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Current possibilities of the diagnosis of prestressing steel in structures

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Abstract. The field of diagnosis of structures has been experiencing a dynamic development in the last decades caused by the development and expansion of new NDT methods and instrumentation. At the same time, it is possible to observe changes in the focus of interest in this field, or more precisely, alternating waves of interest in specific types of diagnosis targeted at special types of structures. These waves of interest are always caused by a certain trend in the development of the society or building industry, and most often, by some major even in the field. In the last few years, particular attention has been paid to prestressed structures, especially to bridges, in connection with the recent accidents of bridges made from prestressed concrete in the Czech Republic and abroad. Considering the relatively large number of these bridges in the Czech Republic built in the second half of the 20th century, attention is paid to basic changes in the pre-construction condition surveys aimed at determining the condition and the remaining life of these structures. The paper focuses on the analysis of possibilities of assessing the condition of prestressing steel at the level of the present state of diagnosis of structures.

1. Introduction to the issue

In the Czech Republic, there is a large number of various types of structures made from prestressed concrete. The most frequent and most attention-drawing structures from the point of view of diagnosis targeted at determining the lifetime include bridges made from prefabricated prestressed girders of various types and bridges built e.g. as monolithic prestressed slabs, but also prestressed truss girders in the structures of industrial halls and other types of elements and structures are in the centre of interest. While hall roof girders, for example, are elements which can be replaced without problems if there are doubts of their functionality in the structure, as regards bridge structures, it is a fundamental problem complicated by general reluctance of the society and investors to consider their replacement, but also a problem at the level of public opinion, which has a tendency to attribute to the structures the character of “eternity” and endless durability.

Considering the recent accidents of prestressed bridge structures in the Czech Republic and abroad, extraordinary attention is paid to the pre-construction condition surveys of prestressed bridge structures with the aim of determining not only their technical condition but primarily of estimating on its basis the remaining lifetime of the structure in order to ensure the safety of its use. Immediately after the accident of the footbridge in Prague – Trója in 2017, attention was first paid to similar structures, which sometimes bordered on thoughtless hysteria oriented towards preventive demolition

IOP Conf. Series: Materials Science and Engineering **549** (2019) 012016 doi:10.1088/1757-899X/549/1/012016

of structures. As regards the remaining prestressed bridges, fortunately, concerns have rather led to performing detailed pre-construction condition surveys and monitoring the condition of the structure.

There is a question, however, whether the contemporary state of diagnostic methods and devices available for their application correspond to the requirements for a perfect survey of the structure, or more precisely, for a survey with the results ideally relevant for determining the condition of the structure.

2. Diagnosis of prestressed structures

In order to assess the overall condition, lifetime and functional characteristics of a prestressed structure, it is essential to determine especially the condition of the prestressing steel. It makes no sense to discuss e.g. cables running freely outside the concrete cross-section, where the determination of the condition is easy, but above all, the prestressing wires and cables placed in the cable channels. The protection of reinforcement in cable channels from corrosion is largely dependent on timely and correct grouting of the cable channel with a suitable grout. Therefore, during the pre-construction condition surveys of prestressed structures and elements, extraordinary attention should be paid not only to the already existing corrosion of the prestressing steel, but also to the existence of correct grouting of cable channels itself, because the absence of grout is a defect which must be immediately repaired to reduce future risks.

Naturally, the diagnosis of prestressed structures pays attention to the other parameters as well, for example to concrete properties, but the basic parameter is the condition of the prestressing steel, or its endangering.

Diagnosis of the condition of prestressing steel can be divided into two phases. In the first phase, it is necessary to determine the precise position or course of prestressing wires or cables, in the second phase, to determine their condition and presence of grout.

3. Methods applicable for determining the position of prestressing steel in a structure

In spite of the fact that the precise position of prestressing steel or cable channels in the pre-tensioned and post-tensioned structures and elements is specified in the technical documentation, it is necessary to expect certain discrepancies arisen during the manufacture. Determining the precise position and course of prestressing channels and therefore also of reinforcement is thus logically the first step in their diagnosis. It must be noted, however, that in a number of cases, cable channels are delimited by steel protection pipes (seamless pipes, Sandrik) [2].

