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ANALYSIS OF PRESTRESSING IN PRECAST PRESTRESSED CONCRETE BEAMS

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Abstract

Knowledge of prestressing force's value is in the case of prestressed concrete structure the most important basis for defining load-carrying capacity and remaining service life. Numbers of prestressed concrete structures are about to reach their limit of service life and they are exhibiting signs of deterioration due to the conceptional errors, inadequate maintenance and environmental distress. All of these factors negatively influence the actual state of prestressing. Thus, it is essential to determine the value of prestressing force considering the degradation of materials, such as corrosion of prestressing strands or wires. While assessing structure in service, it is difficult to apply magnetoelastic sensors or use other direct methods for determining the state of prestressing. Hence, the indirect methods enable to analytically calculate the prestressing force based on the results of measurement, e.g. strain, stress, deflection, or width of the crack. The present paper focuses on numerical analysis of prestressing in a twosome of precast prestressed concrete beams. For the numerical analysis, two indirect methods are applied, specifically Saw-cut method and Crack initiation method. Finally, the results are discussed and recommendations for the experimental campaign are summarized.

Keywords:

Prestressed concrete;
Prestressing force;
Precast prestressed concrete beam;
Saw-cut method;
Crack initiation method.

1 Introduction

The essence of prestressed concrete is the application of prestressing force which induce an axial compression that counteracts all, or part of, the tensile stresses. This fact enables to use concrete's good compressive strength and suppress its low tensile strength (full or partial prestressing). The discovery of prestressed concrete has introduced longer spans of concrete bridges or structures and smaller concrete structures' sections. Furthermore, compressive stress eliminates cracks in concrete member and consequently increase the stiffness of structure which affects the deformation of prestressed concrete structure, as well. An uncracked section is important especially in the case of liquid-retaining structures or structures prone to degradation in an aggressive environment. On the other hand, there are some disadvantages of prestressed concrete too. One of them is more difficult design, as an engineer must divide the design process into design stages which represent a different state of structure and loads. Other cons are not the negligible influence of creep and shrinkage of concrete, much more complicated construction process, and a requirement for higher quality control.

At present, the research activities of the Department of Structures and Bridges are oriented on the existing bridge reliability evaluation and investigation of their real behaviour respecting relevant damages of existing bridges and their rehabilitations in form of reconstructions [1]. In the case of bridges on the road net, the statistics database SRA (Slovak Road Administration) and the available sources show that about 34.2 % of existing bridges do not satisfy the current criteria for reliability and 2.5 % is in very poor and breakdown conditions [2]. The present structural condition of bridges from the first generation is inappropriate, closely related to their maintenance, inadequate inspection, external loads, and careless conceptual design [3]. The problem is very urgent because many

construction projects, especially transport infrastructure, in most European countries are more than 50–60 years old and require rehabilitation based on objective evaluations [4]. Existing bridges are structures that reflect not only the level of the society in which they were built but also the cultural and economic power of present generations, as they reflect the care for these inherited engineering works [5].

Currently, prestressing is provided by high-strength steel. However, first attempts in prestressing were performed using low-strength steel which led to immense prestressing losses. Their value used to reach approximately two-thirds of initial stress value. This approach is superseded, and at present prestressing losses represent around 20 % of initial stress. State of prestressing significantly influence value and redistribution of internal forces. Value of prestressing force decreases immediately after anchoring of prestressing reinforcement, see in Fig. 1. The exhibition of prestressing losses depends on the used method of prestressing. We distinguish two methods of prestressing. First, the pre-tensioned concrete member is cast around the strands which are tensioned between stands. In this case, the prestressing force is transformed into the structure through the bond between the steel reinforcement and concrete. Pretensioned concrete beam usually contains many strands (or wires). This approach is used for short-span and medium span bridges or structures. Second, in the case of post-tensioned concrete, the prestressing force is applied by jacking steel tendons against an already-cast member, so the prestressing in transferred through built-in anchorages. Though, if the space between the tendon and the duct is injected with cement grout, the prestressing force is transferred also through the bond between the steel and concrete. This approach allows us to design curved tendons and provide suitable redistribution of internal forces by changing the distance between the prestressing force and the concrete member's center of gravity.

