

Peter PAŽMA¹, Jakub BRONDOŠ², Jaroslav HALVONÍK³**EXPERIMENTAL VERIFICATION OF SECONDARY EFFECT DUE TO PRESTRESSING****Abstract**

The aim of this article is to describe an experimental program at Slovak University of Technology in Bratislava, Department of concrete structures and bridges and its results. This experimental program was focused on two main subjects. The first one, which is also the topic of this article was an analysis of prestressing effects on the statically indeterminate structures, where the redundancy had been changed up to the kinematic mechanism development. The second topic was an analysis of behaviour of the prestressing units with different bond.

Keywords

Post-tensioning, secondary effects, statically indeterminate structure, plastic hinge.

1 INTRODUCTION

Application of prestressing allows for more effective use of concrete cross sections compare with sections reinforced by reinforcing steel. Reinforcing steel is passive reinforcement in the beams and slabs, therefore takes over only tensile forces in concrete cross-sections. Opposite, prestressing tendon transfers compressive forces and bending moments into concrete members which increases their flexural stiffness at SLS and after cracking it is possible to utilise full tensile capacity of prestressing units at ULS [1]. Thanks to these characteristics, prestressing represents an inevitable solution for the long span concrete structures, particularly for the bridge structures.

In a case of post-tensioning, tendon layout usually complies distribution of internal forces due to the load, e.g. in simply supported beam tendons are located in the bottom part and in continuous beam they have usually polygonal arrangement, which means that in areas with sagging moments are located in the bottom while in areas with hogging moments are in the top. It is because bending moment due to the prestressing is proportional to the distance “ e ” between centre gravity of prestressing unit and the beam. Product $P \times e$ represents then primary effect of prestressing [2]. However in a case of hyperstatic structural systems prestressing generates additional, secondary (parasitic) effects which may significantly influence distribution of internal forces in the beam. The secondary effects depends on the structural system and as well as on the geometry of a tendon. The secondary effects can be even equal to zero in hyperstatic structures if suitable tendon geometry is used (concordant tendon). However in the most of the cases the secondary effects accompany primary effects of prestressing. As it has already been mentioned the secondary effects depends on

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All beams were reinforced with reinforcing steel B500B and with two one-strand tendons $\phi Ls15.7$ mm/1860 MPa having different geometry. The first tendon with polygonal shape had geometry producing minimum secondary effect. The second one, straight, was designed to reach maximum secondary effect. Tendon lay-out of both tendons is displayed in the Fig.2. Experimental beams were prestressed by tendons with different bond. All together there were 3 groups of samples. The first group were beams prestressed by tendons with bond, the second one were beams prestressed by tendons coated with emulsion for protection against corrosion - lower bond, and the last one were beams prestressed by unbonded tendons - monostrands. Plastic ducts with diameter of 22 mm were used for each tendon. Each tendon has been prestressed by force $P_0 = 200$ kN.

Elasto-magnetic sensors placed for each tendon on opposite side of the beam were used for detailed recording of prestressing force.



Fig. 3: Preparation and realization of the experimental beams

Experimental beams were tested in central laboratory of SUT. Beams were installed on three supports, then they were prestressed and grouted. The loading device consisted of two hydraulic cylinders, one for each span. The force from jacks has been divided into two forces, see Fig.2 and Fig.9. The reactions were monitored with a dynamometer on each support. The settlement of supports and displacement of the beam were also measured. Fig.4 displays all measuring gauges used for each beam.

