Long term behavior of epoxy adhesives and FRP's for strengthening of concrete

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ABSTRACT: Epoxy bonded steel plates for strengthening of concrete structures were introduced to the construction industry in the late 1960's, the use of fiber reinforced polymers (FRP's) in the 1990's. Therefore, these materials are used now in construction already for 50 and 25 years, respectively. The monitoring of such applications in construction is very important and gives more confidence to this strengthening technique. In this paper, two different long-term monitoring campaigns over an extraordinary long duration will be presented. Firstly, a 47-year monitoring campaign on a concrete beam with an epoxy bonded steel plate and secondly, a 20-year monitoring campaign on a road bridge with epoxy bonded CFRP strips.

1 INTRODUCTION

The first ideas on strengthening of concrete with epoxy bonded steel plates were presented in the 1960's by L'Hermite et al. (1967) and Bresson (1971). The first applications on a highway bridge and in a building followed in 1966-67 (Ruggli et al. (1980)). In the 1970's and 80's, beside the investigation mentioned above, research on the performance and on a better understanding on the epoxy bonded steel plates was performed at Empa. A good overview of these investigations at Empa is given in Ladner et al. (1981). For example, for a building in Zurich, which was also strengthened by steel plates in April 1973, a large-scale test up to failure was performed, Ladner et al. (1974). Details of the strengthening work are presented in Agthe (1974). One of the first bridges which were strengthened with epoxy bonded steel plates was the Gizenenbridge in Switzerland (Fässler et al. (1980)). Loading tests on the bridge after the strengthening are described in Ladner (1980). A design method for the epoxy bonded steel plates were presented in Ladner (1983).

Carbon fiber reinforced polymers (CFRP) are used for load carrying components in the air and space industry since the 1970's. In the frame work of a media event, Empa experts presented already in 1987 that CFRP can also be used for strengthening of civil constructions, Meier (1987). The public interest was large; however, due to the high costs of the carbon fibers, the transfer to practice was first mistrusted. However, the handling of the very light weight CFRP strips is much easier in comparison to steel plates and working hours can be saved what compensates the higher material costs of CFRP. Today, the strengthening of concrete by CFRP is a state-of-the art technique.

As a world premiere, the Ibachbridge near Lucerne in Switzerland was successfully strengthened with CFRP strips in 1991 (Meier et al. (1991) and Meier (1995)). Therefore, this material is used already for 25 years in construction! However, the application of this material requires not only knowledge of the ultimate and serviceability limit states, but also information on the durability of the CFRP over the remaining lifetime of the structures. Monitoring of CFRP strips provides indications about their long-term behavior, and, consequently, confidence in the use of this material for strengthening civil structures.

In this paper, two different long-term monitoring campaigns over an extraordinary long time will be presented. Firstly, in a long-term laboratory test that have been on-going at Empa since 1970, a concrete beam has been strengthened in flexure using a steel plate. A two component epoxy adhesive was used. The beam was and is still loaded to 87% of the mean ultimate load and is still in good state. Secondly, a monitoring campaign on a road bridge at the boarder of Switzerland with epoxy bonded CFRP strips has been going on since 1996. Displacements are measured manually by using a mechanical strain gauge.

2 CONCRETE BEAM WITH A BONDED STEEL PLATE

2.1 Introduction

Prefabricated reinforced concrete (RC) elements of the roof of an industrial building (Figure 1) had to be strengthened in 1970. The reason for the strengthening was that cracks were observed and it was found that insufficient internal steel reinforcement existed in the prefabricated RC elements. It was decided, that the RC elements shall be strengthened with externally bonded steel plates. Figure 2 shows the strengthened industrial building on a photo in the year 1992. The steel plates are indicated with red arrows. They are hardly visible because of the white paint.

Figure 1: Industrial building in Kreuzlingen in Switzerland, which was strengthened in 1970 by means of steel plates.

Figure 2: Detail of the inside of the building. The red arrows indicate the location of the steel plates. Photo was taken in the year 1992.

