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ANCHORAGE SYSTEMS IN FRP – STRENGTHENED REINFORCED CONCRETE

The main aim of this article was to present recently evolved methods of strengthening flexural reinforced concrete beams, as well as the concrete-anchorage system bond strength problems in composites that were either surface mounted or inserted in the pre-cut grooves in the concrete cover. The focus is on the beams strengthened with the carbon FRP (CFRP – carbon fiber reinforced polymer) composites to show the basic advantages and drawbacks associated with their installation and bond performance. Domestic and foreign experiments investigating the EBR and NSMR strengthening systems were discussed to show their efficacy, common failure modes and the factors initiating the debonding process. Debonding problems and solutions to those problems were illustrated using the example of a composite material attached to the outer surface of concrete in the shear zone of reinforced concrete beams The article provides guidelines for checking the anchorage capacity for the existing longitudinal reinforcement with the simultaneous action of bending moment and shear force in the support zone of the reinforced concrete beam.

Keywords: reinforcing, strengthening, FRP, anchorage systems, failure modes

1. Introduction

External strengthening method is the most popular method used to increase the load-bearing capacity of reinforced concrete (RC) members, with the ease and speed of application being two major factors. The externally bonded systems include steel strengthening (mechanically fastened with steel dowels or adhesive

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resins) or composite strenghtening (fastened with adhesive resins and adhesive resins supplemented with anchor blocks if prestressed). The common use of FRP composites is due to their strength parameters, corrosion resistance, the possibility of using any lengths without joints, low weight, and the ease of transport and application. One of the important problems in the case of using external strengthening methods is to ensure proper anchorage, necessary for correct performance of the system and reinforcing bars in flexure and shear. Extensive studies have been devoted to developing new or improving the existing anchoring methods.

2. Methods of strengthening reinforced concrete beams using metallic and non-metallic materials attached to concrete surfaces or placed in pre-cut grooves in a concrete cover

First research in Poland on the possibility of using external steel elements for strengthening RC beams was carried out by Ciesielski in the 1970s [1]. Flat steel strips were attached to the bottom of the beam, using epoxy resin. The main problem was the concentration of tangential stresses (occurring at the primary crack location) which, by exceeding the resin strength, led to the detachment of steel plates, typically at the ends of the strengthening element due to the highest stress values in the resin. The results reported in [1] were the basis for the concept of fastening steel plates with the use of bolts inserted into RC members [2] to eliminate the bound problems. The bolts were the only joints between the plate and the strengthened member. Depending on the cross-section of the steel plates, the diameter and spacing of the bolts, an increase in load capacity (compared to the load capacity of non-reinforced elements) was in the range 50 to 166.7%. The most interesting observations included significant differences in the forces transmitted to individual bolts. This was evidently due to the presence of cracks and the randomness of their formation process, which is particularly important at high stresses in strengthened beams. The strengthening of girders of the Warsaw Central railway viaducts is an example of the use of this method [3]. The first studies on the use of carbon fibers embedded in epoxy resin for the strengthening of reinforced concrete structures were carried out in the mid-1980s at the EMPA Institute in Switzerland. It was the beginning of externally bonded fiber-reinforced polymer strengthening systems (EBR-FRP) application. One of the solutions to increase the effectiveness of the described strengthening method is to increase the area cooperating with the member/beam by embedding composite reinforcement in the grooves pre-cut in the concrete cover. Such strengthening systems are called NSMR (Near Surface Mounted Reinforcement). Enlarging the contact area of the composite material with the adhesive mortar delays the debonding from the concrete. The simulation of the efficiency of this method [4] showed that with the same surface area of composite reinforcement applied using the EBR and NSMR methods, the load capacity increased by 43% and 137% respectively relative to the beam that was not strengthened. This was confirmed by the results presented in [5] (increase in the use of composite reinforcement strength from 30÷35% (EBR method) up to 80%. The composite reinforcement in the NSMR method needs to be inserted in the pre-cut grooves in the concrete cover, which presents a risk of cutting the existing reinforcement, which is why this method can be used only in cases, where the thickness of the reinforcement cover allows it.

In recent years, research has been carried out to eliminate premature debonding of the composite material and increase the effectiveness of strengthening method through the use of composite anchors combined with substantial reinforcement. This method allows eliminating the drawback of anchorage systems based on steel elements, i.e. susceptibility to corrosion. Reported in [6] a 30% increase in load bearing capacity was obtained with additional composite anchors.

