Acta Polytechnica CTU Proceedings **53**:68–75, 2025
https://doi.org/10.14311/APP.2025.53.0068

EFFECT OF VARIABILITY OF MATERIAL PROPERTIES ON RESISTANCE OF EXISTING POST-TENSIONED CONCRETE BRIDGE – CASE STUDY

Aleš Mezera*, Milan Holý, Miroslav Sýkora

Czech Technical University in Prague, Klokner Institute, Šolínova 7, Prague 166 08, Czech Republic

* corresponding author: ales.mezera@cvut.cz

Abstract. The study deals with the sensitivity analysis in determining the load-bearing capacity of existing bridges made of post-tensioned precast girders. Focusing on a specific road bridge, the effect of variations of important basic variables on load-bearing capacity is investigated. When assessing existing structures, values of some basic variables often need to be estimated due to the lack of background information (missing documentation, limited range of structural survey). The aim of this study is to identify basic variables with key influence on load-bearing capacity of the bridge. Numerical example is specifically focused on the mid-span cross-section of a simply supported KA-73 beam structure. It appears that corrosion is the key factor affecting reliability of the bridge at the Ultimate Limit State while prestressing loss is dominating the Servieability Limit State verification. Further research will be focused on reliability analysis of bridges based on the results of structural surveys.

Keywords: Material properties, resistance, load-bearing capacity, post-tension, concrete, bridge.

1. Introduction

Recently, a large number of existing prestressed bridges have been assessed in the Czech Republic as they are reaching their service life. In the 1960–1980s, post-tensioned concrete bridges were in the Czech Republic often constructed of precast girders of various systems (KA, I, DSC...). During service life, these systems are often experiencing durability issues due to long-term leakages as well as structural and technological deficiencies insufficient concrete cover, transverse joints without mild steel reinforcement, poorly executed or missing grouting of cable ducts, etc [1].

The original design documentation and structural surveys are essential in order to obtain information on the actual structural condition of the bridge (defects, real material properties and geometry, permanent loads) and provide the basis for determining load-bearing capacity.

In this study, the load-bearing capacity is determined according to the Czech standard ČSN 73 6222 [2]. The concept of load-bearing capacity represents the maximum total weight of each of the vehicles that are allowed to cross the bridge under the conditions specified in [2]. For existing bridges, three types of load-bearing capacities are distinguished:

- Normal load-bearing capacity (V_n) refers to maximum weight of the vehicle allowed to cross the bridge without restrictions for other road traffic, bikers and pedestrians, a number of the vehicles is not restricted.
- Load-bearing capacity for a single vehicle (V_r) – maximum weight of the vehicle allowed to cross the bridge as a single vehicle but without restrictions for pedestrians and bikers.
- Exceptional load-bearing capacity (V_e) – maximum weight of the vehicle or special truck with trailers allowed to cross the bridge with all other traffic restricted, at specified speed and in specified transverse position [2].

Load-bearing capacity is estimated in accordance with the Eurocodes [3], following the basis of assessment of existing structures according to ISO 13822 [4] and ČSN 73 0038 [5].

This study explores the effect of variations of selected basic variables on the normal load-bearing capacity V_n, focusing on the mid-span section of the most loaded beam in bending.

2. Bridge under investigation

The bridge under investigation is a representative precast post-tensioned bridge consisting of ten KA-73 beams of 15 m length (Figure 1). The precast beams are 700 mm high and 980 mm wide, simply supported with a span of 14.3 m. The beams are transversely tied to together by concrete slabs reinforced by mild steel. The width of the longitudinal joints between the precast elements is 60 mm. The total width of the bridge superstructure is 10.85 m, the roadway width is 7.75 m.

Concrete of class B500 (corresponding to C35/45) was used for the precast beams. The joints between the beams are made of concrete class B330 (C20/25). Mild reinforcement is of class 10 425/V and 4.5 mm diameter plain patented wires were used as prestressing reinforcement, the number of wires in each cable (tendon) can be seen in Figure 2. The beams were

