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Modern acoustic techniques for testing concrete structures accessible from one side only

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ABSTRACT

This paper presents nondestructive methodologies for investigating selected geometrical and material imperfections in unilaterally accessible concrete structures by means of modern acoustic techniques. The imperfections include: improper structure thickness, delamination, large air voids and zones of concrete macroheterogeneities. The presentation of the methodologies is preceded by a survey of the literature on the subject. The available knowledge, also contributed by the present author, has been collected and systematized as well as complemented with two new methodologies for determining the depth of cracks. The methodologies have been validated in situ on building structures whereby their practical usefulness has been confirmed.

1. Introduction

Structures made of concrete are, for different reasons and at different times (during both their construction and use), subjected to tests [8,14,15,21,37,40]. The many test methods which can be used for this purpose can be divided into: destructive, semidestructive and nondestructive methods [1,5,9,10,16,25–27]. It is mainly samples taken from a structure, rarer entire members or structures, which are subjected to destructive tests. In the course of semidestructive tests the structure of the material is locally slightly (usually superficially) breached [10,16]. No such breach occurs in the case of nondestructive tests and the latter can be used to test large surface areas to a substantial depth. Moreover, the measurements can be performed repeatedly (as regards both time and place).

This paper presents modern acoustic techniques helpful in detecting and identifying selected geometric and material imperfections in concrete structures accessible from one side only. Imperfections (defects) result in deterioration in the initial or design condition of a member or the entire structure [1]. The following imperfections: improper structure thickness, delamination, large air voids, zones of concrete macroheterogeneities, and cracks are considered.

In the case of newly built structures, often their thickness and its conformance to the design need to be checked for quality acceptance purposes. As regards structures which have been in service for many years, such a need arises when, for example, their design documents are missing and their

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load-bearing capacity must be checked through calculations. In such cases, the thickness of a concrete structure when the latter is in contact with groundwater or dammed water on one of its sides cannot be determined by the conventional drill-through method and so nondestructive techniques must be employed. Examples of such structures are the foundations and walls of underground garages, the structural members of hydro-engineering structures, the walls of tunnels and collectors, in both newly built structures and the ones which have been in service for many years.

As a result of significant errors in the execution of layered concrete structures the material may lose its continuity due to the lack of interlayer bonding [1,10]. This material imperfection, referred to as delamination, results in a reduction in the load-bearing capacity and durability of the structure. For this reason (among others), before the acceptance and final handover of large strongly loaded structures, such as garage floorings, tests are carried out to check the interlayer bonding and to detect any delamination. The semi-nondestructive pull-off method is usually used for this purpose, but its effectiveness to a large extent depends on the number of test points. For example, for concrete floorings the standard specifies one test point per 3 m^3 of the tested area. But this is not sufficient if the boundaries of an area in which delaminations may occur are to be precisely determined. Then it is necessary to use a denser grid of test points, which amounts to a substantial breach of the flooring structure.

At places where different structural members are interconnected material imperfections in the form of large air voids, understood as material discontinuities larger than the maximum diameter of the aggregate in the concrete, may arise (usually during casting). These are weak spots (no proper concrete cover on the reinforcement) in the structure. Boreholes can be drilled to locate large air voids, but this is not always effective. One cannot determine the size of an air void in this way, which makes repair difficult. Neither the nondestructive radiological technique can be used to locate such imperfections.

Zones of macroheterogeneities may appear in the unilaterally accessible massive structures of, e.g., hydroelectric power plants and dams. Macroheterogeneities are defined as material discontinuities smaller than the air voids described above. Particularly at the construction stage massive structures are likely to develop defective zones (material imperfections) due to, for example, improper concrete compaction, the use of too coarse aggregate or the insufficient cover of the latter with cement mortar. The concrete in such zones is excessively porous, which under unilateral water pressure combined with, e.g., the operational vibrations of the structure, contributes to cracking through the concrete (the loss of material continuity along the whole cross section) [11].

There is often a need to determine the depth of a crack (understood as a material discontinuity extending along some of the structure's cross section) whose depth and length are significantly larger than its width. Water often leaks through such a crack. Over time the crack may grow larger (as regards its depth, length and width), which may lead to, e.g., a failure condition of the structure. Crack depth is usually determined by drilling a core sample, but in a situation when there is water on the outer side of the structure, exerting pressure on the latter, this method is risky.

Nondestructive acoustic techniques are helpful in the above cases. A classification of the techniques is shown in Fig. 1. The applicability, limitations, advantages and disadvantages of the techniques are presented in [16].

The testing needs indicated above and the relevant nondestructive techniques (used individually or in combination) are matched in Fig. 2.

