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LONG-TERM DEFLECTIONS OF CANTILEVER SEGMENTAL BRIDGES

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Abstract. The long-term deflections of cast-in-place segmental bridges constructed using the cantilever method are often larger than the deflections expected in the design. A detailed structural analysis and monitoring of these types of bridges have therefore become a matter of interest. The paper gives a comprehensive analysis of phenomena that frequently conspire to cause long-span pre-stressed concrete bridges to deflect more than predicted. The analysis is based on a parametric study and long-term monitoring of the behaviour of a motorway bridge across the Vltava River in the Czech Republic. To reveal and quantify possible reasons for excessive bridge deflections, a detailed time-dependent analysis was carried out. The results of the study were compared with in-situ measurements that have been regularly carried out since the very early stage of construction. Theoretical values of the increments of deflections, pre-stressing forces and concrete strains were compared with the measurements.

Keywords: prestressed bridges, concrete bridges, long-term deflections, long-term behaviour, time-dependent analysis, creep, shrinkage.

1. Introduction

It is often encountered in practice that the long-term deflections of pre-stressed bridges are greater than the deflections expected in the design. Especially in case of cast-in-place segmental bridges constructed using the cantilever method, the excessive deflections might occur sometime after completion. Explanation of possible reasons for such large deflections therefore became a matter of interest of many engineers and researches. Consequently, some of them were specified. In spite of the effort no final quantification of the specified reasons and no unambiguous and definite statements have been concluded.

2. Possible reasons for excessive bridge deflections

The phenomena that often conspire to cause long-span pre-stressed concrete bridges to deflect more than predicted, have been identified based on the recommendations of Comité Euro-International du Béton in 1997, and considering the author's observations of the bridge and the results of stochastic analysis, Florian and Navrátil (1998).

A substantial number of reasons for excessive deflection arise from technological errors. They are in particular the enlargement of water content in concrete mixture, insufficient modulus of elasticity, strength or unit weight resulting from a poor quality of concrete, a wrong sequence or time schedule of construction steps, geometrical imperfections and higher pre-stressing losses, unsatisfactory stiffness of temporary supports or poor anchorage, improper and short curing and wrong estimate of the relative ambient humidity, etc.

Another reason for unexpected deflection is the omission of some phenomena during structural modelling of a structure. It concerns for example shear lag and the influence of shear on deformation generally, eccentric position of pre-stressed and non-pre-stressed reinforcement, the contribution of non-structural members, such as parapets and asphalt wearing surface, to the load carrying capacity, stiffness reduction due to cracks development, friction in bearings, etc.

A frequently discussed reason is the underestimation of the rheological effects, which is caused especially by using an inappropriate physical model, or which results from uncertainty of the creep and shrinkage prediction calculated only from the composition and strength of concrete.

Not fully appreciated is excessive creep and shrinkage of concrete resulting from the exposition of the structure to the harsh conditions in situ, e.g. long-term high temperatures of concrete, cyclic load, cyclic humidity or acceleration of drying due to micro-cracking, e.g. Bažant and Hubler (2013).

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The underestimation of long-term losses of the pre-stressing caused especially either by excessive shrinkage or creep of concrete decreases the level of applied pre-stressing and consecutively increases the deflection.

Creep and shrinkage related is also the underestimation of non-uniform drying of concrete in the section: the differential drying of differently sized parts of the cross-section, non-uniform drying across the thickness of slabs and walls or the influence of bridge deck waterproofing on drying of concrete cross-section.

3. Bridge across the Vltava River

To reveal and quantify the possible reasons for excessive bridge deflections the parametric study of long-term behaviour of the motorway bridge across the River Vltava was carried out. In parallel extensive technical supervision has been performed, followed by long-term monitoring since the construction of the bridge started in 1995.

3.1. Long-term monitoring

The construction of the bridge was carefully documented and an extensive testing program was carried out during the construction. The instrumentation for long-term measurements has been placed in the main span of the bridge, Fig. 1. In total five sections have been instrumented by mechanical or electric-resistance concrete strain gauges and two sections by electric-resistance thermal sensors.