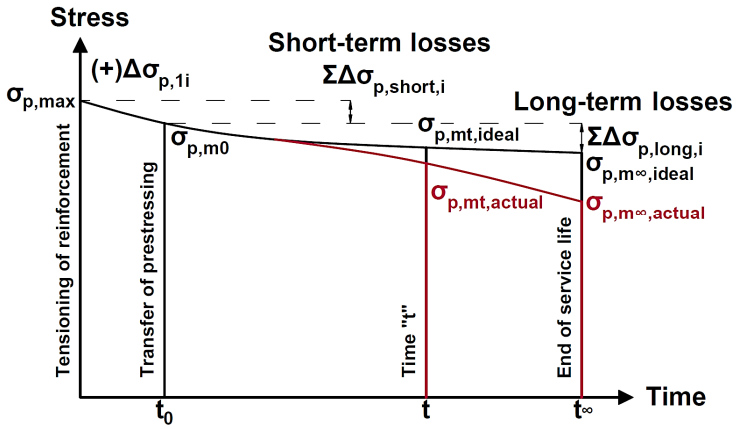


Fig. 1: The relation between stress in prestressing tendon and time.

Available standards offer the approaches for determining the value of prestressing losses considering construction stages, methods of prestressing, and expected service life of the structure. This way, an engineer is able to calculate summary prestressing loss at the end of service life. Nevertheless, standards do not take into account prestressing losses due to the degradation of materials. Thus, there is a need for methods for determining the actual state of prestressing considering all of the influences which the prestressed concrete structure was exposed until its assessment. In engineering practice, methods for the derivation of prestressing force fall into two main categories – direct and indirect methods. The approach of direct methods is the evaluation of prestressing directly from the measurement. There are several methods which can be used. Direct methods are usually non-destructive, and their important advantage is possible real-time monitoring of prestressing force in the strand. The most used is the Magnetoelastic method based on observing of magnetic field intensity. However, its use is considerably limited to new structures. Therefore, the application of indirect methods for determining the state of prestressing on prestressed concrete structures in service appears to be a suitable alternative. Indirect methods can be both non-destructive and destructive. Classification of direct methods according to their influence on the investigated structure is in some cases debatable. The techniques with only local effect on the structure can be considered as non-destructive, as damages caused by their application can be properly and easily fixed without any influence on the structure's integrity. This group of methods include, e.g. methods based on stress relief in concrete member (Saw-cut method, Stress-relief coring technique/Drilling

method), Strand-cutting method, Exposed strand method, and Structural response method (Crack initiation method, Crack reopening method).

The pivotal object of this paper is the numerical analysis of Saw-cut method and Crack initiation method applied on a pair of precast prestressed concrete beams with a different initial value of prestressing force. The concept of Saw-cut method is the isolation of concrete block from acting forces caused by a twosome of saw-cuts. Then, the value of the prestressing force is derived from stress or strain relief monitored in the area adjacent to performed saw-cuts. The isolation of concrete block is done when increasing height of saw-cuts no longer cause any noteworthy change of strain measured by the strain gauge. Usually, we use foil strain gauge which is installed in the middle of the axial distance between saw-cuts prior sawing. So-called Crack initiation method belongs to a group of Structural response method. The principle of this method is based on gradual loading of the structure until the level of the tensile strength of concrete is reached and the first crack occurs. Subsequently, the prestressing force is evaluated from known stress (tensile strength of concrete) and applied external load which initiated a critical moment. In this study, a static scheme of the simply supported beam is considered, therefore there is no influence of the secondary moment. Assuming a statically indeterminate structure, the contribution of the secondary moment must be taken into consideration.

