Chapter 4

Applying Post-Tensioning Technique to Improve the Performance of FRP Post-Strengthening

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51523

1. Introduction

Reinforced concrete structures are, frequently, submitted to interventions aiming to restore or increase their original load capacity. According to Garden & Hollaway [1], the choice between upgrading and rebuilding is based on factors specific to each individual case, but certain issues are considered in every case. These are the length of time during which the structure will be out of service or providing a reduced service, relative costs upgrading and rebuilding in terms of labor, materials and plant, and disruption of other facilities.

Several post-strengthening techniques were developed in the last decades. Most of them are based on the addiction of a structural element to the external face of the element to be post-strengthened.

According to Täljsten [2], the method of post-strengthening existing structures with steel plates bonded to the structure with epoxy adhesive was originated in France, in the nineteen sixties, when L'Hermite (1967) and Bresson (1971) carried out tests on post-strengthened concrete beams. Additionally, Dussek (1974) reported the use of this post-strengthening method in South Africa in the middle 60's. In both cases the post-strengthening was successful and the load bearing capacity was increased. These first investigations in France and South Africa inspired future research in Switzerland (1974), Germany (1980), United Kingdom (1980), Japan (1981) and Belgium (1982). The idea of post-strengthen existing reinforced concrete structures with bonded steel was improved due to the development of synthetic adhesives, based on epoxy resins, suitable to ensure good adhesion and chemical resistance to aggressive agents.

In the last decades, non-corrosive, low-weight and high-resistant materials started to be developed and applied on the construction of new buildings, aiming to produce durable structures. These materials, called Fiber Reinforced Polymers (FRP), started to be investigated in the middle 80´s at EMPA (Swiss Federal Laboratories for Materials Testing and Research), in Switzerland. At that time, the carbon fiber was elected as the most suitable for post-strengthening applications due to its low-weight, high tensile strength, high modulus of elasticity and resistance to corrosion. Since then, many structures were post-strengthened with FRP in Japan, Europe, Canada and United States and nowadays the use of FRP is growing worldwide.

Most of FRP post-strengthening systems used nowadays consist of carbon fibers embedded in epoxy matrices and provide high modulus of elasticity and tensile strength. For bridge repair, carbon fiber is the material best suited in most cases, because the fiber is alkaline-resistant and does not suffer stress corrosion, two very important arguments for such applications. Actually, there are many reasons that make carbon fibers one of the most attractive alternatives for post-strengthening concrete structures. Considering all reinforcing fiber materials used to produce FRP, the carbon fibers have the highest specific modulus and specific strength that provide a great stiffness to the system, being an ideal choice to be applied in structures sensitive to weight and deflection. Compared with steel, carbon fibers can be 5 times lighter and present a tensile strength 8 to 10 times higher.

The main impediment to the massive use of CFRP (Carbon Fiber Reinforced Polymers) regards to the high cost of the carbon fibers. Meier, in 2001 [3], pointed out that the functionality and the mechanical properties of CFRP should be better explored, due to its relatively high cost. Indeed, the use of only 10%-15% of the tensile strength of the CFRP, as it happens in some bonded post-strengthening systems, is not economically viable.

This chapter aims to analyze the efficiency of prestressed CFRP strips used to post-strengthen reinforced concrete beams, by means of cyclic and static loading tests, as an alternative to better use the tensile strength of these materials.

2. Reinforced concrete elements post-strengthened with prestressed FRP strips

The aim in prestressing concrete beams may be, according to Garden and Mays [4], either to increase the serviceability capacity of the structural system of which the beams form a part or to extend its ultimate limit state.

According to El-Hacha [5], FRP are well suited to prestressing applications because of their high strength-to-weight ratio that provides high prestressing forces, without increase on the self-weight of the post-strengthened structure. The prestressing technique may improve the serviceability of a structural element and delay the onset of cracking. When prestressed FRP are used, just a small part of the ultimate strain capacity of the material is used to prestress the FRP, the remaining strain capacity is available to support external loads and also to ensure safety against failure modes associated to peeling-off at the border of flexural cracks and at the ends of the post-strengthening.

Several FRP prestressing systems are currently available consisting of rods, strands, tendons or cables of FRP. However, in some cases, it may be advantageous to bond FRP sheets or strips onto the structural element surface in a prestressed state. According to fib Bulletin 14 [6], prestressing the FRP 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. The neutral axis remains at a lower level in the prestressed case if compared to the unstressed one, resulting in greater structural efficiency.
- Crack formation in the shear span is delayed and the cracks, when they appear, are more finely distributed and narrower. Thus, serviceability and durability are improved, due to reduced cracking.
- The same level of strengthening is achieved with smaller areas of stressed FRP, compared to unstressed ones.
- Prestressing significantly increases the applied load at which the internal steel reinforcement begins to yield if compared to an unstressed structural member.

On the other hand, prestressing FRP systems are more expensive than the non-prestressing ones, due to the greater number of operations and the equipment that is required to prestress the FRP.

2.1. Losses of prestressing force

Prestressed FRP bonded to concrete structures are sujected to prestress losses, as it happens in any prestressing system. Such prestress losses may be instantaneous, due to immediate elastic deformation of concrete, or time dependent, due to creep and shrinkage of concrete and relaxation of the FRP.

Immediate elastic deformation of the concrete may reach 2% to 3%, according to fib Bulletin 14 [6], and happens when the prestress force is transferred into the concrete beam. If prestress is applied by reacting against the structural member there will be no loss. It happens because if the prestressing device if fixed on the structural element that will be post-strengthened, a compensation occurs: as the FRP is being stressed, the concrete is being compressed. However, FRP elements that have already been prestressed will experience a loss of prestress due to the shortening of the beam upon the prestressing of subsequent FRP elements. In such cases it is necessary to determine the average loss of prestress per FRP element.

Time dependent losses, due to creep and shrinkage of concrete, according to the fib Bulletin 14 [6], reach about 10% to 20% and are similar to the ones of conventional prestressing.

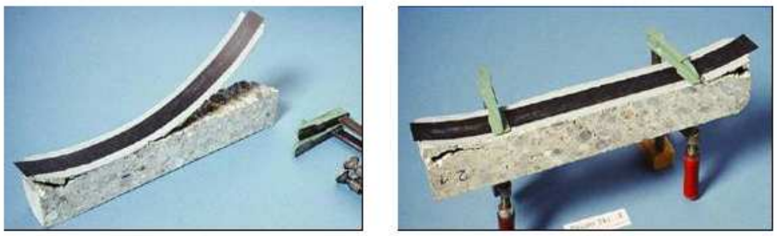
Prestressing losses due to relaxation of FRP depends, according to ACI 440.4R-04 [7], on the characteristics of the FRP composite. The document also informs that losses due to relaxation of fibers may be neglected when CFRP are used, since the relaxation of carbon fibers is very low. Losses of 0,6% to 1,2% must be considered due to the relaxation of the polymer and losses of 1% to 2% must be considered due to the straightening of fibers.

Results of a research program developed by Triantafillou et al. [8] indicate that, when prefabricated CFRP are used, prestress losses of 10% must be considered, due to the instantaneous and time dependent losses at the concrete and adhesive and also due to the relaxation of the CFRP.

Garden and Mays [4] consider that prestressed FRP also suffer prestress losses due to the shear transferred through the adhesive and into the concrete by the FRP tension. This shear action is sufficient to fracture the concrete even at low prestress levels so it is necessary to install anchorages at the ends of the FRP element to resist this action.

2.2. Maximum prestressing force

Figure 1(a), by Triantafillou et al. [8], shows the premature failure of a concrete beam post-strengthened with a CFRP strip, without any anchorage system, immediately after the complete release of the prestressing force. Horizontal shear cracks propagated from both ends of the CFRP strip through the concrete layer and stopped at a certain length. Figure 1 (b) shows that this failure mode may be prevented if anchorage systems are used at the ends of the strips. The authors suggest that the maximum prestressing force that avoids the need of anchorage systems provide very low prestressing levels, 15% to 20%, depending on the cross section of the CFRP strip.



(a) (b)

Figure 1. (a) Premature failure of a prestressed CFRP strip without anchorage; (b) Action of an anchorage system (Triantafillou et al. [8]).

Thus, the addition of anchors at the end of the prestressed FRP sheets or strips reduces the shear deformation that occurs within the resin or adhesive layer upon releasing the prestressing force and reducing the shear stresses transferred to the base of the concrete section. Thereby, anchorage systems minimize the possibility of premature failures (El-Hacha [5]).

According to El-Hacha et al. [9], prestressing levels of at least 25% of the FRP tensile strength may be necessary to achieve a significant improvement in terms of the structural stiffness and load carrying capacity.

Meier [10] suggests that a prestress level as high as 50% of the CFRP strength might be necessary to increase the ultimate strength by delaying the premature failure. Experimental results presented by Deuring [11] showed that increasing the level of prestress in the CFRP from 50% to 75% reduced the strength of the beam because the highly prestressed laminates had little strain capacity remaining and the CFRP presented premature failure.

It is important to have in mind that, when post-strengthening is prestressed the modulus of elasticity of the FRP is of great significance, since the FRP element needs to be stiffer to hold up a significant loading that, before the post-strengtnening, was made only by the steel reinforcement (El-Hacha, [5]).

2.3. Prestressing techniques

Various approaches to prestress FRP have been proposed by researches and used experimentally. These methods are based on directly or indirectly prestress the FRP prior to bonding and are described bellow.

2.3.1. Cambered beam prestressing technique

In this method, developed by Ehsani & Saadatmanesh [11], no tension is directly applied to the fibers, but the FRP sheets are indirectly prestressed by cambering the beam to be post-strengthened before bonding them to the bottom face of the concrete beam.

The beam is first deflected upward by means of hydraulic jacks, as one can see in Figure 2 (a). The beam is then held in the deflected position until the adhesive is completely cured. After the cure of the adhesive, the FRP is completely bonded to the lower face of the beam and the jacks may be removed, as showed in Figure 2 (b). Once the jacks are removed, the beam will deflect downward and tensile stresses will be induced in the lower face of the beam.

