SPECIAL MOBILITY STRAND

CONTEMPORARY METHODS FOR RECONSTRUCTION OF CONCRETE STRUCTURES

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Why strengthening in 21 century?

Degradation and functional inappropriateness of construction

- *ageing,*
- *environmental impacts,*
- *unexpected* accidental *loads,*
- *increasing the traffic loads*
- *increasing the number of usersageing*
- *poor initial design*
- *poor construction*
- *lack of maintenance*

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Repair, strengthening, retrofit

- *more stringent design requirements*
- *increased traffic loads*
- *increased number of users*
- *seismic risk*

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Externally bonded FRP reinforcement

- *Advantages*
  - *Immunity to corrosion*
  - *Low weight*
  - *Easier application*
  - *Very high tensile strength*
  - *Stiffness tailored to the design requirements*
  - *Large deformation capacity*

- *Disadvantages*
  - *Reduced ductility*
  - *High cost of material*
  - *Incompatible thermal expansion coefficient with concrete*

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Use of FRP in buildings

- Reinforcement of concrete with reinforcement, sheets, profiles and fabrics
- Pre-stressing concrete with external and internal cables
- Construction elements – beams, columns and slabs

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Application of externally bonded FRP reinforcement

slabs

beams

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Application of externally bonded FRP reinforcement

columns

Shear strengthening

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Use of glass reinforcement

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Components of Fiber reinforced polymers

Matrices – protect the fibers against abrasion or environmental corrosion, to bind the fibers together and to distribute the load. Type of matrix influence on transverse modulus and strength, shear and compression properties

- *Thermosetting type -* thermal stability, chemical resistance, reduced creep and stress relaxation, low viscosity- excellent for fiber orientation

  common material with fabricators
  - *epoxy resin*
  - *polyester*
  - *vinyl ester*
  - *polymers with good processibility and chemical resistance*

- *Thermoplastic type -* room temperature material storage, rapid, low cost forming, reformable, forming pressures and temperatures

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Components of Fiber reinforced polymers

Fibers – very effective transfer of load via matrix material to the fibers. They carry load along the length of the fiber, provides strength and or stiffness in one direction. Can be oriented to provide properties in directions of primary loads.

- Continuous with diameter 5-20 μm
- Unidirectional or bi-directional

➢ *Type of fibers*

- Glass (E-glass, S-glass, AR-glass)
- Aramid
- Carbon

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Fiber reinforcement

- Glass (e-glass)
  - most common fiber used
  - high strength
  - good water resistance
  - good electric insulating properties
  - low stiffness
- *Aramid (kevlar)*
  - superior resistance to damage (energy absorber)
  - good in tension applications (cables, tendons)
  - moderate stiffness
  - more expensive than glass
- *Carbon*
  - good modulus at high temperatures
  - excellent stiffness
  - more expensive than glass
  - brittle
  - low electric insulating properties

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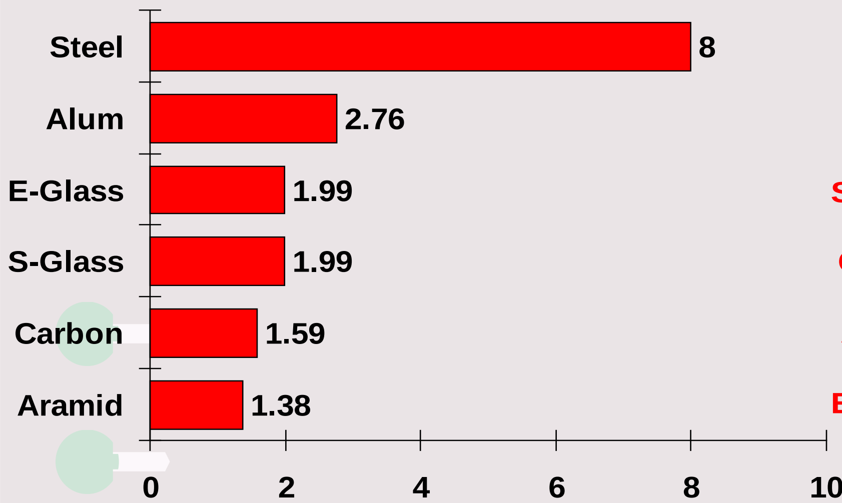
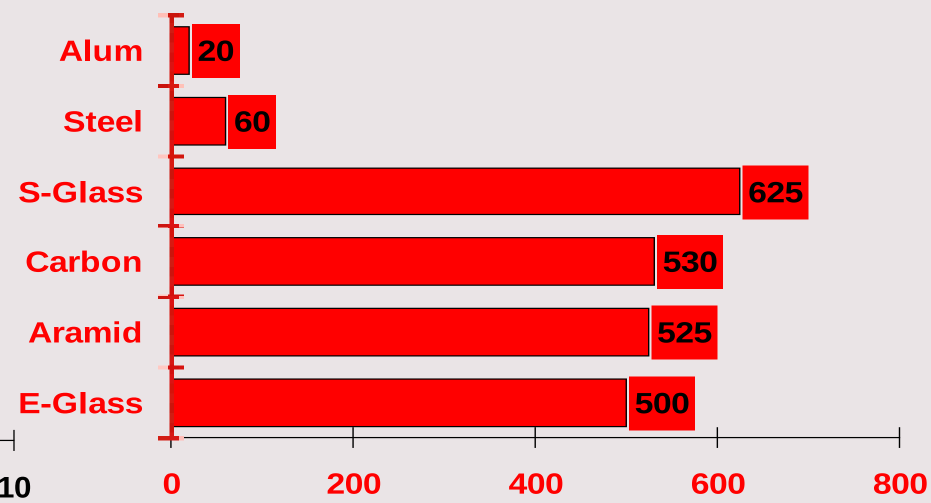
Fiber properties

density [g/cm³]



tensile strength



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Reinforcement summary

- *Tailoring mechanical properties*

  - type of fiber
  - percentage of fiber
  - orientation of fiber

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Fiber reinforced polymers

FRP materials consist of a large number of small, continuous, directionalized, non-metallic fibers with advanced characteristics, bundled in a resin matrix.

