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Creep Behaviour and Residual Flexural Capacity of GFRP and CFRP Pretensioned Concrete Slabs

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Abstract - **The objective of this study is to examine the flexural behaviour of concrete slabs pretensioned withdomestic Glass Fibre Reinforced Polymers (GFRP) and Carbon Fibre Reinforced Polymers (CFRP) under sustained loading. In order to achieve this, set of twoconcrete slabs 4.5 meter long were examined. Concrete slabs were pretensioned with four and five reinforcing bars (rebars) in case of GFRP and CFRP reinforcement, respectively. Set of additional eleven slabs was casted for quasi-static loading. Quasi-static loading was performed in order to verify flexural capacity and to check residual flexuralcapacity of the slabs after sustained loading. It was verified experimentally that GFRP pretensioned concrete slab is not suitable for long-term loading due to massive deflection evolution in time. On the other hand CFRP pretensioned slab showed reasonable flexural behaviour in terms of deflection evolution and crack propagation. It was also concluded that sustained loading has no significant effect on flexural capacity of the both FRP pretensioned concrete slabs.**

Keywords: **Carbon, Concrete, Creep,Fibres, Flexure, Glass, Pretensioning**

I. INTRODUCTION

Prefabricated and pretensioned concrete slabs are very often used elements in administrative building or warehouses where quick installation is necessary. It consists only from the main longitudinal pretensioned steel tendons with no other structural reinforcement.Steel reinforcement has its reasonable strength and ductility. On the other hand it often suffers from corrosion. Slabsand panels especially in the industrial warehouse could be loaded by aggressive environment and therefore steel can suffer. This generally ends up with formation of corrosive product which is accompanied with additional spalling and cracking of concrete. Industrial warehouses are very often highly loaded structures which can lead to some long-term unacceptable deflections. FRP is corrosion proof by nature therefore is well suitable as internal reinforcement where aggressive environment is on everyday order. FRP reinforcement has in general higher strength than ordinary steel and lower elastic modulus. The most effective way to use full capacity of the FRP bars,to 'remove' much of the initial strain capacity and to improve serviceability, which usually is the governing criterion in design, is to pretension the FRP bars (Ibell *et al.,* 2009).

Stress-strain diagram of FRP reinforcement differs rapidly from the conventional steel reinforcement. Steel has its reasonable ductility but FRP reinforcement have no yield point and no plastic plateau. Stress-strain diagram of FRP reinforcement is therefore linear elastic up to the brittle rupture of the bar. However final materials characteristics of FRP rebar are significantly depended on the manufacturing process where fibres and matrix are coupled. This is mainly percentage of the fibres in the bar which in the case of pultrusion can vary from 43 % till 83 %. This significantly influences final material characteristic as tensile strength and modulus of elasticity.

Sa *et al.* (2011) conducted research on creep behaviour of pultruded GFRP elements. They reported that small-scale specimens have failed for load levels as low as 50% of the ultimate stress. In addition the creepocity was quite significant after the first hours, even for an average load level of 30%.

Shang *et al.* (2010) examined reinforced concrete beams with pre-stressed CFRP with tensile strength 2510 MPa and elastic modulus 165 GPa. They concluded very small creep of domestic carbon fibres and thus they recommended this reinforcing material as reinforcement for concrete beams.

Zou and Shang (2006) presented a theoretical framework for time-dependent concrete strains, curvature and deflection calculations. They concluded that CFRP can be used as internal prestressing tendons in structural concrete with acceptable level of long-term performance in terms of deflection, curvature and concrete strains.

A. Research Significance

Composite reinforcement is relatively new material and it has a potential to be widely applied in structures where special properties such as corrosion resistance or magnetic wave transparency are required. In fact, FRP reinforcement has been implemented in several structures all over the world. However, composite materials, including FRP, are highly dependent on the production technology and process. Therefore every producer creates a unique product which is very similar to products of other producers but not exactly the same – feature that reminds uniqueness of fingerprints. FRP bars consist of two main components - fibres and matrix. Every component can be chosen accordingly to the specific needs of a customer. This gives the much needed adjustability and variability of building materials. Moreover the final characteristics of the entire bar will be different than characteristics obtained by simple summation of properties of fibres and matrix. This effect is called synergism.