In general, there are four basic methods for determining the position of reinforcement in concrete.

- **Chopped probes –** a method based on a mechanical removal of the covering layer of concrete using a hammer drill. It is a method widely used in the civil engineering surveys of aged structures, with a limited potential. For a specific case of determining the position of prestressing steel, it is a completely unsuitable method [5, 6].
- **Electromagnetic indicators of reinforcement –** devices based on the principle of electromagnetic field, formation of eddy currents, and the magnetic properties of steel reinforcement. The major disadvantage of this method is a limitation, given by the principle of the method, by the depth of the reinforcement under the structure surface, by the distance between individual bars and by the complexity of reinforcement in general. The applicability of this method is problematic, as regards determining the position of prestressing steel, due to the fact that the detection depth of the probes is very limited, and it is also probable that there might be some soft reinforcement between the concrete surface and the prestressing steel, which will not allow for localizing other elements deeper in the concrete. [5, 6].
- **Georadar –** a method based on the principle of transmitting radio-frequency electromagnetic pulses into the material and the detection of their reflection from the inhomogeneities in the environment. With the appearance of the Hilti PS-1000 radar, this method started to be highly applicable also for the above mentioned problem. Its advantages include the detection depth (Hilti PS1000 up to 400 mm, GPR Proceq up to 700 mm), immediate visualization of the result, and

independence of other reinforcement closer to the surface. The position of prestressing steel can be determined by both linear and areal measurements [5, 6].

Today, only two georadars are available on the market and they are designed primarily for the diagnosis of reinforced concrete structures. Hilti PS1000 X-Scan and Proceq GPR Live. Hilti PS1000 is equipped with three aerials in one probe with a frequency of 1.5 GHz and a detection depth of 300 mm, Proceq is equipped with one aerial of 0.9 – 3.5 GHz with a depth of up to 700 mm. In both devices, it is possible to transform the measurement results into a fully-fledged 3D image.

Its disadvantage is, on the contrary, the necessity to perform the measurements from the flat surface of the structure, and the fact that certain minimum dimensions of the measured area are necessary. Therefore, it is not possible to determine the reinforcement e.g. in the intricately-shaped or inaccessible parts of the structure, which is especially the case of some types of prefabricated bridge girders.

- **Radiography –** a well-known traditional method utilizing the irradiation of the structure with γ-rays from the Co60 source, and subsequently the attenuation of the radiation when passing through the structure depending on the volume mass and irradiated width. Considering the fundamental difference between the volume mass of concrete and the density of steel, it is possible to represent the entire reinforcement on the output medium (radiographic film, electronic imaging media, etc.), and in the case of irradiation from several points of view, to determine precisely the position of reinforcement. Its disadvantage, on the contrary, is the relatively small area examined given by the size of the recording medium (usually 300 x 400 mm), and currently, the problematic availability of this diagnostic method [5, 6].

On the basis of the extensive experience of the author's institution, the choice of georadar is clear, it is an ideal method for determining the precise position of prestressing steel in the structure; in the case of elements for which the reinforcement is inaccessible for the radar measurement, it would be necessary to use radiography, which is not currently available in the Czech Republic for the generally known reasons (Co60 radiography) [3].

3.1. Examples of practical application of localizing the prestressing cables

The following examples illustrate the radar determination of the position of prestressing cables (Hilti PS1000 X-Scan device) on three common types of prefabricated bridge girders.

KA girder

The first example is a KA-67-type girder with a length of 12 m, designed as a closed profile of approximately rectangular cross-section with an inner hexagonal chamber. KA girders have been developed since the second half of the 1950s and standardized later by Dopravoprojekt Bratislava [1]. The girder is reinforced with a total of 13 prestressing cables made of 7 to 12 prestressing wires of Ø 4.5 mm. In the middle of the span, 9 cables are situated near the bottom face of the girder, two cables near the bottom face in the second layer, and two cables near the upper face, of which the two peripheral cables from the bottom layer and two from the second layer rise to the upper face towards the end of the girder. The position of cables was determined by means of Hilti PS1000 X-Scan radar.