The sensors have been placed in cross-section so that it would make the measurement of non-uniform distribution of temperature possible, Fig. 2. Magneto-elastic force sensors have been used for long-term monitoring of changes of pre-stressing. In total 37 geodetic points have been fixed in the box of the main girder for the measurements of the deflection.

A series of measurements have been executed since the end of construction in 1996, with the most recent measurement done in November 2008. Some of them are compared with theoretical values in this paper.

3.2. Parametric study

The detailed finite element model was developed for the analysis. The deterministic analysis of the bridge was carried out repeatedly for different input parameters, which enabled to quantify the phenomena significant for bridge deflection analysis. The full stochastic approach was not used due to the necessity to deal with a vast amount of data. The analysis aimed especially at the calculation of the long-term deflection of the main span.

Structural model. Certainly the structural model of bridges constructed using the cantilever method must respect the changes of static system and boundary conditions. New structural members are assembled or cast, post-tensioning is applied and temporary support elements are removed. Concrete of structural elements of various ages is combined. Therefore, during both construction and throughout the service life, account must be taken of the creep and shrinkage of concrete. Variety of static systems and the effects of creep and shrinkage make the structural

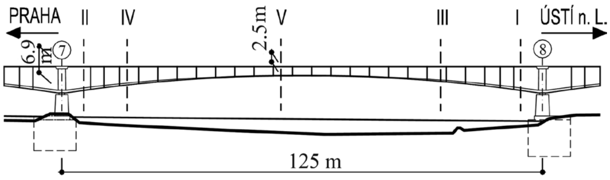

Fig. 1. Instrumented sections in the main span of the bridge

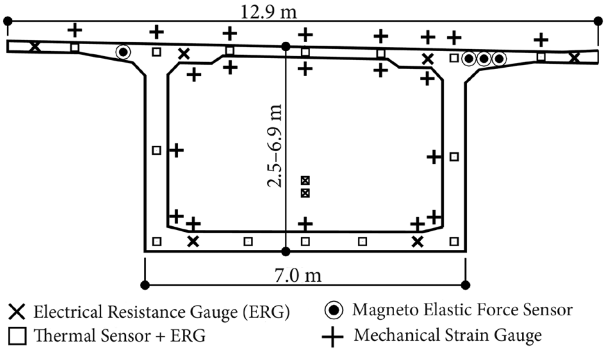

Fig. 2. Layout of measuring instrumentation in section IV

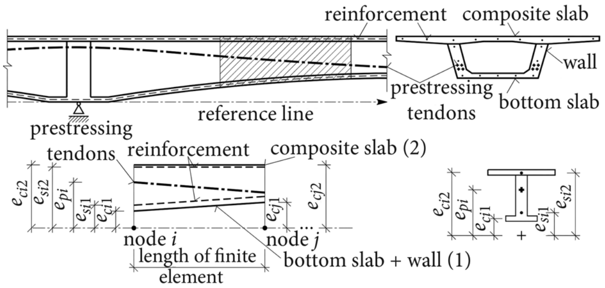

Fig. 3. TDA finite element model

analysis complicated. That is why sophisticated general methods are needed for the structural analysis, especially for the verification at intermediate stages of construction in structures where properties vary along the length. Such realistic modelling of structural behaviour was achieved using program TDA, Navrátil (1992). Limited space does not allow for the description of the details about the method used for the time-dependent analysis. Therefore the main features of modelling are summarized here only.

The finite elements on eccentricity represent the concrete box girder, pre-stressed tendons, diaphragms, piers, and temporary anchoring ties, non-pre-stressed reinforcement and the elements representing the formwork traveller, Fig. 3.

In general, the cross-section of the structural members consists of parts of various materials, e.g. concrete girder or composite slab, pre-stressed tendons or reinforcement that are modeled by individual elements. Therefore the centroidal axis of the element has to be placed in an eccentricity relating to the reference axis which connects the nodes.

The axial and transverse displacements and the shear strain are expressed in terms of the local degrees of freedom. Six external and two internal degrees of freedom are used. The axial and transverse displacements are approximated by the polynomial function of order 2 and 3, respectively. The static condensation of internal nodes parameters is used, thus full compatibility between eccentric elements is fulfilled.