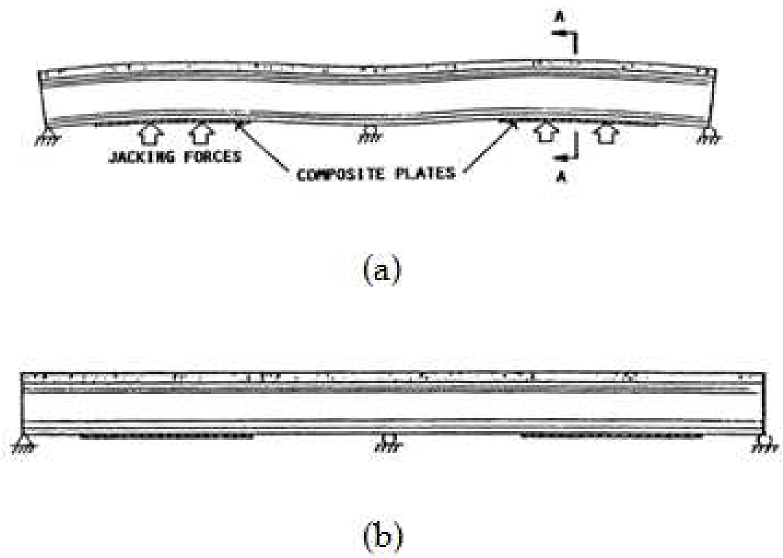


Figure 2. Sequence of prestressing procedures: (a) Camber by jacking; (b) Remove jacks when epoxy is cured (Ehsani & Saadatmanesh [11]).

The level of prestress will depend on the length of the beam and the degree of camber induced in the beam. According to Ehsani & Saadatmanesh [11], the level of prestress in this method is not high and since the highest prestress will be present at the midspan of the beam, anchorage systems are not required.

According to El-Hacha [5], in field applications, the effort required to camber the bridge near midspan is extensive relative to the low prestressing force induced in the FRP.

2.3.2. FRP prestressed against the strengthened element

In this prestressing system, developed at Queen's University and Royal Military College of Canada and presented by Wight et al. [12], the sheets are tensioned by reacting directly on the beam. The prestressed sheets are bonded to the lower face of the beam and the ends of the sheets are attached to the beam by a mechanical anchorage system. Multiple layers of prestressed sheets may be applied to the beams in successive layers, when required, due to the limits on the tensile capacity of individual sheets or due to the need to limit the load at an anchorage location.

In this process, the beams are inverted to receive the prestressing system. The mechanical prestressing and anchorage system used for the reinforced concrete beams are shown in Figure 3. According to Wight et al. [12] the mechanical anchorage system consists of steel roller anchors bonded to the sheets and steel anchor assemblies fixed to the beam. The roller anchors that grip the sheet consists of two stainless-steel rollers bonded to each end of the sheet. Prior to prestressing operations, the sheet is wrapped and bonded round the roller. To prestress the sheets, the roller at one end of the FRP sheet is fixed to the beam and the roller at the other end is movable. During prestressing, the movable roller is attached by steel prestressing strands to a hydraulic jack that reacted against the beam. The prestress is applied to the sheet, and the sliding roller is then attached, in its extended position, to a second permanent anchorage assembly. Subsequent layers may be added to the beam, using the same technique, until the desired thickness of FRP is achieved. The authors suggest that a weight perpendicular to the beam surface may be used to bring the sheet into contact with the beam surface.

El-Hacha at al. [9] used this technique to post-strengthen damaged concrete beams under severe environmental conditions. Results presented by the authors suggest that keeping the mechanical anchorage system in place prevented failures associated with high shear stresses at the ends of the sheets. Anchorages also prevented tensile fracture in the concrete cover thickness upon transfer of sheet prestress into the concrete. The prestressing system used to post-strengthen the beams improved the serviceability, controlling the formation of new cracks, delaying the formation of new cracks and limiting deflections in the beams tested. Furthermore, the prestressed CFRP sheets contributed to the load carrying capacity of the beams and significantly redistributed the stress from the internal steel reinforcement to the CFRP sheet.

2.3.3. Technique of prestressing FRP prior to bonding

In this method, studied by Triantafillou & Deskovic [13, 14], Deuring [15], Quantril & Hollaway [16] and Garden & Mays [4], the FRP sheet is first pretensioned and applied on the tensile face of the beam as one can see in Figure 4 (a) and (b). Aluminium tabs are epoxy bonded on both faces of the FRP to provide stress distribution in the end regions and then each end of the FRP is sandwiched between two predrilled steel plates bolted on at each end. The system is loaded into a prestressing frame. A vacuum bag technique may be necessary to support the external FRP during bonding.

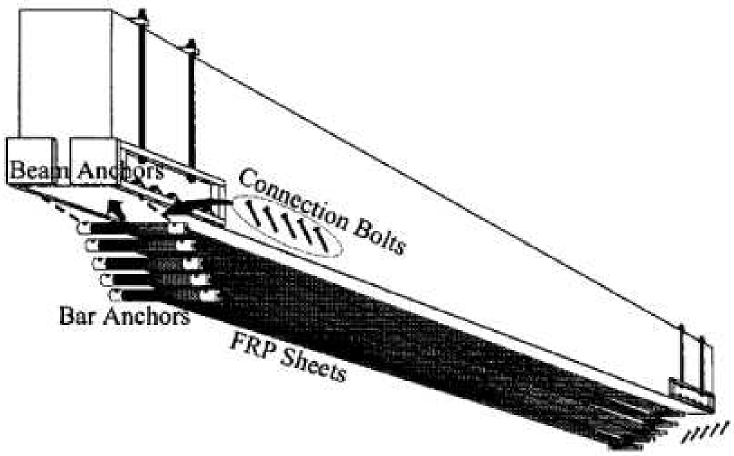


Figure 3. Prestressing system (Wight et al. [12]).

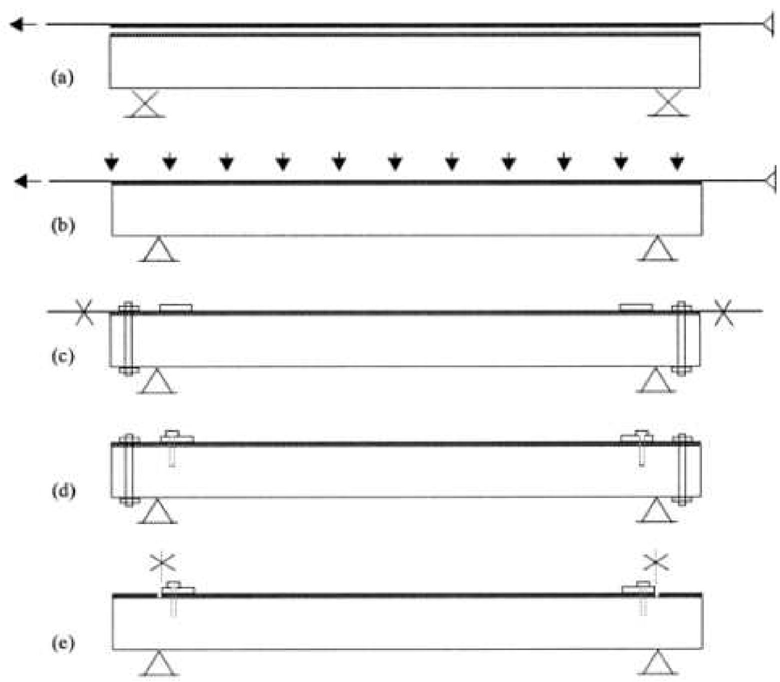


Figure 4. Sequence of prestressing procedures: (a) Pretensioning of the strip; (b) Application of the pretensioned strip on the tensile face of the beam; (c) Cutting of the sheet to transform it into a prestressing element; (d) Placement of the steel bolts; (e) End damps are removed (Garden & Mays [4]).

After the adhesive is fully cured, steel clamps are installed at each end of the beam to ensure adequate anchorage and the two ends of the FRP are cut. Then the sheet is transformed into a prestressing element as showed in Figure 4 (c).

In the next step, showed in Figure 4(d) holes are drilled through the FRP and the adhesive into the concrete beam to receive steel bolts that are bonded into the holes and allowed to cure.

Figure 4 (e) shows the last stage of the procedure, when the end clamps are removed and the FRP is cut through at each end. Then, the bolted steel endplates will play the role of the anchorage system.

Quantril & Hollaway [16] noted that cracking under the action of a given external load was found to be much less extensive and less developed than for an identical non-prestressed specimen. Besides that, prestressing produced significant increases in the load which causes yield of the internal steel over a non-prestressed specimen. Gains may be still larger if FRP action can be maintained past steel yielding to loads approaching failure. Applying the prestress prior to bonding also affects the mode of failure of the specimen, reducing the amount of shear cracking which could initiate failure in the shear spans. The greater the level of prestress, the better is the confinement effect on the development of shear cracking what increases the failure load for cases governed by shear failure. Results also suggest the levels of ductility and stiffness may be increased as well as the maximum strains in the FRP at a given load level. Despite all the advantages presented by the authors, field application of this technique would probably require methods and procedures adaptations due to working restrictions such as the overhead position and limited access of most structural elements.

According to Garden & Mays [4] the level of prestress that can be applied is limited by the tensile strength of the FRP and should not precede either yielding of the internal steel or compressive failure of the concrete to ensure adequate ductility. Results showed by the authors suggest that the level of prestress may also be limited by the strength of the plate and anchorages, by the horizontal shear strength of the adhesive-FRP interface and by the bottom layers of the concrete.

One potential benefit of this technique is the reduction of FRP material associated costs since the same strength levels can be reached with reduced area fraction (Triantafillou & Deskovic [14]). According to Triantafillou et al. [8] the method can also lend itself to prefabrication because of its simplicity and the important properties offered by FRP materials.

