Synopsis:
The appearance of cracks and spalling in concrete columns in a new 8 storey office building let to the concern that the injection of the ducts in the columns was of poor quality. The cracks were mainly present at one floor and trial drillings into the ducts on columns with severe cracks disclosed the presence of water and loose gravel and aggregates. Opening a duct revealed that the duct was either partially empty, filled with compacted gravel, or fully grouted.

It was decided to use the impact-echo (IE) method to investigate the columns and ducts.

Each column contains 4 ducts with a 25 mm diameter reinforcing rebar for distribution of the shear stress at the lower and upper 1.0 meter to each floor. Testing was performed for each 0.1 meter elevation in these areas. The criterion to approve the injection was that at least 0.7 m of the column at the floor or the ceiling was fully injected. After testing the columns on 3 floors, it was decided to investigate the ducts in the walls of the 3 stairwells of the building as they were vital for transferring the stresses of the reinforcement down through the building.

Verification of the IE-system by drilling cores showed that it was possible to distinguish between empty ducts, fully injected ducts and ducts with compacted gravel. More than 35,000 measurements were made. The examination of the ducts showed that approximately 63 % of tests at the top and approximately 86 % at the bottom of the columns and walls indicated full injection.

Keywords:

1 Ramboll Denmark A/S, Bridge maintenance and Material technology. Bredevej 2, DK-2830 Virum
INTRODUCTION
A few days after a period with cold weather and temperatures below 0˚C in January 2008, cracks and spalling started to appear suddenly on columns in a new 8-story office building, which was still under construction. A visual inspection revealed the presence of cracks and spalling in 29 out of 489 columns distributed on 6 floors with 13 of the damaged columns on Level 4. The cracks were mainly visible at the tops of the columns and always directly in front of the cable ducts in each column. Figure 1 shows a column with spalling and the sectional view of a column shows one of the cable ducts highlighted with a solid circle.

Each column has 4 cable ducts, 80 mm in diameter with a concrete cover of approximately 80 mm. For distribution of the shear forces between the floors of the building a 25 mm diameter reinforcing rebar is embedded in each duct reaching 1 m into the duct above and below the floor. See Figure 2, where the bars at the top of a column are highlighted as solid vertical lines.

To investigate the cause of the cracking, holes were drilled with a 25 mm diameter drill bit into the cable duct at 10 cm and 45 cm below the ceiling. The purpose of this preliminary investigation was to investigate if:

1. The duct was fully grouted or empty, and
2. The grout has “no strength”.

The preliminary investigation disclosed the presence of:
1. Empty, fully grouted, and partly grouted ducts; 
2. Water in the ducts; and
3. Grout with no strength – and which appeared to be segregated

A surprising discovery was the presence of larger aggregates in the grout. Breaking up the ducts revealed the presence of aggregates with a diameter up to 32 mm. This means that the “grout” in the ducts was the same concrete as has been used for casting each floor and not the prescribed mortar mixture. With a 25 mm reinforcing rebar in the centre of an 80 mm duct, the chance of having a blocking due to the large aggregate particles is high and may explain the presence of voids and partly filled ducts. See the photo in Figure 3.

The cracking and spalling can be explained by the presence of water in the ducts, which froze during the few days with temperatures below 0˚C and hence expanded. Construction photos from casting of the floors showed the drainage of the formwork let the water directly to some of the columns. Figure 4 shows a photo of an empty duct, which had been full of water and caused corrosion on the reinforcing rebar.

Due to the findings in the preliminary investigations, the contractor requested assistance in locating ducts with defects and to delimit the defects in each duct within 1 meter from the top and bottom of each column and walls of the stairwells. The request from the contractor was that the testing should be fast, reliable and non-destructive to prevent unnecessary repairs and further delay of the building project.

Preliminary tests with a few selected NDT systems and verifications showed that the best correlation between the findings, repeatability and a fast system was obtained with an impact-echo test system. Drilling cores confirmed 94 % of the findings with the impact-echo system. The system was able to distinguish between fully grouted and empty ducts with a high degree of certainty. In a few cases it was possible to classify the content of the ducts as “compacted aggregates and sand without any strength”.