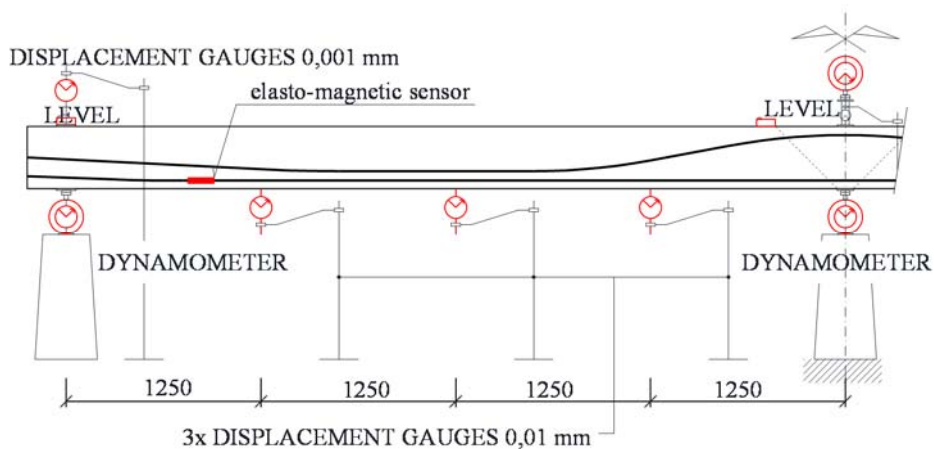


Fig. 4: Scheme of the measuring gauges arrangement

3 RESULTS

Obtained results of the experimental program have been compared with the theoretical analysis. The theoretical analysis was performed with taking into account nonlinear material behavior. For this purpose material properties of concrete, reinforcing and prestressing steel have been tested. Material characteristics for concrete and grouting mortar were measured at same time as experiment. Following material properties were obtained:

$f_{cm, cube}$ – characteristic cube strength of concrete at the time of the experiment,

E_{cm} – secant modulus of elasticity of concrete,

$f_{ym} f_{tm}$ – mean values of yield strength and tensile strength of reinforcing steel,

E_s – modulus of elasticity of reinforcing steel,

$f_{pm}, f_{p0,1m}$ – mean values of strength and 0,1% proof-stress of prestressing steel,

E_p – modulus of elasticity of prestressing steel.

Tab. 1: Material properties of concrete

	N1	N2	N3	N4	N5	N6
$f_{cm, cube}$ [MPa]	53.93	53.32	60.0	66.1	60.78	61.48
E_{cm} [GPa]	33.161	34.132	35.584	37.784	37.414	36.578

Tab. 2: Material properties of reinforcing and prestressing steel

ϕ	f_{ym}	f_{tm}	E_s	ϵ_u	f_{pm}	$f_{p0,1m}$	ϵ_u	E_p
[mm]	[MPa]	[GPa]	[GPa]	[%]	[MPa]	[MPa]	[%]	[GPa]
12	508	601	212	11.0	1862	1516.3	6.0	195.7
8	567	649	200	8.0				