- GFRP – glass fiber based
- CFRP – carbon fiber based
- AFRP – aramid fiber based

Fibers are the principal stress bearing constituents, while the resin transfers stresses among fibers and protect them.

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Design variables for composites

- Type of fiber
- Percentage of fiber or fiber volume
- Orientation of fiber
  0^o, 90^o, $+45^o$, -45^o
- Type of polymer (resin)
- Cost
- Volume of product - manufacturing method

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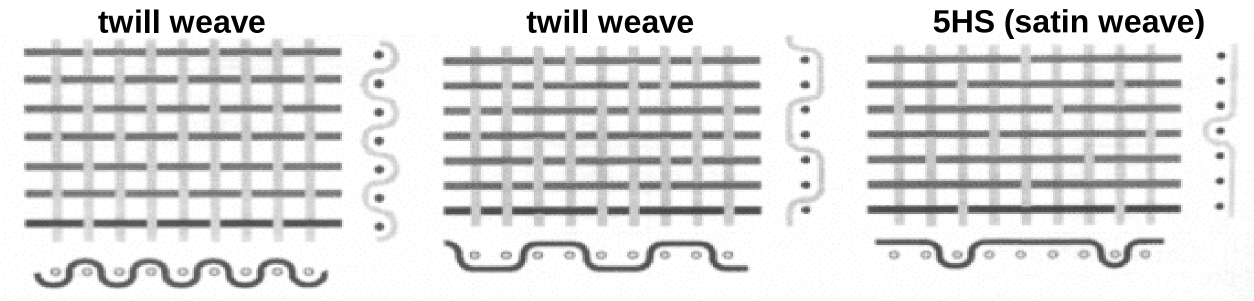
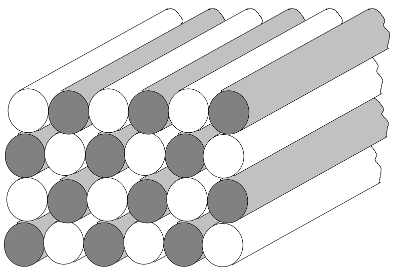
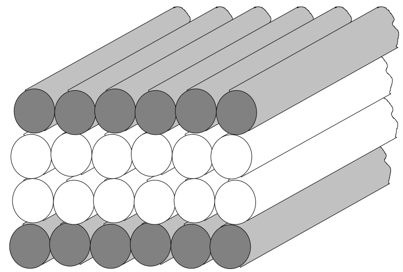
Composition of fibbers and layers of composites