In the 1970s, the idea of active strengthening, i.e. the use of pre-stressed fibers, was born. This solution has a number of advantages, such as lower deflections and thus reduced crack widths (greater member stiffness) and the stress reduction, especially in steel bars. Examples include the SIKA CarboDur LEOBA and STRESS-HEAD systems, Polish IBDiM system, BBR-stahlton, S & P, and NEOXE [5, 7]. The most important problem is to ensure adequate bonding, especially at the ends of the strengthening strips, where the tangential stresses are the greatest (high likelihood of debonding).Additional anchoring elements such as anchor blocks should effectively carry the stress, thereby providing protection against losses of prestressing force and, at the same time, avoid excessive compression in the composite strengthening[8]. The disadvantage of such solutions are steel elements (anchored steel plates with bolts) remaining permanently connected to the structure and exposed to corrosion. These strengthening methods are mainly used in bridge structures exposed to aggressive environments. The problem of steel corrosion can be resolved by eliminating the use of mechanical anchors, as in the EMPA systems and Tenroc Technologies (stepwise prestressing). The NSM prestressing system is being developed at the Lodz University of Technology, which, in contrast to the EBR, has been found to be much more effective.

A lot of attention has been paid in recent years to the methods of providing anchorage for shear strengthening of reinforced concrete beams. The limited possibility of obtaining a suitable anchorage in this case results from the fact that the composite strengthening cannot be fixed on the whole perimeter of the cross-section of the beam due to the presence of a floor slab. Three leading solutions can be distinguished:

- use of steel anchor plates (usually these are elements with a steel angle cross-section) fastened with steel bolts in the corner (connection of the plate with the beam). Not always, but in a majority of cases, their use is associated with the necessity to make holes (damage to the composite fibers), which leads to undesirable concentration of stresses. If the strengthening material is carbon fiber, there is an increased risk of galvanic corrosion [9] (figure 1B),

- UA anchorage type – used mainly for flaccid composite sheets. This method consists in bending the end of the composite and fixing it in the previously prepared pre-cut grooves in a concrete cover. (This method can also be used in the case of bending reinforcements),
- use of composite anchors. The part left outside is fan-folded on the surface. Then the proper reinforcement is attached to the element prepared in this way, as shown by the SikaWrap FX Fiber Connector [10] (figure 1A).

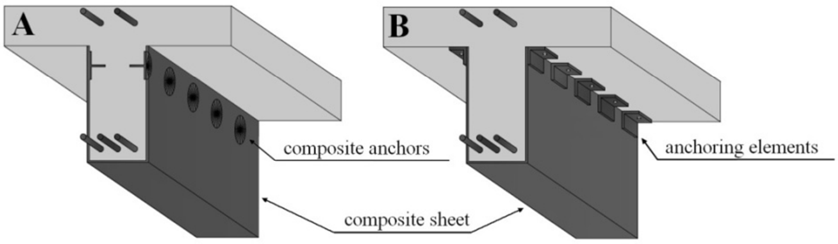

Fig 1. Anchoring the composites attached to the side surfaces of the reinforced concrete beam by means of: A-steel anchor plates, B – composite anchors

3. Cooperation with the reinforced concrete beam and proper anchorage

To use a composite strengthening material, the peel strength of the concrete substrate obtained using the pull-off method cannot be lower than 1.0 MPa. The recommendations set forth in the Fib 14 bulletin give a minimum value of 3.0 MPa [11]. These requirements have to be met to obtain the correct cooperation between the strengthening material and the strengthened element, which is not easy in old structures.

Difficulties related to ensuring proper bond and embedment of reinforcements attached to RC members result from the presence of high inter-layer shear stresses in the laminate (mainly at the end of strengthening element, e.g. CFRP laminate). This is particularly important in the case of pre-stressed composite reinforcements.

