Reliability of non-destructive testing methods for detecting steel rebar in existing concrete structures

Selek, I.

Award date:
2015

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
Reliability of non-destructive testing methods for detecting steel rebar in existing concrete structures

Final Thesis

A-2015.113

I. SELEK
Author:

Name  Ibrahim Selek
Student number  0717873
Academic year  2014 – 2015
Education  Architecture, building and planning
Faculty  Structural Design
Mail address  i.selek@student.tue.nl

Publication:

Version  Final colloquium
Date  15-10-2015
Place  Eindhoven

Supervisors:

1st supervisor  prof.ir. S.N.M. (Simon) Wijte
2nd supervisor  prof.dr.ir. T.A.M. (Theo) Salet
3rd supervisor  ir. M. (Maarten) Swinkels
Acknowledgment

Handing in my master thesis is the final step in completing the Master of Science program to become a Structural Engineer at Eindhoven University of Technology. Foremost, I would like to express my sincere gratitude to my graduation committee, namely: prof.ir. Simon Wijte, prof.dr.ir. Theo Salet and ir. Maarten Swinkels, for their helpful guidance. Writing this master thesis was a rewarding and interesting process, which would not be possible without the help and support of my graduation committee.

Secondly, I would like to thank the five consultants, namely: Theodoor Gijsbers, Mürsel Şahin, Bas Bruins Slot, Ronald van Boekel and Hamid Soori, for measuring and analyzing the specimens. This research would not be possible without reinforced concrete specimens. Therefore, I would like to thank Dikkerboom Betonbroing B.V. and Hurks Prefabbeton B.V. for providing reinforced concrete specimens. I also want to thank Julia Zanona and Niels Arendsen from Hilti for their time and sharing their experiences and knowledge with me.

Finally, I would like to thank SGS Intron for the continuous support, interest and immense knowledge during my graduate internship period. I would also like to thank my friends and family for their support during this challenging and stressful period.
Abstract

In the year 2011, the Netherlands was shocked by a disaster in the city Leeuwarden. One of the cantilevered reinforced concrete gallery plates of the Antillenflat collapsed due to the higher external loading than calculated, less accurate construction and corrosion of the rebar’s. After the Antillenflat disaster, many other apartments, mainly built in the period 1950 – 1970, with cantilevered reinforced concrete gallery plates are considered as hazardous in the Netherlands. These hazardous gallery plates are mainly inspected for the cover depth and rebar diameter with the use of non-destructive testing methods.

The graduation project provides information about the reliability of non-destructive testing methods by determining the amount of rebar’s, cover depth and rebar diameter in existing concrete structures. Analyzing the results of the rebar diameter measurements was not unambiguous as was the case with the analysis of the cover depth measurement. There is no guideline given by the manufacturer in order to analyze the rebar diameter measurement results. Therefore, the Block Analysis Method is introduced in the project in order to analyze the rebar diameter measurement results.

Several test cases are measured with the use of the covermeter (Hilti Ferroscan PS200) and the Ground Penetrating Radar (Hilti PS1000). The measured amount of rebar’s were fully in line with the real amount of existing rebar’s. Accuracy of the cover depth measurements were also in line with the given range for accuracy, which is provided by the manufacturer. Furthermore, the accuracy of the cover depth measurements significantly increases when the rebar diameter of the measured structure is known.

Giving an advice for the rebar diameter measurement with the use of the Block Analysis Method results in an accuracy of ±0.36mm, but the standard deviation is 3.06mm. The standard deviations of the rebar diameter measurement results are significantly large, which means that the spread of the measurement results are spread over a large area. This large spread gives the impression of unreliable measurement results. Furthermore, the accuracy of the measurement results decreases when the rebar diameters is larger than or equal to 20mm. Partly destructive testing the measured structure provides substantial local insight into the rebar diameters and cover depth. Combining non-destructive testing with partly destructive testing results in more reliable knowledge about the analyzed structure and increases the reliability of non-destructive rebar diameter measurement results.
The large spread of the measurement results is probably caused by the unexpected effect of concrete on the measurement results. The covermeter creates an electromagnetic field in the reinforced concrete element, measures the disruption of the created electromagnetic field and translates this information to measured cover depth and rebar diameter. Presence of magnetic elements in the concrete element disturbs the created electromagnetic field. Manufacturers of covermeters assumed that only the presence of steel elements effect the disruption of the created electromagnetic field. The influence of the electrical resistivity of concrete on the conduction of the electromagnetic field and the influence of the magnetic permeability of concrete on the disruption of the electromagnetic field are neglected. However, this study gives the impression that the neglected electrical resistivity and magnetic permeability of concrete causes the large spread of the rebar diameter measurement results.
Contents

1. Introduction .................................................................................................................................................. 8
2. Reinforced concrete ........................................................................................................................................ 11
  2.1 Importance of reinforced concrete ............................................................................................................. 11
  2.2 Structural calculation reinforced concrete .................................................................................................. 12
3. Non-destructive testing methods .................................................................................................................... 15
  3.1 Covermeter Testing Method ....................................................................................................................... 16
  3.2 Ground Penetrating Testing Method .......................................................................................................... 19
  3.3 Radiographic Testing Method ..................................................................................................................... 21
4. Devices .......................................................................................................................................................... 23
  4.1 Covermeter Hilti Ferroscan PS200 and GPR Hilti PS1000 ................................................................. 23
  4.2 Measurement preconditions ....................................................................................................................... 24
    4.2.1 Quickscan measurement .................................................................................................................... 25
    4.2.2 Imagescan measurement ................................................................................................................... 28
  4.3 Declared accuracy Hilti Ferroscan PS200 .................................................................................................. 30
5. Analyzing methods ......................................................................................................................................... 32
  5.1 Quick Analysis Method for rebar diameter measurement ........................................................................ 32
  5.2 Block Analysis Method for rebar diameter measurement ........................................................................ 33
  5.3 Line Analysis Method for rebar diameter measurement ........................................................................... 34
6. Test cases ....................................................................................................................................................... 36
  6.1 London City Island ..................................................................................................................................... 37
    6.1.1 Specimen I ......................................................................................................................................... 38
    6.1.2 Specimen II ....................................................................................................................................... 39
    6.1.3 Specimen III ..................................................................................................................................... 40
  6.2 Apartment Eikenstraat Leeuwarden ........................................................................................................... 41
    6.2.1 Specimen IV ..................................................................................................................................... 41
    6.2.2 Specimen V ....................................................................................................................................... 42
  6.3 Parking Garage VI ...................................................................................................................................... 43
    6.3.1 Specimen VI ..................................................................................................................................... 43
  6.4 Antoni van Leeuwenhoek Ziekenhuis ......................................................................................................... 44
    6.4.1 Specimen VII .................................................................................................................................... 44
  6.5 Dikkerboom ............................................................................................................................................... 45
6.5.1 Specimen VIII, IX and X ................................................................. 45

7. Measurement results ........................................................................... 47

7.1 Specimen I ......................................................................................... 48
  7.1.1 Horizontal and vertical rebar diameter with Quick Analysis Method .... 48
  7.1.2 Horizontal and vertical rebar diameter with Block Analysis Method .... 49
  7.1.3 Horizontal and vertical rebar diameter with Line Analysis Method .... 50
  7.1.4 Comparison of Quick, Block and Line Analysis Methods ................. 51
  7.1.5 Concrete cover depth ...................................................................... 53
  7.1.6 Analysis specimen I ........................................................................ 54

7.2 Overview measurement results ............................................................. 55

7.3 Obtained accuracy ................................................................................ 58
  7.3.1 Cover depth measurement accuracy ............................................... 58
  7.3.2 Rebar diameter measurement accuracy .......................................... 59

7.4 Accuracy for Non-European trade size .................................................. 63

7.5 Partly destructive testing ................................................................. 65

7.6 Conclusion ......................................................................................... 66

8. Influence of concrete ........................................................................... 68

8.1 Measuring rebar in the “air” ................................................................. 69

8.2 Influence of surface water ................................................................. 72

9. Conclusions ......................................................................................... 74

10. Recommendations .............................................................................. 76

Bibliography .......................................................................................... 77

Interviews .............................................................................................. 80
1. Introduction

In the year 2011, the Netherlands was shocked by a disaster in the city Leeuwarden. One of the cantilevered reinforced concrete gallery plates of the Antillenflat collapsed. Due to the collapsed gallery plate, four other underlying gallery plates also collapsed. Figure 1.1 presents the damage of the Antillenflat, which is caused by the collapsed gallery plates (VNconstructeurs, 2011). Research published by CUR Bouw & Infra has shown that the collapse of the gallery plate was caused by a combination of inaccurate construction, partial corrosion of the steel rebar’s and a higher external loading on the gallery (De Jonker, Mans, & Wijte, 2012). Figure 1.2 presents the corroded steel rebar’s (Meilink, 2011).

Several bending cracks probably appeared on the collapsed gallery plate during the construction phase of the Antillenflat in 1965. These bending cracks were possibly caused by the temporary storage of building materials on the gallery plate during the construction phase of the building. The weight of the temporarily stored building materials was likely higher than the calculated design load of the gallery plate. These bending cracks occurred exactly in the corner, which is where the gallery plate connects to the building structure. The presence of the bending cracks in the concrete gallery plate has caused the accessibility of water in the gallery plate. Existence of water has caused the corrosion of the steel rebar’s (Meilink, 2011). The consequence of corrosion is that the capacity of the steel rebar’s decreases at the location where corrosion occurs.

Various other gallery plates which are built in the period 1950-1970 are inspected after the disaster by the Antillenflat. This inspection has shown that some of the gallery plates are not constructed according to the design documents. The position of the steel rebar’s in some gallery plates were not in line with the design documents (De Jonker, Mans, & Wijte, 2012). Research by Econstruct BV has shown that the deviant position of the steel rebar’s has also contributed to the collapse of the Antillenflat gallery plate (Meilink, 2011).

Figure 1.1  Damage Antillenflat.  
Figure 1.2  Corroded steel rebar’s.
Figure 1.1 shows that a large amount of the gallery plates of the Antillenflat were still intact after the disaster. However, how safe are these gallery plates? Several gallery flats, mainly build in 1950-1975, are considered as hazardous in the Netherlands ever since 2012. The gallery plates of these gallery flats should be inspected for the amount of rebar and the presence of corrosion on the rebar’s (Rijksoverheid, 2012). The graduation project focuses on inspecting the amount of steel rebar’s, rebar diameter and cover depth of existing concrete structures.

There are two methods for inspecting concrete elements, namely destructive and non-destructive testing methods. Destructive testing is accompanied with partly damaging the concrete element in order to inspect the structure. In contrast to destructive testing, non-destructive testing (NDT) methods are not accompanied with damaging the concrete elements. For the graduation project, the focus will be on non-destructive testing methods.

The demand for non-destructive testing has increased due to the improvement of NDT methods (Gijsbers, 2013, p. 3). It is expected that modern NDT methods will help the engineers to obtain more information of existing concrete structures (Gijsbers, 2012, p. 55). The use of NDT methods seems to be the solution for the analyses of existing concrete structures without damaging. However, obtaining information from NDT methods raises questions about the accuracy.

The primary aim of the master research project is to determine the reliability of non-destructive testing methods by detecting the concrete cover depth, steel rebar diameter and number of steel rebar’s in existing concrete structures. The main research question of the graduation project is the following:

‘What is the reliability of non-destructive testing methods for determining the amount and position of steel rebar’s in existing concrete structures?’

Figure 1.3 Position of steel rebar’s in concrete structures.
The main research question of the graduation project consists of several sub-questions. These sub-questions are as follows:

- What is non-destructive testing (NDT)?
- Which kinds of NDT methods are available for detecting steel rebar in concrete structures?
- Does combining partly destructive testing with non-destructive testing add a significant value on the reliability of the results?

