Modern NDT Techniques in Diagnostics of Transport Infrastructure Concrete Structures

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ABSTRACT

In recent years intensive development of the Non-Destructive Testing (NDT) techniques as applied to the assessment of the condition of transport infrastructure concrete structures (bridges, roads, railways, tunnels, etc.) has been observed. In this paper, classifications of the techniques, based on various criteria, are proposed and discussed. Special attention is paid to advanced acoustic techniques as applied to the identification of delaminated areas, the detection of internal material defects, the discovery of crack parameters and the precise measurement of structural element thickness, the location of reinforcement, prestressing wires, etc. This paper focuses on ultrasonic tomography, the impulse-response technique and the impact-echo technique. The techniques are illustrated with practical examples, including descriptions of the equipment, the testing procedures, the data acquisition and recording systems, and the numerical data processing procedures based on comprehensive algorithms. The range and conditions of the application of the considered NDT techniques in the diagnostics of transport infrastructure concrete structures are proposed and discussed.

Key words: transport infrastructure structures, acoustic techniques, ultrasonic tomography, impulse-response technique, impact-echo technique.

INTRODUCTION

The methods used to diagnose transport network structures can be divided into destructive, semi-destructive and non-destructive (fig. 1). Destructive tests can be applied to samples and natural scale elements. Both the former and the latter are destroyed in the course of the test [1-3] whereby the number of destructive tests on natural scale elements is most often limited to some representative elements. Semi-destructive tests are also applied to samples and natural scale elements and structures. Usually the surface of the tested element is locally breached (and
so needs repairing), which leads to the local loss of the element’s functional properties. No such breaching occurs when natural scale members and structures are non-destructively tested. Moreover, the same members and structures can be subjected to non-destructive tests repeatedly and at different times, whereby non-destructive techniques are useful in diagnosing building structures both during their erection and in the many years of their service [1-3]. It is also important that various NDT techniques can be applied in the same area of the tested structure and results can be compared in the condition assessment process.

**Fig. 1**: General division of methods useful in diagnosing transport infrastructure structures.

Figure 2 shows a detailed classification of non-destructive techniques which can be used to diagnose transport infrastructure concrete structures. Acoustic techniques form a major group of non-destructive techniques. Recently intensive development of acoustic techniques has been observed. The latest of the techniques are concisely described further in this paper.

**Fig. 2**: Non-destructive techniques useful in diagnosing transport infrastructure concrete structures.

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NON-DESTRUCTIVE ACOUSTIC TECHNIQUES

Non-destructive acoustic techniques are used to test elements made of concrete in order to assess interlayer delamination, the thickness of elements accessible from one side only, defects not visible on the surface, the depth of cracks in elements and the distribution of reinforcement in reinforced concrete members. The modern non-destructive techniques useful in diagnosing transport network structures, i.e. the impulse-response technique, the impact-echo technique and ultrasonic tomography, are graphically presented and briefly described in the table 1.

For each of the considered modern acoustic non-destructive techniques the following information is presented:

- name and short description of the technique,
- schematic drawing of arrangement of the testing equipment and photos illustrating practical application of the testing tools,
- list of parameters determined during the test and examples of the graphical form of test results.

The testing methods shown in table 1 can be applied in the process of condition assessment of various concrete structures belonging to the transportation network, like bridges made of reinforced or prestressed concrete, retaining walls, concrete road pavements, etc.

Tab. 1: Comparison of modern acoustic non-destructive techniques [5-25].

<table>
<thead>
<tr>
<th>Technique name and description</th>
<th>Schematic of test setup and view of equipment</th>
<th>Registered parameters and exemplary test results</th>
</tr>
</thead>
</table>
| **The impulse-response technique** | ![Schematic](image1.png) | The values of the following parameters are registered:  
- average mobility $N_{av}$,  
- stiffness $K_{st}$,  
- mobility slope $M_{av}/N$,  
- mobility times mobility slope $N_{av} \cdot M_{av}/N$,  
- voids index $v$.  
An exemplary map of average mobility $N_{av}$: |
| consists in exciting an elastic ultrasonic wave in a tested element by means of a rubber-tipped hammer. The frequency of the excited wave is in a range of 1-800 Hz and the extent of excitation around the test point is about 1000 mm. This technique is suitable for the approximate location of areas in which defective concrete (honeycombing) zones may occur, to a depth of about 1500 mm. The impulse-response technique is suitable for the quick scanning of large concrete surfaces for defects, such as delamination, cracks and air voids, and assessing the adhesion between concrete layers. | ![Schematic](image2.png) | ![Average mobility map](image3.png) |
Tab. 1: Comparison of modern acoustic non-destructive techniques [5-25] (cont.).

