Ana Trombeva-Gavriloska [1]

Marijana Lazarevska [2]

CONTEMPORARY METHODS FOR RECONSTRUCTION OF CONCRETE STRUCTURES

Abstract: A large number of existing RC structures exhibit non adequate performance in terms of diminished bearing capacity and there is need of post strengthening during their service life. Externally bonded reinforcement by FRP (fibber reinforced polymers) plates is frequently used to increase bearing capacity of flexural loaded structural elements. Knowledge about the characteristics of the composite materials and their components is essential in their use in the civil engineer constructions. Experimental researches show the main factor for strengthened structure response is bond between concrete and external bonded FRP reinforcement.

Key words: composite material, construction

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[1] Assoc. Prof., Ss. Cyril and Methodius University in Skopje, Faculty of Architecture, Blvd. Partizanski odredi 24, 1000 Skopje, Macedonia, agavriloska@arh.ukim.edu.mk

[2] Assis. Prof., Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering, Blvd. Partizanski odredi 24, 1000 Skopje, Macedonia, marijana@gf.ukim.edu.mk

1. COMPOSITE MATERIALS FOR STRENGTHENING REINFORCED CONCRETE CONSTRUCTIONS

1.1. Repair, strengthening, retrofit

The issue of upgrading the existing civil engineering infrastructure has been one of great importance for over a decade. Detorioration of bridge decks, beams, girders and columns, buildings may be atributed to aging, enviromentally induced degragation, poor initial design and/or construction, lack of maintance and to accidental events such as earthquakes. The infrastructure's increasing decay is frequently combined with the need for upgrading so that structures can meet more stringent design requrements (increased loads), and hence the aspect of civil engineering infrastructure renewal has recived considerable attention.

1.2. Externally bonded FRP reinforcment (EBR)

The reasons why composites are increasingly used as strengthening materials of reinforced concrete elements may be sumarised as follows: immunity to corrosion, low weight, easier application in confined space,reduction of labour costs, very high tensile strength, stiffness wich may be tailored to the design reqirments, large deformation capacity. Composites have disadvantages such as: linear elastic behaviour to failure without any significant yielding or plastic deformation wich lead to reduced ductility, high cost of the material, incompatible thermal expansion coefficients with concrete

1.3. Application of EBR

Composites have found their way as strengthening materials of reinforced concrete elemnts such as beams, slabs, columns, where conventional strengthening techniques may be problematic.

1.4. Composite material

Composite material is a combination of two or more materials (reinforcement, resin, filler, etc.), differing in form or composition on a macroscale. The constituents retain their identities, i.e.., they do not dissolve or merge into each other, although they act in concert. Normally, the components can be physically identified and exhibit an interface between each other.

Fiber Reinforced Polymer (FRP) Composites are defined as: A matrix of polymeric material that is reinforced by fibers or other reinforcing material.

Composites are composed of polymers, reinforcing fibers, fillers, and other additives. Each of these ingredients play an important role in the processing and final performance of the end product.

In general terms, it could be said that the polymer is the “glue” that holds the composite and influence the physical properties of the composite end product, whilw the reinforcement provides the mechanical strength properties to the end product. The fillers and additives are processing aids and also impart "special" properties to the end product.

1.4.1.Matrices

The matrix for a structural composite material can eighter be of thermosetting type or of thermoplastic type. The function of the matrix is to protect the fibers against sbrasion or enviromental corrosion, to bind the fibers together and to distribute the load. The matrix has a strong influence on several mechanical properties of the composite, such as transverse modulus and strength, the shear properies ond the properies in compression.

Epoxy resins, polyester and vinylester are the most common matrix materials. They are thermosetting polymers with good processibility and chemical resistance. Epoxies have, in general, better mechanical propreties than polyesters and vinylesters, and outstanding durability, whereas polyesters and vynilesters are cheaper.

1.4.2.Fibers

A high fibre aspect ratio (length/diameter ratio) permits very effective transfer of load via matrix materials to the fibers. Fibers can be manufactured in continous or discontinous form. Such fibers have a diameter in order of 5-20 μm and can be manufactured as unidirectionl or bi-directional. The fibers used for strengthening exhibit linear elastic behaviour up to failure.