Domestic GFRP reinforcement had strength equals to 650 MPa and CFRP reinforcement had its extraordinary strength equals to 2000 MPa. On the other hand elastic modulus is typically lower than that of steel. GFRP had elastic modulus equals to 42 GPa which is 20% of steel reinforcement. Elastic modulus of CFRP was equal to 120 GPa. Volume friction of the fibres in the rebar was 73% (Figure 1).

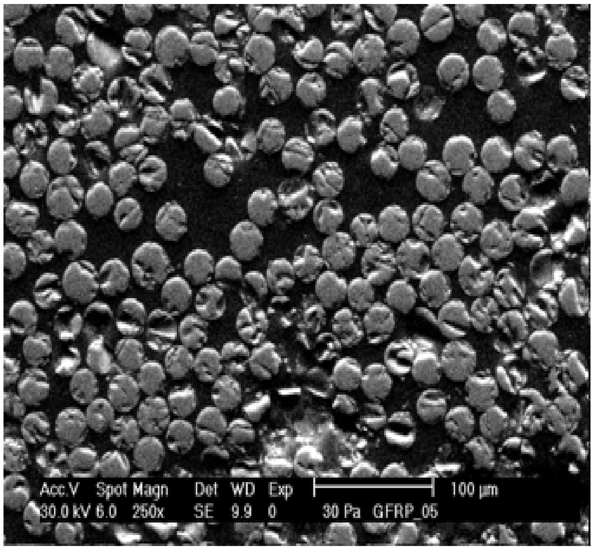

Fig. 1 Glass fibres and matrix distribution over the domestic rebar cross-section with 14 mm in diameter

To utilize high tensile strength and high strain capacity of FRP bars it is extremely useful to prestress the bars (Ibell et al., 2009).Based on these facts it is important to conduct extensive research in this specific area in order to describe, clarify and completely understand behaviour of concrete structures pretensioned with domestic FRP reinforcement.

II. EXPERIMENTAL PROGRAM

In this way experimental program was consisting of 13 concrete slabs 4.5 m long with 4.0 m clear span. Cross section of the slabs was 600 x 200 mm. All FRP pretension slabs were consisting only from the main pretension rebars and no other reinforcement was provided along the slabs.First four slabs were pretensioned with 4 GFRP rebars with diameter 14 mm each. Other nine slabs were pretensioned with 5 CFRP rebars with diameter 6 mm each. Distance from the centroid of the slab to the centroid of the pretensioned rebars was exactly 50 mm in both cases. All FRP rebars were supplied by the local manufacturer.After the FRP tendons were pretensioned, concrete was casted in the moulds and vibrated. Each slab was properly cured by moisturising its surface until testing. After 14 days prestressing force was released in to the slabs. After 28 days from casting, the slabs were tested in four point bending test or subjected to sustained loading.

A. *Material Properties*

Before the loading tests were performed mechanical characteristics of material used during the research were determined. The elastic modulus, the modulus of rupture and the compressive strength of concrete were determined. 300 mm high cylinders with 150 mm in diameterwere used to determine the elastic modulus. 100x100x400 mm sized beams were used for the modulus of rupture measurements. Cubes of 150 mm were used for the determination of the ultimate compressive strength. The average of these measurements are summarized in Table1.

TABLE I MATERIAL CHARACTERISTICS OF USED CONCRETE

	Age of concrete	
	14th day	28th day
Compressive strength [MPa]	32.3	42.8
Modulus of rupture [MPa]	3.7	4.7
Modulus of elasticity [GPa]	32.0	35.7
Density [kg/m^3]		2350

Material characteristics of the FRP bars were given by the local manufacturer and were not verified experimentally. Values are shown in the Table II.