The second aim of this master research project is to incorporate the obtained reliability in the structural safety of existing concrete structures. There are several safety factors for structural calculations. For example, the design value ($R_d$) of the tensile strength of a steel rebar is defined as the characteristic value ($R_k$) divided by a safety factor ($\gamma_s$). Safety factor ($\gamma_s$) of 1.15 is used for calculating the tensile capacity of a steel rebar. This value of the safety factor is determined through experiments and statistical calculations. A similar safety factor, for structural calculations with the results of a non-destructive test, will be elaborated in the graduation project.

Therefore, the second research question of the graduation project is the following:

‘How can the obtained reliability be incorporated in structural calculations of existing concrete structures?’
2. Reinforced concrete

Concrete is composed of a mixture of four elements, namely cement, sand, gravel and water. The mixture ratio of these four elements depends on the required durability and capacity of the concrete element. Structural concrete also contains reinforcement in the composition and is called reinforced concrete. Concrete has a high compressive strength and a low tensile strength. The tensile strength of concrete is approximately 10% of the compressive strength. Tensile stresses could occur in structural concrete elements, due to external tension forces and moments and therefore reinforcement is needed to withstand the occurred tensile stresses in structural concrete elements.

Placing steel rebar’s at the locations where tensile stresses can occur in concrete structures is the most commonly used method. The tensile strength of steel is around seven times higher than the tensile strength of concrete. Using steel rebar’s in concrete elements results in a stronger concrete structure. The importance of reinforcing concrete structures will be explained in the next paragraph.

2.1 Importance of reinforced concrete

A concrete beam supported on two edges could deflect due to the bending moment caused by the loading of a standing human. Figure 2.1 presents the sketch of this situation. Figure 2.2 presents the beam section on the left side and the stress diagram of the beam on the right side. The stress diagram shows that compression stresses occur on the upper half and tensile stresses occur on the lower half of the beam section due to the deflection. When the occurring tensile stress exceeds the tensile strength of the concrete, then the beam will collapse. The use of reinforcement in the beam of figure 2.1 is essential in order to prevent the collapse of the beam, which is caused by exceeding the tensile strength of concrete.
Steel rebar’s should be applied on the bottom of the beam to improve the tensile capacity. In the case of a concrete beam that is reinforced with steel rebar’s, most of the tensile stresses are carried by the steel rebar’s after exceeding the tensile strength of concrete. Due to safety reasons, the tensile strength of concrete is neglected in structural calculations of the bearing capacity of reinforced concrete structures.

Figure 2.3 Reinforced concrete beam supported on two edges.

Figure 2.4 Section (left) and stress diagram (right).

Figure 2.3 presents the same beam of figure 2.1, but now with steel rebar’s on the bottom of the concrete beam. Figure 2.4 presents the section of the beam with reinforcement on the left side and the stress diagram of the section on the right side. The moment capacity of the reinforced concrete beam depends mostly on the steel grade of the rebar, rebar diameter, the amount of rebar’s and the cover depth of the beam. Reliability of NDT methods for obtaining information about the rebar diameter, amount of rebar’s and cover depth of existing concrete structures will be investigated in the graduation project.

### 2.2 Structural calculation reinforced concrete

Rules for the structural design of buildings and other civil engineering works are developed by the European Committee for Standardisation and called the Eurocodes. Rules for structural design of concrete structures are included in Eurocode 2. However, Eurocode 2 does not yet contain information about analyzing of existing concrete structures.

The graduation project focuses on the reliability of NDT methods for detecting the concrete cover depth, steel rebar diameter and number of steel rebar’s in existing concrete structures. The concrete cover depth is the distance from the surface of the concrete element to the surface of the rebar’s. The importance of the thickness of the concrete cover depth, rebar diameter and number of rebar’s for the capacity of reinforced concrete structures will be described with the use of formula 2.1.
The bending moment resistance of a reinforced concrete beam and slab is defined as:

$$M_{rd} = A_s \cdot F_{yd} \cdot z$$  \hspace{1cm} (2.1)

Where:

- $M_{rd}$ - design value of the bending moment resistance [N·mm]
- $A_s$ - surface area of steel rebar [mm$^2$]
- $F_{yd}$ - design value yield strength steel rebar [N/mm$^2$]
- $z$ - internal lever arm (see figure 2.5) [mm]

Design value of the yield strength of the steel rebar depends on the used steel quality. Frequently used steel rebar in contemporary concrete structures is FEB500 with a design value for the yield strength of 435 N/mm$^2$.

Figure 2.5 presents the stresses in a simple reinforced concrete beam (Braam & Lagendijk, 2008). In figure 2.5 it can be seen that the value of the internal lever arm $(z)$ partly depends on the effective height $(d)$. The global value of the internal lever arm can be estimated as (Braam & Lagendijk, 2008):

$$z = 0.9 \cdot d$$  \hspace{1cm} (2.2)

The effective height $(d)$ of the structure from figure 2.5 is as follows:

$$d = h - c - \frac{1}{2} \cdot \varnothing$$  \hspace{1cm} (2.3)

Where:

- $h$ - total height of the structure [mm]
- $c$ - concrete cover depth of the structure [mm]
- $\varnothing$ - diameter of the steel rebar [mm]

![Figure 2.5](image_url)  \hspace{1cm} Stresses in a concrete block.
In the case of steel rebar’s with a circular cross-section, the value of the surface area \( A_s \) is defined as:

\[
A_s = n \cdot 4 \cdot \pi \cdot \varnothing^2
\]  

(2.4)

Where:

- \( n \) - amount of steel rebar’s in the structure  
- \( \varnothing \) - diameter of the steel rebar

Combining the equation 2.1 to 2.4 results as follows:

\[
M_{rd} = n \cdot 4 \cdot \pi \cdot \varnothing^2 \cdot F_{yd} \cdot 0.9 \cdot (h - \zeta - \frac{1}{2} \cdot \varnothing)
\]  

(2.5)

The underlined values in equation 2.5 are the values, which will be determined with the use of NDT methods. Equation 2.5 shows the importance of the accuracy of the used NDT methods by detecting the amount and position of the steel rebar’s in order to determine the bending moment resistance of the reinforced concrete structure. Especially, accuracy of the detected steel rebar diameter is of great importance due to the fact that the diameter is squared in the formula.
3. Non-destructive testing methods

Non-destructive testing methods are techniques for inspecting structures without damaging or destroying parts of the structure. The main goal of the research is to determine the reliability of NDT methods by obtaining information about the cover depth, amount of rebar’s and diameter of the rebar’s in existing concrete structures. There are several NDT methods for analyzing existing concrete structures, but not all of these methods are able to determine information about the reinforcement. Table 3.1 presents the most common NDT methods and the field of use for concrete structures (The International Atomic Energy Agency, 2002).

Table 3.1 Most common NDT methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Field of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>Observing geometry and surface condition of the structure.</td>
</tr>
<tr>
<td>Half-cell electrical potential</td>
<td>Detecting the corrosion potential in reinforced concrete.</td>
</tr>
<tr>
<td>Rebound hammer</td>
<td>Evaluating the surface hardness of concrete.</td>
</tr>
<tr>
<td>Windsor probe</td>
<td>Measuring the surface harness of concrete by using penetration resistance.</td>
</tr>
<tr>
<td>Covermeter testing</td>
<td>Measuring the concrete cover, diameter and location the steel rebar in reinforced concrete.</td>
</tr>
<tr>
<td>Radiographic testing</td>
<td>Detecting discontinuities and obtaining information about the diameter of steel rebar’s, distance between steel rebar’s in reinforced concrete and concrete cover depth.</td>
</tr>
<tr>
<td>Ultrasonic pulse velocity testing</td>
<td>Measuring the compressive strength, cement hydration and dynamic Modulus of Elasticity (E_d) of concrete.</td>
</tr>
<tr>
<td>Impact echo testing</td>
<td>Detecting discontinuities and delamination in concrete.</td>
</tr>
<tr>
<td>Ground penetrating testing</td>
<td>Detecting the position of reinforcement bars in reinforced concrete, measuring the concrete cover depth, measuring the thickness of concrete slabs and beams, localization of voids and detecting delamination’s in concrete structures.</td>
</tr>
<tr>
<td>Infrared thermography</td>
<td>Detecting discontinuities, delamination and water entry points in concrete structures.</td>
</tr>
</tbody>
</table>
As shown in table 3.1, *covermeter testing*, *ground penetrating testing* and *radiographic testing* are the most suited NDT methods for obtaining information about the steel rebar in concrete structures. These three NDT methods will be further described in the next three sub-paragraphs.

### 3.1 Covermeter Testing Method

The used device by the Covermeter Testing Method is called the covermeter. A covermeter makes it possible to measure the cover depth, rebar diameter and to locate the position of the rebar. Most of the covermeter devices are based on the eddy-current principle with pulse-induction (Sivasubramanian, Jaya, & Neelemeegam, 2013). The eddy-current principle is based on electromagnetism. Electromagnetism is the fact that an electrical current flowing through a conductor causes a magnetic field around the conductor (Hellier, 2003). A covermeter measures the disruptions of a generated electromagnetic field. In a reinforced concrete structure, the disruptions of a generated electromagnetic field are caused by the steel elements (Prabakar, Bharathkumar, & Chellappan, 2006). Influence of concrete on the disruption of the electromagnetic field can be neglected (Zanona, 2015). The covermeter translates the measurements in such a way that it is possible to obtain information about the rebar location, rebar diameter and cover depth (Swinkels, 2001).

![Measurement principle covermeter](image)

**Figure 3.1** Measurement principle covermeter (Hilti, 2014).

The modern covermeters are portable devices, which make the use of the covermeter more attractive. Measurements with the covermeter can be easily operated by a trained worker (Shohet, Wang, & Warszawski, 2001). Due to the development in the techniques and required software for covermeters, it becomes easier to perform measurements on a large concrete surface (Swinkels, 2001). Modern covermeters are also able to immediately present the measurement results in graphs with the use of a portable monitor. Information about the concrete cover depth and the steel rebar can be determined by using these graphs or with the use of the attached software of the covermeter.
In the case of a concrete structure with rebar’s in more than one layer, the obtained information of the covermeter about the rebar’s becomes inaccurate. The presence of steel or iron elements, other than reinforcement bars, close to the covermeter disrupts the created magnetic field and this can lead to inaccurate measurement of the rebar diameter (Shohet, Wang, & Warszawski, 2001).

Sivasubramanian, Jaya and Neelemegam (2013) have conducted an experimental research in order to determine the accuracy of the Covermeter Testing Method by obtaining information about the rebar diameter and cover depth in high strength concrete. During the experimental research, several measurements with covermeter (Proceq Profometer 4) were carried out on ten high strength concrete specimens. The specimen’s differ from each other in the used rebar diameter and cover depth.

The diameter of the used rebar’s in the specimens are 12, 16, 20, 25 and 32 millimeters. The cover depths of the specimens are 50mm or 100mm. Figure 3.2 presents on the left a specimen with a cover depth of 50mm and on the right side a specimen with a cover depth of 100mm (Sivasubramanian, Jaya, & Neelemegam, 2013).

![Figure 3.2](image)

According to the experimental research by Sivasubramanian, Jaya and Neelemegam (2013), the accuracy of the covermeter, by measuring the rebar diameter, decreases when the cover depth increases. Table 3.2 presents the rebar diameter accuracy table of Sivasubramanian, Jaya and Neelemegam (2013). Table 3.2 shows that both cover depth and steel rebar diameter affect the accuracy of the covermeter. The accuracy of the covermeter, when detecting a rebar with diameter of 32mm in a high strength concrete structure with cover depth of 50mm, is 98.75%. By decreasing of the rebar diameter to 16mm in a high strength concrete structure with cover depth of 50mm, the accuracy of the covermeter decreases to 88.12%.
Table 3.2 also presents that the rebar diameter is not detectable for the covermeter by a cover depth of 100mm. Furthermore, the rebar was not detectable for the covermeter in the specimen with cover depth of 50mm and rebar diameter of 12mm.

