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Increasing of deflection of prestressed concrete structures due to incorrect and harmful tendon layout

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ABSTRACT

The choice of prestress tendon layout, i.e., the location and profile, is often governed by construction stages, as well as the cross-section geometry. But it is important to optimize the layout of tendons so as to minimize deflections. Low deflections during the cantilever construction stages do not ensure acceptable deflections during the service life. The tendons installed during cantilever erection stages are usually very efficient during construction. However, after changes of the structural system (e.g., closing of the midspan joints) to make the structure continuous, the cantilever tendons might not significantly inhibit the long-term deflection growth because creep produces additional forces due to the redundancy of the new structural system.

1. INTRODUCTION

Apart from durability, the most important factor in the whole life design of reinforced and, in particular, prestressed concrete bridges, is the Service Limit State. From this point of view, prestressed concrete bridges are very sensitive to long-term increase of deflections. In particular, large bridges (exceeding 100 m span) exhibit in many cases a gradual increase of deflections during a very long time of service life (even after more than 30 years). This phenomenon has paramount importance for serviceability, durability and long-time reliability of such bridges.

Due to excessive deflections, many bridges must be either closed or repaired well before the end of their initially projected lifespan. The cost of reduced service life of structures is tremendous for society, the owners and users. In fact, it greatly exceeds, in strictly economic terms, the cost of catastrophic failure due to mispredicted safety margin.

This is why a reliable prediction of deflections in bridges during their construction as well as during their service life is of crucial importance for achieving good durability and long-term serviceability.

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2. ARRANGEMENT OF PRESTRESSING TENDONS LAYOUT

Prestressed slender bridges are extremely sensitive to deflections in general. Deflection is a result of two opposite actions: the first one is caused by the external (vertical) loadings like dead load and live load, the other one, which has the opposite direction, is the effect of prestressing. Both mentioned actions, when acting separately, would produce individually significant deflections of opposite directions. The resulting deformation due to simultaneous action of the both loadings - due to external (vertical) loads and due to prestress - is, however, different from the mentioned deflections. This difference of large numbers is very sensitive; a small change in one of these numbers may result in a very significant change of their difference, i.e., a change of the final deflection value.

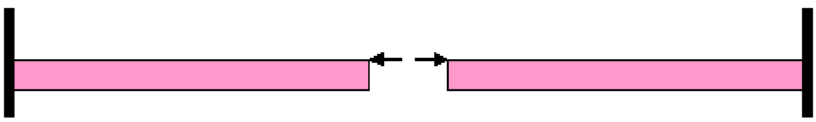
In reality, all the parameters are of a random nature. The dead and live loads are usually known rather reliably. On the other hand, the prestressing shows much larger deviations from the assumed values. This initial uncertainty comes from, amongst other factors, unknown prestress losses in the initial state of the structure. Further increase of prestress losses depends on many factors, and the losses are not easy to predict, in particular if the stress can vary along the length of the tendon. Regarding the above-mentioned sensitivity of deflections on the contributing components, the randomness of prestressing plays a very significant role when predicting deflections.

Efficiency of prestressing to reduce deflections is very significantly affected by the layout arrangement of prestressing tendons. The cantilever tendons, applied in erection stages, are usually very efficient during construction. However, after changes of the structural system making the structure continuous in the final structural system (e.g., closing of the midspan joints), their efficiency on the long term growth of deflections may be significantly limited, since the additional forces are developed due to the redundancy in the new structural system.

Among the important issues concerning efficiency of the prestressing layout arrangement thus belongs the question in what manner the bridge long-term deflection are influenced (in the final structural system) by the prestressing layout arrangement applied during the construction stages. It can be shown that low deflections of the bridge during the cantilever construction stages do not automatically result also in acceptable deflections during the bridge service life.

This can be demonstrated on two elementary examples:

(i) Two cantilevers are prestressed by tendons anchored at their end cross-sections as in Fig. 1. This arrangement of prestressing layout is very efficient to reduce deflections in the cantilever stage, but it is absolutely inefficient to reduce deflection increments after the cantilevers are made continuous to form a final structural system. Such a final system (a clamped beam) deforms as being without any prestressing.



No effect for reduction of future growth of deflections!

Fig.1 Prestressing in the cantilever stage

(ii) The final structural system of a bridge is formed by a three-span continuous beam as in Fig. 2. The effects of two locations of a prestressing tendon on the midspan deflection are discussed and compared. Using the influence line of the midspan deflection, it can easily be shown that a relatively small shift of the tendon locations results in quite opposite effects on the midspan deflection (Fig. 2).

