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Post-Tensioning Level Criterion for Bridge Design and Rehabilitation

Critère du niveau de la précontrainte
pour le projet et le renforcement de ponts

Kriterien für den Grad der Vorspannung bei der Bemessung und beim
Unterhalt von Brücken

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SUMMARY

The choice of post-tensioning level has important consequences on the serviceability and durability of bridges. Because of competition, designers often choose the most economical solution corresponding to the code requirements. While such a choice guarantees the resistance of the structure, the serviceability and the durability are not always satisfactory. From 20 years of experience it was observed that bridges with a low level of post-tensioning have often exhibited unsatisfactory behaviour characterised by cracking and instability of deflections. Through the analysis of the behaviour of more than 200 bridges, an appropriate level of post-tensioning is proposed to ensure the satisfactory behaviour of a bridge. A case study is presented.

RÉSUMÉ

Le choix du niveau de la précontrainte dans un ouvrage a des conséquences déterminantes sur son aptitude au service et sa durabilité. A cause de la compétition, les concepteurs de ponts ont tendance a choisir les solutions de précontrainte les plus économiques qui satisferont les critères des normes de construction. Ce choix assure évidemment la sécurité structurale de l'ouvrage; par contre l'aptitude au service et la durabilité ne sont pas toujours satisfaisantes. A partir de 20 ans d'expérience il a été observé que les ponts ayant un faible niveau de précontrainte ont souvent montré un comportement en service non satisfaisant, caractérisé par la fissuration et la non-stabilisation des déformations. A travers l'analyse du comportement de plus de 200 ponts, un niveau de précontrainte approprié est proposé afin d'assurer un comportement satisfaisant d'un pont. Un cas d'étude est présenté.

ZUSAMMENFASSUNG

Die Wahl des Vorspanngrades in einem Bauwerk spielt eine massgebende Rolle für seine Gebrauchstauglichkeit und Dauerhaftigkeit. Infolge des harten Wettbewerbes um preisgünstige Lösungen wird die Intensität der Vorspannung meistens nur so hoch gewählt, als dass sie gerade die Vorschriften der Normen erfüllen, unter Missachtung der eindeutigen Qualitätssteigerung durch eine höhere Vorspannung. Beobachtungen an bestehenden Brücken wahrend 20 Jahren sowie über 200 Belastungsproben haben einen eindeutigen Zusammenhang zwischen Vorspanngrad und Dauerhaftigkeit (Risse und Verformungen) gezeigt. Es wird ein konkreter Vorschlag für die Wahl der Vorspannung abgeleitet. Aus einer Fallstudie wird berichtet.

1. Load balancing method

The degree of load balancing β is the ratio of the equivalent load due to the curvature of the cable u to the permanent load of the structure g (Eq. 1) :

$$\beta = u / g \tag{1}$$

where; β : degree of load balancing, g : permanent load, u : equivalent load given by Eq. 2 :

$$u = 8 \cdot f \cdot P/\ell^2 \tag{2}$$

where; P : prestressing force, f : sag of the parabolic cable, ℓ : span.

2. Influence of load balancing degree and loading level on bridge stiffness

Figure 1 shows the correlation between the degree of load balancing and the ratio of measured deflections to those calculated in state I for 20 post-tensioned bridges. The ratio of measured to calculated instantaneous deflections increases when the load balancing degree decreases. This means that a low prestressing level allows cracking in the superstructure which results in deflections that are higher than those calculated in state I without any cracking.

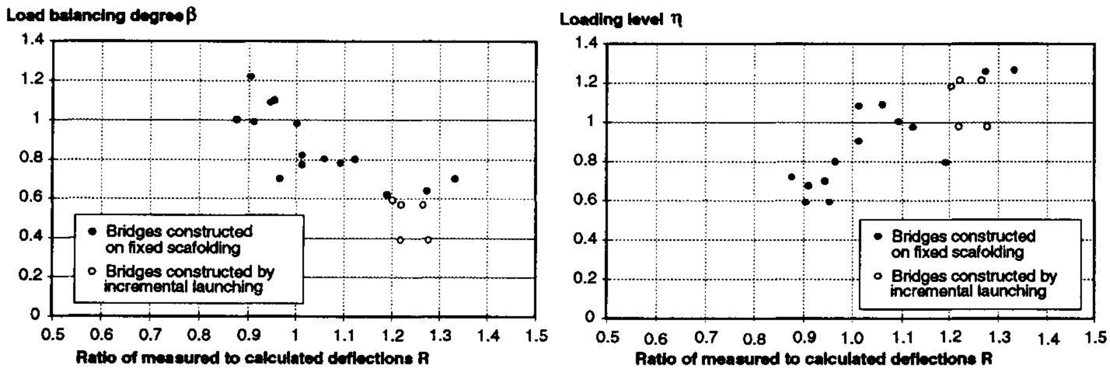

Figure 1: Load balancing degree β and loading level η versus the ratio of measured to calculated instantaneous deflections in state I

