediction of the stress-strain behaviour should be obtained through tensile testing. Hence the material properties should be given for the combined FRP directly,so to reflect the fibre and matrix characteristics as well as the micro-structural aspects such as fibre diameter,distribution and parallelism of fibres,local defects,volume fractions and fibre-matrix interfacial properties.

Typical commercial FRP products in the form of prefabricated strips have the properties given in Table 2-2,where the properties for mild steel are also given for comparison.

In case of prefabricated strips,the material properties based on the total cross-sectional area can be used directly in calculations;these properties are usually supplied by the manufacturer(see Table 2-2).However,in case of in-situ resin impregnated systems,the final FRP thickness and hence the fibre volume fraction is uncertain and may vary.For this reason a calculation based on the FRP properties for the total system(fibres and matrix)and the actual thickness is not appropriate.Note that manufacturers often supply the material properties for the dry fibres as well as the laminate properties obtained from testing.One should be careful when comparing properties of different systems,as laminate properties can be given in relation to the actual or nominal laminate thickness, or to the dry fibre thickness of the fabric.Furthermore it is crucial that in calculations the appropriate material properties for the applied system are used.In the following,the difference between both approaches is explained and elucidated with an example.

Table 2-2 Typical properties of prefabricated FRP strips and comparison with steel

Material	Elastic modulus E, (GPa)	Tensile strength f, (MPa)	Ultimate tensile strain ε (%)
Prefabricated strips			
Low modulus CFRP strips	170	2800	1.6
Mid modulus CFRP strips	210	2800	1.6
High modulus CFRP strips	300	1300	0.5
Mild steel	200	400	25*

Yield strain=0.2%

Due to the fact that the stiffness and strength of the fibres(Eand f_{fib})is much higher than the stiffness and strength of the matrix(E„andf),respectively,the properties of the FRP (E,and f)are governed by the fibre properties and the cross-sectional area of the bare fibres. When the FRP properties are based on the total cross-sectional area(fibres and matrix) this means that,compared to the properties of the bare fibres,the stiffness and strength is lower.It may be the case that the strength and stiffness of the total system is not affected much,because this reduction is compensated by an increase of the cross-sectional area compared to the cross-sectional area of the fibres.So,there is a strong relation between the fibre volume fraction and the FRP properties to be used in calculations.This is illustrated in Table 2-3 and Fig.2-1.For certain chosen properties of the fibres and the matrix,the effect of the volume fraction of the fibres on the FRP properties is shown. For a constant amount of fibres(cross-sectional area =70 mm2)the failure load,axial stiffness and strain at failure is only very little affected by an increase of the amount of matrix.The FRP elastic modulus and strength to be used in calculations based on the total cross-sectional area,however,are strongly influenced.

The example given above demonstrates that for a comparison of FRP materials it may not be sufficient only to compare values for strength and/or stress-strain relations.It is important also to know the composition of the FRP material to which the given property belongs.In case of uncertainty about the thickness(like with in-situ impregnation)it may be more convenient to base calculations on the fibre properties and fibre cross-sectional area than on properties for the total system.The latter approach is also possible;however,the material properties and nominal thickness(nominal cross-sectional area)as specified by the manufacturer should then be used and not the actual thickness that is realised in practice.

Table 2-3 Example showing the effect of volume fraction of fibres on the FRP properties

Chosen properties for constituent materials of FRP: E=220 GPa fA=4000 MPa E_m = 3 GPa fm=80 MPa									
Cross-sectional area				FRP properties				Failure load	
A (mm²)	A (mm²)	A_f* (mm²)	V (%)	E, [Eq. (2-1)] (GPa)	EA (kN)	f IEq. (2-2)] (MPa)	%	(kN)	(%)
70	0	70	100	220.0	15400	4000	1.82	280.0	100.0
70	30	100	70	154.9	15490	2824	1.82	282.4	100.9
70	70	140	50	111.5	15610	2040	1.82	285.6	102.0

*In case of a strip with a width of 100 mm dividing this value by 100 mm gives the thickness of the strip (0.7 mm,1.0 mm and 1.4 mm).

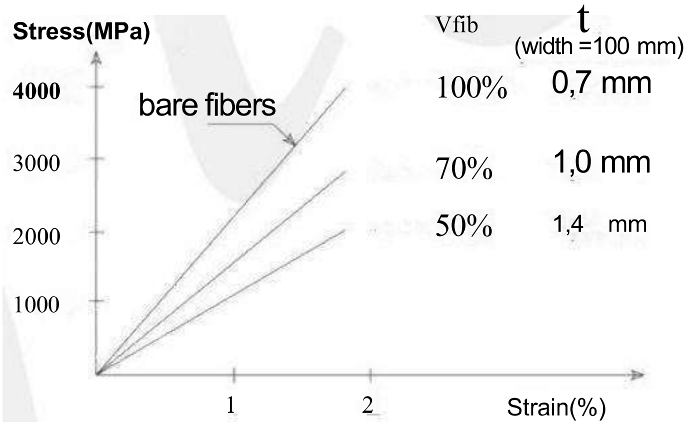


Fig.2-1 Stress strain relations corresponding to various fibre volume fractions V.in Table 2-4

As mentioned,in case of in-situ impregnated systems,one may calculate the properties of the FRP based on those of the bare fibres only.In this case the second term in Eqs(2-1)-(2-2)may be ignored,V.should be taken equal to 1 and the dimensions of the externally bonded reinforcement (e.g.cross-sectional area)should be calculated based on the nominal dimensions of the fibre sheets or fabrics.If this approach is adopted,the resulting property (e.g.elastic modulus,tensile strength)should be multiplied by a reduction factor r(r and r,for the modulus and the strength,respectively),to account for the efficiency of the fibre-resin system and for the sheet or fabric architecture.This factor should be provided by the FRP system supplier based on initial and periodic testing.Alternatively (and preferably),the FRP supplier could provide directly the properties of the in-situ impregnated system (e.g. thickness,elastic modulus,tensile strength)using the same type of resin as for the on-site installation and based on testing FRP coupons.To illustrate this,we may assume that a sheet has a nominal thickness t.and elastic modulus E(both calculated based on bare fibre properties).After impregnation,the EAR has a thickness t,and an elastic modulus E,The two systems are equivalent in terms of stiffness according to the condition r.Entm=E:t and in terms of strength according to the condition r;Ea·tio=Et.

