Partial prestressing with and without bonding in bridge decks

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Partial Prestressing with and without Bonding in Bridge Decks

Précontrainte partielle par câbles adhérents ou non dans les tabliers des ponts

Teilweise Vorspannung mit und ohne Verbund bei Fahrbahnplatten

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SUMMARY

Prestressed structures can be treated consistently with all degrees of prestressing. Basic criteria are given on how to select the appropriate solution as compared to the present practice of thinking in separate classes. This consistent approach is demonstrated for the design of bridge decks so that an optimum solution with bonded and unbonded strands can be given. It is shown that the amount of prestressed and non-prestressed reinforcement used in the slabs can be selected for various boundary conditions with consideration on aspects of reliability and economy.

RÉSUMÉ

Les structures précontraintes peuvent être traitées d'une façon cohérente à tout degré de précompression. Les critères de base permettant de sélectionner la solution optimale sont donnés, en comparaison avec la pratique actuelle des classes distinctes. Cette approche cohérente est démontrée dans le cas du dimensionnement des dalles de roulement, afin de présenter une solution optimale par câble adhérents au non. On montre ainsi que la quantité d'armature passive et précontrainte dans les dalles peut être sélectionnée pour divers conditions aux limites tout en tenant compte de la sécurité et de l'économie d'ensemble.

ZUSAMMENFASSUNG

Spannbetonkonstruktionen können einheitlich mit verschiedenen Vorspanngraden untersucht werden. Grundsätzliche Kriterien werden erläutert, wie eine geeignete Lösung zu wählen ist, im Vergleich mit dem augenblicklichen Denken in getrennten Güteklassen. Dieses einheitliche Vorgehen wird erläutert für den Entwurf von Fahrbahnplatten, damit eine optimale Lösung für Litzenspannglieder mit und ohne Verbund erreicht wird. Der Anteil an vorgespannter und schlaffer Bewehrung in den Fahrbahnplatten kann für verschiedene Randbedingungen unter Beachtung der Zuverlässigkeit und der Wirtschaftlichkeit gewählt werden.

1. Introduction

The question which appears every time when designing bridge-superstructures is: Which construction of the roadway slab in prestressed concrete has to be chosen for different boundary conditions taking into account durability and economy?

The general opinion which assumes that there is an increase of quality from reinforced concrete to partial prestressing and up to limited or even full prestressing needs to be corrected, because this simple point of view is not correct. This thinking in different quality classes must be overcome by summing up the whole range to structural concrete [1].

2. Degree of prestressing

The sign of the so far still differently named structures is the degree of prestressing κ. This degree is defined as the fraction of the whole sum of actions, which - together with the chosen prestressing - is leading to decompression at the unfavourable cross-section-fibre, this means a concrete tension zero.

Regarding beam structures under bending with axial force, this definition corresponds to the ratio of the internal forces - decompression moment to load moment -, which are related to the relevant kern point. The degree of prestressing has the following clearly defined boundaries:

$\kappa = 0$ reinforced concrete
$\kappa = 1.00$ full prestressing
$\kappa \approx 0.70$ to 1.00 limited prestressing

The partial prestressing covers the range of κ=0 to approximately 0.70, because only for the κ-fold part of the complete actions in the service state there are compressive stresses in the whole examined cross-section.

The practical application shows that especially the degree of prestressing from 0.40 to 0.70 often results in constructively and economically favourable solutions. However, values of κ≤0.40 can only be used efficiently to improve the properties of reinforced concrete in the service state [2].

$$\text{degree of prestressing } \varkappa = \frac{\sigma_{c,p}}{\sigma_{c,g+q}} = \frac{M_0 + N_0 k_0}{M_{G+Q} + N_{G+Q} k_0}$$

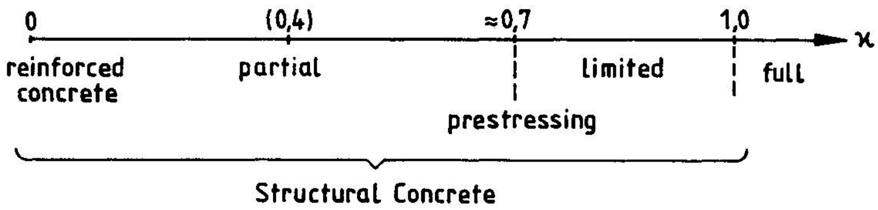

Fig.1: Definition for the degree of prestressing and the range of structural concrete

For the whole range of the structural concrete, one could give the following recommendation: Only as much prestressing as necessary, in order to achieve a favourable behaviour in the service state by means of additional axial and transverse forces with regard to deflections and reduced crack formations. But not less reinforcement as reasonable, in order to assure the durability and the reliability of the prestressed reinforced concrete concerning crack width control.