2 Description of precast prestressed concrete beams

Used specimens for the study are designed as precast prestressed concrete beams with a length of 4200 mm and cross-section dimensions 200 x 400 mm. The prestressing force is provided with one 15.7 mm strand placed in a duct with a diameter of 48 mm which is fully injected with cement grout, thus prestressing is transferred through the build-in anchor and bond between steel and concrete. Conventional reinforcement of beams includes two B500B 10 mm bars at a bottom and two at a top, while the edges of beams are reinforced with U shape bars of 6 mm (sited longitudinally and transversally). Two-legged stirrups are designed as 6 mm bar with a maximum spacing of 200 mm, see in Fig. 2. The beams are made from the concrete strength class of C30/37.

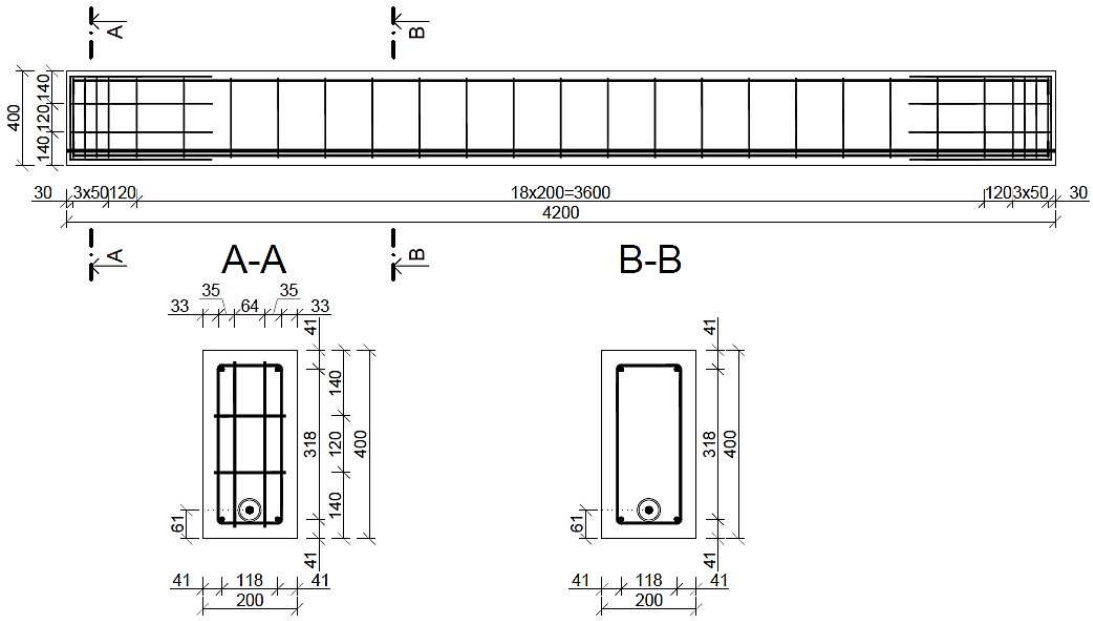


Fig. 2: Reinforcement of precast prestressed concrete beams, dimensions are in [mm].

3 Numerical analysis

Numerical analysis is an important basis for later performed experimental measurements. A 2D numerical analysis with the assumption of nonlinear behaviour was performed in ATENA 2D Software applied on precast prestressed concrete beams with parameters mentioned above. In the numerical analysis, two different values of prestressing force were used P_1 = 61.70 kN; P_2 = 145.0 kN. Accordingly, the ratio between these two values of the prestressing force was approximately one to two. The intention was to observe the efficiency of performed indirect methods in a distinct state of prestressing. Material properties used in the model are listed in Table 1. The beam was supported by

two steel plates 200 x 200 x 20 mm positioned at the bottom in an axial distance of 4.0 m (effective span of a simply supported beam).

Table 1: Material properties used in numerical analysis.

