

# Non-destructive testing of joints in precast element structures

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**ABSTRACT:** Strength and durability of precast concrete structures are determined to a great extent by the strength and durability of the connections between the precast elements. Most common problems are improper grouting and packing of the filling material in the joints, as well as excess of shrinkage or inadequate bond to the boundaries. Therefore, ensuring a proper filling of joints is a must to avoid undesirable effects such as cracks, steel corrosion, lack of stiffness or loss of load carrying capacity. However, it is not easy to be sure that the workmanship has been done correctly unless coring or drilling of holes are performed. This paper presents a case study carried out on vertical joints of precast concrete wall elements improperly grouted to show fast and reliable non-destructive techniques, for quality control or inspection survey, that require access to only one face of the element: the impact-echo method and an ultrasonic-echo tomographer.

## 1 INTRODUCTION

In order to form a monolithic structure using precast concrete wall elements, vertical shear connections are usually made as keyed joints reinforced with overlapping U-bars. They form a cylindrical core in which a locking bar is positioned, and all the joints are grouted with mortar. Another alternative is replacing the U-bars with high strength looped wire ropes since their flexibility makes the installation of wall elements easier. The wire ropes are usually pre-installed in “wire boxes” embedded in the precast walls with a rebar in the middle (Jorgensen, 2015).

While these types of joints have proved to be structurally appropriate, sometimes the grouting procedure at the job site is not properly done (Lund et al, 2015). A vertical shear connection joint with defects in the filling mortar can lead to stress concentrations that may induce undesirable plastic deformations in the U-bars or a brittle failure in the looped wire ropes due to their lack of yield plateau in the stress-strain relationship (Jorgensen, 2015). Furthermore, even if the load carrying capacity is not compromised, the service life of the structure might be, because cracks and voids make concrete susceptible to water intrusion and consequently steel corrosion may become a problem or ice can be formed during freezing temperatures, expanding and cracking the surrounding concrete.

A demonstration of quality inspection of joints with looped wire ropes was performed in a multi-story building where precast concrete walls were used extensively. Knowing that the grouting process is

very susceptible to human error, looking for possible defects is critical. Two instruments were used, the DOCTer, which is based on the Impact-Echo method, and MIRA, an ultrasonic-echo tomographer. The stress wave NDT assessment methods are totally sensitive to these types of defects and fully accomplished the investigation. Results are discussed and compared. Cores were extracted for verification.

### 1.1 *The DOCTer Impact-Echo principle (Carino, 2015)*

A short mechanical impact is produced on the concrete surface with a small steel sphere. This impact generates stress waves that propagate into the concrete. When the P-wave (the longitudinal wave) reaches a material (e.g. air, steel, soil, etc.) with a different acoustic impedance (wave speed x density), it is reflected and travels back to the surface where the impact was generated. The reflective surface is normally the back side of the concrete member but if this concrete has embedded objects or defects such as voids, honeycombs, cracks, etc., they also act as reflective surfaces. A sensitive displacement transducer next to the impact point picks up the displacement of the surface due to the arrival of the P-wave. The P-wave is then reflected back into the member and the cycle begins again. Thus the P-wave undergoes multiple reflections between the two surfaces and the recorded waveform of surface displacement has a periodic pattern that is related to the depth of the

reflective surface for a given wave speed. This displacement waveform is transformed into a frequency domain to produce an amplitude spectrum that shows the predominant frequencies in the waveform (see Fig. 1). The analysis of these frequencies is the basis of the Impact-Echo method which is governed by the equation shown below:

$$f = \frac{C_p}{2D} \quad (1)$$

where  $f$  = frequency;  $C_p$  = P-Wave speed; and  $D$  = travel path.

The DOCTer instrument is illustrated in operation in Figure 2. Each measurement takes only 1 second.