The person who is about to examine unilaterally accessible concrete structures for geometric and material imperfections must choose a proper technique and equipment and use a proper test methodology enabling the detection and

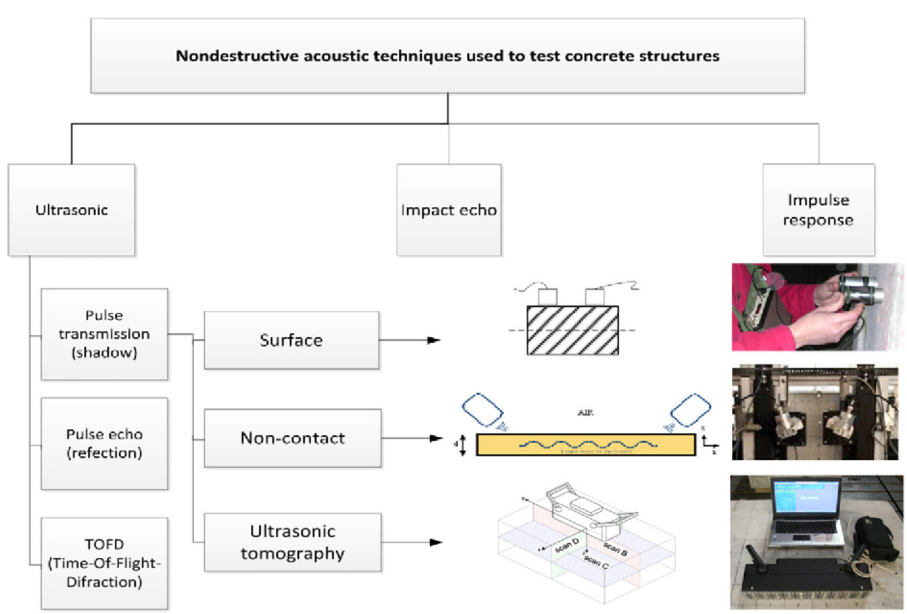

Fig. 1 – Nondestructive acoustic techniques for detecting geometric and material imperfections in concrete structures accessible from one side only.

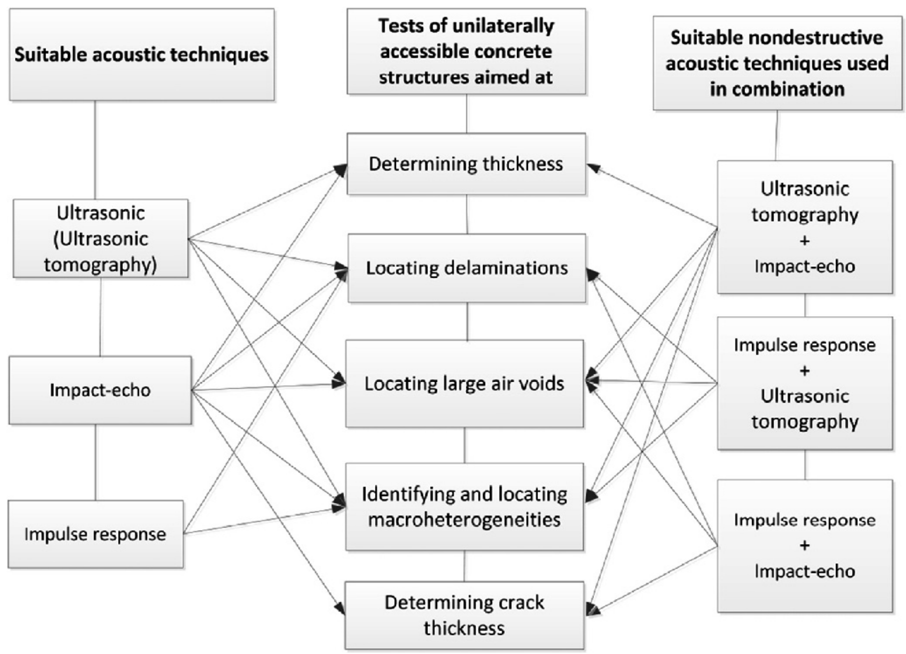

Fig. 2 – Suitability of particular nondestructive acoustic techniques, used individually or in combination, for testing unilaterally accessible concrete structures.

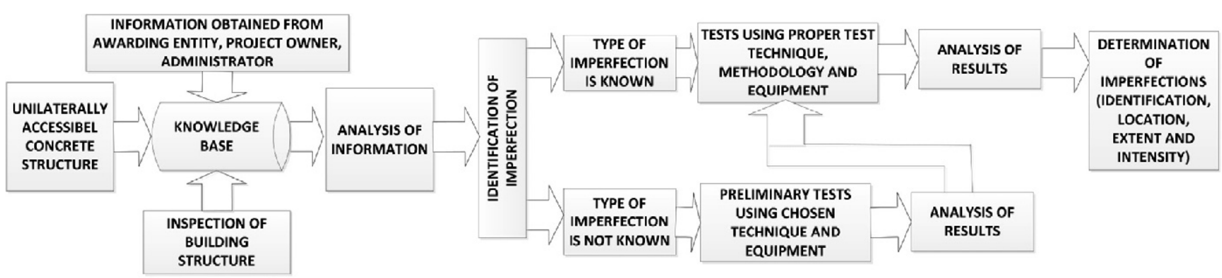

Fig. 3 – Methodology for determining geometrical and material imperfections in concrete structures accessible from one side only.

identification of possible defects. If there is no information about the type of imperfection, one must carry out preliminary tests using a chosen technique and equipment [16] and then on the basis of a heuristic analysis of the results employ the proper test technique, methodology and equipment, as shown in Fig. 3. The situation is simpler if the client provides information about the type of imperfection. For further analysis one must know the location, extent (the size of the affected area) and intensity (advancement) of the identified (diagnosed) imperfection.

