sciendo DOI: 10.2478/ace-2018-0073 ARCHIVES OF CIVIL ENGINEERING
Vol. LXIV ISSUE 4 2018

PRE-STRESS LOSSES IN FRP PRE-STRESSED REINFORCED CONCRETE – SUBJECT OVERVIEW

M. PRZYGOCKA[1], R. KOTYNIA[2]

Fiber reinforced polymers (FRPs) due to their specific high-strength properties become more and more popular and replace traditional structural materials like conventional steel in prestressed concrete structures. FRP reinforced structures are relatively new when compared to structures prestressed with steel tendons. For that reason only several studies and applications of pre-tensioned FRP reinforcement have been conducted until now. Moreover, researchers only considered short-term behavior of FRP reinforced concrete members. The precise information about long-term behavior of FRP reinforcement is necessary to evaluate the prestress losses, which should be taken into account in the design of prestressed RC structures. One of the most important factor influencing long term behavior of FRP reinforcement is stress relaxation. The overview of experimental tests results described in the available literature considering the prestress losses obtained in FRP prestressed concrete members is presented herein.

Keywords: FRP, long-term performance, pretensioning, prestress losses, relaxation, rheology

1. INTRODUCTION

All materials (bodies) deform as a response to an applied loading. Continuous materials demonstrate elastic behavior in both limited extent of strains and low speed of deformation. The increase of influence of viscosity is observed with the increase in speed of deformation as well as the rheological effects appears related to change of the material properties in time.

[1] MSc., Eng., Lodz University of Technology, Faculty of Civil Engineering, Architecture and Environmental Engineering, Al. Politechniki 6, 90-924 Lodz, Poland, e-mail: martaprzygocka@wp.pl
[2] Associate Prof., PhD., Eng., Lodz University of Technology, Faculty of Civil Engineering, Architecture and Environmental Engineering, Al. Politechniki 6, 90-924 Lodz, Poland, e-mail: renata.kotynia@p.lodz.pl

FRP (fiber reinforced polymer) is a type of bi-component material reinforced with unidirectional, nonmetallic, continuous, high-strength fibers (dispersed fraction) embedded in a polymer matrix (continuous fraction). FRP materials are characterized by higher tensile strength and stiffness than other structural materials. In addition, they are highly anisotropic due to material arrangement (unidirectional fibers). Tensile strength of FRP increases with the increase of dispersed fraction in the material volume. Additionally, the relative proportion of fibers affects the density, rate of thermal expansion and elasticity modulus of composite. Different creep and relaxation behavior is evident for different types of fibers. Furthermore, one of the main factor influencing the composite characteristics is contact between fractions at the components interface. Particular components of composite material (fibers and matrix) differ in the deformation manner under external loading. The nonmetallic fibers of dispersed phase deform in a linear elastic manner managed by Hook principle. However, polymer matrix deforms both in an elastic manner (reversibly) in the early stage of strain and inelastic (irreversible) after exceeding the strain limit value. After all, FRP composites are subjected to creep and relaxation mainly resulting from great viscoelastic strain of matrix. The behavior of viscoelastic material differs substantially from terms of linear elastic theory (linear stress-strain relationship independent from time) and is characterized by time. The stress-strain relationship curve of Inelastic material differs between loading and unloading cycles under external loading. The difference is a result from absorption and dissipation of a portion of energy as a result of attenuation. Different sources of energy dissipation occur in fiber composites as: viscoelastic nature of matrix, phase between fiber and matrix, damage, visco-plastic absorption and thermo-elastic absorption.

Prestress losses obtain in the prestressed concrete are the main issue affecting the durability and structure behavior under loading. The general division of prestress losses distinguishes immediate losses, which appear immediately after the termination of the prestressing and delayed or time-dependent losses. Relaxation losses associated with FRP prestressing tendons can be assessed in the same manner as for traditional prestressed steel tendons. The initial losses are associated with elastic shortening of concrete, slippage in anchorage, and friction between the FRP laminate and surrounding concrete. Time-dependent losses are associated with creep and shrinkage of concrete and relaxation of tendons. The relaxation loss can be expressed as:

$$\Delta F = \Delta F_D + \Delta F_A + \Delta F_{FR} + \Delta F_{CR} + \Delta F_{SH} + \Delta F_R \tag{1.1}$$

Where:

ΔF_E – elastic shortening of concrete, ΔF_A – slippage in anchorage, ΔF_{FR} – friction between the FRP laminate and surrounding concrete, ΔF_{CR} – creep of concrete, ΔF_{SH} – shrinkage of concrete, ΔF_R – relaxation of FRP.