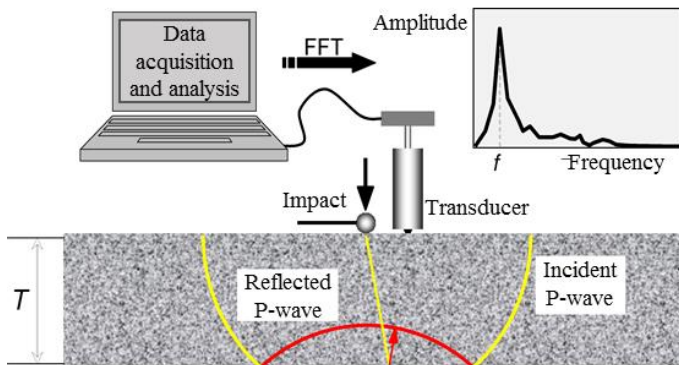


Figure 1. The Impact-Echo method.



Figure 2. DOCTer Impact-Echo testing in progress.

## 1.2 The MIRA ultrasonic-echo tomographer principle (Hoegh et al, 2011)

MIRA is a portable instrument based on the ultrasonic pulse-echo method using transmitting and receiving transducers in a "pitch-catch" configuration. One set of transducers sends out a shear wave pulse and all other sets of transducers receive the reflected pulse. The time from the start of the pulse until the arrival of the echo is measured. For a known shear wave speed,  $C_s$ , the depth of the reflecting interface can be calculated. The instrument itself measures automatically the shear wave speed.

The 4 x 12 transducer array antenna produces many transit time measurements during each test that are later analyzed using the synthetic aperture focusing technique (SAFT) in real time to reconstruct a 2D image of the cross section below the instrument. It takes about 3 to 4 seconds to complete data acquisition and data processing at each location.

The data captured can later be transferred to a computer with a dedicated software to create a 3D image that allows views of different slices of the reconstructed internal structure to identify the locations of the reflecting interfaces, which can be the opposite side of the concrete member (back wall reflection), reinforcing bars or concrete-air interfaces such as voids, delaminations, honeycombing or other defects alike. Figure 3 shows the instrument.



Figure 3. The MIRA ultrasonic-echo tomographer. To the left, front face displaying a cross section scan; to the right, the 4 x 12 transducer array antenna; and at the bottom, testing in progress.

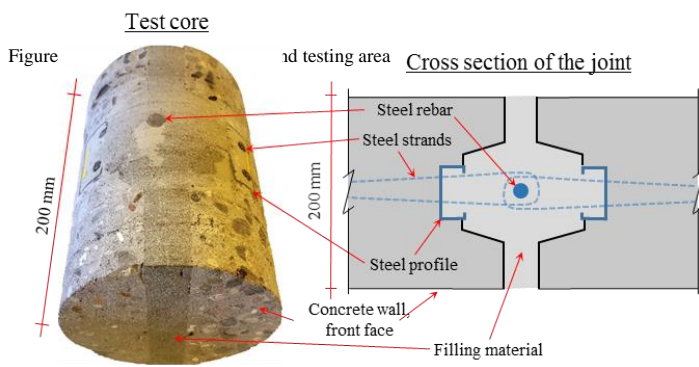
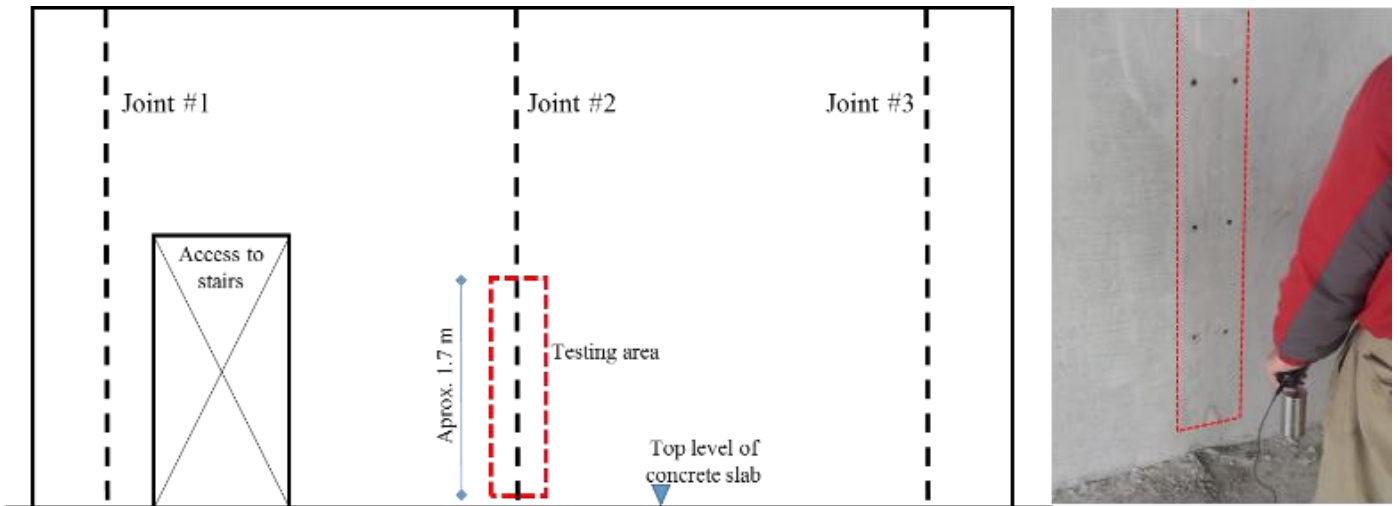