2. Survey of knowledge

Acoustic methods began to be used in the Middle Ages. In Codex Germanicus it was proposed to assess the quality of sulphur and its properties by exploiting what is now known as the propagation of acoustic waves in air [22]. The method consisted in crushing sulphur with one's fingers and identifying the sounds emitted by it. The propagation of acoustic waves in construction materials began to be scientifically studied since the 19th century. The idea to use ultrasonic waves to investigate the structure of materials appeared in the 1920s and the first prototype ultrasonic diagnostic device was constructed in 1931. In 1940 Prof. Floyd Firestone from the Michigan University constructed an ultrasonic measuring instrument which was initially used to test steel members. Since 1950 ultrasonic equipment became commonly available and began to be used for testing concrete members [5,27]. Initially the equipment had many shortcomings, but as it was improved it became increasingly useful whereby the equipment and the associated theoretical knowledge began to be developed [8].

On the basis of this knowledge, contained in, e.g., [8,10,18], one can generally say that elastic waves are defined as the propagation of vibrating particles of a medium, in space. Depending on the direction in which the particles vibrate during wave propagation one can distinguish surface waves, transverse waves, Lamb waves and longitudinal waves, as shown in Fig. 4.

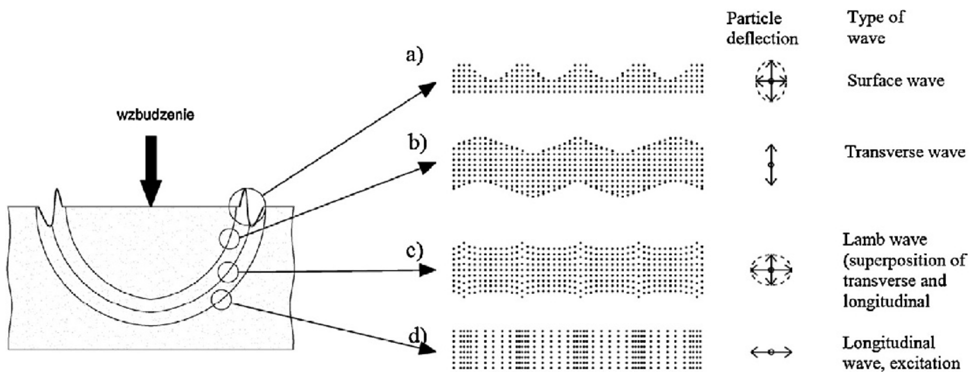

Fig. 4 – Types of ultrasonic waves – schematic representation of particle vibrations during propagation of: (a) surface, (b) transverse, (c) Lamb and (d) longitudinal elastic wave [9,10].

For many years attempts have been made to investigate geometrical and material imperfections in concrete members by exploiting the propagation of elastic waves.

The assessment of the thickness of concrete members, particularly the ones accessible from one side only, has been the subject of research by, among others, Kozlov, Samokrutov et al. [2,20,28], who proposed to use the ultrasonic echo technique for this purpose. Wiggenhauser et al. [38], Krause et al. [4], Garbacz [10] and Sansalone [29] propose to use the impact-echo technique for such tests. In most cases, up to 500 mm thick members were tested in this way. Schabowicz and Hoła [31–33] recommend the state-of-the-art ultrasonic tomography technique for determining the thickness of unilaterally accessible members. Since this technique is relatively new, it has not been frequently applied and reported yet. According to [31–33], concrete members up to 2500 mm thick can be tested using this technique. The successful implementation attempts made by the above researchers, each time involved the use a single testing technique. It is, however, difficult to find documented cases of the identification of unilaterally accessible concrete members, involving the simultaneous use of two or more techniques, e.g. the ultrasonic tomography technique and the impact-echo technique. Kurz et al. [19] and Hoła, Schabowicz et al. [11,16,17] came up with the idea of using the above techniques in combination (the former researchers applied this idea to industrial floorings while the latter ones applied it to walls and foundation slabs), demonstrating that in this way the techniques complement and verify each other whereby they are more effective.

The identification of delaminations in layered concrete members accessible from one side only has been the subject of studies by, among others, Delatte et al. [7] and Oh et al. [23]. They proposed a way of determining a delamination map on the floor surface by means of the pull-off method. Also Garbacz [10] proposed to use the pull-off method to determine a delamination map on the surface of layered concrete members, including a flooring with an overlaid repair layer. Davis [6] and Hertlein and Davis [13] recommend the modern impulse response technique for searching for delaminations in concrete floorings. Ottosen et al. [24], Garbacz [10] and Sansalone [29] propose to use the nondestructive impact-echo technique for this purpose. They successfully applied this technique to small-area concrete floorings. However, no cases of delamination identification through the combined use of the impulse response technique and the impact-echo technique were to be found in the literature on the subject. Hoła,

