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Long-term behavior of RC slabs strengthened with EB CFRP strips subjected to sustained load and exposed to solar radiation

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ABSTRACT: During the last decades, traffic loads by heavy vehicles have increased due to requirements of the current society and this fact has to be considered when the state of existing bridges is evaluated. Many concrete structures, for instance lateral cantilevers of highway box-girder bridges, can be strengthened on the upper side with Externally Bonded (EB) Carbon Fiber Reinforced Polymer (CFRP) strips in order to increase their load-bearing capacity in flexure. These additional reinforcements can be applied as a non-prestressed or prestressed system. The main goal of this paper is to study the long-term behaviour on the bond between the concrete substrate, the epoxy adhesive, and the EB CFRP strips.

1 INTRODUCTION

Externally Bonded (EB) Carbon Fiber Reinforced Polymer (CFRP) strips are nowadays a popular strengthening technique for structurally defficient Reinforced Concrete (RC) structures. One possible application of this strengthening method are lateral cantilevers of concrete box-girder bridges in transverse direction (Figure 1). These bridges can be exposed to extreme weather conditions, and sun exposure in the summer period is of particular interest.

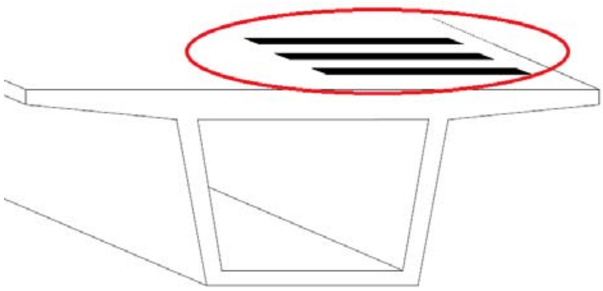


Figure 1. RC box-girder bridge strengthened in transverse direction with EB CFRP strips

Measurements on strengthened RC cantilever slabs with an asphalt layer on the top and exposed to outside weather conditions in Zurich area showed temperatures in the asphalt surface of approximately 60°C under direct solar radiation exposure in summer. Due to the warming up of the mastic asphalt layer, these elevated temperatures induce an increase of the epoxy temperature that could affect the rheological properties of the adhesive. During these critical summer days the epoxy temperature could reach 50°C or more.

In this paper, an experimental investigation concerning the long-term behavior of RC slabs strengthened with EB CFRP strips and subjected to sustained loading and solar radiation exposure is presented. For such purpose, three large-scale RC slabs strengthened with non-prestressed and prestressed EB CFRP strips were fabricated. These specimens were fixed as cantilever slabs and exposed to outer weather conditions in the region of Zurich (Switzerland) during more than one year. Strain gauges were installed on the strips to record the evolution over time of the strip strains.

2 EXPERIMENTAL CAMPAIGN AT EMPA

2.1 Motivation

To study the long-term behaviour due to the seasonal temperature fluctuations, cantilever RC slabs strengthened with prestressed and non-prestressed EB CFRP strips under sustained load were installed and continuously monitored in time simulating a typical top deck slab belonging to a highway RC box-girder bridge strengthened in transverse direction. The experimental measurements started in 2015 and will continue during the following years.

2.2 Materials, procedure and test setup

Large-scale tests were carried out in RC slabs strengthened with EB CFRP strips. The CFRP strips and the epoxy adhesives used for the experimental campaign were provided by S&P Clever Reinforcement (S&P (2013)) and Sika (S&P (2011)). Unidirectional strips were used with a nominal width and thickness of 100 mm and 1.2 mm, respectively. According to the datasheets of the companies S&P Clever Reinforcement and Sika, the strip elastic modulus was about 170 GPa and the tensile strengths were approximately equal to 2800 MPa and 3100 MPa, respectively. The two-component cold-curing epoxy adhesives S&P-220 and Sikadur30 Normal were used as bonding materials.