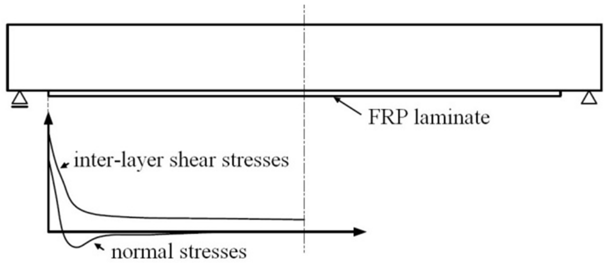

Fig. 2. Distribution of inter-layer stresses along the length of the FRP laminate

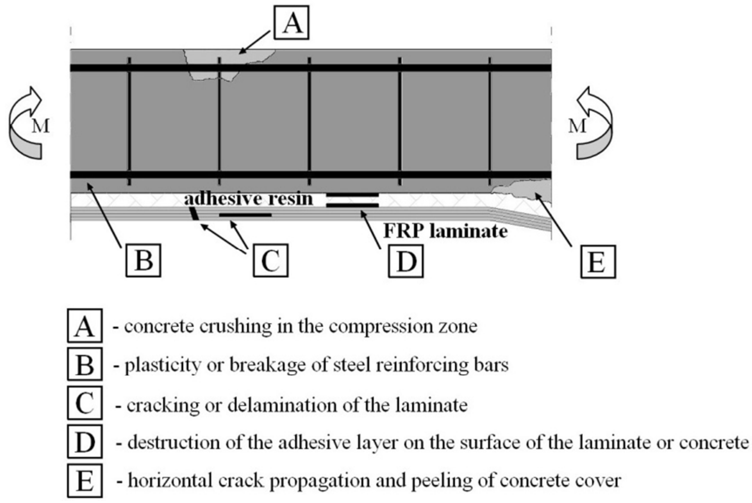

Fig. 3. Failure modes of a reinforced concrete beam strengthened with a composite laminate

Several failure modes of RC concrete beams strengthened with a composite laminate (Fig. 2, 3) can be distinguished. The three most common were reported in [12]. The first mechanism is caused by intermediate crack induced debonding (ICD). The second mechanism consists in rupturing the composite reinforcement in the middle of the element – R (rapture). The third mechanism is initiated by shear (despite working on bending) or by crushing of compressive concrete – CC, loss of anchoring at composite ends (ED – end debonding, CCS – concrete cover separation, A – anchorage failure) [11]. This mode is not typical in flexural elements and is therefore dangerous. An example of failure of the RC beam strengthened with the NSMR system is shown in figure 4. Separation of the FRP proceeded rapidly and extended over the support zone and the area of pure bending. Failure was caused by horizontal crack propagation and concrete cover peeling. The separation plane passed along the surface of the steel bars and the concrete cover remained bonded to the laminate. Research carried out at the Lodz University of Technology also showed that the pursuit of maximum use of tensile strength of composite reinforcement (especially in the absence of

Fig. 4. Failure mode by horizontal crack propagation and peeling of concrete cover

additional anchoring) may contribute to a reduced level of structural safety due to sudden debonding, occurring with little warning (so-called brittle failure) [13].

The test results reported in [5] show that the dimensions of the element cross-section, the type of composite reinforcement, the distance of its ends from the support, the steel reinforcement scheme and the distribution of cross-section forces in the strengthened element are the parameters that affect the effectiveness of passive reinforcement. According to Barros and Sena Cruz who used the NSMR method in their study of the adhesion of composite reinforcements [14], the value of the maximum adhesive force increases with the increase in the embedment length. In [15] the aspect of composite reinforcement bond to the concrete substrate was also considered in relation to the grade of concrete. The increase in the compressive strength of concrete was found to delay the debonding of the laminate and had a beneficial effect on the adhesive stress.

In addition to the concrete strength, plasticity of steel and the related increase in crack width are important factors initiating the debonding process. The Lodz University of Technology research confirmed these factors but did not confirm the bonding reduction despite the fact that the concrete strength in the reinforced elements was very low ($f_{c,cube} = 20$ MPa). Another factor that contributes to the composite-concrete debonding is the vertical "fault" that appears beside the inclined shear crack mainly in the elements with a low degree of transverse reinforcement [13].

Another important aspect of strengthening RC beams is the anchoring of the existing steel reinforcement, especially on external supports. The need to strengthen the structure is often associated with the design errors or use change. In both cases, some elements will have insufficient load bearing capacity, compensated by means of strengthening the additional steel reinforcement or, increasingly used, composite reinforcements. An equally important issue as determining the basic number of reinforcing elements and their anchoring is also the load bearing capacity of the existing (basic) reinforcement and appropriate anchor length [16, 17]. This is due to the fact that strengthening elements are often anchored but not put into their supports.