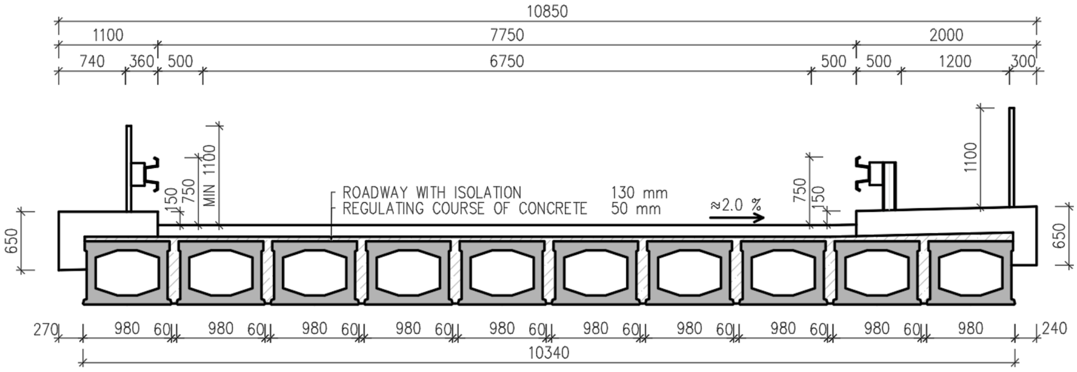
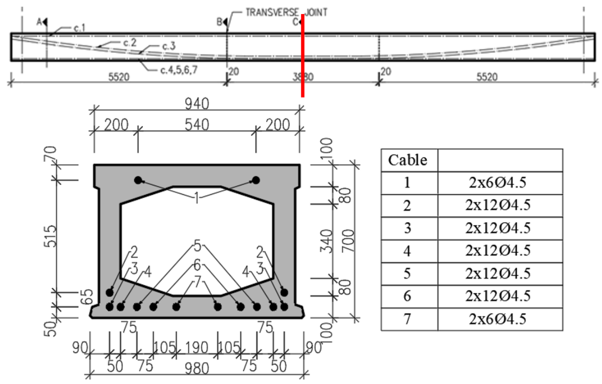


FIGURE 1. Cross-section of the bridge, dimensions in mm.

longitudinally made of 3 segments, and thus contain 2 unreinforced transverse joints of 20 mm width filled with mortar.

In this study, the most loaded beam is considered, for which only the mid-span section is analysed (Figure 2). It is worth noting that the most loaded beam may not always be critical for reliability of the bridge, as beams may be exposed to vastly different levels of degradation. The most damaged beams tend to be the edge beams, as they are the most exposed to the external environment and drainage is often brought to the edges [1, 6]. In terms of design, apart from the cross-section in the mid-span, shear at the support can be critical in the area in the case of sloping bridges.



Cable	
1	2x6Ø4.5
2	2x12Ø4.5
3	2x12Ø4.5
4	2x12Ø4.5
5	2x12Ø4.5
6	2x12Ø4.5
7	2x6Ø4.5

FIGURE 2. Longitudinal section with the investigated section marked in red line (up), cross-section of the KA-73 beam in mid-span (left), number of cables in one beam (right) [2].

3. Numerical model and basic variables

The determination of the internal forces from the permanent and traffic loads was performed using a 3D slab model that takes into account the load distribution on the structure. The 2D model of the KA-73/15 beam, which was created in SCIA Engineer (Figure 3), is essential for the study performed. The prestressing was modelled according to the producer's documentation [7]. The material characteristics for the numerical model are taken from [7] and concrete characteristics from [3]. Overview of the basic variables is given in Table 1. The prestressing process according to [7] was considered in the numerical model (Figure 4). The resulting prestressing losses were determined in the model for time-dependent analysis. The resulting losses at the end of life (100 years) are estimated to 32.6 % in the mid-span.

4. Sensitive analysis

The sensitive analysis investigates the effects of variability of basic variables on resistance of the selected cross-section under permanent and traffic load effects. In this study, the assessment considers both the ultimate limit state (ULS) and the serviceability limit state (SLS). For the latter, the frequent load combination is applied and the stress limitation criterion is evaluated, considering the tensile stress limit value f_{ctd} in accordance with ČSN 73 6222 [2].

Initially, the key element of the critical beam's resistance – prestressing reinforcement is analysed. The effects of corrosion loss of prestressing reinforcement on ultimate strain are investigated. Afterwards, the sensitivity analysis follows with the effect of concrete strength and non-uniform thermal action.

4.1. Corrosion loss, ductility

The assessment of the corrosion condition of prestressing reinforcement is an essential part of the structural survey of bridge. The survey is mainly based on destructive probes that the conditions at selected locations. Corrosion damage is assessed visually and depends largely on experience of the expert, thus being somewhat subjective. According to ČSN 73 6221 [8], a maximum corrosion loss value of 5 % is set for prestressing reinforcement. In practice, however, the corrosion damage may be much higher and may reach up to several tens of percent at critical locations. Such damaged prestressing reinforcement no longer contributes to resistance of the section [9]. Furthermore, the corrosion damage reduces the ultimate strain of the prestressing reinforcement, for reinforcement unaffected by corrosion $\epsilon_u = 40$ ‰ according to [10], the mean value can be considered as $\epsilon_u = 50$ ‰ accord-