3. Restrictions of the standards

The rules of the DIN 4227, which are actually used in Germany, contain different restrictions which limit the application of the partial prestressing to a great extent. In the following they are explained by the limiting values of the concrete stresses at the unfavourable edge of the cross section:

DIN 4227, Part 1 (full and limited prestressing) prescribes that the tensile stresses - resulting of dead load, imposed deformations and 1.0-fold live load - may not exceed the given values ($\approx 2{,}5 \div 3.5$ N/mm^2) and that for the sum of the actions - including 0.5-fold live load - no tensile stresses appear.

In Part 2 (partial prestressing with bond) no stress checks are required, but it must be checked that for the actions including 0.5-fold live load the sheathing of the tendons is situated in the compressive area of the cross-section.

Part 6 (unbonded tendons) gives no limitations for the degree of prestressing. However, instead the general demand of the bridge authorities is relevant. This lays down that for the sum of actions and 0.3-fold live load - as the quasi permanent live load - at the unfavourable edge of the cross-section no tensile stresses might appear. This leads to the unintentional result that usually for all actions and 1.0-fold live load the tensile stresses do not exceed the values of DIN 4227, Part 1 and a planned crack formation does not occur (see the following examples).

Fig.2 shows the relation between the degree of prestressing κ and the usual ratio of live load moment to the permanent load moment, which in general is placed between 0.5 and 2.0. Moreover the required degree of prestressing, which is necessary to ensure that for the decompression moment the edge stress is zero, results with the quasi-permanent combination value ψ_Q [1] from the formula:

$$\text{dec}M = M_G + \psi_Q M_Q = \kappa (M_G + M_Q)$$

This degree of prestressing results from the given simple hyperbolic formula. One can recognize three facts:

1. The transition from limited prestressing and partial prestressing does not appear at a constant value, but varies between 0.8 and 0.7 with increasing ratio of M_Q to M_G.
2. If - including 0.3-fold live load - no tensile stress is required, the degree of prestressing can only be reduced by the hatched part. This means κ between 0.7 and 0.55.
3. If one follows a proposal of Menn [3] for the normal design of roadway slabs in Suisse - prestressing only for permanent load, i.e. $\psi=0$ - the result would be a considerably greater constructive possibility. Then the degree of prestressing could be reduced to approx. 0.4.

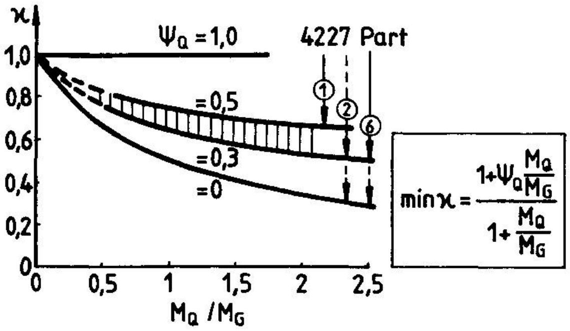

Fig.2:
Degree of prestressing for the decompression moment $M_G+\psi_Q M_Q$ with variation of ψ_Q
For bridges:
according to DIN 4227,P.1: min $\psi_Q \geq 0.5$
for Part 2+6 usually required: $\psi_Q > 0.3$

4. Application to roadwayslabs

For the construction and the design of roadway slabs one has to regard some peculiarities, such as the high percentage of live loads - $M_Q/M_G = 1\div2$ -, the dynamic actions and the attack of deicing salt. Therefore different answers are possible to satisfy the three principal requirements: load capacity, durability and economy.

For the problematic characteristics of the different constructions, examinations were carried out [4]. Fig.3 shows the cross-sections - box girder and double T-beam - which were half of the size of a normal German motorway (BAB). Especially, the results of middle and large dimensioned cantilevers are very expressive as a decision-making help if and how much prestressing is necessary for the transverse direction of the bridge.

The length of the cantilever were changed from 3 to 4.5 m and the depth of the connection from 0.4 to 0.65 m. The other dimensions were adapted. They do not lead to unfavourable results.

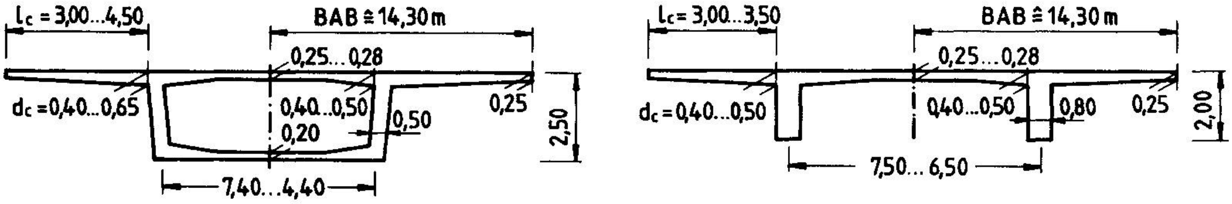

Fig.3: Form and dimension of the examined cross-sections

If the designer makes use of the partial prestressing, he has the best possibility to reach a construction with a reasonably increased amount of reinforcement and a sufficient amount of prestressing steel regarding load capacity and durability and, at the same time, a minimum of deformation.