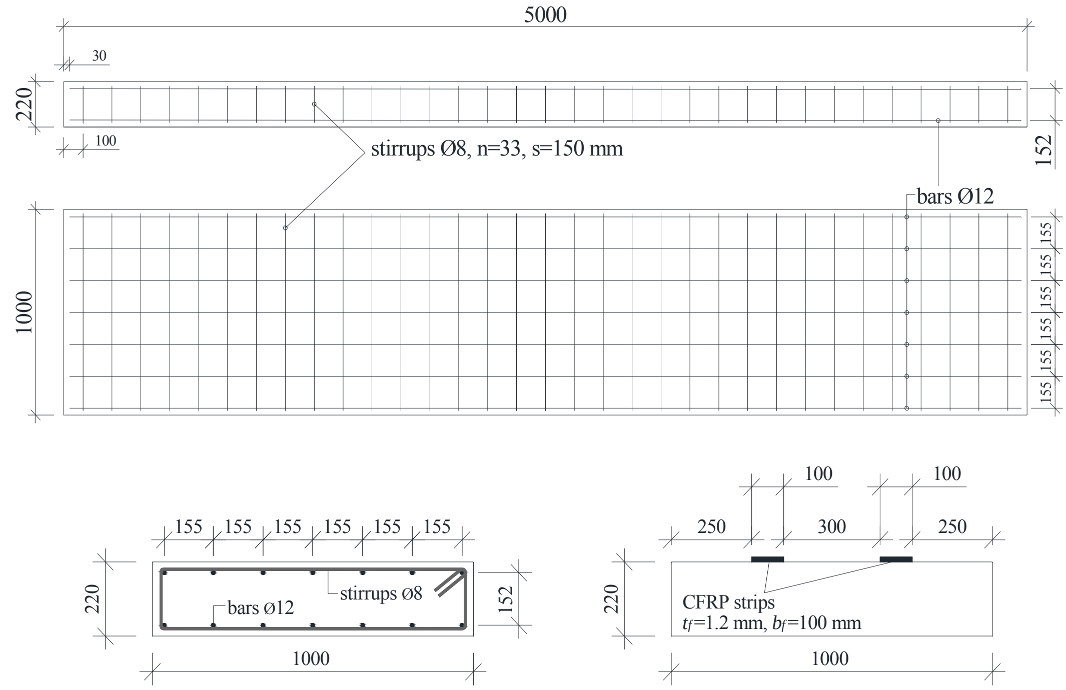


Figure 2. Geometry of the slabs and distribution of the steel reinforcement.

The specimens were built with similar concrete mixtures, being the maximum aggregate size equal to 32 mm. The water/cement ratio was 0.50 and the content of cement (CEM II) was 325 kg/m^3. The steel reinforcement consisted of hot-rolled deformed bars with characteristic yield and ultimate strength of 595 and 670 MPa, respectively.

The specimens were designed according to the usual dimensions of a typical cross-section of a highway RC box-girder bridge (Figure 1) in order to assess the behaviour in transverse direction of such lateral cantilevers strengthened with prestressed and non-prestressed EB CFRP strips. The slabs had 5 m length, 1 m width and 0.22 m thickness. The longitudinal steel reinforcement consisted of two layers of 7ϕ12 mm bars on each side. The shear reinforcement consisted of ϕ8 mm stirrups spaced at 150 mm. The specimens were strengthened on the top side with two EB CFRP strips (5000 mm x 100 mm x 1.2 mm). On Slab No.3, strips and epoxy from S&P were used, while strips and epoxy from Sika were applied on Slab No.4. The geometry of the slabs and the distribution of the steel and CFRP reinforcements are shown in Figure 2.

The slabs were tested as cantilever elements, being supported in the middle and in the slab end where the vertical displacement was also fixed. According to this setup, the central support represents the deck support provided by the web of the box-girder cross-section while the load was applied on the free end as Figure 3 shows.

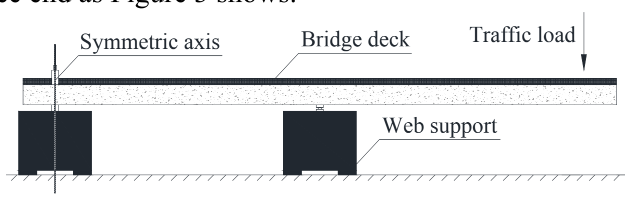


Figure 3. Sketch of the test setup based on a real top deck slab of a highway concrete box-girder bridge.