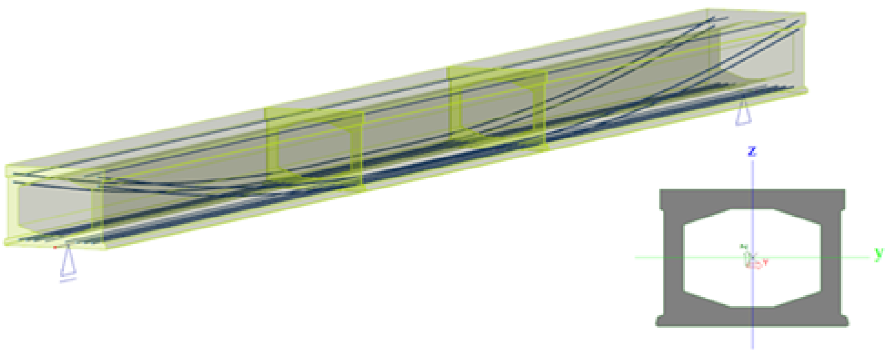


Figure 3. Numerical model of beam KA-73/15 for time-dependent analysis (SCIA Engineer).

Material properties of concrete			
characteristic value of concrete compressive strength	f_{ck}	35	[MPa]
characteristic value of concrete tensile strength	f_{ctk}	3.2	[MPa]
mean value of modulus of elasticity	E_{cm}	34	[GPa]
Material properties of prestressing reinforcement			
characteristic value of tensile strength	f_{pk}	1650	[MPa]
yield strength	$\sigma_{0.2}$	1 200	[MPa]
increased yield strength (keeping stress during posttensioning)	$\sigma_{0.2,i}$	1 350	[MPa]
initial tension	$\sigma_p(t_0)$	1 325.4	[MPa]
mean value of modulus of elasticity	E_p	195	[GPa]
Prestressing parameters			
coefficient of friction in curved part of tendon	μ	0.19	[-]
anchorage set – initial value	a	3	[mm]
unintentional angular displacement	k	0.005	[rad m^{-1}]
duration of keeping stress	t_p	120	[s]
relaxation class I			
prestressing loss (mid-span, t = 100 years)		32.6	[%]
ductility	ϵ_{ud}	20	[‰]
corrosion loss	c_x	0	[%]
Internal forces			
char. bending moment in mid-span (self-weight load)	$M_{y,g0}$	252	[kNm]
char. bending moment in mid-span (other permanent load)	$M_{y,g}$	167	[kNm]
char. bending moment in mid-span (V_n = 32 t)	M_{y,V_n}	291	[kNm]
dynamic factor (acc. ČSN 73 6222)	δ_{V_n}	1.20	[-]
Resistance			
ultimate bending resistance in mid-span	$R_{d,ULS}$	1 322	[kNm]
service bending resistance in mid-span	$R_{d,SLS}$	588	[kNm]
load-bearing capacity (bending) in mid-span (ULS)	$V_{n,ULS}$	52	[t]
load-bearing capacity (bending) in mid-span (SLS)	$V_{n,SLS}$	40	[t]

Table 1. Overview of basic variables.

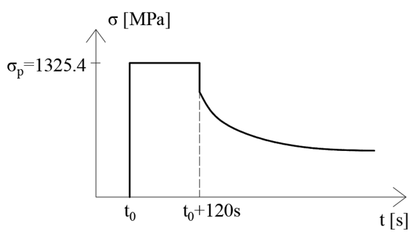


Figure 4. Prestressing procedure according to [7].

ing to [11]. The effect of corrosion loss is shown in Figure 5 and Figure 6.

It can be seen from Figure 5 that the relationship between load-bearing capacity and corrosion loss is linear. A change in this trend appears at high corrosion loss (about 40 % or more) where reduced ultimate strain starts playing a role. At a corrosion loss of about 40 %, the ductility of the prestressing reinforcement is reduced to 0.5 ‰ [10]. The stress-strain diagram for prestressing reinforcement given in EN 1992-1-1 [3] suggests that the reduced ultimate

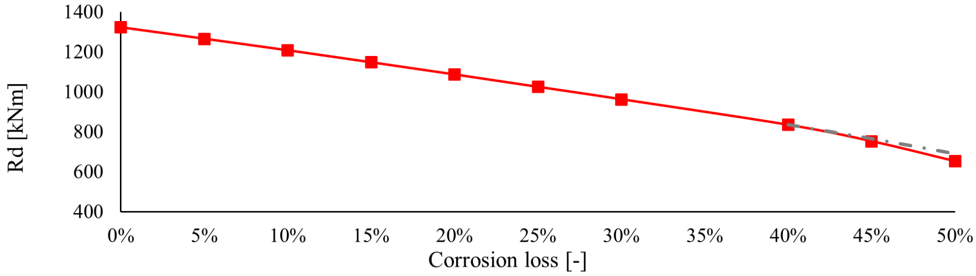


FIGURE 5. Effect of corrosion weakening on design (assessment) value of load-bearing capacity, R_d.

