In-depth defect inspection of precast double walls using non-destructive techniques

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Abstract. Precast double walls are frequently used for building applications and consist of a pair of precast reinforced concrete shells connected by a lattice girder creating an inner cavity. Once placed at its final position this cavity is filled with freshly cast and compacted concrete. Aside from benefits such as increased ease in installation, reduced cost and shorter construction time also some pitfalls are recognized. Due to the restrained space and the presence of the truss girder undesired defects (e.g. voids, honeycombing, etc.) might occur without being noticed, as the outer wall elements also act as formwork. This actually might reduce the load capacity and jeopardize the structural integrity of the concrete structure. Therefore, different non-destructive tests are being used in order to assess the filling degree of the cavity in the double walls and to localize defects, with varying success ratio (i.e. the detectability). Different techniques were applied on a test wall with intentionally embedded defects (polystyrene blocks) with varying diameter: rebound hammer, ultrasonic pulse velocity via direct transmission, ultrasonic shear-wave tomography, ground penetrating radar and active infrared thermography. The success and the limits of these techniques for in depth defect localization are being discussed in this paper. The effect of the selected detection method and the surface-on-depth ratio of the defect itself has an effect on its detectability.

1 Introduction

Non-destructive testing (NDT) techniques are used frequently for building pathology applications. NDT has an increased application field due to its inherent non-destructive nature and quick and accurate service, which enables its applicability to a broad range of near-surface and even in-depth testing (e.g. detection of cracks, honeycombing, delamination, etc.). Collecting and interpreting the obtained results and collecting the time-consuming measurements are known downsides of those methods.

For this study a precast double wall is being created as test object in order to qualify and compare the (dis)advantages and identify the applications of different frequently used NDT's with varying working principles. Defects are introduced into the object by means of polystyrene blocks with varying sizes, shapes and locations. These flaws represent internal voids and honeycombing inside the prefabricated element, which is commonly found in practice due to limited space during filling, and actually reduce the load capacity and jeopardize the structural integrity of the concrete structure. Therefore, identification and quantification of the defects by means of fast, accurate and reliable techniques is needed.

2 Selected non-destructive techniques

2.1 Research scope

In order to evaluate the detectability of internal flaws by means of the different selected NDT's a precast double wall with implemented polystyrene blocks with known size, shape, depth and location, is being created and investigated. As undesired effects (e.g. voids, honeycombing, debonding, etc.) might occur during filling of the inner cavity of those precast elements, post-investigation and analysis of the inner structure might reveal these shortcomings. An illustration of this type is honeycombing of concrete (Fig. 1), which can appear around the reinforcements of hollow walls (Fig. 1 middle) due to insufficient compaction or a poor concrete mix design and/or casting process.

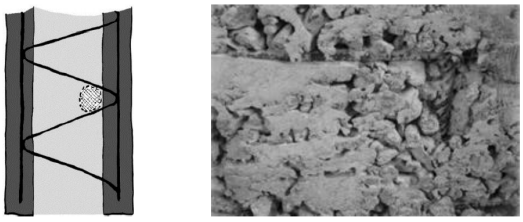

Fig. 1. Example of honeycombing in precast double walls

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In order to assess the actual load capacity and structural integrity of the concrete element it is important to reveal and quantify possible internal weaknesses.
Several techniques with different working principles and (dis)advantages were selected and evaluated in this comparative study. Each one of those techniques has their own working principle, applications and shortcomings, as briefly explained in section 2. and summarized in Table 1.