2.1.5 Adhesives for bonding EAR

The purpose of the adhesive is to provide a shear load path between the concrete surface and the composite material,so that full composite action may develop.The science of adhesion is a multidisciplinary one,demanding a consideration of concepts from such topics as surface chemistry,polymer chemistry,rheology,stress analysis and fracture mechanics.It is not the objective of this Bulletin to cover this field in any detail; it is only to emphasise that key information about adhesives relevant to their use needs to be provided by the manufacturer of the strengthening system.

Structural adhesives in construction are generally thermoset polymers.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),discussed later.Depending on the demands of the application,the adhesive may contain fillers,softening inclusions,toughening additives and others.The successful application of an adhesive system requires the preparation of an adequate specification, which must include such provisions as adherent materials,mixing/application temperatures and techniques,curing temperatures,surface preparation techniques,thermal expansion and creep properties.Provisions with regard to abrasion and chemical resistance should also be included if required.

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 days.Open time is the time that one can have available after the adhesive has been applied to the adherents and before they are joined together.Another important parameter to consider is the glass transition temperature,T.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.This temperature level is defined as glass transition temperature,and is different for different polymers.The glass transition temperature of a two component epoxy adhesive strongly depends on curing time and temperature (see Section 4.3).Structural epoxy adhesives in construction are typically used in their glass-like domain at service temperatures below glass transition temperature. Their mechanical properties are quite strongly dependent on service temperature and their maximum service temperature is related to the glass transition temperature.

Epoxy adhesives have several advantages over other polymers as adhesive agents for civil engineering use,namely[11]:

-High surface activity and good wetting properties for a variety of substrates.

-May be formulated to have a long open time.

-High cured cohesive strength;joint failure may be dictated by adherent strength.

-May be toughened by the inclusion of dispersed rubbery phase.

-Lack of by-products from curing reaction minimises shrinkage and allows the bonding of large areas with only contact pressure.

-Low shrinkage compared with polyesters,acrylics and vinyl types.

-Low creep and superior strength retention under sustained load.

-Can be made thixotropic for application to vertical surfaces.

-Able to accommodate irregular or thick bond lines.

Typical properties for cold cured epoxy adhesives used in civil engineering applications are given in Table 2-4[12]2.For the sake of comparison,the same table provides information for concrete as well as mild steel.

Table 2-4 Comparison of typical properties for epoxy adhesives,concrete and steel

Property (at 20℃)	Cold-curing epoxy adhesive	Concrete	Mild steel
Density(kg/m^3)	1100-1700	2350	7800
Young's modulus(GPa)	0.5-20	20-50	205
Shear modulus(GPa)	0.2-8	8-21	80
Poisson's ratio	0.3-0.4	0.2	0.3
Tensile strength(MPa)	9-30	1-4	200-600
Shear strength(MPa)	10-30	2-5	200-600
Compressive strength(MPa)	55-110	25-150	200-600
Ultimate tensile strain(%)	0.5-5	0.015	25
Approximate fracture energy (m^2)	200-1000	100	10^5-10^6
Coefficient of thermal expansion(106/℃)	25-100	11-13	10-15
Water absorption:7 days-25℃(%w/w)	0.1-3	5	0
Glass transition temperature(℃)	50-80	____	___

Alternative materials to epoxies may be of the **inorganic binder** type,commonly referred to as mortars.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 fibres (textiles)will be maximised. General requirements for inorganic binders are high shear(that is tensile)strength,suitable consistency,low shrinkage,low creep and good workability13,14.

2.2 Externally applied reinforcement systems

Different systems of externally applied reinforcement(EAR)exist,related to the constituent materials,the form and the technique of the EAR strengthening.Each system is composed as a set of compatible components.In general,these can be subdivided into "cured in-situ" systems and "pre-cured" (or "prefab") systems. In the following, an overview is given of the different forms of these systems. Techniques for FRP strengthening are given in Section 2.3.

2.2.1 Cured in-situ systems

- Dry unidirectional non-woven fibre sheet and woven or knitted fabric, where fibres run predominantly in one direction partially or fully covering the structural element. The composite material is created on-site by saturating sheet or fabric with a suitable resin. Two different processes can be used to apply the sheet/fabric:
  - sheet or fabric is applied directly into the resin, which has been applied uniformly onto the concrete surface (dry application). Saturating resin may at the same time also serve as primer on the concrete surface.
  - sheet or fabric is impregnated on-site with the saturating resin either manually or in a saturator machine and then applied wet to the substrate prepared with primer and tack coat, which can also be one product (wet application).
- Dry multidirectional fabric (woven or knitted), where fibres run in at least two directions. The installation requires saturating resin. The fabric is applied using one of the two processes described above.
- Resin pre-impregnated uncured unidirectional sheet or fabric (prepreg), where fibres run predominantly in one direction. Installation may be done with or without additional resin.
- Resin pre-impregnated uncured multidirectional sheet or fabric (prepreg), where fibres run predominantly in two directions. Installation may be done with or without additional resin.
- Dry fibre tows (untwisted bundles of continuous fibres) that are wound or otherwise placed onto the concrete surface. Resin is applied to the fibre on-site prior to application or directly during winding.
- Pre-impregnated fibre tows that are wound or otherwise mechanically placed onto the concrete surface. Product installation may be executed with or without additional resin.
- Multidirectional textiles with fibres in at least two directions (loose or stabilised fibres in shape in forms of grid or mesh). Installation on the concrete surface is accomplished using an inorganic binder.