There are mainly three types of fibers that are used for strengthening of civil engineering structures, namely glass, aramid and carbon fibers. Physical and mechanical properties can vary a great for a given type of fiber.

Glass fibers are clasified into three types: E-glass, electrical resistant fibers, S-glass, high strength and high stiffness fibers, AR-glass, alkali resistant fibers for use in cement substrates and concrete. S-glass fibers are stronger and stiffer than E-Glass and is used in more demanding applications were their extra cost can be justified.

Aramid fibers are anisotropic and gives higher strength and modulus in the fiber longitudinal direction. Aramid fibers respond elastically in tension but they exhibit non-linear and ductile behaviour under compression, they also exhibit good toughness, damage tolerance and fatigue characteristeics. Aramid fibers offer good mechanical properties at a low density with the added advantage of toughness or damage resistance. They are characterized as having reasonably high tensile strength, a medium modulus, and a very low density. There is a significant cost difference compare with glass fibers. Since aramids are lightweight, they have an advantage in their strength/weight and stiffness to weight ratios. It should be noted that they have relatively low compressive strengths.

Carbon fibers combine high modulus with low density and make them very attractive. Carbon fiber is created using polyacrylonitrile, PAN based fibers wich have good strength, modulus and excellent compression strength for structural applications or created from petroleum or coal tar pitch, pitch fibers with extremely high modulus values.

It should be noted that Carbon fiber composites are more brittle than glass or aramid and can show galvanic corrosion when used next to metal. A barrier material, such as glass, and sometimes epoxy, must be used.

Glass has very good impact resistance due to their high strain to failure, when compared to other fibers. Aramid also has excellent impact resistance, particularly to ballistic impact.

To summarize the mechanical strength properties are dependent on the type, amount, and orientation of the reinforcement that is selected for the particular product. With the variety and many different forms of reinforcements that are commercially available, an almost limitless number of composite systems are available to meet the strength requirements of any applications. Additionally, the ability to orient the composite strength characteristics to the specific performance requirements of the application, provides a unique advantage for composites that translates to weight and cost advantage as compared to traditional homogeneous structural materials.

1.4.3.FRP materials

FRP materials consist of a large number of small, continous, directionalizeed, non-metalic fibers with advanced characteristics, bundled in a resin matrix. Depending on the type of fiber they are refered as AFRP (aramid fiber based), CFRP (carbon fiber based) or GFRP (glass fiber based). Tipically the volume fraction of fibers in FRP equals about 50-70% for strips and about 25-35% for sheets. Due to the fact that the stiffness and strength of the fibers is much larger than the stiffnes and strength of the matrix, the propertise of the FRP composite material are governed by the fiber properties and the cross-sectional area of the bare fibers. There is a strong relation between the fiber volume fraction and the FRP properties. For a constant amount of fibers the failure load and strain at failure is only very little affected by an increase of the amount of resin.

Reinforcing fibers contribute to the mechanical strength characteristics of the composite. The strength is dependent on:

- the type or species of fiber
- the amount of fiber
- the orientation of the fiber
- the fiber surface treatment
- and its compatibility with the matrix polymer.

By varying these parameters, a broad range of mechanical properties are possible. For example, a composite which has all the fibers aligned in one direction, it is stiff and strong in that direction, but in the transverse direction, it will have a lower modulus and low strength. Also, the fiber volume fraction heavily depends on the method of manufacture. Generally, The higher the fiber content the stronger the composite. These same parameters allow the tailoring of the mechanical properties of the composite to the specific property requirements of the end product application. This is a major feature of composite materials that allows their efficient use in highly stressed applications.

2. FRP STRENGTHENING MATERIALS AND TECHNIQUES

2.1. Basic technique

The basic FRP strengthening technique involves the manual application of wet lay-up systems by means of cold cure adhesive bonding. External reinforcement is bonded onto the concrete surface with the fibers as parallel as practically possible to the direction of principal tensile stresses.

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

Two different processes can be used to apply the fabric:

- The fabric can be applied directly into the resin which has been applied uniformly onto the concrete surface
- The fabric can be impregnated with the resin in a machine and then applied wet to the sealed substrate

2.2. Special techniques

Besides the basic technique, several special techniques have been developed.