Type of material	Material properties
Concrete	E_c = 33 010 MPa f_{cu} = 37.00 MPa f_c = 31.45 MPa f_t = 2.665 MPa μ = 0.20
Prestressing reinforcement	σ_y = 1 660 MPa E_p = 195 000 MPa
Conventional reinforcement	σ_y = 500 MPa E_s = 200 000 MPa
Steel plates	E = 210 000 MPa μ = 0.30
Saw-cuts	E_c = 1 kPa μ = 0.30

Nonlinear analysis in ATENA 2D Software was done assuming stress-strain curves which are detailed for each material in Fig. 3. In the performed numerical analysis the Newton – Raphson method was used.

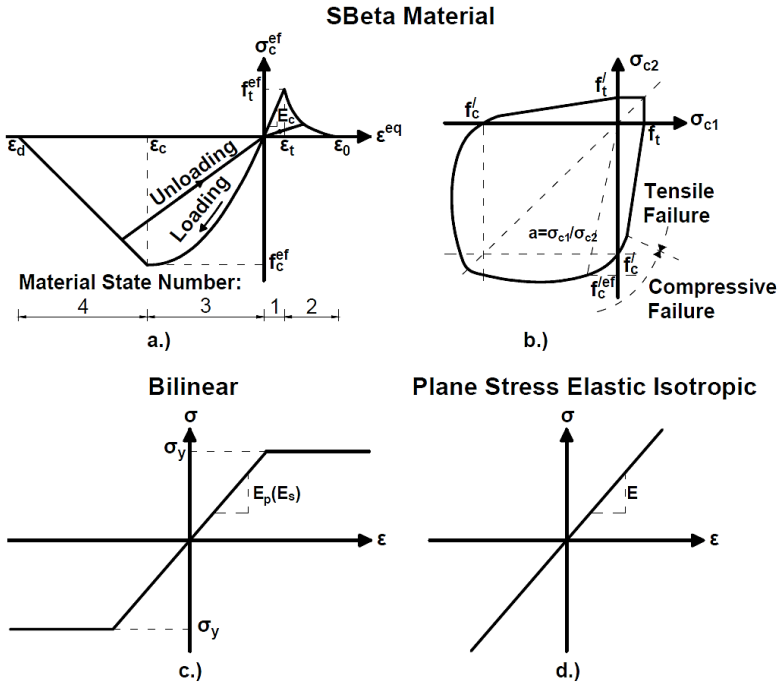


Fig. 3: ATENA 2D – a) Stress-strain curve for concrete; b) Biaxial failure function for concrete; c) Stress-strain curve for prestressing and conventional reinforcement; d) Stress-strain curve for steel plates and saw-cuts [12].

3.1 Crack initiation method

For the study, a four-point bending test scheme was chosen, ergo the negative influence of shear stress was effectively avoided. The critical load Q is distributed into two identical forces $Q/2$ in the axial distance of 1.0 m while their distance from the ends of the beam is 1.60 m Fig. 4. In the model, this load is distributed by steel plates 200 x 200 x 20 mm on the upper edge of the beam. The essence of this method is to determine critical load which initiate critical moment M_{cr}. This load was defined as a load when the tensile stress at a bottom of the prestressed concrete beam reaches its tensile strength. The stress monitoring point was located in the middle of the concrete beam at a bottom edge (2.10 m from the beam's eds). An external load was applied to the structure gradually in steps.

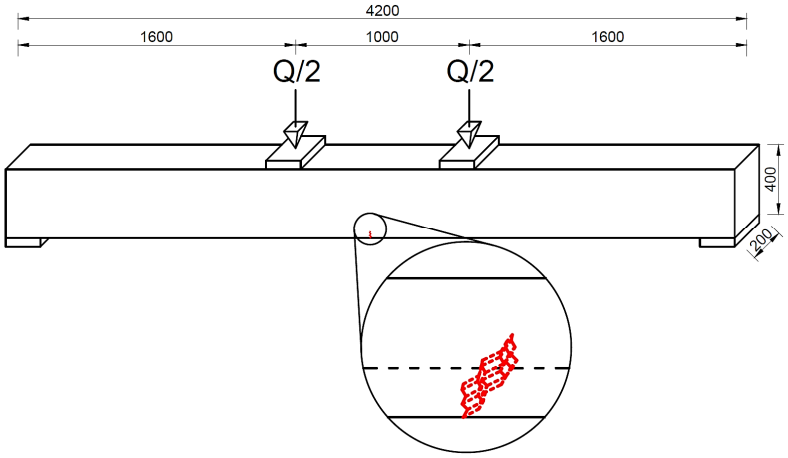


Fig. 4: Crack initiation method.