IOP Conf. Series: Materials Science and Engineering **549** (2019) 012016 doi:10.1088/1757-899X/549/1/012016

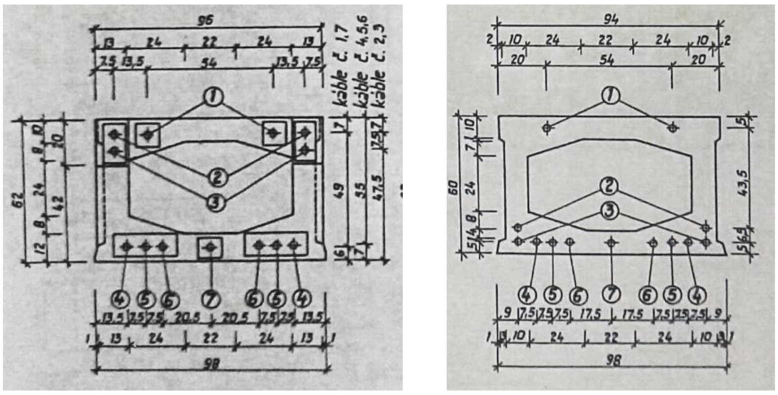


Figure 1. Type drawing of a KA-67 element, on the left: a cross-section at the front of the element, on the right: in the middle of the span [1].

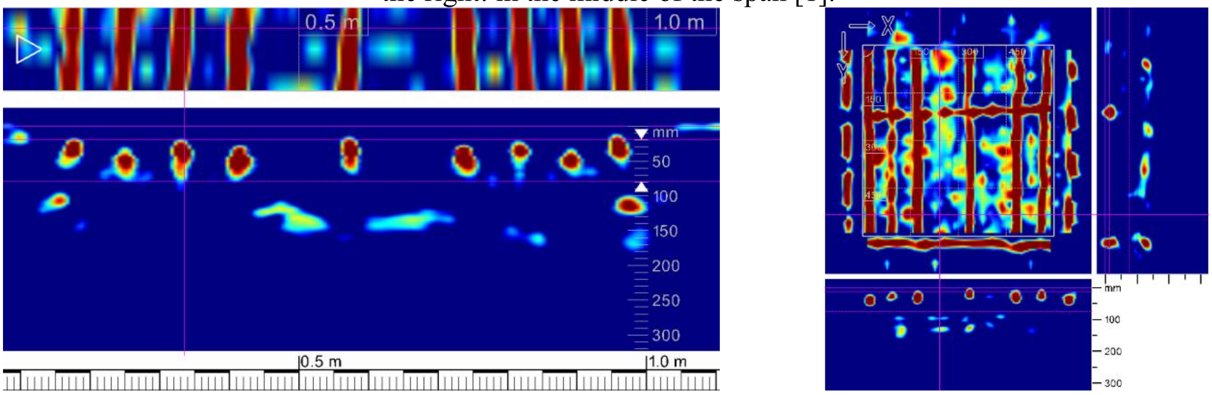


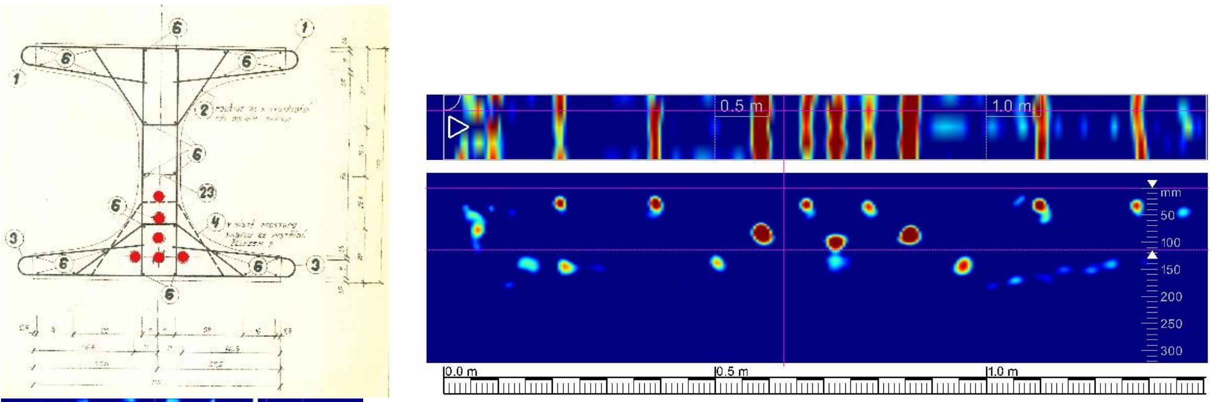
Figure 2. Radar scans (radarograms) taken on the lower side of the KA-67 girder, approximately in the middle of the span. On the left, a line scan across the girder captures all the 11 prestressing cables near the lower face including those in the second layer. The right picture shows an areal scan of 600 x 600 mm at the same place capturing the same cables and stirrups.