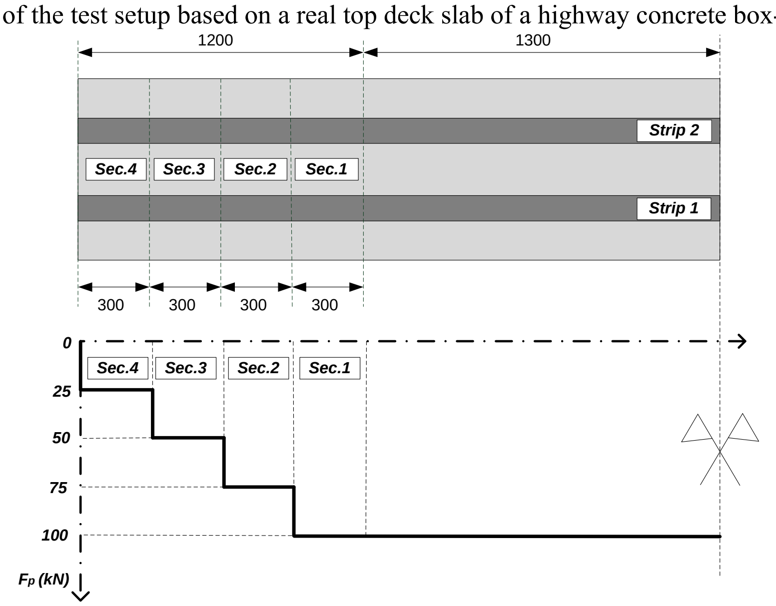


Figure 4. Distribution of the prestress force in each strip after releasing.

One of the slabs (Slab No.6) was designed with similar dimensions but prestressed EB CFRP strips anchored according to the gradient anchorage method developed at Empa (Michels et al.

(2013)) were used. This innovative technique avoids mechanical anchorages for prestressed EB CFRP strips due to the application of a local curing of the epoxy adhesive accelerated by heat and followed by the release of the prestress force in different stages at both strip ends.

A schematic distribution of the strip prestress force after the application of the gradient anchorage method is represented in Figure 4. The prestress force in the strip was released in four steps over a total gradient anchorage length of 1200 mm. Each gradient anchorage was divided in four sectors of 300 mm. The initial prestress force in each laminate was equal to 100 kN that corresponds to a strip strain approximately equal to 5000 μm/m. This stress level in the strips of about 850 MPa corresponds to approximately 30% of the ultimate tensile strength.

The described process used to anchor the CFRP strips has been defined based on previous investigations performed at Empa (Michels et al. (2016)). A heating time of 35 minutes of accelerated curing at approximately 90°C epoxy temperature and a following cooling of 15 minutes was used to cure each sector. After heating and therefore curing the adhesive in sectors 1, the initial prestress force was reduced 25 kN (Michels et al. (2014)) simultaneously on both ends. Then, sectors 2 were cured followed by a reduction of the prestress force of 25 kN. The same heating and releasing procedures were repeated in sectors 3 and 4 until the prestress force in both strip ends was equal to zero (Figure 4). Approximately 3 hours were required to anchor each strip.

Figure 5. Test setup: (Top) Strengthened slabs with non-prestressed strips and mastic asphalt; (Bottom) Strengthened slab with prestressed strips and a protection paint layer.

The sustained load was the same in all the tests and consisted in several concrete blocks applied on the free edge. This load was defined to represent the usual service load level of these structural elements. As Figure 5 shows, the slabs were placed outside, loaded and exposed to environmental conditions.

The load level defined for such long-term tests is represented in Figure 6 together with the corresponding load-tip displacement curve measured during the static reference tests at room temperature. For the slabs strengthened with non-prestressed strips (Slabs No.3 and No.4), the maximum bending moment was slightly higher than the cracking moment while for the prestressed slab this threshold was not reached.