2. RELAXATION OF FRP MATERIALS ACCORDING TO CODES AND PROVISIONS

According to the ACI440.4R the relaxation loss (REL) in FRP tendons is the sum of three different causes defined by the following formula:

(2.1) $$\mathrm{REL} = R_p + R_s + R_f$$

where:

R_p – relaxation of polymer, R_s - straightening of fibers, R_f - relaxation of fibers

Relaxation of polymer (R_p) appears within the first 24 to 96 hours and is the effect of seizing a portion of loading by matrix. Polymer relaxation depends on two characteristics of the tendon: the resin-fiber modular ratio (n_r) defined as the elastic modulus of the resin (E_r) over the fiber modulus (E_f) and the volume fraction of fibers in FRP specimen (v_f). The relaxation loss (R_p) caused by relaxation of polymer is defined by the following formula:

(2.2) $$R_p = n_R \cdot v_R$$

Where:

n_r – modular ratio of the resin, v_r – volume fraction of resin ($v_r = 1 - v_f$)

The total relaxation of polymer reaches values within the range of 0.6% to 1.2% of the transfer stress. This relaxation loss can be compensated by overstressing of the composite reinforcement, however this is not recommended due to permanent overstrain of the fibers. The loss caused by straightening of fibers R_s is the result of the arrangement of fibers which are not parallel in the material volume. When the FRP material is pre-tensioned the fibers straighten and this phenomena is considered as the relaxation loss. Third source of the relaxation of FRP composites is the relaxation of fibers which is dependent on the fiber type. Carbon fibers are considered to evince no relaxation. Aramid fibers creep when loaded, and this creep behavior is reflected in its relaxation behavior.

In accordance to the Canadian Code provisions, for the assessment of the FRP relaxation for design of prestressed concrete structure the following dependences can be used:

$$\mathrm{REL} = 0.231 + 0.345\log(t) \text{ for the CFRP} \tag{2.3}$$

$$\mathrm{REL} = 3.38 + 2.88\log(t) \text{ for the AFRP} \tag{2.4}$$

Where:

t – time in days

In Fib Model Code 2010 the relaxation of different types of FRP composites depending on the type of fibers is specified according to Table 1 based on 3000 hours relaxation tests.

Table 1. Relaxation of FRP according to Fib Model Code 2010.

Type of tendon	1000h [%]	50 years [%]
GFRP	1.8 – 2.0	4.0 – 14.0
CFRP	0.5 – 1.0	2.0 – 10.0
AFRP	5.0 – 8.0	11.0 – 25.0

Fib Bulletin 40: FRP specifies the relaxation behavior on the basis of the experimental investigations described in the available literature. According to code the relaxation rates reach values in the ranges of: 2.0% to 3.1% and 18.4% and 23.4% respectively for CFRP and AFRP bars.

