DEFECT DETECTION IN CONCRETE STRUCTURES WITH NDT METHODS: IMPACT-ECHO VERSUS RADAR

Andrzej GARBACZ 1), Jakub STEINBRUCH 2), Zbyněk HLAVÁČ 3), Leonard HOBST 3), Ondřej ANTON 3)

1) Warsaw University of Technology, Warsaw, Poland
2) INSET s.r.o., Praha, Czech Republic
3) Brno University of Technology, Brno, Czech Republic
Contact e-mail: a.garbacz@il.pw.edu.pl

SUMMARY

Two massive concrete blocks were tested in the yard of Brno University of Technology. The first was under-reinforced with predefined failures in the concrete. The second was made of plain concrete as the control (for reference). An ultrasonic test was done to verify pulse velocity and to determine the places in the section with different properties. Several defects, such as large honeycombing and badly compacted concrete, were preliminarily detected.

A georadar test was applied to analyze the situation properly. Three honeycombing areas and reinforcing steel bars were detected clearly by different ranges of working frequency.

Finally an impact-echo test was done to verify the measured results. Detailed analysis of the massive structure was made with the necessary help of previous results. Certain positions of bars, ducts and honeycombing were determined knowing their approximate distribution. The detection ability of impact-echo and radar methods along with problems with signal analysis were specified.

1. Introduction

The Impact-Echo Method (I-E) and Ground Penetrating Radar (GPR) are considered as two most useful NDT techniques for assessing the quality of concrete structures [1]. They can be used to detect various types of defect, such as voids, honeycombing, delaminations, cracks, lack of sub-base support, etc. The techniques for flaw detection are generally based on the following simple principle: the presence of an internal anomaly interferes with the propagation of certain type of waves. The presence of the anomaly can be inferred by monitoring the response of the test object when it is subjected to these waves.

The GPR technique is based on the propagation of short electromagnetic pulses with a time period in the order of ns or shorter in the investigated medium [2]. It is mostly used in reflection mode. Variations in the electromagnetic properties of the material cause a reflection of the electromagnetic wave, which is then recorded by the radar system. The varying values of the magnetic permittivity, electric conductivity and dielectric permittivity in the medium are related, for instance, to the presence of heterogeneities (including voids, fissures, steel rebar in concrete), the
presence of layers of the studied structure (contact of materials with a difference in electromagnetic properties) or changes in the physical properties of the medium (e.g. water content, porosity or chloride content) [3]. The propagation velocity through the environment \( v \) can be approximately determined using the simplified formula:

\[
v = c \varepsilon_r^{1/2},
\]

where \( v \) is the propagation velocity of the electromagnetic signal in the medium, \( c \) is the propagation velocity in a vacuum \((c = 0.3 \text{ m/ns})\) and \( \varepsilon_r \) is the relative permittivity of the medium.

Impact-echo is a method for the non-destructive evaluation of concrete [4], based on the use of an elastic low energy impact on the surface to generate low frequency stress waves (mainly below 60kHz). These waves consist of compression (P), shear (S) and Rayleigh (surface) (R) components which propagate through the structure and are reflected by interfaces within the material or external boundaries. The I-E method is very often used for quality assessment of concrete structures in the following ways: estimation of member thickness from one side; detection of internal flaws such as voids, delaminations and honeycombing; estimation of depth of surface-opening cracks; evaluation of multilayer system quality [5].

On the basis of the frequency spectrum, the depth of the reflecting interface (e.g. flaws) can be determined according to the formula:

\[
d_d = \beta C_p / 2 f_d
\]

where: \( d_d \) is the depth of interface, \( C_p \) is the P-wave velocity, \( f_d \) is the frequency of the dominant peak in the frequency spectrum and \( \beta \) is a “shape factor” that depends on the geometry of the structure being tested and the key frequency (called the “thickness frequency”) — this is the vibration frequency induced by multiple P-wave reflections between the top and bottom surfaces. The shape factor \( \beta = 0.96 \) is valid for a plate structure.

2. Object of the investigations

The concrete blocks located in Brno University of Technology have a complex shape (Fig.1a,c). Different non-homogeneities (steel bars and plastic ducts) and artificial defects of the honeycombing type were introduced during concrete casting (Fig.1b,c).

