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Experimental verification of secondary effects of prestressed beam at ULS☆

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Summary The paper deals with secondary effects of prestressing at ultimate limit state when statically indeterminate structure has changed its structural form due to development of plastic hinges in critical cross-sections. The article presents results of an experimental program which was carried out at Slovak University of Technology in Bratislava on two span continuous beams post-tensioned by two single-strand tendons subjected to experimental load which has changed structural system into kinematic mechanism.

Introduction

Application of prestressing is based on more effective use of concrete cross sections compare with sections reinforced by reinforcing steel. Reinforcing steel is passive reinforcement because stresses develop here after loading of a structural member. Opposite, prestressing tendons transfer actively compressive forces and bending moments into concrete members thanks to its prestrain. This increases flexural stiffness of prestressed elements at SLS and after cracking we can usually utilize full tensile capacity of prestressing units to the bending capacity at ULS (Navrátil, 2014).

In a case of post-tensioned structural members, tendon layout usually complies distribution of internal forces due to the load, e.g. in simply supported beams tendons are located in the bottom part of the structure and in continuous beams they have usually polygonal arrangement (Moravčík et al., 2014). It means in areas with sagging moments are located in the bottom while in areas with hogging moments in the top part of a member. It is because bending moments due to the prestressing are proportional to the prestressing force ''P'' and distance ''e'' between center gravity of prestressing unit and the beam. Product $P \times e$ represents primary effects of prestressing. In case of

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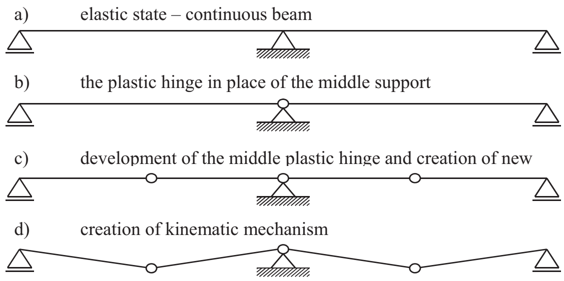

Figure 1 The scheme of a change of structural form from statically indeterminate beam to kinematic mechanism.

statically indeterminate structures prestressing may generate additional internal forces so called secondary (parasitic) effects which can significantly influence distribution of stresses in the structure (Andrew and Witt, 1951). The secondary effects develop due to the restraining of by tendons imposed deformations by hyperstatic restraints. Therefore they depend mainly on the structural system and as well as on the geometry of the tendon. The secondary effects can be equal to zero if suitable tendon layout is used (concordant tendon). Because the secondary effects depends on the structural system the question is how to treat with these internal forces at ULS when the structure changes structural form due to formation of plastic hinges in critical cross-sections with ultimate state — kinematic mechanism?

Description of the experimental program

Detailed analysis of above mentioned issue was the main part of experimental program. The samples of the experiment were post-tensioned concrete beams laying on three supports. This resulted in a form of two-span continuous beam with the same span length. With gradual increase of the external forces, bending capacity of critical cross sections was reached which finally resulted in development of the kinematic mechanism. The statically indeterminate structure (Fig. 1a) has been transformed into the statically determinate structure (Fig. 1b) after plastic hinge formation at internal support. Further growth of external load led to the development of plastic hinge in the spans (Fig. 1c) and to the kinematic mechanism as final stage (Fig. 1d) — destruction of the structure.

Together 6 concrete beams were cast for the purpose of the experiment with same cross section dimensions 0.25×0.4 m and the length of 10.5 m. Concrete strength class of C35/45 has been used. Beams were produced in specialized factory ZIPP Bratislava, s.r.o., Sereď division. Pictures taken during preparation and execution of the beams are in Fig. 2.

All beams were reinforced with reinforcing steel B500B and with two single strand tendons ϕLs15.7 mm/1860 MPa with different geometry. The first tendon had polygonal shape and geometry produced zero secondary effects (concordant tendon). The second tendon was designed to reach maximum secondary effect. Tendon layouts of each tendon are shown in Fig. 3. Plastic ducts with diameter of 22 mm were used for each tendon.