2.2.1. Automated wrapping

The technique invloves continuous winding of wet fibers under a slight angle around columns by means of a robot.

2.2.2. Prestressed FRP

The technique invloves bond of external FRP reinforcement onto the concrete surface in a prestressed state. Presstressing the strips prior to bonding has the following advantages:

- Provides stiffer behavior 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 finally distributed
- Closes cracks in structures with pre-existing cracks
- Improves serviceability and durability due to reduced cracking
- Improves the shear resistance of member as a whole concrete section will resist the shear, provided that the concrete remains uncracked
- The same strengthening is achieved with small areas of stressed strips compared with unstressed strips
- with adequate anchorage presstressing may increase the ultimate moment of resistance by avoiding failure modes associated with pilling off at cracks and the ends of the strips

- presstresing significantly increases the applied load at which the internal steel begins to yield, compared to a no stressed member.

The technique has also some disadvantages:

- it is more expensive than normal strip bonding
- the operation takes longer
- the equipment must remain in place until the adhesive has hardened sufficiently.

When the presstresing force is too high, failure of the beam due to release of the oresstresing force will occur at the two ends, due to the development of high shear stresses in the concrete, just above the FRP. Hence, the designing construction of the end zones requires special attention.

2.2.3.Fusion-bonded pin-loaded straps

Strengthening technique that involves replacing solid and thick strips by developed system.

The strap comprises a number of non-laminated layers formed from a single, continuous, thin tape, which consists of fibers 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 eachother, thus redusing the unwanted secondary bending stresses. Control od the intial tensile process allows interlaminar shear stresses concentrations to be reduces, so that a unfiform strain distribution in all layers is achieved.

2.2.4.In situ fast curing heating device

Instead of cold curing of the bond interface heating devices can be used. In this way it is possible to reduce curing time, to allow bonding in the regions where the tempretaures are too low, to allow cold curing, to apply the technique in winter time.

Different systems for curing can be used, such as electrical heaters, infrared heating systems and heating blankets. This system takes advantage of the electrical conductivity of carbon fibers.

2.2.5.Prefabricated shapes

Prefabricated type of FRP are mostly applied in the form of straight strips or in other form, depending on the foreseen application. By shaping that prefabricated systems can be employed in applications where normaly the more flexible wet lay-up systems are used.

2.2.6.CFRP inside slits

CFRP in concrete slits may be thought of as a special method of supplementing reinforcement to concrete structures. The slits are cut into the concrete structure with a depth smaller than concrete cover and CFRP strips are bonded into these slits. It was shown that a higher anchoring capacity compared with CFRP strips glued onto to surface of a concrete structure is obtained. The mechanical behaviour is stiffer under serviceability loads but more ductile in the ultimate limit state. The tensile strength of the CFRP can be reached in beams with additional reinforcement of strips in slits, if there is enough load carrying capacity of the compression zone in the concrete and for shear. The bond behaviour with high strength and ductility allows to bridge wide cracking without peeling-off.

2.2.7.FRP impregnation by vacuum

Vacuum impregnation is comparable with wet lay-up. 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.

The advantages of the vacuum impregnation are that with this method it is possible to avoid hand contact with the epoxy adhesive and the waste at the work site can be kept to a minimum and the quality of the composite can be improved. But this method requires a large investment and can be some dificuites in a acheving a high degree of vacuum with surface of rough texture or in complicated geometries and locations.

2.3. Basis of design

2.3.1.General requirements

Externally bonded FRP reinforcement is an 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.

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.

2.3.2.Verification of the SLS

It should be demonstrated that the strengthened structure performs adequately in normal use. To meet this requirements, the SLS verification concerns:

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

2.3.3.Verification of the ULS

In ULS, different failure modes that may occur have to be considered. In general, the failure modes can be subdivided to those assuming full composite action between the RC member and EBR system and those verifying the different debonding mechanisms that may occur.

2.4. Failure modes-ULS

The failure modes of a reinforced concrete element strengthened with externally bonded FRP reinforcement may be divided into two classes:

- Those where full composite action of concrete and FRP is maintained until the concrete reaches crushing in compression or the FRP fails in tension;
- Those where composite action is lost prior to previous failure mode due to peeling-off of the FRP.