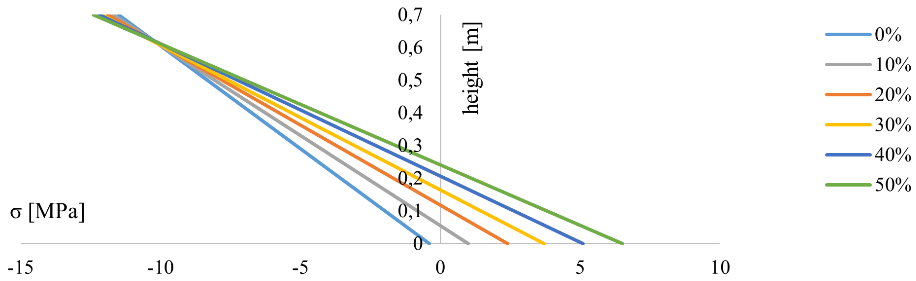


FIGURE 6. Effect of corrosion loss on stress at bottom of selected section for frequent load combination (SLS).

strain affects resistance if $\epsilon_{ud} < f_{pd}/E_p$ where ϵ_{ud} is the design (assessment) value ($\epsilon_{ud} = 20$ ‰ in [3]) and fpd is the design value of the tensile strength of the prestressing reinforcement.

The effect of corrosion loss depends on a considered limit state. Figure 5 indicates a linear relationship between corrosion weakening and ULS capacity. The effect on SLS (frequent load combination) is also significant as displayed in Figure 6. As the corrosion loss increases, the tensile stress in the lower fibers of the cross section (mid-span cross section) appears and further increase with increasing corrosion level.

One of the most important factors that can prevent corrosion of prestressing reinforcement is proper grouting. Well-executed grouting provides several protective mechanisms for the reinforcement. Cement grout has an alkaline pH that forms a passive layer on the surface of the steel, preventing corrosion. It also restricts the access of water and oxygen to the reinforcement, which are necessary conditions for the development of corrosion. Good quality grouting therefore provides long-term protection and significantly extends the life of the reinforcement and the entire structure [12].

On the other hand, imperfect or poor-quality grouting can even accelerate corrosion. The most common problems include incomplete filling of ducts, the formation of voids or cracks in the grout. Another problem is poor bond between the grout and cables, which can cause localised loss of protection and allow development of pitting corrosion. This type of corrosion is particularly dangerous as it causes rapid local weakening of the reinforcement. It can also lead to grout cracking due to volume changes or loading of the structure, which further compromises the protective function of the grouting.

The composition of the grout can also influence corrosion. If it is poorly designed, for example if a water ratio is high and cement content is low, the grout insufficiently resists the ingress of moisture and aggressive substances. It is therefore essential that grouting materials conform to standards and are applied under controlled conditions.

4.2. PRESTRESSING LOSSES

Prestressing losses represent a reduction in the prestressing force applied in the prestressing reinforcement during the construction process and after the structure is in service. These losses have a significant effect on the effective transfer of prestress and on the resulting capacity and service life of the structure. They are divided into short- and long-term.

4.2.1. SHORT-TERM LOSSES

These losses occurring immediately after tensioning include:

- Frictional losses caused by movement of the reinforcement during tensioning, especially for curved cable ducts or when there is non-uniform friction between the reinforcement and the duct. These losses are influenced by the curvature of the duct and the quality of grouting.
- Slip in the anchor: after anchoring the tensioned reinforcement, shifts (settlements) of the anchoring devices may reduce the tension in the reinforcement.
- Deformation of concrete: when prestressing is applied to cables, deformation of concrete reduces stresses in the already prestressed cables.

4.2.2. Long-term losses

Long-term losses during the lifetime of the structure are caused by:

- Concrete creeping, mainly due to permanent loads.
- Concrete shrinkage.
- Reinforcement relaxation.

Prediction of these rheological effects is generally associated with large uncertainty as they depend on a number of material and geometrical properties and local environment. The models for prediction of prestressing losses have changed since the 1960–1980s.

Prestressing losses commonly have an insignificant effect on load-bearing capacity at ULS. However, they play the major role at SLS as the tensile stresses in the bottom fibres appear with increasing prestressing losses. This is why SLSs often govern reliability of existing bridges and it is essential to accurately determine the prestressing losses. The following factors affecting prestressing losses are investigated in the following sensitivity analysis in detail: anchorage slip, frictional losses, effect of cable geometry, duration of keeping stress and reinforcement relaxation. Based on experience, these are likely the major factors.