The relation between the applied load Q and monitored tensile stress is shown in Fig. 5 and Fig. 6. As you can see, in the case of prestressing force P_1, a crack occurred when the load outreached the value of 34.0 kN. Presuming prestressing force P_2, tensile strength was reached for Q = 57.0 kN. Obtained results enable us to provide an inverse calculation of prestressing force using formula (1). Such an approach requires knowledge of stress state prior testing. In practice, the investigated structure has to be out of order, therefore only known the dead and external load is applied. The accuracy of this method depends on our ability to evaluate cross-section and material parameters. Critical load determined by numerical analysis is an important base for experimental measurement, as we need to know the rough value of load when the crack occurs in the prestressed concrete beam.

$$P = \frac{f_t - \frac{M_G}{I_y} \cdot z - \frac{M_Q}{I_y} \cdot z}{\frac{1}{A} + \frac{e_p}{I_y} \cdot z}\ , \tag{1}$$

where: σ – stress, f_t – tensile strength of concrete, P – prestressing force, A – cross-section area, e_p – eccentricity of prestressing force, I_y – second moment of inertia, z – position of the neutral axis, M_G – moment due to dead load, M_Q – moment due to external load.

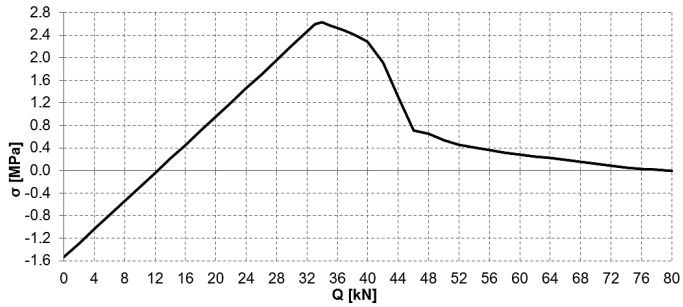


Fig. 5: Stress in monitoring point P_1 = 61.70 kN.

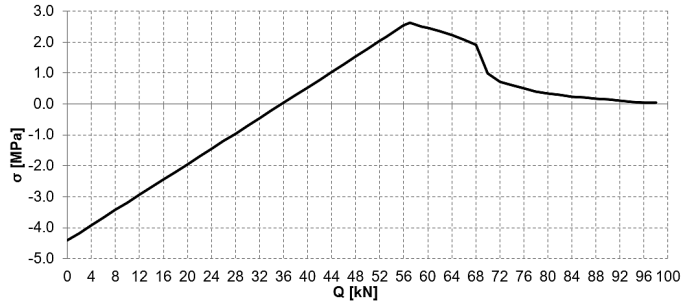


Fig. 6: Stress in monitoring point P_2 = 145.0 kN.

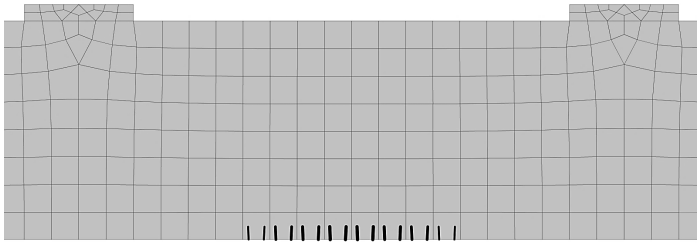


Fig. 7: Cracks in the analysed prestressed concrete beam P_1 = 61.70 kN.