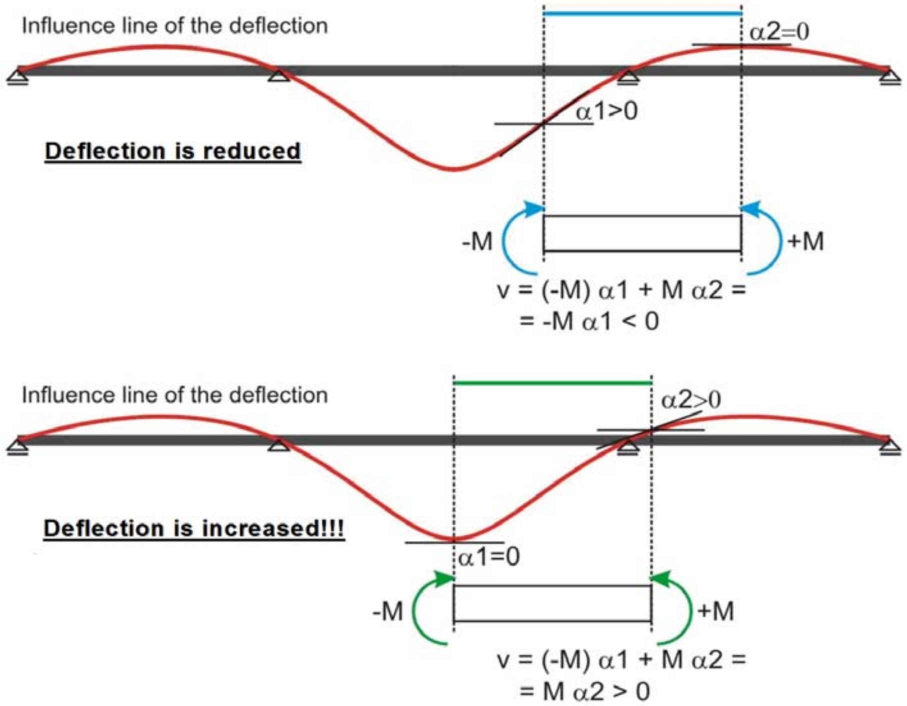


Fig. 2 Different arrangement of a prestressing tendon location resulting in opposite midspan deflections: a) midspan deflection is reduced, b) midspan deflection is increased

3. ASSESSMENT OF EFFICIENCY OF PRESTRESSING TENDON LAYOUT FOR REDUCTION OF DEFLECTIONS OF REAL EXISTING BRIDGES

Two examples elucidating significance of the tendon arrangement layout are presented below.

Bridge over the River Labe in Melnik

As the first example, the bridge over the River Labe in Melnik built in 1992 in Central Bohemia - three span continuous box girder bridge (72,050 + 146,200 + 72,050 m – Fig. 3) with tapered shape, erected using the cantilever technology - is considered and analyzed. The main task is to discover a possible unsuitable arrangement of the tendon layout that can result in harmful effects – as such tendons cause long-time increase (instead of reduction) of the midspan cross-section deflections.