4.2.3. Slip in anchor

Anchor slip contributes to prestressing loss. The basic slip value, $a = 3$ mm, is provided in the documentation for KA-73 beams [13]. However, a larger value of 6 mm was often experienced in practice. Based on the authors' judgement, the lower limit is estimated to 2 mm. These three values are taken into account in the analysis. It appears that the slip has an insignificant effect on the prestressing losses only (Figure 7), with expected value of prestressing loss of about 33 % for 3–6 mm slips.

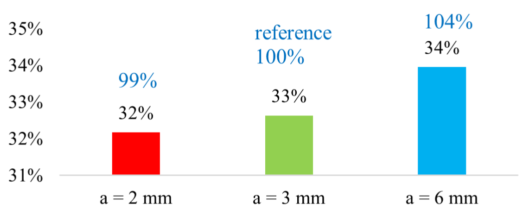


Figure 7. Effect of anchor slip on prestressing losses at midspan.

4.2.4. Frictional losses

Frictional losses are particularly important for post-tensioned structures. During tensioning, friction between the cable and the walls of the cable duct causes two components of the loss:

- In curved cables, related to friction coefficient: the basic value of friction coefficient, $\mu = 0.019$, is taken from EN 1992-1-1, Table 5.1 [3]. A higher value of 0.35 is considered according to [14, 15]. The lower limit of 0.12 is based on the authors' judgement.
- Due to corrugation of straight cables [16]: values of 0.003, 0.005 and 0.01 rad m^{-1} are considered. The value k = 0.003 rad m^{-1} corresponds to the requirements of previous standards [14, 15] and a range of 0.005–0.001 rad m^{-1} is recommended in [3].

Figure 8 indicates that the friction coefficient has a small effect on the prestressing losses, and consequently on SLS load-bearing capacity. A similar conclusion is drawn for the corrugation of straight cables (Figure 9).

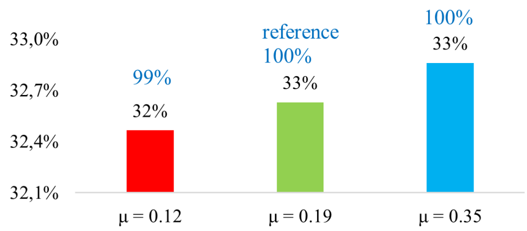


Figure 8. Effect of friction coefficient on prestressing losses in mid-span.

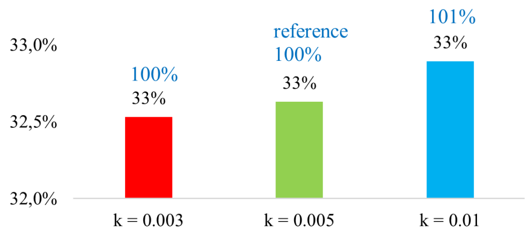


Figure 9. Effect of corrugation of straight cables on prestressing losses in mid-span.

4.2.5. Duration of keeping stress

The duration of keeping stress refers to the time interval during which the tension in the prestressing reinforcement is maintained during the tensioning and anchoring, having a positive effect on relaxation and slip in anchors. Three time intervals (60, 120 and 300 s) – the most common in practice – are selected (Figure 10).

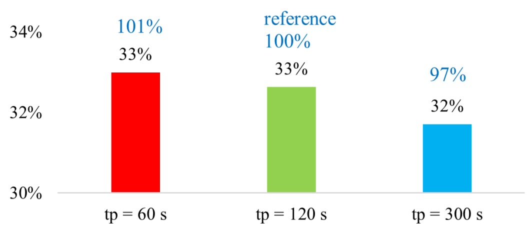


Figure 10. Effect of duration of keeping stress on prestressing losses in mid-span.

Even though it seems that duration of keeping stress has a negligible effect on prestressing losses, it is important to take this parameter into account in the

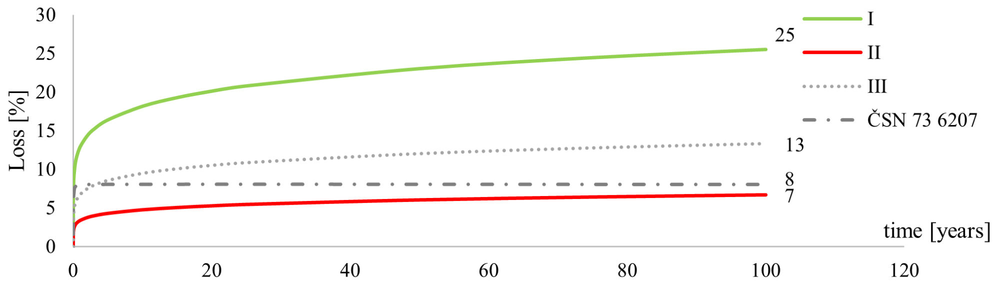


FIGURE 11. Relaxation time course depending on the relaxation class considered.