Table 3.2  Accuracy of the covermeter by detecting the rebar diameter.

<table>
<thead>
<tr>
<th>Actual rebar diameter [mm]</th>
<th>Cover depth [mm]</th>
<th>Detected rebar diameter [mm]</th>
<th>Error in detection [%]</th>
<th>Accuracy [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>50</td>
<td>32.4</td>
<td>1.25</td>
<td>98.75</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>25.6</td>
<td>2.40</td>
<td>97.60</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
<td>27</td>
<td>35.00</td>
<td>65.00</td>
</tr>
<tr>
<td>16</td>
<td>50</td>
<td>17.9</td>
<td>11.88</td>
<td>88.12</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>ERROR</td>
<td>100.00</td>
<td>0.00</td>
</tr>
<tr>
<td>32</td>
<td>100</td>
<td>ERROR</td>
<td>100.00</td>
<td>0.00</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>ERROR</td>
<td>100.00</td>
<td>0.00</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>ERROR</td>
<td>100.00</td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
<td>ERROR</td>
<td>100.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

If the cover depth of the measured structure is known, then the rebar diameter measurement becomes more accurate (Algernon, Hiltunen, Ferraro, & Ishee, 2010). The cover depths of the specimens were known in the experimental research of Sivasubramanian, Jaya and Neelemegam (2013). If the cover depths were not known, then the accuracy of the measurements in table 3.2 are expected to become lower. The British Standard 1881 (Testing concrete part 205) suggests that the accuracy of covermeter devices, by obtaining information about the cover depth of a concrete structure with cover depth less than 100mm, is the greatest value of 15% or 5mm (Shohet, Wang, & Warszawski, 2001).

In the graduation project the Covermeter Testing Method is used for measuring the cover depth, rebar diameter and the number of rebar’s in existing reinforced concrete structures.
3.2 Ground Penetrating Testing Method

The used device by the Ground Penetrating Testing is called the ground penetrating radar (GPR). The GPR generates electromagnetic energy pulses and sends the pulses through a transmitter antenna to the object that has to be inspected. The pulse gets reflected from the particles in the object. The reflected pulses are collected by the GPR with the use of a receiver antenna. The monitor of the GPR translates the data of the received pulse into a graph (Hasan & Yazdani, 2014). The basic principle of a GPR is given in figure 3.3 (Breysse, 2012). Figure 3.4 presents an example of a mobile GPR for analysis of concrete roads or concrete bridges (Hasan & Yazdani, 2014).

![Figure 3.3 Basic principle GPR.](image1)

![Figure 3.4 Mobile GPR.](image2)

Steel elements reflect the penetrated electromagnetic pulse completely (Swinkels, 2001). The GPR is widely used as a detector for metal elements in soil. GPR can also be used for detecting the position of the steel rebar’s at the top layer of a concrete structure, estimating the cover depth, measuring the thickness of concrete beams and slabs, localization of voids in concrete structure and detecting of delamination’s in concrete structures (Wiggenhauser, 2009).

The simplicity of the GPR is the biggest advantage of the Ground Penetrating Testing Method. People without precognition of the device can easily use the GPR. The data of the measurements are saved by the GPR and can be retrieved on a computer at a later stage in the experiment (Lim & Cao, 2011). Powerful computer systems are available to handle large amounts of data (Wiggenhauser, 2009). The possibility to store the measurement data and the mobility of the most GPR’s makes it possible to analyze large areas in a short period of time (Lim & Cao, 2011).
The data saved by the GPR can be very complicated to analyze (Lim & Cao, 2011). Therefore, a person with knowledge of ground penetrating testing is required in order to analyze the obtained data from the measurements with the GPR. The relationship between the reflected electromagnetic energy pulse and the information about the analyzed object is in many cases not straightforward (Breysse, 2012). In some cases, additional information such as design documents of the object is required to support the interpretation of the data (Breysse, 2012). When the design documents are missing, the information obtained by the GPR could be very inaccurate.

The accuracy of the GPR largely depends on the moisture content of the concrete structure. Presence of water in the concrete causes disruptions in the measurement results, due to reflection of the penetrated electromagnetic pulse by water (Lim & Cao, 2011). Therefore, the concrete structure must be completely hardened in order to perform measurements with the GPR. Furthermore, obtaining information about the surface under the steel rebar’s in reinforced concrete elements is not possible (The International Atomic Energy Agency, 2002). This is caused by the fact that the steel rebar completely reflects the penetrated electromagnetic pulse of the GPR. The penetrated electromagnetic pulse does not reach the layer under the rebar.

The Ground Penetrating Testing Method is in the graduation project used for measuring the number of rebar’s in existing reinforced concrete structures. As mentioned before, number of rebar’s in concrete structures can also be measured with the Covermeter Testing Method. The contemporary covermeters can only detect rebar’s up to a depth of about 100mm while the contemporary GPR’s are able to detect rebar’s up to a depth of 300mm (Hilti, 2014). Therefore, the GPR is mainly used in the graduation project in order to compare the measured amount of rebar’s with the results of the covermeter and to visualize the different rebar layers in the concrete elements.
3.3 Radiographic Testing Method

Radiographic Testing Method uses very short wavelength electromagnetic radiation, namely X-rays or gamma-rays. The difference between X-rays and gamma-rays is that X-rays are produced by an X-ray tube and gamma-rays are produced by radioactive sources (Hellier, 2003). The method penetrates X-rays or gamma-rays through a solid material. Part of the penetrated X-rays or gamma-rays will be absorbed by the radiated medium. The radiation that passes through the medium will be detected and monitored by electronic sensing device at the other side of the medium (McCann & Forde, 2001). The amount of absorbed X-rays or gamma-rays by the concrete structure depends on the quality of the radiated X-rays or gamma-rays, the thickness of the structure and the density of the concrete (The International Atomic Energy Agency, 2002).

Radiographic Testing Method is a method with a large field of use. For example, the method is frequently used in healthcare for making radiographs in order to analyze the internal body of a human. In the matter of non-destructive testing of concrete structures, the method can be used for estimating the cover depth, determining the rebar location in reinforced concrete structures, estimating the rebar diameter and evaluating of the concrete condition (Shohet, Wang, & Warszawski, 2001).

The Radiographic Testing Method is not often used in the Netherlands because of the fact that the method is time consuming (Swinkels, 2001). There are Radiographic Testing Methods with more powerful radiation sources that are not time consuming. However, these methods are banned in the Netherlands because of the health risk that radiation has on the performer (Swinkels, 2001). Using the Radiographic Testing Method is in any case harmful to human health. Radiographic devices are even harmful to human health when it is transported or stored (Vink & Brekel, 2009).

The test setup of the Radiographic Testing Method is important to get accurate results from the measurements. Figure 3.5 presents a typical test setup of the Radiographic Testing Method. The application of the setup requires 60% of the inspection time (Vink & Brekel, 2009). Using the Radiographic Testing method requires a significant amount of knowledge from the performer (Swinkels, 2001). The concrete surface needs to be radiated for a long time to get information about the radiated particle. The implementation of this method is expensive when large areas need to be analyzed (Breysse, 2012).
The concrete structure should be accessible on two sides in order to penetrate X-rays or gamma-rays on one side and to receive the non-absorbed X-rays or gamma-rays on the other side (Gamidi, 2009). It is important to be aware of the influence of the structure thickness has on the accuracy. According to the research of Gamdi (2009), the accuracy of the Radiographic Testing Method decreases when the thickness of the structure is increased. Penetration of gamma-rays through concrete structures is limited by a thickness of 600mm, but x-rays can be penetrated through a concrete thickness of 1200mm (Breysse, 2012).

![Diagram of Radiographic Testing Method](image)

**Figure 3.5**  Test set up Radiographic Testing Method (Central Federal Lands Highway, 2015).

Radiographic testing method is rarely used in the Netherlands for doing non-destructive tests on concrete structures. The use of this method is time consuming, harmful for the users health and very expensive. Therefore, this method is not considered in the graduation project.
4. Devices

The Covermeter Testing Method and the Ground Penetrating Testing Method are used in the graduation project. In practice, these two methods are often used in combination in order to analyze concrete structures. The covermeter PS200 of Hilti and the GPR PS1000 of Hilti are used for the measurements of the graduation project.

4.1 Covermeter Hilti Ferroscan PS200 and GPR Hilti PS1000

The Ferroscan PS200 of Hilti is used for measuring the concrete cover depth, rebar diameter and number of rebar`s in the concrete structures. The monitor PSA100 of Hilti is used for monitoring the measurements of the Ferroscan PS200. Ferroscan and the monitor are connected with each other with the infrared connector. Infrared connection between the two devices makes it possible to easily load the measurements of the Ferroscan on the monitor.

The GPR PS1000 of Hilti is used for measuring the number of rebar’s in the concrete structures. Hilti PS1000 is able to detect rebar’s in different layers up to a depth of 300mm in concrete structures. By combining the GPR PS1000 with the monitor PSA100, it is possible to visualize the measurement results in 2D or 3D view. The GPR of Hilti is not suited to measure the rebar diameter in concrete structures, but it is possible to make a rough estimation of the rebar diameter and cover depth by looking at the graphs on the monitor.

---

Figure 4.1  Hilti Ferroscan PS200 and Hilti monitor PSA100 (Hilti, 2014).

Figure 4.2  Hilti Radar PS1000 and Hilti monitor PSA100 (Hilti, 2014).
4.2 Measurement preconditions

There are two different types of measurements possible with the Hilti Ferroscan PS200, namely the quickscan and the imagescan measurement. Quickscan measurement makes it possible to obtain information about the measured cover depth and number of rebar’s. Imagescan measurement makes it possible to obtain information about the number of rebar’s and rebar diameter. Several preconditions are given by Hilti in order to obtain reliable cover depth and rebar diameter measurement results. For reliable scanning results, the following precondition must be fulfilled (Hilti, 2013):

- Concrete surface smooth and flat.
- Reinforcement in reinforced concrete not corroded.
- Reinforcement lying parallel to concrete surface.
- Concrete does not contain additives or components with magnetic properties, with the exception reinforcement bars.
- Reinforcing bars are not welded.
- Neighboring bars are of similar diameter.
- Neighboring bars are at a similar depth.
- Accuracy specifications are valid only for the first layer of reinforcement.
- No interfering influences from external magnetic fields or objects nearby with magnetic properties.
- Reinforcing bars have relative magnetic permeability of 85-105.
- The Hilti PS200 and PS1000 wheels are clean and free from sand or grit.
- All 4 scanner wheels rotate on when scanner is moved across the object to be scanned.

In addition, the accuracy of rebar diameter measurement depends on the bar spacing (s) and cover depth (c) of the reinforced concrete element. The ratio between bar spacing (s) and concrete cover depth should be at least 2:1. Furthermore, the bar spacing should be at least 36mm and the concrete cover depth should be at least 10mm (Hilti, 2013).

Figure 4.3 Bar spacing (s) and concrete cover depth (c).
If the measurement fulfills all of the above listed preconditions, then the tables 4.1 and 4.2 (see paragraph 4.3) apply. However, some of the preconditions could be unknown if the design documents of the measured element are not available. For example, you don’t know if the diameter of the neighboring rebar’s are the same and if they are at the same depth. Correct use of the device is as important as the above listed preconditions in order to obtain reliable measurement results. The measurements for the graduation project are carried out by consultants with knowledge about the use of the Ferroscan PS200 and GPR PS1000.

