IABSE Symposium - Rio de Janeiro - August 25-27, 1999

Deflection Monitoring of Prestressed Concrete Bridges Retrofitted by External Post-Tensioning

Olivier BURDET
Ph.D.
Swiss Fed. Inst. of Techn.
Lausanne, Switzerland

Olivier Burdet, born 1960, is a lecturer in reinforced and prestressed concrete. His research interests include serviceability, bridge design and monitoring techniques.
He is a member of the Publication's Committee of IABSE SEI Journal.

Marc BADOUX
Ph.D.
Swiss Fed. Inst. of Techn.
Lausanne, Switzerland

Marc Badoux, born 1961, is an assistant-professor of Structural Engineering. His research interests include the serviceability behaviour of concrete structures, high performance concrete applications and the seismic protection of existing buildings

Summary

The paper presents the findings of the monitoring of the long-term deflections of three bridges which were retrofitted with external post-tensioning. The emphasis is on the effect of the additional post-tensioning on the bridge behaviour in the years following the retrofit. The bridges are highway prestressed concrete box-girder bridges built by the balanced cantilever method and retrofitted with additional exterior post-tensioning cables for deflection control. It is shown that external post-tensioning can be a successful retrofitting technique for bridges with serviceability limit state problems. The reported examples also highlight the value of long term monitoring of concrete bridges for the assessment of bridges, and for the design of retrofitting scheme.

Keywords: prestressed concrete, in situ measurements, bridge monitoring, long-term deflections, bridge retrofitting, external post-tensioning

1. Introduction

Additional post-tensioning has become one of the leading techniques for the retrofitting of bridges, in particular prestressed concrete box girder bridges. This paper describes the use of external post-tensioning for the retrofitting of three Swiss highway bridges. These bridges are representative of a family of bridges common in the 1970's and which have often experienced larger than expected long term deflections [1,3,4,7]. In all three cases, the decision to retrofit was governed by serviceability considerations, namely deflection control, rather than structural safety considerations. External post-tensioning has proven well suited for this type of intervention [2]. Findings of extensive long term monitoring of the bridge deflections are presented, with an emphasis on the effect of the additional post-tensioning on the bridge behavior in the years following the retrofit.

2. Retrofitting by external post-tensioning

The Lutrive, Chillon and Fégire bridges are highway bridges located near Lausanne in western Switzerland. These bridges share several common features: they are variable depth prestressed concrete box girder bridges built between twenty and thirty years ago by the balanced cantilever method. A further commonality is that they have been retrofitted with additional exterior post-tensioning cables for deflection control. In the following, the three bridges and their post-tensioning retrofitting schemes are described briefly.

Lutrive Bridges

Construction of the cast-in-place twin north and south Lutrive bridges (fig. 1) was completed in 1972. They are 395 m long, feature four spans, and are curved (r = 1000 m) in plane. The cross section (fig. 2) shows the variable depth of the box girder and the slightly asymmetric cantilevers chosen to offset the torsion linked to the bridge curvature. In the center of both main spans, the girders are discontinuous except for the top slab. This detail creates prestressed concrete flexural hinges (called "articulations" in figs. 1 and 2) which are an unusual feature of these bridges.