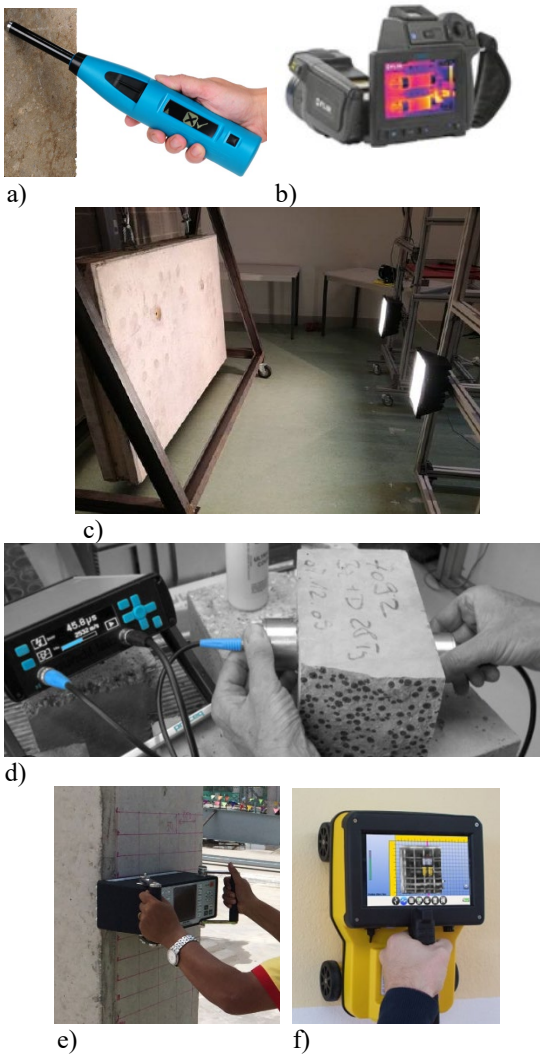

Fig. 2. Visualization of used non-destructive techniques
a) RH – Proceq SilverSchmidt Type N
b)-c) AIRT – FLIR T640 + heating test set-up
d) UPV – Proceq Pundit Lab
e) USWT – ACS MIRA Tomographer
f) GPR – Cthrue IDS Georadar

2.2 Rebound hammer

The rebound hammer (RH) measures the rebound of a spring-loaded mass impact, with defined energy, after direct impact on the surface of a concrete sample. The influence of the concrete on the measurement reaches a depth of about 3.0 cm. Consequently, deeper defects will not be noticed by this device.
Because of this approximation method, there is doubt about the reliability of the rebound hammer for flaw detection. The condition of the surface has a high influence on the readings. Hence, it is recommended to treat the surface with an abrasive stone preceding the test to minimize these influences. Furthermore the type and the hardness of the aggregate (rebound number is false if used over an exposed aggregate) and the carbonation degree, as it increases the surface hardness of the concrete, will have a big influence on the rebound readings [1].

Table 1. Advantages and limitations of various NDT's

NDT	Applications	Limitations
Rebound hammer	Surface condition Uniformity in hardness Strength estimation	Limited to surface conditions Smooth surface contact required Labour intensive for large area mapping
Ultrasonic Pulse Velocity	Surface conditions Uniformity assessment Crack depth determination Strength estimation	Good surface contact required Direct transmission not always possible Labour intensive for large area mapping
Active infrared thermography	Localisation of near-surface imperfections Easily large area mapping without surface contact	Heat source dependency In-depth investigation limited
Ground penetrating radar	Visualisation and locating in-depth reinforcement, internal delamination and layer thickness Easily large area mapping One-side contact 3D reconstruction	Complex post-analysis
Ultrasonic shear-wave tomography	Visualisation and locating in-depth reinforcement, internal delamination, voids and flaws One-side contact 3D reconstruction	Slow data acquisition Time consuming Complex post-analysis

2.3 Ultrasonic pulse velocity

Ultrasonic pulse velocity testing (UPV) is applied by measuring the propagation speed of ultrasound waves through the material. It can be used for the appraisal of uniformity, the location of defects or cavities, for the determination of the depth of fractures and for the assessment of the elastic modulus and therefore of the compressive strength of the concrete [1]. The path of the ultrasonic pulse depends on the position of the wave emitter and the signal receiver: these can be placed in a direct, semi-direct or indirect position. A high pulse velocity will result in a good quality concrete and therefore a higher compressive strength. Imperfections in the material can be detected by reflecting, intercepting or otherwise influencing the sound waves.