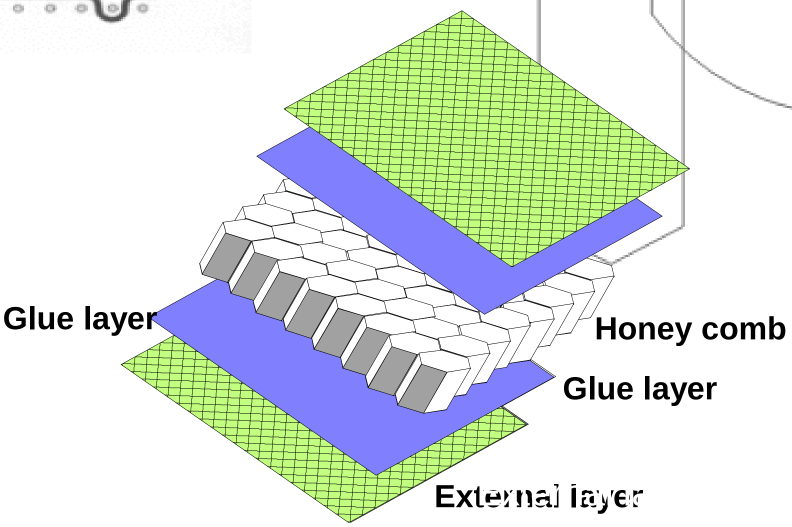




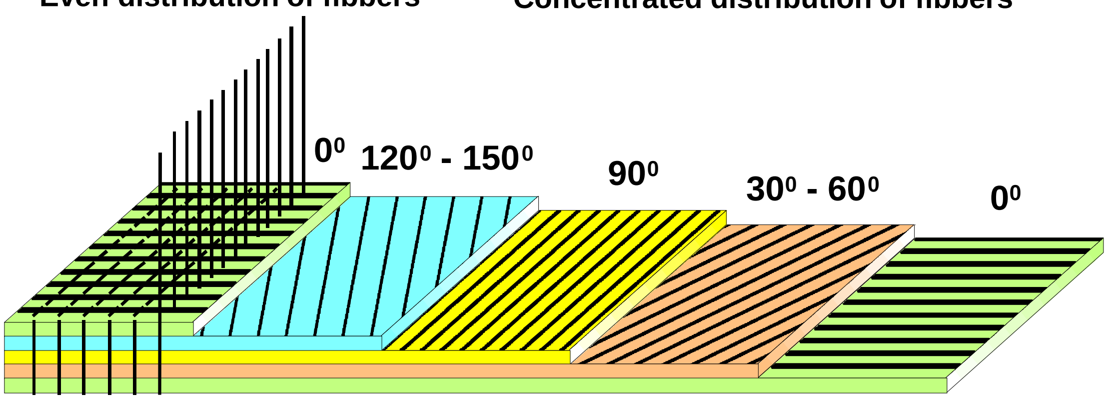
Even distribution of fibbers



Concentrated distribution of fibbers



Sandwich composites



Stitched layers composite with differently oriented fibbers

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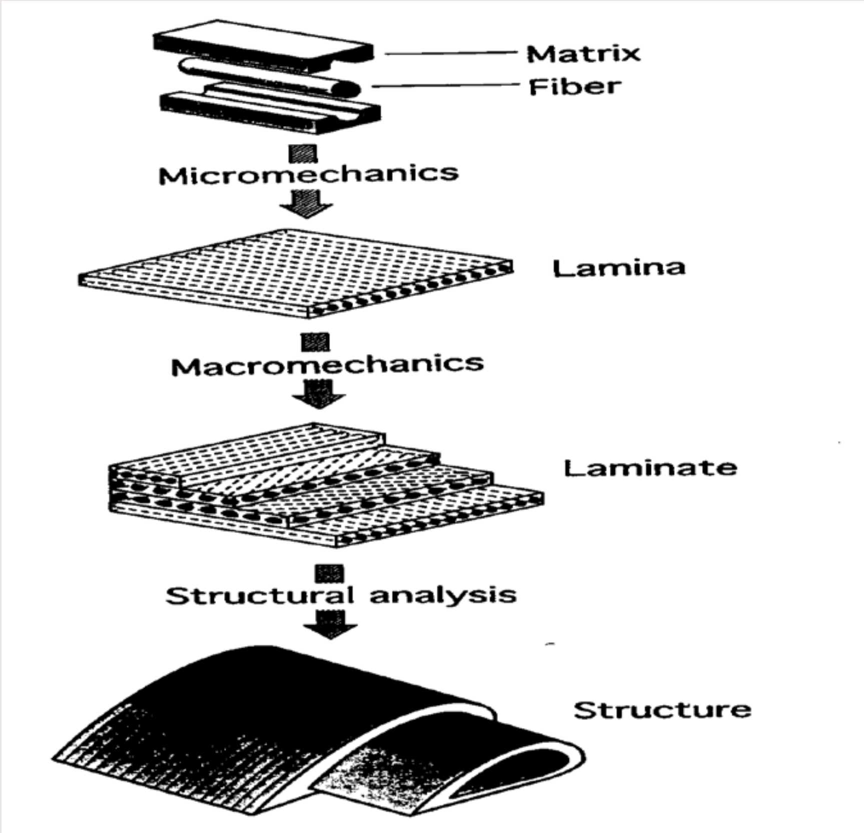
Structural design with FRP composites



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Design variables for composites

- Physical:
  - tensile strength
  - compression strength
  - stiffness
  - weight, etc.

- Environmental:
  - fire
  - uv
  - corrosion resistance

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Tailoring composite properties

- *Major feature*
- *Place materials where needed – oriented*
- *Strength*
  - longitudinal
  - transverse
  - or between
- *Strength*
- *Stiffness*
- *Fire retardancy*

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Traditional materials

Advantages:

- well known characteristics of materials
- cheap raw materials
- developed manufacturing and processing technology
- wide knowledge

Disadvantages:

- durability under demanding application
- degradation

Reinforced composites

Advantages:

- high strength
- high fatigue strength
- corrosion resistance
- design of characteristics
- low maintenance costs
- easy construction

Disadvantages:

- high cost of material
- lack of knowledge about material characteristics
- lack of knowledge about design process
- lack of standards and rules
- durability
- rigid fracture (linear behavior)

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Characteristics comparison of FRP and steel

Characteristic	Range	Comparison with steel
Module of elasticity	20 up to138 GPa	1/10 up to 2/3 from steel
Stiffness	340 up to 1700 MPa	1 up to 5 times than f_y
Failure deformation	1 up to 3%	1/10 up to 2/3 from steel
Density	1,4 up to 2,0 g/cm^3	4 up to 6 lighter than steel

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Composites in construction

Strengthening of constrictions

Wood
Reinforced concrete
Massive

- **Sanction**
  - Sanction of damages
  - Protection against decay
- **Strengthening**
  - Strengthening
  - Increase of bearing capacity and durability
- **Seismic strengthening**
  - Increase of seismic capacity

New buildings

- Optimized structural elements
- Reliable element joints
- Reinforcement

FRP strengthening systems

- Wet lay-up system
- Prefabricated elements
- Special systems (automated wraping, prestering)

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Wet lay-up system

Installation on the concrete surface requires saturating resin after a primer has been applied.

- The fabric can be applied directly into the resin
- The fabric can be impregnated with the resin

External reinforcement is bonded onto the concrete surface with the fibers as parallel as practically possible to the direction of principal tensile stresses

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Special techniques

Automated wrapping – continuous winding of wet fibers under a slight angle around columns by means of a robot.

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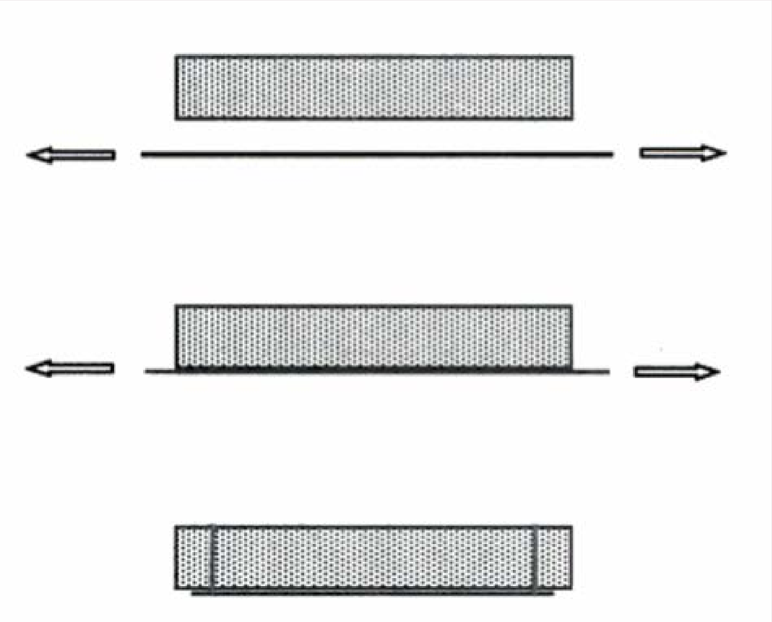
Special techniques

Prestressed FRP – bond of external FRP reinforcement onto the concrete surface in a prestressed state.