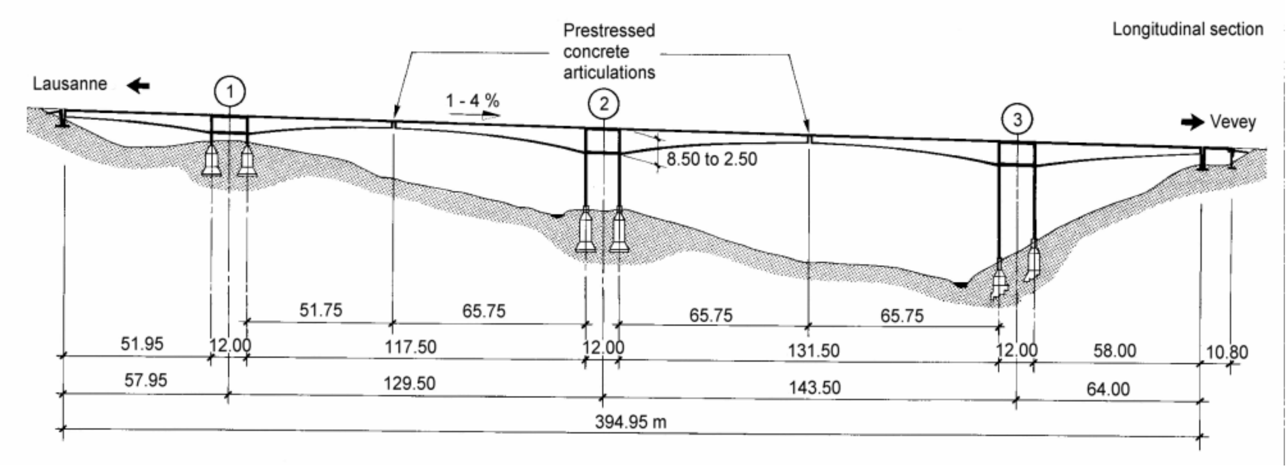

Figure 1: Elevation of the south Lutrive bridge

The monitoring of the bridge deflection from 1973 to 1987 showed that both bridges were experiencing substantial permanent deflections. During that time, the mid-span downward deflection of the 143,5 m long main span increased about 160 mm (figs. 8 and 9). More alarmingly, there was no clear sign of stabilisation of the deflection over time. The cause of the excessive deflection could not be clearly determined, in spite of an extensive in–situ and numerical investigation. It is thought however that the main cause is that actual initial post-tensioning was lower than specified.

In 1988, the bridge was retrofitted with additional exterior post-tensioning cables in order to stabilise, and partially reverse, the observed deflections. As shown in fig. 2, the additional post-tensioning consists of 2x2 cables per girder with an initial post-tensioning force of approximately 13,000 kN. The cables are anchored at both abutments and go through the hinges. In the two main spans, the cables are located directly below the top slab and have a linear layout. Their effect on deflection is therefore the result of the additional longitudinal normal force introduced in the girder (rather than the vertical component of deviatory post-tensioning forces). A positive moment is generated in the cantilever because of the eccentricity of the post-tensioning force with respect to the centroidal axis of the girder (due to the varying girder depth, this eccentricity increases toward the pier). The role of the steel deviators installed in the girder is to allow the horizontal deviation required by the bridge in plane curvature.