Figure 5. A solid concrete core extracted from the joint for verification together with a drawing of the cross section of the joint.

## 2 TESTING

Both methods described above were used in a demonstration project that consisted of testing two wire loop joints of precast wall elements during the construction of the Life Science & Bio Engineering Building at the Technical University of Denmark, Campus Lyngby: Joint # 2 in the Ground Level (2GL) and Joint # 2 in the First Level (2FL). The joints were grouted with a fluid mortar, but there were suspicions that a bad procedure of grouting could have been done. The focus of the testing was to find the position and size of possible defects to be repaired.

A vertical column of 17 testing points, with 100 mm spacing in between, were selected for the joint in the ground floor and 18 points, same spacing, for the joint in the first floor. The tested concrete walls were 200 mm thick (see Fig. 4).

### 2.1 Testing with DOCTer

In order to obtain the P-wave wave speed ( $C_p$ ) of the mortar, the instrument was calibrated in an area of the wall with known good quality filling (see Figure 5)

and the wave speed was estimated to be 3,800 m/s (a reasonable P-wave speed for the mortar) from the equation (1):

$$f = \frac{C_p}{2D}$$

$$C_p = 2Df = 2(200)(9.5) = 3,800 \text{ m/s}$$

with  $f = 9.5$  kHz, measured by DOCTer from the same well known solid area (see the highest peak in the frequency spectrum from Fig. 6).

#### 2.1.1 Solid joint

Figure 6 shows the frequency spectrum of the verification test in joint 2FL which was the reference for comparing the rest of the testing points. It can be seen that the main peak is indicating the 9.5 kHz value used for the calculation of the wave speed velocity and that there are no other major peaks indicating other reflective surfaces than the one from the back side of the wall.

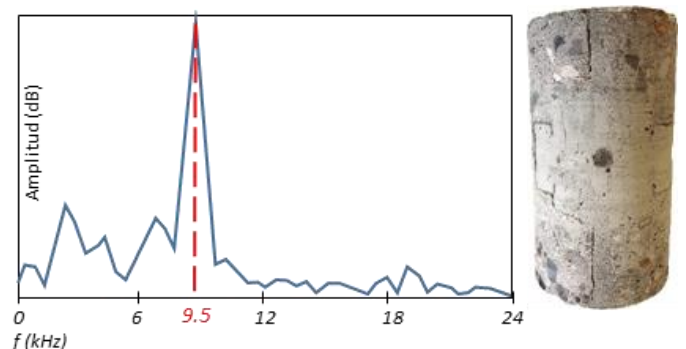


Figure 6. Recorded spectrum of a filled-out joint section. One single main peak is displayed, 9.5 kHz in this case (red line), corresponding to a thickness of 200 mm for a P-wave speed of 3,800 m/s. A 150 mm diameter core was taken from the section for verification, shown adjacent.

### 2.1.2 Joint with a limited defect

For a limited size of defect, reflections occur mainly from the back side of the member but partly also from the internal small voids. Because the P-wave runs around the defect(s), it will travel longer and the main or solid frequency will drop in the spectrum to a lower frequency value. Yet, the other reflections coming from the defect itself will produce a high amplitude peak on the right side of the frequency spectrum. If this peak is big enough to be clearly identified, the depth of the defect can be estimated using the equation (1).