4.2.1 Quickscan measurement

Quickscan measurements can easily be performed by rolling the Ferroscan PS200 over the reinforced concrete surface. The quickscan measurement results can be analyzed by using the Hilti Profis software. Figure 4.4 presents a typical quickscan measurement result. The number of blue rods in figure 4.4 gives an indication about the number of rebar’s in the measured area and the center to center distance between the blue rods gives information about the center to center distance of the measured rebar’s.

The height of the blue rods gives information about the measured cover depth. Value of the measured cover depths could be read on the screen or could be exported as a CSV file and opened with Microsoft Excel on the computer.

Figure 4.4 Quickscan measurement result.
First step by measuring the cover depth of a concrete structure is to determine the location to measure. Subsequently, the consultant will search for design documents of the element which will be measured and analyzed by this consultant. The presence of the design documents makes it possible to compare the non-destructive testing results with the information in the design documents. However, it could be the case that the design documents of the structure are missing. If the design documents are missing, than the structure should be partly demolished in order to obtain information about the real rebar diameter and real cover depth of the structure. Information about the real rebar diameter is of big importance for the cover depth measurements, because the accuracy of the quickscan measurement increases by a known rebar diameter (Hilti, 2013).

The second step is to determine if the real cover depth of the structure fulfils the minimum requirement. Real cover depth of the structure must be at least 10mm. Furthermore, the surface of the element should be smooth in order to roll the Ferroscan PS200 over the surface (Hilti, 2013). If the element does not fulfill one of these two requirements, than a non-metallic intermediate element could be used in order to enlarge the cover depth or to make the surface of the element smooth. Figure 4.5 presents a rough concrete surface with a non-metallic intermediate element. Cover depth of all specimens of the graduation project were larger than 10mm and also the surface of all elements were smooth. Therefore, all measurements are directly carried out on the concrete element without an intermediate element.

The last step before carrying out the measurement is to determine the starting and ending point of the Ferroscan PS200. Both starting and ending point of the Ferroscan PS200 must not on a rebar. The Ferroscan PS200 is programmed for starting and ending the measurement not on a rebar. If the measurement starts or ends on a rebar, than the device starts or ends up in a situation where it is not programmed for and this will influence the measurement results of the device. These three steps are checked for all measurements of the graduation project. The quickscan measurements are only analyzed for structures which satisfies these three preconditions.

![Figure 4.5](image_url) Non-metallic intermediate element on rough surface.
Figure 4.6 presents a flowchart which is used for the quickscan measurements of the project.
4.2.2 Imagescan measurement

Hilti has two grids for the imagescan measurements. The first grid is 600 x 600mm\(^2\) and the second grid is 1200 x 1200mm\(^2\). Figure 4.7 presents the 600 x 600mm\(^2\) grid. Both grids contain squares of 150 x 150mm\(^2\). These squares are a tool for the starting point of the imagescan measurement. Figure 4.8 shows how the Ferroscan PS200 must be placed on the grid. The Ferroscan must be rolled over all the horizontal and vertical starting points in order to obtain information about the rebar’s (Hilti, 2013).

Figure 4.7 Hilti grid 600 x 600mm\(^2\).

Figure 4.8 Ferroscan PS200 on grid.

Figure 4.9 presents a typical 600 x 600mm\(^2\) imagescan measurement result.

Figure 4.9 Imagescan measurement result.
Figure 4.10 presents the flowchart for rebar diameter measurements which is used in the graduation project.
4.3 Declared accuracy Hilti Ferroscan PS200

Accuracy of the Hilti Ferroscan PS200 depends on the known parameters of the specimen. When the rebar diameter of the reinforced concrete element is known the accuracy of the Ferroscan PS200, when measuring the cover depth, is higher than when the rebar diameter is not known. The same applies when the rebar diameter is measured with the covermeter. If the cover depth is known, then the accuracy of the covermeter is higher than when the cover depth is unknown (Algernon, Hiltunen, Ferraro, & Ishee, 2010). However, both rebar diameter and cover depth could be unknown in reality if the detail drawings of the reinforced concrete element are not available. Therefore, the rebar diameter and cover depth of the specimens are assumed as unknown in the graduation project.

The accuracy of the Hilti Ferroscan PS200 is given in the manual of the device. Table 4.1 presents the accuracy of the Hilti Ferroscan PS200 by measuring the concrete cover depth of a reinforced concrete structure with unknown steel rebar diameter (Hilti, 2013).

<table>
<thead>
<tr>
<th>Rebar diameter [mm]</th>
<th>Concrete cover depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>± 2</td>
</tr>
<tr>
<td>8</td>
<td>± 2</td>
</tr>
<tr>
<td>10</td>
<td>± 2</td>
</tr>
<tr>
<td>12</td>
<td>± 2</td>
</tr>
<tr>
<td>14</td>
<td>± 2</td>
</tr>
<tr>
<td>16</td>
<td>± 2</td>
</tr>
<tr>
<td>20</td>
<td>± 2</td>
</tr>
<tr>
<td>25</td>
<td>± 2</td>
</tr>
<tr>
<td>28</td>
<td>± 2</td>
</tr>
<tr>
<td>30</td>
<td>± 2</td>
</tr>
<tr>
<td>36</td>
<td>± 2</td>
</tr>
</tbody>
</table>

The accuracy of the cover depth measurement is given in mm.

0: Rebar is detectable for the device but the concrete cover depth cannot be measured.

X: Rebar cannot be detected at this depth.
Hilti does not give detailed information about the accuracy of the Ferroscan PS200 when measuring the rebar diameter in reinforced concrete elements. Table 4.2 presents the accuracy of the Hilti Ferroscan PS200 by measuring the rebar diameter (Hilti, 2013). Table 4.2 presents the accuracy of the rebar diameter measurement in so-called European trade sizes. European trade sizes for steel rebar diameters are given as: 6, 8, 10, 12, 14, 16, 20, 22, 25, 28, 32 and 40mm (Hilti, 2013). For example, by measuring a reinforced concrete element with rebar diameter of 20mm and cover depth of 20mm the result of the rebar diameter could be 16mm, 20mm or 25mm.

The so-called European trade sizes for steel rebar’s are actually conventional trade sizes, because there is not a European norm for steel rebar sizes. In addition to the so-called European trade sizes, there are also other rebar sizes used in the Netherlands. Some reinforced concrete gallery plates, mainly build in the period of 1950-1970, contain reinforcement meshes of ∅7 or ∅9mm. This raises questions about what the device gives as result by measuring a concrete structure with rebar diameter of ∅7 or ∅9mm.

Table 4.2 Accuracy of Hilti Ferroscan PS200 by measuring rebar diameter.

<table>
<thead>
<tr>
<th>Rebar diameter [mm]</th>
<th>Concrete cover depth [mm]</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>16</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>20</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>25</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>28</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>30</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
<tr>
<td>36</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>± 1</td>
<td>X</td>
</tr>
</tbody>
</table>

The accuracy of the rebar diameter measurement is given in European trade sizes.

X: Rebar cannot be detected at this depth.
5. Analyzing methods

Measurement preconditions for covermeter devices are provided in the manual of these devices. Nevertheless, information about how to analyze the cover depth and rebar diameter measurement results is not given in the manual and in addition there is no protocol in the Eurocode. This leads for a lot of confusion by the consultants, because there is not one method for analyzing the measurement results. Therefore, several test cases are measured in cooperation with several NDT consultants from three different companies, namely SGS Intron, BAS Research & Technology and Bartels in order to obtain information about the analyzing methods for cover depth and rebar diameter measurements that are used in practice.

The used test cases are analyzed by the consultants for the existing amount of rebar’s, diameter of the rebar’s and the cover depth of the reinforced concrete elements. Analyzing the amount of existing rebar’s and the cover depth measurement results is unambiguous according to the manual of the Ferroscan PS200 (Hilti, 2013). However, each consultant has their own method when analyzing the rebar diameter measurements. Remarkable is that most of the organizations for NDT measurements do not have internal guidelines for these analysis. It could be the case that two consultants which are working for the same company use different methods for analyzing the rebar diameter measurement results.

The following rebar diameter measurement analyzing methods are introduced in the graduation project and further discussed in this chapter:

- Quick Analysis Method
- Block Analysis Method
- Line Analysis Method

5.1 Quick Analysis Method for rebar diameter measurement

Quick Analysis Method is the fastest method to analyze the measurement results. Rebar diameter measurements are carried out with the use of a covermeter. The portable monitor of the used covermeter makes it possible to see the measurement results directly without the use of a computer. The navigation tool of the monitor makes it possible to read the diameter of the detected steel rebar’s. The consultant provides advice about the steel rebar diameter by looking up the smallest measured rebar diameter. This method is a time-saving and conservative method.
5.2 Block Analysis Method for rebar diameter measurement

A typical covermeter device contains multiple coils in order to create an electromagnetic field. The receivers of the covermeter device measure the disruption of the created electromagnetic field. The Ferroscan PS200 contains seven coils and five of the seven coils have a receiver to measure the disruption of the created electromagnetic field. The outer two coils are needed in order to create a strong electromagnetic field (Hilti, 2014). Each coil of the Ferroscan PS200 separately assigns a diameter to the measured piece of the rebar. This means that the steel rebar measurements consist of multiple blocks.

Figure 5.1 shows a typical rebar diameter measurement with multiple blocks. There are two different types of blocks, which are the verified (blue) and not verified (lime) blocks. The measured diameters of the blue blocks are more reliable than the diameters of the lime blocks (Hilti, 2014). The PC-software of Hilti makes it possible to obtain information about each measured block diameter. Block Analysis Method makes a distinction between the measured diameter of the horizontal and vertical steel rebar’s. The diameter of each horizontal and each vertical rebar is assumed as the same. For example, diameter of rebar A from figure 5.1 is assumed as the same diameter as rebar B. In practice, this will probably be the case for most of the reinforced concrete elements.

The consultant can provide advice about the rebar diameter by looking up the median of the measured blue block diameters in the horizontal and vertical directions. Another option is to give advice by using the average value of the horizontal and vertical measured blue block diameters. The Block Analysis Method is more time consuming and therefore more expensive than the Quick Analysis method. Nevertheless, this method provides significantly more information about the spread of the measured rebar diameters.
5.3 Line Analysis Method for rebar diameter measurement

The Line Analysis Method also makes use of the blue blocks in order to provide advice about the rebar diameter. In comparison with the Block Analysis Method, Line Analysis method does not assume the same diameter for each horizontal or vertical steel rebar. For example, diameter of rebar A from figure 5.2 is assumed as different as diameter of rebar B. This method considers each rebar separately. The measurement of figure 5.2 consists of three horizontal and three vertical steel rebar’s.

Each rebar consists of several measured block diameters. The consultant can provide advice about the steel rebar diameter, for each steel rebar separately, by looking up the median of the measured blue block diameters in the direction of the corresponding rebar. It is also possible to provide advice by calculating the mean value of the measured blue block diameters of each steel rebar separately. The Line Analysis Method is particularly relevant for reinforced concrete structures in which different steel rebar diameters are expected or measured.

![Figure 5.2](image)

**Figure 5.2**  Rebar diameter measurement of two horizontal and two vertical steel rebar’s.
Figure 5.3 presents a flowchart for analyzing the imagescan measurement results. Only Line Analysis Method and Block Analysis Method are included in the flowchart. Quick analysis method is not included in the flowchart, because it is a conservative method.

**Figure 5.3** Flowchart for imagescan (rebar diameter) measurement analysis.
6. Test cases

Several measurements are carried out in order to determine the reliability of the covermeter testing method and the ground penetrating testing method by obtaining information about the existing amount of rebar’s, rebar diameters and cover depth in existing concrete structures. Reinforced concrete test cases are used in order to perform measurements with the covermeter (Hilti PS200) and the GPR (Hilti PS1000). The measurements are collaborated in cooperation with SGS Intron, BAS Research & Technology and Bartels. Table 6.1 presents a list of the used test cases. The measurement results of the test cases are further discussed in chapter six of the graduation project.