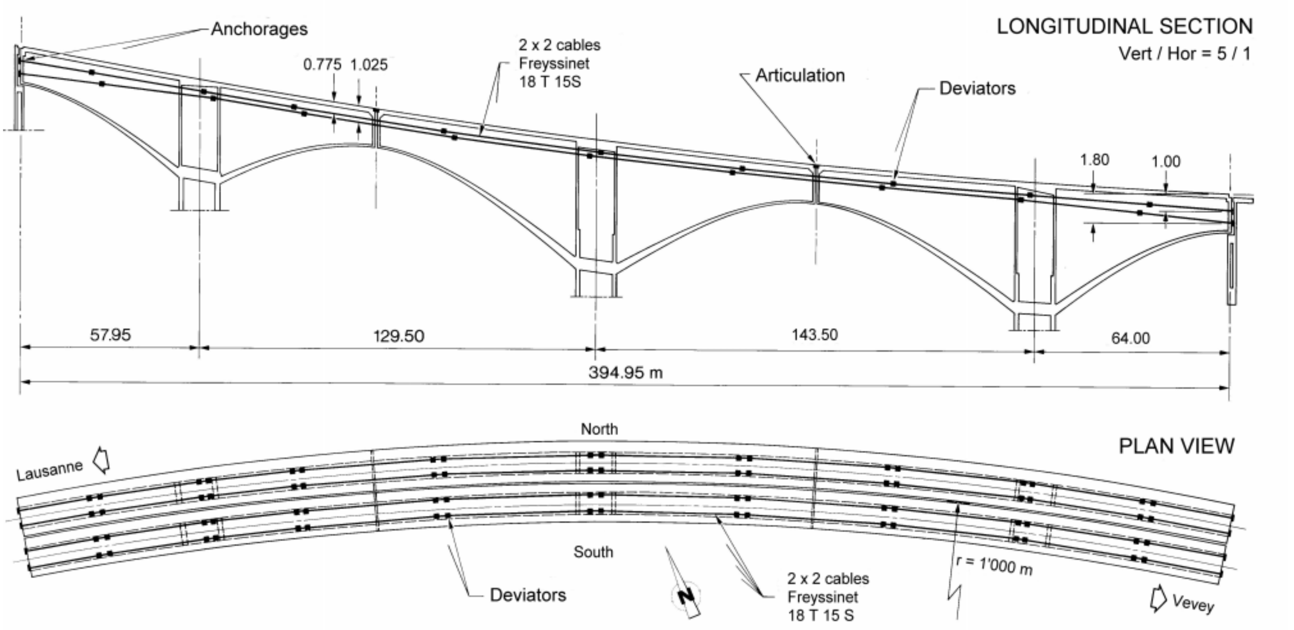

Figure 2: Additional post-tensioning for the Lutrive bridge

Chillon Bridges

The parallel Chillon bridges were built of match-cast precast concrete segments by the balanced cantilever method in the late 1960's. They both feature 22 spans and follow a sinusoidal roadline. Typical spans are 92 m long and the girder depth varies between 2.2 m and 5.00 m. Because of their length (over 2'000 m), the bridges feature several expansion joints as shown in fig. 3. The girder is hinged at the expansion joints, with a shear transfer system guaranteeing the compatibility of the vertical deformations of the bridge on both sides of the joints.

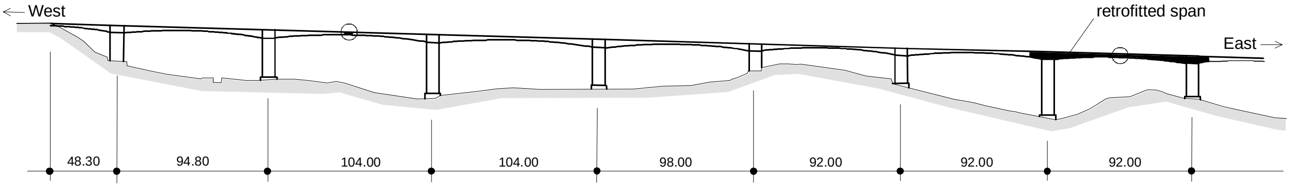

Figure 3: Elevation of the south Chillon bridge

Because of slight geometrical inaccuracies during construction and because of time dependent effects, the downward girder deflections at some of the expansion joints of the south bridge became substantial. In 1996 this permanent deflection was partially compensated at three of the four expansion joints of the south bridge by the application of an additional overlay. This corrective overlay was installed to improve the riding comfort and to reduce dynamic effects at the joints.

The overlay corrective measures were preceded by the installation of additional external post-tensioning in the three affected hinged spans (fig. 3). In addition to its own weight, the post-tensioning retrofit was designed to counterbalance the weight of the additional overlay. Without this post-tensioning, the additional overlay would have increased the deflections it was meant to compensate. The additional post-tensioning was not required form the structural safety standpoint.

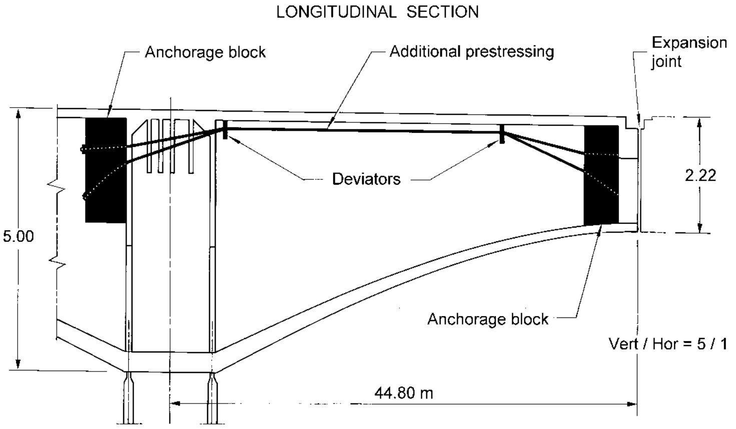

Figure 4: Additional post-tensioning for the Chillon bridge

The additional post-tensioning consists of 2 x 2 additional cables with an initial post-tensioning force of 18'500 kN on each side of the expansion joint. Because normal forces can not be transferred across the joint, the additional post-tensioning does not go through the joint (unlike the Lutrive Bridges). As shown in fig. 4, the cables are anchored in concrete anchorage blocks placed near the expansion blocks for one, and behind the pier for the other. Steel deviators near the joint and at the pier were installed to maximise the uplift effect of the additional post-tensioning.