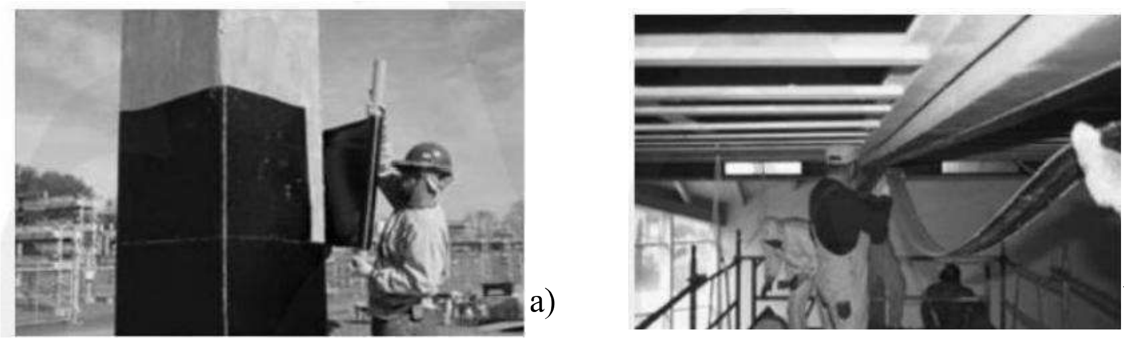
2.2.2 Pre-cured (prefabricated) elements

- Pre-manufactured cured straight strips or bars, which are installed typically through the use of adhesives. Sometimes application of strips with multidirectional fibres is possible using mechanical fasteners (e.g. powder-activated nails or bolts). The strips are typically in the form of thin ribbons, rods or grids that may be delivered in a rolled coil. Normally, the strips are pultruded. In case they are laminated, also the term laminate instead of strip may be used.
- 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.

2.3 Techniques for EAR strengthening

2.3.1 Basic FRP technique

The basic strengthening technique, which is most widely applied, involves the manual application of either cured in-situ (so-called hand lay-up) or pre-cured systems by means of cold cured adhesive bonding. This is the so-called classical FRP strengthening technique, denoted as externally bonded reinforcement (EBR) or more precisely as surface bonded reinforcement (SBR). Common in this technique in strengthening applications is that the external reinforcement is bonded onto the concrete surface with the fibres as parallel as practically possible to the direction of principal tensile stresses. If the aim of the application is to increase ductility, the fibres are placed in the hoop direction. Typical applications of the hand lay-up and prefabricated systems are illustrated in Fig. 2-2. More details on the basic technique are provided in Chapter 10.



a) b)

Fig. 2-2 (a) Hand lay-up of CFRP sheet, and (b) Application of prefabricated strips

2.3.2 Subsequent or special techniques

Besides the basic technique, several subsequent or special techniques have been developed, originating from the basic surface bonded FRP systems. Without aiming to provide a complete overview of these techniques, a number of them are briefly explained in the following sections. Some of the techniques described below are patented by the companies that developed them.

2.3.2.1 Near-surface mounted (NSM) reinforcement

Near-surface mounted (NSM) reinforcement may be thought of as a special method of supplementing reinforcement to concrete structures. In this method, the reinforcement is placed into slits or grooves which are cut into the concrete structure with a depth smaller than the concrete cover[15,16].

CFRP strips, e.g. with a thickness of 2 mm and a width of 20 mm, or FRP bars of different diameters, from 2-20 mm, are bonded into these grooves (Fig. 2-3). Dry fibre tows saturated with resin prior to application can be used to create irregularly shaped NSM reinforcement. The surface texture of strips or bars, which affects the bond behaviour of NSM reinforcement, can be smooth, sand-blasted, sand-coated, or roughened with a peel-ply surface treatment. Round bars can also be spirally wound with a fibre tow, or ribbed. The groove filler has to ensure the bond between the concrete substrate and the NSM reinforcement. The most common and best performing groove filler is two-component epoxy. As an alternative, cement paste or mortar has recently been explored in an attempt to lower the material cost, reduce the hazard to workers, minimise the environmental impact, allow effective bonding to wet substrates, achieve better resistance to high temperatures and improved thermal compatibility with the concrete substrate.

The general advantages of NSM over conventional FRP are listed below:

- Better bond characteristics; sealing of cracks is not a basic requirement for efficiency.
- The activation of controlled debonding failure mechanisms increases the ductility of strengthened members.
- The mechanical response is stiffer under serviceability loads.
- Peeling-off failure due to flexural or shear cracks is less critical.
- Excellent fatigue behaviour.
- Reduced site work, as surface preparation other than grooving is not required (plaster removal is not necessary; unevenness and irregularities of the concrete surface can be accommodated; removal of the weak laitance layer on the concrete surface is not needed).
- Easier anchorage to adjacent members to prevent debonding; this feature is particularly attractive in the flexural strengthening of beams and columns in rigidly-jointed frames, where the maximum moments typically occur at the ends of the member (e.g. flexural strengthening of columns).
- Unevenness in the surface can be compensated with the depth of the groove.
- Protection from mechanical damage, accidental impact and vandalism; this aspect makes this technology particularly suitable for the strengthening of negative moment regions of beams/slabs.
- Unchanged aesthetics.

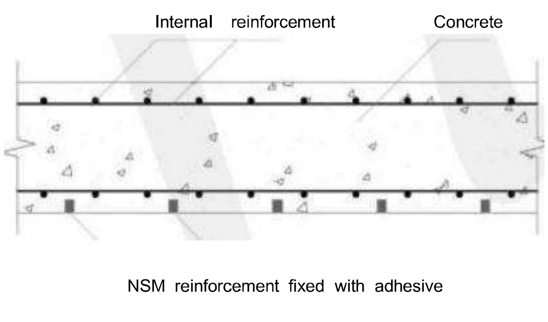


Fig.2-3 CFRP strips glued into slits

On the negative side, disadvantages of the NSM technique are the following:

- Need for sufficient concrete cover to accommodate the slits or grooves (in principle it is possible to increase the cover using mortars; in this case the bond between the old structure and the new cover should be verified).
- In shear strengthening only a two-sided pattern is practical (an efficient wrapping of the tensile zone is not cost effective).