In 1970, the knowledge on the strengthening technique of bonding steel plates with epoxy adhesive to concrete was at the beginning. Therefore, in this year a test program was performed at Empa to investigate this technique. Six prefabricated RC elements and strengthened by epoxy bonded steel plates were tested statically in a four point bending test, one element was tested under fatigue and one was used for a long-term sustained loading test. This test is still running today and will be presented in this paper. See also Egger (2003).

2.2 *Materials and Test set-up*

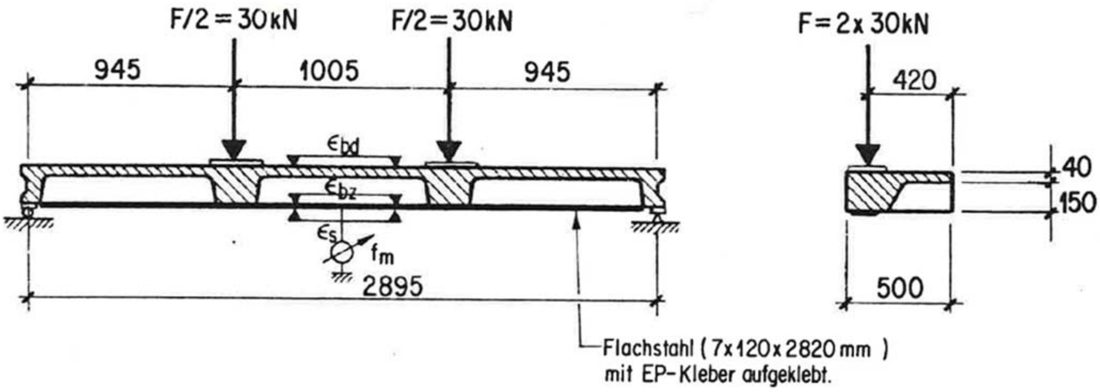

Figure 3: Dimension and measurements of the long-term test.

The RC elements for the experiments were produced from a Swiss prefabrication company and were delivered to Empa. Unfortunately, only limited documents from the investigation today exist. However, the material properties were reconstructed in the year 2002: the concrete compressive strength after 28 day was $f_{c,cube,28} \approx 28$ MPa, in 2002 the concrete strength was $f_{c,cube} \approx 58$ MPa, the steel plate is likely to be an ordinary construction steel S235 with a yielding strength of $f_y \approx 236$ MPa and the adhesive is a two component epoxy adhesive probably from the company Ciba-Geigy (Hugenschmidt (1980)).

Figure 4: Long-term test at Empa: RC beam strengthened with a bonded steel plate under a sustained load.

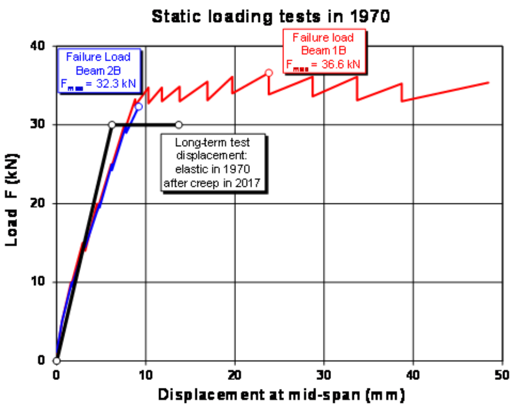

Figure 5: Load-displacement diagram of the static loading tests.

The beam is loaded as a four-point bending test (Figure 3 and Figure 4) and constantly loaded with 2 × 30 kN with lead weights. The beam is an edge beam as visible in Figure 2, what explains the nose cross beams visible in Figure 3. The constant load of 2 × 30 kN corresponds to 87% of the mean value of the failure load of the two static tests (Figure 5). This can be considered as a very high value near to failure. A photo of the failure mode during the static loading test of one of the beams is given in Figure 6.

The mid-span displacement of the long-term test is measured with a dial gauge (Figure 4) and the strains with a mechanical strain gauge. In the year 1986, the test had to be relocated in the laboratory and at this occasion, the loading with concrete blocks was changed to lead weights.

Unfortunately, during the reconstruction of the Empa laboratory in 2000, the base for the displacement measurements was damaged. Therefore, these measurements were corrected; however, the strain measurements are not affected from this issue.