2. Relaxation of FRP materials according to literature

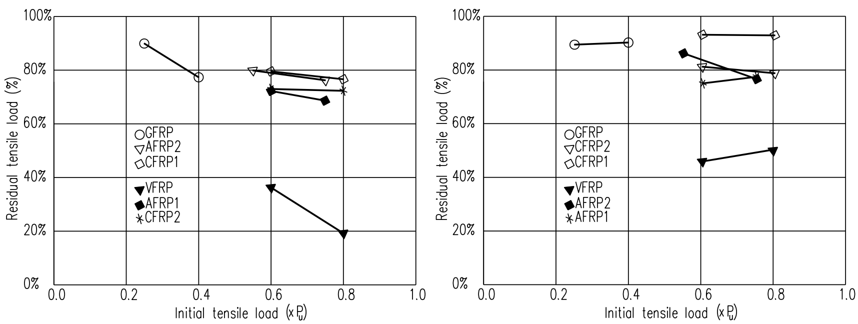
Oskouei and Taleie (2010) tested four different test setups, each lasted at least 1000 hours. The aim of the study was to evaluate the relaxation of FRP composites subjected to the uniaxial tension. Two different types of FRP composites were tested: carbon and aramid in the form of dry straight fabrics and pre-cured sheets. The first setup included two carbon samples (SF-C1 and SF-C2) and two aramid samples (SF-A1 and SF-A2) to assess the relaxation of small sheets in the form of straight dry fabrics. Alike, four pre-cured small sheets samples including two carbon fabric specimens (SP-C1 and SP-C2) and two aramid fabric specimens (SP-A1 and SP-A2) were tested in the second setup. The levels of pre-tensioning were selected as 20% and 30% of the maximum tensile strength for the first and second pre-tensioning limit, respectively. The test results except the relaxation loss contained the slip of FRP in the anchorage zone. The most part of relaxation loss occurred within the first hours of the experiment. The amount of stress reduction due to material relaxation for carbon small sheets registered in the tests was higher than 7%. For comparison, 23% of stress reduction was registered in the aramid samples. According to test results, the amounts of AFRP relaxation are not dependent upon the pre-tensioning limit.

Table 2. Relaxation of aramid and carbon FRP samples (Oskouei and Taleie, 2010).

Specimen	F_{pi} [kN]	f_{pi}/f_{pu} [-]	Stress losses after 48h [%]	Stress losses after 1000h [%]
SF-A_1	5.81	19.3	12.5	13.6
SF-A_2	9.61	32	8.6	14
SP-A_1	7.99	21	27	35.7
SP-A_2	12.41	32.6	23.4	34
SF-C_1	2.00	18.1	10.3	15.6
SF-C_2	3.00	27.3	15.6	19.2
SP-C_1	5.27	23	13.8	18.8
SP-C_2	7.55	34	19	26.2

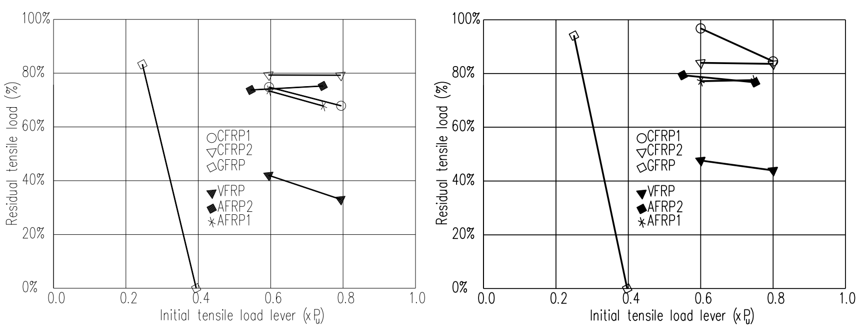
F_{pi} -pre-tensioning force of FRP, f_{pi} – initial pre-tension of FRP, f_u – FRP tensile strength.

Sasaki and Nishizaki (2012) tested six different types of FRP tendons exposed to different environmental conditions (direct sunlight and sea water) and pre-tensionig limits. Tests included two types of carbon specimens (CFRP), two types of aramid composites (AFRP), one type of glass sample (GFRP) and one type of vinyl tendon (VFRP) which gave 96 samples in total. Carbon and vinyl composites were initially pre-tensioned to $0.8P_u$ and $0.6P_u$ (P_u – FRP tensile strength) while aramid samples were pre-tensioned to the limits of $0.75P_u$ and $0.55P_u$. Glass samples were initially loaded to values of $0.4P_u$ and $0.2P_u$. Samples were placed on the deck platform for 17 years, however, part of samples were unloaded after 3 years. After 17 years, the residual tensile force of CFRP and AFRP samples was in the range of 70-80% with direct sunlight and 90% and 80% without direct sunlight exposure in CFRP1 and CFRP2, AFRP1-2, respectively. Considering the carbon and aramid samples the loss of pre-stressing force between 3.5 and 17 years is almost negligible. Fig. 1 and Fig. 2 illustrate the residual tensile load of FRP tendons with and without direct sunlight after 3.5 and 17 years, respectively. GFRP tendons pre-tensioned to $0.4P_u$ ruptured due to creep during the test. Although, pre-stressing load in GFRP samples remained at the level of 90% and 80% in specimens pre-tensioned to $0.2P_u$ of tensile strength respectively without and with sunlight exposure. Residual pre-stressing load of VFRP samples was less than 50%. The direct sunlight influences the relaxation behavior of CFRP samples causing the increase of the relaxation limit. There was no change in the relaxation of aramid composites regardless of insolation. In the case without direct sunlight, apparent relaxation ratio at 1,000h in $0.7P_u$ tensile loading indicates 5% for CFRP1 and 11-14% for the other cables.