The element formulation is based on the assumption that the plane of the cross-section remains plain, but not necessarily perpendicular to the center line, after deformation. The element stiffness matrix and load vector terms include the effect of axial, bending and shear deformations.

Linear aging viscoelastic theory is applied for time-dependent analysis. The method is based on a step-by-step computer procedure in which the time domain is subdivided by discrete times (time nodes) into time intervals. The finite element analysis is performed in each time node.

All operations in the construction are respected in the structural analysis according to the real production schedule. Real dead weight and real pre-stressing including the losses at transfer are considered in the analysis according to the records of both the contractor and independent observer. The contribution of the parapets to the stiffness of the structure and the friction in the bearings are neglected.

The studied input parameters. The structural model described above was a basis for the parametric study and it is marked as Variant 0 in this paper. In this variant the B3 rheological model is used in the basic formulation, see Bažant and Baweja (2000). The modulus of elasticity is calculated for stress duration Δ = 0.01 days and for designed composition of concrete, Table 1. The proper curing of concrete is assumed for the first three days. The average effective cross-section thickness is calculated for the whole cross-section with respect to the influence of bridge deck waterproofing. The average measured ambient humidity h = 0.77 is taken into account.

Table 1. Input parameters of B3 Model

w, kgm^{-3}	c, kgm^{-3}	a, kgm^{-3}	α_1	α_2	k_s	f'_{cyl}, MPa
170	410	1810	1.1	1.0	1.0	36.5

The composition, strength, and curing of concrete are the only material input properties for the majority of rheological prediction models. The composition and strength of concrete cast-in-situ always differ from the designed values, and they also differ for different segments. Detailed measurements of the quality of concrete during the construction of the bridge were collected by the authors, and used for the updating of input data in Variant 1 of the study.

In Variant 2 the real composition of concrete is modified in the way that water-cement ratio is kept constant, but both the water and cement contents are increased by 10% (simultaneously the aggregate content is decreased to retain the unit weight of fresh concrete). The lack of work discipline at the site very often leads to an increase in the water content, which makes the concrete easier to work with. To keep constant strength of concrete cement concrete is also proportionally increased, which increases the creep and shrinkage of concrete.

The type of curing is studied in Variant 4. In the case of the analysed structure, the curing was carried out through moistening of the fabric covering the horizontal parts of the box girder. The frequency of moistening was decreased during the first three days after casting. Therefore the effectiveness of the curing is questionable. For curing in water the value 1.0 of parameter α_2 is recommended by Bažant and Baweja (2000). In Variant 4 α_2 is considered 1.2, which is the value recommended for sealed specimens.

The largest source of uncertainty of creep and shrinkage prediction is the dependence of model parameters on the composition and strength of concrete. To reduce this uncertainty the short-time laboratory measurements of creep and shrinkage of small size specimens were carried out and were used for the updating of the prediction, Navrátil (1998a).

The updated B3 rheological model is used with parameters τ_{sh} = 245 days, p_6 = 1.4, p_1 = 0.13383·10^{-7}, and p_2 = 0.778397 in Variant 5. The quality of updated prediction was checked through the measurements of creep and shrinkage of specimens placed inside of the box of the box girder.

The influence of shear deformation on long-term deflection is tested in Variant 3. The contribution of shear deformation is respected in all variants of this study. The shear reduction factor is used for the calculation of effective area of the cross-section. In practice usually the area of the walls of the box girder is used as the effective area. But using this approach the effect of shear lag is neglected, which may lead to underestimation of deflections, see Bažant *et al.* (2008). For simplicity the modified effective area is used according to the recommendations in Petřík and Křístek (1998). The value of reduction factor 0.5 is used in Variant 3. All other input data are identical with Variant 1.

The effect of the drying of concrete is approximately expressed in terms of effective cross-section thickness. It depends on volume to surface ratio and it is calculated for the whole cross-section with respect to the influence of bridge deck waterproofing. The calculation itself is simple but still the calculated value is ambiguous. The uncertainties result from the differences in size between the laboratory specimens and a real bridge cross-section, and from the differences in ambient humidity inside and outside of the box. The sensitivity of long-term deflections on effective cross-section thickness is deduced from Variant 8 and 9 respectively, in which the effective thickness is decreased and increased by 10%. All other input data are again identical with Variant 1.

