Numerical verification of the saw-cut method

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Abstract. In Slovakia and other countries, a contemporary challenge for engineers and academics is an assessment of the state of existing prestressed concrete structures. The main components of assessment include regular inspections, maintenance, and diagnostics. For defining the load-carrying capacity and remaining service life, more reliable results of diagnostics are required. A need for detailed knowledge of the actual value of prestressing force is becoming a crucial aspect of civil engineering. There are many prestressed concrete structures built in the previous century which are about reaching their limit of service life. These structures are about sixty years old and many of them are exhibiting signs of deterioration due to the design and construction deficiencies, such as overloaded vehicles, environmental distress, and inadequate maintenance. In this paper, dozen concrete specimens are numerically analysed using the indirect non-destructive Saw-cut method. Ten of them are loaded by different level of compressive force which initiates compressive stress from 2.0 MPa to 12.0 MPa. Performed numerical analysis is an important basis for the experiment. The influence of temperature change caused by sawing will be later experimentally investigated on the remaining two concrete specimens. For numerical analysis, a 2D finite element model with the assumption of nonlinear material behaviour is performed. Subsequently, the correlation between the distance and depth of the saw-cuts, and amount of released strain or stress, as a result of numerical analysis, is outlined. Finally, the outputs obtained from numerical analysis are discussed and recommendations for the experiment are summarized.

1. Introduction

Nowadays, we are facing the problems related to precast prestressed concrete structures designed and constructed in the middle part of the 20th century. It is evident that this fact results in a growing need for new in-situ methods to define their load-carrying capacity and remaining service life. Replacement of existing structure by new, technologically advanced structure should be used only as a last resort. The rapid development of prestressing technology increased in the early 1980s. The length of girder increased to 30 m. The maximum length of post-tensioned girders made from three members is 42.0 m [1]. In the case of prestressed structures, knowledge of the state of prestressing force is required. Reliable methods for determining the level of prestressing force are essential for assessment.

The importance of this issue can be presented on the first generation of precast prestressed concrete bridges situated in Northern Slovakia (figure 1). Since 2015, three bridges of same building technology were classified as the state of emergency. Their construction problems can be summed up to two main groups of leading causes of failure. First, the problems related to improper design such as the absence of conventional reinforcement. The girders have been acting as the plain concrete members with partially bonded or even unbonded prestressing. Second, insufficient inspections and
inadequate maintenance result in corrosion of prestressing wires due to absence of proper grouting of the ducts. Moreover, the anchors were installed without grouting or any other relevant protection. Half of them have not been protected against the influence of water. On the other hand, concrete of the beams was in surprisingly good condition.

Figure 1. The collapse of a precast prestressed concrete bridge in Trstená, Slovakia.

The methods for determining the state of prestressing force can be classified according to their influence on the structure or approach to the calculation of the level of prestressing. In relation to the effect of the performed technique on the investigated structure, we distinguish destructive and non-destructive methods. Classification of some techniques is debatable because the line between destructive and non-destructive approach is extremely thin and depends on the author's judgment. Generally, methods with none or only minimal impact on the structure are considered as non-destructive. These methods include, for example, a method based on the exposure of strand, Drilling method, and Saw-cut method, which is the pivotal object of this paper. In the case of using a destructive approach, we are not able to avoid a significant effect of our actions on the investigated structure. This group involve a method based on the initiation of crack or crack reopening in concrete member, and the Strand cutting method. Another classification divides the techniques into direct and indirect methods. As the name suggests, direct methods enable us to determine the level of prestressing directly from the results of the measurement. Unfortunately, these methods suffer from a plethora of pitfalls. In practice, we mostly use the Magnetoelastic method which is applied typically in new structures. The benefit of this method is the possible real-time monitoring of the prestressing force. Application of direct methods in existing structures is very limited. Indirect methods require measurement of physical or other quantities such as deformation, strain, or width of the crack. Subsequently, the value of the prestressing force is calculated using the results obtained from the abovementioned measurement.

The principle of the Saw-cut method is stress relief initiated by sawing, which fully isolates the concrete block from the acting forces. Stress relief is monitored in the area adjacent to performed saw-cuts. The concrete block can be considered as fully isolated if the increasing depth of saw-cuts no longer causes any significant change of measured strain or stress. Eventually, the results gained from the strain or stress relief measurement enable us to calculate the actual state of the prestressing force in the investigated structure. This method has only a negligible impact on the concrete structure because saw-cuts can be properly fixed. Therefore, the Saw-cut method is usually considered as a non-destructive indirect method.

2. Description of the experiment
Twelve concrete push-out specimens with the label from CS1 to CS12 will be tested in the laboratory. For the experiment, standard concrete testing specimens (figure 2) with a length of 700.0 mm and
cross-section dimensions of 150.0 mm will be prepared. Beams will be produced from low-strength concrete of grade C30/37. Since only compressive stress in specimens is considered, no reinforcement will be used. In addition to specimens, nine cylinders (150.0 × 300.0 mm) for mechanical properties testing will be produced to determine compressive strength and modulus of elasticity of concrete.

Figure 2. Preparation of concrete specimens in the laboratory.

To simulate different conditions in the real prestressed concrete structures, non-identical level of compressive stress will be initiated in each pair of specimens. Specifically, the range of compressive stress in specimens will be from 2.0 MPa to 12.0 MPa. The saw-cuts application will be performed in the central area of the specimens, while the 5 cm long foil strain gage will be placed in the middle of the axial distance between adjacent saw-cuts. Figure 3. presents the testing scheme with the labelling of saw-cuts applied in the experimental specimen.