Table 6.1 Test cases

<table>
<thead>
<tr>
<th>Project name</th>
<th>Type of element</th>
<th>Number of elements</th>
<th>Used devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>London City Island</td>
<td>Prefabricated wall</td>
<td>3</td>
<td>Hilti PS 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hilti PS 1000</td>
</tr>
<tr>
<td>Apartment Eikenstraat Leeuwarden</td>
<td>Cantilevered gallery plate</td>
<td>2</td>
<td>Hilti PS 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hilti PS 1000</td>
</tr>
<tr>
<td>Parking garage VII</td>
<td>Floor</td>
<td>1</td>
<td>Hilti PS 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hilti PS 1000</td>
</tr>
<tr>
<td>Antoni van Leeuwenhoek Ziekenhuis</td>
<td>Chemotherapy room wall</td>
<td>1</td>
<td>Hilti PS 200</td>
</tr>
<tr>
<td>DikkerBoom</td>
<td>Reinforced concrete specimens</td>
<td>3</td>
<td>Hilti PS 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hilti PS 1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GSSI SIR-4000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Prosec PM-6</td>
</tr>
</tbody>
</table>

1) The covermeter Proseq PM-6 and radar GSSI SIR-4000 are only used in order to compare the measurement results of the Hilti devices.
6.1 London City Island

London City Island is a riverside development in London. Hurks is involved in the project as the manufacturer of the prefabricated concrete wall elements for the concrete towers. The concrete wall elements of the towers are prefabricated in the factory of Hurks in the Netherlands. Three concrete walls are used as test cases for the graduation project.

The detail drawings of the three test cases are included in annex A of the graduation project. A detail drawing provides information about the position, amount and diameter of the included steel rebar’s in the concrete wall elements. Detail drawings of the elements are checked in the construction phase on February 27, 2015. The diameter of the steel rebar’s are measured with the use of a caliper and the amount of steel rebar’s in the wall elements are counted. Furthermore, the center-to-center distance of the steel rebar’s and the concrete cover depth of the wall elements are measured with the use of a tapeline.

Finally, the measurements are compared with the detail drawings. The steel rebar diameters and the amount of steel rebar’s in the detail drawings were completely in accordance with reality. Measurements of the concrete cover depth and the center-to-center distance of the steel rebar’s were not in accordance with the detail drawing. However, the deviation between measurements and values of the detail drawings were ± 2 mm. Therefore, the values of the concrete cover depth and center to center distance of the steel rebar’s are assumed as correct.
6.1.1 Specimen I

Specimen I is a solid reinforced concrete partition wall. The wall is reinforced with the use of two mesh reinforcements placed in two different layers. Figure 6.4 presents the detail drawing of the double block reinforcement of specimen I. The two mesh reinforcements are bundled with the use of steel stirrups. Figure 6.5 presents the front elevation of specimen I. There are five rubber grout tubes placed in the element. Figure 6.5 also presents the measured area of the element. The measurements are carried out on the pour side of the element. Surface of the measured area is 1200 x 1200 mm².

Figure 6.4  Detail drawing.  Figure 6.5  Front elevation specimen I.

Figure 6.6 presents the detail drawing of the measured area of specimen I. The detail drawing, on scale, is also included in annex A. The real cover depth of the measured area is 30mm.

Figure 6.6  Detail drawing measured area specimen I.
6.1.2 Specimen II

Specimen II is also a solid reinforced concrete partition wall. The wall is reinforced with the use of two mesh reinforcements placed in two different layers and steel stirrups. There are four rubber grout tubes placed in the element. Figures 6.7 and 6.8 present the measured area of the element. The measurements are carried out on the smooth side of the element. The surface of the measured area is 1200 x 1200 mm².

Figure 6.7 Measured area. Figure 6.8 Front elevation specimen II.

Figure 6.9 presents the detail drawing of the measured area of specimen II. The detail drawing, on scale, is also included in annex A. The real cover depth of the measured area is 30mm.

Figure 6.9 Detail drawing measured area specimen II.
6.1.3 Specimen III

Specimen III is the inner skin of a cavity wall. The wall could also be interpreted as a portal structure. The wall is reinforced with the use of two mesh reinforcements placed in two different layers and steel stirrups. There are two rubber grout tubes placed in each “column” of the element. The measurements are carried out on the pour side of the element. Surface of the measured area is 600 x 600 mm².

Figure 6.10  Measured area.  Figure 6.11  Front elevation specimen III.

Figure 6.12 presents the detail drawing of the measured area of specimen III. The detail drawing, on scale, is also included in annex A. The real cover depth of the measured area is 50mm.

Figure 6.12  Detail drawing measured area specimen III.
6.2 Apartment Eikenstraat Leeuwarden

After the Antillenflat disaster, many other apartments, mainly built in the period 1950 – 1970, with cantilevered reinforced concrete gallery plates are considered as hazardous in the Netherlands. Apartment Einkenstraat was built in the year 1964. The cantilevered reinforced concrete gallery plates of the apartment were assessed as “unsafe” and have been removed in the year 2014.

6.2.1 Specimen IV

Two of the removed reinforced concrete gallery plates are used as test case for the project. The gallery plates of the apartment are uncoupled with the use of a concrete saw and raised to the ground. Figure 6.14 presents the third gallery plate, as seen from the staircase, of the seventh floor. The measurements are carried out on the edge of the sawn side.

Information about the rebar diameter, center-to-center distance of the rebar’s, amount of the rebar’s and cover depths of the gallery plate are measured with a roller on the sawn side of the plate.
6.2.2 Specimen V

Figure 6.17 presents the sixth gallery plate, as seen from the staircase, of the seventh floor. If required, both specimen IV and specimen V were allowed to be demolished. The measurements are carried out on the edge of the sawn side. As executed with specimen IV, information about the rebar diameter, center-to-center distance of the rebar’s, amount of the rebar’s and the cover depths are measured with a roller on the sawn side of the gallery plate.

Figure 6.17 Specimen V.

Specimen IV and V are identical gallery plates whereby the detail drawings of these gallery plates are also identical. Figure 6.18 presents the detail drawing of the measured area of specimen IV and V. The detail drawing, on scale, is also included in annex A. The real cover depth of the measured area varies between 40 - 50mm.

Figure 6.18 Detail drawing measured area specimen IV and V.
6.3 Parking Garage VI

The contractor does not allow mentioning the name of the parking garage. Therefore, the project is called Parking Garage VI. The floor of the parking garage consists of a combination of hollow-core and wide cast slabs with reinforced concrete screed. The screed of the parking garage is inspected due to presence of cracks at some locations.

6.3.1 Specimen VI

The screed of the parking garage floor is cracked on many locations and the crack width varies between 0.5 mm and 5.0 mm. Non-destructive and destructive tests are carried out on six different locations of the parking garage floor in order to find out the cause of the cracks. The non-destructive tests for each location are carried out over an area of 600 x 600 mm². By each measured area two destructive cylinder samples are drilled. The cylinder samples are necessary in order to verify the measurements. Information about the real rebar diameter and cover depth are measured on the cylinder samples. However, the cylinder samples are only useable for verifying the measurements of a specific position on the measured area of 600 x 600 mm².

Each non-destructive measurement is verified on two positions with the use of the obtained information from the cylinder samples. This means that only information about twelve specific positions is available for the project. Figure 6.21 presents the detail drawing of the measured area of specimen VI. The real cover depth of the measured area is 40mm.
6.4 Antoni van Leeuwenhoek Ziekenhuis

Antoni van Leeuwenhoek Ziekenhuis is a hospital that is specialized in treatment of cancer patients. The chemotherapy treatments of the patients are carried out in concrete bunkers. The hospital decided to buy a new chemotherapy device. However, this device does not fit through the door of the bunkers. Therefore, an opening had to be cut in the wall of one concrete bunker.

6.4.1 Specimen VII

The thickness of the concrete bunker walls are 1200mm and the thickness of the concrete bunker ceiling is about 1000mm. One of these concrete bunker walls is measured over an area of 1200 x 1200mm². The measured area is sawn in several pieces and this made it possible to obtain information about the rebar’s and cover depths. The rebar diameters are measured with the use of a caliper and the amount of rebar’s in the wall element are counted. Furthermore, the cover depths of the wall elements are measured with the use of a tapeline. The concrete bunker has steel mesh reinforcement in three different layers of the thickness. However, the used covermeter (Hilti PS200) is only able to obtain information about the mesh reinforcement in the first layer. Therefore, only the obtained information about the mesh reinforcement in the first layer is used for the project. Figure 6.21 presents the detail drawing of the measured area of specimen VII. The real cover depth of the measured area varies between 40 - 50mm.
6.5 Dikkerboom

Dikkerboom is specialized in drilling and sawing reinforced concrete elements. The company has often reinforced concrete specimens in order to test the drilling equipment’s. Three of the reinforced concrete specimens of Dikkerboom are used as test cases for the project.

6.5.1 Specimen VIII, IX and X

Dimensions of the reinforced concrete specimens are all the same, namely 1500 x 1000 x 300mm³. The cover depth of the specimens varies between 40 and 50mm, but the steel rebar diameters differ from each other. Measurements are carried out on the top surface over an area of 600 x 600mm² with the use of Hilti PS 200, Hilti PS 1000, Prosec PM-6 and GSSI SIR 4000. The amount of rebar’s, rebar diameter and cover depth were known by Dikkerboom. Each specimen is partly demolished in order to verify the rebar diameter and the cover depth. The specimens should completely be demolished in order to verify the amount of steel rebar’s. However, only partly demolishing the specimens was allowed by Dikkerboom.

Diameter of the visible rebar’s in the demolished part of the specimens and the cover depth are measured with the use of a caliper. The assumption is made that the amount of reinforcement corresponds to the detail drawings of Dikkerboom.
Specimen VIII and IX are identical reinforced concrete elements whereby the detail drawings of these gallery plates are also identical. Figure 6.28 presents the detail drawing of the measured area of specimen VIII and IX. Figure 6.29 presents the detail drawing of the measured area of specimen X. The detail drawings, on scale, are also included in annex A. The real cover depth of the measured area varies between 40-50mm.

Figure 6.28  Detail drawing specimen VIII and IX.

Figure 6.29  Detail drawing specimen X.
7. Measurement results

Probability is the branch of statistics that focuses on studies of randomness and uncertainties. A brief explanation about the probability theory and continuity correction is included in annex B. In any study in which one or a number of possible outcomes may occur, the theory of probability can be used to quantify the chances associated with the various outcomes (Carlton & Devore, 2014). In the project probability is used for the analysis of the measurement results. Hilti Ferroscan PS200 presents the measured rebar diameter according to European trade size for steel rebar diameters. The cover depth and the amount of steel rebar’s are given as integers. Since the measurement results of the graduation project are limited, multinomial distribution is more relevant for the analysis. The multinomial distributions of the measurements are transferred to a continuous normal distribution by using the continuity correction.

Each test case from chapter 6 is in the project analyzed for the obtained information about the amount of rebar’s, rebar diameter and the cover depth. Only the verified blocks of the imagescan are used for the statistical analysis of the rebar diameter measurements. The standard deviation ($\sigma$) and mean value ($\mu$) of the cover depth and rebar diameter measurements are used for analyzing the accuracy of the used NDT methods. The more the mean value of the continuous normal distributions approaches the value of the reality, the more accurate the method is. The standard deviation provides information about the spread of the measurement results. A small standard deviation can be associated with a higher accuracy than a large standard deviation.