The creep and shrinkage of concrete exposed to the harsh conditions is accelerated and increased. These effects are approximately expressed by the extensions of the B3 model and were analysed in Navrátil (1998b). The updated B3 rheological model with extension for cyclic humidity is used in Variant 7, in which all other input data come from Variant 5. The environmental humidity cycles were monitored, recorded and analysed by the authors. For this study the period of humidity cycles is considered 210 days, and the amplitude of environmental relative humidity is taken as 0.27.

Variant 5 is also a basis for Variant 6, in which the effect of micro-cracking on the drying of concrete is studied. The updated B3 rheological model with no extensions is used. The effect of micro-cracking is respected via the correction of shrinkage half-time τ_{sh}. The diffusivity C_1 of given intact concrete is calculated from measured shrinkage half-time. The micro-cracks will increase the diffusivity as much as twice. Using new diffusivity it is possible to calculate new τ_{sh} and the new value of drying penetration depth D_p.

Variant 18 links together the preceding Variants 5, 6, 7. The updated B3 model with all extensions and with respect to micro-cracks is used together with real composition and measured strength of concrete.

In Variant 19 the mean values of measured relative environmental humidity were supplied in time intervals used for the time-dependent analysis. All other input data are again identical with Variant 18. This variant should therefore be the most sophisticated and closest to the reality so far.

The selection of a proper rheological model is of crucial importance for the realistic prediction of deflection. It is known that the models often reasonably differ. For this reason comparative calculations were performed for various models used in Czech and international codes: *ČSN 736207 – Design of Prestressed Concrete Bridge Structures, ČSN 731201 – Design of Concrete Structures of Buildings, CEB-FIP Model Code 1978* and *CEB-FIP Model Code 1990*. Two variants for each model were calculated. One for designed and one for measured composition and strength of concrete. From this point of view the input data are comparable in Variants 0, 10, 12, 14 and 16, and in Variants 1, 11, 13, 15 and 17. The input data were adapted for each rheological model specifically, including the effective cross-section thickness, concrete strength and modulus of elasticity, see Table 2. For the rheological model according to the *CEB-FIP Model Code 1990* the type of aggregate was determined as basalt.

The influence of differential shrinkage and creep of differently sized parts of the cross-section is usually neglected in design practice. Based on the study in Navrátil *et al.* (1999) and Křístek *et al.* (2006), the question arose of what the impact of this effect would be on real structures with more complicated geometrical shapes and construction. That is why a new structural model of the Motorway Bridge across the River Vltava was created based on Variant 5. The model therefore contains real composition and strength of concrete, B3 rheological model updated using short-time laboratory measurements, and mean values of measured relative environmental humidity.

The cross-section of the main span of the bridge is split into nine structural elements placed on appropriate

Table 2. Moduli of elasticity for various rheological models

Code	73 6207		73 1201		CEB-FIP 78		CEB-FIP 1990	
Variant	10	11	12	13	14	15	16	17
E, GPa	36.0	38.5	34.5	37.5	32.4	35.1	39.7	42.9