Figure 7 shows this case with data obtained from joint 2FL. A mixed frequency shows up, partly the solid frequency at 9.5 kHz and partly a frequency at 7.5 kHz related to a longer travel path than the 200 mm thickness of the wall. The interpretation is a partly injected joint with small voids, which was confirmed by the core drilled out shown adjacent to the spectrum. A smaller frequency peak at 22 kHz is also showing up at the right side of the spectrum, however, it is not high enough to identify it clearly in this case.

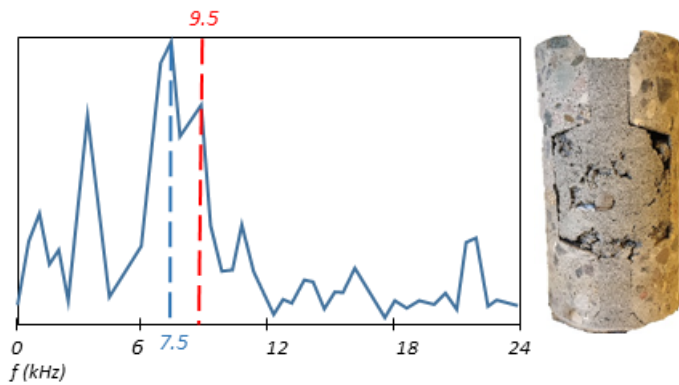


Figure 7. The frequency of the main peak has dropped to 7.5 kHz (blue line). The red line shows the position at 9.5 kHz where the main peak should have been according to Figure 6. The amplitude in this point is still high, meaning that part of the P-wave still runs through solid material. Notice also the 22 kHz frequency peak coming up, related to a larger possible defect. The 150 mm core was taken from the section for verification.

It can be also noticed that there are some other peaks on the left side of the spectrum (low frequency region), most certainly caused by e.g. the Rayleigh Wave or flexural displacement. They are not important, keeping a focus only on the main peaks of the solid frequency during the analysis, a drop in this frequency and higher frequency peaks coming up.

### 2.1.3 Joint with a large defect

This time the drop of the main peak of the spectrum is followed by a large second main peak in the higher frequency region, meaning that the defect is big enough to clearly transmit a reflection by itself for the impactor selected. Using this high frequency with the same equation, the depth of the defect can be calculated with equation (1) as follows:

$$D = Cp/2f = 3,800/2(22) = 86 \text{ mm}$$

Figure 8 shows this case with data obtained from joint 2FL.

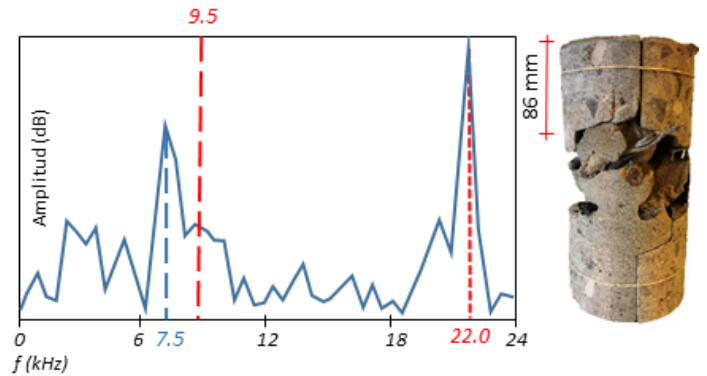


Figure 8. The blue dotted line at 7.5 kHz indicate a longer travel path than the 200 mm related to a frequency of 9.5 kHz. The P-wave runs around a defect. A second main peak in the spectrum shows reflection from a large defect at 22 kHz related to the depth of the defect. A 150 mm core was taken from the section for verification and it can be seen that the depth of the defect was predicted accurately.

### 2.1.4 Summary

As a summary, the testing points were classified as shown in Figure 12C with 3 colors: blue for solid or filled-out region of the joint, yellow for small voids or defects and red for large voids or defects.