2.3.2.2 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[17,18,19] shows that prestressing represents a significant contribution to the advancement of the FRP strengthening technique, and methods have been developed to prestress the FRP under real life conditions[20,21].

Prestressing the strips prior to bonding has the following advantages:

- Provides stiffer behaviour as at early stages most of the concrete is in compression and therefore contributing to the moment of resistance
- Crack formation in the shear span is delayed and the cracks when they appear are more finely distributed and narrower (crack widths are also a matter of bond properties)
- Closes cracks in structures with pre-existing cracks
- Improves serviceability and durability due to reduced cracking
- Improves the shear resistance of the member as the whole concrete section will resist the shear, provided that the concrete remains uncracked
- The same strengthening is achieved with smaller areas of stressed strips compared with unstressed strips
- With adequate anchorage, prestressing may increase the ultimate moment resistance by avoiding failure modes associated with peeling-off at cracks and the ends of the strips
- The neutral axis remains at a lower level in the prestressed case than in the unstressed one, resulting in greater structural efficiency
- Prestressing significantly increases the applied load at which the internal steel begins to yield compared to an unstressed member

The technique has also some disadvantages

- It is more expensive and more complicated than traditional EBR or NSM due to the greater number of operations and equipment that is required
- The operation also takes somewhat longer

The concept for applying a prestressed strip is shown schematically in Fig. 2-4. When the prestressing force is too high, failure of the beam due to release of the prestressing force will occur at the two ends, due to the development of high shear stresses in the concrete just above the FRP. Hence the design and construction of the end zones requires special attention. Tests and analysis have shown that if no mechanical anchorages are provided at the ends, FRP strips shear-off (from the ends) with prestress levels in the order of only 5-10% of their tensile strength (for CFRP). But a technically and economically rational prestress would require a considerably higher degree of prestressing, in the range of 50% of the FRP tensile strength, which may only be achieved through the use of special anchorages applying vertical confinement (see Fig. 2-4c). Such systems have been developed for practical applications as well as research purposes. An illustration of stressing devices is given in Fig. 2-5.

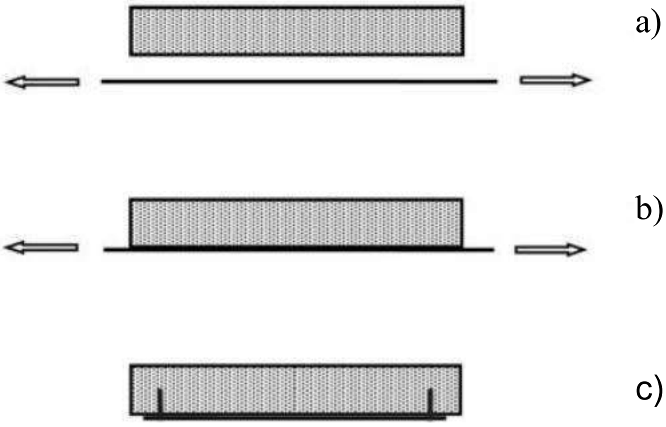


Fig.2-4 Strengthening with prestressed EAR strips:(a)prestressing;(b)bonding;(c)end anchorage and FRP release upon hardening of the adhesive

Another possibility,instead of using anchorage systems,is to reduce the prestressing force in the strip at its ends,see Fig.2-6a,so that the force is transferred into the concrete over a certain length.A special method is required to produce this force gradient22,23.The principal idea behind it is the sector-wise heating of the adhesive and step-wise releasing of the force.The gradient length in this method is approximately 0.5 to 1.0m long.The main advantage of this method is that the strips need no permanent anchorage systems; however,the application needs specialised knowledge and equipment(e.g.Fig.2-6b).

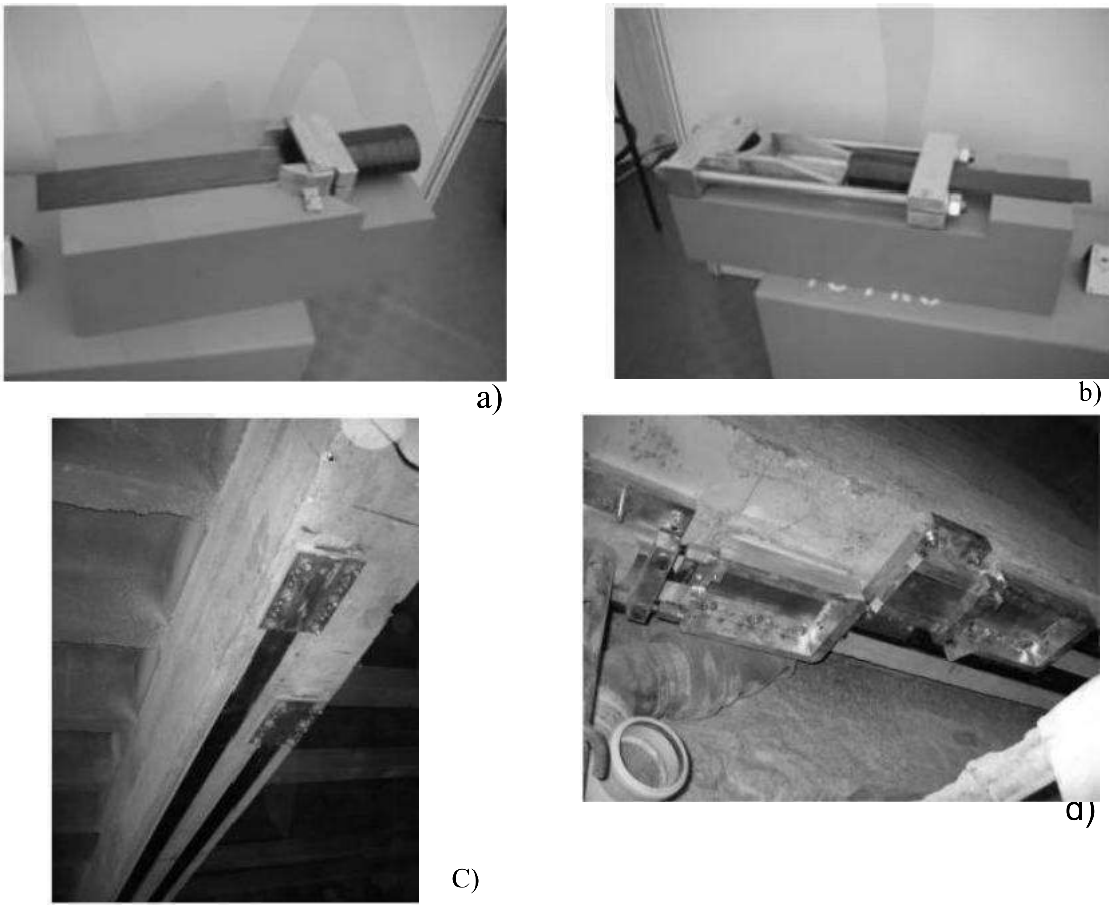
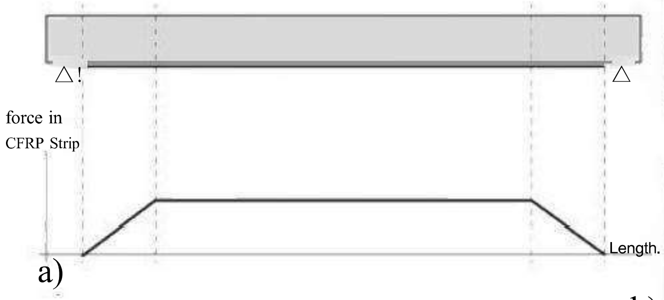