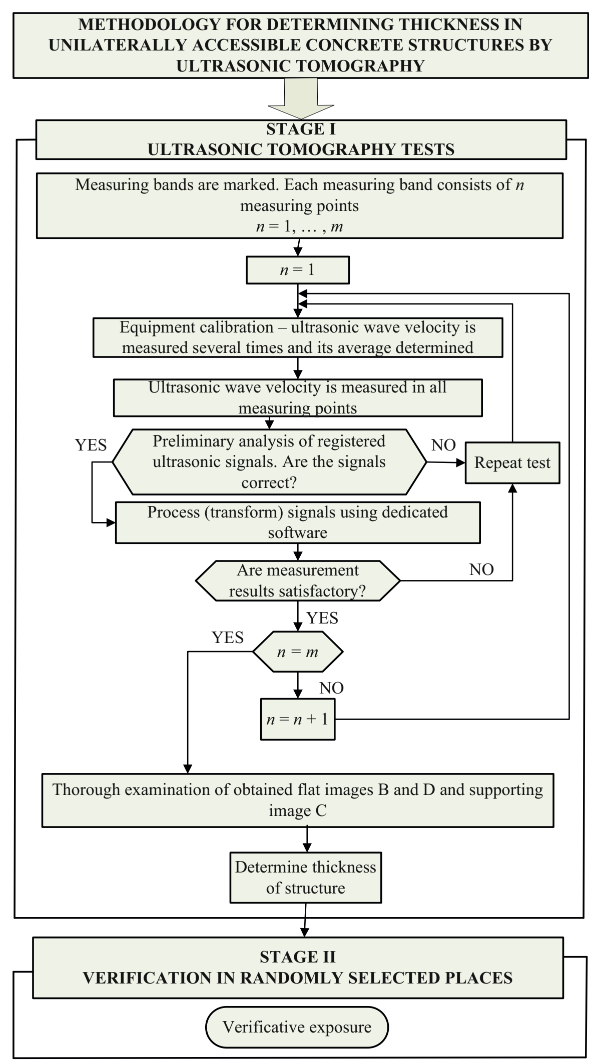

Fig. 5 – Methodology for determining thickness in unilaterally accessible concrete structures by means of ultrasonic tomography.

Schabowicz et al. came up with such an idea, showing this approach to be more effective in delamination testing, especially in the case of large-area concrete floorings.

Stawiski [36] carried out studies on the location of air voids in concrete members by means of the nondestructive ultrasonic technique using point probes. However, only small areas could be tested in this way. Under similar limitations, Sansalone [29] proposes to use the nondestructive impact-echo technique to identify air voids. Bishko et al. [2], Kozlov et al. [20], Samokrutov et al. [28] and Shevaldykin et al. [35] – the designers of the multi-probe measuring antenna used in the ultrasonic tomograph – propose to use ultrasonic tomography for this purpose. However, there are no standard images available which could make it possible to interpret the results obtained in this way. Samokrutov and Shevaldykin et al. in [28,35] described the multiprobe antenna and its possible uses and presented an image generating algorithm. Schabowicz and Suvorov in [33,34] on the basis of laboratory studies carried out using the tomograph introduced a change into the image generating algorithm whereby it became possible to isolate the surface wave signals from the total picture of the wave and to remove noise for the benefit of the location of air voids in

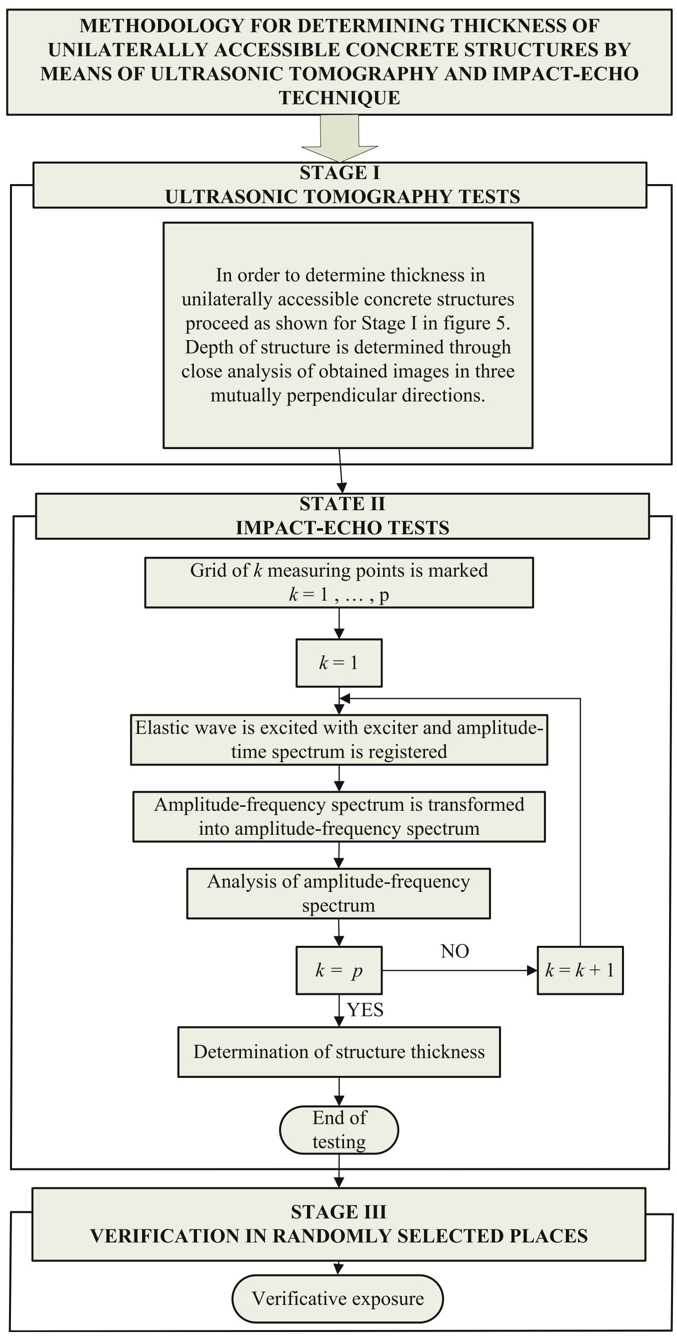

Fig. 6 – Methodology for determining thickness in unilaterally accessible concrete structures by means of combined ultrasonic tomography and impact-echo technique [32].

concrete members available from one side only. The aim of the laboratory studies was to facilitate the interpretation of in situ test results.