Before the application of the sustained load in Slabs No.3 and No.4 (non-prestressed strips), a real mastic asphalt layer was applied according to the typical procedure followed in Switzerland to strengthen these types of bridges. Previous tests performed at Empa demonstrated that such slabs strengthened with EB prestressed CFRP strips are not stable during the application of the mastic asphalt layer. For that reason, in the prestressed slab (Slab No.6) the mastic asphalt layer was not applied and the sustained load was directly placed on the top surface in the free edge. In this slab a special paint was applied along the top surface in order to protect it against the water and the sun radiation.

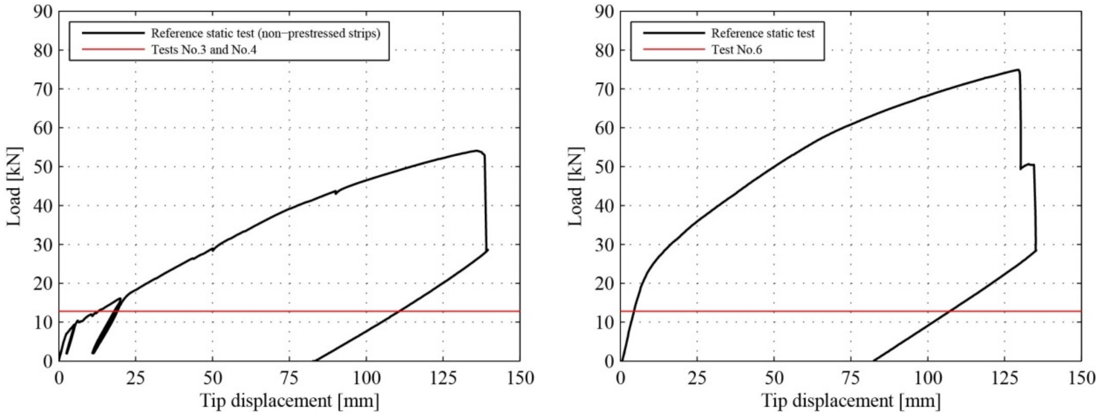


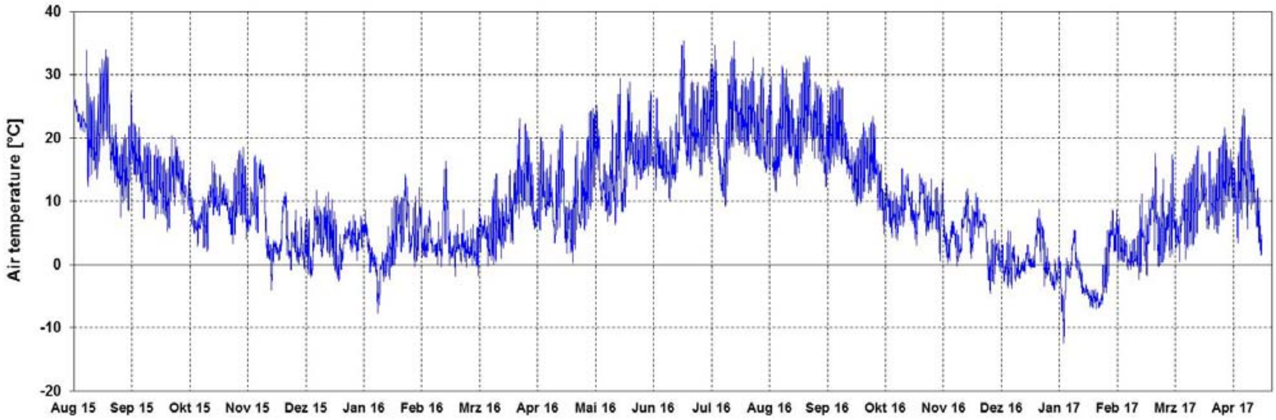
Figure 6. Load level: (Left) Strengthened slabs with non-prestressed strips and mastic asphalt (Slabs No.3 and No.4); (Right) Strengthened slab with prestressed strips and without mastic asphalt (Slab No.6).