Elasto-magnetic sensors placed in characteristic cross sections for each tendon on opposite side of the beam were used for detailed recording of prestressing force. Experimental beams were prestressed by tendons with different bond. All together there were 3 groups of samples. The first one were beams prestressed by tendons with bond N1 and N2, the second one were beams prestressed by tendons coated with emulsion for protection against corrosion

Figure 2 Preparation and realization of the experimental beams.

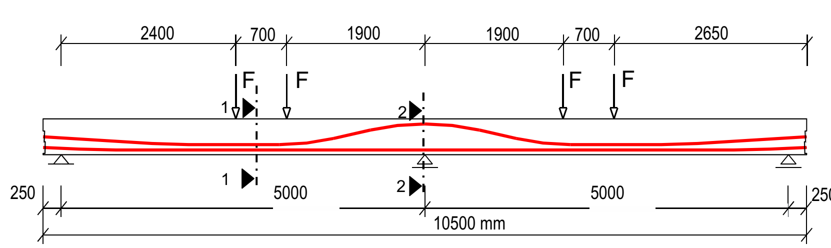

Figure 3 The tendon lay-outs.

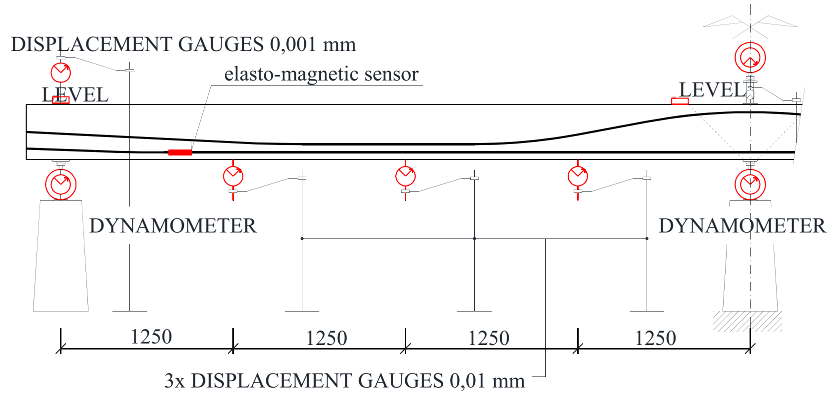

Figure 4 Scheme of the measuring gauges arrangement.

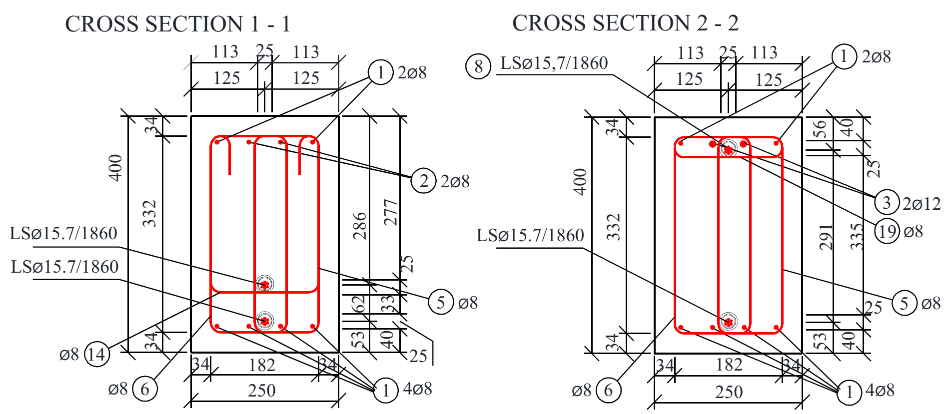

Figure 5 Schemes of assumed critical cross-sections.

— lower bond, N3 and N4, and finally beams prestressed by unbonded tendons — monostrands. Each tendon has been tensioned by force $P_0 = 200$ kN.

Beams were installed on the 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. 3. The reactions were monitored on each support with dynamometers. The settlement of supports and displacement of the beam were also measured. All measuring gauges used for each beam are displayed in Fig. 4.