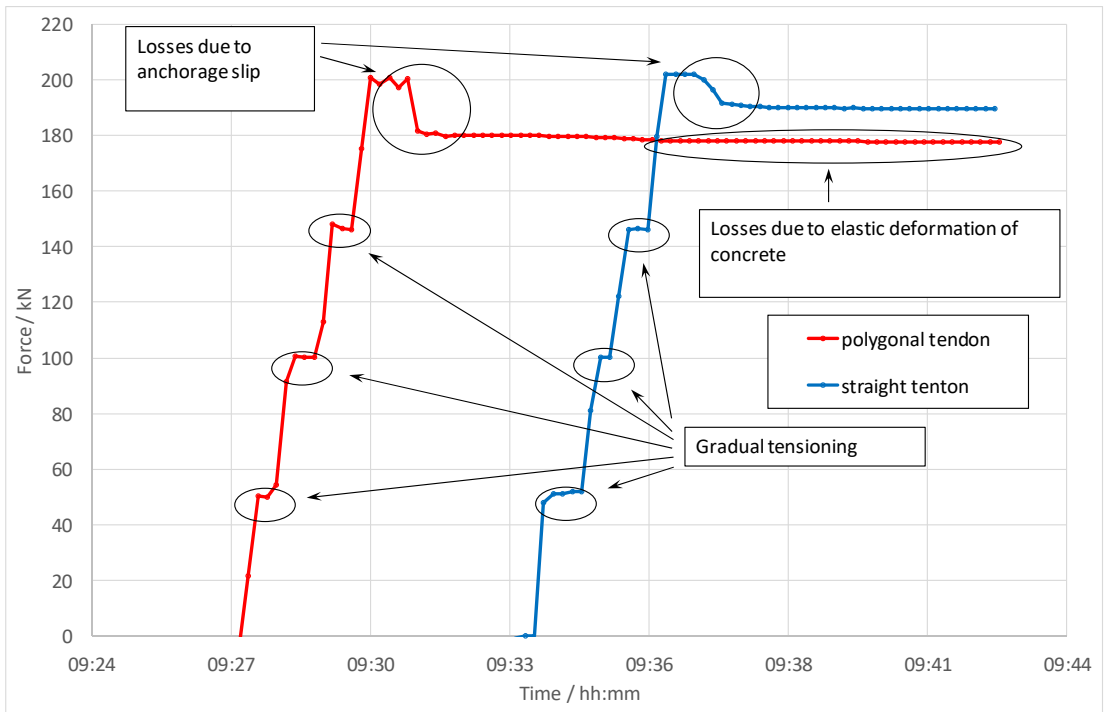


Fig. 5: Development of prestressing force in time recorded by elasto-magnetic sensor

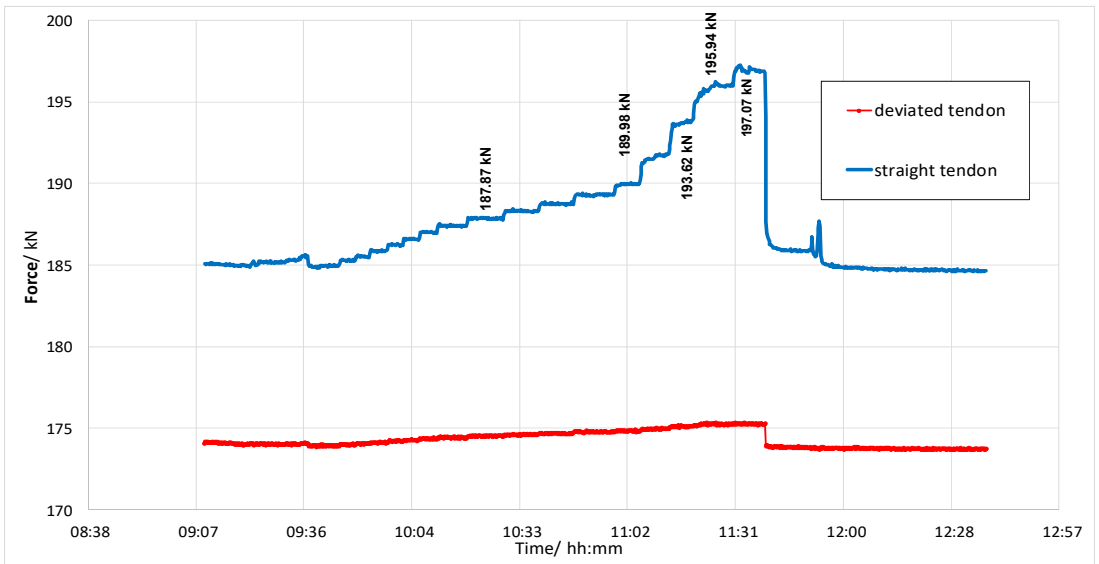


Fig. 6: Diagram of elasto-magnetic sensors measurements during the experiment for bonded tendons

Diagram of elasto-magnetic sensor measurements in time during prestress transfer is displayed in Fig.5. Detailed behaviour of each tendon can be seen in this figure. Each beam was prestressed in same order of tendons, first deviated one and then straight one. Each tendon was

prestressed in sequence with increasing force by 50 kN, what is $\frac{1}{4}$ of the overall force, see Fig.5. Prestress losses due to slip at anchorages and losses caused by elastic deformation of beam during gradual prestressing can be seen in this diagram. Obtained results from EM sensors were used for calibrating numerical, theoretical analysis, especially immediate losses due to prestressing.