The employment of tendons with bond requires special examinations regarding fatigue resistance and special corrosion problems - e.g. fretting corrosion and deicing salt effects.

If the internal transverse tensioning is carried out without bond, one will have the advantage of a durable corrosion protection and a larger allowable prestressing steel stress, but this construction leads to greater costs. I will leave the question beside, whether, at a later point of time, the tendons are actually changed or lengthened with widening of bridge superstructures.

Fig.4a explains the interaction between prestressing steel and reinforcing steel with different altitudes in the acceptance of the ultimate moment M_u for the concrete cantilever dimensions l_c=3.7 m and d_c=0.5 m. The sum of the A_p and the proportional A_s is shown versus the chosen degree of prestressing κ. The amount of the reinforcing steel is reduced with the ratio of the yield stresses of the reinforcing steel to the usual prestressing steel. This ratio - approx. 1:3.1 - nearly corresponds to the ratio of the costs.

You can recognize that for κ=0 and A_s=3.1·7=22 cm^2 the limit of a rational design in reinforced concrete is nearly reached. On the other hand you can see that from κ=0.5 the existing safety against rupture is greater than 1.75. If you take the additional contribution of the minimum reinforcement into consideration, the hatched saving of the prestressing steel will enlarge about this proportional amount of reinforcing steel. An economical and at the same time technical optimum is clearly situated at the partial prestressing with κ=0.5 to 0.6.

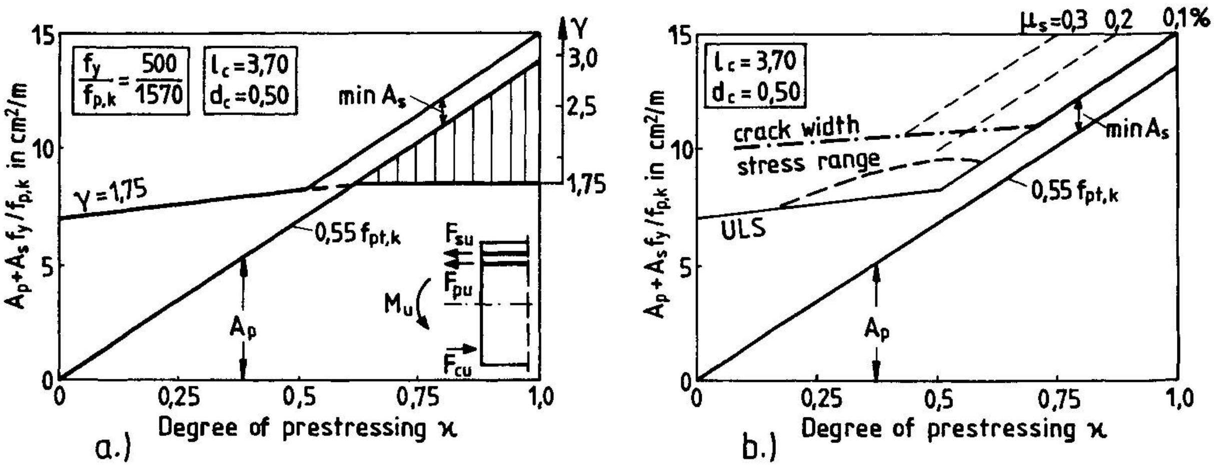

Fig.4: Proportional amount of reinforcement in a posttensioned cross-section
a.) from the check of the load capacity (ULS)
b.) from the check of the crack width and the stress range (SLS)

Among the transferred results from the ultimate limit state (ULS) the demands of the durability in the service state are supplementary analysed in Fig.4b. A substantial greater amount of reinforcing steel for the partial prestressing is the result of the crack width control according to DIN 4227 - paragraph 10.2, including ΔM - which is actually not yet conforme to DIN 1045. However, the crack width control is not responsive for limited prestressing (κ=0.75), so that you cannot make use of a reasonable percentage of reinforcement μ_s=0.2 to 0.3% for the load carrying capacity.

In the case of partial prestressing, the range of the stress amplitude of the prestressing steel might not exceed the reduced value of 110 N/mm^2 to guarantee the fatigue resistance. Moreover, Fig.4b shows that for roadway slabs this checking is not decisive and the required amount of reinforcing steel is smaller than the amount which results from the crack width control.

The demands and the knowledge which are explained in Fig.4a and 4b can be transmitted into design nomographs. These nomographs can be used as a help for the decision on the choice of the quantity and the sort of prestressing as well as for the design of cantilevers.