Fig.2-5 Anchorages of different prestressed CFRP products:(a),(c)Passive;(b),(d)Active



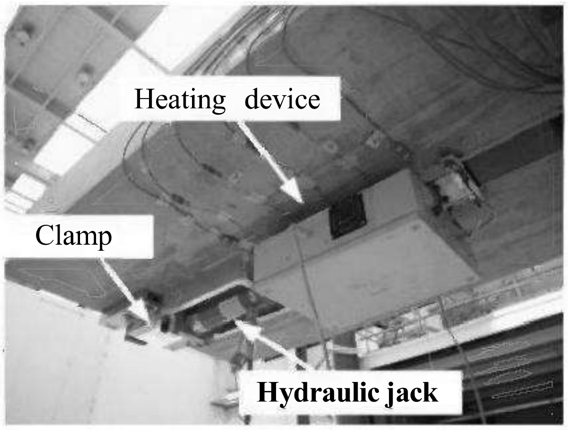


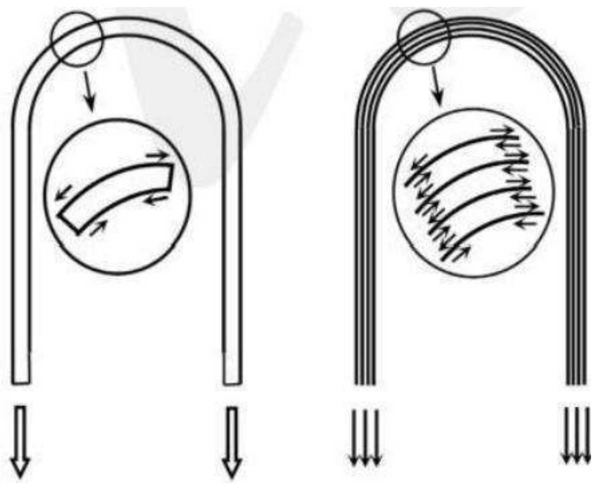
Fig.2-6(a)Reduced prestressing to avoid anchorage systems at strip ends.(b)Photograph of equipment (Michels et al.2013)

Prestressing of column jackets(active confinement)can be achieved by pretensioning the fibre bundles during winding or with unstressed jackets by making use of,e.g., expansive mortar or injection of mortar or epoxy resins under pressure.

2.3.2.3 Fusion-bonded pin-loaded straps

Another interesting development of the FRP strengthening technique involves replacing solid and relatively thick strips(Fig.2-7a)by the system shown in Fig.2-7b,known as pin-loaded strap[24].The strap comprises a number of non-laminated layers formed from a single,continuous,thin tape,which consists of fibres in a thermoplastic matrix.The outside,final layer of the tape is fixed to the previous layer by a fusion bonding process. Such a system enables the individual layers to move relative to each other,thus reducing the unwanted secondary bending stresses.Careful control of the initial tensioning process allows interlaminar shear stress concentrations to be reduced,so that a uniform strain distribution in all layers is achieved.

a)



b)

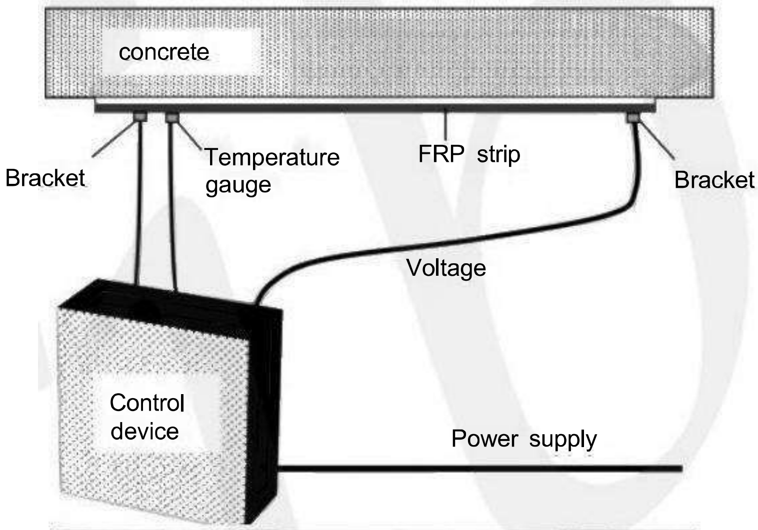
Fig.2-7 Wrapping with (a)thick strips and (b)non-laminated straps