Record of prestressing force development obtained from elasto-magnetic sensors directly during the experiment is in Fig.6. Jack load was symmetrically applied on both spans using one hydraulic aggregate and two hydraulic cylinders. It can be seen here each step of force increment, particularly in the straight tendon.

Measured results from EM sensors show good agreement between experimental values and values declared by producer, see Tab.3. Producer of the prestressing system, VSL Company, declared the average anchor slip 6mm. This value is comparable with 5mm, what is the average experimental value. Measured friction coefficient was 0.135. For this type of duct (VSL PT-PLUS) is declared to be 0.12-0.14. Correctness of prestressing system installation has been confirmed by these basic results and obtained results are usable for further analysis.

Tab. 3: Results from elasto-magnetic sensors – beams prestressed by bonded tendons

Average force on active side of polygonal tendon after prestress transfer	177.7 kN
Average force on passive side of polygonal tendon after prestress transfer	187.5 kN
The average anchor slip	5 mm
Measured friction coefficient for bonded strands	0.135

Measured prestressing effects are displayed in Fig.7. These effects are caused by prestressing of straight bonded tendon. As it is shown, the secondary effects of prestressing represented 122 % of the primary effects. Further experimental results, separate bending moments and reactions for each load type, are displayed in Tab.4.

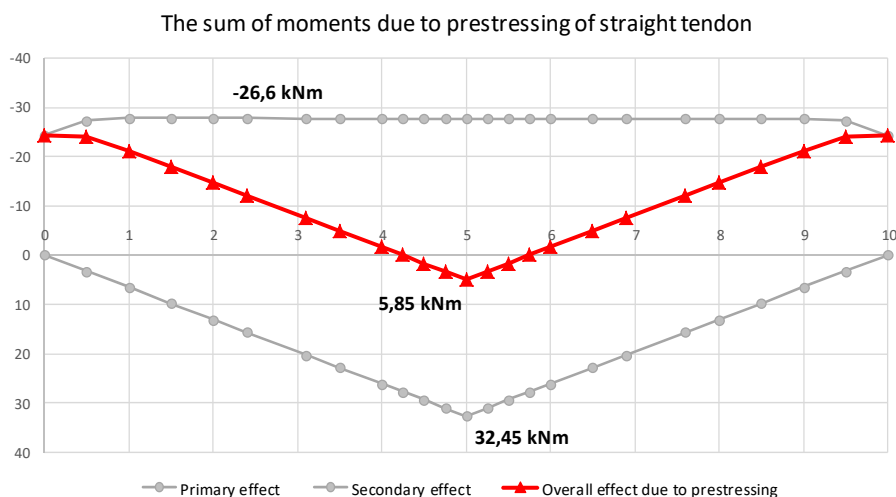


Fig. 7: The scheme of primary and secondary effect of prestressing on tested beams

Tab. 4: The reaction results (R1 – edge supports; R2 – intermediate support) and bending moment for beam with bonded tendons – N1 and N2

N1 and N2	R1	R2	Bending moment at mid. span	Bending moment at intermediate support
	[kN]	[kN]	[kN.m]	[kN.m]
Self-weigh g_0	6.09	12.47	6.37	-2.68
Loading devices	0.37	0.83	0.89	-0.40
Secondary effects	6.49	-12.98	15.54	31.88
External force 259.05 kN	77.74	357.92	186.58	-177.51

Final comparison between experimental results and numerical analysis is shown in Tab.5. Results are compared with and without secondary effects of prestressing and were evaluated on experimental beams, N1 and N2, with bonded tendons.