**METHOD**

The impact-echo system (IE) used comprises a mechanical spherical impactor source - normally in the range from 3 to 12 mm in diameter - and a displacement transducer placed approximately 5 cm adjacent to the impact point. The impactor generates a pressure wave (P-wave), which travels into the concrete and is reflected from the back of the column/wall or an internal anomaly as for example a void, back to the surface. This P-wave is reflected several times and the arrival of the reflected P-wave are detected by the displacement transducer on the surface. The time-displacement response is converted to a frequency response using a fast Fourier transform (FFT) algorithm. Figure 5 shows a sketch of the setup of the IE system and testing in progress on the columns.

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** Germann Instruments (Denmark/USA)
For a plate-like structure the IE system can be used to measure the thickness of the concrete or depth to the defect below the test-point. The time, \( \Delta t \), taken for the reflected P-wave to reach the transducer depends on the P-wave velocity, \( C_p \), in the concrete and the thickness, \( T \), of the concrete, and is given by:

\[
\Delta t = \frac{2 \cdot T}{C_p}
\]  

(1)

By using the FFT-algorithm the plate thickness or frequency, \( f \), can be determined, which is the inverse of the travel time in equation (1). Thus the plate thickness is related to the thickness frequency as follows:

\[
T = \frac{C_p}{2 \cdot f}
\]  

(2)

- The thickness, \( T \), of the solid plate is either measured directly on the structures or is known from the structural drawings.
- The P-wave velocity, \( C_p \), can be obtained by calibration on a structure of known thickness or by directly measurement on the surface by using two transducers at a known separation and measuring the P-wave travel time between the two transducers.

Test program:
Three sizes of columns are investigated. The diameters were 450 mm, 560 mm and 650 mm. The largest column has a 300 mm thick drop panel below the ceiling. Each column has 4 embedded cable ducts from level -2 (deepest basement) to level 4 (3rd floor). From level 4 and up to level 8, only 2 cable ducts are embedded in the columns. Adjacent to two of the ducts – perpendicular to each other – plastic tubes are embedded for electrical wiring. The top and bottom of these plastic tubes were visible and were used as guidelines to locate the ducts. At level -1 and -2 the plastic tubes was not embedded in the columns and hence the ducts were located by means of a ground penetrating radar system with a 1.6 GHz antenna.

An elevation and sectional views of the columns as well as the testing points are shown in Figure 6.
Using the IE system on plate-like structure is normally relatively easy and a test gives ideally only one clear frequency peak corresponding to the thickness or depth to an anomaly. Testing round columns requires knowledge of expected modal frequencies of the cross section to avoid misinterpretation of the data. Modal frequencies occur as the stress waves that are sent into the columns are reflected from the entire boundary of the column and not just the back side. If the diameter and the P-wave velocity is known, these frequencies can be calculated. (Sansalone and Street)

Verification tests on the columns have shown that the P-wave velocity is approximately 3800 m/s. The depth to the ducts is 80 mm ± 10 mm. With knowledge of the diameter, location of ducts and P-wave speed in the concrete, it is possible to calculate the expected frequencies for a “solid” signal (back side of column), the different modal frequencies and expected frequencies for voids in the ducts. The results are shown in Table 1, and the most interesting frequencies used for evaluating the data are highlighted:

Table 1 -- Overview of expected frequencies for a column with fully grouted ducts and if voids are present in the ducts.

<table>
<thead>
<tr>
<th></th>
<th>Column 450 mm</th>
<th>Column 560 mm</th>
<th>Column 650 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Solid&quot; frequency</td>
<td>4.22 kHz</td>
<td>3.45 kHz</td>
<td>2.92 kHz</td>
</tr>
<tr>
<td>1. mode</td>
<td>6.3 kHz</td>
<td>5.2 kHz</td>
<td>4.4 kHz</td>
</tr>
<tr>
<td>2. mode</td>
<td>8.4 kHz</td>
<td>6.9 kHz</td>
<td>5.9 kHz</td>
</tr>
<tr>
<td>3. mode</td>
<td>10.1 kHz</td>
<td>8.3 kHz</td>
<td>7.0 kHz</td>
</tr>
<tr>
<td>4. mode</td>
<td>12.2 kHz</td>
<td>10.0 kHz</td>
<td>8.5 kHz</td>
</tr>
<tr>
<td>5. mode</td>
<td>13.9 kHz</td>
<td>11.4 kHz</td>
<td>9.7 kHz</td>
</tr>
<tr>
<td>Void at 80 mm depth</td>
<td></td>
<td></td>
<td>23.8 kHz</td>
</tr>
<tr>
<td>Void at 160 mm depth</td>
<td></td>
<td></td>
<td>11.9 kHz</td>
</tr>
</tbody>
</table>