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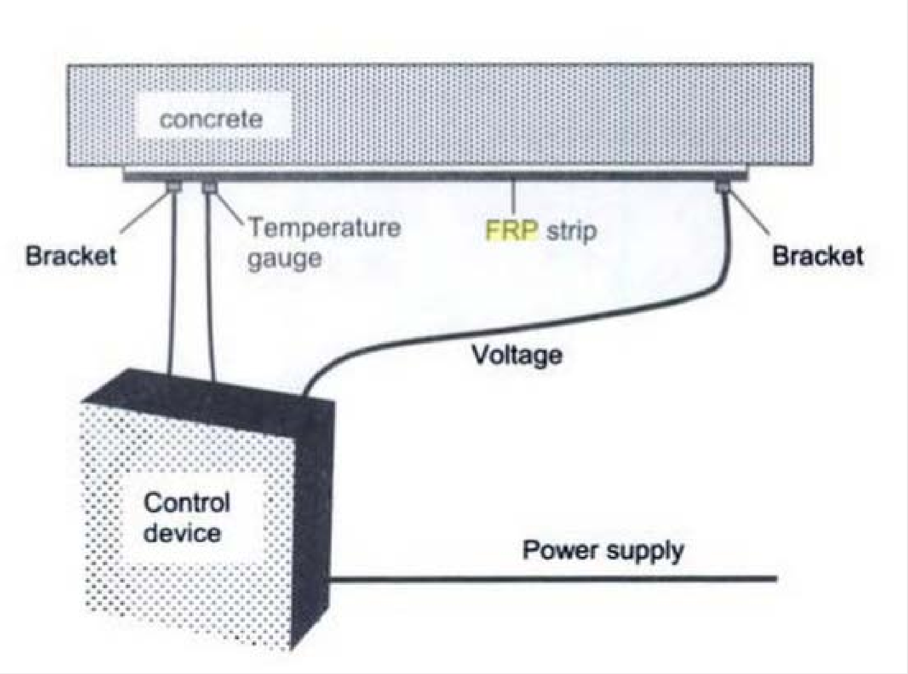
Special techniques

In situ fast curing heating device – instead of cold curing of the bond interface heating devices can be used. Different systems for curing can be used, such as electrical heaters, infrared heating systems and heating blankets.



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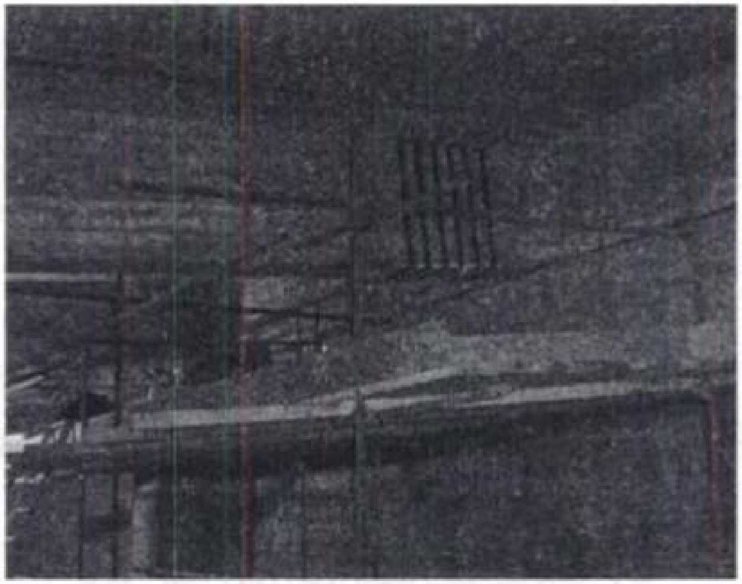
Special techniques

Prefabricated shapes – applied in the form of straight strips or in other form, depending on the foreseen application.

(a)



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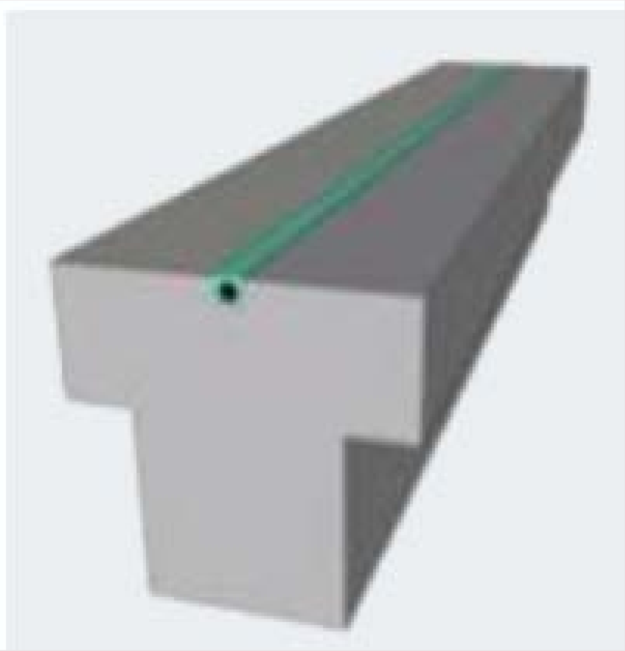
Special techniques

CFRP inside slits – slits cut into the concrete structure with a depth smaller than concrete cover and CFRP strips are bonded into these slits.



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Special techniques

FRP impregnation by vacuum – the surface is cleaned carefully, primer is applied and after curing of the primer the fibers are placed in predetermined directions. It is important that fabrics have channels where the resin can flow. A vacuum bag is placed on top of the fibers, the edges of the bag are sealed and a vacuum pressure is applied. Two holes are made in the vacuum bag, one for the outlet where the vacuum pressure is applied and one for the inlet where the resin is injected.

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Basis of design

General requirements – efficient technique that relies on the composite action between a reinforced or prestressed concrete element and externally bonded reinforcement. To guarantee the overall structural safety of the strengthened member it is important that proper systems are used, which depend on type of FRP, type of adhesive, method of curing, material preparations.

- The state of the repaired structure prior to strengthening should be taken as a reference for the design of the externally bonded FRP reinforcement.
- The design procedure should consist of a verification of both the serviceability limit state SLS and the ultimate limit state ULS.

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Basis of design

The following design situations have to be considered:

- Persistent situation, corresponding to the normal use of structure
- Accidental situation, corresponding to unforeseen loss of the FRP EBR
- Special design considerations, fire resistance, impact resistance

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Verification of the SLS

It should be demonstrated that the strengthened structure performs adequately in normal use. SLS verification concerns:

- Stresses, have to be limited in order to prevent steel yielding, damage or excessive creep of concrete and excessive creep or rupture of the FRP
- Deformations or deflections, may restrict normal use of the structure, induce damage to non load-bearing members
- Cracking, may damage the durability, functionality or integrity of the bond interface between FRP and concrete

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Verification of the ULS

Different failure modes that may occur have to be considered, such as those assuming full composite action between the RC member and EBR system and those verifying the different debonding mechanisms that may occur.