Fégire Bridge

Construction of the cast-in-place Fégire bridge was completed in 1979. The linear bridge is 512 m long and does not feature intermediate joints. The three main spans are over 107 m long. Since a single bridge was built to carry both directions of the highway, the bridge cross section is relatively wide: over 10 m for the girder and over 20 m for the top slab.

The bridge was retrofitted in 1995 with additional post-tensioning to counter excessive vertical deflections that were not stabilising as expected. The additional post-tensioning is parabolic (fig. 5), and consists of 2x4 cables with an initial prestressing force of 28'000 kN. The additional cables are unusually long since the anchorage blocks are located at both abutments, over 500 m apart.

The massive anchorage blocks were designed for the case that a future retrofit would double the additional post-tensioning installed in 1995. Thanks to a simple and elegant design, the steel deviators (fig. 6) transfer the deviation forces to the girder webs without inducing transverse moments.

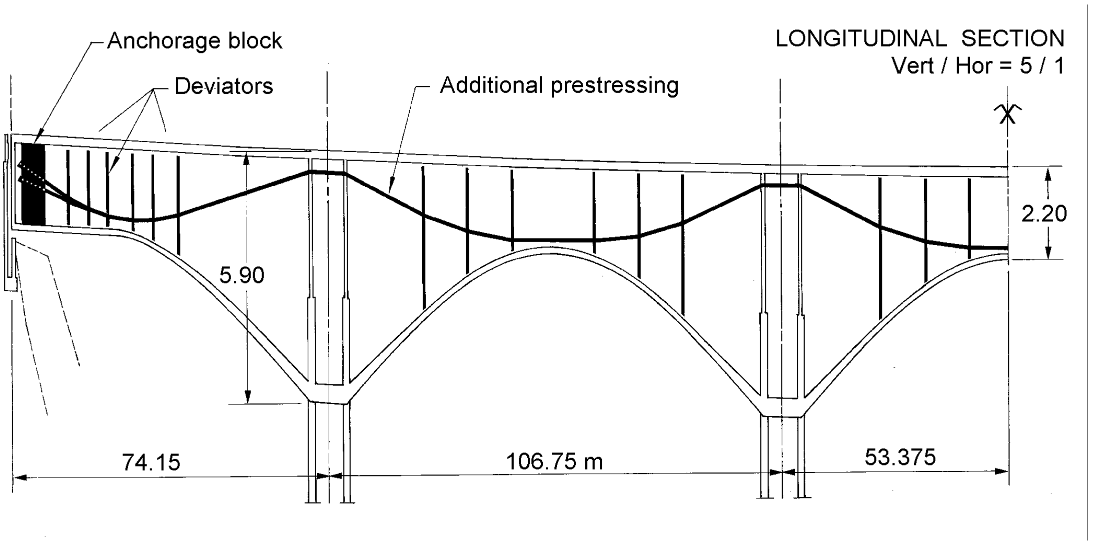

Figure 5: Additional post-tensioning for the Fégire bridge

Figure 6: Vertical deviator for the parabolic post-tensioning

3. Long-term behaviour

The structural concrete research group (IBAP) of the Swiss Federal Institute of Technology at Lausanne has long been involved in long term monitoring of bridges. The main monitoring system used is an hydrostatic leveling system developed by IBAP. Based on the simple principle of communicating vessels, this system has the advantage of being very robust, simple to install, and inexpensive both in initial and service costs. Fig. 7 shows a leveling device, with a simple graduated glass container. The deflection can be obtained in any point of the structure by simple sums and differences of measured levels at the various points. This system has several additional advantages:

- Discontinuous operations are possible, permitting the reactivation of an unused system after years of discontinued service, provided that new tubing is installed.
- Operation is possible even under heavy traffic, as the system exhibits a large inertia.