Quiviger in [39] proposed a way of identifying zones of macroheterogeneities and macrocracks in unilaterally accessible concrete members by means of the nondestructive echo technique, but to a depth of only 500 mm. Garbacz [10], Krause et al. [4], Taffe, Wiggenhauser [19,38] proposed to use the impact-echo technique for this purpose, also to a depth of 500 mm. Davis [6], Hertlein and Davis [13], Ottosen et al. [24] recommend the nondestructive impulse response technique for detecting zones of heterogeneities in unilaterally accessible, up to 500 mm thick, concrete members. Except for work [11], no cases of identifying and locating defects in the form of zones of excessively porous concrete in unilaterally accessible over 500 mm thick massive concrete members through the combined use of two techniques, i.e. the impulse response technique and ultrasonic tomography, have been reported in the literature on the subject.

The problem of determining the depth of cracks in concrete members was studied by Garbacz [10] and Sansalone [29], who proposed to use the impact-echo technique for this purpose. Also Berkowski, Schabowicz et al. [3] employed the impact-echo technique to determine the depth of cracks in a steel/concrete floor. Kaszyński [18] and Stawiski [36] recommend using the ultrasonic technique for this purpose while Goszczyńska et al. recommend the acoustic emission method [12]. Whereas Hoła, Schabowicz et al. [30,31] demonstrated for foundation slabs that ultrasonic tomography and the impact-echo technique used in combination are highly effective in determining the depth of cracks. It should be mentioned here that the problem of determining the depth of cracks filled with

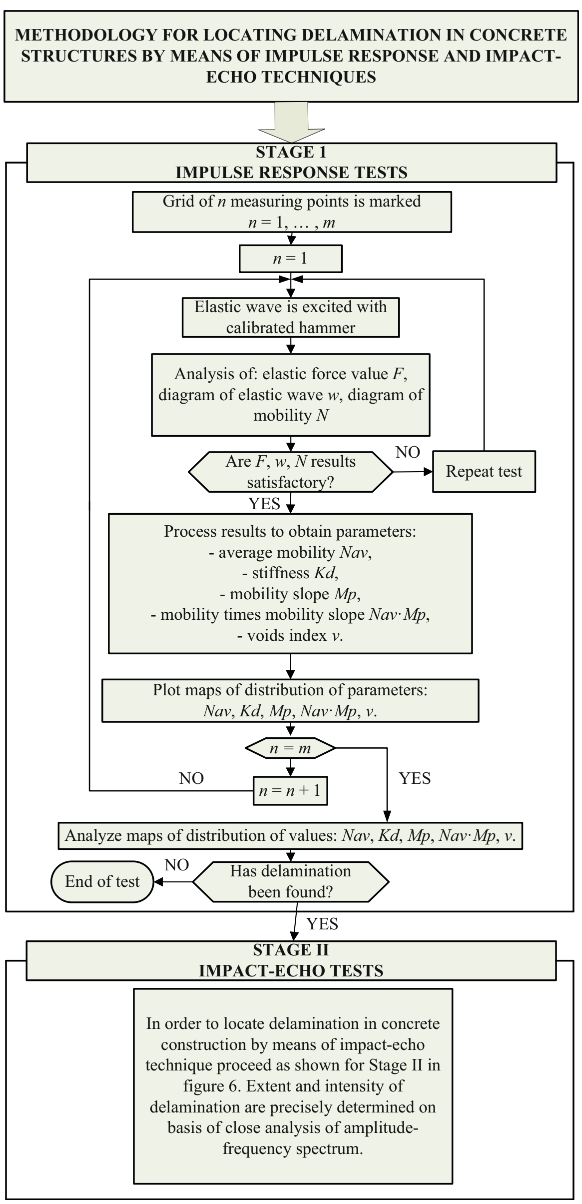

Fig. 7 – Methodology for locating delaminations in unilaterally accessible concrete structures by means of impulse response and impact-echo techniques [17].

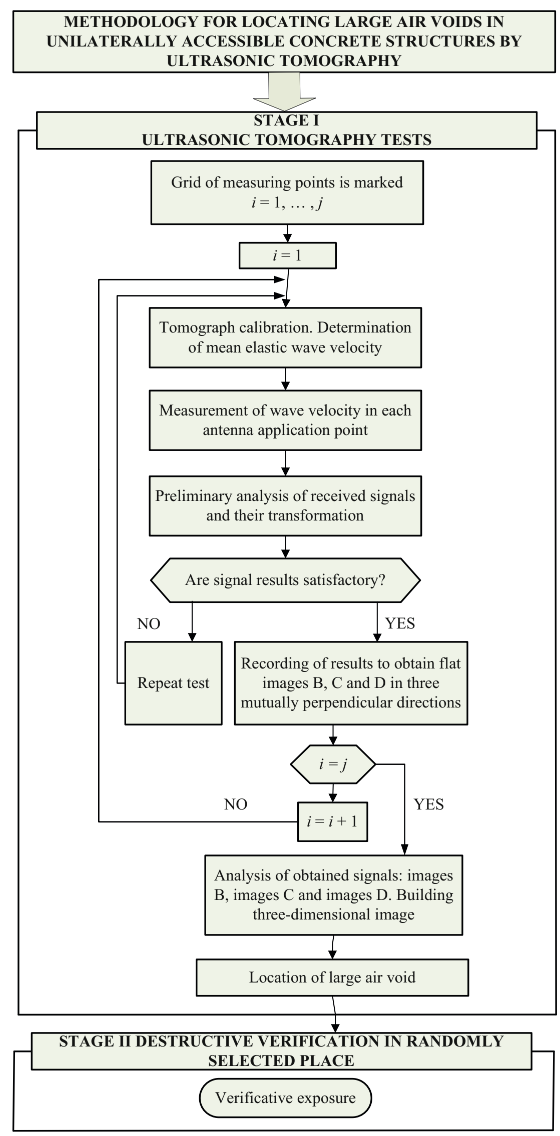

Fig. 8 – Methodology for locating large air voids in unilaterally accessible concrete structures by means of ultrasonic tomography.