2.4 Active infrared thermography

By means of infrared techniques, a huge amount of information regarding the structure can be obtained in a shorter period of time. Based on its non-invasive nature and cost efficiency, the technology is applied across a number of fields including material characterization, investigation of historic buildings, detection of thermal bridges, inspection and diagnosis of concrete elements [2-4]. Therefore, lock-in halogen heating is used, where

active heating leads to enlarged differences. The existing research on active thermography on building materials, mainly focuses on the assessment of near-surface structures. IRT is limited in its use for defect detection beyond certain depths of the target subsurface due to lateral diffusion. When an object is heated, its temperature is increased due to energy absorption. Heat exchange between the object and the environment is a dynamic process of conduction, convection and radiation. Heat radiation can be seen as the propagation of electromagnetic waves consisting of a series of wavelengths. With infrared thermography, the temperature distribution on the surface of any structural component can be recorded as an image, called a thermogram. No direct contact with the surface is required. If extra energy is induced in the structure by means of heating or cooling, this procedure is called active thermography. Because advanced non-destructive testing methods are mainly suitable for the detection and characterization of inhomogeneities deeper than 5 to 10 cm, active thermography closes the opening for testing the near surface area between the surface and a depth of about 10 cm.

2.5 Ground penetrating radar

Ground-penetrating radar (GPR) is a frequently used technology for civil engineering infrastructures. Standard practice in concrete scanning with GPR involves the use of high-frequency antenna systems (typically from 1GHz to 3GHz) with antenna dipole being oriented orthogonal to the scanning direction. Reflections are produced if the electromagnetic pulse encounters a change in Relative-Dielectric-Permittivity (RDP). RDP is a material property influenced by the composition and presence of moisture. The difference in RDP of different materials creates reflections which are detected by the receiver. With a very high speed of data collection, GPR can generate a large amount of data, which comprises a series of A-scans at discrete survey locations. Those A-scans can either be interpreted directly for layer-like structures (e.g. pavements), or serve as the raw inputs for further data processing or image reconstruction. For concrete structures, GPR has different applications: steel bar detection, cover thickness estimation, deterioration progression monitoring, etc. of structural members. It is also possible to survey an area in depth. No image processing is done on the hand-held wagon device itself, only basic operations are performed. Specialised post-processing of the obtained surveys needs to be done in software with specific data processing algorithms [5]

2.6 Ultrasonic shear-wave tomography

Ultrasonic shear wave tomography (USWT) is a stress-wave technique whereby shear waves are specifically generated, utilized, and introduced into a concrete structural member. The structural member will absorb, refract, or reflect the wave energy. Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances of the materials on each side of the boundary (e.g. reinforcing steel, tendons, tendon ducts, voids, honeycombs, cracks, etc.) Signal reflections originate from boundaries where the incident signal encounters a boundary where the acoustic properties of materials change. Two materials with similar elastic properties and densities will not produce large reflections, but the boundary between concrete and air for instance generates a very high intensity reflection, which is received and processed.
To generate the subsurface image a synthetic-aperture-focusing-technique is employed and is processed on the device. Additional software enables the user to view map scans in 3D, with all corresponding object slice directions. [6-7]

3 Experimental set-up

3.1 Test-wall configuration

A precast double wall (concrete specifications: CEM I 52.5R, 0/4 sea sand, 0/6 limestone, 6/14 limestone, W/C-ratio 0.49, f_{ccub28} = 53.3 MPa, BE500S steel reinforcement ϕ8, cover 30 mm) is produced with eight embedded defects (A -> H) made from expanded polystyrene blocks, cut to varying sizes, placed and fixed inside the inner cavity at various positions with known shape (circle O or half circle D), dimensions (varying diameter ϕ and surface A), depth d (6 cm), thickness t (8 cm) and locations (Fig. 3). The defects simulate honeycombing or internal voids and have varying A/d ratio (Table 3). The overall dimensions of the wall are approximately 1.0 m x 1.5 m with an overall thickness of 0.20 m (shell thickness 2x0.06 m, inner cavity thickness 0.08 m).