<table>
<thead>
<tr>
<th>Technique name and description</th>
<th>Schematic of test setup and view of equipment</th>
<th>Registered parameters and exemplary test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>The impact-echo technique</td>
<td><img src="image1" alt="Schematic of test setup" /></td>
<td>The values of the following parameters are registered:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- transmitting pulse amplitude $A$,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- frequency $f_D$ of an ultrasonic wave reflection from a defect,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- frequency $f_T$ of ultrasonic reflection from the bottom.</td>
</tr>
<tr>
<td></td>
<td><img src="image2" alt="Exemplary image in direction" /></td>
<td><img src="image3" alt="Exemplary amplitude-frequency graph" /></td>
</tr>
<tr>
<td>The ultrasonic tomography</td>
<td><img src="image4" alt="Schematic of test setup" /></td>
<td>Three images, i.e. B, C and D, in three mutually perpendicular directions are recorded:</td>
</tr>
<tr>
<td>technique</td>
<td></td>
<td><img src="image5" alt="Exemplary image in direction" /></td>
</tr>
<tr>
<td></td>
<td><img src="image6" alt="Schematic of test setup" /></td>
<td><img src="image7" alt="Exemplary image in direction" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td><img src="image8" alt="Exemplary image in direction" /></td>
</tr>
</tbody>
</table>

The impact-echo technique consists in exciting an elastic wave having a frequency of 1-60 kHz in the tested element, by striking its surface with an exciter in the form of a steel ball. The equipment includes a set of steel balls with different diameters. Specialist software enables the recording of the elastic wave propagating in the tested element, as an amplitude-time graph and the transformation of the latter into an amplitude-frequency spectrum by means of the Fourier transform. The impact-echo technique is suitable for testing concrete members and assessing: thickness at unilateral access, cable conduit injection effectiveness, surface crack depth, adhesion between concrete layers, delamination, cracks, inclusions and air voids.

The ultrasonic tomography technique consists in exciting an elastic wave in the tested element by means of a multihead antenna made up of ultrasonic heads for receiving and processing signals. The heads generate 50 Hz ultrasonic pulses. The maximum range, in terms of the tested element thickness, amounts to 2500 mm. The technique can be used to test concrete elements in order to determine their thickness at unilateral access and to detect cracks, inclusions, air voids and other places which may be empty or filled with a liquid or a material whose density differs from that of the surrounding concrete. In the course of testing the tomograph antenna is shifted stepwise by a distance of 100 mm in the same direction in a 380 or 500 mm wide (depending on the antenna type) test band. The obtained results, in the form of images of the cross sections in each antenna position, are collected in a three-dimensional matrix table.
EXEMPLARY APPLICATIONS

Two examples of the integrated simultaneous application of two of the non-destructive acoustic techniques presented in table 1 are provided below. The authors’ experience indicates that the two techniques when used in an integrated way complement each other and so can be highly useful for testing transport infrastructure.

In the first example, the impulse-response technique and the impact-echo technique are used together for the nondestructive identification of delaminations in an extensive concrete floor topping in a multi-level garage.

In the second example, the impulse-response technique and the impact-echo technique are supported by the optical technique and artificial neural networks in order to non-destructively estimate the pull-off adhesion of the concrete layers.

Other examples of the use of the ultrasonic technique combined with the impulse-response technique or the impact-echo technique were presented in [4, 12].

Non-destructive identification of delamination in concrete floor topping in multi-level garage

A defective concrete floor topping, covering the area of 2000 m$^2$, in a multi-level car park building was tested using the impulse-response technique and the impact-echo technique combined [13]. After about one year of service, defects, such as cracks (fig. 3a) and rising of some field corners, appeared in the concrete floor topping. The concrete floor topping would curl under moving vehicles. In winter, water from melting snow carried in on the tires of cars would penetrate into the cracks. As cars drove onto the floor topping the water would be squeezed out and then would penetrate back into the cracks. This indicated that defective areas, where there was no cohesion between the top layer and the base layer, occurred in the floor. The aim of the tests was to locate the defective (lacking adhesion) areas.

The non-destructive identification of delamination was carried out in two stages. In stage 1, tests were carried out using the impulse-response technique in order to roughly identify the concrete floor topping areas where there was no adhesion at the interface between the layers (fig. 3b) while in stage 2, tests were carried using the impact-echo technique in order to precisely identify the defective area, especially its boundaries (fig. 3c).