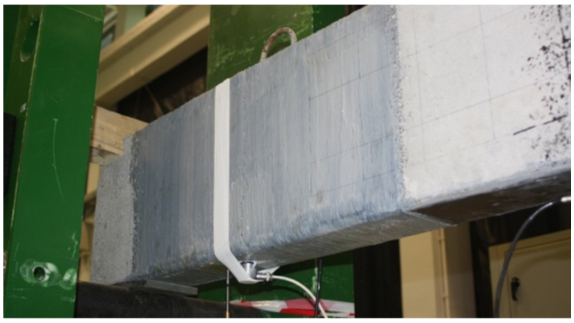

Fig. 5. Passive reinforcement of reinforced concrete beams using CFRP tapes anchored with a mat CFRP

As a result, due to the increased cross-sectional forces, basic reinforcement bars anchored in these supports are subjected to considerable stresses. Improper anchorage will lead to the pulling out the rods and in consequence to the failure of the element. Bacharz and Goszczyńska in [18] show a 30% decrease in the load capacity of the element with insufficient anchoring of the main tensile reinforcement compared to the elements with full anchorage, as a result of which the beam failed due to the main reinforcement bars breaking off in the support zone (Fig. 6). In the case described in [18], the point support in the form of a steel cylinder was used(type of support similar to those found on actual bridge structures).

Fig 6. Failure of a reinforced concrete beam with insufficient bond length in the support zone of the main tensile reinforcement [18]

As a result, the longitudinal reinforcement at the anchoring point was stressed mainly due to the shear force, not the bending moment. This is important because according to currently used Mörsch truss model, it is possible to underestimate this force, represented by the following formula

$$l_{b,rqd} = \frac{\phi}{4} \frac{\frac{M}{A_{s1} \cdot z} + \frac{0,5 \cdot V \cdot (\cot\theta - \cot\alpha)}{A_{s1}}}{f_{bd}} \tag{1}$$

where: ϕ – diameter of the anchored bar [mm],
A_{s1} – cross-sectional area of anchored tension reinforcement [m^2],
M – bending moment [kNm],
V –shear force [kN],
f_{bd} – limit design bond stress [MPa],
σ_{sd} –stress in anchored steel [MPa],
$\cot\theta$ – cotangens of the inclination angle of the pressed concrete struts,
$\cot\alpha$ – cotangens of inclination angle of transversal reinforcement.

Underestimated force is the consequence of the possibility of accept any value of cotangens of inclination angle of the compression struts θ from the range 1.0 to 2.0. The acceptance of 1.0 is associated with the adoption of transversal reinforcement with considerable stocks and at the same time contributes to 50% reduction in the design force carried to the longitudinal reinforcement. This situation is particularly dangerous with external support, especially joint supports with shear as a predominant force. Therefore, as confirmed by the analyses reported in [18, 19, 20], the recommended value of the $\cot\theta$ is 2.0. This value gives proper estimation of the shear force carried to the longitudinal reinforcement and safe level of shear reinforcement capacity. In addition to the designing of strengthening method, it is also important to determine the anchoring capacity of the existing longitudinal reinforcement with simultaneous bending moment and shear force assuming $\cot\theta$ equal to 2.0.

4. Summary

This review of currently used methods of strengthening flexural reinforced concrete beams and the problems of the bond of strengthening elements and existing longitudinal reinforcement shows that this subject requires further analysis. The use of composite materials as external strengthening systems for reinforced concrete elements are currently the most popular, relatively easy, and quick capacity improvement methods. In the paper, special attention was paid to the beam strengthening using carbon fiber composites, CFRP, their basic advantages and fundamental problems associated with the strengthening technology, bonding and embedment of composites. The experimental studies carried out so far in Poland and abroad were the basis for the discussion of the effectiveness of the strengthening systems, EBR and NSMR, the most frequently occurring failure modes, and the factors initiating the process of composite separation. The debonding problem was considered using the examples of composites externally strengthening the concrete surface and existing reinforcement of RC beams. Solutions were provided for the problem of insufficient bonding. In old structures, ensuring adequate adhesion of metallic and non-metallic reinforcements bonded to the surface of concrete or embeded in the concrete cover is difficult due to low concrete strength or surface condition. The selection of appropriate strengthening technology is a critical design stage. It should take into account, for example: fire protection requirements, environmental conditions, constraints imposed by the structure and requirements set by the architect and client. The following factors should be taken into account in the design of strengthening systems: the arrangement of bars, bars diameters, the strength of steel, bond/embedment length, and the strengthening capacity of existing longitudinal reinforcement with the simultaneous effect of the new bending moment and shear force.

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