Among the main disadvantages of the system are:

- Impossibility to obtain continuous measurements: the system requires human intervention for the taking of measurements
- The system is not operational under freezing conditions. The liquid used is pure demineralized water, which has proven to be the best medium for the task. However, the system is not damaged by freezing.
- The accuracy of the measurement is proportional to the number of intermediate readings to reach a given point. Typical values for the accuracy are about 0.5 mm per intermediate reading, for a total of 4-10 points per span.

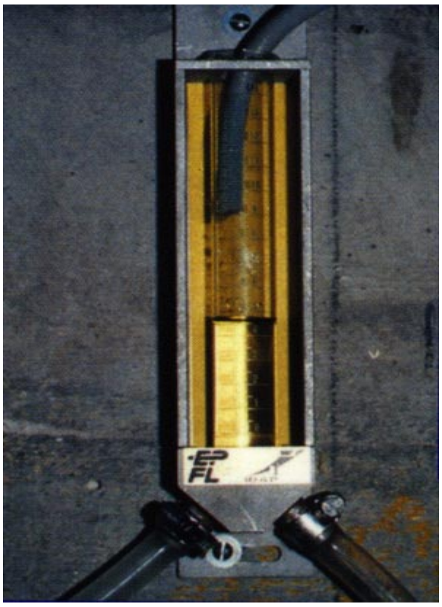

Figure 7: Hydrostatic leveling device with graduated glass container

- The requirement that the level must be the same on both sides of any circuit may lead to a large number of circuits in bridges with a large longitudinal slope.

The system has been successfully installed in more than 10 bridges in Switzerland. In some cases, it is operated by the local bridge authority, and in others the measurements are made by our research team. Under normal operating conditions, measurements are taken three times a year, in the spring, summer and fall. Because of freezing, no measurements are taken in the winter time. The three bridges presented here have been instrumented for more than ten years.

The Lutrive bridges received an additional external post-tensioning in December 1988, shortly after the installation of the hydrostatic leveling system. The result of the additional post-tensioning is visible in fig 8 for the Northa bridge, with an instantaneous uplift of the structure of approximately 30 mm, and a stabilisation of the mid-span deflection over the past ten years.

The result of the application of additional post-tensioning to the South bridge was initially similar with an uplift of the same magnitude (fig. 9). It was soon obvious, however, that the bridge’s long-term behaviour had not stabilised, as mid-span deflections continued to increase. As a consequence, it was recently decided to again add external post-tensioning cables to the structure, to stabilise deflections. The measurements made clear that the observed mid-span deflections result from an overall bending of the superstructure (fig. 10)

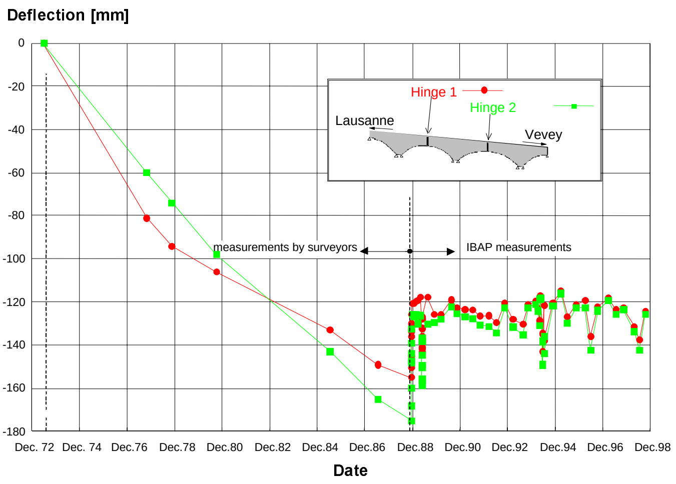

Figure 8: Evolution of mid-span deflections of the North Lutrive bridge since 1973