2.3.2.4 In-situ fast curing using heating device

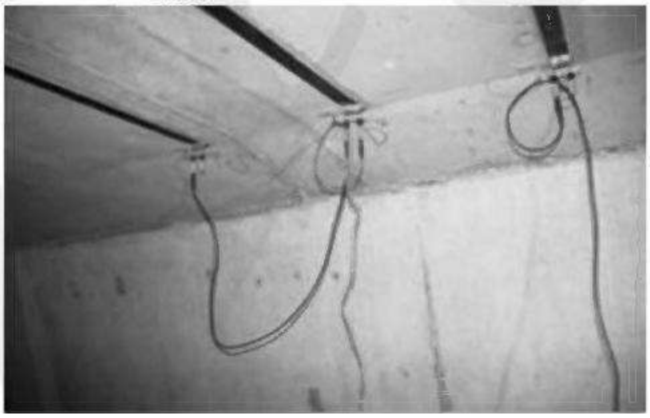
Instead of cold curing of the bond interface (curing of the two-component adhesive under environmental temperature),heating devices can be used.In this way it is possible to reduce curing time,to allow bonding in regions where temperatures are too low to allow cold curing,to apply the technique in winter 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.2-8 is also possible.This system takes advantage of the electrical conductivity of carbon fibres.It uses a special device for generating heat at the bond interface by passing 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 80℃ may be achieved in 3 hours)but also increases the glass transition temperature of special adhesives up to 90℃.



a)



b

Fig.2-8 Fast curing using heating device:(a)Schematic,(b)photograph of end brackets

2.3.2.5 Prefabricated shapes

Pre-cured types of FRP systems are mostly applied in the form of straight strips.However, these pre-cured systems can also be produced in other forms,depending on the required application.By shaping them,pre-cured systems can be employed in applications where normally the more flexible cured in-situ systems are used.

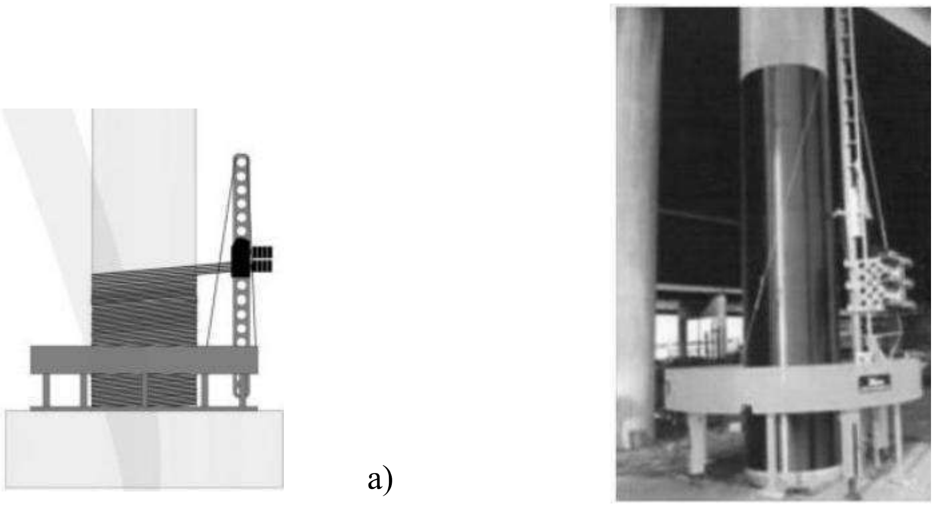
a) b) c)

Fig.2-9 Examples of prefabricated shapes for strengthening. (a) Angle, (b) application of angles, (c) shell

For shear strengthening of beams, pre-manufactured angles can be used as shown in Fig.2-9a-b. Figure 2-9c shows prefabricated 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. For new structures, FRP castings may be used. These act as formwork during construction, and as external reinforcement for the loaded structure.

2.3.2.6 Automated wrapping

The FRP 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, shown in Fig.2-10, involves continuous winding of wet fibres under a slight angle around columns or other structures (e.g. chimneys, as has been done in Japan) by means of a robot. A key advantage of the technique, apart from good quality control, is rapid installation.



a) b)

Fig.2-10 Automated RC column wrapping (a) Schematic (b) Photograph of robot-wrapper

2.3.2.7 Mechanically anchored or fastened FRP and the use of spacers

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, the use of extra mechanical anchorages postpones debonding failures and obtains a more ductile failure, due to the extra mechanical shear connection at the strip to concrete interface and 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 fibres in many directions, so that a sudden shearing type of failures in the strips may be avoided.

Among the disadvantages are the higher cost of strips (as they contain fibres in multiple directions, or because extra measures are needed if conventional unidirectional strips are used) and the risk of damaging the existing reinforcement.

Based on the concept of introducing extra mechanical anchorage, two subsequent strengthening methods have been developed for special application demands. In the so-called mechanically fastened FRP technique[25] 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. 2-11). This system requires simple hand tools, lightweight materials and minimally trained labour. 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. It is sometimes referred to as rapid intervention strengthening, for cases where serviceability limit state behaviour is of less concern.


a)

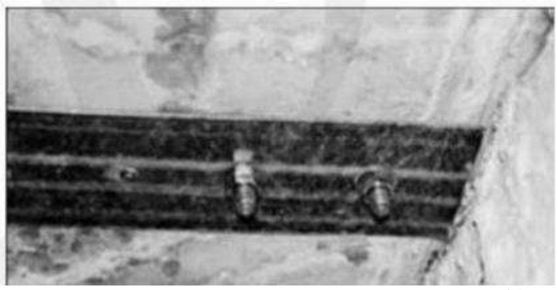

b)

Fig. 2-11 (a) Mechanically fastened FRP. (b) Detail of end anchorage with a combination of anchors and powder actuated nails

By using the so-called spacer technique[26], an increased lever arm between the FRP tensile member and the concrete compression zone is introduced (Fig. 2.12). As such, this application is especially suited for serviceability limit state considerations where concrete stresses tend to become too high due to strengthening, or to be able to significantly increase the stiffness of the cross-section when there may be a need to limit deflections after strengthening. To increase the lever arm, a spacer is bonded between the concrete surface and the external reinforcement, generally requiring extra bolt anchors to aid transfer of shear stresses over this multi-component system.