A dedicated software has been developed recently to facilitate the interpretation. The application creates 2D and 3D visual representations of the results obtained from a grid of closely-spaced test points (see Fig. 9).

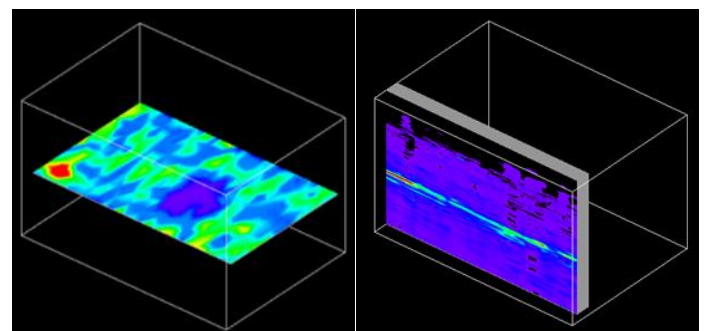


Figure 9. Screenshots of impact-echo representations made by the MIRA d'Or software. On the left, a cross section parallel to the surface at 150 mm depth in a slab. The purple/violet area in the middle shows some honeycombing and the red one shows a void. On the right, a cross section perpendicular to the surface showing the backwall represented by the bright green line.

The technique consists in using the amplitude spectrum to construct a volume model of the test region from which locations of reflecting interfaces can be presented as images where a color coding is used to

represent the amplitude of each frequency. This software was however not used in this case as only 1 line of testing points was implemented.

## 2.2 Testing with MIRA

Regarding the use of the MIRA ultrasonic-echo tomographer, one measurement was done at each point that had been previously tested with the Impact-Echo method. However, with MIRA, the coverage of each measurement is about 250 mm width and the image of the plane below the instrument is displayed in 3-4 seconds, the so-called “B-scans” (see Fig. 10).

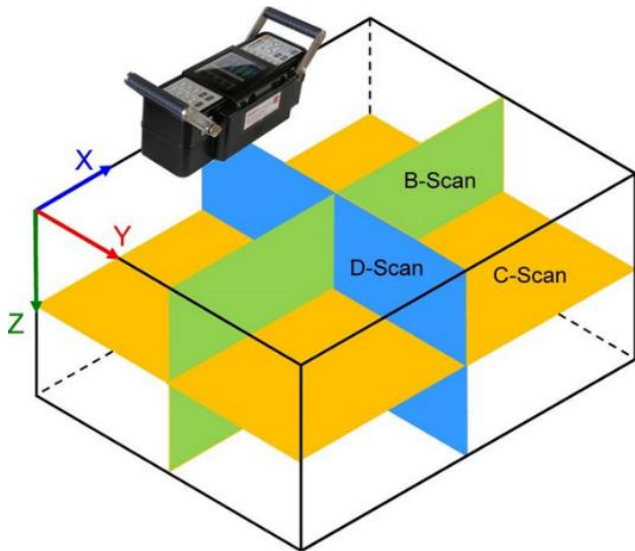


Figure 10. Identification of the 3 orthogonal planes of MIRA according to its position on the surface.

The instrument was firstly calibrated in an area of the wall with known good quality filling. This was done

only once at the beginning where the parameters such as color gain and testing emitting frequency were set.

This calibration should be made carefully before every specific testing job, otherwise the color contours in the images could easily be interpreted erroneously. Furthermore, because reflections could be an indication of other embedded objects, interpretation is recommended to be followed by some testing cores for verification at the beginning before continuing making ample testing.

Figure 11 shows examples of B-scans from 3 different points corresponding, from left to right, to a filled-out joint, a joint with small defects and a joint with big defects. Since the MIRA was placed transversally to the longitudinal direction of the vertical joint as shown in Figure 4, the plane of a B-scan corresponds to the transversal cross section of the joint.

All 2D images obtained from each point were afterwards processed in a laptop with a dedicated software to reconstruct a 3D view of a joint. Figure 13 shows the final results of both instruments, MIRA and DOCTer in joint 2FL for comparison.

The table with the Impact-Echo data from the testing points has been positioned to match the height of the images of MIRA and compare the color classification given as explained before. As it will be seen, there is good agreement between both methods.