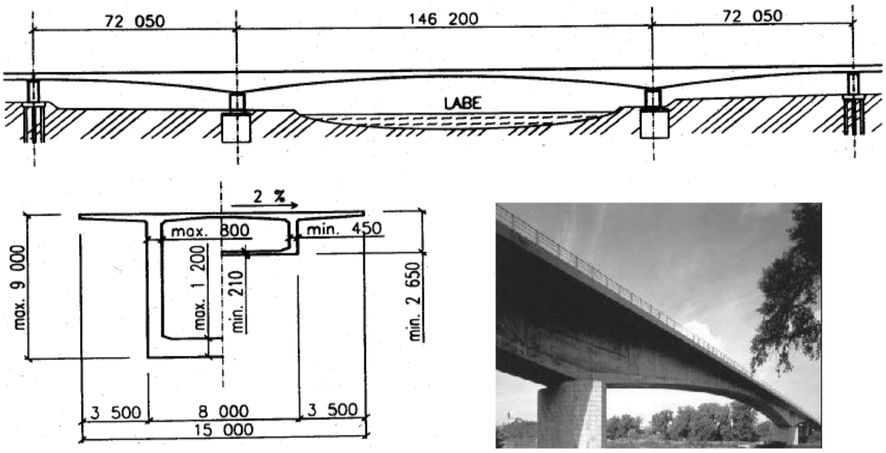


Fig. 3 Bridge over the River Labe in Melnik

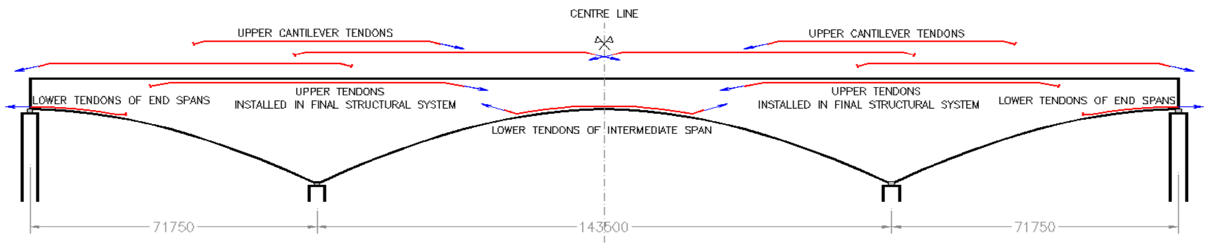


Fig. 4 Scheme of layout of prestressing tendons

Several categories of tendons, corresponding to individual stages of the construction process, were used during construction (see Fig. 4):

A) Tendons located at the top surface, applied during cantilever erection stage
B) Tendons located at the bottom surface of the middle (main) span
C) Tendons located at the bottom surface of the first and third spans
D) Tendons located at the top surface over internal supports, applied at the time when box girder cantilevers are joined continuously at their ends to form the final structural system

Effects of individual tendons were evaluated applying program **OPTI 1.1** (described in detail in Appendix); the results, indicating how individual tendons affect the midspan deflection, are summarized in Table 1.

Table 1

Tendon category	Total number of tendons	Unfavorable tendons	
		Number	[%]
A	80	14	18
B	12	1	8
C	8	8	100
D	4	0	0
total	**104**	**23**	**22**

It can be concluded that 22% of the total prestressing tendons affect the investigated bridge unfavorably, contributing to an increase of deflections. The tendons located at the bottom surface of the first and third spans (see Fig. 4) proved to be extremely harmful, since all of them produced deflection increase in the central region of the main span of the bridge.

Among the tendons located at the top surface, applied during cantilever erection, the straight tendons, which are passively anchored in the vicinity of internal supports and follow the top surface, are harmful. In the discussed bridge, the unfavorable tendons in the first (or in the third) span are anchored typically at distance of approximately 15 m from the ends of the bridge, the unfavorable tendons in the main span are anchored typically at distances of approximately 30 m from the midspan (see Fig. 4).

It should be noted that the locations and the lengths of the harmful regions vary due to the stiffness relations of the bridge under investigation.

Highway (D8) bridge over the river Ohre

The second example, the bridge on highway D8 over the river Ohre built in 1996 in North Bohemia – also three span continuous box girder bridge (70,5 + 137+ 70,5 m – Fig. 5) with tapered shape, erected using the cantilever technology - is considered and analyzed in the same way as the first example.