2.4.1.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.

2.4.2.Loss of composite action-debonding and bond failure modes

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.

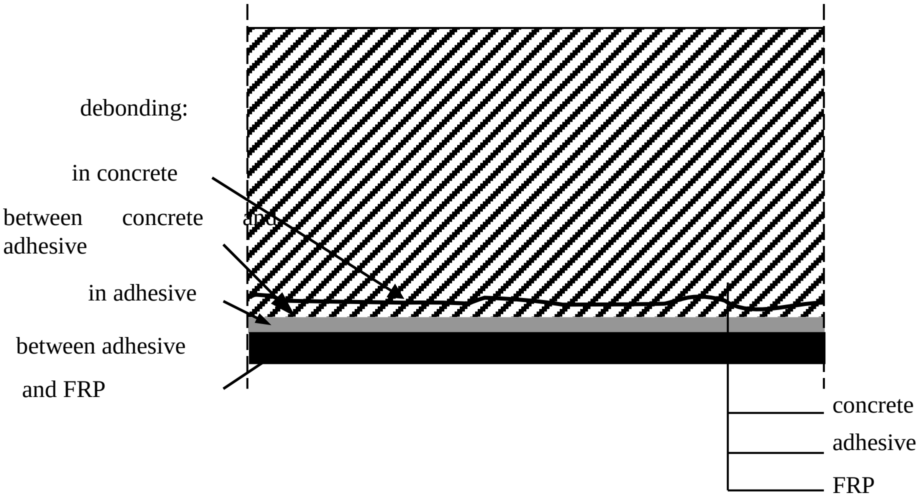


Figure 1 –Different interfaces for bond failure

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

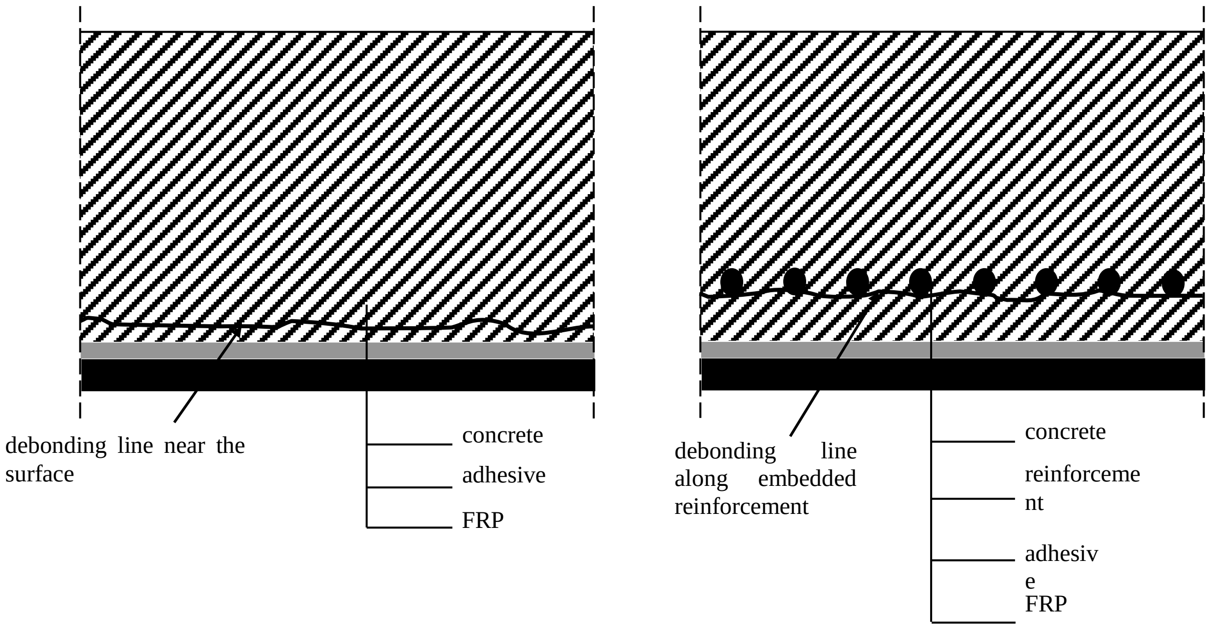


Figure 2 –Different debonding lines in the concrete

- 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.
- 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.