(a) (b)

Fig. 1. Residual tensile load in FRP samples after 3.5 years of exposure: (a) with direct sunlight; (b) without direct sunlight (Sasaki and Nishizaki, 2012).



(a) (b)

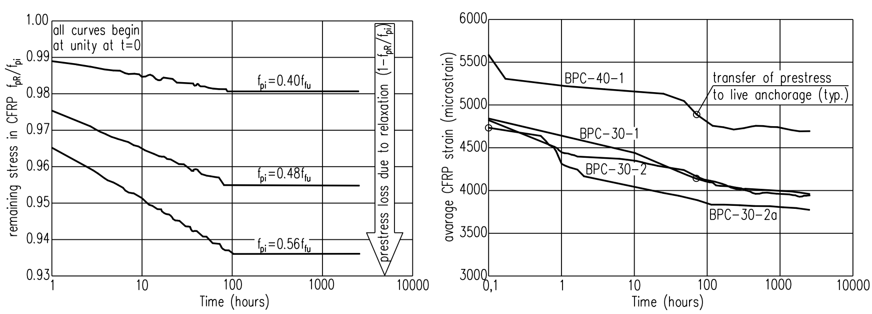
Fig. 2. Residual tensile load in FRP samples after 17 years of exposure: (a) with direct sunlight; (b) without direct sunlight (Sasaki and Nishizaki, 2012).

Wang et al. (2012) carried out an experimental study of flat CFRP samples subjected to sustained loading and flexural tests of RC beams strengthened with pre-tensioned CFRP to investigate long-term prestress losses. The test variables consisted of the pre-tensioning limit and different strengthening ratios. The relaxation tests of three samples under unidirectional tensile test were conducted with different initial loading corresponding to 40, 48, and 56% of the CFRP tensile strength (Table 3). The CFRP strain was kept constant over a period of 2,500h. Test results indicates that after first nonlinear decrease of prestressing force between the time from 0h to 100h the prestress loss change the behavior and the load decreased linearly. Nevertheless, the biggest drop of load was observed in the first phase and further decrease was negligible. In Fig. 3(a) the relaxation of samples during entire test period is shown.

Table 3. Reduction of CFRP strain registered in uniaxial tensile tests (Wang et al., 2012).

Specimen	F_{pi} [kN]	f_{pi} [MPa]	f_{pi}/f_{pu} [-]	Ratio of CFRP samples pre-tension remaining after 2500 h
CP-1	30.1	1294.5	0.40	0.978
CP-2	33.3	1553.4	0.48	0.941
CP-3	37.1	1812.2	0.56	0.934

F_{pi} – initial pre-tensioning force in CFRP, f_{pi} – initial pre-tensioning limit of CFRP, f_{pu} – CFRP tensile strength



(a) (b)

Fig. 3. Loss of pre-stressing force: (a) due to relaxation of CFRP samples depending on pre-tensioning limit in unidirectional tension test; (b) in strengthened before beam's loading (Wang et al., 2012).