Some minor differences may be expected because Impact-Echo are point readings below the position of the single transducer whereas MIRA makes a reconstructed map over the whole length of the joint with a width of about 250 mm. However, the general interpretation of both tools for the practical purpose of quality control or quality assurance is equivalent.

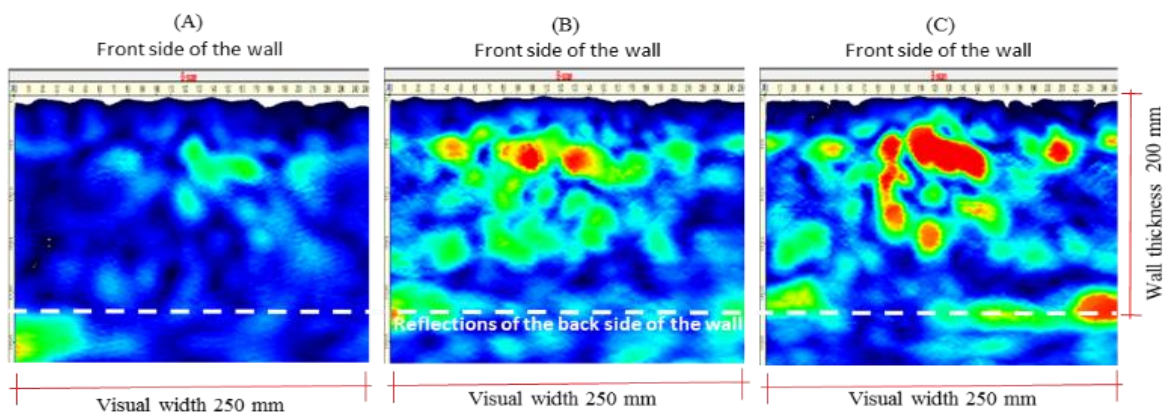
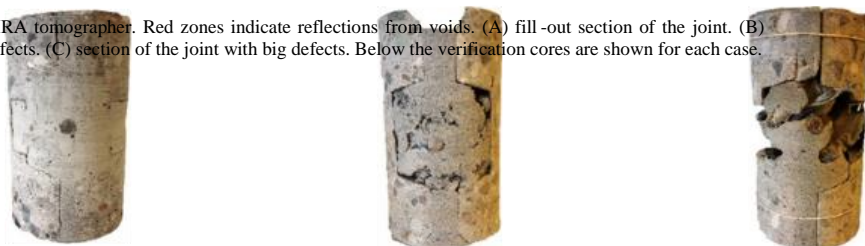


Figure 11. B-scans from the MIRA tomographer. Red zones indicate reflections from voids. (A) fill-out section of the joint. (B) section of the joint with small defects. (C) section of the joint with big defects. Below the verification cores are shown for each case.