![Random Variable Diagram]

**Figure 7.1** Continuity correction.
7.1 Specimen I

Specimen I is in this paragraph used as example in order to show how the rebar diameter and cover depth measurement results are analyzed in the graduation project. The measured area of specimen I consists of a steel mesh reinforcement. Both horizontal and vertical rebar’s of the reinforcement mesh have a diameter of 10mm. Figure 7.1 presents the radar measurement and figure 7.2 presents the rebar diameter measurement of specimen I. Figure 7.2 shows a disturbance of the measurement at Grid A-B, 6-7. The disturbance is caused by two rebar’s that are located close to each other. Hilti Ferroscan PS200 recognizes the two adjacent rebar’s as one single bar. The use of the Ferroscan PS200 is not suitable in the case of a bar spacing smaller than 36 mm. Therefore, the measurement results of this grid are eliminated from the analysis. Rebar diameter measurement of specimen I is analyzed with the Quick, Block and Line Analysis Method in order to substantiate the method which is used in the graduation project.

![Figure 7.1 Radar measurement specimen I.](image1)

![Figure 7.2 Rebar measurement specimen I.](image2)

7.1.1 Horizontal and vertical rebar diameter with Quick Analysis Method

Table C1.1 in annex C presents all measured rebar diameters for specimen I. Smallest measured horizontal and vertical rebar diameters are both 6mm. However, only 5% of all verified block diameters are 6mm. The choice for giving 6mm as advice is of course a very conservative decision. The difference between the real and measured rebar diameter is -4mm for this method.
7.1.2 Horizontal and vertical rebar diameter with Block Analysis Method

Figure 7.3 presents the multinomial distribution of the verified horizontal rebar diameters. The horizontal steel rebar diameter measurement contains 225 verified block diameters. Mean (μ) of the verified horizontal rebar diameters is 11.48mm and the difference with the real diameter is +1.48mm. The standard deviation (σ) is 2.29mm.

Figure 7.3 Multinomial distribution of the horizontal rebar diameter measurement.

Figure 7.4 presents the multinomial distribution of the measured vertical rebar diameters. The mean value of 276 verified block diameters is 11.07mm and the standard deviation (σ) is 1.88mm. The difference with the real diameter is +1.07mm.

Figure 7.4 Multinomial distribution of the vertical rebar diameter measurement.
7.1.3 Horizontal and vertical rebar diameter with Line Analysis Method

Each measured rebar on figure 7.2 must be analyzed separately for the rebar diameter in the Line Analysis method. Rebar diameter measurement of specimen I contains six horizontal and seven vertical rebar’s. All rebar’s are analyzed for the measured mean value ($\mu$), the standard deviation ($\sigma$) and the difference between the mean value and real rebar diameter. Table 7.1 presents an overview of the Line Analysis Method results for the horizontal rebar’s of specimen I.

<table>
<thead>
<tr>
<th>Rebar</th>
<th>Mean value ($\mu$) [mm]</th>
<th>Standard deviation ($\sigma$) [mm]</th>
<th>Difference with reality [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A-B, 1-8)</td>
<td>13.58</td>
<td>2.10</td>
<td>+3.58</td>
</tr>
<tr>
<td>(B-C, 1-8)</td>
<td>12.05</td>
<td>1.64</td>
<td>+2.05</td>
</tr>
<tr>
<td>(C-D, 1-8)</td>
<td>12.00</td>
<td>1.55</td>
<td>+2.00</td>
</tr>
<tr>
<td>(D-E, 1-8)</td>
<td>9.08</td>
<td>2.69</td>
<td>-0.82</td>
</tr>
<tr>
<td>(E-F, 1-8)</td>
<td>10.84</td>
<td>2.32</td>
<td>+0.84</td>
</tr>
<tr>
<td>(F-G, 1-8)</td>
<td>11.75</td>
<td>4.58</td>
<td>+1.75</td>
</tr>
</tbody>
</table>

1) See figure 7.1 and 7.2 for the grid of the rebar measurement.

Table 7.2 presents an overview of the Line Analysis Method results for the vertical rebar’s of specimen I.

<table>
<thead>
<tr>
<th>Rebar</th>
<th>Mean value ($\mu$) [mm]</th>
<th>Standard deviation ($\sigma$) [mm]</th>
<th>Difference with reality [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1-2, A-G)</td>
<td>10.75</td>
<td>1.93</td>
<td>+0.75</td>
</tr>
<tr>
<td>(2-3, A-G)</td>
<td>10.68</td>
<td>2.02</td>
<td>+0.68</td>
</tr>
<tr>
<td>(3-4, A-G)</td>
<td>10.86</td>
<td>2.06</td>
<td>+0.86</td>
</tr>
<tr>
<td>(4-5, A-G)</td>
<td>11.44</td>
<td>1.69</td>
<td>+1.44</td>
</tr>
<tr>
<td>(5-6, A-G)</td>
<td>11.45</td>
<td>1.79</td>
<td>+1.45</td>
</tr>
<tr>
<td>(6-7, A-G)</td>
<td>11.00</td>
<td>1.41</td>
<td>+1.00</td>
</tr>
<tr>
<td>(7-8, A-G)</td>
<td>11.45</td>
<td>1.67</td>
<td>+1.45</td>
</tr>
</tbody>
</table>

1) See figure 7.1 and 7.2 for the grid of the rebar measurement.
7.1.4 Comparison of Quick, Block and Line Analysis Methods

Table 7.3 presents an overview of the horizontal rebar diameter analysis and table 7.4 presents an overview of the vertical rebar diameter analysis for specimen I. These tables can be used in order to make a comparison between the Quick, Block and Line Analysis Method. From table 7.3 and 7.4, it can be concluded that the Quick Analysis Method is the most inaccurate method for analyzing the rebar diameter measurement results. The deviation of the Quick Analysis Method with the real rebar diameter is -4mm. Therefore, using the Quick Analysis Method results in a very conservative advice for the measured rebar and will not be used in the graduation project.

Comparing the Line Analysis Method with the Block Analysis method is complicated, because the Line Analysis Method results in several mean values and standard deviations. The line Analysis Method gives for each horizontal rebar a measured mean value and standard deviation, while the Block Analysis Method gives one mean value and one standard deviation for all horizontal rebar’s. The measured mean value for the Line Analysis Method is in between 9.08mm and 13.58mm for the horizontal rebar’s. Significant difference between these measured mean values makes it complex to give an advice for the measurement results.

### Table 7.3  Overview horizontal rebar diameter measurement results of specimen I.

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>Mean value (μ) [mm]</th>
<th>Standard deviation (σ) [mm]</th>
<th>Difference with reality [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick</td>
<td>6²) n/a³)</td>
<td></td>
<td>-4</td>
</tr>
<tr>
<td>Block</td>
<td>11.48</td>
<td>2.29</td>
<td>+1.48</td>
</tr>
<tr>
<td>Line¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A-B, 1-8)</td>
<td>13.58</td>
<td>2.10</td>
<td>+3.58</td>
</tr>
<tr>
<td>(B-C, 1-8)</td>
<td>12.05</td>
<td>1.64</td>
<td>+2.05</td>
</tr>
<tr>
<td>(C-D, 1-8)</td>
<td>12.00</td>
<td>1.55</td>
<td>+2.00</td>
</tr>
<tr>
<td>(D-E, 1-8)</td>
<td>9.08</td>
<td>2.69</td>
<td>-0.82</td>
</tr>
<tr>
<td>(E-F, 1-8)</td>
<td>10.84</td>
<td>2.32</td>
<td>+0.84</td>
</tr>
<tr>
<td>(F-G, 1-8)</td>
<td>11.75</td>
<td>4.58</td>
<td>+1.75</td>
</tr>
</tbody>
</table>

¹) See figure 7.1 and 7.2 for the grid of the rebar measurement.
²) The Quick Analysis method does not have a mean value.
³) The Quick Analysis method does not have a standard deviation.
Furthermore, from table 7.3 and 7.4 it can be concluded that the accuracy of the Line Analysis Method depends on the chosen rebar to analyze. The vertical rebar at grid 2-3, A-G gives a more accurate indication about the real rebar diameter than the vertical rebar at grid 5-6, A-G. The Block Analysis Method is more user friendly in comparison with the Line Analysis Method, because the Line Analysis Method is more complex to analyze. In addition, the Line Analysis Method is more confusing than the Block Analysis Method due to the different measured mean values for the same real rebar diameter. Therefore, the Block Analysis Method is in the graduation project used for analyzing the rebar diameter measurement results of the specimens from chapter 6.

Table 7.4  Overview vertical rebar diameter measurement results of specimen I.

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>Mean value (µ) [mm]</th>
<th>Standard deviation (σ) [mm]</th>
<th>Difference with reality [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick</td>
<td>6</td>
<td>n/a</td>
<td>-4</td>
</tr>
<tr>
<td>Block</td>
<td>11.07</td>
<td>1.88</td>
<td>+1.07</td>
</tr>
<tr>
<td>Line¹:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1-2, A-G)</td>
<td>10.75</td>
<td>1.93</td>
<td>+0.75</td>
</tr>
<tr>
<td>(2-3, A-G)</td>
<td>10.68</td>
<td>2.02</td>
<td>+0.68</td>
</tr>
<tr>
<td>(3-4, A-G)</td>
<td>10.86</td>
<td>2.06</td>
<td>+0.86</td>
</tr>
<tr>
<td>(4-5, A-G)</td>
<td>11.44</td>
<td>1.69</td>
<td>+1.44</td>
</tr>
<tr>
<td>(5-6, A-G)</td>
<td>11.45</td>
<td>1.79</td>
<td>+1.45</td>
</tr>
<tr>
<td>(6-7, A-G)</td>
<td>11.00</td>
<td>1.41</td>
<td>+1.00</td>
</tr>
<tr>
<td>(7-8, A-G)</td>
<td>11.45</td>
<td>1.67</td>
<td>+1.45</td>
</tr>
</tbody>
</table>

¹) See figure 7.1 and 7.2 for the grid of the rebar measurement.
²) The Quick Analysis method does not have a mean value.
³) The Quick Analysis method does not have a standard deviation.
7.1.5 Concrete cover depth

In comparison with the rebar diameter measurement analysis, the cover depth measurement analysis are unambiguous. The cover depth measurement of specimen I is carried out over grid E, 1-8 (see figure 7.1). Figure 7.7 presents the cover depth measurement result of this grid. The real cover depth at the measured area of specimen I is **30 mm**.

![Figure 7.5](image)

**Figure 7.5** Cover depth measurement of specimen I.

Figure 7.6 presents the multinomial distribution of the cover depth measurement with unknown rebar diameter. The mean value of 41 measured cover depths is 33.05 mm. The difference with the real cover depth is **+3.05 mm**.

![Figure 7.6](image)

**Figure 7.6** Multinomial distribution cover depth measurement unknown rebar diameter.
The accuracy of the cover depth measurement increases by a known rebar diameter (Hilti, 2013). Figure 7.7 presents the multinomial distribution of the cover depth measurement with known rebar diameter. The mean value of 41 measured cover depths is 29.74 mm. By a known rebar diameter the difference with the real cover depth becomes -0.26mm. The cover depth measurements are analyzed twice for each specimen, namely once with known and once with unknown rebar diameter.

![Multinomial distribution cover depth measurement known rebar diameter.](image)

**Figure 7.7**  Multinomial distribution cover depth measurement known rebar diameter.

### 7.1.6 Analysis specimen I

In conclusion, the rebar diameter measurements are analyzed with the Block Analysis Method in the graduation project. The difference of the rebar diameter measurement with the real rebar diameter is +1.48mm for the horizontal rebar`s and +1.07mm for the vertical rebar`s. The standard deviation for the horizontal rebar diameter measurement is 2.29mm and for the vertical rebar diameter measurement 1.88mm (see annex B1 table B1.1). The conclusion can be drawn that the rebar diameter measurement of specimen I is less accurate and the spread of the measurement results is large.