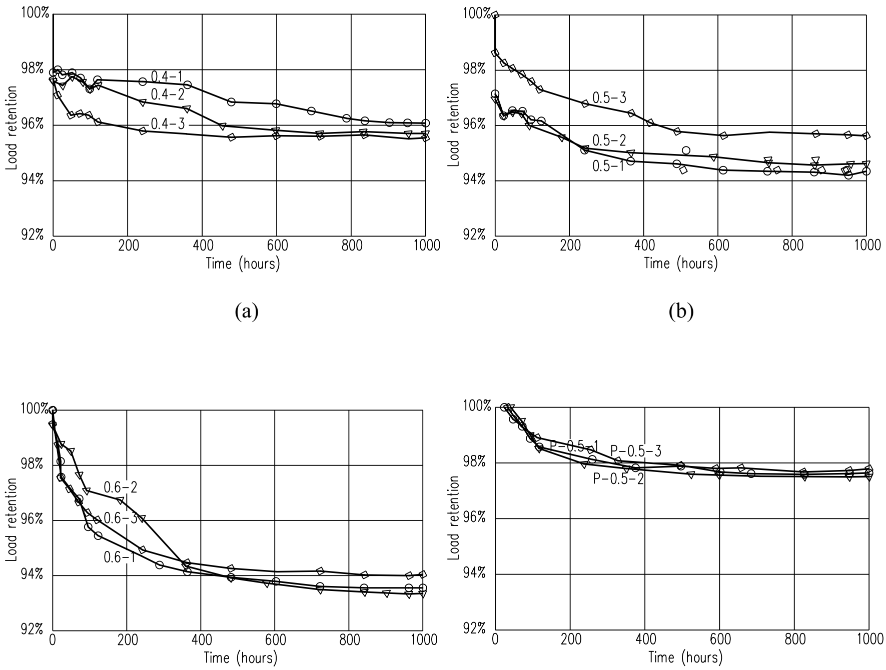
Second part of the experimental program was composed of eight RC beams in total strengthened with CFRP sheets externally bonded to the bottom surface of the specimens. For strengthening the same composite sheet was used as in the unidirectional tests. Six beams were strengthened with pre-tensioned CFRP sheets from which four were strengthened with one composite layer of 140 mm wide (BPC-30-1, BPC-40-1, BPC-50-1, BPC-60-1) and remaining two were strengthened with two composite layers (BPC-30-2, BPC-30-2a). The pre-tensioning limits of CFRP composites reached values of 30%, 40% , 50% and 60% in case of beams strengthened with one composite layer and 30% in both members strengthened with two composite layers. All members were initially preloaded to the value which represented 63% of flexural capacity due to damage simulation of existing structures. Therefore beams were unloaded and strengthened under dead load only. In all beams, except BPC-30-2a member, the hydraulic jack were kept with applied force for three days which were meant to effectively transfer the prestress to the anchorage and specimen. In specimen BPC-30-2a the prestressing force was immediately released for the purpose of investigation the influence of prestress transfer during epoxy curing on the relaxation loss. The estimated time-dependent loss based on the relaxation tests in specimens in which the adhesive was priming for 72 hours was approximately 2.2%. However, the obtained in the test losses reached value of 3.7% in comparison to the initial pre-tensioning load. In the specimen BPC-30-2a where the prestressing force was transferred on the RC beam before resin curing, the loss reached value of 2.3%. The higher prestressing loss was caused by creep of resin between concrete and CFRP sheet which was not investigated in the relaxation tests. The resin in specimen BPC-30-2a did not transfer any part of prestressing load, therefore no creep of resin could occur. The total loss of prestressing after 2500 hours was higher in specimen in which transfer of prestress was before the epoxy cuing (20.5%) than in specimens where the resin cured before the transfer (17.9%). Considering time-dependent losses the most part of loss was observed in the first 100 hours as in the relaxation tests. The increase of the pre-tensioning level from 40% to 50% of the FRP tensile strength resulted in the increase of the prestress loss from 2.2% to 6.6% of the initial prestressing load. The prestressing losses are primarily consisting of the initial losses which are mainly affected by the anchorage slip reaching values in the range of 12.6% - 18.2% of initial pre-tensioning force. However, the time dependent losses induced by creep and shrinkage of concrete and relaxation of CFRP are relatively small (from 2.3% to 3.9%). The mean values of the strains in the CFRP before and after transferring the prestress force to the anchors and after 2,500 h under conditions of no external load are presented in Table 4.