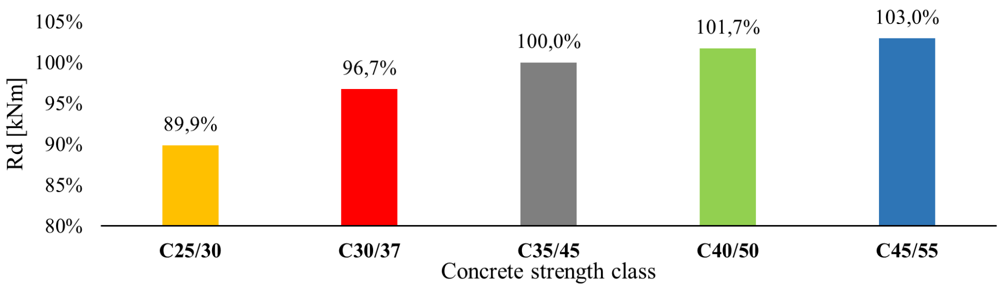


FIGURE 12. Effect of concrete strength class on resistance in mid-span.

calculation of prestressing reinforcement relaxation. Relaxation is a key factor in prestressing losses and is largely dependent on the applied stress and duration of keeping stress.

To determine the relaxation losses, it is important to consider the prestressing process (Figure 4, adapted from [7]). According to EN 1992 [3], relaxation class I is considered in the assessment. Note that classes I and II apply for wires and tendons with normal relaxation and class III for hot rolled bars [3]. This assumption is conservative and in-situ measurements often indicate lower levels of relaxation [3]. For the bridge under investigation relaxation class I is considered. For $\rho_p/f_{pk} = 1\,325/1\,650 = 0.803$, relaxation loss is predicted to about 25 %. Therefore, relaxation contributes to about 2/3 of the total prestressing losses (25 % out of 32.6 %). If the prestressing reinforcement had been prestressed to 1 650 MPa, relaxation loss would have increased from 25 % to 35 %. Figure 11 shows the relaxation losses over time for all relaxation classes.

Previous standards [14, 15], according to which existing structures that are currently beyond half of their design life (100 years) were designed, assumed that 100 % of relaxation loss would take place within the first year. In contrast, EN 1992 [3] suggests that approximately 50 % of relaxation loss takes place in the first year only.

4.2.6. Concrete strength class

The strength class of concrete is indicated by its compressive strength, on the basis of which other mechanical properties of concrete are normally specified. C35/45 was most often used according to the design documents for these types of precast bridges; the actual material properties are determined for the bridge under investigation by a structural survey. Concrete strengths from surveys are usually higher than those in the design documentation, mainly as a consequence of hardening.

The effects of strength class on ULS load-bearing capacity are shown in Figure 12. Regarding SLS, the strength class has only bearing on concrete tensile strength that contributes in the cases where tensile stresses in concrete are allowed.

It appears that the effect of strength class on ULS resistance in the ultimate limit state is moderate for lower concrete strengths. For higher concrete classes, an increase becomes small.

The effect of the strength class on prestressing losses appears to be less significant, with a decrease of 5 % between C25/30 and C45/55 (Figure 13). Nevertheless, it is necessary to analyse the prestressing losses as accurately as possible, as they can have a major impact on SLS load-bearing capacity as discussed in Section 5.

4.2.7. Temperature

Although thermal actions on statically determined structures do not induce internal forces as in the case of statically indeterminate structures, the non-linear temperature difference of thermal actions (procedure 2 according to EN 1991-1-5 [17]) results in self-equilibrated stresses in the cross-section. These stresses may have a significant effect particularly on SLS (stress and crack width limitation) that is commonly decisive in the case of prestressed bridges. The effect of the non-linear temperature difference compo-

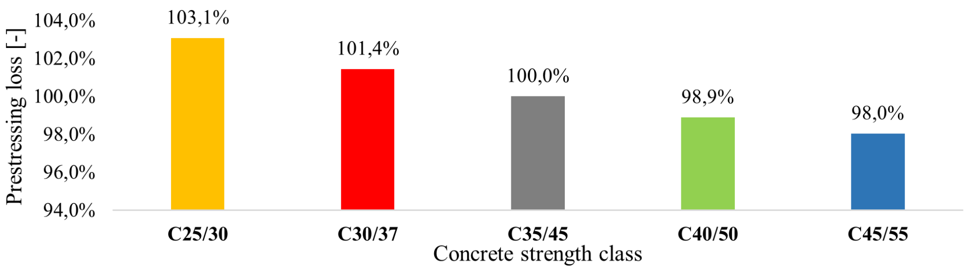


Figure 13. Effect of concrete strength class on prestressing losses.