2.3.4. Prestressing method developed by Stoecklin & Meier [17]

Stoecklin & Meier [17] developped, at EMPA (Swiss Federal Laboratories for Material Testing and Research) a method to apply prestressed FRP strips to concrete structures. In this method, the FRP strip is first prestressed then bonded at the beam that will receive the post-strengthening. Since it is very complicated to grab and prestress the FRP strip, due to its anisotropic behavior, a prestressing device was designed, as one can see in Figure 5. The prestressing device consists of two wheels which are connected to a beam of the required length, as shown in Figure.

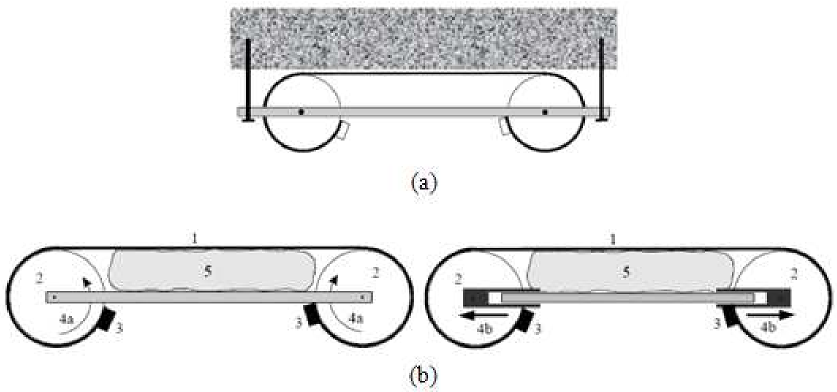


Figure 5. Prestressing device developed by Stoecklin & Meier [17]: (a) Placement of the prestressing device under the beam; (b) Two ways of prestressing a CFRP strip.

The FRP strip (1) is wrapped around the wheels (2) and clamped at its ends (3) as shown in Figure 5 (b). The strip can be prestressed by rotating one or both wheels (5a) or displace the wheels (5b). As one can see in Figure 5(a), the prestressing device with the prestressed FRP strip is temporarily mounted to the structure and can be pressed against the structure with a constant pressure by means of an air-cushion (5) between the FRP strip and the beam. (Stoecklin & Meier [17]).

In a new version of the prestressing device developed by Stoecklin & Meier [17], two separate prestressing units at each end of the strip are directly mounted to the structure, what means that the FRP strip is prestressed against the structure, as shown in Figure 6.

Figure 6. New version of the prestressing device developed by Stoecklin & Meier (Meier [10]).

To overcome anchorage problems at the ends of the FRP strips, the prestressing force can be reduced gradually from the mid-span to both ends of the FRP strips.

As described by Meier et al. [18], gradual anchoring is achieved by first bonding a fully pretensioned section in the middle of the FRP strip at mid-span. A system of electric heating may be used to speed up curing of the adhesive in the bonded section within the pot life of the adhesive. After curing the central part of the FRP strip at mid-span, the prestressing force is slightly reduced and another section is bonded at each side of the strip also using the electric heating system to speed up curing the adhesive.

This process is repeated in several stages until the entire length of the strip is bonded and the prestressed level at the ends of the strips has been reduced to a low level, as one can see in Figure 7. In this way, anchorages are not required at the end of the prestressed strip.

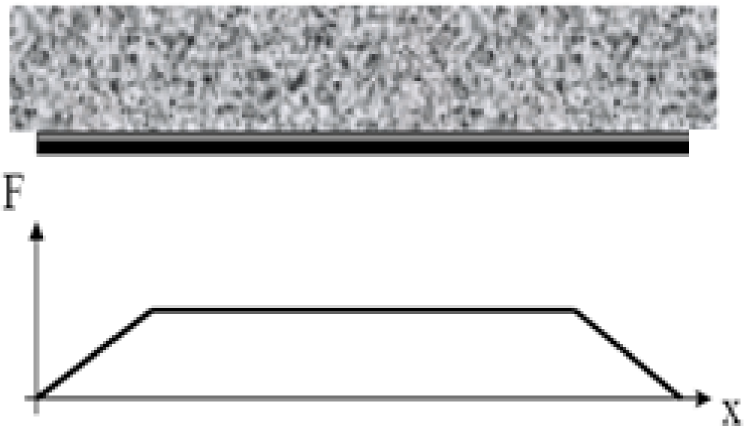


Figure 7. Gradual anchorage of prestressed CFRP strips (Stoecklin & Meier [17]).

In the prestressing method developed by Stoecklin & Meier [17] the strip is prestressed before the application at the beam. In such case, prestressing is applied by reacting against the structural member, since the prestressing device is mounted to the structure.

When the first FRP strip is prestressed, using the device developed by Stoecklin and Meier [17], imediate losses of prestress due to elastic deformation of the concrete, that happen when the prestress force is released, can be neglected, since prestressing is applied by reacting against the structural member. However, strips that have already been prestressed will experience a loss of prestress due to the shortening of the beam upon the prestressing of subsequent FRP strips.

2.4. Failure Modes of reinforced concrete beams post-strengthened with prestressed FRP submitted to static loading

According to Hollaway [19], the anisotropic behavior of the composite materials leads to a complex rupture mechanism that may be characterized by extensive damages on the composite material when submitted to static and cyclic loading. The level of damage, however, depends on the properties of the composite material and on the applied loading.

Failure modes of reinforced concrete structures post-strengthened with FRP include crushing of concrete, yielding of steel reinforcement or tensile failure at the FRP.

Teng et al. [20] report that failure modes of reinforced concrete beams post-strengthened with FRP can be broadly classified into two types: those associated with high interfacial

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stresses near the ends of the bonded FRP and those induced by a flexural or flexural-shear crack away from the ends, which is also referred to as intermediate crack-induced debonding. Thus premature failures, in general, are associated to:

- High interfacial stresses near to the ends of the bonded FRP, also called peeling-off.
- Flexural or flexural-shear crack away from the ends, as shown in Figure 8.

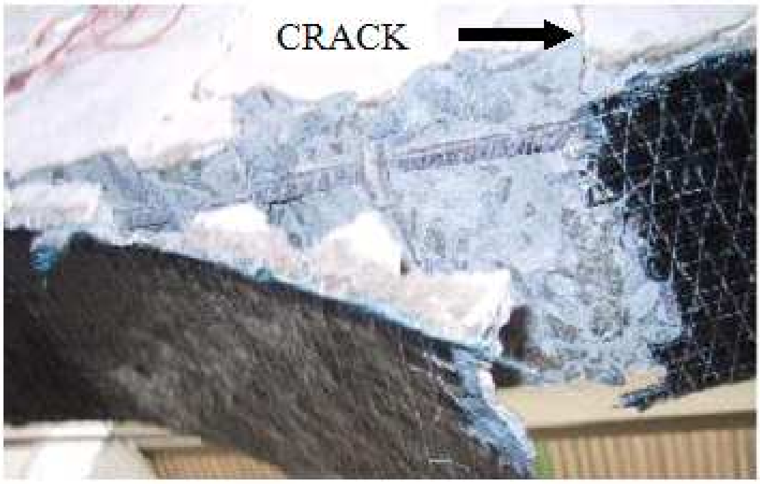

Figure 8. Rupture of FRP close to a flexural crack tip.

Concrete structures post-strengthened with prestressed FRP also show premature failures as described by Teng et al. [20]. However, in prestressed systems, the high strength of the FRP used to post-strengthen structures is much better used, and, depending on the configuration of the post.-strengthening, tensile failure of the FRP may be achieved.

Garden and Hollaway [1] presented, in 1998, a specific study regarding the failure modes of reinforced concrete beams post-strengthened with prestressed FRP, with prestressing levels ranging from 25% to 50% of the FRP strength. Results showed that a high prestress level was required to enable the ultimate capacity of strip to be reached, before shear displacement reached its critical value.

According to Garden and Mays [4], the level of prestress that can be applied will be limited by the tensile strength of the FRP. Tensile failure of the FRP should not precede either yielding of steel reinforcement or crushing of concrete, to ensure adequate ductility. Results of the experimental program showed that the level of prestress may also have to be limited by the strength of the anchorage devices, by the horizontal shear strength of the adhesive/FRP interface and by the bottom layers of concrete.

2.5. Failure of post-strengthened beams submitted to cyclic loading

Fatigue may be defined as a permanent and progressive damage process that induces gradual and cumulative crack growth and might, ultimately, result in the complete fracture of the elements subjected to cyclic loads, if the stress variation and the number of load cycles are large enough. This term was established by the first researchers of the theme due to its nature: a progressive damage process caused by cyclic loads, difficult to observe, that changes the ultimate capacity of the material (Meneghetti et al. [21]).

The usual fatigue failure mechanism for post-strengthened RC beams, when subjected to cyclic loads, is marked by the rupture of one of the steel rebars, followed by a stress redistribution that overloads the remaining bars.

Meier U. [22] highlights that the steel rebars fail before the FRP post-strengthening, as can be seen in Figure 9 that shows the steel rebars of a post-strengthened concrete beam after a fatigue failure. However, cyclic loads can also damage the adhesive and affect the interface concrete-adhesive and adhesive-FRP, leading to premature failures.

Figure 9. Failure of concrete beam after fatigue loading test.

According to Ferrier et al. [23], the performance and the durability of a concrete structure post-strengthened with FRP, when subjected to cyclic loads, depends not only on the FRP fatigue behavior but also depends on the interface concrete-adhesive and adhesive-FRP. Authors point out the importance of understanding the behavior of these materials under cyclic

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loading, since a typical reinforced concrete highway bridge deck with a design life of 40 years may experience a minimum of 58×10^8 loading cycles of varying intensities.

3. Experimental analysis of reinforced concrete beams post-strengthened with prestressed FRP

3.1. Description of specimens

Aiming to analyze the behavior of concrete beams post-strengthened with prestressed CFRP strips under static loading three beams were tested: VT, VFC_NP_01 VFC_PE_01 (Table 1). Regarding the cyclic loading tests two beams were tested: VFC_PC_01 and VFC_PC_02 (Table 2). Stress levels applied at beam VFC_PC_01 were 50% and 80% of the yielding stress observed at beam VFC_PE_01, tested under static loading. Stress levels applied at beam VFC_PC_02 were more reasonable, 50% and 60% of the yielding stress observed at beam VFC_PE_01.