TABLE II MATERIAL CHARACTERISTICS OF FRP REBARS USED

	GFRP	CFRP
Tensile strength [MPa]	650	2000
Modulus of elasticity [GPa]	42	120
Surface	Sand-coated	

B. *Pretensioning Procedure*

The pretensioning procedure was relatively simple. A wooden mould was constructed on the floor of the lab and FRP tendons were inserted inside. The FRP tendons were 6 m long with resin filled anchors at both ends. The anchors were inserted into a fixed holder on one side of the mould and on the other side they were gripped into specially developed jacking mechanism (Figure 2). This mechanism consisted of anchor holder and a screw steel bar. During the pretensioning procedure a load transducer cell was attached to the end of the screw bar and the bar was tightened with a moment inducing wrench. When the tensile force measured by the load transducer reached 32.3 kN and26.8 kN which corresponds to the stress 210 MPa and 950 MPa in the GFRP and CFRPrebar, respectively, the pretensioning procedure was finished (Table 3). After that the screw bar was fixed in its position by a female screw.

C. *Quasi-Static Loading Tests*

Three slabs pretensioned with GFRP rebars and eight slabs pretensioned with CFRP rebars were tested in four point bending test. Tested slabs were 4.5 m long with a clear span of 4 m. The loading points were approximately in thirds of the span, thus the constant moment region was exactly 1.4 m. The setup of the experiment is shown on Figure 3.

TABLE III CROSS SECTIONS

	GFRP	CFRP
Dimension of the cross -section (b x d) [mm]	600 x 200	
Number of tendons	4	5
Diameter of tendons [mm]	14	6
Pre-tensile force per tendon [kN]	32.3	26.8
Pre-tensile force per slab [kN]	129.2	134.0
Eccentricity of tendons from the top of the cross-section [mm]	150	

Fig. 2 Jacking mechanism with
load cell attached to the end of the screw bar

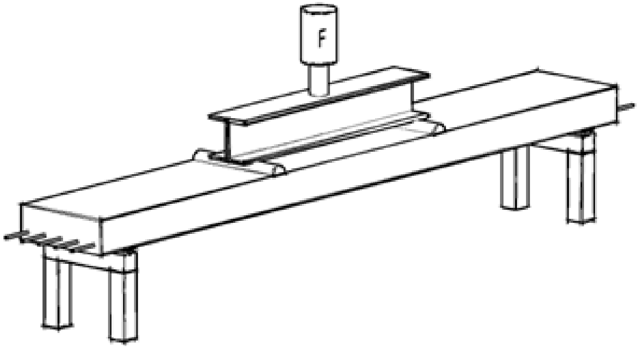

Fig. 3 Experimental setup of quasi static – four point bending test

D. Creep Tests

One GFRP pretensioned slab and one CFRP pretensioned slab was subjected to sustained loading for one year. The sustained load was formed by two 10 kN weights The slabs were pretensioned to the same level as in the previous cases. Weights were placed on the slab as it is shown on the Figure 4 where distance between weights was 1400 mm. Weights represented 158% of dead weight which is typical for heavily loaded industrial slabs. Magnitude of two applied weights was designed in order to cause tension at the bottom of the cross-section in the mid-spanwhere the tension was required to be smaller than tensile strength of the concrete. No other reinforcement than pretension rebars (tendons)was in the slab.The concrete slabs were provided with four vibrating wire strain gauges in order to measure the strain evolution in time. A couple of these were placed at the mid span 50 mm from the upper side and 50 mm from the bottom of the cross-section. Another couple was placed at the support cross-section at the same vertical levels.Three deflection sensors were placed along the slab from the bottom. Two of these were placed under the weights and the third one was placed in the middle of the span from the bottom side of the cross section. Readings were taken manually in the regular time intervals. Prestressing force was released into the slabs when concrete was 14 days old. The sustained load formed by two 10 kN weights was applied on the slab on day 28 in case of GFRP and on the day 49 in case of CFRP. The delay in case of CFRP was caused due to technical problems in the lab.