The difference of the cover depth measurement is +3.05mm by an unknown rebar diameter and -0.26mm by a known rebar diameter. The standard deviation for the cover depth measurement with unknown rebar diameter is 1.26mm and for the cover depth measurement with known rebar diameter is 1.10mm (see annex B1 table B1.2 and B1.3). The conclusion can be drawn that the cover depth measurement becomes more accurate when the rebar diameter of specimen I is known.
### 7.2 Overview measurement results

Specimen I is in detail analyzed for the rebar diameter and cover depth measurement results in paragraph 7.1 of the report. The measurements of all other specimens are analyzed in the same manner and included in annex C. The cover depth measurement analysis are unambiguous in the case of a constant cover depth for the rebar’s in the same layer of the structure. However, the cover depths of specimen IV and V where not constant due to less accurate construction of these plates. The cover depth measurements of specimens IV and V are regardless analyzed with the same principle, because the accuracy of the Ferroscan should be ±3 a ±5mm for this range by an unknown rebar diameter and ±3 a 4mm by a known rebar diameter (Hilti, 2013). Table 7.5 presents the mean value with unknown rebar diameter ($\mu_{uk}$), mean value with known rebar diameter ($\mu_k$), standard deviation with unknown rebar diameter ($\sigma_{uk}$) and the standard deviation with known rebar diameter ($\sigma_k$) for the cover depth measurement of each specimen.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Real cover [mm]</th>
<th>Rebar diameter [mm]</th>
<th>$\mu_{uk}$ [mm]</th>
<th>$\mu_k$ [mm]</th>
<th>$\sigma_{uk}$ [mm]</th>
<th>$\sigma_k$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>30</td>
<td>10</td>
<td>+3.05</td>
<td>-0.26</td>
<td>1.26</td>
<td>1.10</td>
</tr>
<tr>
<td>II</td>
<td>30</td>
<td>12</td>
<td>+3.30</td>
<td>+1.20</td>
<td>3.86</td>
<td>1.93</td>
</tr>
<tr>
<td>III</td>
<td>42</td>
<td>8</td>
<td>+7.08</td>
<td>+1.58</td>
<td>2.19</td>
<td>2.19</td>
</tr>
<tr>
<td>IV + V</td>
<td>47-78</td>
<td>10</td>
<td>-2.01</td>
<td>-0.38</td>
<td>3.69</td>
<td>2.15</td>
</tr>
<tr>
<td>VI</td>
<td>35-55</td>
<td>12</td>
<td>-0.70</td>
<td>-1.10</td>
<td>4.07</td>
<td>2.33</td>
</tr>
<tr>
<td>VII</td>
<td>40-55</td>
<td>12</td>
<td>+2.26</td>
<td>-0.40</td>
<td>2.81</td>
<td>2.12</td>
</tr>
<tr>
<td>VIII</td>
<td>30</td>
<td>20</td>
<td>+0.79</td>
<td>+1.14</td>
<td>2.42</td>
<td>1.51</td>
</tr>
<tr>
<td>IX</td>
<td>30</td>
<td>20</td>
<td>-1.36</td>
<td>+0.57</td>
<td>2.59</td>
<td>1.99</td>
</tr>
<tr>
<td>X</td>
<td>30</td>
<td>25</td>
<td>+0.86</td>
<td>+1.07</td>
<td>4.04</td>
<td>2.16</td>
</tr>
</tbody>
</table>

The mean value of the cover depth measurement with unknown rebar diameter ($\mu_{uk}$) of specimen III has a major deviation of +7.08mm. The mean value ($\mu_k$) of this cover depth decreases to +1.58mm by a known rebar diameter. This shows the effect of partly demolishing the structure in order to obtain information about the real cover depth. The accuracy of the Ferroscan increases significantly by a known rebar diameter. However, the accuracy of the cover depth measurement with known rebar diameter does not increase for all specimens. For specimens VI, VIII and X the accuracy decreases by a known rebar diameter.
Table 7.6 presents an overview of the rebar diameter measurement results for each specimen. The mean value (µ), standard deviation (σ), given advice and the difference between the real diameter and given advice for each specimen are used in order to determine the accuracy of the Block Analysis Method. Distinction is made in Table 7.6 between the horizontal and vertical rebar’s, because the diameter of the horizontal and vertical rebar is not always similar to each other in the specimens.

Furthermore, the cover depth of the horizontal and vertical rebar’s in a reinforced concrete element differs from each other. The concrete cover depth of all specimens is between 30mm and 78 mm. So, all measured specimens fulfill the requirement with regard to the measurement range of the Ferroscan PS200 for rebar diameter measurements. The advices in Table 7.6 are based on the Block Analysis Method and the European trade sizes for rebar’s. For example, the mean value (µ) for the horizontal rebar’s of specimen I is 11.48mm and the nearest European trade size is 12mm.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cover depth [mm]</th>
<th>Rebar diameter [mm]</th>
<th>µ [mm]</th>
<th>σ [mm]</th>
<th>Advice [mm]</th>
<th>Difference [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>40</td>
<td>10</td>
<td>11.48</td>
<td>2.29</td>
<td>12</td>
<td>+2</td>
</tr>
<tr>
<td>I &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>30</td>
<td>10</td>
<td>11.07</td>
<td>1.88</td>
<td>12</td>
<td>+2</td>
</tr>
<tr>
<td>II &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>30</td>
<td>12</td>
<td>12.50</td>
<td>2.55</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>II &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>42</td>
<td>12</td>
<td>14.80</td>
<td>1.17</td>
<td>14</td>
<td>+2</td>
</tr>
<tr>
<td>III &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>54</td>
<td>8</td>
<td>9.39</td>
<td>1.62</td>
<td>10</td>
<td>+2</td>
</tr>
<tr>
<td>III &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>42</td>
<td>12</td>
<td>13.40</td>
<td>1.51</td>
<td>14</td>
<td>+2</td>
</tr>
<tr>
<td>IV + V &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>47-60</td>
<td>8</td>
<td>6.85</td>
<td>3.05</td>
<td>6</td>
<td>-2</td>
</tr>
<tr>
<td>IV + V &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>47-60</td>
<td>10</td>
<td>8.83</td>
<td>2.92</td>
<td>8</td>
<td>-2</td>
</tr>
<tr>
<td>VI &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>35-47</td>
<td>8</td>
<td>7.29</td>
<td>1.21</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>VI &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>43-55</td>
<td>12</td>
<td>9.84</td>
<td>2.10</td>
<td>10</td>
<td>-2</td>
</tr>
<tr>
<td>VII &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>55</td>
<td>12</td>
<td>9.58</td>
<td>3.67</td>
<td>10</td>
<td>-2</td>
</tr>
<tr>
<td>VII &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>40</td>
<td>12</td>
<td>12.70</td>
<td>2.27</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>VIII &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>30</td>
<td>10</td>
<td>8.93</td>
<td>1.01</td>
<td>8</td>
<td>-2</td>
</tr>
<tr>
<td>VIII &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>40</td>
<td>20</td>
<td>17.53</td>
<td>2.20</td>
<td>16</td>
<td>-4</td>
</tr>
<tr>
<td>IX &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>30</td>
<td>10</td>
<td>9.84</td>
<td>3.20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>IX &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>40</td>
<td>20</td>
<td>16.72</td>
<td>2.17</td>
<td>16</td>
<td>-4</td>
</tr>
<tr>
<td>X &lt;sub&gt;hor&lt;/sub&gt;</td>
<td>30</td>
<td>10</td>
<td>8.70</td>
<td>0.96</td>
<td>8</td>
<td>-2</td>
</tr>
<tr>
<td>X &lt;sub&gt;ver&lt;/sub&gt;</td>
<td>40</td>
<td>25</td>
<td>18.27</td>
<td>3.35</td>
<td>20</td>
<td>-5</td>
</tr>
</tbody>
</table>
Giving an advice with the use of the mean value (μ) and looking up the nearest European trade size for rebar’s is not always that simple as by the advice for the horizontal rebar of specimen I. For example, the mean value (μ) of the vertical rebar diameter measurement of specimen I is 11.07mm and this is in between two European trade sizes, namely 10mm and 12mm. Figure 7.8 presents the normal and multinomial distribution of the vertical rebar diameter measurement result of specimen I. The peak at 12mm in the multinomial distribution has led to the given advice as 12mm.

Figure 7.8   Multinomial and normal distribution vertical rebar diameter result specimen I.

Figure 7.9 presents the normal and multinomial distribution of the vertical rebar diameter measurement result of specimen VI in one figure. The mean value (μ) of the vertical rebar measurement is 9.84mm. The multinomial distribution has two peaks, namely by 8 and by 12mm. Using the mean value of the measurement in order to give the nearest European trade size as advice is not the best choice for this measurement. Analyzing the measurement results requires for some measurements more expertise of the analyst.

Figure 7.9   Multinomial and normal distribution vertical rebar diameter result specimen VI.
7.3 Obtained accuracy

The non-destructive measurement results of the specimens are used in order to analyze the accuracy of the measured amount (n) of rebar’s, diameter of the rebar’s and cover depth. The measured amount of the rebar’s are completely in line with the real amount of rebar’s in the measured specimens. This means that the covermeter and the radar have a high accuracy by measuring the amount of rebar’s in a concrete element.

7.3.1 Cover depth measurement accuracy

Each quickscan measurement is analyzed twice for the measured cover depth, namely once with unknown rebar diameter and once with known rebar diameter. Minimum cover depth of all specimens is 30mm and maximum cover depth 76mm. So, all measured specimens fulfill the requirement with regard to the measurement range of the covermeter Ferroscan PS200.

Figure 7.10 presents an overview of all cover depth measurement results in one graph. Figure 7.10 shows the mean of difference between the real and measured cover depth (µ) and the standard deviation (σ). The graph shows that, for most of the specimens, the mean value of the measurement with known rebar diameter approaches more to zero in comparison with the measurement with unknown rebar diameter. Moreover, the spread of the measurement results decreases for all measurements by a known rebar diameter measurement in comparison with an unknown rebar diameter measurement.

![Figure 7.10: Overview cover depth measurement results in millimeters.](image)
7.3.2 Rebar diameter measurement accuracy

The imagescan measurements are separately analyzed for the horizontal and vertical rebar diameters with the use of the Block Analysis Method. Figure 7.11 presents an overview of all measurement results in one graph. Figure 7.11 shows the mean of difference between the real and measured rebar diameter (μ) and the standard deviation (σ). The mean of difference should be ±1 European trade size of rebar diameter (Hilti, 2013). European trade sizes for rebar’s are given as: 6, 8, 10, 12, 14, 16, 20, 22, 25, 28, 32 and 40mm (Hilti, 2013).

For example, real diameter of the horizontal rebar of specimen I is 10mm. The mean of difference for specimen I should between plus and minus 2mm. Mean of difference of the measurement result is 2.29mm, thus not far away from ±1 European trade size. However, a difference of one European trade size has a significant impact on the moment capacity calculation of specimen I. Equation 2.5 is repeated in order to emphasize the importance of the rebar diameter accuracy.

\[
M_{rd} = \pi \cdot 4 \cdot \phi^2 \cdot F_{yd} \cdot 0.9 \cdot (h - c - \frac{1}{2} \cdot \phi) \tag{2.5}
\]

Equation 2.5 shows that the rebar diameter is squared in the moment capacity calculation of a reinforced concrete element. Deviation of +1 European trade size results in an overestimation about 40% of the real capacity of specimen I.