water is still unsolved. Only in [30] a way, consisting in the temporary removal of water from a crack to make examination by the impact-echo technique possible, is presented.

It emerges from the above survey of literature on the investigation of various geometric and material imperfections in concrete members accessible from one side only that there is a lack of a work which would recapitulate the knowledge on this subject [11,17,29,33,38]. Such a recapitulation, including a newly developed method of determining crack depth, is provided below. The range of application, limitations, advantages and disadvantages of the methodologies are presented in [11,17,31–34].

3. Determination of thickness

The methodology for determining thickness in unilaterally accessible concrete members by means of ultrasonic tomography is shown, acc. to [33], in Fig. 5. Using ultrasonic tomography one obtains flat images of the inside of the examined structure in three mutually perpendicular directions. By closely examining the images one can determine the thickness, and on this basis the location and extent, of anomalous places in concrete structures accessible from one side only.

The two-stage methodology for determining thickness by means of the nondestructive techniques of ultrasonic tomography and impact-echo used in combination is presented in Fig. 6.

In the first stage, three mutually perpendicular flat images of the inside of a concrete structure are obtained and on their basis the thickness of the structure is determined with an accuracy of about 20–30 mm. In the second stage, impact-echo tests are carried out to even more precisely determine the thickness identified by means of the ultrasonic tomograph and in this way to verify the impact-echo results obtained in the first stage. In each of the measuring points, an elastic wave is excited and the amplitude–time spectra are registered and transformed into amplitude–frequency spectra. By analyzing the spectra one can determine the thickness and extent of the irregularities with an accuracy of about 5–10 mm and their

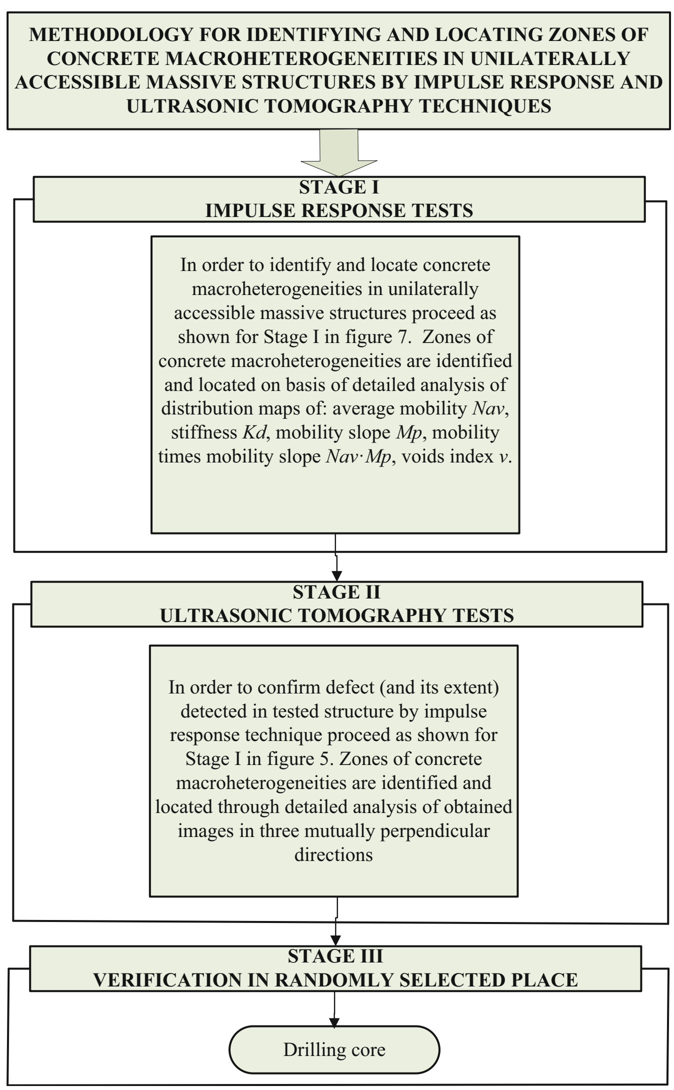

Fig. 9 – Methodology for identifying and locating defective (macroheterogenous) concrete zones in unilaterally accessible massive structures by means of impulse response and ultrasonic tomography techniques [11].

variation and intensity in the investigated area. In this way the results obtained in stage I are fine-tuned.

In the case of both the methodologies, it is recommended to verify the results through exposure (a borehole) in a randomly selected place(s). The two methodologies have been validated in situ on structures [30,33].