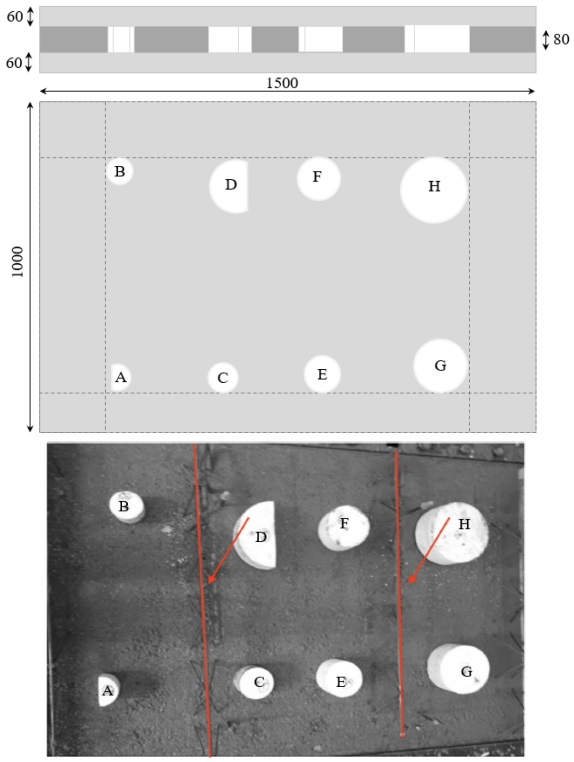

Fig. 3. Sketch of test-wall

Table 2. Properties of the polypropylene defects

	Shape	ϕ [cm]	A [cm²]	d [mm]	ϕ/d [-]	A/d [mm]
A	D	8	25,13	60	1,33	4,19
B	O	8	50,27	60	1,33	8,38
C	O	9	63,62	60	1,50	10,60
D	D	20	157,08	60	3,33	26,18
E	O	11	95,03	60	1,83	15,84
F	O	13	132,73	60	2,17	22,12
G	O	16	201,06	60	2,67	33,51
H	O	20	314,16	60	3,33	52,36

3.2 Testing methodology

At first, for each NDT, a test grid is being determined and prepared in accordance with past experience and best practices. The approximate time of execution is also (without post-processing time) being registered:

- RH: grid 10x10 cm (150 areas), 5 measurements per area (i.e. 750 impact tests), equipment: Proceq SilverSchmidt Type N, post-processing analysis: MS Excel. Execution time: 18'25".
- UPV: grid 10x10 cm (150 areas), 1 measurements per area (i.e. 150 tests), equipment: Proceq Pundit Lab, post-processing analysis: MS Excel. Execution time: 12'45".
- AIRT: no grid applied, heating during 30 minutes, cooling during 30 minutes, 5 thermograms during heating, 5 during cooling (i.e. 10 tests), equipment: FLIR T640 including heating test set-up, post-processing analysis: -. Execution time: less then 1', excluding heating/cooling time.
- GPR: grid 10x10 cm with continuous measurements, equipment: C-Thrue by IDS Georadar which consists of two-cross polarised antennae pairs with central frequencies of 2 GHz, post-processing analysis: GRED HD software. Execution time: 8'20".
- USWT: grid 5x15 cm (horizontal vs. vertical direction) (i.e. 200 tests), equipment: ACS MIRA Tomographer, post-processing analysis: Introview Concrete software. Execution time: 13'05".