Failure modes

- Full composite action of concrete and FRP until the concrete reaches crushing in compression or the FRP fails in tension.
- Composite action is lost prior to previous failure due to peeling-off of the FRP

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Full composite action

- Steel yielding followed by concrete crushing.

The flexural strength may be reached with yielding of the tensile steel reinforcement followed by a crushing of the concrete in the compression zone, whereas the FRP is intact.

- Steel yielding followed by FRP fracture

For relatively low ratios of both steel and FRP, flexural failure may occour with yielding of the tensile steel reinforcement followed by tensile fracture of the FRP.

- Concrete crushing

The relatively high reinforcement ratios, failure of the RC element may be caused by compressive crushing of the concrete before the steel yields. This mode is brittle and undesirable.

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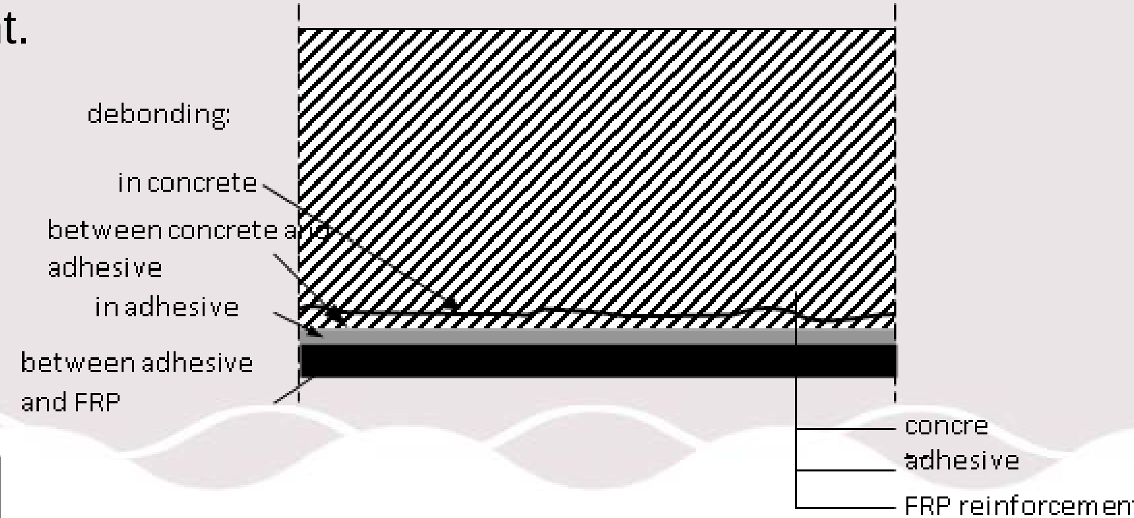
Loss of composite action

Bond is necessary to transfer forces from the concrete into the FRP, hence bond failure modes have to be taken into account properly. Bond failure in the case of EBR implies the complete loss of composite action between the concrete and the FRP reinforcement, and occurs at the interface between the EBR and the concrete substrate.

Bond failure may occur at different interfaces between the concrete and the FRP reinforcement.



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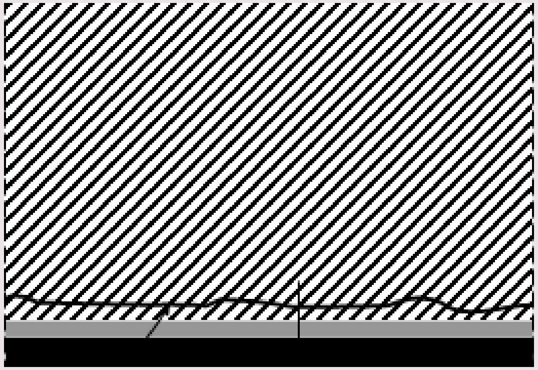
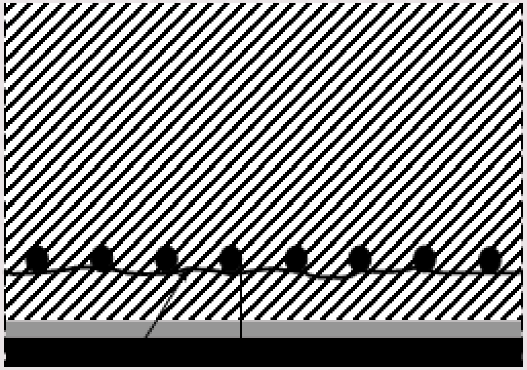
Loss of composite action

Debonding in the concrete near the surface or along a weakened layer





- **debonding in the adhesive – cohesion failure**. As the tensile and shear strength of adhesive is higher than the tensile and shear strength of concrete, failure will occur in concrete. A thin layer of concrete will remain on the FRP reinforcement. Debonding may occur through the adhesive only if its strength drops below that of concerete.

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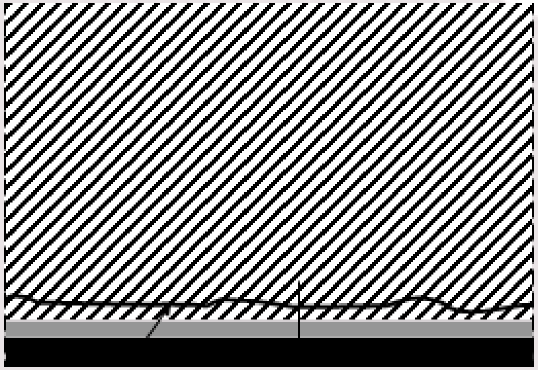
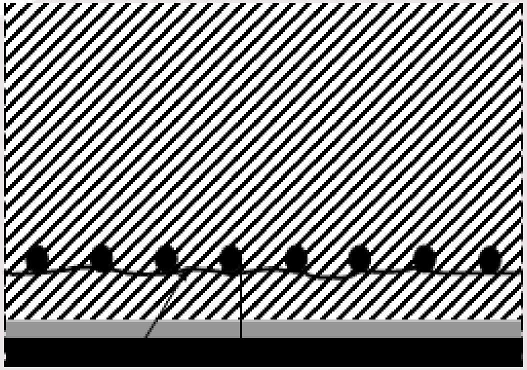
Loss of composite action





- **debonding at the interface between concrete and adhesive or adhesive and FRP-adhesion failure**. Bond failures in the interface between concrete and adhesive or adhesive and FRP will only occur if there is insufficient surface preparation during the FRP application process, because the cohesion strength of epoxy resins is lower than the adhesion strength.