On this type of girder it is therefore possible to determine precisely the position of cables as long as they are situated near the bottom face of the girder, including the second layer. Cables near the upper face cannot be detected due to the hollow in the element. Cables which rise cannot be detected because of the depth limitation of the device. In case a radar with a higher depth range was used, it would probably be possible.

I girder

The second type of prestressed girder developed simultaneously with the KA girder is the so-called I girder. I girders were linked with the so-called latch connection at the protruding transverse reinforcement, the result of which was a slab with longitudinal holes [1]. The I girder variant used as an example is reinforced by six prestressing cables in the base of the vertical shaft and in the shaft itself (variant with a height of 1100 mm). The position of cables was determined by means of Hilti PS1000 X-Scan radar.

IOP Conf. Series: Materials Science and Engineering **549** (2019) 012016 doi:10.1088/1757-899X/549/1/012016



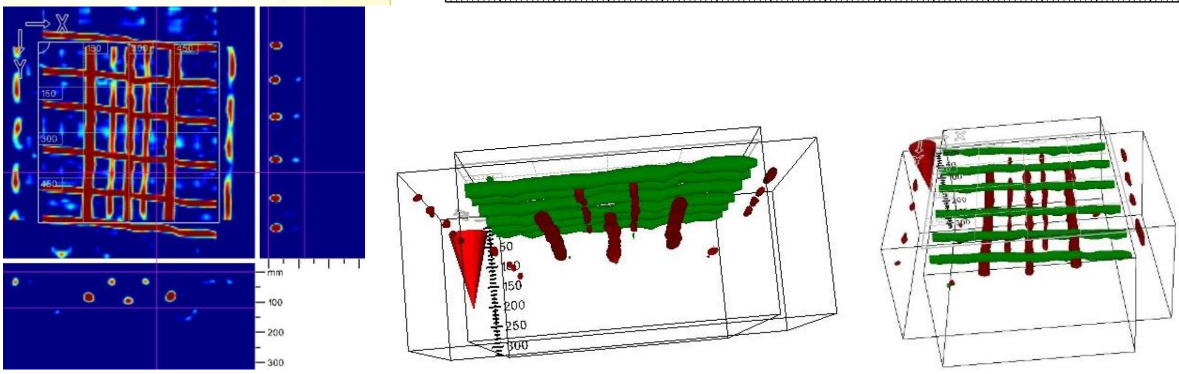


Figure 3. On the left, a type drawing of an I-girder (cross-section in the middle of the span) [1], on the right, a radar line scan from the bottom face capturing the bottom triple of prestressing cables and all the longitudinal soft reinforcement in the element.

Figure 4. A radar areal scan of 600 x 600 mm taken in the same place, for illustrative purposes in 2D, and in the middle and on the right, in 3D in various tilts. All the reinforcement is clearly visible.

Also in this type of girder it is possible to determine precisely the position of cables, but only for the bottom three ones. The remaining three cables situated in the shaft cannot be detected due to the low width of the shaft and their coverage by the lower cables. It might be possible to a certain extent from the inside of the chamber, but it is not accessible. The only exception is the peripheral girders with the accessible side surfaces.

DS-A girder with a strut frame structure and a central field

The last example is a DS-A girder with a strut frame structure and a central field from a motorway bridge. The girder is a chamber-type girder with prestressing reinforcement in the side walls [1].