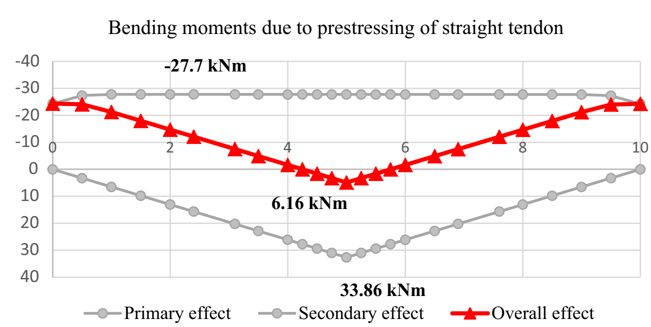

Figure 6 The scheme of primary and secondary effect of prestressing on tested beams.

Results

Obtained results of the experimental program have been compared with the theoretical analysis. The plastic analysis has been used because it allows to consider formation of plastic hinges after reaching bending capacity in the critical cross-sections. There is also a possibility to apply an additional load after formation of the plastic hinge. Formation of several plastic hinges in the structure, which means development of kinematic mechanism, was the ultimate state of this analysis. Two critical cross sections were determined based on this knowledge. The first one was section located at the intermediate support, where first plastic hinge has developed. The second one was section located in the middle of each span. The scheme of these critical cross sections is displayed in Fig. 5. The theoretical bending capacity was calculated using axial force balance in structural materials $\sum F_i = 0$ and assumption of reaching ultimate concrete strain of $\varepsilon_{cu} = 0.0035$.

Measured prestressing effects are displayed in Fig. 6 for beam N1. 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 Table 1 for beam N2.

Table 1 The reaction results (R1 — edge supports; R2 — intermediate support) and bending moment for beam with bonded tendons — N2.

Bonded tendons N2	R1 [kN]	R2 [kN]	Bending moment at mid. span section [kN m]	Bending moment at intermediate support [kN m]
Self-weigh g_0	6.09	12.58	6.34	−2.04
Loading devices	0.41	1.19	0.98	−0.21
Secondary effects	6.45	−12.90	15.48	32.25
External force 330 bar	69.97	370.06	167.93	−197.13

Table 2 Comparison between theoretical and experimental results — bending moments.

Beam types	Cross section	Theoretical bending capacity $M_{Rd.teoret}$ [kN m]	Reached bending moment — with secondary effect $M_{Ed.exp}$ [kN m]	Reached bending moment — without secondary effects $M_{Ed.exp}$ [kN m]
N1 and N2	1-1	192.32	190.82	175.13
	2-2	−150.80	−166.93	−199.62
N3 and N4	1-1	192.29	190.68	174.98
	2-2	−150.78	−157.79	−190.49
N5 and N6	1-1	167.75	163.75	148.06
	2-2	−130.52	−130.52	−163.21

Table 3 The percentage differences between theoretical and experimental results.

$M_{Rd,teort}/M_{Ed,exp}$		Reached resistance— with secondary effects [%]	Reached resistance— without secondary effects [%]
Beam types	Cross section		
N1 and N2	1-1	−0.8%	−9.8%
	2-2	9.7%	24.5%
N3 and N4	1-1	−0.8%	−9.9%
	2-2	−4.4%	20.8%
N5 and N6	1-1	−2.5%	−13.4%
	2-2	−0.8%	−9.8%

Conclusion

The results presented in Tables 2 and 3, show that the secondary effects of prestressing did not disappeared after reaching the bending capacity in critical cross-sections and even after transformation of the continuous beams into kinematic mechanism. They have had permanent influence on the internal forces in the structure.

The average difference between in experiment achieved bending moments without secondary effects (cross-section 1-1, in Fig. 3) and theoretical flexural resistance was 10%, while in a case of assuming secondary effects the difference fell to 0.8% for beams prestressed by tendons with bond a partial bond. The similar differences were achieved also for section 2-2. In case of prestressing tendons without bond are differences even more eye striking. In case of assuming secondary effects the differences are less than 4% while without these effects more than 13% for section 1-1. For section 2-2 it is 0.8% compare to 10%.

Based on the presented results we can conclude that secondary effects of prestressing represent permanent part of the internal forces in a structure. Secondary effects influence stress state of a member also after changing the structural system due the development of plastic hinges in a structure and even after development of kinematic mechanism.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgments

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