Two critical cross sections were assumed in the comparison. The first section was located at the intermediate support, where first plastic hinge formation was observed. The second one was located in the middle of each span. The scheme of these critical cross sections is displayed in Fig.8.

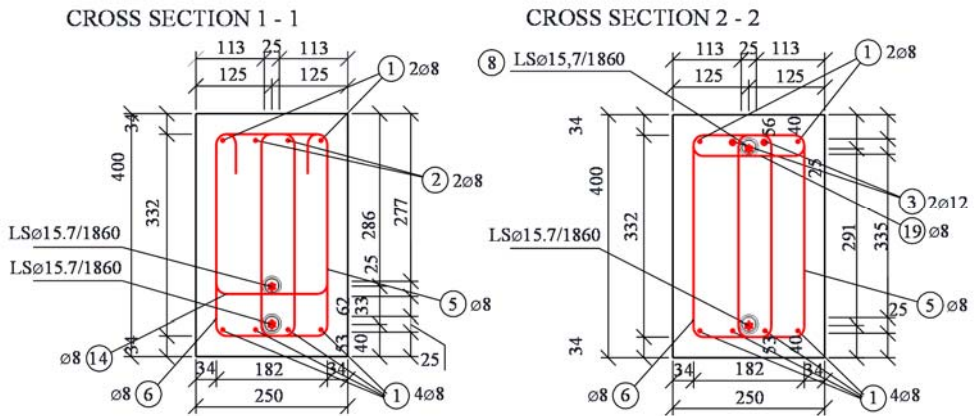


Fig. 8: Schemes of assumed critical cross-sections

Experimental bending moments in Tab.5 were obtained from measuring of reactions. Thanks to measuring of reactions due to the prestressing during tensioning, the secondary effects were easily constructed. It allowed us to determine internal forces with and without secondary effects of prestressing after development of plastic hinges. Obtained experimental bending moments were then compared with theoretical bending capacity assessed in selected critical sections with properties of structural materials introduced in Tab.1 and Tab.2. Experimental results in Tab.5 represents average values of two beams N1 and N2. The theoretical bending capacity was assessed using axial force balance in concrete, reinforcement and prestressing tendons $\sum F_i = 0$ and an assumption of reaching ultimate concrete strain of $\varepsilon_{cu} = 0.0035$.

Tab. 5: Comparison between theoretical and experimental results - bending moments in critical cross-sections

Beams N1, N2 prestressed by bonded tendons	Theoretical bending capacity	Experimentally obtained bending moments – with secondary effects	Experimentally obtained bending moments – without secondary effects
	$M_{Rd,teoret}$	$M_{Ed,exp}$	$M_{Ed,exp}$
SECTION 1-1	192.3 kN.m	190.8 kN.m	175.1 kN.m
SECTION 2-2	150.8 kN.m	-166.9 kN.m	-199.6 kN.m
SECTION 1-1	100 %	98.9 %	91.1 %
SECTION 2-2	100 %	110.7 %	132.4 %



Fig. 9: Displacement of experimental beam N1

4 CONCLUSION

From above presented results (shown in Tab.5) it is clear that the secondary effects of prestressing neither disappeared nor dropped down after reaching the bending capacity in critical cross-sections and after plastic hinges formation. They have had permanent influence on the cross section bending capacity. Results have shown that theoretical bending capacities are approaching to the experimental results with secondary effect considering.

The difference between theoretical flexural resistance without secondary effect (cross-section 1-1, Fig. 8) and cross-section resistance reached by experiment was -9.9%, while in a case of assuming secondary effects the difference descended to -1.1%. For cross-section 2-2, the differences are even more eye striking. In a case without secondary effects the difference was 32.4%, while assuming secondary effect 10.7 %.

Based on these results we can conclude that secondary effects of prestressing represent permanent part of the bending capacity. Secondary effects influence remains also after changing of the structural system due the development of plastic hinges in a structure and even after development of kinematic mechanism.

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