Four concrete cylinders were casted from the same batch in order to record the shrinkage of the concrete. One vibrating wire strain gauge was placed in each cylinder. Cylinders and both slabs were kept in the laboratory environment, i.e. 20 °C, RH 50%.

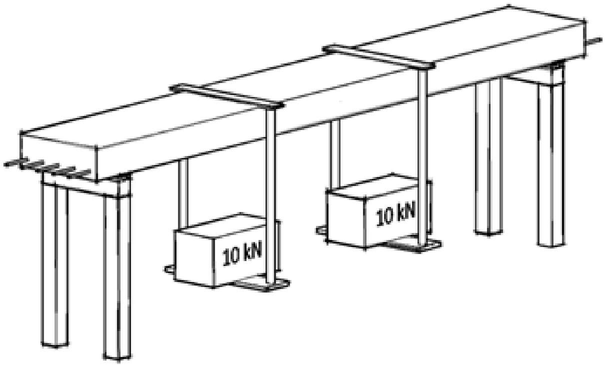

Fig. 4 Experimental setup of the creep test formed by two 10 kN weights

III. TESTS RESULTS AND DISCUSSION

A. Quasi-Static Loading Tests

The load-deflection diagram of concrete members pretensioned with CFRP and GFRP bars is bilinear. The first part, so-called un-cracked elastic is typical for small increments of deflection within rising bending moment. The second linear part is called cracked-elastic. It is expected that the tensile stress is carried solely by the reinforcement. Because of the linear-elastic behaviour of FRP bar the second part of the stress-strain diagram is also liner-elastic.

1. GFRP Pretensioned Concrete Slabs

As rather big deflections were observed during the experimental procedure it is evident that the serviceability limit state will be the limiting factor when designing concrete members with GFRP reinforcement. Maximal service deflection is specified in EC2 as a 1/250 of the clear span which is in our case 16 mm. In this way it can be seen at Figure 5 that right after cracked-elastic part begins service condition is reached so slightly more than half of the flexural capacity can be utilized for design.

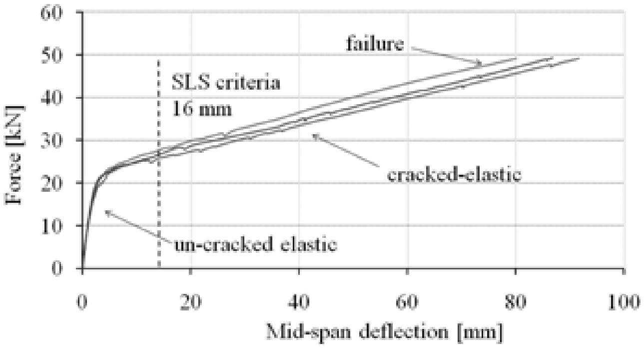

Fig. 5 Force - Mid-span deflection diagrams of the three GFRP pretensioned concrete slabs till failure

The flexural capacity of GFRP pretensioned slabs varied from 48.9 to 49.1 kN with corresponding deflections that varied from 80 to 91 mm (Figure 5). Slabs failed due to the rupture of the pretensioned GFRP rebars.

2. CFRP Pretensioned Concrete Slabs

Pretensioning of CFRP bars benefits from its high tensile strength and slabs therefore performs significantly better in terms of deflection and crack development compared to non-prestressed elements. Slabs also failed due to the brittle rupture of the pretensioned CFRP rebars (Figure 5).Serviceability limit state was also reached prior to the ultimate flexural capacity of the slab.

The flexural capacity of CFRP pretensioned slabs varied from 53.6 to 64.0 kNwith corresponding deflections that varied from 67 to 87 mm (Figure 5). The main crack causing the collapse of a slab was located in each case in between acting forces i.e. at the place where maximal bending moment occurred. The vertical slope of the cracks pointed out the flexural behaviour without any significant affection by shear. Prior to the failure ample warnings were observed in terms of large deflections and crack propagation. CFRP pretensioned concrete slab failed due to the rupture of the pretensioned rebars.