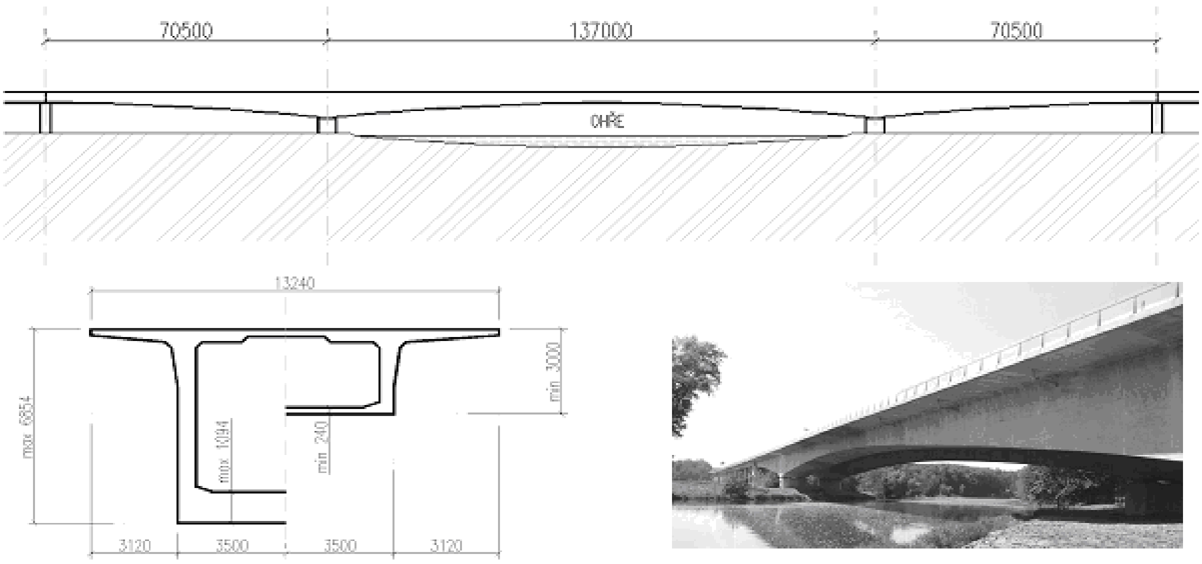


Fig. 5 Bridge on highway D8 over the river Ohre

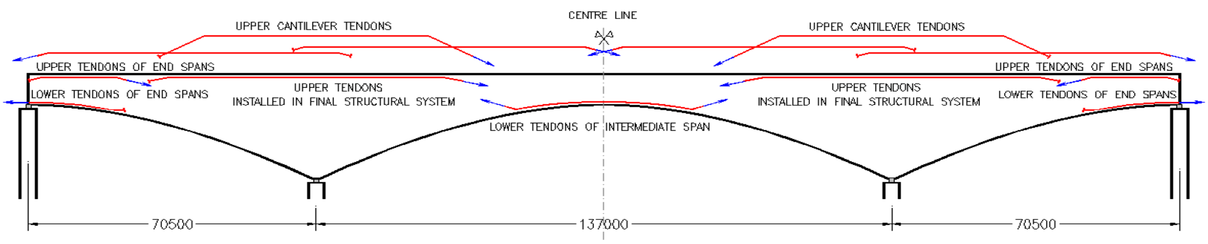


Fig. 6 Scheme of layout of prestressing tendons

Several categories of tendons, corresponding to individual stages of the construction process, were used (see Fig. 6):

- α) Tendons located at the top surface, applied during cantilever erection stage; part of these tendons (located nearby supports) is anchored at the bottom surface of the beam
- β) Tendons located at the bottom surface of the middle (main) span
- χ) Tendons located at the bottom surface of the first and third spans
- δ) Tendons located at the top surface of the first and third spans
- ε) Tendons located at the top surface over internal supports, applied at the time when box girder cantilevers are joined continuously at their ends to form the final structural system

Effects of individual tendons were evaluated again applying program **OPTI 1.1**. The results are summarized in Table 2.

Table 2

Tendon category	Total number of tendons	Unfavorable tendons	
		Number	[%]
	62	0	0
	14	0	0
	8	8	100
	4	0	0
	14	0	0
total	**102**	**8**	**8**

Only the tendons of the category χ, located at the bottom surface of the first and third spans (see Fig. 6), were proved to be harmful; all of them produce deflection increase in the central region of the main span of the bridge.

All other tendons reduce deflection at the midspan of the bridge. An important finding has been achieved by this analysis: it has been found that it is favorable for the reduction of midspan deflection if anchorages of the top surface located tendons are situated on the bottom surface of the box beam. Thus, in contrast to the first example (bridge over river Labe in Melnik), all the top surface located tendons of this bridge are efficient for deflection reduction. This arrangement is also very beneficial to reduce shear forces nearby internal supports.

4. A SIMPLE TOOL TO IDENTIFY THE MOST EFFICIENT LOCATION OF A TENDON

A simple method is proposed to determine the most efficient location of a tendon for reduction of deflections. The method is suitable for tendons that are equidistant from the centroidal axis of the bridge girder. The method, which is intended for use as an ideal design aid, allows the determination of the most efficient tendon location from a very simple graphical procedure.

The task is to determine the location of a tendon of length *s* with eccentricity *e* to produce maximum upward deflection of a bridge at cross-section *P* (see Fig. 7).

Provided that concrete creep represents a dominant effect, the time increment of deflections of a bridge of common arrangement in the final structural system caused by creep may be approximated as

$$\Delta y(t) = [\varphi(t,t_0) - \varphi(t_r,t_0)]\, y_e$$

in which φ is the creep coefficient, t_0 is the age of concrete at loading, t_r is age of concrete at the instant of change of structural system, t is the age of concrete at the investigated time, y_e is the instantaneous deflection in the final structural system due to the applied loads.

It is evident that this relationship is quite simple - the time increment of deflections may be approximated simply as a product of the instantaneous deflection and the difference of the creep coefficients. The proposed graphical procedure for determination of location of a tendon to produce maximum upward deflection is based on this relation.