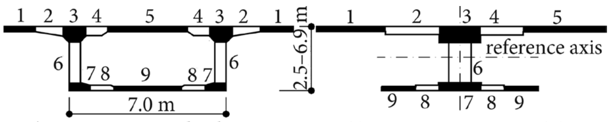

Fig. 4. Cross-section and the structural model

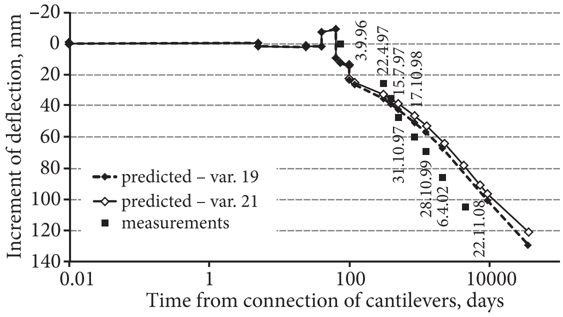

Fig. 5. Relative deflection at mid-span

eccentricity related to the reference axis, see Fig. 4. The cross-sections of other spans of the bridge are split into three structural elements (top slab, web, bottom slab). Hence this adaptation of the structural model results in a significant increase of finite elements. The effective cross-section thickness is calculated in three variants (i) for the cross-section (not split into elements) with bridge deck waterproofing – Variant 20, (ii) for the cross-section split into elements with bridge deck waterproofing – Variant 21, and (iii) for the cross-section split into elements without bridge deck waterproofing – Variant 22. It is assumed that the waterproofing is applied immediately after the end of curing (for simplicity) and it influences the drying of the cross-section.

3.3. Results

For this paper the outputs are limited to the vertical deflection in the middle of the main span and to an illustration of force variation in one pre-stressing tendon.

The variation of mid-span deflection over time is shown in Fig. 5 for two (most comprehensive) variants of the time-dependent analysis, for more variants (Navrátil 1999). The calculated vertical deflections are compared with measured values, which were adjusted for reference temperature and zero deformation of the piers. The deflections are related to the date of 21st June 1996, when the first geodesic measurement was performed after the connection of two ends of both double-cantilevers.

From that time, the uncertainties resulting from temporary supporting were eliminated, as the structure became continuous. It should be emphasised that the prestressing, parapets, barriers and surfacing had not yet been completed and the ballast had not yet been removed at that

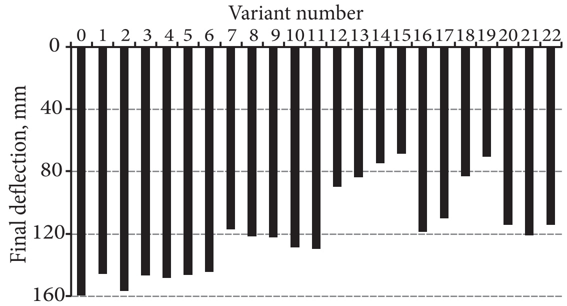

Fig. 6. Final relative deflection at mid-span

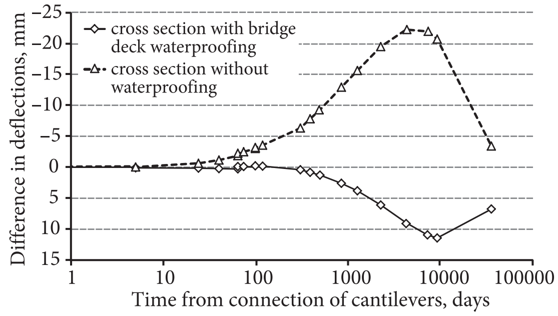

Fig. 7. Relative deflection at mid-span caused by differential shrinkage

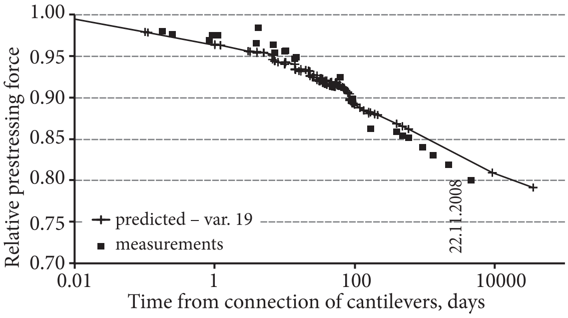

Fig. 8. Pre-stressing force in tendon

time. For the purpose of clear arrangement the final deflections at the time of 100 years are shown in Fig. 6.

Differential shrinkage and creep cause the deflection, which increases in time with the max reached approx 5000 days after the structure is made continuous. Further ahead the deflection decreases and it is close to zero at 100 years. It is seen in Fig. 7.

The difference in deflections calculated using the models in which the cross-section is and is not split into elements (e.g. Variants 20 and 21) is drawn on the vertical axis. The models with bridge deck waterproofing show the increase of the deflection approximately by 11.5 mm. Conversely disregarding the effect of waterproofing the decrease of the deflection by 22.3 mm is obtained. It documents the error made by the designer, who neglects the effect of waterproofing for the whole lifespan of the structure even though he takes into account differential shrinkage and creep. The underestimation of the deflections would be quite significant.