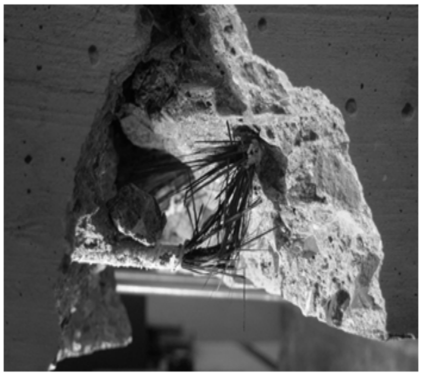

Fig. 6 Brittle failure of the CFRP pretensioned rebar in the concrete slab

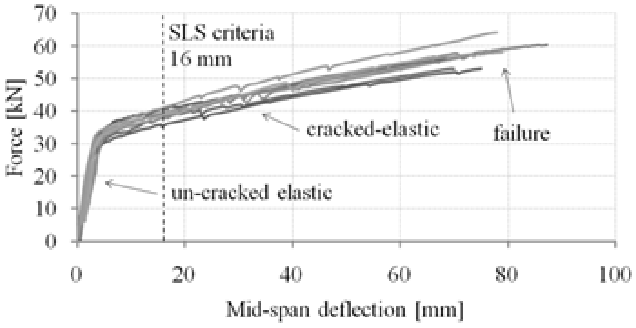

Fig. 7 Force - mid-span deflection diagrams of the eight CFRP pretensioned concrete slabs till failure

From the results of the quasi static loading tests a magnitude of the sustained load was confirmed. As mentioned above tension in concrete at the bottom of the cross section in the mid span was required. Moreover this tension should be smaller than the tensile strength of the concrete so no cracks should be present after the sustained load is applied on the slab. 2x10 kN sustained load is still on the un-cracked elastic part of the Force – Mid-span deflection diagram on both figures dealing with GFRP (Figure 5) and CFRP (Figure 7) pretensioned slabs.

B. *Creep Tests*

One vibrating wire strain gauge was placed in each of four cylinders in order to record shrinkage of the concrete. Cylinders as well as slabs were kept at the same laboratory environment.

The average reading from all vibrating wire strain gauges was -312.611 µ m/m, -404.245 µ m/m, -471.024 µ m/m, -506.346 µ m/m and -528.846 µ m/m in 50th, 100th, 200th, 300th and 400th day, respectively.

1. *GFRP Pretensioned Concrete Slab*

Uniform constant load was applied to a 28-day-old slab pretensioned with GFRP rebars. Deflection was measured with three analogue deflection gauges along the slab under the weights and in the mid-span. The initial elastic deformationwas 2.65 mm measured in the middle of the span of the slab. This deflection, however, was related only to the sustained load and not to the dead-load or pretensioning.The time dependent mid-span deflection of the GFRP pretensioned slab reached the value 8.97 mm, 13.29 mm, 17.10 mm and 18.55 mm which makes the ration to the initial elastic deformation 4.44, 5.43, 6.75 and 7.10 in 50th, 100th, 200th and 300th day, respectively. After a year under the sustained load the ratio was 7.49 which was determined from thedeflection reading 19.86 mm (Figure 9). Eurocode 2 specifies maximal service deflection to 1/250 of the clear span which is 16 mm in our case. In this way SLS criteria were overstepped in 135th day from loading and 163rd day from concrete casting. The massive increase of the deflection in time could be explained by high stress relaxation of the GFRP tendon itself. Fornůsek and Konvalinka (2010) reported very high stress relaxation in domestic GFRP prestressed rebars based on the experimental result. Most likely high relaxation is the reason for the massive increase of deflection in time which may lead to the creep rupture of the GFRP rebars. Furthermore deflection evolution was recorded under the weights which were 650 mm from the mid span. The average from both readings was 7.37