The results presented hereafter are related (Fig.1c) to wall no.1 and 2 (W1 and W2 respectively), tested with radar and impact-echo. Wall no.3 was additionally tested with impact-echo. The W1 surface was divided into a grid of measurement points (Fig.1d). In general, measurements were carried out at the points of ultrasonic testing. For W1 the tests were carried out at all points of the ultrasonic test grid; for the rest, every second line starting at line 3 and finish at line 13. The point symbols of the ultrasonic grid were used in the analysis of the results of impact-echo tests. The tests with impact-echo were performed with the DOCccter impact-echo system produced by German Instruments.
3. Results of concrete block investigation with radar

GPR measurements were carried out as part of a complex research project focused on the application of different ND techniques. GPR equipment used for test measurements was the commercial system RAMAC made by Mala GeoScience, coupled with shielded monostatic antennas of frequencies 500 MHz, 800 MHz and 1600 MHz. GPR measurements were performed from the front side in a grid of perpendicular lines with 10 cm separation (5 cm for measurement with 1600 MHz antenna) and from the rear side in a system of parallel lines oriented vertically with 10 cm separation. Data were gathered along lines with a step of 1 cm.

![Fig. 1 Scheme of tested concrete block with non-homogeneities and artificial defects: a) view of concrete block shape, b) view of steel bars and defect during concrete casting, c) scheme of non-homogeneities, defects and imperfections localization, d) grid of measurement points at wall W1]

Experimental measurements proved that the GPR method can be successfully deployed for the detection of different types of structural elements and non-homogeneities. The honeycombing areas (B3 + E5; H4 + K5; N3 + Q5; O11 + Q13) and plastics ducts (lines 8 and 10) were very well visible with the 800 MHz GPR antenna. The higher frequency 1600 MHz antenna allows the location of steel bars. In the case of plastic ducts, the detected locations were shifted a little: one duct was visible between lines 8 and 9 and the second one between lines 10 and 11. GPR
gave very good results in detecting anomalies when they were placed relatively close to the surface (ca 20 centimeters). For greater thicknesses of concrete the GPR signal of lower frequency has to be applied with a significant decrease in resolution. In complicated and more complex environments deeper targets may be shadowed by reflection from the shallow objects.

Fig. 2 Comparison of results for 500 MHz GPR antenna and 800 MHz GPR antenna. Reflections of 2 horizontal plastic and 3 honey-combs (in red circle)

Fig. 3 Example of 3D processing of surface measurements at 1600 MHz; on the left is section in time $t=1.6$ ns ($h = \text{cca } 8 - 10$ cm), on the right is section in time $t=2.0$ ns ($h = \text{cca } 10 - 12$ cm); reinforcing steel bars are evident as white stripes

4. Results of concrete block investigation with impact-echo method

The irregular shape of the blocks causes multiple reflections of stress waves and strong effect of surface waves (R-waves) on the signal and frequency spectrum. The signals contain high amplitude normal R-waves or repeatable, abnormal, separated R-waves. Therefore it was necessary to remove R-waves in every signal for further analysis. Additionally, the irregular and non-plate shape of the concrete member caused multiple reflections of the P-wave. In the results, besides the fundamental mode, the additional modes of vibration are visible in the frequency spectrum. The particular modes are usually calculated on the basis of eigenvalue analysis. In the case of the tested blocks the $d/B$ ratio ($d$ is the thickness of the member in the impact direction, $B$ is the shorter cross-sectional dimension) is higher than 0.8. The introductory tests indicated that the shape factor 0.96 can be taken for further analysis.

If defects are present in the structure, an amplitude of particular modes should be lower while the amplitude of the frequency peak corresponding to the reflection
from the defect should be higher. In the considered case they are: steel bars, defects of honeycombing types and plastic ducts filled with cement mortar. The expected frequencies can be calculated taking equation 2, considering the scheme of their localization (Fig.1c) and pulse velocity measured by ultrasonic.

According to the impact-echo principle, steel bars can be detected if a ratio of bar diameter to its depth is higher than 0.3. In our case only the steel bar of Ø32 fulfills this requirement. They should be visible at the frequency 19.4 ÷ 20.4 kHz. Steel bars of Ø22 are at the limits of detection – they could be visible at the frequency 17.0 ÷ 17.9 kHz. Steel bars of Ø12 cannot be detected.

The expected frequencies for honeycombing were calculated on the assumption that they can be present at the depth of 150, 200 or 250 mm. The corresponding expected frequencies are: 12.8 kHz, 9.9 kHz and 7.7 kHz respectively.

The duct could be detectable if it contains air voids around steel cable or around a duct. If there are no voids, this kind of duct, especially with plastic walls, is difficult to detect. Assuming that the duct could be located at the depth of: 100, 120 or 140 mm, the expected frequencies are: 18.7 ÷ 19.7 kHz, 15.6 ÷ 16.4 kHz and 13.4 ÷ 14.1 kHz, respectively.