2.4.3. Loss of composite action-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.

- 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.
- 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 anhorage;

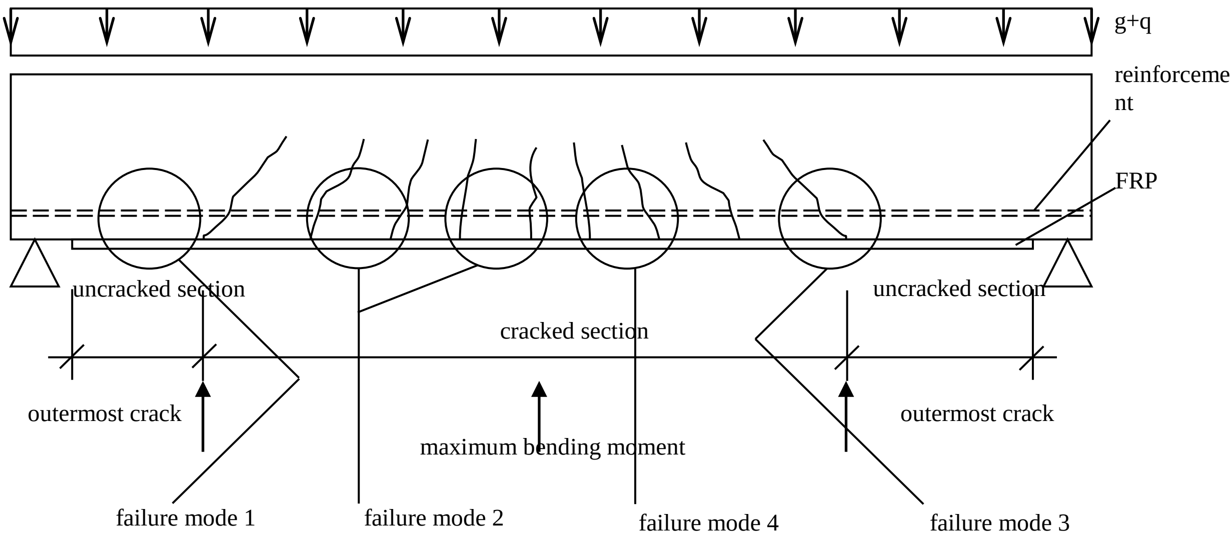


Figure 3 – Bond failure modes of concrete member with EBR

- 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.

2.5. 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 application of the FRP EBR depends on the type of reinforcement. An overview of the basic steps in applying the FRP EBR is given in Figure 4.

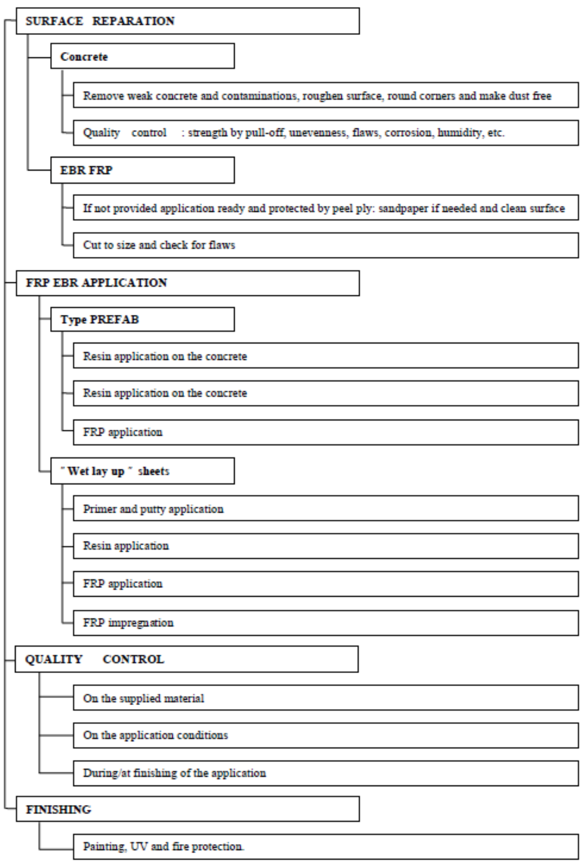


Figure 4 – General scheme for practical execution and quality control

2.5.1.Preceding repair

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. The following aspects should be considered:

- the minimum concrete tensile strength should be greater than 1.5 N/mm2. 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.