Different criteria are being considered for the evaluation of the detectability of the defect of the selected NDT's: defect detected (yes (Y) or no (N)), location (spot on (o), shift left (←), shift right (→), shift up (↑), shift down (↓)), size (equal (=), smaller (.), bigger (O), unidentified (?)) and shape (yes (y), no (n)). This is being translated into an objective approach via a score between 1-5, with 5 meaning the defect was unambiguously detectable, 1 the defect was not detected.

Also the A/d-ratio (area of the defect vs. depth) was taking into account in this comparative study.

4 Results and discussion

4.1 Evaluation approach

For each non-destructive testing technique, the obtained results are being processed and evaluated. First of all, the detectability score (going from 1 to 5) is determined as mentioned in section 3.2. Furthermore, the detectability of the defects is linked to the A/d-ratio, for each defect and each NDT separately. Finally the results are compared and discussed. A summary and visualization of this comparative study can be found in Fig. 9 and Table 3.

4.2 Rebound hammer and ultrasonic pulse velocity

From the result of the mapping obtained by the rebound hammer, no clear distinction can be made even in case of high A/d-ratio. Only one of the eight defects (E) was detected, but without any information on the size, shape or depth. Furthermore, it is believed that this hit is mainly a coincidence rather than a detection hit, and the lower value actually represents a lower hardness of the outer concrete prefabricated element. It can be concluded that during the tests of the rebound hammer, even in the most extreme cavity, no clear distinction could be made between the defect and the surrounding concrete. Consequently, RH testing is of little relevance for detecting cavities: a detectability score of 1 is obtained for all defects (except for defect E).

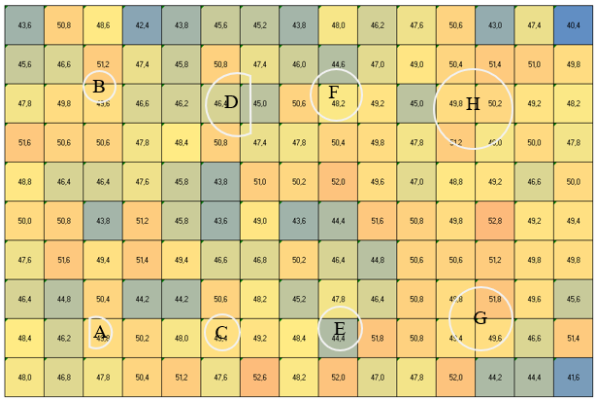

Fig. 4. Results of investigation via RH

Using UPV, the location of the existing defects inside the test object are clearly visible, as a significant difference in pulse velocity is noticeable for areas containing the polystyrene blocks: an averaged value of 2660 m/s compared to 3790 m/s in non-affected areas. All defects and its locations were detected using UPV, however it was not possible to identify its size, shape or depth as the standard variation of the obtained pulse velocity at the location of the defects is small compared to the averaged value (i.e. 75 m/s). A detectability score of 3 was obtained for all eight defects, regardless of the A/d-ratio. By decreasing the grid size, a more accurate prediction of shape and size could be made possible, however this measure also has its downside. In case a 5x5 cm grid would be used, execution time increased by

a factor 4. Furthermore, due to the size of the transmitter and receiver of the equipment (approximately 5 cm), it is not possible to reduce the grid size lower than 5x5 cm due to geometrical restrictions. Consequently, UPV testing is able to perform a quick-scan of a concrete element and briefly locate possible internal defect, however without any further identification of size, shape and depth of the flaws.