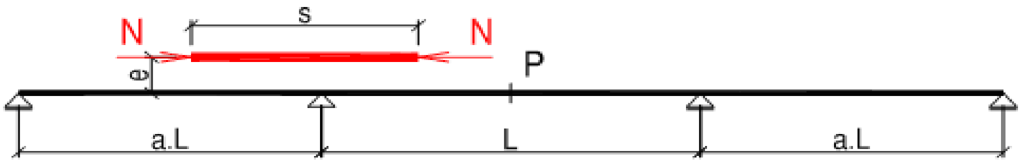


Fig. 7 Location of the tendon

The procedure consists of the following consequent steps:

1. construct the diagram of the derivative of the influence line of bridge deflection at section *P* (the full line in Fig. 8)
2. move this diagram to the left direction along the bridge axis about the tendon length *s* (the dashed line in Fig. 8)
3. the cross-sections with extreme differences of the both lines indicate the most efficient cross section *A* in Fig. 8 (or the most harmful cross section *Z* in Fig. 8) for location of the left tendon anchor
4. intersections of the both lines indicate the anchorage locations without any effect on deflection of cross-section *P*
5. intersections of the both lines demark the regions of beneficial effects (the dotted area in Fig. 8) and adverse effects (the dashed area in Fig. 8)

Nothing can be simpler.

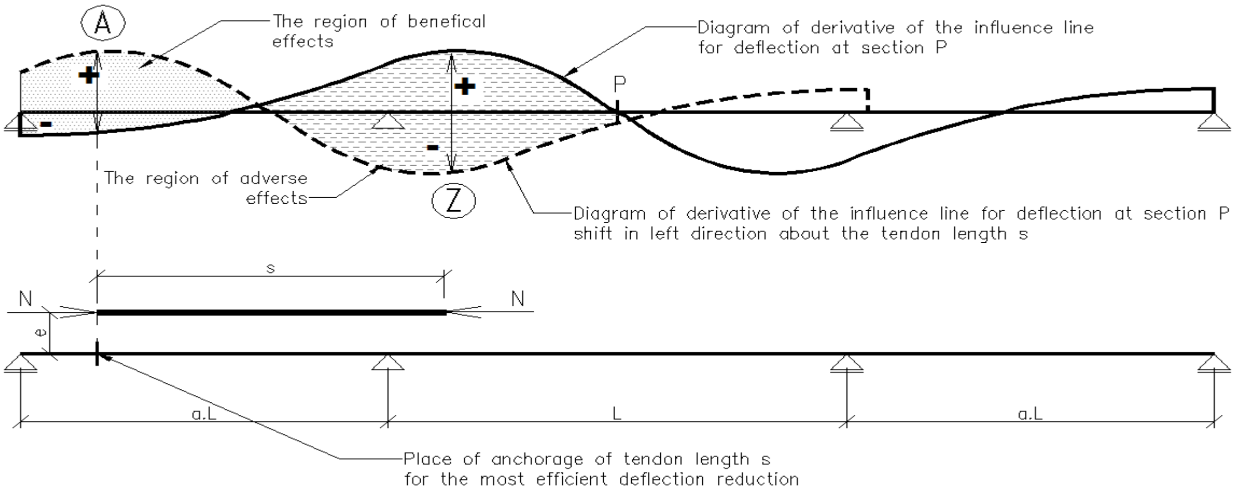


Fig. 8 Simple graphical tool to determine the most efficient location of a tendon for deflection reduction

6. CONCLUSIONS

The prestressed box girder bridges typically exhibit only a portion of deflections during the first period and then continue to deflect. Extensive monitorings on many bridges confirm these observations.

It may be summarized that the excessive and with time increasing deflections of long-span prestressed bridges are caused by a combination of several simultaneously acting factors. The research on this problem is extremely important, not only to avoid excessive deflections resulting in long-term serviceability impairments. It also should be noted that a wrong prediction of the development of deflections means that also prediction of the distribution of internal forces, particularly in bridges changing the structural systems, can be quite far from reality.

This paper has elucidated the significance of the tendon arrangement layout and presents methods to assess its efficiency on bridge deflections. The advantage of the proposed methods is their ease of application, which allows the optimal tendon layout to be determined from procedures. Examples of studies performed on real existing bridges are presented and the results discussed. The method was programmed (see Appendix) and is freely available on a web site and proposed as a design aid without recourse to expensive solutions.

Lessons from assessment of existing bridges can be learnt: bridge design should be performed on two different levels, including two equivalent parts – not only common stress analysis, but also optimization of prestressing tendon layout should be compulsorily performed to reach acceptable deflection variations.

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