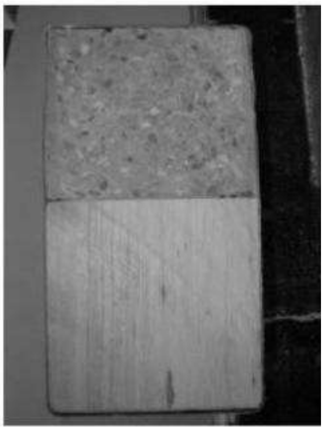


Fig.2-12 Cross-section of concrete beam(top)strengthened with CFRP(soffit)and in between spacer

2.3.2.8 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 behaviour at high temperatures and the relatively high cost. One possible solution to alleviate these problems would be the simple replacement of resins with inorganic binders.However,because of the granularity of the mortar,penetration and impregnation of conventional fibre sheets is very difficult to achieve;also,mortars cannot wet individual fibres,unlike resins.Bond conditions in cementitious composites could be improved and fibre-matrix interactions could be made tighter when continuous fibre sheets are replaced by textiles.These materials comprise fabric meshes made of long woven,knitted or even unwoven fibre tows in at least two (typically orthogonal)directions(Fig.2-13).

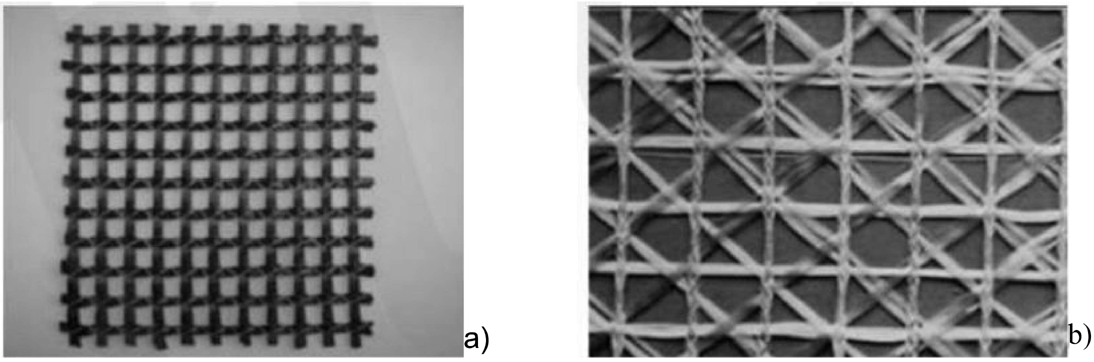


Fig.2-13(a)Bidirectional carbon fibre and(b)multidirectional glass fibre textiles

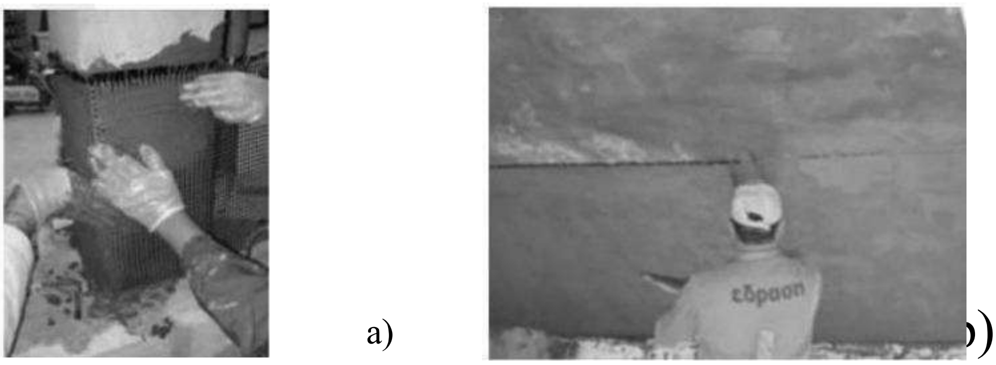


Fig.2-14(a)Textile-reinforced mortar (TRM)jacketing at the base of an RC column;(b)Strengthening of RC slab with TRM

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. 2-14), which appears quite promising for jacketing of RC members[13,14,27,28,29], masonry walls[30,31,3] as well as masonry infills in RC frames[33]. The same technique in North American terminology is known as FRCM, which stands for fabric reinforced cementitious matrix systems[34]. A detailed treatment of the topic is provided e.g. in Triantafillou (2016)[35].

2.3.2.9 Embedded through section reinforcement

When only the top or bottom faces of the concrete member are accessible, as in the case of bridge beams made contiguous within a deck or for corbels, a deep embedment technique can be applied[36]. Hereby, the reinforcement is embedded through the section: vertical holes are drilled into the concrete in the shear zones, high-viscosity epoxy resin is injected and then FRP bars are embedded into place (Fig. 2-15).