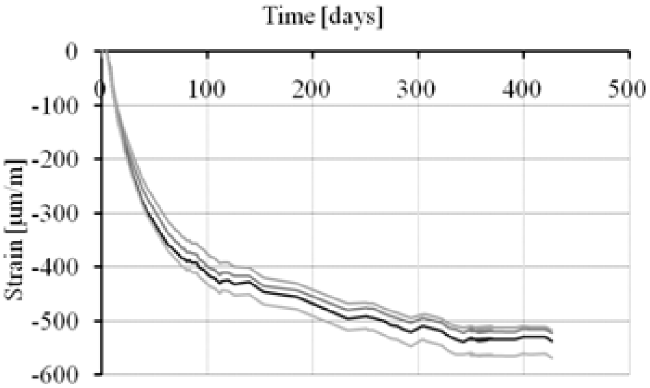

Fig. 8 Shrinkage evolution in time measured on concrete cylinders

mm, 10.96 mm, 14.16 mm and 15.38 mm in 50th, 100th, 200th and 300th day, respectively. The initial average elastic deflection was 2.23 mm and the ultimate deflection after the year was 16.45 mm (Figure 9).

The initial elastic strainat the mid-span from the sustained load application was -59.645 µ m/m and 62.889 µ m/m in the upper and lowergauge, respectively. The time dependent to initial strain ratio was in the case of upper gauge determined as3.47, 6.03, 8.30 and 9.59 in 50th, 100th, 200th and 300th day, respectively. The ultimate recorded strain after a year under sustained loading was -623.172 µ m/m which make ration equals to 10.45 (Figure 10).In the case of the lower gauge the time dependent to initial strain ratio was 3.54, 6.73, 10.21 and 11.06 in 50th, 100th, 200th and 300th day, respectively. The ultimate recorded strain after a year under sustained loading was 796.322 µ m/m which makes the ration of time dependent to initial strain equals to 12.66 (Figure 10). Readings from gauges placed above the support were related mainly to the shrinkage of the concrete and creep from the pretensioning force. At the end of the year the readings were -328.355 µ m/m and - 392.252 µ m/m in the upper and lower gauge,

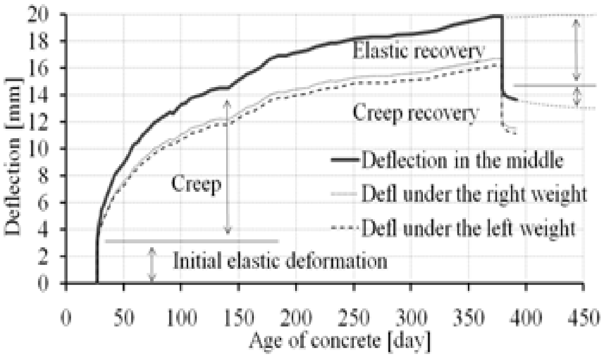

Fig. 9 Deflection evolution in time of GFRP pretensioned slab after one year of continuous loading with unloading and creep recovery

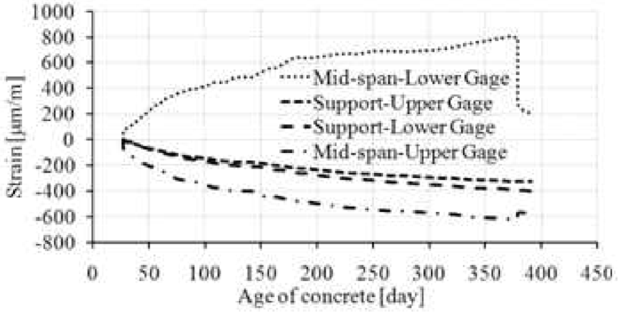

Fig.10 Strain evolution in time of GFRP pretensioned slab after one year of continuous loading with unloading and creep recovery

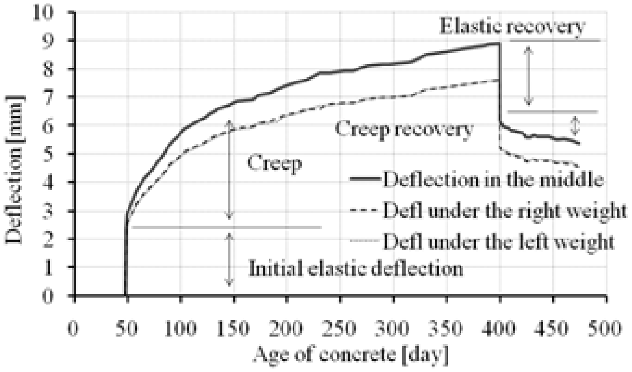

Fig.11 Deflection evolution in time of CFRP pretensioned slab after one year of continuous loading with unloading and creep recovery

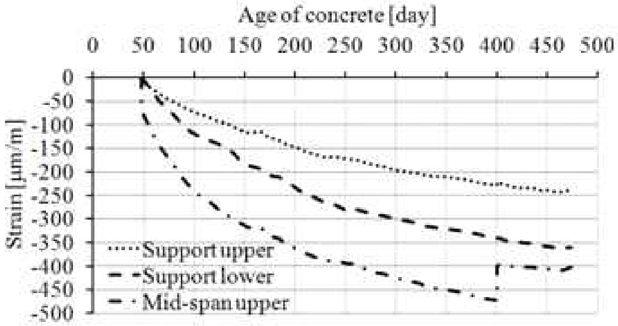

Fig. 12 Strain evolution in time of CFRP pretensioned slab after one year of continuous loading with unloading and creep recovery

The creep rate was taken from the secondary creep, so-called steady-state creep in which there is a balance between work hardening and recovery process. It led to a minimum constant creep rate. The creep rate of the GFRP prestressed slab was determined as 0.012 mm/day which is equal to $4.86 \cdot 10^{-4}$mm/hr and 1 mm per 86 days.

After a year the uniform sustained load was removed which is indicated in the Figure 9 as a elastic recovery. Right after the sustained load wasremoved, slab was subjected to the quasi static four point loading test following the static loading scheme with 4 meter clear span and 1.3 meter constant moment region. Force deflection diagram followed bi-linear trend which is typical for FRP reinforced or prestressed members. Maximal measured force was 60.6 kN with corresponding mid-span deflection equals to 96 mm (Figure 14 –Creep GFRP).

2. CFRP Pretensioned Concrete Slab

The sustained load was applied to 49-day-old CFRP pretensioned concrete slab. The delay of the sustained load application was caused due to some technical problems in the lab. Initial elastic deflection was 2.37 mm after the application of the sustained load. This deflection, however, was related only to the sustained load and not to the dead-load or pretensioning. The CFRP prestressed slab reached time dependent initial deflection ratios 2.47, 3.15 and 3.63 in 100th, 200th, and 300th day from loading, respectively (Figure 11).

After a year the loading interval deflection was 8.90 mm, representing multiple of 3.76 to the initial elastic deformation and multiple of 1/450 to the clear span. Small cracks were observed within the frame of the loading interval. Maximal measured crack width was 0.05 mm at the end of the creep test while average crack spacing over the constant moment region was circa 200 mm. Moreover deflection evolution was recorded under the weights which were 650 mm from the mid span. The average from both readings was 4.83 mm, 5.79 mm, 6.79 mm and 7.36 mm in 50th, 100th, 200th and 300th day from the day of sustained load application, respectively. The initial average elastic deflection was 2.11 mm and the ultimate deflection after the year was 7.60 mm (Figure 11).