4. Location of delaminations

The two-stage test methodology, according to [17], employing the two nondestructive techniques of impulse response and impact-echo for the location of delaminations in unilaterally accessible layered concrete structures is presented in Fig. 7. First the area in which delamination occurs is approximately (with an accuracy of 250–500 mm in plan view, depending on the measuring grid size) located using the impulse response technique. Then the defective area (with regard to its extent and intensity) is more precisely (with an accuracy of 50–100 mm in plan view) located using the impact-echo technique, as shown in Fig. 7 [17]. The methodology has been validated in situ on a building structure [17].

5. Location of large air voids

The methodology for locating large air voids in unilaterally accessible concrete structures by means of ultrasonic tomography is shown in Fig. 8 [33,34].

The methodology procedure is similar to that of the thickness determination methodology presented in Fig. 5 in Section 3. The methodology was developed on the basis of laboratory tests of specimens with modelled material imperfections in the form of inclusions whose density was about a hundred times lower than that of the concrete. The results of the tests were reported in [33,34]. The laboratory tests were carried out after difficulties in interpreting the results of tests carried out in situ on a building structure were encountered [30].

6. Identification and location of zones of concrete macroheterogeneities

The methodology for the nondestructive identification and location of zones of concrete macroheterogeneities in

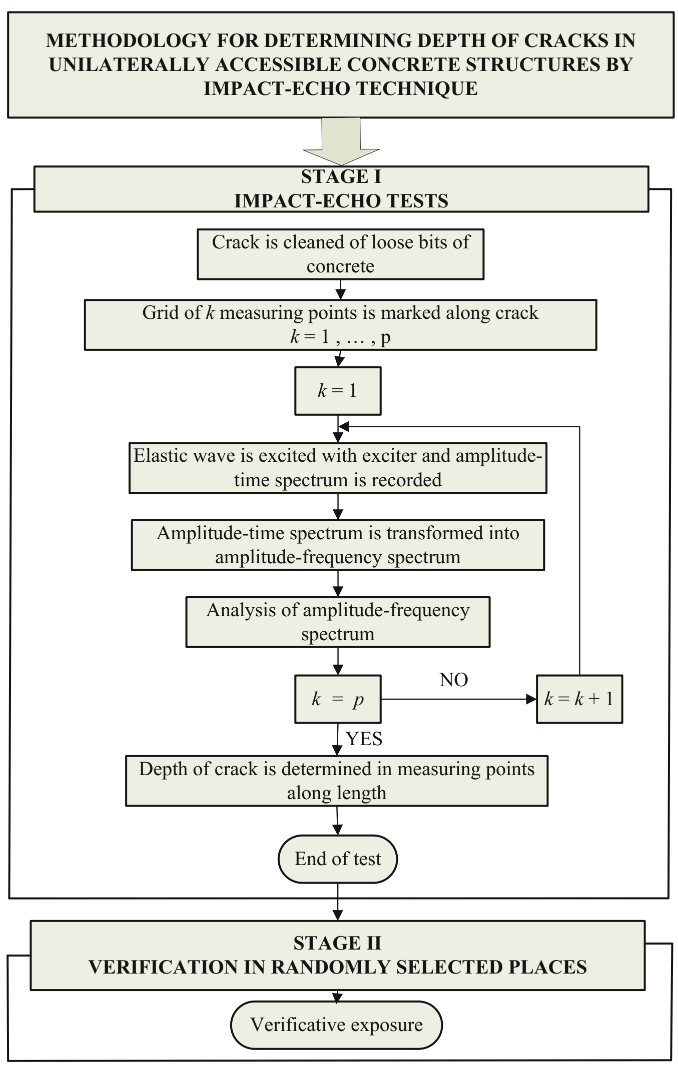

Fig. 10 – Methodology for determining depth of cracks in unilaterally accessible concrete structures by impact-echo technique.

unilaterally accessible massive structures by means of the combined techniques of impulse response and ultrasonic tomography is presented in Fig. 9 [11]. As shown in [11], the combined use of the two techniques ensures reliable test results.

It is proposed to carry out the tests in two stages. In the first stage, the impulse response technique is employed to identify and locate defective concrete zones in the tested structure. In the second stage, ultrasonic tomography is used to confirm the defect detected in the structure by means of the impulse response technique and to locate it along the depth (determine its extent and intensity) with an accuracy of 20–30 mm. This is done through a detailed analysis of the flat images obtained in three mutually perpendicular directions, showing the inside of the concrete structure in the tested zone. The methodology has been validated in situ on a building structure.

7. Determining depth of cracks

The methodology for nondestructively determining the depth of cracks in unilaterally accessible concrete structures by means of the impact-echo technique is shown in Fig. 10 and described below.

According to Fig. 10, the depth of a crack is determined (after loose concrete bits are removed from it) along its length by examining the amplitude–frequency spectrum with an accuracy of 5–10 mm. Then in order to verify the results random destructive tests, consisting in exposure by core drilling, are carried out. In this way the extent and intensity of the crack are determined. This method is particularly useful when there is water in the crack and the latter cannot be tested to its full depth by the impact-echo technique (although water can be temporarily removed, one never knows exactly to what depth).

It may be difficult to determine the depth of cracks also because of their geometry. Even more difficult is the case when a vertical crack is not visible on the surface of the structure and so it cannot be visually located. Then it is recommended to use the nondestructive techniques of ultrasonic tomography and impact-echo in combination, as shown in Fig. 11. First, ultrasonic tomography is used to locate the crack and then its extent and intensity (changes in depth along the crack) are determined using the impact-echo technique. Crack depth is determined with an accuracy of 5–10 mm.