2.5.2.Preparation of 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. Most of the wet lay-up systems require a smoother surface. Mechanical methods that may compromise the quality of the outermost concrete should not be allowed. The unevenness depends on the type of FRP EBR. Strips already have their stiffness before application and are applied with a high viscosity adhesive, so they are less sensitive to unevenness. Fabrics and sheets are very flexible and will follow unevenness. The implications of the concrete unevenness are more important for fabrics and sheets. Regardless of the method, execution should not damage the concrete.
- The concrete should be sound and free from serious imperfections (steel corrosion, wide cracks) and potential damage mechanisms.
- The prepared surface should be dry and dust free before application of the strengthening technique. The allowable surface moisture content is given by the manufacturer.
- The concrete surface shall be marked where the FRP EBR has to be applied. For the application of sheets or fabrics around sharp edges, corners shall be rounded.
- Application of a primer is normally not necessary. If specified by the manufacturer of the adhesive a primer shall be used according to the specifications given by the manufacturer.

2.5.3. Preparation of FRP EBR

Strips and laminates should be supplied to site at the specified width and cut to the necessary length as specified on the design drawings. They should be free from any contamination like oil, dust, carbon dust. For strips provided with an in-built peel-ply, the ply should be removed immediately before application and the surface must not be touched by hand again. If the strips are provided without a peel ply but with surface ready for bonding, handling should be with extra care. The strips should be handeled with clean gloves and under dry conditions. They have to be verified for possible damage resulting from transportation, handling or incorrect cutting.

Sheets or fabrics are cut to the necessary plan-dimensions as specified on the design drawings. They should be kept free from any contamination and checked for possible damage resulting from transpotation, handling or wrong cutting. Protecting foils should be removed just before application. Handling and preparation precautions provided by the manufacturer should be followed.

2.5.4. FRP EBR application

The application depends on the type of FRP EBR. For strips and laminates the adhesive ensures bonding only. For sheets and fabrics the resin ensures both bonding and impregnation. The application of the FRP EBR is performed according to the specifications given by the manufacturer in addition, the information provided by the manufacturer in terms of allowable temperatures and relatively humidity, mixing ratio, mixing time, should be taken into account.

- **Strips or laminates**

The adhesive is applied as a thin layer to the concrete immediately after mixing. The adhesive is applied to the FRP sheet in a dome shape, having slightly more thickness along the centre line of the plate. This reduces the risk of forming voids when the strip is applied. The strip is offered to the concrete surface applying pressure by means of a rubber roller to ensure intimate contact with the concrete. The extra adhesive should be squeezed out along the sides. The final bond line should be of equal thickness along the strip.

- **″Wet lay up″ type**

To achieve the required evenness of the concrete surface it will specified to apply a primer. This shall be done in accordance with the specifications given by the manufacturer. 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 in a such way that is stretched without introduction of voids. Impregnation and further pressing is performed by appling adhesive on top of the sheet with roller brush (overcoating). The final bond line should be of equal thickness along the sheet.

2.5.5.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.

3. REFERENCES

[1] Barbero, E., J. (1999), *Introduction to composite materials design*, Taylor & Francis, USA.

[2] Chawla, K., K. (1998), *Composite materials*, Springer-Verlag, USA.

[3] FIB Bulletin 14 (2001), *Externally Bonded FRP Reinforcement for RC Structures*, Sprint-Digital-Druck Stuttgart.

[4] Teng, J. G., Chen, J. F., Smith, S. T., Lam, L. (2002), *FRP-Strengthened RC Structures*, John Wiley & Sons, Ltd, England.