To monitor the strip strains over time, strain gauges were glued on top of the EB CFRP strips. These strain gauges were located in the section over the central support subjected to the maximum bending moment and in two symmetric sections at 600 mm from the central support. The measurements were registered (Figure 7) by means of the long-term monitoring system from the Empa spin-off company Decentlab (Decentlab GmbH).

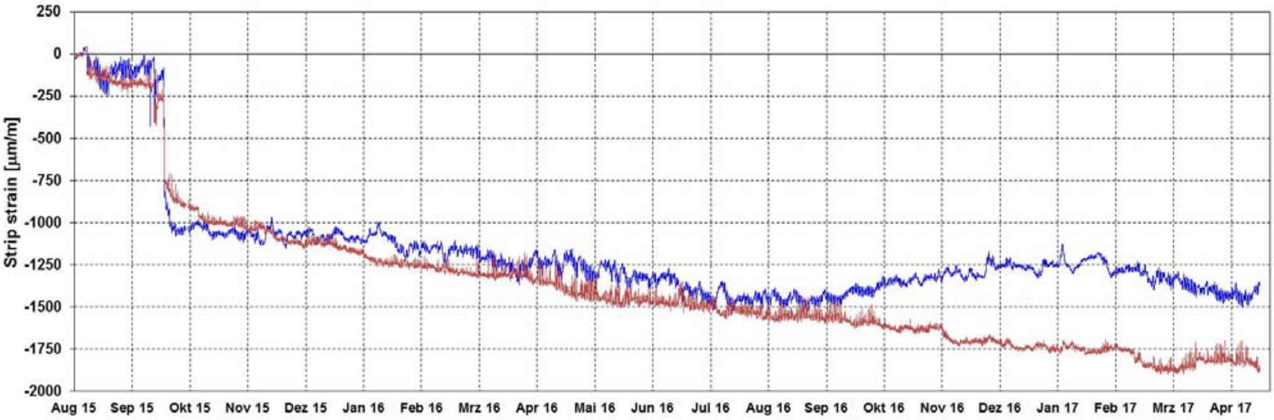
2.3 Experimental results

2.3.1 Slabs strengthened with EB non-prestressed CFRP strips (Slabs No.3 and No.4)

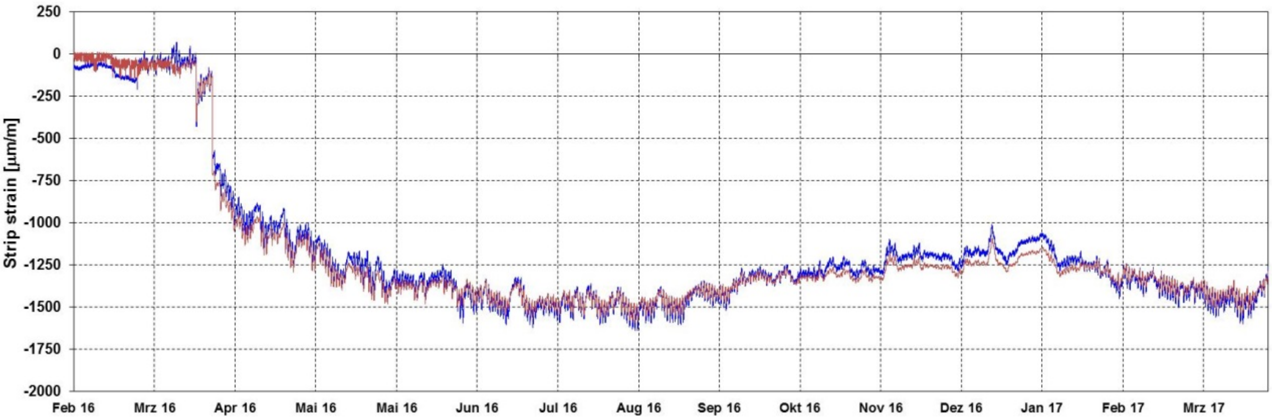
The evolution in time of the strip strains measured in both strips in the section subjected to the maximum bending moment is represented in Figure 7. Considering that for this load level the maximum bending moment due to the self-weight of the cantilever beam, the mastic asphalt layer and the sustained load is significantly higher than the cracking moment, the theoretical maximum strip strain should be equal to 1500 μm/m when the concrete section is fully cracked. As Figure 7 shows, after the application of the sustained load the measured strip strains (≈ 900 µm/m) were significantly lower than the theoretical value obtained through a cross-section analysis (≈ 1500 µm/m). This fact has been related to the collaboration of the mastic asphalt layer to resist tensile forces.