3.2 Saw-cut method

Numerical analysis of the Saw-cut method (Fig. 8) was divided into two construction stages. In the first place, a prestressed concrete beam is supported on the steel plates (supports) and only dead load is considered. In the second stage, no additional load is applied, and the saw-cuts are performed in the central area of the concrete beam. Saw-cuts are taken into account by the reduction of modulus of elasticity of their representative macro-elements. In the model, the width of the saw-cuts is 5 mm. Subsequently, the level of concrete block's isolation is calculated as the percentage change of stress, whereas stress monitoring point is situated in the middle of the axial area between saw-cuts. This is done for both values of the prestressing force P_1 and P_2.

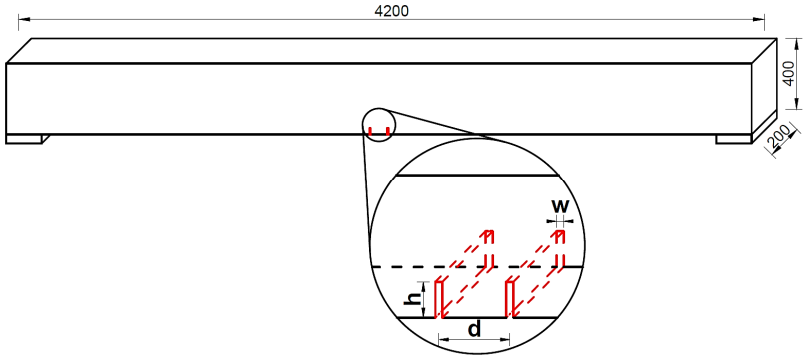


Fig. 8: Saw-cut method.

In the study, axial distance between saw-cuts of 100 mm was chosen, while the stress relief was verified for height h) from 10 mm to 50 mm. An intention was to find suitable saw-cuts' parameters for the experimental campaign which could result in full isolation of concrete block (100 % stress change). Distribution of stress at middle cross-section before and after sawing is presented in Fig. 9 and calculated values of stress change are summarized in Table 2.

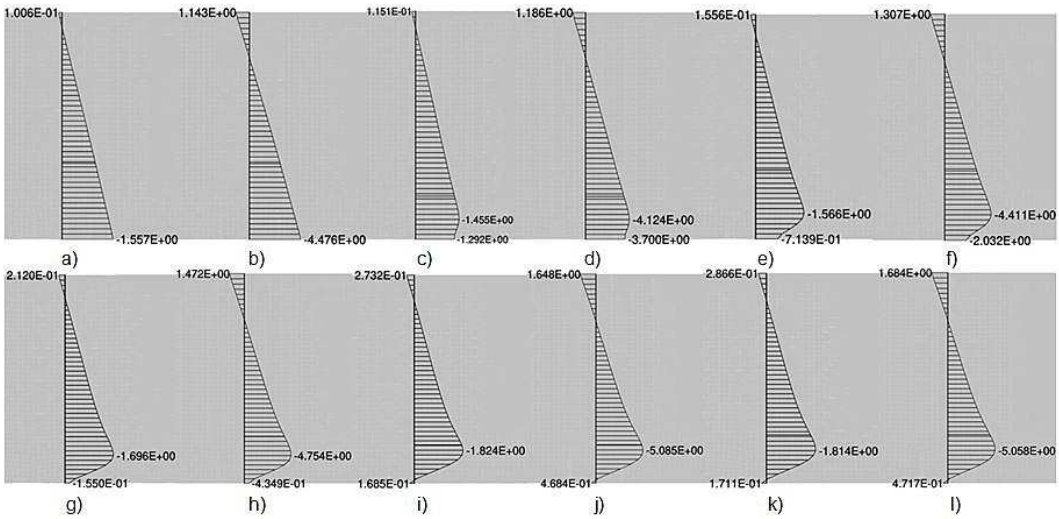


Fig. 9: Distribution of stress – a) before sawing, P_1; b) before sawing, P_2; c) h = 10 mm, P_1; d) h = 10 mm, P_2; e) h = 20 mm, P_1; f) h = 20 mm, P_2; g) h = 30 mm, P_1; h) h = 30 mm, P_2; i) h = 40 mm, P_1; j) h = 40 mm, P_2; k) h = 50 mm, P_1; l) h = 50 mm, P_2; stress in [MPa].