A completely empty duct will give a reflection from a depth of 80 mm, which corresponds to a frequency of 23.8 kHz. IE can only detect the depth to the first interface between the concrete and an empty duct. It can not tell how thick the void is. If a void is present at the back side of the duct at a depth of 160 mm, a frequency of 11.9 kHz would be expected. For the smallest size of columns the 4th modal frequency of 12.2 kHz can be confounded with the frequency for a void in a depth of 160 mm. But in practice this is not important as the “solid” signal will change in case there is a void and hence all the modal frequencies. If the “solid” frequency is not present in the data and a dominant peak occur within the frequency range of 11.9 to 23.8 kHz, this may indicate the presence of a void in the ducts.
To be able to “see” a void at a depth of 80 mm and the reflection from the backside of the column the correct, impactor has to be chosen. The size of the impactor influences the size and depth to an anomaly that can be detected. A small impactor generates waves of high frequencies and can detect small defects close to the surface. A larger impactor can only detect larger anomalies that are at greater depth. For this specific case, only a few impactor diameters were available; 5.0, 8.0 and 12.5 mm. The range of anomaly size and depth each impactor can detect can be calculated.

An impact to a surface will produce a force-time function. The force-time function created by any impact to a concrete surface, will determine the frequency components of the stress wave traveling into the concrete. The minimum, lateral, flaw size, the depth to the flaw and the maximum depth that can be detected is related to the contact time between the impactor and the concrete surface, the diameter of the impactor and the wave speed in the concrete.

Table 2 gives the calculated smallest flaw size, the minimum depth, and the maximum depth that can be detected for each impactor size based on empirical “rules”. (Sansalone and Street).

<table>
<thead>
<tr>
<th>Impactor size [mm]</th>
<th>Flaw size, minimum [mm]</th>
<th>Min. depth of flaw size [mm]</th>
<th>Max. depth of flaw size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>70</td>
<td>35</td>
<td>280</td>
</tr>
<tr>
<td>8.0</td>
<td>111</td>
<td>56</td>
<td>444</td>
</tr>
<tr>
<td>12.5</td>
<td>175</td>
<td>88</td>
<td>700</td>
</tr>
</tbody>
</table>

It was decided to use the 5.0 mm diameter impactor as an empirical rule is “to use the largest size of impactor that will work to simplify spectrum”. The 5 mm diameter impactor can detect a minimum flaw size of 70 mm – and we can expect an 80 mm “flaw” from a hollow duct. At the same time it can not detect if the duct on the opposite side of the column is empty and hence give wrong interpretations.

One of the interesting tasks of this project was to evaluate if IE could detect the presence of ducts with segregated gravel with no strength. This question arose as the discussion about the injection procedure was planned. Part of the ducts with only lose gravel should be repaired with epoxy, which is very expensive, and empty ducts should be injected with micro cement, which is less expensive. Normally IE is not used for this kind of determinations and hence several verifications were made on site. The results of the verifications lead to the following 3 typical signals for a column with a diameter of 560 mm:

1. Solid, a clear peak at 3.42 kHz is present indicating a fully grouted duct. See Figure 7
2. Indication of presence of a void in the duct (or indication of lose gravel). See Figure 8.
3. Empty duct and/or a minor delamination of the surface near the test point. Figure 9.

![Figure 7](image7.png)  
**Figure 7** – Frequency peak (arrow) due to reflection from back side of column at a depth of 556 mm and no peak corresponding to the presence of air in the duct (about 24 kHz).