(a)



(b)



(c)

Figure 7. Experimental measurements: (a) Air temperature in shade (b) Maximum strip strains in Slab No.3; (c) Maximum strip strains in Slab No.4.

The theoretical value of the maximum strip strain was reached approximately at the beginning of the summer period, when the collaboration of the mastic asphalt to resist part of the tensile force was negligible and the concrete section over the central support can be considered as fully cracked. The decrease of the maximum strip strains started again at the end of the summer due to the decrease of the temperatures. So far a good behaviour of both slabs has been observed without significant creep deformations.

2.3.2 Slabs strengthened with EB prestressed CFRP strips (Slab No.6)

The evolution in time of the strip strains were also measured in the slab strengthened with prestressed strips (Slab No.6) without seeing a significant variation after the application of the sustained load. Despite this slab was exposed to direct solar radiation, the prestress force showed a stable behaviour so far.

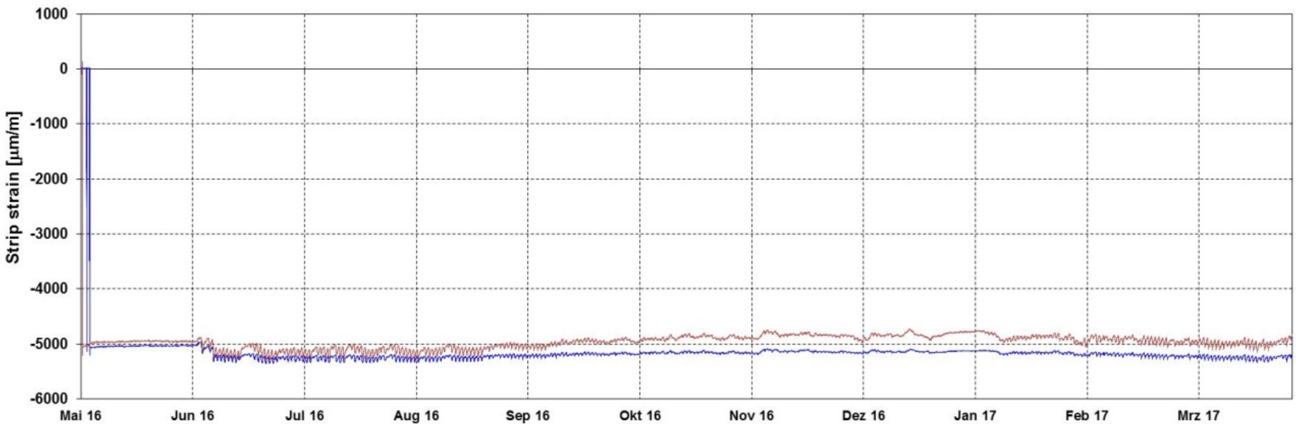


Figure 8. Experimental measurements of the strip strains in Slab No.6: Maximum strip strains.

3 CONCLUSIONS

Several conclusions can be drawn from the presented experimental investigation:

- Experimental measurements on strengthened RC cantilever slabs with an asphalt layer on top and exposed to outdoor weather conditions have showed temperatures in the asphalt surface of approximately 60°C under direct sun exposure. These elevated temperatures induce an increase of the epoxy temperature that could affect the long-term properties of the adhesive due to the warming up of the mastic asphalt layer.
- Large-scale RC cantilever slabs strengthened with non-prestressed and prestressed EB CFRP strips have been tested under sustained load without seeing significant creep deformations after more than one year exposed to outdoor weather conditions and seasonal temperature fluctuations.

4 ACKNOWLEDGEMENTS

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