In the nomograph in Fig.5a you can directly see the amount of the prestressing steel which belongs to the chosen cantilever length, the cantilever depth and the requested degree of prestressing. The left dimensional line applies to 0.55$f_{pt,k}$ for bonded prestressing, the right dimensional line is applicable to 0.7$f_{pt,k}$ for unbonded prestressing. For the bridges which are carried out in Germany the following values result: Wannebach with κ=0.61: A_p=8.4 cm^2/m, Berbke with κ=0.66: A_p=7.4 cm^2/m.

From Fig.5b you can get the amount of reinforcing steel for the crack width control for prestressing with bond. For the example Wannebach-Bridge with l_c=4.25 m and d_c=0.62 m, you can pick out the value of 11 cm^2/m and with this the solid reinforcement of ø12, e=10cm at the cantilever connection, whereas for κ>0.75 only 5 cm^2/m would be necessary.

From the nomograph in Fig.5c you can get the tensile stresses in the uncracked state. For reasonably chosen dimensions and κ=0.5 to 0.7 the maximal stresses are not greater than the tensile stresses which are allowed for the limited prestressing. For the Wannebach- and Berbke-Bridge they reach with 2 N/mm^2 only 60% of the allowed stresses from DIN 4227, Part 1. For this reason, a planned crack formation does not appear. Simultaneously, you can directly pick out the limit of a construction in reinforced concrete with κ=0 and the maximum permissible values of transverse bending.

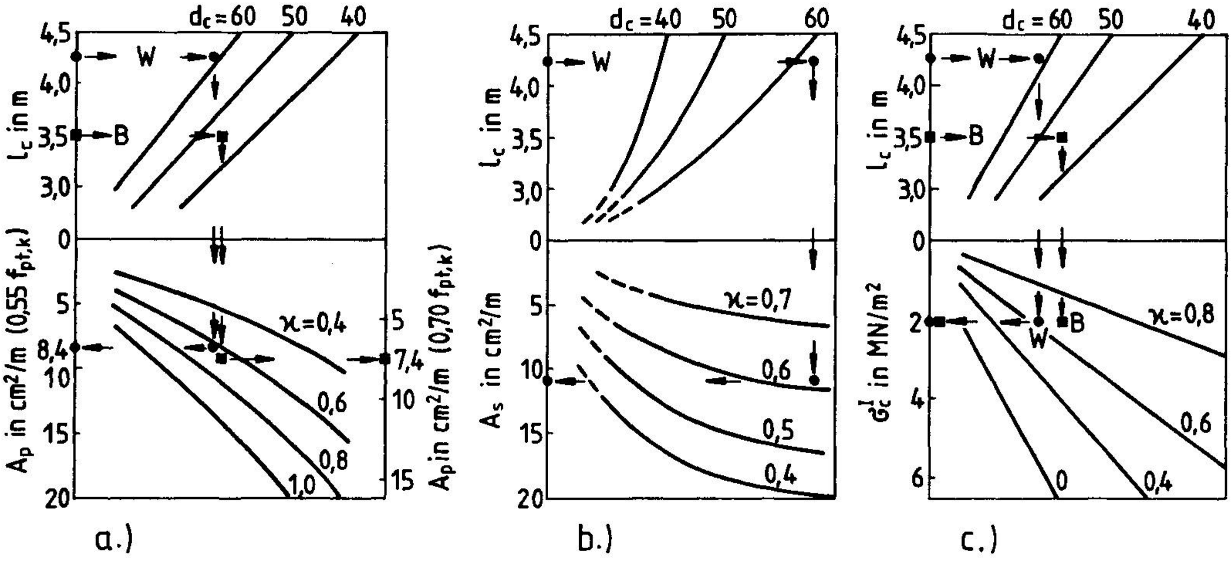

Fig.5: Nomographs for chosen cantilever dimensions (l_c and d_c) and the degree of prestressing (W=Wannebach-Bridge, B=Berbke-Bridge as examples)

a.) Amount of prestressing steel at prestressing with bond ($0.55f_{pt,k}$) and without bond ($0.70f_{pt,k}$)

b.) Amount of reinforcing steel of partial prestressing with bond resulting from the crack width control (w_{min} for ø12 mm)

c.) Edge stresses of the concrete in the uncracked state

5. Summary

With these general diagrams, which are based on the examinations of M. Empelmann [4], the designer has fundamental decision-making helps at his disposal to answer the question, which was submitted at the beginning: Whether or how much prestressing in combination with a sufficient reinforcement has to be chosen. In order to reach an economical and technical optimum, the degree of prestressing can be recommended to $\kappa=0.5 \div 0.7$ and the percentage of reinforcing steel to $\mu_s=0.2\% \div 0.3\%$. Further details about the carrried out Wannebach- and Berbke-Bridge with the consequences of the degree of prestressing can be taken from [5].

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