Figure 6: Failure mode in the static loading test on Beam 2B. Photo from the year 1970.

Figure 7: Bottom side of the beam in the year 2015. Surface corrosion is visible on the steel plate.

2.3 Results

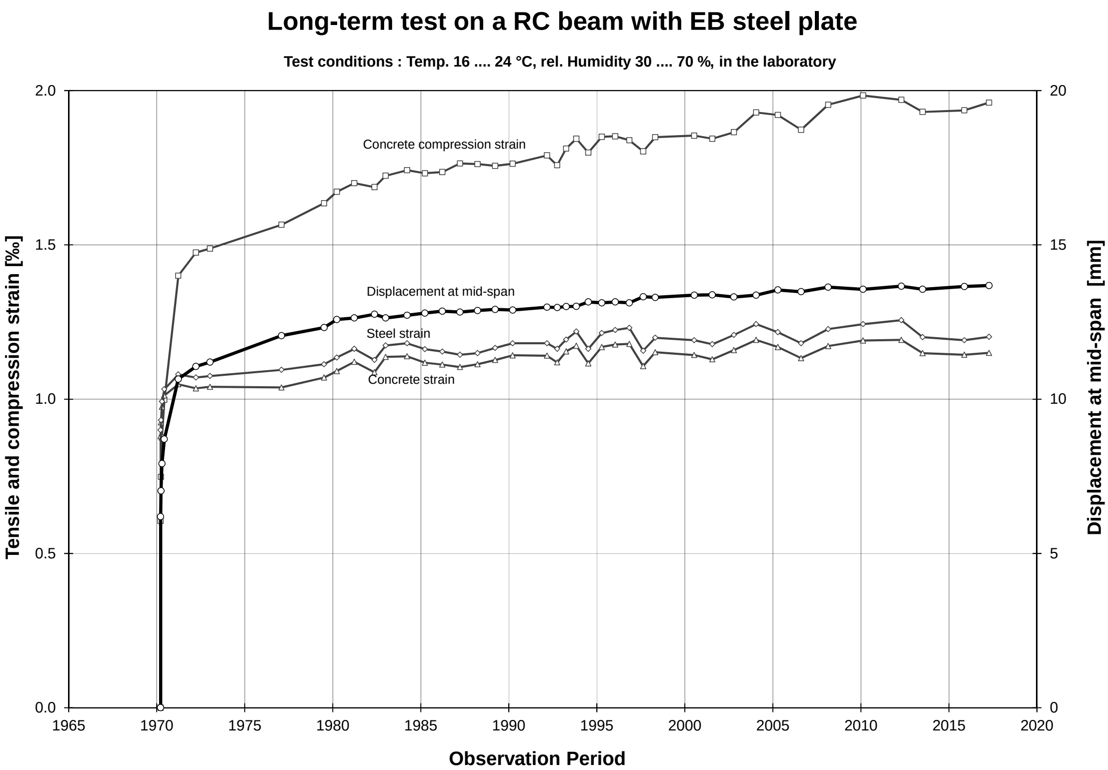

Figure 8: Long-term measurements since 1970 on the RC beam strengthened with an epoxy bonded steel plate.

After 47 years, the beam is still in a good condition. The steel plate has some corrosion at the surface, what is considered as not relevant (Figure 7). The strain-time and displacement-time diagram is given in Figure 8. It shows that the main creep occurs in the concrete in the compression zone. The corresponding creep factors (calculated by the ratio of displacement or strain at 11.4.2017 to 24.3.1970) are given in Table 1. It can be concluded that almost no creep takes place in the epoxy adhesive.

Table 1: Overview of the measured displacements and strains shortly after loading and after 47 years of long-term monitoring. Furthermore, the creep factors are given.