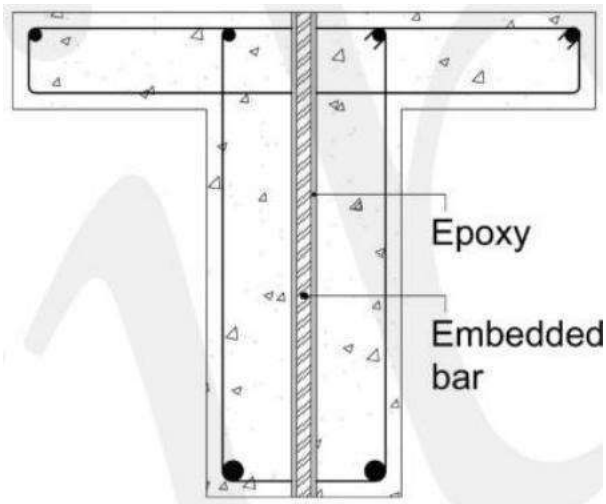


Fig. 2-15 Embedded through section reinforcement

5. Bond

5.1 Bond behaviour

5.1.1 Differential equation of bond

Generally the bond of reinforcement can be described by the differential equation:

$$\frac{ds^2}{dx^2} - p_f\left(\frac{1}{E_f \cdot A_f} + \frac{1}{E_c \cdot A_c}\right)\tau_b(s) = 0 \quad (5\text{–}1)$$

where s is the slippage;pE,and A,are the bonded perimeter,the elastic modulus and the cross sectional area of the FRP reinforcement,respectively;E and Aare the elastic modulus and the cross sectional area of the concrete volume mobilizing the FRP reinforcement,respectively;and t_6(s)is the local bond stress-slip law.p,can be set equal to the width b,of the externally bonded FRP strips,2b,for near surface mounted FRP strips and πφ for near surface mounted FRP bars with diameter φ.The bond stress-slip laws are described in Sections 5.1.2 and 5.1.3 for externally bonded reinforcement(EBR) and near surface mounted(NSM)reinforcement,respectively.In most cases the concrete deformation can be neglected in the differential equation of bond,which leads to the simplified equation:

$$\frac{ds^2}{dx^2} - \frac{p_f}{E_f \cdot A_f}\tau_b(s) = 0 \quad (5\text{–}2)$$

5.1.2 Bond-slip law for surface bonded FRP

In RC members externally strengthened with open FRP systems(e.g.flexural strengthening, shear strengthening with U-shaped jackets)the stress transfer between the concrete and the EBR governs the effectiveness of strengthening.When the stress field transferred from the FRP system to the concrete substrate attains the concrete strength,a premature failure due to the loss of bond strength between the FRP reinforcement and the concrete surface occurs.The term"debonding"is adopted to designate failure occurring within the adhesive or FRP,at the FRP-adhesive and adhesive-concrete interface,or just a few millimetres inside the concrete substrate,with the last case being the most common one.

The FRP-concrete bond behaviour is typically expressed by a relationship between the shear stress at the interface and the corresponding slip(T,-s relationship).In the context of the physical meaning of debonding,the t-s simulates the shear stress transfer behaviour and the debonding process between the FRP strengthening system(FRP and adhesive)and the concrete substrate.Such a relationship depends on the mechanical characteristics of the materials and the geometry of both the strengthened element and the strengthening system.

The bond behaviour at the FRP-concrete interface can be well represented by a -generally-non-linear ascending branch,followed by a descending branch due to the progressive damage occurring in the materials (adhesive,concrete and interfaces)during the process of stress transfer from the concrete element to the FRP.

This chapter was mainly authored by Ceroni.

Experimental studies on the assessment of the bond strength and the bond stress-slip relationship have been numerous1,2,3,4.The simplified bilinear t -s relationship represented in Fig.5-1 is typically suggested for analysis.The significant values of parameters that define this relationship can be evaluated using experimental results in terms of bond strength and mode II fracture energy(defined by the area under the t-s diagram).The bilinear law is given by an initial linear relationship between slip,s,and bond stress,t,up to the bond strength,t_{b1},followed by a linearly softening branch until the maximum slip s_o .The maximum shear stress $t_1$depends on the concrete tensile strength,which can be correlated to its compressive strength.

To define the slope of the initial branch,k_1,both the compliance of the adhesive layer (whose thickness is of the order of one millimetre)and of the concrete surface,whose deformation contributes to the interfacial slip,should be considered in terms of thickness and shear modulus.

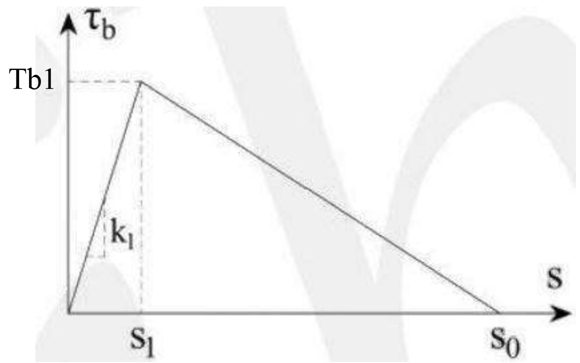


Fig.5-1 Generic bilinear t -s constitutive law for bond in EBR FRP system

The values of the maximum shear bond stress,t_1,and ultimate slip,s_o ,depend on properties of the concrete,the strengthening system and other geometric characteristics. Some proposals for the evaluation of these parameters are reported in AppendixA5.1.1.1.

5.1.3 Bond-slip law for near surface mounted FRP

For modelling the bond behaviour of NSM FRP systems in the context of strengthening concrete structures,a local bond shear stress versus slip relationship(t-s)is also used.This relationship is affected by several parameters,among which the mechanical properties of the materials(FRP reinforcement,groove filler and concrete substrate),the surface properties of the FRP reinforcement and of the grooves,the shape of the strengthening system(bars or strips),the dimensions of the groove,the distance of the groove from the edge of the member and the depth of the FRP reinforcement into the groove5,6,7,8,9,10.11,12,13,14.

Further details and references on bond of NSM and bond stress-slip relationships are reported in Appendix A5.1.2.1.Due to the large number of parameters affecting the local bond-slip behaviour of NSM reinforcements,the local bond-slip relationship for a given NSM system should be determined experimentally by selecting the most appropriate test set-up.Notably,as for EBR,also for NSM systems a simplified bilinear bond law can be assumed[1]5.