The loading level is defined as the ratio between the moment caused by the testing load and the moment of Code design load without multiplication by the load factors. This ratio is calculated at the middle of the loaded span considered as a simple beam. Figure 1 shows the correlation between the loading level and the ratio of measured to calculated deflections. A high loading level results in a high measured to calculated deflections ratio which means a decrease in the bridge stiffness caused by cracking.

3. Concept of compensation of deformations

It is not always easy to apply the load balancing method. An example is provided by the case of concrete structures with straight cables and with variable inertia. Thus, the concept of compensation of deformations can be used as an extension of the load balancing method. In this concept, the deformation of the structure due to any cable geometry is calculated and compared to the one due to permanent load. The ratio between these two deformations is defined as the degree of compensation of deformations and is also denoted β.

4. Recommended load balancing or compensation of deformations degree

The detailed analysis of 20 bridges together with a parametric study enabled us to establish a correlation between the load balancing degree, the loading level and the ratio of measured to calculated deflections. For a loading level equal to one (the code's design load), the load balancing degree is a function of R (the ratio of measured to calculated deflections) according to Eq.3.

$$\beta = 0.83 - 0.9 \ln R \qquad (3)$$

where : β : load balancing degree;

R : ratio of measured to calculated deflections or ratio of stiffness in state I to the mean stiffness with cracking.

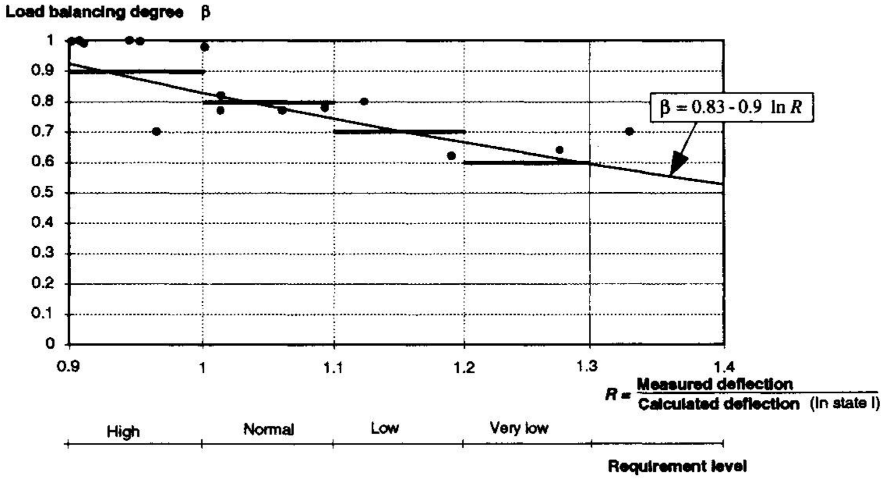

Figure 2: Recommended load balancing degree as a function of requirement level shown with the results of load tests carried out on 15 bridges constructed on fixed scaffolding

Figure 2 shows the load balancing degree described in Eq. 3 as a function of (R). The load balancing degree of 15 bridges constructed on fixed scaffolding are also represented as a function of (R) measured during a load test. Requirement levels are defined as a function of the importance of cracking (expressed by R) and a load balancing or compensation of deformations degree is recommended as a function of the importance of the bridge, the service load and the bridge environment.

The **high requirement level** is recommended when no cracking is allowed under the code representative loads. This requirement is necessary for bridges that have heavy loads or in unfavourable conditions. In these cases a β of 0.9 of permanent loads is necessary to fulfil a satisfactory behaviour. The **normal requirement level** means that the bridge could have a limited cracking but without risk with respect to the bridge durability. In this case a β of 0.8 is recommended. For little importance bridges with low loads and in favourable conditions a **low requirement level** can be accepted. In such bridges a β of 0.7 is sufficient.

5. Case of strengthening : Lutrive bridges

Lutrive bridges (North and South) are two parallel twin bridges. Each one supports one side of the Swiss national motorway RN9 between Lausanne and Vevey. Built in 1971/72 by the corbelling method with central articulations, the two bridges are gently curved (r = 1000 m) and each bridge is approximately 395 m long with four spans of: 57.95 - 129.50 - 143.50 and 64.00 m (Figure 3).