- **debonding inside the FRP**. This failure mechanism between fibers and resin may be explained by fracture mechanism. This might be the case with high strength concretes.

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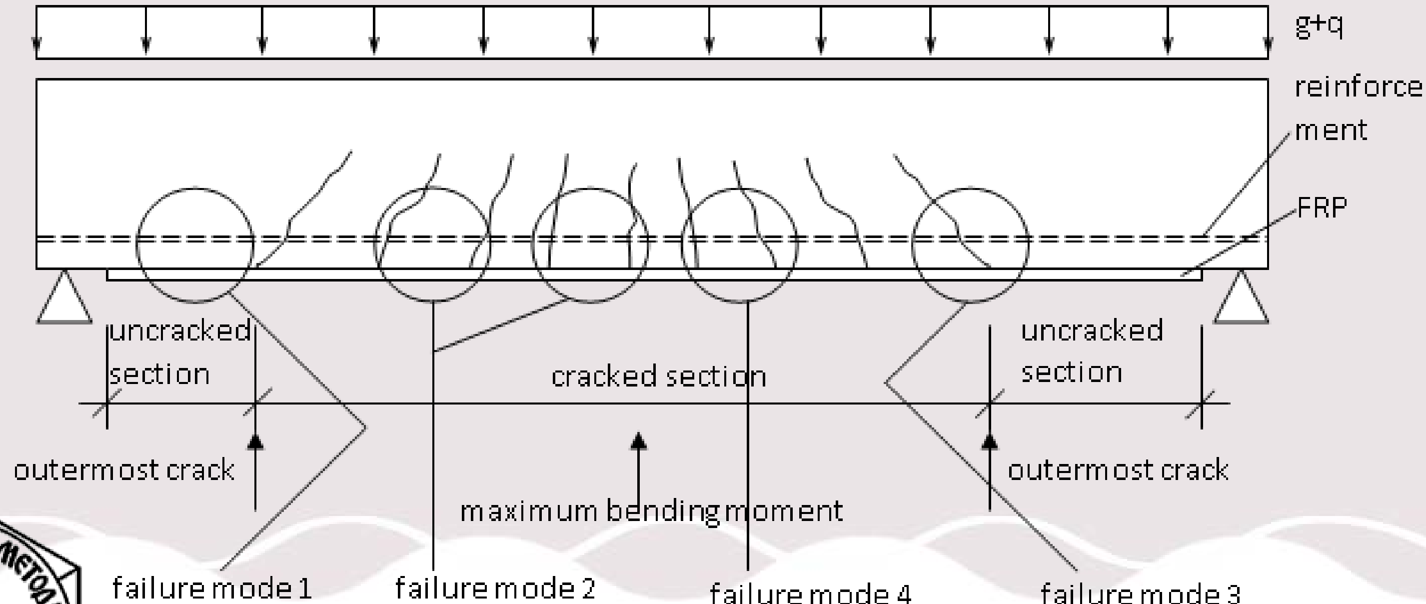
Bond behavior of RC members strengthened with FRP

Most failures of RC members strengthened with FRP are caused by peeling-off of the EBR element. The weakest point in the bond between the EBR and the concrete is in the concrete layer near the surface. Depending on the starting point of the debonding process, the following failure modes can be identified.



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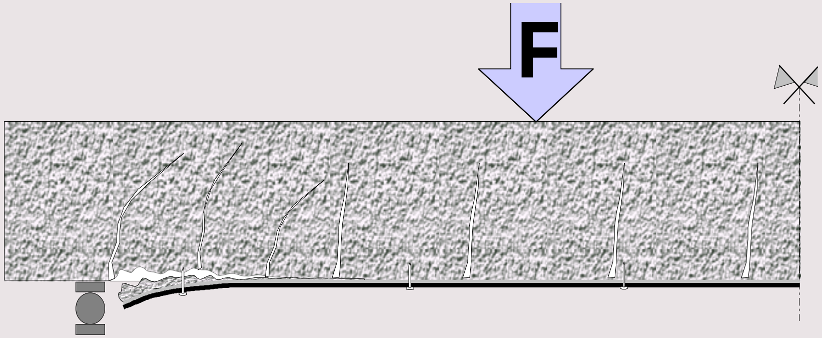
Bond behavior of RC members strengthened with FRP

Mode 1: pilling-off in an uncracked anchorage zone. The FRP may peel-off in the anchorage zone as a result of bond shear fracture through the concrete.



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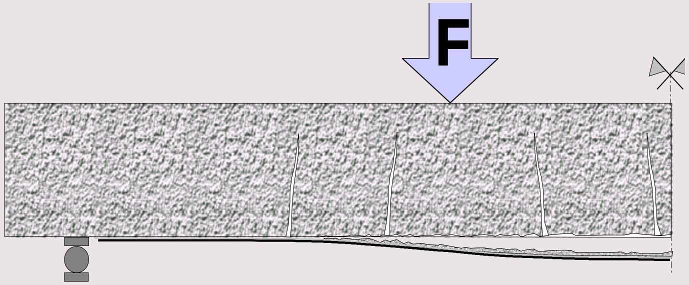
Bond behavior of RC members strengthened with FRP

Mode 2: pilling-off caused at flexural cracks. Flexural cracks in the concrete may propagate horizontally and thus cause peeling-off of the FRP in regions far from the anchorage;



Mode 3: pilling-off caused at shear cracks. Shear cracking in the concrete generally results in both horizontal and vertical opening, which may lead to FRP peeling-off. In elements with sufficient internal shear reinforcement the effect of vertical crack opening on peeling-off is negligible;

Mode 4: pilling-off caused by the unevenness of the concrete surface. The unevenness or roughness of the concrete surface may result in localized debonding of the FRP, which may propagate and cause peeling-off.