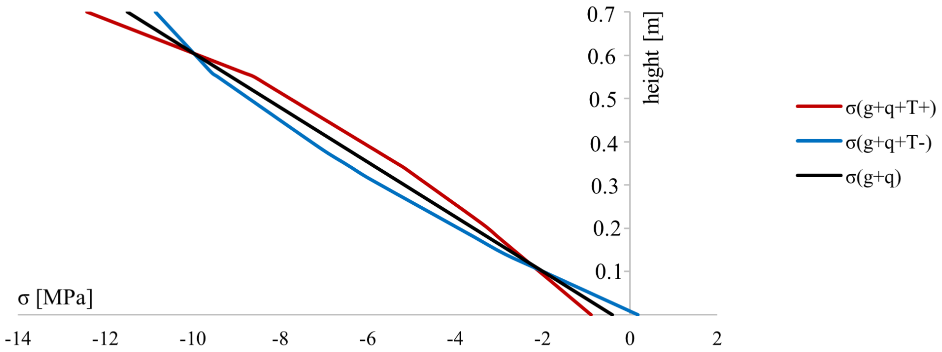


Figure 14. Stress from permanent and traffic load (black) combined with self-equilibrated stress from heating (red) and self-equilibrated stress from cooling (blue), the non-linear temperature difference of thermal actions (procedure 2 according to EN 1991-1-5 [17]).

nent determined according to procedure 2 of [17] on the self-equilibrated stress is shown in Figure 14.

Load effects due to the temperature difference (cooling) reduces the compressive stress in the bottom fibres and has a significant effect on estimated load-bearing capacity. The effect of thermal actions is therefore not negligible even for statically certain structures.

5. Summary

The effects of the selected basic variables on load-bearing capacity of the bridge under consideration are overviewed in Table 2.

For ULS at the mid-span section, bending load-bearing capacity is 52 t. A 1 % corrosion loss results in a load capacity of 51 t. The 1 % corrosion loss corresponds to a 0.14 MPa (unfavourable) reduction in compressive stress in the bottom fibres of the section. It follows that corrosion of prestressing reinforcement is one of the key factors for the service life of prestressed concrete structures and it is important to prevent or control it during service life. Relaxation is governing prestressing losses. Despite a relatively low influence of the other factors such as slip in anchor or frictional losses on total prestressing losses, changes in these factors can have an influence on SLS load-bearing capacity. The change in slip of the anchor affects the prestress loss by 1.3 %. For the assessment using the frequent load combination, this already needs to be taken into account. For the reference case (Figure 7 through Figure 10), the load-bearing capacity in the midspan is 40 t (SLS) while with increased prestressing loss due to a higher slip in the anchor, the load-bearing capacity reduces to 37 t (even though a reduction in compressive stress is only 0.2 MPa). The 3 t reduction in load-bearing capacity demonstrates the importance of the estimate of the slip and consequently of the prestressing loss on the SLS assessment.

		Load-bearing capacity V_n [t]	
		ULS	**SLS**
Corrosion loss	0 %	52	40
	1 %	51	38
Prestressing loss	20 %	52	48
	25 %	52	45
	30 %	52	42
	32.6 %	52	40
	35 %	52	37
Concrete strength class	C 30/37	50	40
	C 35/45	52	40
	C 40/50	52	40
Temperature	g+q	52	40
	g+q+T+	52	41
	g+q+T-	52	38

Table 2. Effect of variability basic variables on mid-span load-bearing capacity, default variant marked in blue.

The influence of the duration of keeping stress during tensioning on the SLS assessment is moderate. Duration of 300 s increases the load-bearing capacity by about 2 t, i.e. to 42 t.

In the SLS assessment, a stress change of about 0.4 MPa induced by the self-equilibrated stress due to the non-linear temperature difference component of thermal action reduces load-bearing capacity by 4 t.