The investigations proved the impulse-response technique and the impact-echo technique to be useful for identifying delamination in concrete floor topping covering a large surface area. As a result of the tests the areas were delamination occurred (the pull-off adhesion amounted there to zero) were identified. Moreover, a general investigation methodology was developed on the basis of a number of similar tests and published in [13].

This methodology deals with the assessment of the interlayer debonding in concrete floors, using the zero/one (no bond/bond) system. It is proper to note that using developed methodology it is not possible to determine the values of pull-off adhesion between the concrete layers.
Fig. 3: View of: a) crack in top layer of floor, b) fragment of tested floor with defective area roughly located using impulse-response technique where there was no adhesion at the interface between the layers, c) fragment of floor with delamination boundaries precisely determined using impact-echo technique [13].

Non-destructive estimation of pull-off adhesion of concrete layers

Using the impulse-response technique and the impact-echo technique one can quite easily identify the areas where delamination occurs. But is rather difficult to non-destructively determine the values of pull-off adhesion between the concrete layers. In [25] an attempt was made to determine reliable correlations between each of the parameters and pull-off adhesion $f_{pb}$ estimated by the pull-off method. But the obtained low values of determination coefficient $R^2$ indicated that this approach was not viable. However, such correlations can be determined when the investigations are supported with the optical technique and artificial neural networks as a results processing tool. This was demonstrated in [26-28] where the aim was the non-destructive identification of pull-off adhesion $f_{pb}$ between the top layer and the base layer. This was achieved using the base layer surface roughness parameters estimated by the optical technique (fig. 4a) and the parameters estimated on the floor surface by the acoustic techniques mentioned above (figs 4b and c).
Non-destructive estimation of pull-off adhesion:

a) determination of base layer surface roughness by non-destructive optical technique,

b) testing by impulse-response technique,

c) testing by non-destructive impact-echo technique,

d) testing by semi-nondestructive pull-off method.

The parameters were determined in several hundred measuring places distributed on the surface of a model test specimen. Then cores were drilled in the top layer and pulled off from the base layer to determine pull-off adhesion $f_b$ (fig. 4d). The test results (the values of the parameters) were subjected to statistical analyses whereby a few parameters (see table 2) suitable to be used as input variables for the training and testing of an artificial neural network were selected. A proper structure and a training algorithm were adopted for the ANN.

**Tab. 2:** Values of input variables used to train and test artificial neural network.

<table>
<thead>
<tr>
<th>Test point number</th>
<th>Name of test method and parameter symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optical technique</td>
</tr>
<tr>
<td></td>
<td>$S_a$</td>
</tr>
<tr>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>1</td>
<td>0.276</td>
</tr>
<tr>
<td>2</td>
<td>0.375</td>
</tr>
<tr>
<td>3</td>
<td>0.262</td>
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<tr>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>460</td>
<td>0.025</td>
</tr>
</tbody>
</table>
A unidirectional multilayer backpropagation ANN with the QUASI-NEWTON training algorithm, 10 hidden layer neurons and hidden layer activation function $tanh$ was employed and subjected to training and testing. Linear correlation coefficients R equal to respectively 0.9775 and 0.9725 (figs 5a and 5b) were obtained. After training and testing the ANN was subjected to experimental verification and very good agreement between the results was found (fig. 5c). Hence it was concluded that the reliable neural identification of pull-adhesion $f_{c,b}$ of the top concrete layer from the base layer is possible on the basis of the parameters estimated by the three non-destructive techniques.

![Fig. 5: Correlation between pull-off adhesion $f_b$ experimentally determined by semi-nondestructive pull-off method and pull-off adhesion $f_{c,b}$ identified by ANN for training (a), testing (b) and experimental verification (c) [28].](image)

**CONCLUSION**

A classification of non-destructive techniques useful for diagnosing transport infrastructure concrete structures has been proposed. Attention was drawn to the advanced acoustic techniques since the latter are especially suitable for assessing interlayer delamination and adhesion between concrete layers, as illustrated by the two examples.

An presented examples of the combined use of the impulse-response technique and the impact-echo technique to non-destructively identify delamination in underground garage concrete floor topping and the use of the above two techniques together with the optical technique.
and artificial neural networks to non-destructively estimate the adhesion between the concrete layers was provided.

Proposed methodology of the multi-technique NDT testing can be applied for condition assessment of various concrete structures of the transportation network, like: bridges, tunnels, retaining walls, road pavements, underground structures, etc.

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REFERENCES