Date	Years	Displacement [mm]	Concrete Compression Strain [‰]	Steel Tensile Strain [‰]
24.3.1970	0	6.2	0.61	0.90
11.4.2017	47.1	13.7	1.96	1.20
	Creep factor:	2.2	3.2	1.3

3 RHINE BRIDGE OBERRIET WITH EXTERNALLY BONDED CFRP STRIPS

Empa researchers developed the idea of using CFRP's instead of steel already in the 1980's, see Meier (1987) and Meier (1991). As already mentioned above, the Ibachbridge near Lucerne in Switzerland was successfully strengthened with CFRP strips in 1991 as a world premiere. These CFRP strips have up to now only once, in September 2008, been monitored due to very difficult access. The results, with a similar monitoring system as described in the following section, were fully satisfactory. The Rhine Bridge, built in the year 1963, connects Oberriet in Switzerland and Meiningen in Austria and crosses the Rhine River with three continuous spans (Figure 9). The steel-concrete composite superstructure comprises two steel girders and a cast-in-place concrete deck (Figure 10). The owner of the bridge is the Canton St. Gallen and the Land Vorarlberg.

Figure 9: Bridge over the river Rhine near Oberriet in Switzerland.

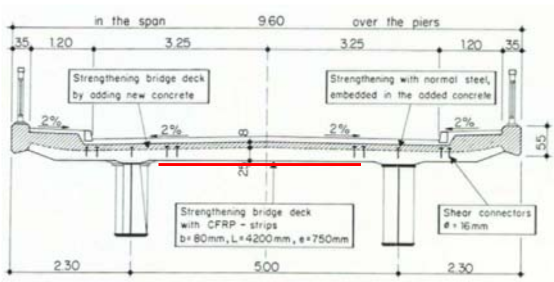

Figure 10: Cross-section of the bridge. Figure taken from Walser et al. (1997). The location of the CFRP strips are indicated with a red line.

The strengthening project in 1996 was necessary because of higher road loads and chloride contaminated concrete. On top of the concrete slab, a concrete layer was replaced and a new steel reinforcement for the negative bending moment in bridge cross direction was embedded. On the bottom of the slab, CFRP strips from the company Sika with a cross-section of 80 x 1.2 mm and a length of 4.2 m were applied in order to strengthen the positive bending moment in bridge cross-direction (Figure 10). Totally, approximately 670 meter strips were used. See Walser et al. (1997). A description of the design of the strengthening can also be found in Walser et al. (1997). The project engineer was Bänziger & Köppel & Partner from Buchs in Switzerland.

Displacement measurements with a mechanical strain gauge on two of the CFRP strips and the adjacent concrete have been performed on a regular basis since 1996. The stainless steel measurement points were protected with a threaded cover (Figure 13 and Figure 14). The measurement length of the mechanical strain gauge is 200 mm. Measurements are performed on the CFRP strip at mid-length and strip-end, and at adjacent locations on the concrete. See also Czaderski et al. (2006).

Figure 11: Underside of the bridge. The CFRP strips for the strengthening of the cross-direction are visible between the steel girders.

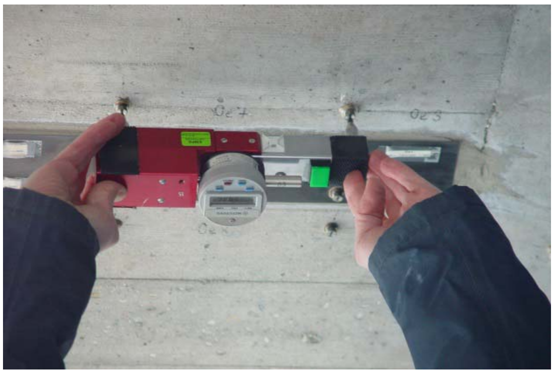

Figure 12: Mechanical strain gauge, which is used for the measurements.

Figure 13: Measurement points at the end of a CFRP strip.

Figure 14: Measurement points at the mid-length of a CFRP strip.

Some measurements of the variations of the displacements are given in Figure 15 and Figure 16. It is visible, that the displacements have a strong relation to the temperatures. With a temperature change between winter and summer of $\Delta T \approx 25°C$ and a temperature expansion coefficient of $\alpha_T = 10^{-5}$, a displacement variation of $\Delta T \times \alpha_T \times L \approx 0.05mm$ has to be expected. Therefore, the measurements in Figure 15 and Figure 16 show only structural expansions and contractions due to seasonal temperature variations and no damages of the bond. Furthermore, the photos in Figure 13 and Figure 14 and visual inspection show that the CFRP strips are still in a good condition. The CFRP strips are bonded at the bottom of the bridge and therefore protected from UV radiation and extensive rain exposure. However, air humidity in foggy weather situations and from the river Rhine which flows under the bridge are still expected. Nevertheless, this study shows that all these effects over 20 years did not influence the externally bonded CFRP strips negatively.