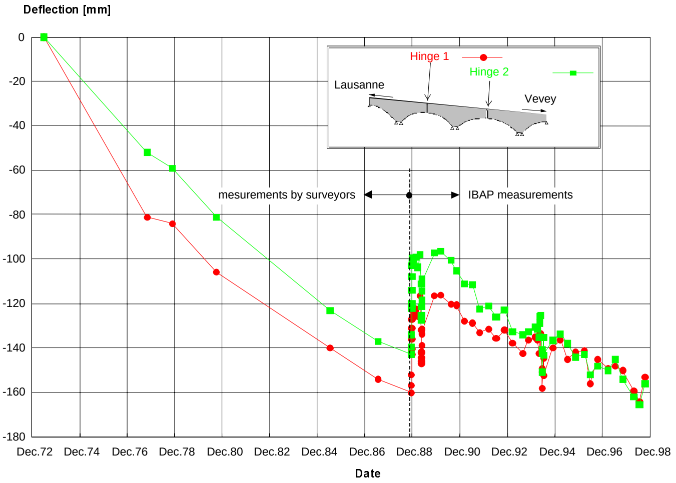

Figure 9: Evolution of the mid-span deflection of the South Lutrive bridge since 1973

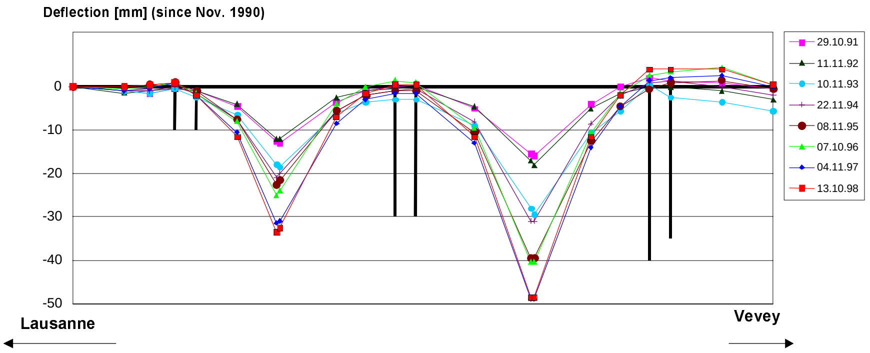

Figure 10: Deflected shape of the South Lutrive Bridge relative to its position after the retrofitting

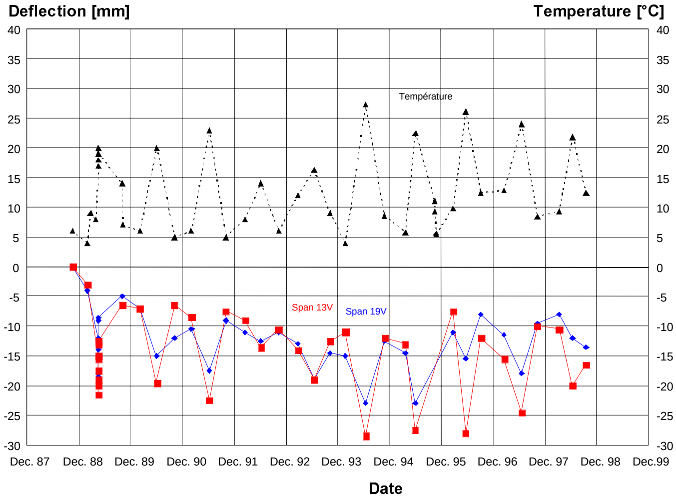

Figure 11: Long-term deflections of the South Chillon Viaduct at two hinges (13V and 19V, retrofitted in winter 1995-96)

The Chillon bridges exhibit a completely different behaviour than the Lutrive bridges. Although they exhibit a permanent deflection at mid-span in the spans with an expansion joint, these deflections are almost entirely stabilised, and of a completely different order of magnitude than those of the Lutrive bridges. As fig. 11 shows, there is a small downward tendency of about 1 mm/year. After the application of the additional post-tensioning in the winter 1995-96, no clear change in the yearly deflections is detectable. The additional post-tensioning has achieved its intended function. It even appears that the slight downward tendency at the joint has been reversed, although this observation may be due to varying temperatures at the time of the measurements. The most striking pattern in the measurements of the Chillon bridge, is its extreme sensitivity to climatic conditions. The rythm of seasons is clearly visible in the deflections, and has a strong correlation to the air temperature.