Figure 3. Scheme of the concrete specimen.

The realization of the Saw-cut method will be performed after compressive stress in the concrete specimen reaches the intended value. The parameters of specimens, external load, level of compressive stress during push-out testing, and applied saw-cuts are presented in table 1.
### Table 1. Parameters of the specimens and saw-cuts.

| Specimen  | Specimen dimensions | $F$ [kN] | $\sigma_c$ [MPa] | Saw-cut parameters |
|-----------|---------------------|----------|------------------|-------------------|
| CS1, CS2  | 150.0 150.0 700.0   | 45.00    | 2.00             | 100.0 h 35.0      |
| CS3, CS4  | 150.0 150.0 700.0   | 90.00    | 4.00             | 100.0 h 35.0      |
| CS5, CS6  | 150.0 150.0 700.0   | 135.00   | 6.00             | 100.0 h 35.0      |
| CS7, CS8  | 150.0 150.0 700.0   | 180.00   | 8.00             | 100.0 h 35.0      |
| CS9, CS10 | 150.0 150.0 700.0   | 270.00   | 12.00            | 100.0 h 35.0      |
| CS11, CS12* | 150.0 150.0 700.0 | -        | -                | 100.0 h 35.0      |

*Verification of the influence of temperature change caused by sawing.

### 3. Numerical analysis

In order to analyse the stress change in concrete specimens, a 2D numerical model with the assumption of nonlinear material behaviour in ATENA Software was performed. Quadrilateral finite element mesh with a defined element size of 0.01 m was generated automatically (figure 4) for all used macro-elements. Dimensions of concrete specimens and saw-cuts were used in accordance with table 1, while the thickness of steel plates placed on the edges of the specimens was 1.0 cm. The contact between the concrete specimen and steel plates was considered as rigid. Material properties of macro-elements are presented in table 2.

### Table 2. Material properties of macro-elements used in a 2D numerical model.

| Macro-element | Description           | Material type | $E$ [GPa] | Other properties                          |
|---------------|-----------------------|---------------|-----------|------------------------------------------|
| 1             | Concrete specimen     | SBeta         | 28.06     | $f_{cu} = 25.00$ MPa $f_c = 21.25$ MPa $f_t = 2.052$ MPa $\mu = 0.20$ |
| 2 and 3       | Steel plates          | Plane Stress Elastic | 210.00  | $\mu = 0.30$ |
| 4 and 5       | Saw-cuts              | Isotropic     | $1.00 \times 10^{-6}$ | $\mu = 0.30$ |

*Figure 4. A 2D numerical model of the push-out specimen in ATENA Software.*

The analysis using the Newton – Raphson method was divided into two construction stages (figure 5.). First, the specimen is supported on the upper and lower edge on the steel plates, while the load is applied on the upper steel plate longitudinally to the axis of the specimen. Second, the load remains constant and the saw-cuts are performed. The application of the Saw-cut method is exhibited by the reduction of modulus of elasticity of macro-elements which represent saw-cuts. Stress monitoring point is placed in the middle of the axial distance between adjacent saw-cuts.
Since the initial stress in the concrete structure in practice is unknown, the stress (or strain) relief is presented as percentage change which well describes the rate of isolation of concrete block. The distribution of compressive stress in the concrete specimen with the initial stress level of 2.0 MPa before and after application of saw-cuts is shown in figures 6, 7 8.

Figure 5. Construction stages of numerical analysis – a) first stage; b) second stage.

Figure 6. Stress [MPa] in concrete push-out specimen CS1/CS2 before application of saw-cuts.

Figure 7. Stress [MPa] in concrete push-out specimen CS1/CS2 after application of saw-cuts.
4. Conclusions

Saw-cut parameters for push-out testing are based on the results of numerical analysis. The goal was to find the relation between depth and axial distance of saw-cuts which would result in full stress relief in monitored point. The numerical analysis indicates that the level of initial stress does not significantly influence the percentage change of stress or strain after application of saw-cuts (figure 9 and table 3). This fact is promising for the planned experimental push-out testing and application of this technique in real structures in practice. Monitoring of influence of the temperature change will be very important for the description of measurement accuracy in real structures. In case of its significant effect, the consideration of modification of saw-cuts parameters, especially the axial distance, will be necessary.

**Table 3.** Stress relief results obtained from a 2D numerical model.

| Specimen | Saw-cut parameters | Stress | Stress relief |
|----------|--------------------|--------|---------------|
|          | $h$ [mm] | $d$ [mm] | $\sigma_c$ [MPa] | $\sigma_{c2}$ [MPa] | $\Delta\sigma_c$ [%] |
| CS1, CS2 | 35.0     | 100.0    | -2.02          | 0.03               | 101.44         |
| CS3, CS4 | 35.0     | 100.0    | -4.02          | 0.09               | 102.35         |
| CS5, CS6 | 35.0     | 100.0    | -6.02          | 0.27               | 104.49         |
| CS7, CS8 | 35.0     | 100.0    | -8.01          | 1.22               | 115.22         |
| CS9, CS10| 35.0     | 100.0    | -12.00         | 1.79               | 114.94         |
| CS11, CS12* | 35.0  | 100.0   | -            | -                  | -               |

*Verification of the influence of temperature change caused by sawing.
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