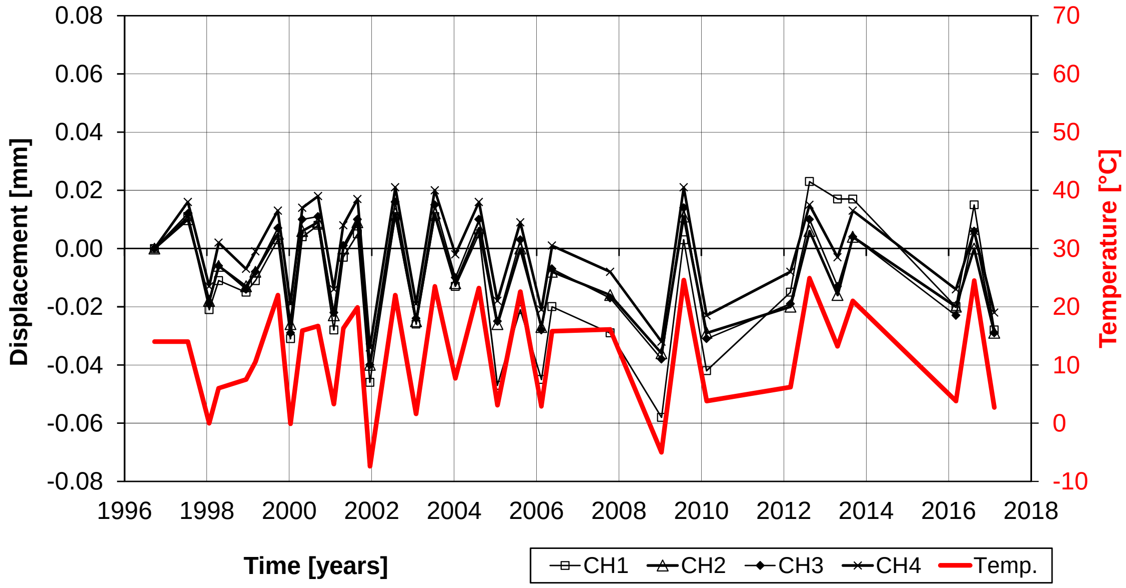

Figure 15: Displacement measurements over the last 20 years. Measurements CH 1 and 2 are from the strip end to the concrete surface and CH 3 and 4 on the concrete surface (see Figure 13).