[5] Trombeva, A. (2004), *Modeliranje utrditve armiranobetonskih konstrukcij s trakovi FRP s prekinjenim veznim stiokom*, magistarsko delo, Univerza v Ljubljani, Fakulteta za gradbeništvo in geodezijo, Ljubljana, Slovenija.

[6] Žarnić, R. (2003), *Lastnosti gradiv*, Potens, Ljubljana.

Gostujuće predavanje na temu:
CONTEMPORARY METHODS FOR RECONSTRUCTION OF CONCRETE STRUCTURES
Predavač: Prof. Ana Trombeva Gavriloska, PhD
Ss. Cyril and Methodius University, Faculty of Architecture, Skopje, N. Macedonia
Mesto: Visoka tehnička škola strukovnih studija u Novom Sadu
Datum: 14. mart 2019.

Student: ……………………………………………………………………….. Broj indeksa: ……………………………………….

PITANJA ZA PROVERU ZNANJA

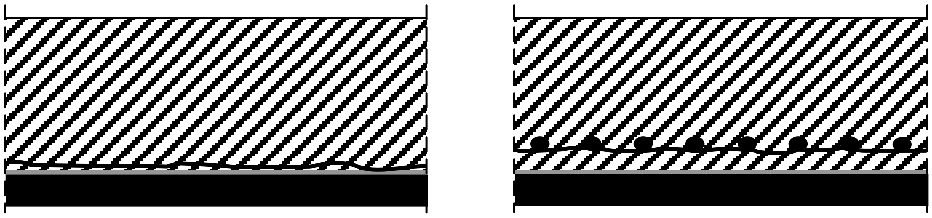
1. What is the composite material?
   Šta je kompozitni materijal?

2. Which are the two main components of the composites?
   Koje su dve glavne komponente kompozita?

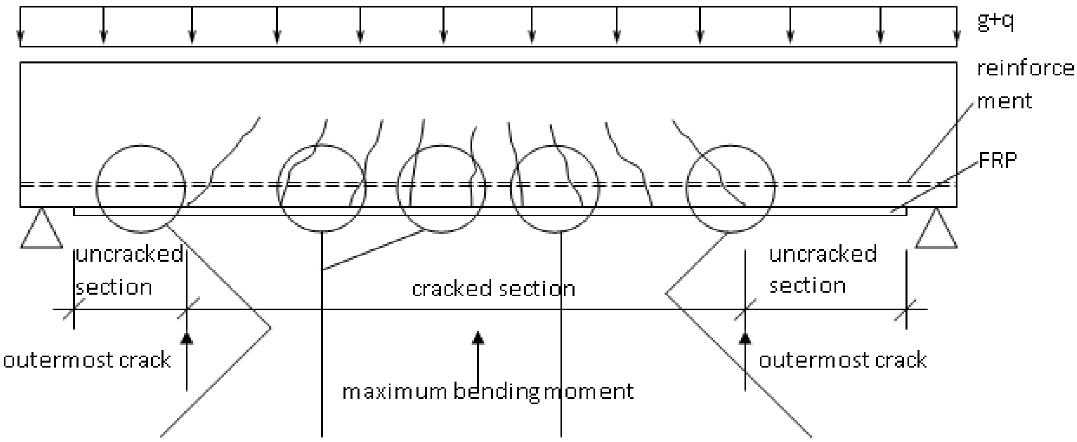
3. What type of construction elements could be strengthened by FRP (fiber-reinforced polymer)?
   Koje vrste građevinskih elemenata se mogu ojačati pomoću FRP?

4. How are divided failure modes of reinforced element strengthened with externally bonded FRP reinforcement?
   Kako se dele vrste oštećenja armiranog elementa ojačanog eksterno vezanom FRP armaturom?

5. Bond failures that occur at different interfaces between the concrete and the FRP reinforcement are classified in four main types. They are:
   Postoje četiri glavna tipa oštećenja veze između betona i FRP armature. To su:



6. Mark the different failure modes depending on the starting point of the debonding process.
   Označite različite vrste oštećenja od početne tačke procesa pucanja nadalje.



7. Which surfaces should be prepared in the process of application of EBR FRP?
   Koje površine treba pripremiti u procesu primene EBR FRP?

Co-funded by the
Erasmus+ Programme
of the European Union