![Figure 8](image8.png)  
**Figure 8** – Frequency peak (left arrow) due to reflection from back side of column from at a depth of 556 mm. And frequency peak (right arrow) due to the presence of air in the duct at a depth of 75 mm.
Figure 9 -- Frequency peak (lower arrow) due to reflection from back side has shifted and shows a depth of 648 mm corresponding to the presence of and empty the duct.

In Figure 7 several peaks are present to the right of the peak at 3.42 kHz. These peaks correspond to the modal frequencies listed in Table 1.

The signal in Figure 8 is atypical because it is showing a clear peak due to reflections from the back side of the column, which would normally indicate a fully grouted duct, as well as an indication of a void at a depth of 75 mm. Normally a solid frequency peak and a flaw peak are not present at the same time. If a void is present in a structure, the echo from the back side will normally shift to a frequency that is lower than the solid frequency as the path of the waves is longer as they have to travel around the void and back again, and a peak indicating the depth to the void is present. (Sansalone and Street).

When coring was performed at locations with these signals, some lose aggregates were present and with it air. However, the signal indicates that it may only be minor air pockets as the thickness frequency has not shifted to a lower frequency. Air may be present around some of the aggregates while others are still bound together by the mortar and provide a direct path for the P-wave.

The signal in Figure 9 is also a little atypical, as there is no peak at the expected 24 kHz, indicating an empty duct. However, verification of the interpretation of the data by coring and breaking up the ducts showed that the ducts were empty. The data showing the reflection of the P-wave in the upper curve indicates that there is a problem with a “shallow delamination” of the surface tested. This is indicated in the upper curve/waveform as the oscillation of the waveform does not diminish as fast as in the other examples. This may explain why there are no depth indications shown by a clear peak at 24 kHz. The frequency of the impactor used is not high enough to “see” these shallow defects.

Testing details:
Each column was tested along each duct within 1 meter up from the floor and within 1 meter down from the ceiling in steps of 0.1 m where access was possible. This gave a total of 80 test points for each column. Because testing was performed relatively late in the construction phase, access to the some parts of the columns at some of the floors was obstructed by railings towards the atrium, ventilating and heating pipes, building materials or adjacent walls as shown in Figure 10.
Late in the testing phase, revised calculations showed that grout around the reinforcing rebars was only required within 0.62 m from the floor or ceiling. All data were exported to a spreadsheet for evaluation and the new criterion was therefore easy to incorporate.

Approximately 35,000 tests were made on 489 columns and 515 ducts embedded in the walls of the three stairwells. A total of 316 man-hours were spent on the testing and reporting of data. On average 1,500 IE tests were performed per day.

In Figure 11 -- Summary overview of the data are shown for the bottom and top of the columns.

**Results from IE on bottom of columns**

- 10.0% "Uncertain"
- 4.1% "OK"
- 85.9% "Void"

**Results from IE on top of columns**

- 32.8% "Uncertain"
- 4.3% "OK"
- 62.9% "Void"
CONCLUSION
The investigations showed that almost 10% of the ducts at the bottom of the columns and approximately 33% at the top of the columns were empty. Approximately 4% of the tests were classified as “uncertain” and could be both lose gravel/aggregates or an empty duct.

For verification of the impact-echo data, 50 cores were drilled into the ducts. 39 of the cores were in accordance with the data interpretation. 8 cores showed an empty duct and the interpretation of the impact-echo data said empty or possible lose aggregates. These 8 tests were accepted. The last 3 cores showed an empty duct and the impact-echo data had evaluated the data as “solid”.

The use of the impact-echo method gave the contractor a good overview of the actual condition of the ducts in the columns and saved the repair of many holes if drilling would have been used to investigate the ducts.

Empty or partly grouted ducts were found on all levels. The most flawed columns were, however, found on one floor built during a few weeks with extensive rain. The repair and injection of the columns took 4 men 4 month in total. Quality assurance (QA) of the workmanship during the construction phase had been applied on all levels and at all columns - according to the documentation supplied! NDT however showed that the QA program was not effective.

Reference: