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Experimental Stress Analysis

Flexural capacity of the CFRP prestressed concrete slabs subjected to sustained & fatigue loading

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Abstract: The behaviour of concrete slabs with prestressed carbon fibre reinforced polymer (CFRP) composite bars is investigated in this paper. The main advantage of CFRP bars is their high strength/self-weight ratio. On the other hand, Young's modulus is lower compared to steel reinforcement which is the main cause for large deflections. To eliminate such deflections and to utilize high tensile strength of CFRP bars it is extremely useful to prestress the bars. During the experimental work a set of fifteen 4.5-metre-long concrete slabs were casted. Each slab was prestressed with five CFRP bars. Eight slabs were subjected to static - four point bending test. Six slabs were subjected to fatigue and one slab was subjected to sustained loading for one year. The load-deflection diagram of a CFRP prestressed slab is traditionally bi-linear up to the rupture of the prestressed CFRP bars. It was verified experimentally that high-cycle fatigue has no significant effect on the flexural capacity of the slab. The long-term investigation showed suitable behaviour of CFRP prestressed slab under heavy sustained load.

Keywords: Concrete, CFRP, Creep, Fatigue, Prestressing, Slab

1. Introduction

Fibre-reinforced polymer (FRP) reinforcement is corrosion resistant by nature. Hence it can be successfully used in highly corrosive environments such as bridge decks, off-shore structures and slabs in chemical factories where high corrosion resistance is required. Furthermore, FRP reinforcement has other valuable properties such as magnetic transparency, thermal non-conductivity and generally higher tensile strength than steel.

The behaviour of FRP bars, however, is different than that of steel and is highly dependent on the type of fibre and the production process [1], [2]. FRP reinforcement is linear-elastic up to the failure and its elastic modulus is typically lower than that of steel. For instance, the FRP bars reinforced with carbon fibres (CFRP) have typically a modulus of elasticity which is of 50% of that of steel. Furthermore, there are FRP bars with various surface textures available on the market and every producer makes a unique type of bar. For this reason the design of the structures reinforced with FRP bars must be approached with maximal caution.

As mentioned above the low elastic modulus is the determinant issue that needs to be considered when designing concrete structures reinforced with CFRP bars. The main problem

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is that the overall stiffness of the CFRP reinforced concrete member decreases significantly after concrete cracks in the tension zone [3].

One of the methods to eliminate unacceptable deflections on the serviceability limit state (SLS) is the pretension of CFRP reinforcing bars. This paper describes static, fatigue and creep analysis of concrete slabs that are prestressed with CFRP bars.

2. Experimental procedure

Experimental work was conducted in laboratories of Experimental Centre in the faculty of Civil Engineering, Czech Technical University in Prague. Set of 15 slabs was casted. All slabs were casted from the same batch and prestressed to the same force. Each slab was prestressed with five CFRP bars with diameter of 6 mm. The bars were pretensioned to 950 MPa which corresponds to the force 26.8 kN per a CFRP bar and which is 47.5% of its tensile strength. Eccentricity of the pretensioned CFRP bars was 50 mm from the centroid of the slab, thus the clear cover of the CFRP bars was 47 mm. There was no shear reinforcement or upper reinforcement provided in the slabs.

Eight slabs were subjected to four point bending test; six slabs were subjected to high-cycle fatigue and after that to the four point bending test (Fig. 1). One slab was subjected to sustained loading for one year (Fig. 2).

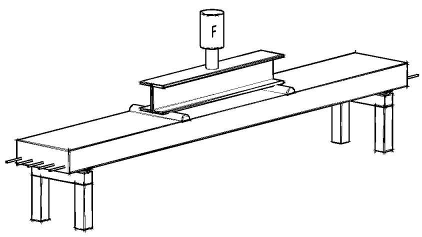

Fig. 1. Static and fatigue loading scheme

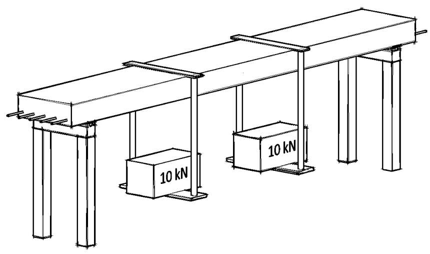

Fig. 2. Sustained loading scheme

2.1. Pretensioning procedure

The pretensioning procedure was relatively simple. A wooden mould was constructed on the floor of the lab and CFRP tendons were inserted inside. The CFRP 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. This mechanism consisted of anchor holder and a screw steel bar (Fig. 4). 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 26.8 kN which corresponds to stress 950 MPa in the CFRP bar, the pretensioning procedure was finished. After that the screw bar was fixed in its position by a female screw.

2.2. Static test

Eight slabs prestressed with CFRP bars were tested in four point bending test. The 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 1400 mm.

After the CFRP 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. At the beginning of the experimental procedure each slab was loaded twice to 30% of its calculated ultimate strength. After the two cycles, the loading force was increased in constant force increments until the failure. Deflections were measured with standard deflection gauges in the middle of the span and under the loading points. Strain gauges were attached at the bottom and on top of the slabs.

2.3. Fatigue

The high cycle fatigue loading test was performed on six slabs. The force ranging from 3 to 20 kN (F/2 = 1.5 to 10 kN) was following sinus signal and was acting on each slab. Consequently stresses were low and deformation primarily elastic. Force was acting on the slab at 4Hz frequency. In total $1.2 \cdot 10^6$ cycles were executed on each slab. After the cycles were executed, static loading test was performed on each of the slabs. No preloading was preformed this time. The four point bending test was driven by the force with the speed of 1.25 kN/min until failure of the slab. Deflection was measured in the same manner as in the previous case i.e. with the standard deflection gauges at the mid-span and under the loading points.

2.4. Creep

The sustained load was formed by two 10 kN weights (F/2 = 10 kN). The slabs were prestressed to the same level as in the previous cases. Weights represented 158% of dead weight which is typical for heavily loaded industrial slab. Magnitude of two applied weights was designed in order to cause tension at the bottom of the cross-section where the tension was required to be smaller than tensile strength of the concrete.

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.

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 49.

2.5. Material characteristics

Before the loading tests were performed exact mechanical characteristics of materials used during this research were determined. This was necessary for eliminating the number of variables. The elastic modulus, the modulus of rupture (MOR) and the compressive strength of concrete were measured. 100x100x400 mm – sized beams were used for the modulus of elasticity and MOR measurements. Cubes of 150 mm were used for the determination of the ultimate compressive strength. The average results of these measurements are summarized in Table 1.

Concrete characteristics were measured on day 14, when the prestressing force was released into the slabs. Other measurements were done on day 28, as common.

Table 1. Material characteristics of used concrete

Age of concrete	14^{th} day	28^{th} day
Compressive strength [MPa]	32.3	42.8
Modulus of rupture [MPa]	3.7	4.7
Modulus of elasticity [MPa]	32 000	35 700
Density [kg/m3]	2350	2350

The batch consisted of 343 kg/m^3 of cement, 1786 kg/m^3 of aggregate and 175 kg/m^3 of water. Maximal size of the aggregate was 16 mm.

Furthermore, the basic properties of CFRP such as the modulus of elasticity and the stress-strain diagram were determined. The tensile strength was defined by the producer and was not revised by the researchers. These material characteristics are compared with standard steel properties in Table 2. The CFRP bars were produced by a local manufacturer Prefa Kompozity, a.s.

Table 2. Material characteristics of CFRP bar in comparison with steel

	CFRP	Steel B500
Tensile strength [MPa]	2000	500
Modulus of elasticity [GPa]	120	210
Stress-strain diagram	Linear-elastic	Bilinear with hardening
Fibres to matrix ration	75:25	N/A
Surface characteristic	Grain covered	Ribbed

3. Results

The stress-strain diagram of concrete members reinforced with CFRP bars is bilinear (Fig. 3). 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 CFRP bar the second part of the stress-strain diagram is also liner-elastic.

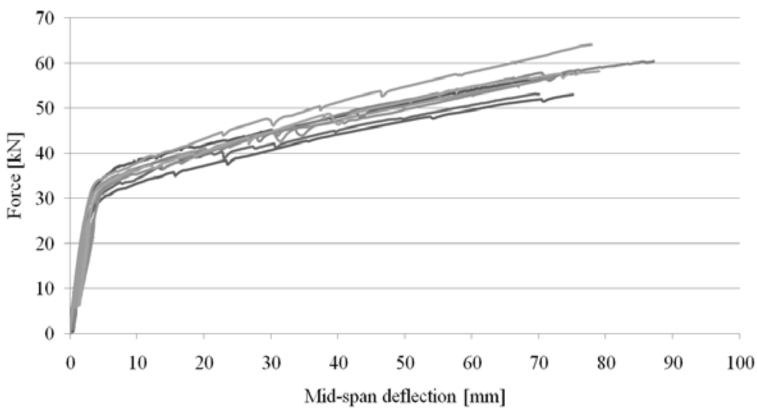

Fig. 3. Force- deflection diagram

3.1. Static

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 CFRP reinforcement.

Pretensioning of CFRP bars benefits from the high tensile strength of CFRP and performs significantly better in terms of deflection and crack development compared to non-prestressed elements. Slabs failed due to the rupture of the CFRP bars (Fig. 5). The flexural capacity for non-fatigue loaded slabs varied from 53.6 to 64.0 kN with corresponding deflections that varied from 67 to 87 mm. 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 moment occurred. The vertical slope of the cracks pointed out the flexural behaviour without significant affection by shear. The slabs failed suddenly without previous warning.

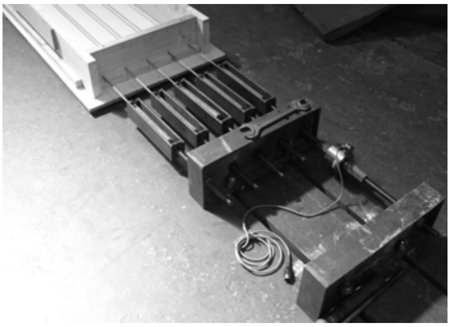

Fig. 4. Jacking mechanism

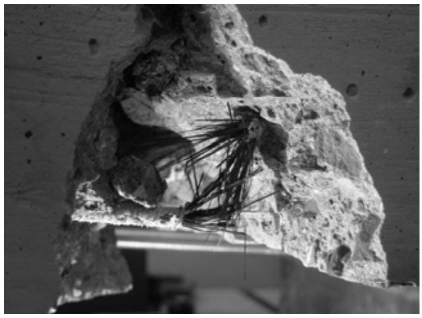

Fig. 5. Rupture of prestressed CFRP bar

3.2. Fatigue

The high cycle fatigue test ($1.2 \cdot 10^6$ cycles) was performed on six CFRP prestressed slabs. No cracks were observed during the test. Afterwards slabs were tested in flexure. The flexural capacity for the slabs subjected to fatigue varied from 53.7 to 61.5 kN. Corresponding deflections varied from 72 to 81 mm. It was verified experimentally that there is no remarkable difference between the flexural capacities of the prestressed slabs subjected to fatigue and the slabs subjected to fatigue not.

3.3. Creep

The sustained load was applied to 49-day-old concrete slab. The initial elastic deflection was 2.37 mm after the application of the load. This deflection, however, was related only to the sustained loading and not to the dead-load or prestressing. The CFRP prestressed slab reached time dependent to initial deflection ratios 2.47, 3.15 and 3.63 in 100^{th}, 200^{th} and 300^{th} day from loading, respectively (Fig. 6). After a year the 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 spacing over the constant moment region was circa 200 mm.

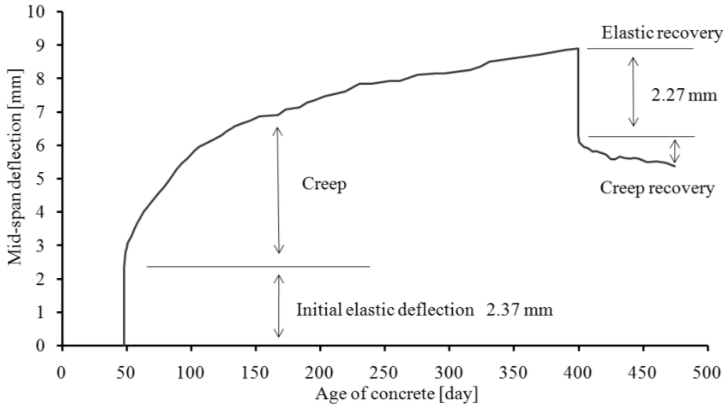

Fig. 6. Mid-span deflection evolution

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 CFRP prestressed slab was calculated to the 0.010 mm/day which equates $4.25 \cdot 10^{-4}$ 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.

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 loading and not to the deal load or prestressing. After one year the ratio of the accumulated strain to the initial strain was 8.86. Consequently the strain was 473.241 μm/m at the end of the loading interval. The ratio of the initial to the time-dependent was 5.77, 7.40 and 8.42 in 100^{th}, 200^{th} and 300^{th} day from the application of the sustained loading, respectively. After the sustained load was removed value of elastic strain recovery was measured to be - 68.70 μm/m (Fig.7).

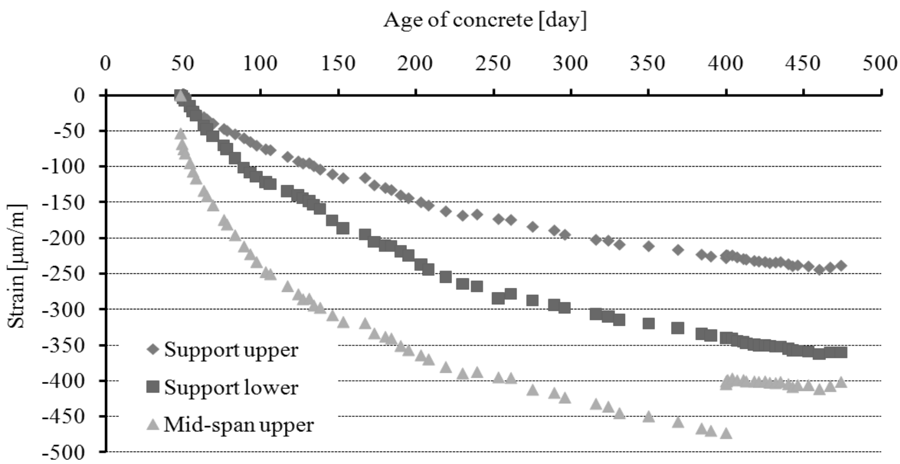

Fig. 7. Strain evolution in support and mid-span

The vibrating wire strain gauges above the support were affected mainly by the prestressing force. No initial strain was visible when sustained load was applied. On the day of removing the sustained load the recorded values were 224.1 μm/m and 340.1 μm/m for upper and lower gauge, respectively.

When the creep test was over the slab was subjected to the four point bending test. No significant difference with slabs which were not subjected to sustained loading was observed in force-deflection diagram. The ultimate force in four point bending test was 54.8 kN with deflection equals to 70 mm.

4. Conclusions

The high strength-weight ratio and the corrosion resistance are characteristics that make CFRP an exceptional structural material. On the other hand, the low modulus of elasticity causes bigger deflections and an early crack development. Prestressing enhances the behaviour of concrete members with CFRP reinforcement significantly. It specifically decreases deformations and therefore prevents early crack development. By prestressing the CFRP reinforcement is more utilized in tension and the usage of CFRP is more economical.

Behaviour of a CFRP prestressed slab is bi-linear which is typical for FRP reinforced members. The failure of the slab comes without an ample warning or any striking change in the trend of load-deflection diagram. The reason is elastic-linear behaviour of the CFRP bar that has neither yield point nor plastic plateau. Failure of the slab occurs due to the exceeding of the tensile capacity of the CFRP bars.

The high cycle fatigue loading has no significant effect on the flexural capacity of the prestressed slab. No cracks were observed after $1.2 \cdot 10^6$ cycles. The flexural capacity of the CFRP prestressed slabs varied from 53.6 to 64.0 kN and from 53.7 to 61.5 kN for concrete slabs subjected only to four point bending test and for concrete slabs subjected to fatigue and then to four point bending test, respectively. The corresponding ultimate deflection varied from 67 to 87 mm and from 72 to 81 mm, respectively (Fig. 8).

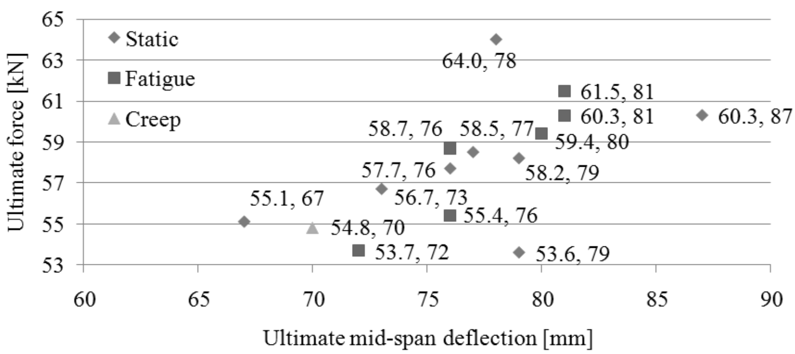

Fig. 8. Ultimate force-deflection scatter

Heavy sustained load representing 158% of the dead load was removed after one year. The SLS requirements in terms of deflection (1/250·L) were not reached. On day 300 mid-span deflection showed value of 8.61 mm which is approximately half of the SLS criteria in terms of deflection (16 mm). The overall deflection was 8.9 mm in the mid-span after a year under the sustained load. That is 1/450 in terms of deflection to the clear span ratio. The creep rate of the CFRP prestressed slab was specified to be 1 mm per 98 days. The very good behaviour of CFRP reinforced concrete is also explained by the fact that the carbon fibres do not relax at all under the sustained loading. Therefore CFRP are suitable for civil engineering purposes where everyday loadings are high.

Acknowledgement

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