Fig. 5. Results of investigation via UPV

4.3 Active infrared tomography

Using AIRT after a warm-up time of thirty minutes and a cooling time of thirty minutes the thermogram clearly reveals ¾ of the defects present, with a significant difference in temperature, except for cavities A and B with A/d-ratio of 4.2 and 8.4 respectively. Cavities G and H, with A/d-ratio 33.5 and 52.4 respectively, have the most pronounced temperature difference, and it shape and size is clearly identifiable: a detectability score of 5 is obtained. The detection of the defects C to F, with A/d-ratio varying from 10.6 to 26.2, is less obvious, but still irrefutable, with detectability score of 3. The cavities with the smallest diameter, namely 4 cm (cavity A) and 8 cm (cavity B) are not detectable even after thirty minutes of cooling: detectability score 1. On the basis of the results of the demo-wall, it can be concluded that defects can be identified in case of a A/d-ratio higher than 10. Identifying shape and size is possible for A/d-ratios higher than approximately 25. AIRT is only valuable for near-surface inspection: the depth of defects cannot be distinguished [8].

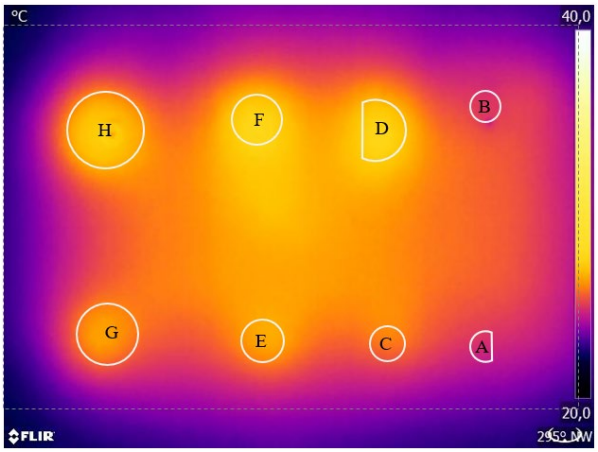

Fig. 6. Results of investigation via AIRT

4.4 Ground penetrating radar and ultrasonic shear wave tomography

In general, the defect detection capabilities of both techniques seem similar, with USWT not being able to detect the defect A with the smallest A/d-ratio compared to the GPR. For both systems higher A/d-ratios do not automatically lead to a higher detectability: for GPR defects F and H have lower detectability, while for USWT defects D, E and H have a score of 4/5. Even more, GPR was able to identify the half-circle shape of defect D, which was not the case for USWT.