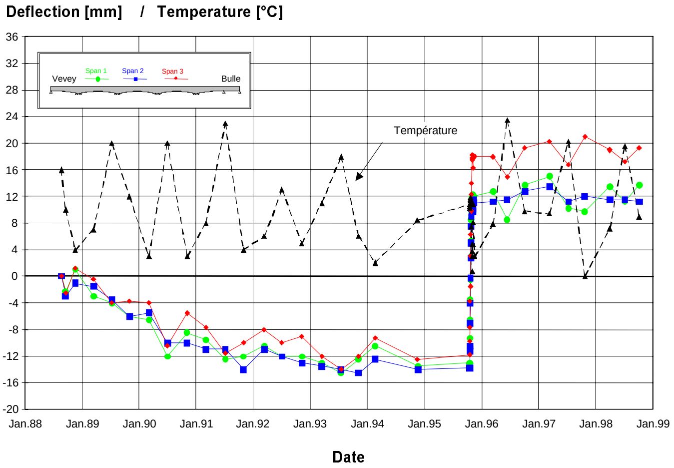

Figure 12: Long-term deflections of the Fégire bridge, retrofitted in winter 1995-96

The Fégire bridge was retrofitted with additional post-tensioning in the winter of 1995. The instantaneous upward deflection at mid-span (middle span) caused by the post-tensioning is just under 30 mm. The previous downward tendency clearly observable in fig. 12 appears to have been reversed by the additional post-tensioning. A slight upward tendency seems to develop. The bridge is less sensitive to temperature variations than the Chillon bridge, probably because it is continuous, without mid-span intermediate hinges.

4. Conclusions

The Lutrive, Chillon and Fégire bridges were retrofitted with additional post-tensioning to counter excessive long-term deflections. On the basis of these examples, it appears that:

- The addition of external post-tensioning can be a successful retrofitting technique for structures with serviceability limit state problems, such as excessive long-term deflections. It is a relatively flexible technique which can be fine-tuned to achieve the required results. It is for example possible to reverse the downward deflection trend of the bridge, as the case of the Fégire bridge shows.
- Long term monitoring of concrete bridges can be very useful. In the examples reported above, the deflection monitoring data proved extremely valuable for the evaluation of the bridge, and for the selection and design of the retrofitting scheme. It also continues to provide valuable feedback on the actual behaviour of the retrofitted bridges.

Acknowledgements
The bridge monitoring was funded by the Swiss Federal Highway Administration (OFROU) and the Highway Administration of the Canton of Vaud, Switzerland. Information regarding the design of the bridge retrofitting scheme was provided by the engineering firms RBA Engineers and Piguet Engineers in Lausanne, Switzerland. Their support is graciously acknowledged.

5. References

[1] FAVRE R., CHARIF H. and HASSAN M., *Post-Tensioning Level Criterion for Bridge Design and Rehabilitation*, IABSE San Francisco, USA, 1995.

[2] HOFACKER H. and BAUMANN K., *Brückenverstärkung durch aussenlilegende Vorspannung (Bridge strengthening by means of external prestressing)*, SIA, Zürich, 1996.

[3] FAVRE R., BURDET O., CHARIF H. et AL., *Enseignements tirés d'essais de charge et d'observations à long terme pour l'évaluation des ponts en béton et le choix de la précontrainte*, Rapport OFR n° 514, Zürich, 1995.

[4] PATRON-SOLARES A., GODART B. and EYMARD R., *Etude des déformations différées du pont de Savines (Hautes-Alpes)*, Bulletin des laboratoires des Ponts et Chaussées, 203, 91-103, France, 1996.

[5] FAVRE R. and MARKEY I., *Long-term Monitoring of Bridge Deformation*, NATO Research Workshop, Bridge Evaluation, Repair and Rehabilitation, NATO ASI series E: vol. 187, pp. 85-100, Baltimore, USA, 1990.

[6] FAVRE R. and MARKEY I., *Généralisation de la méthode de balancement des charges, Generalization of the Load Balancing Method*, 12th FIP Congress, Béton Précontraint en Suisse, pp. 32-37, Washington, USA, 1994.

[7] FAVRE R., BURDET O. and CHARIF H., *Critères pour le choix d'une précontrainte: application au cas d'un renforcement*, Colloque International "Gestion des Ouvrages d'Art: Quelle Stratégie pour Maintenir et Adapter le Patrimoine", pp. 197-208, Paris, France, 1994.