6. Conclusion

The effect of basic variables describing prestressing force, concrete strength and temperature difference component of the thermal action on load-bearing capacity of precast post-tensioned bridge girders (type KA-73/15) is investigated, focusing on bending at the mid-span of a simply supported beam. In addition to the ultimate limit state (ULS), serviceability limit state (SLS) of stress limitation for the frequent load combination is analysed. It is demonstrated that corrosion and prestressing losses have the most significant effect on load-bearing capacity. Even a change in prestress losses of a few percent may affect load-bearing capacity by a few tons (up to 10 %) at SLS while the ULS assessment is basically unaffected by prestressing loss. In contrast, corrosion losses are essential for the ULS assessment. Concrete strength seems unimportant for assessments of this type of structures unless the requirement of full decompression is relaxed and tensile stresses may occur in concrete.

Further, even for statically determined prestressed bridges, the effect of the temperature difference component of thermal action resulting in self-equilibrated stresses has a moderate impact at the SLS assessment.

Further research will be focused on reliability analysis of bridges based on the results of structural surveys, accompanied by the sensitivity analysis considering uncertainties in specification of basic variables.

Acknowledgements

This study has been supported by the Czech Science Foundation under Grants 23-06222S and 24-10892S.

References

[1] R. Ponechal, P. Koteš, D. Michálková, et al. Effect of water condensate on corrosion of wires in ungrouted ducts. *Materials* **14**(24):7765, 2021. https://doi.org/10.3390/ma14247765

[2] Zatížitelnost mostů pozemních komunikací [In Czech; Load bearing capacity of road bridges]. Standard, Czech Standard Institute, Prague, 2015.

[3] European Committee for Standardization. EN 1992-1-1 – Eurocode 2: Design of concrete structures : Part 1-1: General rules and rules for buildings, 2004.

[4] Zásady navrhování konstrukcí – hodnocení existujících konstrukcí [In Czech; Bases for design of structures – Assessment of existing structures]. Standard, Czech Standard Institute, Prague, 2010.

[5] Navrhování a posuzování stavebních konstrukcí při přestavbách [In Czech; Assessment and verification of existing structures – Supplementary guidance]. Standard, Czech Standard Institute, Prague, 2019.

[6] M. Kryštov, A. Čítek, S. Řeháček, D. Čítek. *Vyhodnocení stavu diagnostikovaných mostů z dodatečně předpjatých tyčových prefabrikátů KA–73 po 40 letech provozu [In Czech; Assessment of the condition of surveyed bridges post–tensioned KA–73 precast concrete beams after 40 years of service].* 2023. ISBN 978-80-908943-0-3.

[7] *Konštrukcie cestných a diaĺničných mostov z prefabrikátov KA-73 dĺžky 9–12–15–18 m – Typový podklad [In Czech; Structures of road and highway bridges made of precast KA-73 prefabricates, length 9–12–15–18 m – Type background].* Dopravoprojekt Bratislava, 1973.

[8] Prohlídky mostů pozemních komunikací [In Czech; Surveys of road bridges]. Standard, Czech Standard Institute, Prague, 2018.

[9] *Železniční mosty s předpjatou nosnou konstrukcí v síti Správy železnic [In Czech; Railway bridges with prestressed load bearing structure in the network Správa železnic].* CTU in Prague – Faculty of Civil Engineering, 2021. ISBN 978-80-01-06923-3.

[10] J. Kolísko, V. Vacek, P. Pokorný, M. Kostelecká. Vliv koroze na vlastnosti ocelové předpínací výztuže [In Czech; The influence of corrosion on the properties of steel prestressing reinforcement]. Praha 1: Česká betonářská společnost ČSSI, 2019. ISBN 978-80-907611-2-4.

[11] JCSS probabilistic model code (draft of section 'environmental attack'). Joint Committee on Structural Safety. ISBN 978-3-909386-79-6.

[12] L. Haixue. Grouted post-tensioning tendon evaluation. 2017.

[13] *Konštrukcie cestných a diaĺničných mostov z prefabrikátov KA-73 dĺžky 9–12–15–18 m – Statický výpočet nosníkov dĺžky 15 m část I [In Slovak; Structures of road and highway bridges made of precast KA-73 prefabricates of length 9–12–15–18 m – Static calculation of beams of length 15 m part I].* Dopravoprojekt Bratislava, 1973.

[14] Navrhování konstrukcí z předpjatého betonu [In Czech; Design of prestressed concrete structures]. Standard, Czech Standard Institute, Prague, 1970.

[15] Navrhování mostních konstrukcí z předpjatého betonu [In Czech; Design of prestressed concrete bridges]. Standard, Czech Standard Institute, Prague, 1993.

[16] N. J. *Předpjaté betonové konstrukce [In Czech; Prestressed concrete structures].* Akademické nakladatelství CERM, 2008. ISBN 978-80-7204-561-7.

[17] European Committee for Standardization. EN 1991-1-5 – Eurocode 1: Actions on structures – Part 1–5: General actions – Thermal actions, 2005.