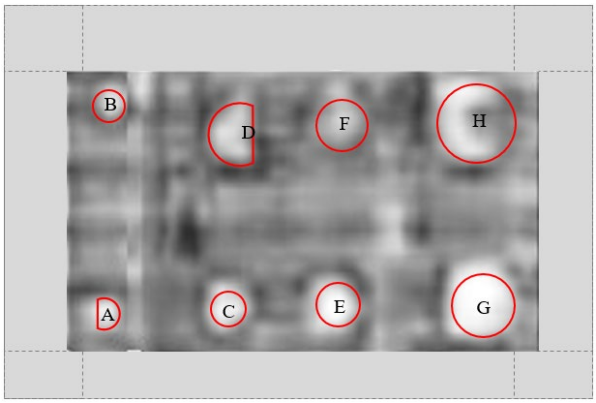

Fig. 7. Results of investigation via GPR

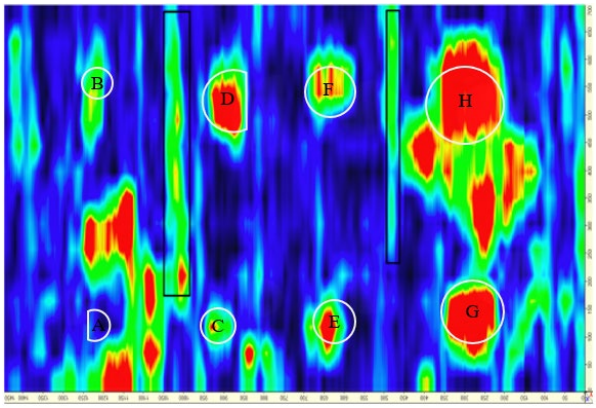

Fig. 8. Results of investigation via USWT

In addition, via post-processing analysis it is possible to provide an in-depth survey and estimation of the present defects, which was not the case for the other techniques (RH, UPV, AIRT). However, it was noticed that for USWT more signal degradation was present at a depth of 6 cm compared to GPR, which could explain why this technique was able to detect more defects. It is possible that these reflections originate from delamination between concrete elements as not all concrete is poured simultaneously during the construction of precast double walls. In general, it can be concluded that GPR is the more accurate measurement tool compared to the USWT. This does not make the latter device obsolete as an entirely different working principle is used, which has other advantages as mentioned in Table 1. One of these advantages is the on device SAFT processing of the received signals which show the subsurface structure on site. Another advantage is the ability to automatically determine the signal velocity without any user input. This enables the user to get a first understanding of the

size and depth of defects detected by the device without the need to manually process the results via post-analysis. Such is the case for GPR, as some basic processing options are available on device, although these are not user adjustable. To get a correct approximation of the RDP, the operator should be knowledgeable to what some common values are, how moisture or other environmental factors influence this, and how the software can aid in determining the correct RDP and as a result, signal speed [9].

Table 3. Summary of the detectability of the selected NDT's

Defect A/d	RH	UPV	AIRT	GPR	USWT
A 4.2	N	Y=?n	N	Y=on	N
B 8.4	N	Y=?n	N	Y=oy	Y↓On
C 10.6	N	Y=?n	Y=?n	Y=oy	Y=oy
D 26.2	N	Y=?n	Y=On	Y=oy	Y=Oy
E 15.8	Y??n	Y=?n	Y=On	Y=oy	Y=on
F 22.1	N	Y=?n	Y=On	Y=on	Y=oy
G 33.5	N	Y=?n	Y=oy	Y=oy	Y=oy
H 52.4	N	Y=?n	Y=oy	Y=on	Y=on

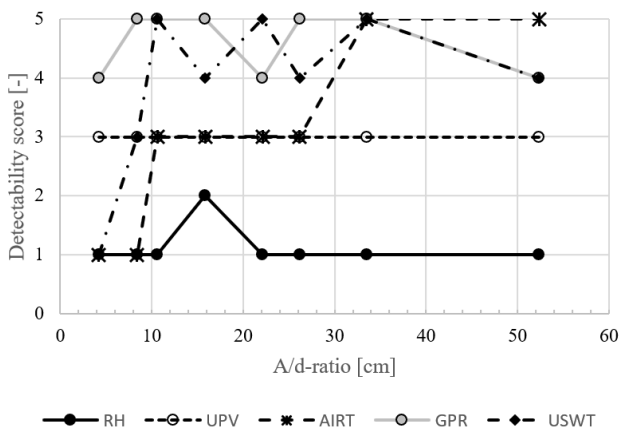

Fig. 9. Detectability score of the selected NDT's

5 Conclusion

Several NDT's are being compared in this study to evaluate their detection capacity, specifically applied for internal voids identification in precast double walls.

Rebound hammer testing is of little relevance for detecting cavities even in case of the most extreme defects, no clear distinction could be made with the surrounding concrete.
Ultrasonic pulse velocity testing is able to perform a quick-scan of a concrete element and briefly locate possible internal defect, however without any further identification of size, shape and depth of the flaws.

Defects can be identified by means of active infrared thermography in case of a sufficiently high A/d-ratio. Identifying shape and size is also possible but determining the depth of the defect is not possible making AIRT specifically valuable for near-surface inspection.

Ground penetrating radar and ultrasonic shear wave tomography are very useful techniques for assessing the inner structure of precast double walls. Both non-destructive techniques are able to locate defects, including size&shape identification and even depth localisation in the structure.

Overall: The larger the defect or the higher the A/d-ratio the easier it is to distinguish it from the heterogeneous nature of the concrete element.

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