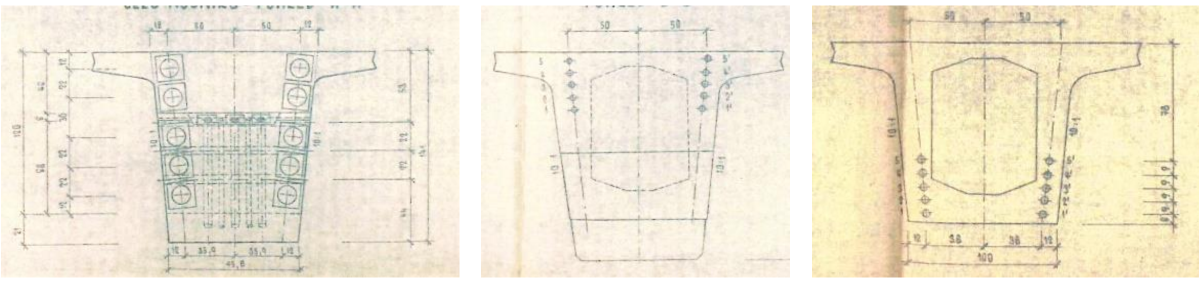


Figure 5. On the left, a type drawing of the DS-A girder, on the left, a cross-section at the end of the girder, in the middle, above the intermediate support (brace), and on the right, in the middle of the central field [1].

IOP Conf. Series: Materials Science and Engineering **549** (2019) 012016 doi:10.1088/1757-899X/549/1/012016

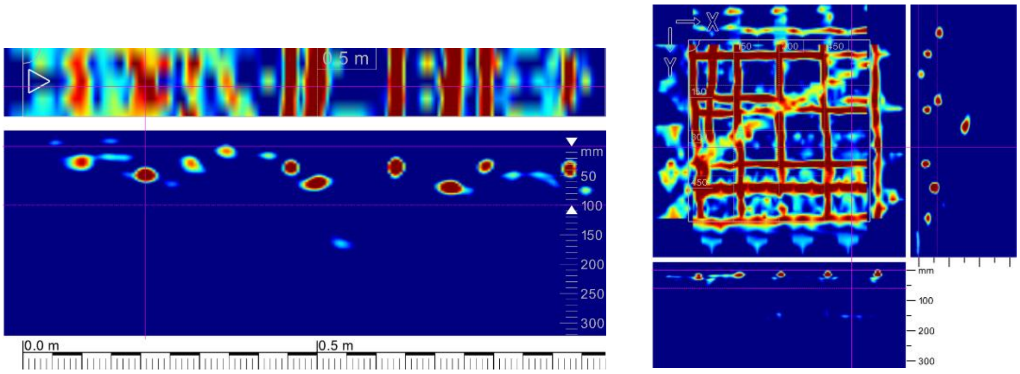


Figure 6. Radar scans (radarograms) taken on the side face of the DS-A girder approximately 3 m from the edge of the girder. Apart from soft reinforcement, the scans captured also 4 and 3 prestressing cables. The remaining two cables could not be detected due to the wider upper part of the girder. In the area above the intermediate supports, it was possible to capture only one or two bottom cables on each side, for the same reason.

Also in this type of girder it is possible to determine precisely the position of cables, but only if they are situated below the flat side of the girder, where the probe can move.

In conclusion of this part it can be said that radar can be used for determining the precise position of cables but, depending on the type of girders, part of the cables are always undetectable (approx. 30 – 50% of the total number or length of cables).

4. Subsequent methods for the detection of grouting of cable channels and condition of cables (corrosion)

4.1. Visual assessment

Unfortunately, the standard method for the determination of cable channel grouting is currently a destructive method, which consists in detecting the position of cables, making a core drill up to the edge of the cable channel (ideally covered by a steel pipe), breaking off the drill, impact drilling to the contact with the prestressing cable, and assessing the grouting, corrosion, or carbonation of the grout.

Figure 7. A drill to the steel protection pipe, breaking off the drill and puncturing the pipe to the cable. Currently, standard practice of checking.

This method has significant shortcomings – when we disregard the risk of damaging the cable when working carelessly, the major disadvantage is only local (point) evaluation of the condition which cannot capture the truly essential part of the structure.