In figures 4 and 5 is shown the situation in the horizontal b-scan of W1 and the vertical b-scan of W2 and W3 respectively. The pre-defected concrete block was analysed point-by-point and visualised in a 3D model. Colours indicate the amplitude, up&down show the horizontal or vertical position (Fig. 4 or 5, respectively) and left-right is the relative frequency, indicating the depth of the defect. The layout of the measured lines is in the scheme-picture on the right.

Figure 4 shows the distributions of relative frequency spectra obtained for particular lines of the wall W1. They show the possibility of the presence of a defect. Their depth from the surface, calculated for P-wave velocity, equals 3900 m/s (line 3) and 4000 m/s (remaining lines). The peaks at the frequency: B3 – 8.8 kHz (213mm), Q5 – 7.3 kHz (261mm), may indicate defects of the honeycombing type. The frequency peaks at 7.81 kHz (F5 and H5) and 13.2 ÷ 14.2 kHz (I3, O3) have low amplitude; they may correspond to the reflections from eventual voids’ subsequent modes of vibration.

In the case of lines located close to the ducts (lines 7,9,11) a few higher peaks were detected indicating eventual voids at a depth:
- line 7: approx. 180mm (G7), 260 mm (Q7);
- line 9: 280 mm (E9, Q9) and 330 mm (K9).

Additionally, some peaks at point N9 may correspond to the reflections from eventual voids close to the duct or the subsequent modes of vibration.

The distribution of relative frequency for line 11 is very complex. The results suggest the presence of voids at C11, E11, P11 and Q11, and long delamination between points G11 and K11. The peaks at the frequency 15.6 ÷ 17.1 kHz suggest the presence of voids around a duct or a reflection from the steel bar at points H13, N13.

The selected area of the wall W1 was tested with an impactor of smaller diameters: 5 and 8 mm with higher resolution ability. The frequency distribution obtained with an impactor of 5 mm did not give more information. What is more, the frequency amplitude is lower, probably due to the higher attenuation and multiple reflections inside the concrete member. The results obtained for line 13 indicate that steel support can significantly effect P-wave propagation by producing additional frequency peaks.
Fig. 4 Relative frequency distribution for wall W1 (with defects) tested with impactor of 12 mm diameter

The frequency distributions for an impactor of 8 mm are similar to those obtained for an impactor of 12 mm. However, some additional information can be inferred:

- in the case of line 5 a frequency peak at Q5 was also observed, an additional peak at high frequency 20 kHz appears that may correspond to the reflection from steel bar or voids,
- in the case of line 7 an additional peak at high frequency 20 kHz appears that may correspond to the reflection from steel bar or voids close to a duct;
the line 11 is also very complex as in the case of testing with an impactor diameter of 12mm. The frequency spectrum determined for point P11 has a high amplitude of fundamental mode; therefore the next existing frequency peaks are the results of subsequent modes of vibration rather than the presence of defects. Although at lower amplitude frequency, a similar conclusion can be drawn in the case of points: J11 and M11.

Fig. 5 Relative frequency distribution for wall W2 (left) and W3 (right) tested in selected places with impactor of 12mm diameter
The frequency distributions obtained for the back wall (W3) confirm that there are no defects at position O and P (Fig.5, right). For position Q, the presence of a defect is noticeable at the depth 220-250 mm close to line 5. Additionally, some defects may exist between lines 9 and 13 at a depth of about 280mm. Figure 5 (left) shows the frequency distribution for the right side wall W2. It indicates the presence of a large void of the honeycombing type, for the position L between lines 10 and 12 at a depth of 260 – 490 mm. This is not visible in position M and N. Smaller voids were detected in all positions L, M, N between lines 7 and 9 at a depth of about 560 mm. Sharp peaks of frequency: 3.4, 6.8, and 10.2 kHz are subsequent modes of vibration.

3. Conclusions

On the basis of the results obtained, the following conclusions related to the detection of defects and non-homogeneities using radar and impact-echo methods can be formulated.

GPR is useful for detecting anomalies when they were placed relatively close to the surface (ca 20 centimeters). For greater thicknesses of concrete the GPR signal of lower frequency has to be applied with a significant decrease in resolution. In complicated and more complex environments deeper targets may be shadowed by reflection from the shallow objects.

The impact-echo method is useful for defect detection if air layers are present. An irregular shape in blocks causes multiple reflections from the member edges and, in the results, the presence of relatively high amplitudes of subsequent modes of vibration besides the fundamental one. This makes the interpretation of frequency spectra more difficult, because frequency peaks corresponding to reflection from eventual honeycombing or ducts lie close to the frequencies of particular modes of vibrations. In general, steel bars were not clearly detectable with impact-echo even in the case of bars of 32. This shows the good quality of the interface between bar and concrete cover.

Acknowledgement

This paper was arranged with benefit of grant GA ČR 103/09/1073.

References