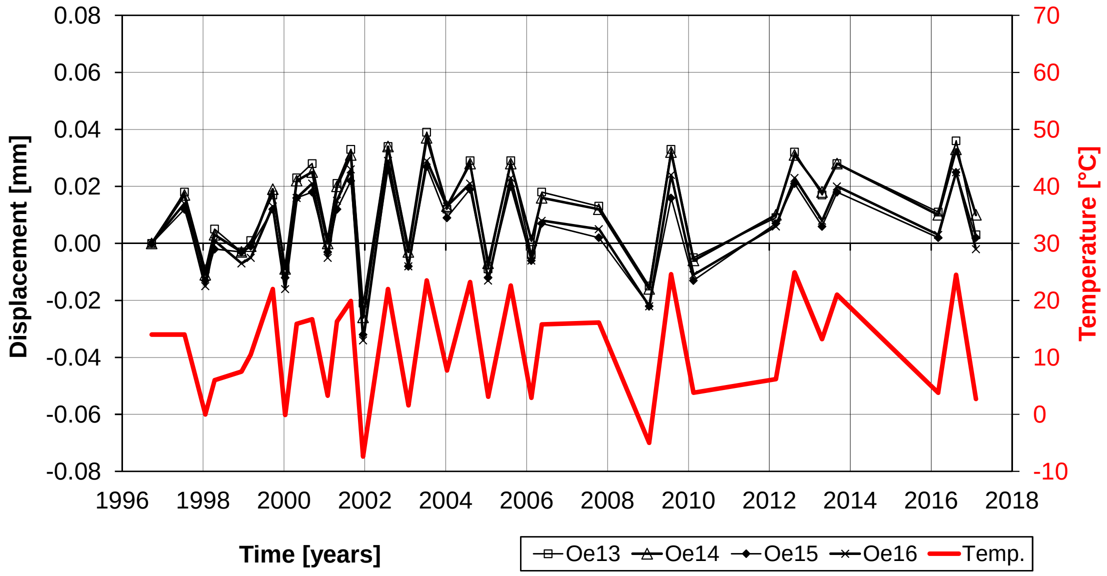

Figure 16: Displacement measurements over the last 20 years. Measurements Oe 13 and 14 are on the strip (at mid-length of strip) and CH 15 and 16 on the concrete surface similar as can be seen on Figure 14.

4 CONCLUSIONS

The 47-year old test on a beam with an epoxy bonded steel plate and a high sustained load showed that:

- the increase of the displacements happens mainly due to creep of concrete
- the epoxy adhesive for the bonding of the steel plate to the concrete is still in good condition.

The 20-year old CFRP strips glued on the bottom side of the Rhine Bridge in Oberriet showed that:

- the CFRP strips are still in good condition
- the measurements show only seasonal temperature deformations.

5 REFERENCES

Agthe, R. (1974). "Die Ausführung der Klebearbeiten." *Schweizerische Bauzeitung* **92**(19): 471-474.

Bresson, J. (1971). "Nouvelles recherches et applications concernant l'utilisation des collages dans les structures. Béton plaqué." *Annales I.T.B.T.P., Série Béton, Béton armé* **278**(116).

Czaderski, C. and U. Meier (2006). Long-Term Behaviour of CFRP Strips for Post-Strengthening. *2nd International fib Congress*, Naples, Italy, June 5-8, 2006.

Egger, G. (2003). "Geklebte Lamellenbewehrungen haben Langzeittest bestanden." *tec21* **129**(5): 11-13.

Fässler, A. and P. Derendinger (1980). "Die Sanierung der Gizenenbrücke über die Muota: Bericht des Bauingenieurs." *Schweizer Ingenieur und Architekt* **98**(41): 1003-1004.

Hugenschmidt, F. (1980). "Die Anwendung von Epoxidharzen in der Bautechnik." *Schweizer Ingenieur und Architekt* **98**(41): 1010-1011.

L'Hermite, R. and J. Bresson (1967). Béton armé par collage d'armature. *Collogue RILEM*, Paris, Séptembre 1967, Eyrolles, Vol. II, p.175.

Ladner, M. and P. Flüeler (1974). "Versuche an Stahlbetonbauteilen mit geklebter Armierung." *Schweizerische Bauzeitung* **92**(19): 463-470.

Ladner, M. (1980). "Die Sanierung der Gizenenbrücke über die Muota: Belastungsversuche." *Schweizer Ingenieur und Architekt* **98**(41): 1006-1009.

Ladner, M. and C. Weder (1981). Concrete structures with bonded external reinforcement. Empa Report No. 206. p.61, http://www.lib4ri.ch/institutional-bibliography/empa/empa-berichte.html.

Ladner, M. (1983). "Reinforced concrete members with subsequently bonded steel sheets." *IABSE reports* **46**: 203-210.

Meier, U. (1987). "Brückensanierungen mit Hochleistungs-Faserverbundwerkstoffen (in German and French)." *Material und Technik* **15**(4): 125-128.

Meier, U. (1991). "Modern materials in bridge engineering." *IABSE reports* **64**: 311-323.

Meier, U. and M. Deuring (1991). "The application of fiber composites in bridge repair - a world premiere at the gates of Lucerne." *Strasse und Verkehr* **77**(9): 534-535.

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

Ruggli, C., P. Wyss and G. Zenobi (1980). "Klebearmierung - eine neue Technik zur Erhaltung von Bausubstanz." *Schweizer Ingenieur und Architekt* **98**(27-28): 653-658.

Walser, R. and W. Steiner (1997). "Strengthening a Bridge with Advanced Materials." *Structural Engineering International*(2): 110-112.