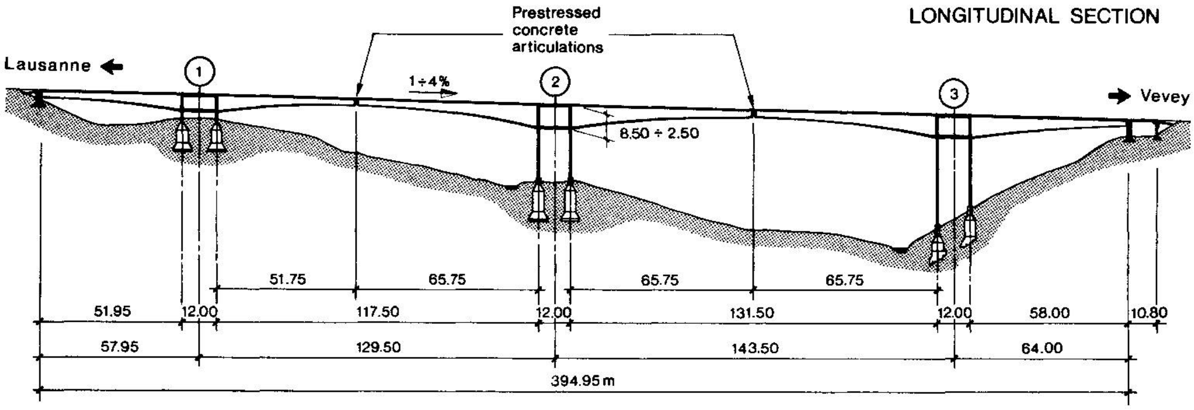

Figure 3: Longitudinal section of Lutrive South bridge

The two bridges have the same cross-section. It consists of a box girder of variable height and two slightly dissymmetric cantilevers, meant to reduce the effect of torsion in the curved bridges (Figure 4).

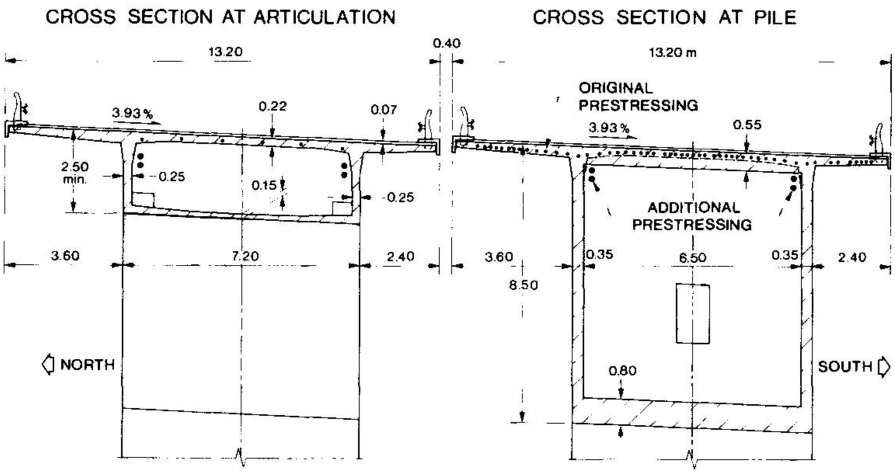

Figure 4: Cross-section at the central articulation and at the pile

The main span, 143.40 m long, underwent an approximate deflection of 16 cm. However this did not include the initial pre-camber of the span which was not measured but estimated at 11 cm. From 1973 to 1987 the deflection was a continuous downward movement which showed no sign of stabilisation (Figure 5).

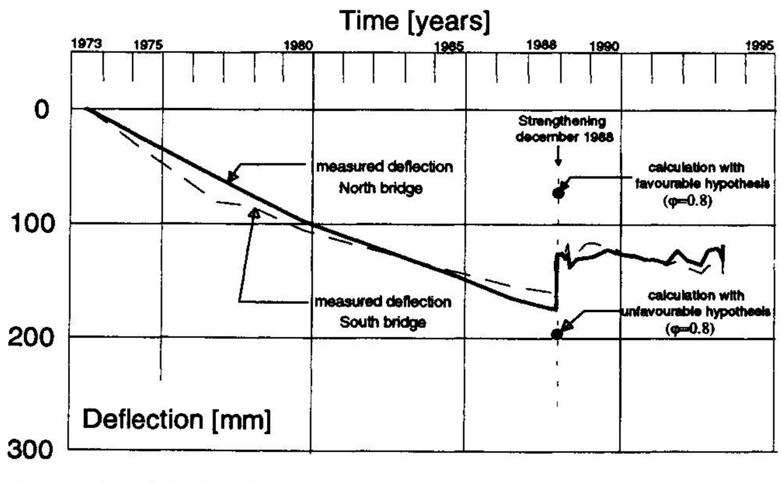

Figure 5: Measured and calculated deflections

Thus, in 1988 it was decided to « repair » the bridges with an additional external prestressing force of $P_0 = 4 \times 3345$ kN = 13380 kN for each bridge (4 Freyssinet cables with 18 strands pretensioned to 0.7 f_{tk}, where $f_{tk} = 1770$ N/mm^2). Figure 6 shows the strengthening project.