This finding explains why the gradient of measured deflections is higher than the gradient of values calculated in the first year of service. The acceleration of deflection might be caused by the application of waterproofing on the top slab of the box girder. Consequently the drying (and the effective cross-section thickness) is changed, which cannot be modelled by software used for the time-dependent analysis yet. Considering the results in Fig. 7, it could be concluded that differential shrinkage has no effect on the final value of the deflection, but it has significant impact on its in-time development. It is obvious that taking it into account the agreement between measured and calculated values improved.

Fig. 8 demonstrates the agreement between the prediction of pre-stressing forces and measured values. The tendon shown in the picture was investigated in segment 3B, close to the anchor. The relative force shown in the diagram was obtained as a ratio of pre-stressing force, which was calculated and measured respectively at a specific time, to the pre-stressing force calculated and measured at the moment of transfer. In this way it was possible to determine the relative level of long-term losses. Measured values of pre-stressing forces were adjusted for reference temperature and corrected with respect to the change of the temperature coefficient of tendon magneto-elastic characteristics, due to the force in the tendon.

4. Findings

Time-dependent analysis was performed for various input parameters and for various material models. Among the studied input parameters the water and cement contents have the greatest influence on long-term deflections. The importance of the selection of the rheological model for the realistic prediction of deflection is manifested in Figs 5 and 6. The most realistic predictions of both the gradients and total values of deflection are obtained by the B3 Model, especially in updated version with extensions (Variants 18 and 19).

The updating of the creep and shrinkage model for specific concrete is of crucial importance. The method for the updating of the prediction described in Bažant and Baweja (2000) and Navrátil (1998a) is efficient and it is usable even at the phase of the preparation of design documentation with relatively low expenses compared to the costs of important long-span bridges. For these reasons the incorporation of the method into present codes of practice is recommended, so that it will be used in future as standard procedure.

As it is shown in Fig. 6, the scatter of the final deflections is less than expected (from 70 mm to 160 mm) although the range of input parameters was relatively high. It might therefore be concluded that common variability of input data cannot be solely a reason for excessive deflections of the structure. Hence the susceptibility of long-span bridges to excessive deflection due to their sensitivity to input parameters is not as high as has been assumed to date. Based on this study it is therefore concluded that the excessive deflections, which have appeared in some bridges, resulted from the combination of serious errors in design (dead load not sufficiently balanced by pre-stressing), insufficient work discipline (imperfections in tendon profiles, higher losses) and adverse service conditions (corrosion of materials).

Neither abrupt drops of the pre-stressing forces nor the significant increase of loads were investigated in this study. These events would have to result from disastrous errors in either design or construction and in their consequence both the upward loads caused by pre-stressing and the stiffness of structural members would rapidly decrease. In such a case the increase of deflections is very impressive and any (even sophisticated) tool for the analysis of such a structure would only help the designer to reveal those errors.

To minimize the danger of such errors appearing, the design of pre-stressing using the load balancing method is strongly recommended. It is the advantage and glory of pre-stressed concrete that the distribution of internal forces in the structure is actively modified. In this concept of pre-stressing, the engineer uses his or her inventiveness, ingeniousness and creativity, especially in the design of statically indeterminate structures. This philosophy was probably used, perhaps intuitively, even earlier, but it was described for the first time by T. Y. Lin in 1963. Nowadays it is recommended by leading engineers worldwide, e.g. Favre and Markey (1994), even though at first sight it is not economical. It requires a greater number of tendons and sometimes even more complicated arrangement of these. On the other hand, it prolongs the lifespan of the structure and improves its serviceability.

5. Conclusion

The parametric study made it possible to quantify the phenomena significant for bridge deflections and to reveal possible reasons for excessive long-term deflections of long-span bridges. From the early stage of construction, extensive measurements of the Motorway Bridge across the Vltava River have been performed. The agreement between the theoretical results and in-situ measurements confirmed the quality of both the material and the structural model.

Both the theoretical and in-situ investigations confirmed the expected total values of bridge deflection. The gradient of deflections is slightly higher than expected.

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