Table 4. Reduction of strain in CFRP registered in beam tests (Wang et al., 2012).

Specimen	f_{pi}/f_{pu} [-]	ε_f [με]			$\Delta\varepsilon_f$ [%]		ε_a [mm]
		A	B	C	B	C	
BPC-30-1	0.36	4860	4150	3960	14.6	3.9	0.99
BPC-40-1	0.40	5610	4910	4700	12.6	3.6	0.98
BPC-30-2	0.28	4840	4150	3970	14.2	3.7	0.96
BPC-30-2a	0.30	4760	3890	3780	18.2	2.3	1.20

f_{pi} – initial pre-tensioned limit of CFRP, f_{pu} – CFRP tensile strength, ε_f – registered strain in CFRP, $\Delta\varepsilon_f$ - obtained strain lost in CFRP, ε_a – slip in anchorage, A – CFRP strain immediately after pre-tensioning at the moment of anchoring, B – CFRP strain of CFRP sheet at releasing of the prestressing force (at transfer), C – CFRP strain after 2500 hours.

Shi J. et al. (2016) investigated the behavior of basalt fiber-reinforced polymer tendons subjected to three levels of initial stresses: $0.4f_u$, $0.5f_u$, and $0.6f_u$ (f_u -ultimate strength). Three specimens were tested in each test group. Moreover, the group of tests with the initial pre-tensioning equal to $0.6f_u$ maintained for 3 hours before the proper pre-tensioning (unloading) to the level of $0.5f_u$ was tested. This initial pre-tensioning was described as the optimum treatment of BFRP tendons. The total duration of each relaxation test was 1000 hours. The proposed test setup eliminated the impact of slippage at the anchor zone influencing the relaxation value. Based on the obtained test results it was found that relaxation increases with the increase of pre-stressing load, however during first 10 hours the relaxation values for different initial loads have no significant differences. During the stage from 10h to 480h, the relaxation rates for the initial stress of $0.6f_u$ are significantly greater than those for $0.4f_u$ and $0.5f_u$. At 1000h, the relaxation rates obtained in the tests were 4.2%, 5.3%, and 6.4% for stresses of $0.4f_u$, $0.5f_u$, and $0.6f_u$, respectively. All samples behave similarly. From comparison of curves in Fig. 4, two different stages of relaxation behavior are visible without distinction of pre-stressing level. First stage was characterized by rapid decrease of stress, whilst in the second stage the relaxation loss decreased with time. This regularity is caused by straightening of fibers with the viscoelastic deformation of the resin. Visible small fluctuations of the relaxation curves are the result of changes in the ambient temperature. Samples initially pre-tensioned and maintained to the value of $0.6f_u$ demonstrated lower decrease of load than without pre-tensioning treatment.



(a) (b)

(c) (d)

Fig. 4. Relaxation curves at different limits of initial stresses of (a) $0.4f_u$; (b) $0.5f_u$; (c) $0.6f_u$; (d) $0.5f_u$ after pretension treatment (Shi et al., 2016).

3. CONCLUSIONS

State of the art of the existing research on application of FRP prestressing to the concrete structures shown that prestress losses are affected by different factors as strength properties of used materials, ambient temperature, humidity, UV radiation, bond between FRP and concrete, type of anchorage and creep of the prestressing system. Two types of tests were considered in the paper: tensile tests of material samples and flexural tests on RC beams strengthened with pre-tensioned FRPs. The results indicated that the relaxation of FRP materials is strongly affected by the level of FRP pre-tensioning, type of fibers, loading history, environmental conditions and scale effect (size of specimens). Different types of fibers exhibit different behavior under sustained loading. A direct sunlight effects a relaxation of CFRP samples causing the increase in the final relaxation. This phenomenon does not concern the AFRP composites, which are resistant to the direct sunlight. The obtained results demonstrated that the increase in the relaxation of FRP composites is proportional to the increase in the pre-tensioning limit. However, the relaxation of aramid fibers tends to be irrespective of the initial applied stress. The carbon and aramid samples indicated that the loss of prestressing force between 3.5 and 17 years were almost negligible in the uniaxial tensile tests. The biggest drop of load was observed in the first 100 hours and further decrease was negligible. Glass fiber reinforced composites exhibit good relaxation properties at low stress values, however they are sensitive to creep. Although unidirectional FRP relaxation tests endure the FRP behavior they are sensitive to the additional creep and relaxation of the adhesive interface. Prestress losses registered in the RC specimens strengthened with CFRP composites glued to the concrete surface occurred in the first 100 hours after pre-tensioning and were negligible thereafter regardless of the initial prestress level. The time dependent prestressing losses depended on the relaxation of FRP materials and creep of the resin in the adhesive layer.