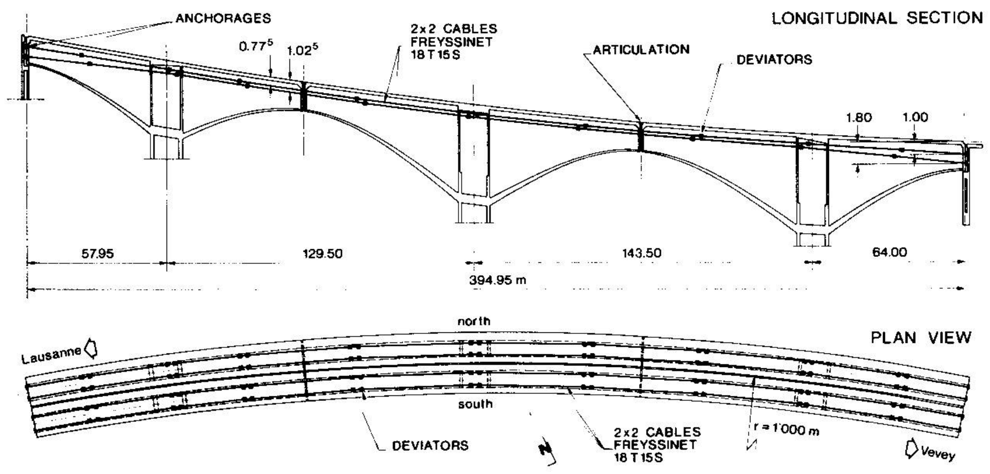

Figure 6: Scheme of the strengthening additional prestressing

The long-term deflections under permanent load of Lutrive bridges were calculated with the non-linear finite element software MAPSDIFF [6] which can take into account the time-dependent effect (creep of concrete), the cracking and the redistribution of solicitations. The calculation was carried out with two assumptions concerning the mechanical and the rheological properties of concrete and concerning the prestressing forces. Tablè 1 shows the values of the parameters considered in the two cases.

	Case	
	"favourable"	"unfavourable"
Elastic modulus E_{co} [kN/mm^2]	35	35
Tensile strength f_{ct} [N/mm^2]	2,5	0,0
Creep coefficient φ (∞, July 73)	0,8	0,8
Concrete self weight g [kN/m^3]	25,0	26,0
Watertightness+Surface g' [kN/m']	28,0	34,0
Traffic quasi-permanent q [kN/m^2]	0,0	2 kN/m^2 or 24 kN/m'
Average prestressing P_m	0,925 P_0	0,75 P_0
Final prestressing P_∞	0,85 P_0	0,68 P_0

Table 1: Considered values for the « favourable » and « unfavourable » assumptions

Figure 5 also shows the calculated deflections. It was noticed that the measured deflection (160 mm) is much closer to the one calculated with the « unfavourable » assumption (196 mm) than the one calculated with the « favourable » assumption (75 mm).

The probable degree of compensation of deformations β for Lutrive bridges can be estimated as follows:

- the degree of compensation of deformations calculated with an average prestressing force $P_m = 0.925\ P_0$ is equal to 0.79.
- according to our calculations, it seems that the real prestressing force was overestimated for these bridges and in reality we have to consider an average prestressing force equal to $P_m = 0.75\ P_0$.
- so the actual degree of compensation of deformations is equal to:

$$\beta_{origin} = (0.75 / 0.925) \times 0.79 = 0.64$$

After strengthening the value of β can be increased by:

$$\beta_{strengthening} = 4.43 / (20.5 + 3.5) = 0.18$$

with

4.43 [cm]: the calculated value of the elastic deflection due to the additional prestressing.

20.5 [cm]: the calculated value of the elastic deflection under self weight $\gamma = 25$ kN/m^3.

3.5 [cm]: the calculated value of the elastic deflection under watertightness + surface of 28 kN/m'.

Thus, the final value of β is equal to:

$$\beta_{total} = 0.64 + 0.18 = 0.82$$

This new degree of compensation of deformations improves considerably the situation and it approaches the recommended value of $\beta = 0.90$ for high quality bridges.

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