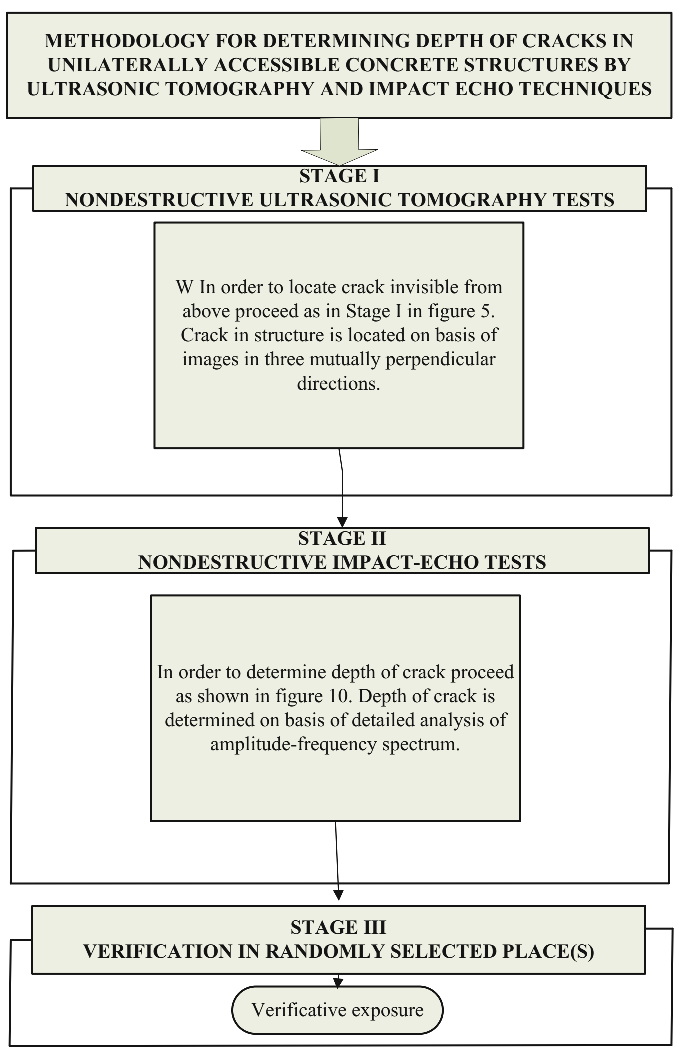

Fig. 11 – Methodology for determining depth of cracks invisible on surface, in unilaterally accessible concrete structures by ultrasonic tomography and impact-echo techniques.

Table 1 – Nondestructive acoustic techniques suitable for investigating geometrical and material imperfections.

Kind of imperfection		Test methodology					
		Ultrasonic (ultrasonic tomography)	Impact-echo	Impulse response	Ultrasonic tomography + impact-echo	Impulse response + ultrasonic tomography	Impulse response + impact-echo
Improper thickness of member	Identification	●	●	–	●	–	–
	Location	●	●	–	●	–	–
	Extent	●	●	–	●	–	–
	Intensity	○	○	–	○	–	–
Delamination	Identification	●	●	●	●	●	●
	Location	●	●	●	●	●	●
	Extent	●	●	○	●	●	●
	Intensity	–	○	–	○	–	○
Large air voids	Identification	●	●	–	●	●	●
	Location	●	●	–	●	●	●
	Extent	●	●	–	●	●	●
	Intensity	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Macroheterogeneities of concrete	Identification	●	●	●	●	●	●
	Location	●	●	●	●	●	●
	Extent	●	●	○	●	●	●
	Intensity	–	○	–	○	–	○
Cracks	Identification	●	●	–	●	–	●
	Location	●	–	–	●	–	–
	Extent	–	●	–	●	–	●
	Intensity	–	●	–	●	–	●

Symbols: ● – suitable, ○ – partially suitable, – – unsuitable, N.A. – not applicable.

In the case of the two methodologies it is recommended that verification through exposure be carried out in randomly selected place or places. The test methodologies have been verified in situ on building structures [3,30,31].

8. Conclusion

The dispersed knowledge relating to the methodologies for the nondestructive investigation of selected geometrical and material imperfections in concrete structures accessible from one side only has been collected and systematized, adding the missing latest methodologies, in this paper. The considered imperfections are: improper structure thickness, delamination between concrete layers, large air voids, zones of concrete macroheterogeneities, and cracks, In Table 1 the imperfections are matched with the techniques suitable for their investigation. As it is evident from this table, particularly the techniques of ultrasonic tomography and impact-echo, used individually or combined (whereby they complement each other), are suitable for many testing applications.

Considering that the above geometrical and material imperfections can have an adverse effect on the load-bearing capacity, life, structural reliability and further service of building structures it is essential to know the techniques suitable for detecting and investigating them.

To sum up, the test methodology, involving the use of ultrasonic tomography or the combined use of the latter technique and the impact-echo technique, is suitable for determining the thickness of structures. The combined techniques of impulse response and impact-echo are proposed for locating delaminations. The test methodology, involving the combined use of the impulse response technique and ultrasonic tomography, is recommended for identifying and locating zones of concrete macroheterogeneities. New methodologies for determining the depth of cracks by means of the impact-echo technique and by ultrasonic tomography and the impact echo technique combined have been developed.

The methodologies presented in this paper have been validated in situ on building structures whereby their practical usefulness has been confirmed.

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