Beam	**Post-strengthening**	**Prestressing level**
VT	-	-
VFC_NP_01	Two CFRP non-prestressed strips	-
VFC_PE_01	Two CFRP prestressed strips	35% of ε_{fu}

Table 1. Description of experimental program – static loading.

Beam	Post-strengthening	Test	Prestressing level applied on the strips	Stress range of fatigue loading
VFC_PC_01	Two CFRP prestressed strips	Bending cyclic loading	35% of ε_{fu}	50% to 80%
VFC_PC_02				50% to 60%

Table 2. Description of experimental program – cyclic loading.

3.2. Reinforced concrete beams

The reinforced concrete beams were rectangular, 6500mm long, 1000mm wide, and 220mm deep. All beams were reinforced with seven bottom 15mm steel bars ($\varrho = 0.0041$). The shear reinforcement consisted of 8mm steel stirrups spaced each 90mm ($11.17 cm^2/m$). Geometry and reinforcement details for the beam are shown in Figure 10.

Aggregates used to produce the concrete were the ones available in the Switzerland region and the cement was the Portland CEM I 42.5 (95% of clinquer, and 5% of other components), equivalent to the Brazilian CPI. The average compressive stress (cube strength) of the concrete, after 28 days, was 44MPa.

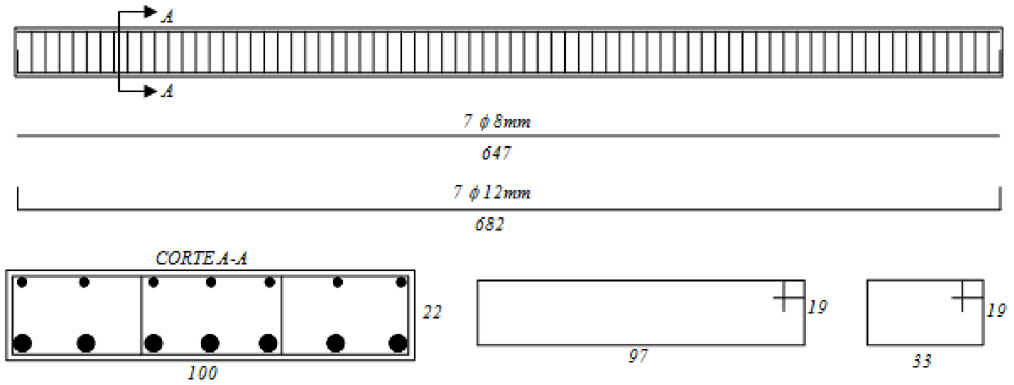

Figure 10. Geometry and reinforcement details of tested beams.

	Carbodur S 512 Strip	
Thickness (mm)	1.2	
Width (mm)	50	
Tensile Strength (MPa)	2,800	
Ultimate Strain ($^{o}/_{oo}$)	17	
Young's Modulus (MPa)	165,000	
Temperature Resistance (°C)	150	
Fiber Volumetric Content (%)	68	
Density (g/cm^3)	1.60	
	Sikadur®-30 Resin	Sikadur®-30LP Resin
Components	3Part A:1Part B	2Part A:1Part B
Pot life at 25ºC (min)	-	60
Pot life at 35ºC (min)	40	-
Pot life at 55ºC (min)	-	30
Tg (ºC)	62	107
Young's Modulus (MPa)	12,800	10,000

Table 3. Post-strengthening system characteristics.

The 8mm steel bars had average yield stress, yield strain, ultimate stress and modulus of elasticity of 554MPa, 2.51º/oo, 662MPa and 220 Gpa, as indicated by tensile tests. The 12mm steel bars had average values of: 436MPa, 1.98º/oo, 688MPa e 215 GPa.

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3.3. Post-strengthening system

Sika® Carbodur (Carbodur S 512 and Sikadur®-30) was the CFRP system used to post-strengthen the beams. However, Sikadur®-30LP adhesive was used to bond the prestressed strips to the concrete, due to its extended pot life. Table 3 shows the characteristics of the strips and adhesives, provided by manufacturer.

3.4. Post-strengthening procedure

The application of Sika® Carbodur system demands a surface preparation for the concrete and the strip. The concrete surface must be clean and free from grasses and oil, dry and have no loose particles. Considering the application of prestressed strips, after concrete and strip surface preparation, the strip is clamped, prestressed and covered with Sikadur®-30LP adhesive. Then, thermocouples are settled at the strip aiming to control the temperature applied to accelerate the cure of the adhesive. Figure 11 shows the application of epoxy adhesive on the strip and the procedure to clamp the strip on the prestressing device.

A gradual anchorage system was applied: after the cure of the adhesive at the middle part of the beam, the prestressing force was marginally reduced and the following areas were bonded. The force was reduced further and the adjacent areas were bonded. This procedure was repeated until there was no remaining prestressing force at the ends of the strip. With the gradual reduction, the level of prestress applied at the ends of the strip is very low or close to zero, eliminating the need of additional anchorage systems.

The maximum prestressing force applied to prestress the strip was 60kN, at mid-span. Then, prestressing force was gradually reduced, to 48kN, 36kN, 24kN, 12kN and, finally, zero, at the ends.

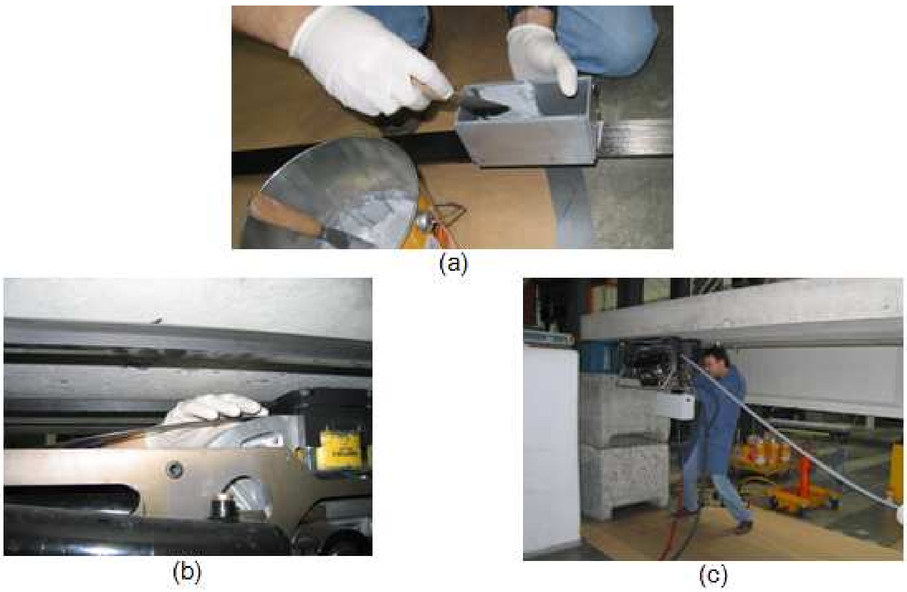


Figure 11. (a) Application of epoxy adhesive; (b) e (c) Procedure to clamp the strip on the prestressing device.

3.5. Test Procedure

The experimental program was developed at EMPA – Switzerland. Loading was applied according to a six point bending test scheme: simple supported beam and four vertical loads, spaced by 12000mm, symmetrically applied along the 6000mm span. Load was applied by two 100kN hydraulic jacks. During the tests, values of deflection at mid-span and specific strain at steel, concrete and FRP were continuously recorded by a computer controlled data acquisition system.

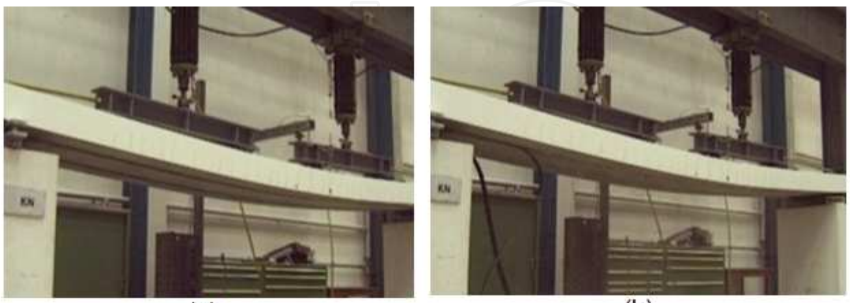
3.6. Behavior of post-strengthened beams tested under static loading

3.6.1. Loads and failure modes

Table 4 shows that the flexural capacity of beam VFC_NP_01, post-strengthened with two non-prestressed CFRP strips, increased 27% when compared to the control beam. On the other hand, post-strengthening of beam VFC_PE_01, two prestressed CFRP strips, increased 62.41% the load bearing capacity of the beam.

Beam	Post-strengthening	Ultimate load	Failure Mode
VT	-	100.14kN	Yielding of steel followed by concrete crushing
VFC_NP_01	Two 1.2mm x 50mm non-prestressed strips	127.25kN	Premature failure (peeling-off)
VFC_PE_01	Two 1.2mm x 50mm prestressed strips	162.41kN	Premature failure (peeling-off)

Table 4. Ultimate Loads and failure modes of post-strengthened beams tested under static loading.



(a) (b)

Figure 12. Beam VFC_NP_01: (a) During test; (b) After premature failure of strips.

Results of beams VFC_NP_01 and VFC_PE_01 can be explained by the principles of prestressing. When the prestressing force applied on the CFRP strips is released, compressive stresses are induced on the concrete. Such compressive stresses delay the concrete cracking and the yielding of the steel reinforcement. Thus, the load bearing capacity of the post-strengthened element is increased.

Premature failures (peeling-off) of beams VFC_NP_01 and VFC_PE_01 occurred due to the high interfacial stresses near to the ends of strips. Peeling-off failures are catastrophic and happen without any previous advice. Figure 12 shows two CFRP strips of beam VFC_NP_01 after peeling-off. Both strips are completely detached from the beam; however, strips do not present any damage, once the failure occurred at the concrete/adhesive interface.

3.6.2. Displacements at mid-span

Figure 13 shows that all post-strengthened beams present similar behavior regarding stiffness until concrete cracking. Results indicate that in such cases the action of the post-strengthening begins just when the structural element is already cracked.

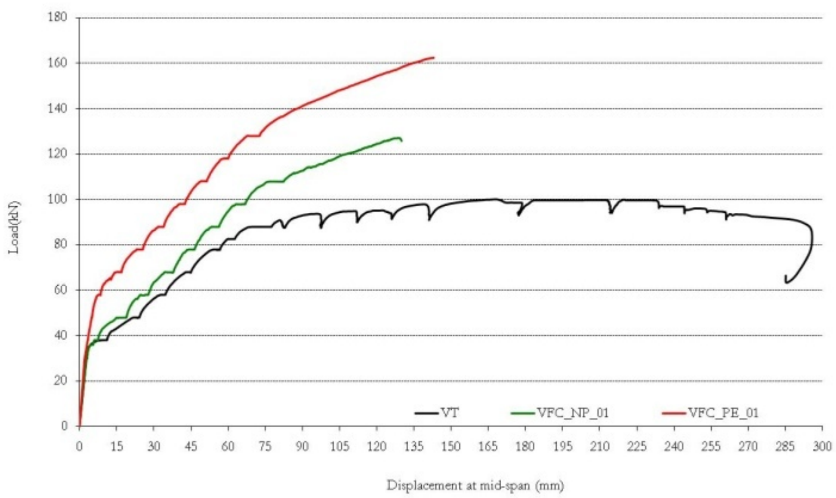


Figure 13. Load vs Displacement response of the beams tested under static loading.

Beam VFC_NP_01 post-strengthened with non-prestressed strips and the control beam, showed no significant difference regarding stiffness. However, beam VFC_PE_01 showed a stiffer behavior, when compared to beans control and VFC_NP_01, due to the increase of the cracking load and the later yielding of the reinforcement steel.

Control beam and beam VFC_NP_01, post-strengthened with non-prestressed CFRP strips present similar values of loading and displacement at mid-span at concrete cracking, due to the fact that the post-strengthening begins to act just after concrete cracking.

Cracking load of beam VFC_PE_01 was 57% higher than the ones of control beam and beamVFC_NP_01. Differences at the first stage of the loading versus displacement response at mid-span happen because prestressing leads to the development of compressive stresses at the bottom face of the beam. When non-prestressed strips are applied, the bottom face of the beam is already tensioned at the beginning of the loading process. Thus, when post-strengthening is prestressed, the loading needed to crack the concrete is significantly higher.

Differences regarding yielding of the reinforcement steel were significant. Increasing of 22% for beam VFC_NP_01 and 45% for beam VFC_PE_01, related to control beam, was observed.

3.6.3. Anchorage system

The gradual anchorage system worked properly and allowed the use of 83% of the tensile strength of the strips. Advantages of the gradual anchorage include the fact that the same device is used to prestress the strip and to gradually reduce the prestress load from the mid-span to the ends of the strip. The result is a prestressed CFRP strip without any external anchorage systems.

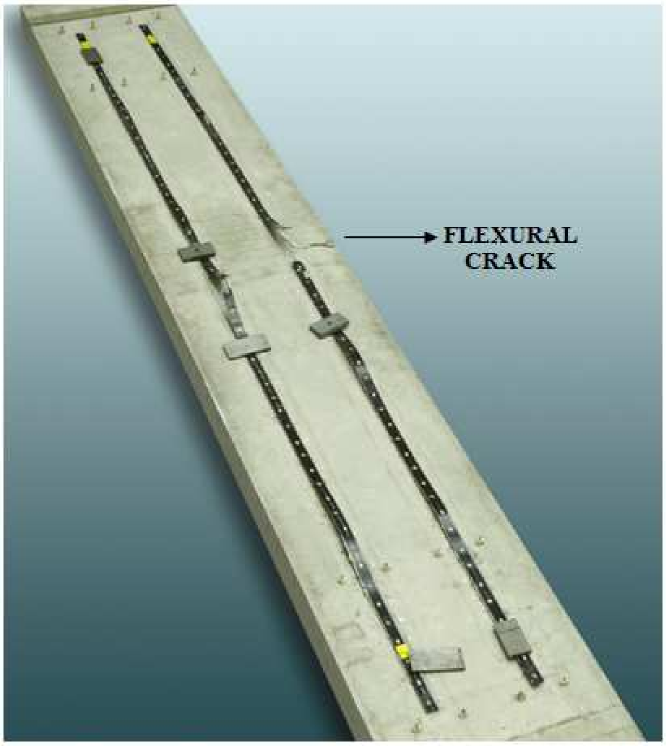


Figure 14. Beam VFC_PC_01 after failure.

3.7. Behavior of post-strengthened beams tested under cyclic loading

3.7.1. Beam VFC_PC_01

Beam VFC_PC_01 was submitted to stress levels of 50% and 80% of the yielding stress observed at beam VFC_PE_01, tested under static loading. Maximum and minimum applied loads were, respectively, 80kN and 40kN, which, added to the self weight, 28 kN, resulted applied loads of 108kN and 68kN (66% and 42% of the ultimate capacity of beam VFC_PE_01). Aiming to produce the first cracks, beam VFC_PC_01 was first pre-loaded up to108kN. Then, cyclic loading was applied at a frequency of 4Hz.

Figure 15. Failure of post-strengthening strips: (a) Next to a flexural crack; (b) Distant from flexural cracks.

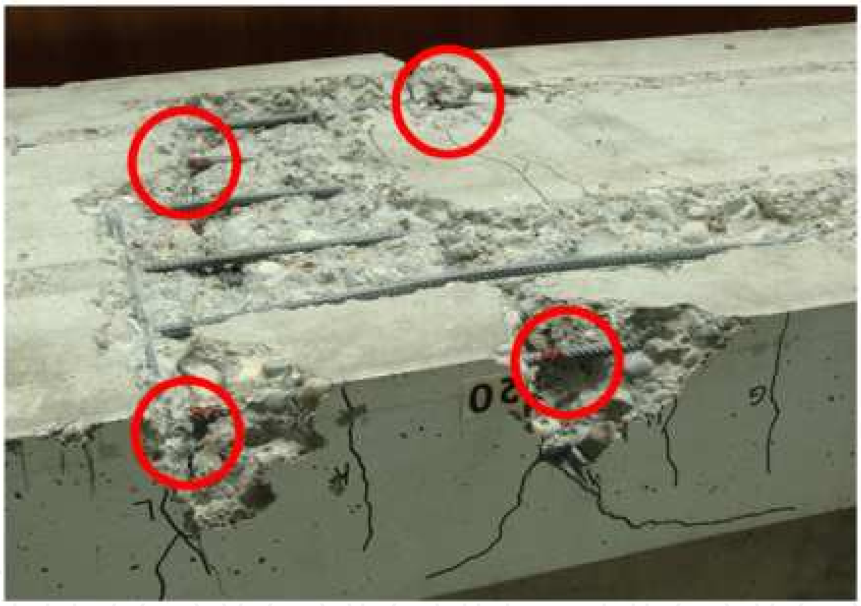


Figure 16. Fatigue failure of steel rebars.

When 282,000 cycles were reached, a crack of about 2.2mm was observed, approximately at mid-span, reaching about 90% of the cross-section. After 331,300 cycles the machine automatically stopped, when the deflection limit was reached. It was not observed any sign of apparent failure at the strips. Larger displacement limits were settled and the test was restarted. However, the post-strengthening failed before the maximum load of 108kN was reached. When the first strip debonded, the sudden release of the pre-tensioning force caused a compressive failure at the CFRP, as a secondary failure (Figure 14). The secondary failure occurred in a region that was damaged due to the presence of the flexural crack showed in Figure 14, which reached about 90% of the cross-section.

Figure 15 shows one of the CFRP strips after the failure of the post-strengthened beam. Flexural crack showed in Figure 14 induced the identification of a steel rebar broken due to fatigue. After the test, the concrete was removed from the bottom of the beam and all steel rebars were inspected. Figure 16 confirms the existence of more steel rebars broken also due to fatigue.

Figures 17 and 18 show strains in the concrete and in the CFRP strips, obtained by deformeters, which gauge points were placed along the bottom of the beam. Measurements were made during pre-loading, after 30,000 cycles, and after 100,000 cycles, with the beam subjected to the maximum load (108kN). It is shown that the measurements made in the CFRP strips allowed the construction of well defined curves. However, due to the crack growing between the gauge points, this behavior could not be observed in the measurements made in the concrete. Nevertheless all obtained responses followed an expected pattern.

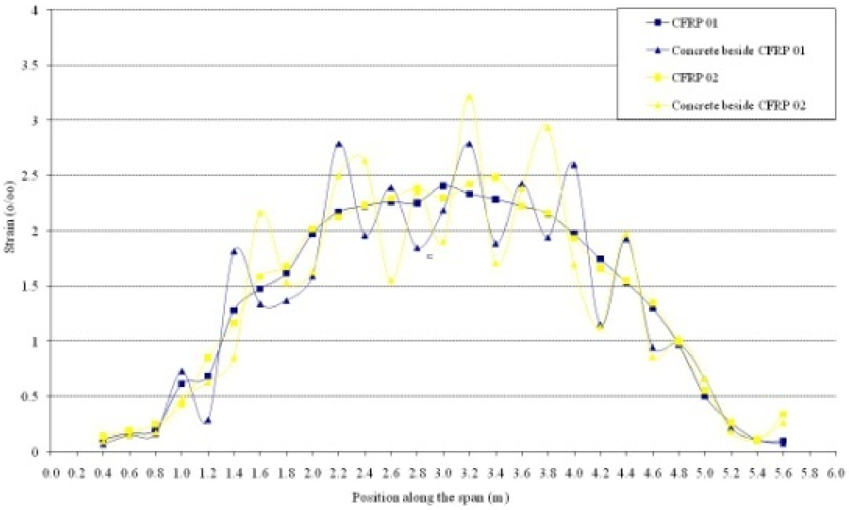
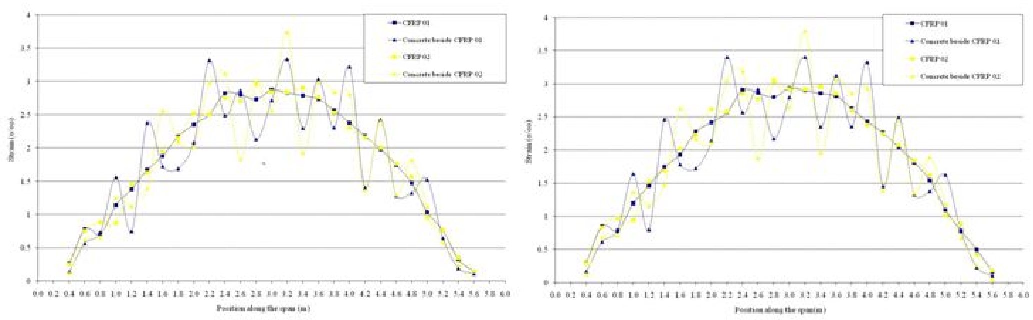


Figure 17. CFRP and concrete strains of beam VFC_PC_01, submitted to 108kN, during pre-loading.



(a) (b)

Figure 18. CFRP and concrete strains of beam VFC_PC_01, submitted to 108kN after (a) 30,000 cycles and (b) 100,000 cycles.

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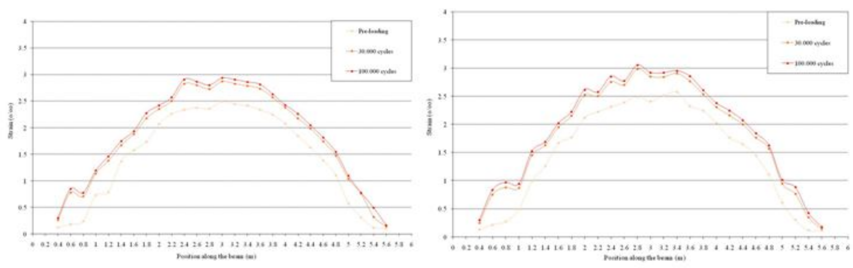
Strains in the CFRP strips, at mid-span, during pre-loading, varied from 2.00º/oo up to 2.50º/oo. At the end of 30,000 cycles, strains increased to levels that varied from 2.50º/oo up to 3.00º/oo. From 30,000 cycles up to 100,000 cycles, it was not observed any significant variation in the strains. Strains measured, added to the strain applied to prestress each strip (5.95º/oo), give for each strip a total strain of of 8.45º/oo and 8.95º/oo. It is also noted that, at mid-span, where most of the cracks could be found, strains measured in the concrete and in the FRP are quite different. It happens because the FRP strip acts as a belt, blocking the concrete crack opening. Therefore, it can be observed that several points along to the beam are subjected to different strains. Such points can, eventually, be related to the occurrence of premature failures. Strains at a distance of 1,2 m from both beam ends, out of the loading region, are not greater than 1.50°/oo, however, these values increased about 100% from pre-loading up to 100,000 cycles.



(a) (b)

Figure 19. CFRP strains of strip 01 (a) and 02 (b) of beam VFC_PC_01 during cyclic loading.

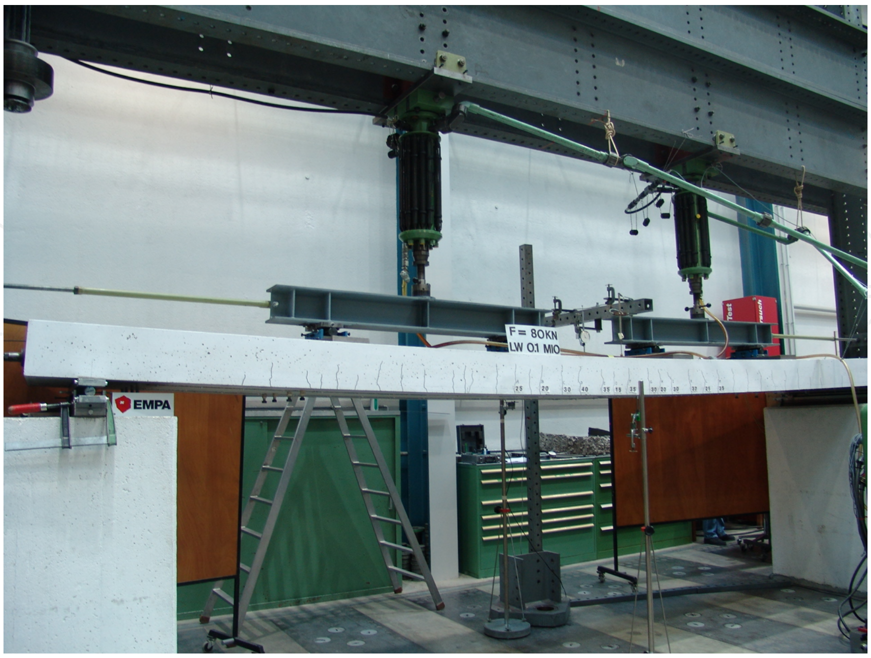


Figure 20. Cracks at mid-span of beam VFC_PC_01 after 100,000 cycles.

Figure 19 shows the strains in the CFRP strips measured during pre-loading, after 30,000 cycles and after 100,000 cycles. Significant variations were not observed in the range from 30,000 to 100,000 cycles. However, strains increased about 0.50º/oo from the pre-loading up to 10,000 cycles. Figure 19 also shows that up to 100,000 cycles the behavior of both strips is similar. However, some variations can be observed at mid-span, due to the high cracking.

The strategy adopted to monitor the crack growing at mid-span of beam VFC_PC_01 can be observed at Figure 20. Results of crack openings and the respective position from the left end of the beam are shown in Figure 21.

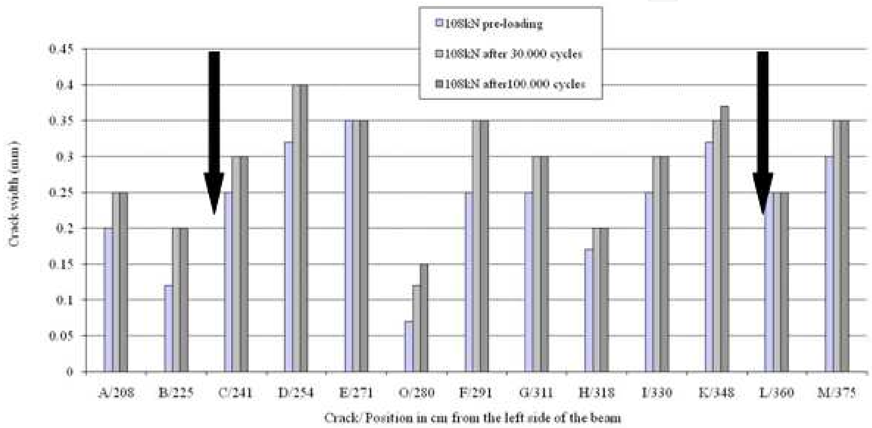


Figure 21. Cracks at mid-span of beam VFC_PC_01 after 100,000 cycles.

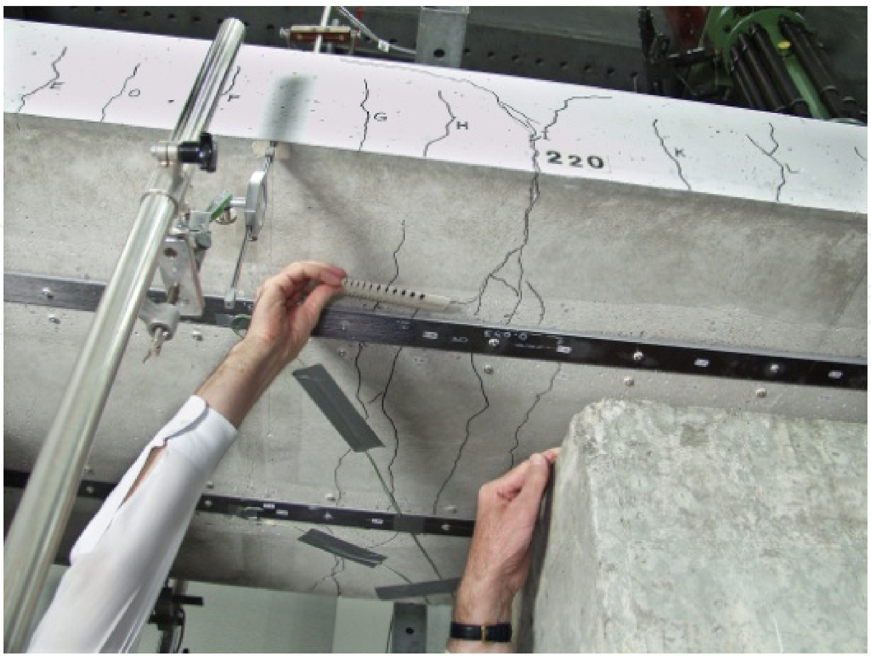


Figure 22. 2,2mm width crack at mid-span of beam VFC_PC_01 after post-strengthening failure.

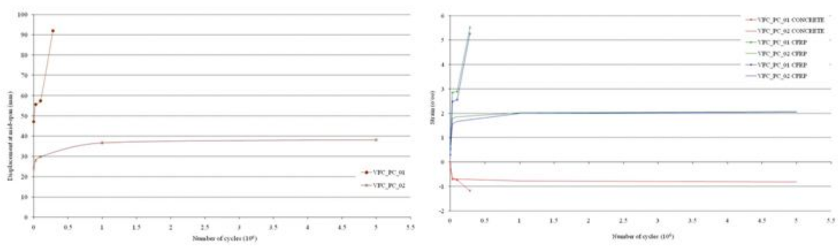
A high concentration of cracks can be observed at the mid-span of beam VFC_PC_01, between the four loading points. Figure 21 shows the crack openings at mid-span between the two central loading points (signaled on the figure by two vertical arrows). It is noteworthy that, before 100,000 cycles, crack openings did not reached 0.05mm.

The highest crack opening after 100,000 cycles, named D, was 0.4mm, located 254cm from the left side of the beam. However, apparently the post-strengthening failed due to a 2.2mm crack opening, named I, after 331,300 cycles. It is important to notice that, after 100,000 cycles, this crack opening was about 0.3mm (Figure 22).

The decision of testing beam VFC_PC_01 under a high stress variation led to the fatigue failure before 5,000,000 cycles, that was considered the pattern of infinite fatigue life. Stress levels applied to the beam VFC_PC_02, however, are more consistent with the ones usually found in real structures. Results of beamVFC_PC_02 will allow a more detailed analysis of the CFRP prestressing technique used, as well as of the gradual anchorage system.

3.7.2. Beam VFC_PC_02

Beam VFC_PC_02 was submitted to stress levels of 50% and 60% of the yielding stress observed at beam VFC_PE_01, tested under static loading. Maximum and minimum applied loads were, respectively, 50kN and 40kN, which, added to the self weight of 28 kN, resulted in applied loads of 78kN and 68kN (48% and 42% of the ultimate capacity of VFC_PE_01). Aiming to produce the first cracks, beam VFC_PC_02 was pre-loaded up to78kN. Then, cyclic loading was applied at a frequency of 4Hz.



(a) (b)

Figure 23. Beams VFC_PC_01 and VFC_PC_02: (a) Displacement at mid-span vs number of cycles (b) Concrete and CFRP strains vs number of cycles.

Figure 23 (a) shows that vertical displacements at mid-span, for beam VFC_PC_02, measured with the beam subjected to the maximum load (78kN) varied 12.70mm from preloading up to 1,000,000 cycles. From this point, up to the end of the test, vertical displacements increased just 1.49mm. Data of beam VFC_PC_01 showed a large increase in the vertical displacements at mid-span after 100,000 cycles, probably due to the fatigue failure of the steel rebars. Strains in the concrete and in the CFRP strips (Figure 23 (b)) behave similarly to the displacements at mid-span, where most of the variations occurred before 1,000,000 cycles, and, after that, showed stability up to 5,000,000 cycles. Beam VFV_PC_01 also showed a similar behavior between strains and vertical displacements at mid-span, however, with a significant increasing after 100,000 cycles, probably due to the fatigue failure of the steel rebars.

Figures 24 to 26 show the strains in concrete and in CFRP strips, obtained by deformeters, which gauge points were placed along the bottom of the beam. Measurements were made during pre-loading, after 30,000 cycles, after 100,000 cycles, after 1,000,000 cycles and after 5,000,000 cycles, with the beam subjected to the maximum load (78kN).

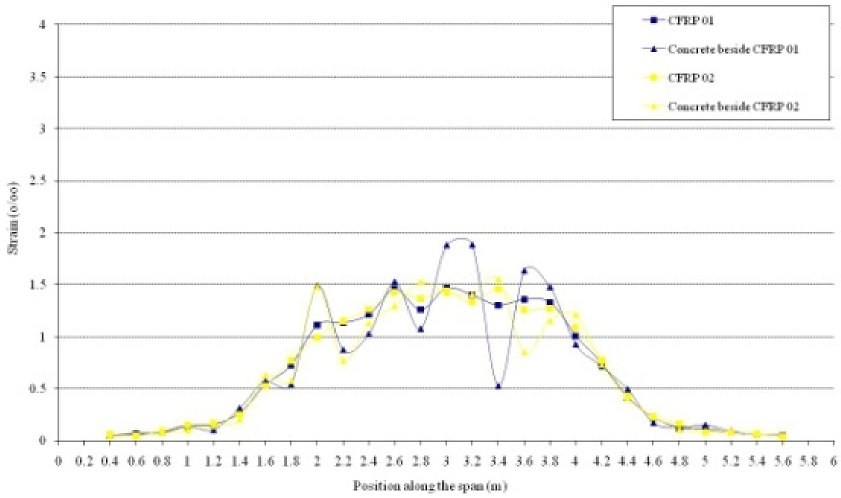
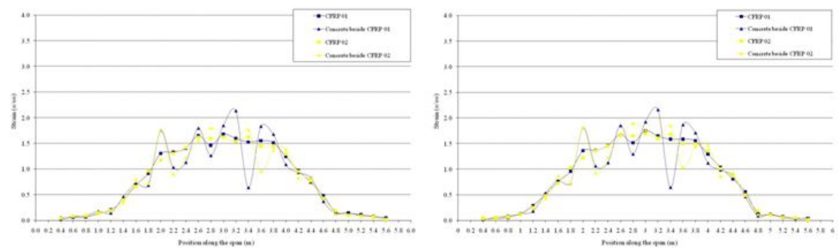


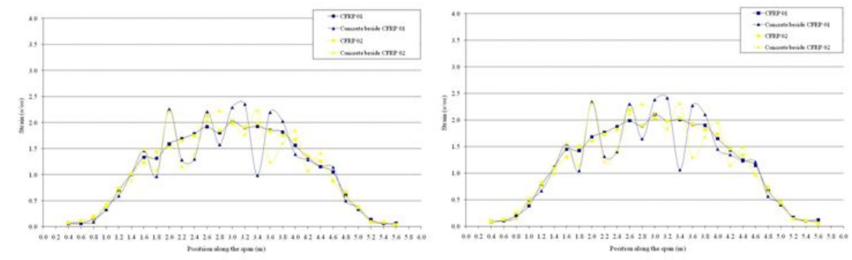
Figure 24. CFRP and concrete strains of beam VFC_PC_02, submitted to 78kN, during pre-loading.



(a) (b)

Figure 25. CFRP and concrete strains of beam VFC_PC_02, submitted to 78kN after (a) 30,000 cycles and (b) 100,000 cycles.

It can be noticed that the strains obtained by deformeters, placed along the bottom of the beam VFC_PC_02, varied from the pre-loading up to 1,000,000, tending to stabilize after 5,000,000, cycles. Portions located between the loading points (1,2 m to 4,8 m from the beam end) clearly show the presence of cracks in the concrete. From the pre-loading up to 30,000 cycles, it was not observed any significant variation in the strains along the gradual anchorage zone (1.2m from the both beam ends). Strains increased after 100,000 cycles, and, after 5,000,000 cycles, the level of strains of the beginning of the test could be observed just along the first 0.6m from both beam ends. Figures 24 to 26 show that strains in the anchorage zones of beam VFC_PC_01 were higher than the ones of beam VFC_PC_02.



(a) (b)

Figure 26. CFRP and concrete strains of beam VFC_PC_02, submitted to 78kN after (a) 1.000.000 cycles and (b) 5.000.000 cycles.

Data of Figures 24 to 26 show that strains in the CFRP strips, between the two central loading points, placed at 2.4m and 3.6m from the beam ends, measured at pre-loading, varied from 1.00 º/oo up to 1.50º/oo. After 30,000 cycles strains increased up to 2.00 º/oo and no significant variation were observed from 30,000 cycles up to 100,000 cycles. Measurements after 1,000,000 and 5,000,000 cycles registered a maximum strain of 2.11º/oo. Such strain, added to the strain applied to prestress each strip (5.95º/oo), give for each strip a total strain of of 8.06º/oo. Strains in the strips of beam VFC_PC_02 were smaller to the ones of beam VFC_PC_02, since, for the second beam, the maximum load and the difference between the maximum and the minimum load were smaller. Results of beam VFC_PC_02 indicate that, up to 5,000,00 cycles, it was not observed any damage on the post-strengthening system, due to the application of the cyclic loading.

Figure 27 (a) shows the strains in the CFRP strips, measured from the pre-loading up to 5,000,000 cycles. The most significant variations occurred up to 1,000,000 cycles. Strains in the CFRP strips varied about 0.85º/oo from the pre-loading up to 5,000,000 cycles. The greatest differences regarding strains were found at 1.8m, 2.8m and 4.6m from the left side of the beam (Figure 27 (a)), and at 2.6m from the left side of the beam (Figure 27 (b)).

Results indicate the existence of a kind of progressive strain at the anchorage regions, which can, ocassionally, generate adherence problems regarding long-term fatigue. Such effect should be better investigated, however, the long time demanded to realize fatigue tests, sometimes, inhibits this initiative.

Crack growing at mid-span of beam VFC_PC_01 can be observed at Figure 28, which shows the results of all crack opening measurements made, from pre-loading up to 5,000,000 cycles. Figure 28 shows the results of crack openings and the respective position from the left side of the beam, at mid-span, between the two central loading points (signaled on the figure by two vertical arrows).

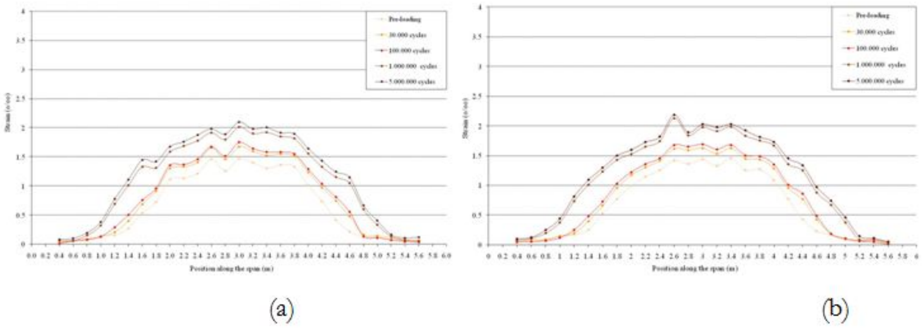


Figure 27. CFRP strains of strip 01 (a) and 02 (b) of beam VFC_PC_02 during cyclic loading.

First cracks at mid-span appeared during pre-loading, reaching less than 0.15mm. From this point up to 100,000 cycle, crack openings increased, but did not exceed 0.20mm. After 1,000,000 cycles the maximum crack opening was 0.22mm, and after 5,000,000, this value was not exceeded. Cracking at the gradual anchorage regions appeared just after 100,000 cycles, however, the maximum cracking opening observed was 0.05mm. From 100,000 up to 5,000,000 cycles, the maximum crack opening measured at these regions was 0.10mm. Results of crack openings obtained from beams VFC_PC_01 and VFC_PC_02 cannot be compared directly, due to the difference regarding the maximum and minimum loads applied to generate the cyclic loading. As the maximum load applied on the beam VFC_PC_01 (108kN) was higher than the one applied on the beam VFC_PC_02 (78kN), beam VFC_PC_01 showed higher values of crack openings once pre-loading. Values of crack openings obtained after 5,000,000 cycles, for beam VFC_PC_02, were reached by beam VFC_PC_01 after just 282,000 cycles.

4. Conclusions

4.1. Post-strengthened beams tested under static loading

Results obtained with the development of the research program allowed the investigation of changes on the behavior of post-strengthened elements due to prestressing. The increasing on the load bearing capacity of the beam post-strengthened with prestressed strips, higher than the one of the beam post-strengthened with non-prestressed strips, highlights the efficiency of the prestressing technique. All post-strengthened beams showed vertical displacements at mid-span lower then the ones of the control beam. However, the stiffer behavior showed by all post-strengthened beams was evidenced only after concrete cracking. Due to the increasing of the concrete cracking load and the later yielding of the reinforcement steel, the beam post-strengthened with prestressed CFRP strips showed a stiffer behavior when compared to the one post-strengthened with non-prestressed CFRP strips. Gradual anchorage worked properly, dismissed the use of any external anchorage system and allowed the use of 83% of the tensile strength of the strip.

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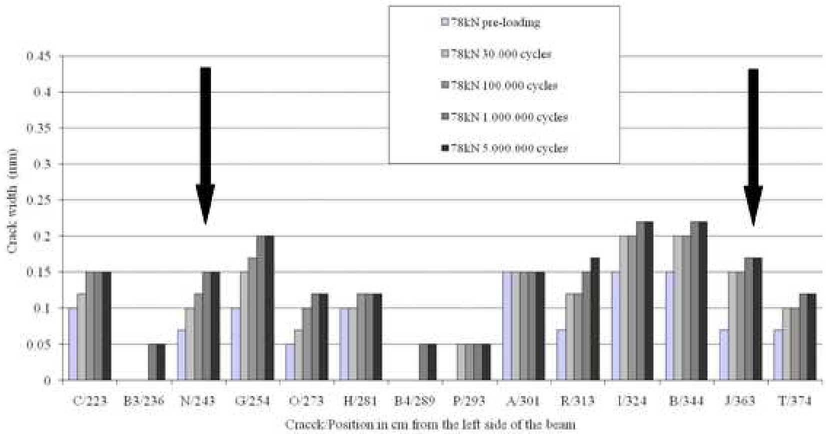

Figure 28. Cracking at mid-span of beam VFC_PC_2 during test.

4.2. Post-strengthened beams tested under cyclic loading

Results of the reinforced concrete beams tested under cyclic loading show that when these structures are post-strengthened with prestressed CFRP strips, damages that occur due to fatigue are mainly related to the level of stress at the steel rebars. Experimental results showed that the damage, which led to the rupture of the steel rebars, is related to the level of stress during loading, and, that it is not related to the type of post-strengthening. Tests showed that an increasing of 20% in the maximum stress of the steel rebars significantly reduced the fatigue life time of the post-strengthened element, decreasing about 15 times the number of cycles up to failure. These results emphasize the importance of proceeding the monitoring of structures that are usually submitted to cyclic loading, such as highway and railway bridges. In some cases, when these structures were designed to support traffic loads smaller to the ones that they are submitted nowadays, the use of post-strengthening may increase their lifetime, since the use of post-strengthening may lead to a reduction in the stress level of the steel rebars.

Acknowledgements

Authors would like to acknowledge CNPq (Portuguese acronym of the Brazilian Ministry of Science's National Research Council) and CAPES (Portuguese acronym of the Higher Education Human Resources Development Agency of the Brazilian Ministry of Education) for providing the financial support needed to develop this project. Authors would also like to express their appreciation for the technical support given by the research team EMPA (Swiss Federal Laboratories for Materials Testing and Research), in Switzerland. Finally, authors gratefully acknowledge Prof. Urs Meier for his support and assistance during the PhD. studies of the first author of this paper, developed at EMPA – Switzerland.

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References

[1] Garden, H. N., & Hollaway, L. C. (1998). An experimental study of the failure modes of reinforced concrete beams strengthened with prestressed carbon composite plates. *Composites Part B*, 29(B), 411-424.

[2] Täljsten, B. (1994). Strengthening of existing concrete structures with epoxy bonded plates of steel or fibre reinforced plastics. *PhD thesis. Lulea University*.

[3] Meier, U. (2001). Polyfunctional use of advanced composite materials with concrete. *N. Banthia, N, Sakai K, Gjørv OE. (eds.) CONSEC01: proceedings of the Third International Conference on Concrete Under Severe Conditions, CONSEC01, Vancouver, Canada. Vancouver: Vancouver B. C.*

[4] Garden, H. N., & Mays, G. C. (1999). Strengthening of Reinforced Concrete Structures Using Externally bonded FRP Composites in Structural and Civil Structures. *Cambridge: CRC Press*.

[5] El-Hacha RMA. (2000). Prestressed CFRP for strengthening concrete beams at room and low temperatures. *PhD thesis, Queen's University* .

[6] Fédération Internationale du Betón. (2001). Externally bonded FRP reinforcement for RC structures- Bulletin 14. *Lausane: FIB;. Technical Report*.

[7] American Concrete Institute. (2004). Prestressing Concrete Structures with FRP Tendons. *Farmington Hills: ACI,*, 35, ACI 440.4R-04.

[8] Triantafillou, T. C., Deskovic, N., & Deuring, M. (1992). Strengthening of concrete structures with prestressed fiber reinforced plastic sheets. *ACI structural Journal:*, 89(3), 235-244.

[9] El -Hacha, R., Wight, G., & Green, M. F. (2004). Prestressed carbon fiber reinforced polymer sheets for strengthening concrete beams at room and low temperatures. *Journal of Composites for Construction:*, 3-13.

http://dx.doi.org/10.5772/51523

[10] Meier, U. (2005). Design and rehabilitation of concrete structures using advanced composite materials. *Klein GMB. (ed.) PRECONPAT05: proceedings of the Pre-Congresso Latino-Americano de Patologia da Construção, PRECONPAT05, Porto Alegre, Brazil. Porto Alegre: UFRGS*.

[11] Ehsani, M. R., & Saadatmanesh, H. (1989). Behaviour of externally prestressed concrete girders. *Iffland JSB. (ed.) STRUCTURES CONGRESS 89: proceedings of the Seventh Annual Structures Congress, STRUCTURES CONGRESS 89, San Francisco, United States. New York: ASCE*.

[12] Wight, R. G., Green, M. F., & Erki, MA. (2001). Prestressed FRP sheets for post-strengthening of reinforced concrete beams. *Journal of Composites for Construction:*, 214-220.

[13] Triantafillou, T. C., & Deskovic, N. (1991). Innovative prestressing with FRP sheets: Mechanics of short-term behavior. *Journal of Engineering Mechanics:*, 117(7), 1652.

[14] Triantafillou, T. C., & Deskovic, N. (1992). Presressed FRP sheets as external reinforcement of wood members. *Journal of Structural Engineering:*, 118(5), 1270.

[15] Deuring, M. (1993). Verstärken von Stahlbeton mit gestpannten Faserverbund-Werkstoffen. *Dübendorf: EMPA*, 276, *Report 224*.

[16] Quantryll, R. J., & Hollaway, L. C. (1998). The flexural rehabilitation of reinforced concrete beams by the use of prestressed advanced concrete plates. *Composites Science and Technology*, 58, 1259.

[17] Stöcklin, I., & Meier, U. (2003). Strengthening of concrete structures with prestressed and gradually anchored CFRP. *Tan KH. (ed.) FRPRCS-6: proceedings of the Sixth International Symposium on FRP Reinforcement for Concrete Structures, FRPRCS-6, Singapore. Singapore:World Scientific*.

[18] Meier, U., Stöcklin, I., & Terrasi, G. P. (2001). Making better use of the strength of advanced materials in structural engineering. *Teng JG. (ed.) CICE01: proceedings od the FRP Composites in Civil Engineering, CICE01, Hong Kong, China. Hong Kong: Elsevier*.

[19] Hollaway, L. (1993). Polymer Composites for Civil and Structural Engineering. *Hong Kong: Blackie Academic and Professional*.

[20] Teng, J. G., Smith, S. T., Yao, J., & Chen, J. F. (2003). Intermediate crack-induced in RC beams and slabs. *Construction and Building Materials:*, 17-447.

[21] Meneghetti, L. C., Garcez, M. R., Silva, Filho. L. C. P., & Gastal, F. P. S. L. (2011). Fatigue life regression model of reinforced concrete beams strengthened with FRP. *Magazine of Concrete Research:*, 63-539.

[22] Meier, U. (1995). Strengthening of structures using carbon fibre/epoxy composites. *Construction and Building Materials:*, 9(6), 341-351.

[23] Ferrier, E., Bigaud, D., Hamelin, P., Bizindavyi, L., & Neale, K. W. (2005). Fatigue of CFRPs externally bonded to concrete. *Materials and Structures:*, 38(1), 39-46.