Table 2: Stress in monitored point.

P [kN]	h [mm]	σ_0 [MPa]	σ_1 [MPa]	$\Delta\sigma$ [%]
61.70	10	-1.557	-1.292	17.0
145.0	10	-4.476	-3.700	17.3
61.70	20	-1.557	-0.714	54.1
145.0	20	-4.476	-2.032	54.6
61.70	30	-1.557	-0.155	90.0
145.0	30	-4.476	-0.435	90.3
61.70	40	-1.557	0.169	110.9
145.0	40	-4.476	0.468	110.5
61.70	50	-1.557	0.171	111.0
145.0	50	-4.476	0.472	110.5

An axial distance of saw-cuts was selected with regard to use 50 mm foil strain gage in the experimental campaign. This length should be in case of analysed precast prestressed concrete specimens sufficient, as their maximum aggregate grain size enables us to use strain gages with shorter measuring grid. As we can see in Table 2 and Fig. 10, approximately full isolation of concrete block can be reached with application of saw-cut with the height of 30 mm. Difference between the height of 40 mm and 50 mm is negligible, thus we can assume that saw-cut with the height of 40 mm adequately isolate concrete block from acting forces and increasing of this parameter does not lead into any significant stress (or strain) change.

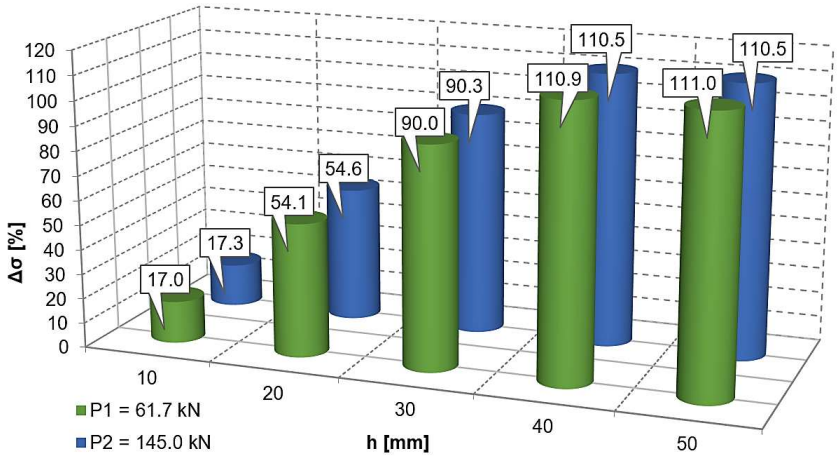


Fig. 10: Percentage stress change.

4 Conclusions

Crack initiation method should be used only in the case of structure which is not pre-cracked. Consequently, it is important to provide a detailed inspection of the investigated structure in advance. The inverse evaluation of prestressing force should be accurate enough, but further experimental investigations are needed. The results of this study indicate that the value of prestressing force and initial stress does not influence percentage stress change after the application of Saw-cut method. Taken together, obtained results seem to suggest that only parameters of saw-cuts are relevant for effective isolation of concrete block from acting forces and determination of initial stress. The accuracy and reliability of both verified methods depend on the knowledge of the load applied to the structure and material properties at a time of testing. Saw-cuts with height above 30 mm and axial distance of 100 mm could eventually be used in the experiment as suitable parameters. However, numerical analysis was performed without considering possible temperature change caused by sawing. This fact could influence the reliability of the obtained results and should be verified, as well. The present conclusions might help to prepare a recommendation for the experimental campaign and possible application in practice. We hope that future tests will confirm our findings from numerical analysis which will serve as a base for future studies on prestressed concrete structures.

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