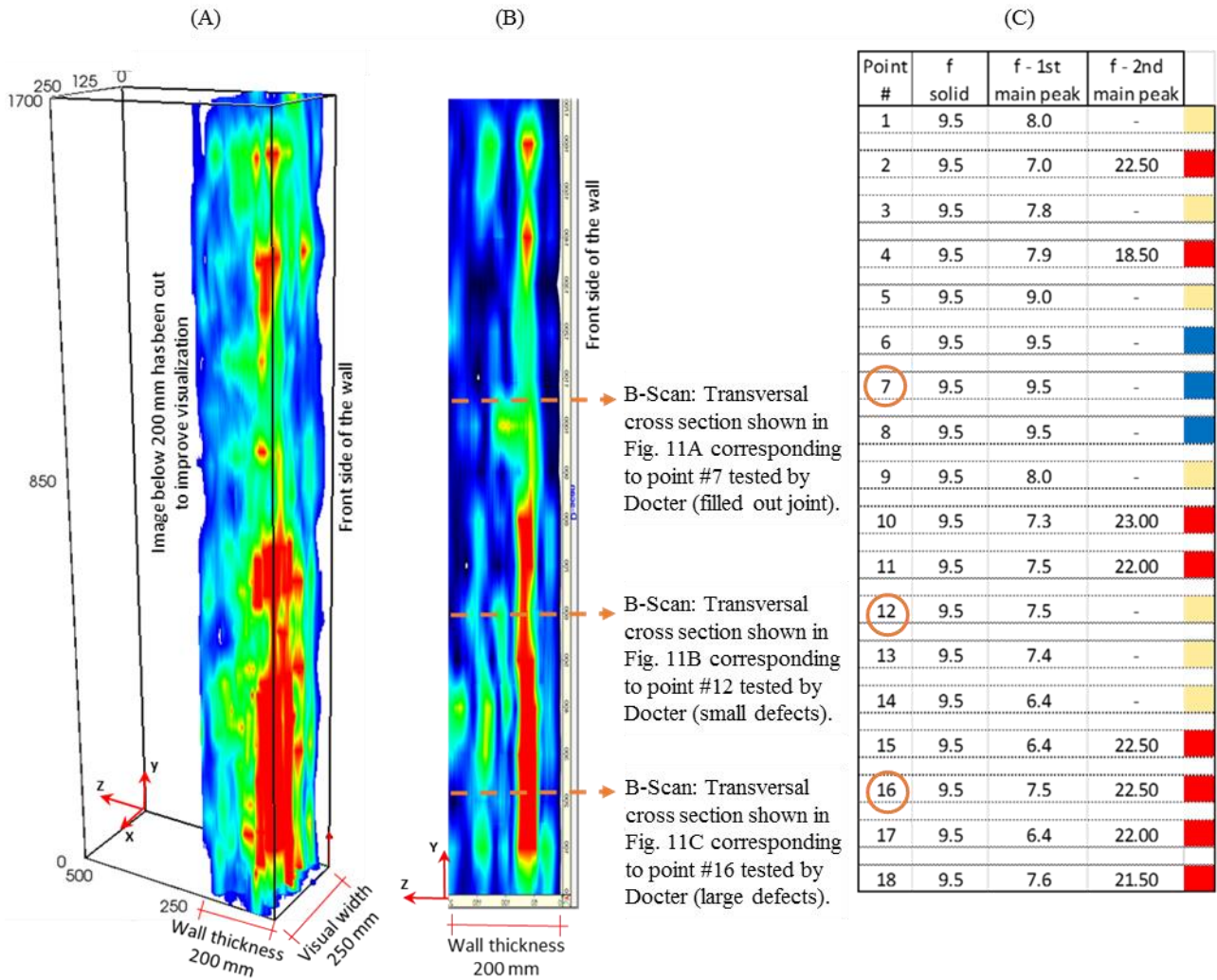


Figure 12. Final results from joint 2FL and comparison between both testing methods. (A) 3D view of the whole testing area of the joint. (B) D-scan view representing the longitudinal cross section of the joint at its center (x = 125 mm) and the position where the transversal cross sections shown in Figure 11 were taken. (C) Impact-Echo method results with the color classification given.

### 3 CONCLUSIONS

Testing from one side only is feasible for checking the quality of injection of joints locking precast elements together. Two such systems are the impact-echo (DOcter) and the ultrasonic-echo method (MIRA). They can help owners or supervisors for quality assurance purposes and contractors by implementing a quick quality control procedure that allows them to change or improve the working conditions or methods to avoid further expense on repairs and delays. The quality of the repair itself can also be tested.

The impact-echo (DOcter) is simple to perform and gives immediate information of the condition of the joint right below the transducer. Once the fundamental frequencies are understood, the testing can take place very quickly, within 1-2 seconds for each test. A newly developed impact-echo software, the MIRA d'OR, allows 2D and 3D images of the joint quality to be produced.

The ultrasonic-echo method performed by means of the MIRA needs careful calibration when starting a testing set, takes a little longer time and it is difficult to perform within confined areas because of the size of the instrument. The advantage is that the 2D color illustration is displayed within 3-4 seconds as a cross section (B-Scan). The 3D reconstruction of the joint condition requires additional time to transfer the 2D data to a laptop with the dedicated 3D software but it is a useful tool to generate friendlier testing reports.

To obtain the full benefits of both systems, the theoretical background should be understood and training in operation of the systems should be received.

### 4 ACKNOWLEDGEMENTS

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