4.2. Radiography

An alternative method is to use Co60 radiography (gammagraphy). With this method it is possible to evaluate, with a suitable irradiating configuration, the grouting (or its absence) without damaging the cable channel or its protection pipe. The problem is that nobody deals with this type of radiography in the Czech Republic at present, but this can change over time. Nevertheless, considering the complicated realization of gammagraphy, it is again a limited, local measurement not capturing the whole structure.

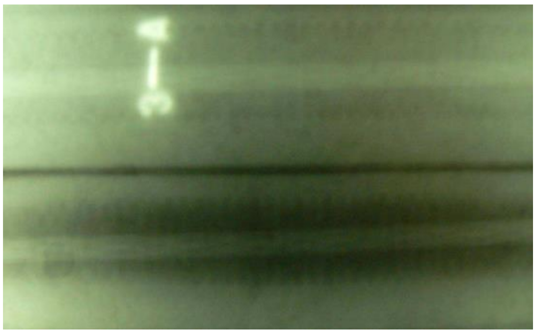


Figure 8 An example of a gammagram of a prestressed structure model with two prestressing cables, thanks to the difference in blackening it is possible to determine unequivocally the grouted and ungrouted parts (the sample below is ungrouted).

4.3. Development of new methods

The present can be characterized by a dynamic development of new diagnostic methods and devices. Hopefully, there will be alternative methods also for the diagnosis of prestressing steel. On the basis of the experiments made in cooperation with the Proceq company, it seems that new radar and ultrasonic devices could be one of the possibilities. On the premises of the Faculty of Civil Engineering, BUT in Brno, tests were performed on model blocks, which also included a model of the grouted and the ungrouted cable channel with reinforcement, by means of the Proceq GPR Live and the ultrasonic reflection device Proceq Pundit PL-200 PE. Preliminary results achieved on this model suggest the possibility of further development and appropriateness of other experiments in this respect.

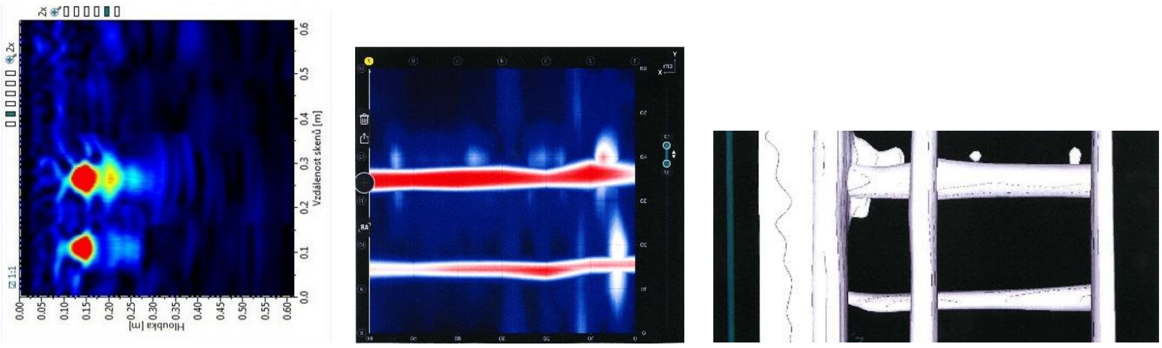


Figure 9. On the left, a recording of the location of a pair of cable channels by the US probe Proceq Pundit PL-200 PE, in the middle and on the right, a recording of the areal scan by the Proceq GPR Live radar. The results show the apparent difference between the grouted and the ungrouted channel (above), and a possibility of using a modification of these methods and devices (naturally with regard to e.g. the presence of steel pipe etc.) [4].

5. Conclusion

On the basis of the long-lasting experience of the institution in the area of pre-construction condition surveys and on the basis of a number of experiments it is possible to say that, as regards examples of structures made of prestressed concrete presented here, the structural systems are far ahead of the level and possibilities of the diagnostic methods. At the current level of knowledge, it is possible to perform diagnosis of the condition of prestressing steel only to a limited extent given by the accessibility of cables and to evaluate the state of reinforcement only at certain points. It is only the development of new methods that could allow for at least expanding this diagnosis to a larger scope of reinforcement volume in the structure, and thus provide a more relevant picture of the condition and the remaining life of the structure.

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