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SUMMARY:

This paper discuss the issue of pre-stress losses which occur in the FRP prestressed concrete structures. The prestress losses consist of immediate losses just after pre-tensioning of the FRP composite and time-dependent losses. Prestress losses are affected by different factors as strength properties of used materials, ambient temperature, humidity, UV radiation, bond between the FRP material and RC specimen, type of anchorage and creep of prestressing system. Two types of tests can be found in the available literature: material samples subjected to sustained uniaxial tension which verify the relaxation of FRP tendons (Wang et al., Sasaki and Nishizaki, Shi et al and Oskouei and Taleie) and flexural tests of RC beams strengthened with pre-tensioned FRPs (Wang et al.). Authors considered different types of composites: carbon (Wang et al, Sasaki and Nishizaki, Oskouei and Taleie), aramid (Sasaki and Nishizaki, Oskouei and Taleie), glass (Sasaki and Nishizaki), vinyl (Sasaki and Nishizaki) and basalt (Shi et al.). According to obtained results, the relaxation of FRP materials is affected by level of pre-tensioning, types of fibers, loading history, environment and size of samples. For most FRP composites, the viscoelastic nature is affected by matrix. To overcome this drawback and reduce the level of relaxation, FRP materials are reinforced with different types of fibers which exhibit different behavior under sustained loading. Although, carbon fibers reveal negligible viscoelastic behavior, when mix with viscoelastic matrix, they manifest relatively small relaxation. It should be noted that the test results are heavily dependent on the ambient temperature. The direct sunlight influences the relaxation behavior of CFRP samples causing the increase of the relaxation limit. This regularity does not concern the AFRP composites, which are resistant for direct sunlight. Obtained results demonstrated that the increase in the relaxation of FRP composites is directly proportional to the increase of the pre-tensioning limit. However, the relaxation of aramid fibers tends to be independent of the initial applied stress. Considering the carbon and aramid samples the loss of prestressing force between 3.5 and 17 years was almost negligible in the uniaxial tensile tests. Test results indicated that the biggest drop of load was observed in the first 100 hours and further decrease was negligible. The prestress loss progress in the nonlinear manner during this first phase. BFRP tendons are recommended to be applied at an initial stress of $0.5f_u$ after pretension treatment. BFRP samples initially pre-tensioned and maintained to the value of $0.6f_u$ demonstrated lower decrease of load than without pre-tensioning treatment. Tests showed that glass fiber reinforced composites exhibit good relaxation properties at low stress values, however these rods are sensitive to creep. The obtained values of relaxation loss after 17 years of exposure for different FRP types were equal to: for CFRP: 10-20% without direct sunlight and 20-30% with direct sunlight, for AFRP: 20-30% irrespective of direct sunlight, for GFRP: around 10% under $0.25P_u$ tensile stress, however, all samples loaded to $0.4P_u$ ruptured by creep behavior. Although direct unidirectional FRP relaxation tests capture the FRP behavior they cannot capture the additional creep and relaxation associated with the adhesive bond line. Prestress losses registered in the RC specimens strengthened with CFRP composites glued to the concrete surface occurred in the first 100 hours after pre-tensioning and were negligible thereafter regardless of the initial prestress level. The time dependent prestressing losses in this case were dependent on the relaxation of FRP and creep of the resin as the connection between the composite and concrete. The initial losses could be reduce by bonding the composite to concrete surface before transferring the prestress force on the RC member. This should involve the part of the composite between the anchorages to transfer the prestressing directly to the member and reduce the slippage in the anchorages.