Shang *et al.* (2010) and Meier *et al.* (2009) both reported very small and rather technically insignificant creep of carbon fibres. This may lead to the very convenient time dependent flexural behaviour compared to the GFRP pretensioned case where stress relaxation is rather excessive (Fornůsek and Konvalinka, 2010). The creep rate was taken from the secondary creep, which led to a minimum constant creep rate. The creep rate of the CFRP prestressed slab was calculated to the 0.010 mm/day which is equal to $4.25 \cdot 10^{-4}$ mm/hr and 1 mm per 98 days. After unloading elastic recovery was measured to be 2.27 mm which is 0.1 mm less than initial elastic deformation (Figure 11).

The initial strain was - 53.4 µm/m when measured 50 mm from the upper side of the mid-span cross-section. This initial stress, however, was related only to the sustained load and not to the deal load or pretensioning. After one year the ratio of the accumulated strain to the initial strain was 8.86. Consequently the strain was -473.241 µ m/m at the end of the loading interval. The ratio of the initial to the time-dependent strain was 5.77, 7.40 and 8.42 in 100th, 200th, and 300th day from the application of the sustained load, respectively. After the sustained load was removed the value of elastic strain recovery was measured to be - 68.70 µm/m (Figure 12).

The vibrating wire strain gauges above the support were affected mainly by the pretensioning force. No additional strain was visible when sustained load was applied on the slab. On the day of removing the sustained load the recorded values were -224.1 µ m/m and -340.1 µ m/m for upper and lower gauge, respectively. Unfortunately lower vibrating wire strain gauge in the mid-span broke down due to some reason and therefore is not plotted in the figure.

When the creep test was over the slab was subjected to the four point loading test. Force-deflection diagram of the slab is plotted against force-deflection diagrams of specimens loaded only at the quasi-static test (Figure 13).

No significant reduction of the flexural capacity was observed after one year of continuous loading. The ultimate force was 54.8 kN with deflection equal to 70 mm (Figure 14 – Creep CFRP).

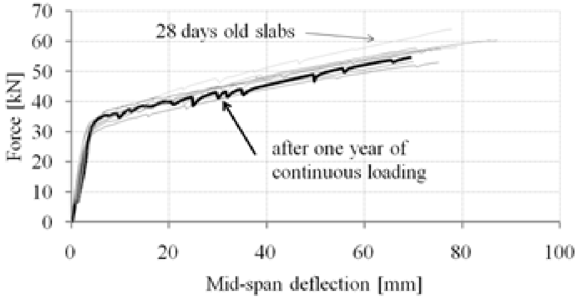

Fig. 13 Force - mid-span deflection diagram of the CFRP pretensioned concrete slabs after one year of continuous loading till failure compared with 28 days old slabs

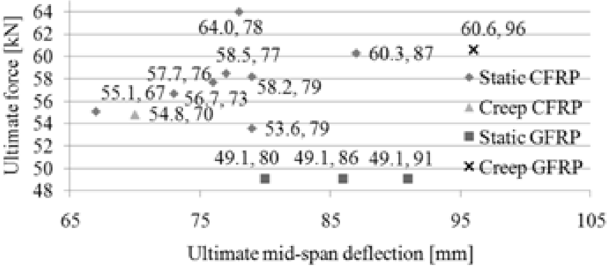

Fig. 14 Scatter of ultimate flexural capacities in terms of force-mid-span deflectionof slabs with different age and loading history

IV. CONCLUSIONS

Based on the executed experimental work and its outcomes in this particular study one may conclude the following:

- Force deflection diagram of the GFRP and CFRP pretensioned concrete slabs is bilinear up to the brittle rupture of the composite tendon,
- Massive creepocity in the initial days was observed in the GFRP pretensioned concrete slab due to the high relaxation of the pretensioned glass fibres,
- Reasonable increase of deformation wasobserved in the CFRP pretensioned concrete slab due to the insignificant stress relaxation of the pretensioned carbon rebars,
- Deflection increments in both cases tends to reduce with time
- No significant reduction of the flexural capacity was observed after a one year under the sustained loading in case of GFRP and CFRP pretensioned slabs, respectively.

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