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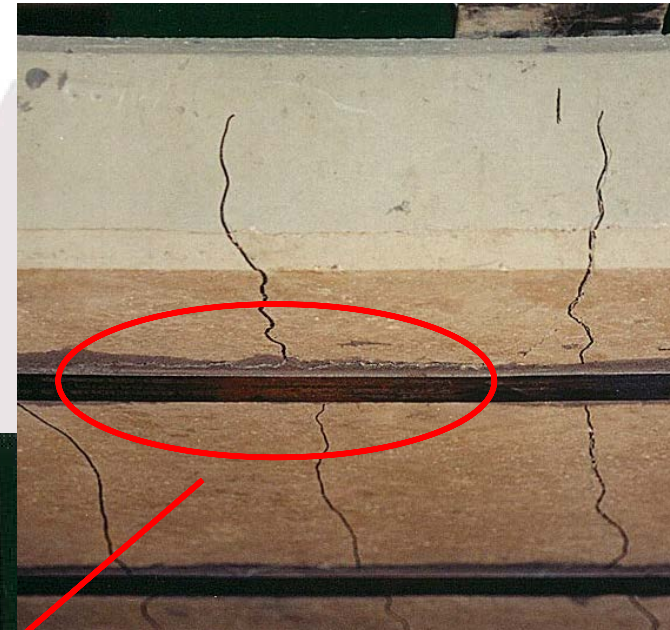
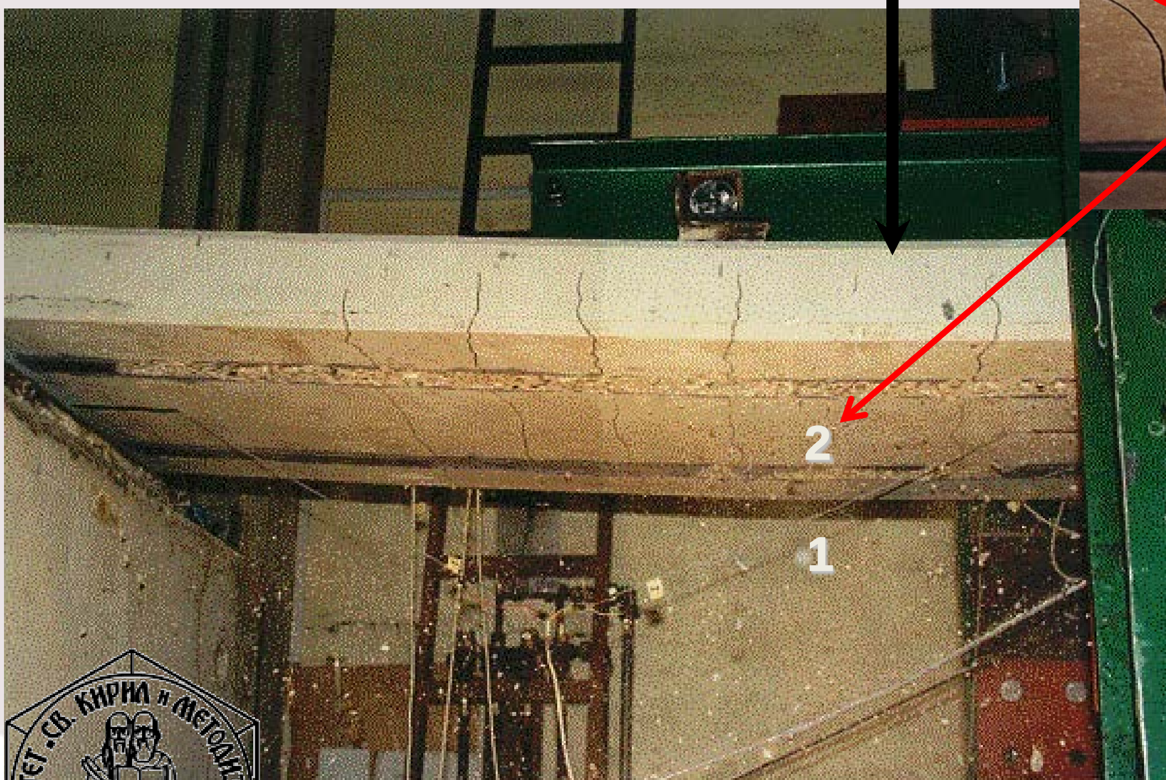
Slab failure strengthened with FRP sheets





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Practical execution

Composite materials are used for strengthening wood, masonry and concrete constructions, in order to increase the bearing capacity of construction under permanent and increased loads caused by earthquakes and environment.

The FRP EBR does not stop existing problems such as steel corrosion, water leakage, high chloride values. Potential damage mechanisms must be minimized and the concrete should be sound. If needed the strengthening has to be preceded by concrete repair and internal steel protection techniques.

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Use of composites in strengthening of buildings

Strengthening of existing structures in addition with new composite elements

- Columns and hinges of frame structures are strengthened by twisting fabrics
- Flexural and shear loaded beams are strengthened by externally added sheets or laminate elements
- Walls are strengthened by strips or fabrics
- Massive floor slabs are replaced by lighter sandwich constructions

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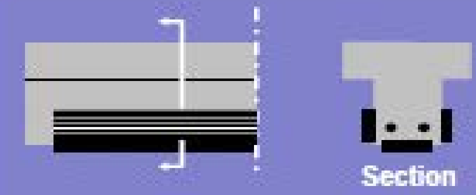
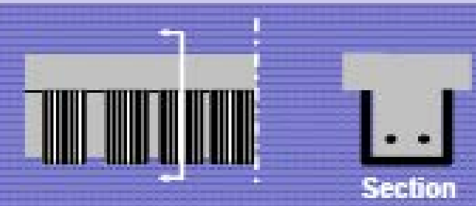
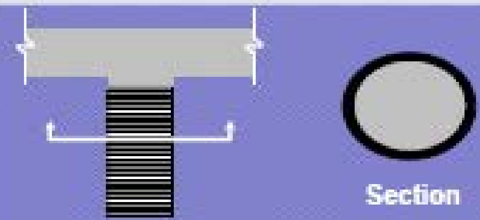
FRP strengthening application

Type	Application	Fibre Dir.	Schematic
Flexural	Tension and/or side face of beam	Along long. axis of beam	
Shear	Side face of beam (u-wrap)	Perpendicular to long. axis of beam	
Confinement	Around column	Circumferential	

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Flexural strengthening of RC structures

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Shear strengthening of RC structures

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Strengthening of columns with FRP

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Construction process

Typical RC beam in need for repair

- corroded steel
- spalling concrete

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Construction process

Deteriorated Column / Beam Connection

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Preceding repair

The following aspects should be considered:

- the minimum concrete tensile strength should be greater than 1.5 N/mm^2. If the deteriorated or damaged concrete has reached a depth that no longer allows shallow surface repair, replacement of the concrete should be considered;
- although the external reinforcement may act as a replacement of the steel reinforcement, corrosion should be stopped to avoid damage to the concrete due to expansive rust. This damage may result in a decreased bond strength and an increased susceptibility to freeze-taw action. Repair or protection is needed if the steel is already corroded or is likely to start corroding. With respect to the latter the carbonation depth and chloride content may need to be verified;
- wide cracks may need sealing by means of injection. Any cracks wider than 0.2 mm should be injected by suitable compatible low viscosity resin to fill and seal the cracks. Also, repair of porous concrete and joints to restore water retaining may be of relevance.

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Preparation of surfaces

Concrete substrate

To provide an adequate bond with the adhesive, the preparation of the concrete substrate should be carried out well:

- The substrate should be roughened and contamination free, in such a way that the concrete quality can be utilized in an optimum way.
- This is done by means of high pressure blasting or grinding. Mechanical methods that may compromise the quality of the concrete should not be allowed.

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Preparation of surfaces

- The unevenness depends on the type of FRP EBR, but most of the wet lay-up systems require a smoother surface.
- Strips are less sensitive to unevenness, while the fabrics and sheets are very flexible and will follow unevenness.
- The concrete should be sound and free from serious imperfections (steel corrosion, wide cracks) and potential damage mechanisms.

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Preparation of surfaces

- The prepared surface should be dry and dust free before application of the strengthening technique.
- The concrete surface shall be marked where the FRP EBR has to be applied.
- Application of primer (if required by the manufacturer)

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Preparation of surfaces and application

- Repair of the existing concrete in accordance to:
  - ACI 546R-96 “Concrete Repair Guide”
  - ICRI Guideline No. 03370 “Guide for Surface Preparation for the Repair of Deteriorated Concrete...”

- Bond Between Concrete and FRP Materials

  Should satisfy ICRI “Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces”

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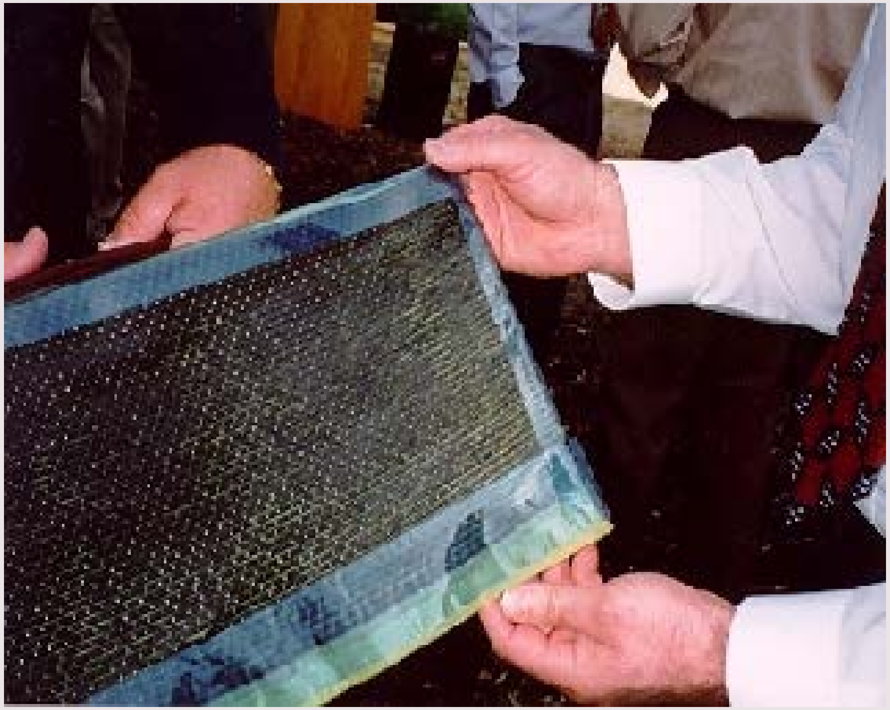
Preparation of surfaces

FRP EBR



- Should be supplied to site at the specified width and cut to the necessary length as specified on the design drawings.

- Have to be verified for possible damage resulting from transportation, handling or incorrect cutting and they should be free from any contamination like oil, dust, carbon dust.

- The ply should be removed immediately before.

- Handling and preparation precautions provided by the manufacturer should be followed.

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FRP EBR application

- The application depends on the type of FRP EBR and is performed according to the specifications given by the manufacturer.
- Strips and laminates - bonding
- Sheets and fabrics - bonding and impregnation.

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FRP EBR application

Strips or laminates

- Immediately after mixing the adhesive is applied as a thin layer to the concrete and to the FRP sheet.
- The strip is offered to the concrete surface applying pressure by means of a rubber roller.
- The final bond line should be of equal thickness along the strip.

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FRP EBR application

˝Wet lay up˝ type

- In accordance with the specifications given by the manufacturer is applied a primer.
- A low viscosity resin is applied to the concrete with sufficient thickness, by means of roller brush (undercoating).
- Then the sheet is applied by pressing it manually onto the adhesive
- Impregnation and further pressing is performed by applying adhesive on top of the sheet with roller brush (overcoating).

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Finishing and Quality control

- Some form of finishing may be required for aesthetic purposes. In terms of fire protection, possible occurrence of damage, protection against U. V. radiation, a finishing layer can be crucial to the long term integrity of the strengthened structure. Different types of finishing layers can be provided such as painting, shot-concrete or fire protection panels. The compatibility between EBR and the finishing layer should be proved.

- For specifications concerning concrete repair technique and steel corrosion protection techniques, reference is made to corresponding guidelines.

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Sanction of reinforced concrete structures

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Thank you
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