![Figure 7.11](image-url)  
**Figure 7.11** Overview rebar diameter measurement results in millimeters.
Figure 7.12 presents the multinomial and normal distribution of all measurements in one graph. The graph is made from 2961 verified blocks of then specimens. Deviation of the measurement results are in the graph shown as European trade sizes. For example, difference between the measured rebar diameter of 12mm and real rebar diameter of 10mm is one European trade size. The accuracy of the Ferroscan PS200 for rebar diameter measurement is given as ±1 European trade size for structures with cover depth smaller or equal to 60mm (Hilti, 2013). Subsequently, the 95% confidence interval of all measurement results from figure 7.12 should between ±1 European trade size and the mean value should be zero. The measurement results are by the Ferroscan presented in integers. Therefore, the boundaries of the 95% confidence interval must be corrected for the Ferroscan to ±1.5 European trade size. The boundaries of the 95% confidence interval should be equal to two times the standard deviation (2σ) of the normal distribution (Carlton & Devore, 2014). This means that the standard deviation of figure 7.12 should be 0.75 European trade size. The graph from figure 7.12 has a mean value of -0.06 European trade size and a standard deviation of 1.30 European trade size. In conclusion, the accuracy of the Block Analysis Method for rebar diameter measurements is in line with the given accuracy from Hilti, but the standard deviation is significantly higher than 0.75 European trade size.

Figure 7.12  Multinomial and normal distribution of all rebar diameter measurements.
Presenting the rebar diameter measurement results in European trade sizes is confusing by analyzing the accuracy of the Ferroscan PS200. Difference between a rebar diameter of 16mm and 20mm is one European trade size and the difference between a rebar diameter of 12mm and 14mm is also one European trade size. Consequently, deviation of one European trade size has not the same effect on the capacity calculation of a concrete element with a real rebar diameter of 12mm and a concrete element with real rebar diameter of 20mm. Therefore, the rebar diameter measurements are also analyzed for the relative difference (RD). The relative difference gives the ratio of the rebar diameter measurement deviation. Equation of the relative difference is given as:

\[
\text{RD} = \frac{\varphi_r - \varphi_m}{\varphi_r} \cdot 100\% \tag{7.1}
\]

Where:

- \(\varphi_r\) - real rebar diameter [mm]
- \(\varphi_m\) - measured rebar diameter [mm]

Figure 7.13 presents the multinomial and normal distribution of the relative difference of all rebar diameter measurements. The mean value of the distribution is 1.07% and the standard deviation is 25.82%. The mean value gives the indication of a very accurate rebar diameter measurement, because the relative deviation of 2961 rebar diameter measurements is very close to zero. However, figure 7.13 shows the large spread of the rebar diameter measurement results.

![Figure 7.15](image)

**Figure 7.15** Multinomial and normal distribution of the relative difference.
There are six different rebar diameters measured in this project, namely specimens with rebar diameter of 6, 8, 10, 12, 20 and 25mm. These diameters are individually analyzed in annex D of the report. Table 7.7 presents an overview of the results from annex D. Table 7.7 gives the indication that the Ferroscan PS200 becomes more inaccurate by a rebar diameter of 20 and 25mm in comparison with the accuracy for diameter of 6, 8, 10 and 12mm. However, this is in contradiction with the rebar detecting theory of covermeters. Rebar with larger diameter should be better detectable for a covermeter in contrast to a rebar with smaller diameter.

Reason for the larger inaccuracy of the covermeter by measuring a rebar with diameter of 20 and 25mm could because of the fact that the measurement results are presented in European trade sizes instead of in mm. Rebar diameter of 25mm is in between 20, 22, 28 and 32mm in the range of European trade sizes for rebar diameters. As a consequence, wrong estimation of one European trade size by the device is a wrong estimation of 3mm. It get worse when the device makes a wrong estimation of two European trade sizes, because this is a wrong estimation of about minus 5 or plus 7mm.

The effect of a wrong estimation of the covermeter by a measured rebar diameter of 10mm is less detrimental in comparison with measuring a rebar diameter of 25mm. Rebar diameter of 10mm is in between 6, 8, 12 and 14mm in the range of European trade sizes for rebar diameters. Therefore, wrong estimation of one European trade size by the device is a wrong estimation of 2mm and a wrong estimation of two European trade sizes is 4mm.

<table>
<thead>
<tr>
<th>Rebar diameter [mm]</th>
<th>Mean value (μ) [mm]</th>
<th>Difference [mm]</th>
<th>Standard deviation (σ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>7.29</td>
<td>+1.29</td>
<td>1.21</td>
</tr>
<tr>
<td>8</td>
<td>8.23</td>
<td>+0.23</td>
<td>2.72</td>
</tr>
<tr>
<td>10</td>
<td>10.53</td>
<td>+0.53</td>
<td>2.32</td>
</tr>
<tr>
<td>12</td>
<td>11.53</td>
<td>-0.47</td>
<td>3.02</td>
</tr>
<tr>
<td>20</td>
<td>17.15</td>
<td>-2.85</td>
<td>2.17</td>
</tr>
<tr>
<td>25</td>
<td>18.27</td>
<td>-6.73</td>
<td>3.35</td>
</tr>
</tbody>
</table>
7.4 Accuracy for Non-European trade size

The rebar diameter of all specimens that are measured in this graduation project are European trade sizes. However, there are also buildings which are not constructed with rebar’s according to the so-called European trade sizes. The apartment from figure 7.16 was built in the period 1950-1970 and contains cantilevered reinforced concrete gallery plates. These gallery plates are constructed with rebar’s which are not European trade sizes. One of the cantilevered gallery plate is measured in order to determine the rebar diameter.

The real rebar diameter of the vertical rebar is 7mm and a rebar diameter of 7mm is not an European trade size. Therefore, the Ferroscan PS200 is not suited to use for measuring the rebar diameter of this gallery plate. The plate on the nineteenth floor of the apartment is measured over an area of 600 x 600 mm² in order to find out if the rebar’s with diameter of 7mm are detected and measured by the Ferroscan PS200 despite the fact that 7mm is not a European trade size. Measured area of the cantilevered reinforced gallery plate is partly demolished over an area of 420 x 105 mm² in order to verify the real rebar diameter of 7mm. Vertical rebar from figure 7.18 is taken out the gallery plate and weighted in the laboratory in order to determine the real rebar diameter of 7mm.
Figure 7.19 presents the rebar diameter measurement results of the gallery plate. The rebar diameter measurement shows that the Ferroscan PS200 detects the presence of the vertical rebar’s despite the fact that these rebar’s are 7mm. Vertical rebar from figure 7.18 is located on grid 4-5, A-C of the rebar diameter measurement. The measurement results of the gallery plate are analyzed with the use of the Line Analysis Method, because only the grid with real rebar diameter of 7mm is analyzed. Disruption of the measurements at grid C, 1-6 is not taken in to account for the analysis.

![Rebar diameter measurement gallery plate.](image)

Figure 7.19  Rebar diameter measurement gallery plate.

Figure 7.20 presents the multinomial distribution of grid 4-5, A-C. The mean value of the measurement is **10.18mm** and the standard deviation is **2.33mm**. In conclusion, the Ferroscan is able to detect and measure rebar’s which are not according to the so-called European trade sizes. The difference between the measured mean value and real rebar diameter is +3.18mm and this will have a significant large impact on the capacity calculation of this gallery plate.

![Multinomial distribution rebar diameter measurement.](image)

Figure 7.20  Multinomial distribution rebar diameter measurement.
7.5 Partly destructive testing

In paragraph 7.3.1 the conclusion was drawn that the accuracy of the cover depth measurements increases if the rebar diameter of the structure is known. Information about the rebar diameter could be obtained with the use of information from detail drawings. However, the detail drawings are not always available and in addition, the reliability of the information on the detail drawings can also be doubt. Inaccurate construction of the structure will result in unreliable detail drawings. Partly destructive testing the structure makes it possible to obtain information about the real rebar diameter and real cover depth of the structure.

In addition, the information obtained from partly destructive testing could also be used in order to verify the non-destructive rebar diameter measurements. Partly destructive testing could be done by drilling concrete cylinder samples. However, information about the real rebar diameter and cover depth could also be obtained easily by drilling a gap of 40 x 40mm$^2$ with the use of a concrete drill. The location to partly demolish is of big importance in order to directly obtain information about the horizontal rebar diameter, vertical rebar diameter and cover depth. It is reasonable to drill the gape of 40 x 40mm$^2$ on the place where the horizontal and vertical rebar intersect. Figure 7.22 presents a gap of 40 x 40mm$^2$ which provides information about the horizontal rebar diameter, vertical rebar diameter and the cover depth of the specimen.

The rebar diameter measurements of the graduation projected are by consultants repeated with the obtained knowledge from the gap of 40 x 40mm$^2$. Information about the non-destructive rebar diameter measurements are combined with the information from the partly destructive tests. This resulted in new advices which were for all specimens for hundred percent in line with the real rebar diameter.

![Figure 7.21 Cylinder sample.](image1)
![Figure 7.22 Gap of 40x40mm$^2$.](image2)
7.6 Conclusion

According to the analyses of paragraph 7.2 and 7.3, the conclusion can be drawn that the covermeter and radar have a large accuracy by detecting the amount of rebar’s. The detected amount of rebar’s are for hundred percent in line with the real amount of rebar’s. Furthermore, the obtained accuracy of the cover depth measurements are in line with the by the manufacturer given accuracy. Accuracy of the cover depth measurements are for all specimens, except for one, about ±3mm. Nevertheless, a difference of 3mm on a real cover depth of 30mm does not have a significant influence on the capacity calculation of a reinforced concrete structure. The accuracy of the cover depth measurement increases by a known rebar diameter to ±1mm.

Accuracy of the rebar diameter measurements are analyzed with the use of the Block Analysis Method. The measured mean value (µ) and measured standard deviation (σ) are taken in to account for the accuracy analysis. The mean value (µ) of the rebar diameter measurements are in line with the by manufacturer given accuracy. However, the standard deviation of the rebar diameter measurements are significantly larger. The standard deviation of the measurements is almost two times larger than given by the manufacturer. The second aim of the graduation project was to calculate a safety factor for incorporating the non-destructive measurement results in structural calculations. The significant large standard deviation of the measurements will lead to an unreasonable high safety factor. Therefore, the safety factor for incorporating the rebar diameter measurement results in structural calculations will not be calculated in the report.

It becomes more interesting to analyze the cause of this large standard deviation. An interesting fact that could possibly help to determine the cause is that repeated measurements on the same concrete structure showed consistent results. Appendix E provides a view of measurement on a concrete structure that was repeated twice. Table 7.8 presents the results of the repeated measurement on the same concrete structure.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean value horizontal verified (µ) [mm]</th>
<th>Mean value vertical verified (µ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6.47</td>
<td>6.03</td>
</tr>
<tr>
<td>II</td>
<td>6.41</td>
<td>6.03</td>
</tr>
</tbody>
</table>
Results from table 7.8 give the impression that the external factors that influence the measurement results are constant for each measurement. The influence of steel rebar’s in the measured structure are taken in to account by the manufacturer. However, the influence of concrete on the measurement results of the covermeter are neglected (Zanona, 2015). A conversation with physics Professor Leo Pel and the significant larger standard deviation give the impression that concrete could have an influence on the rebar diameter measurement results. Therefore, the second research question is changed into:

‘Has concrete an influence on the rebar diameter measurement results of the covermeter?’
8. Influence of concrete

Reason for the significantly large standard deviation in the rebar diameter measurement results could be caused by the neglected effect of concrete when measuring with the covermeter. Rebar diameter measurements with the covermeter are based on the eddy-current principle. The covermeter creates an electromagnetic field in the reinforced concrete element, measures the disruption of the created electromagnetic field and translates this information into measured cover depth and rebar diameter. The electromagnetic field will be disturbed due to the presence of steel elements in the measured concrete structure. However, the results from chapter 7 give the impression that concrete genuinely influence the disruption of the electromagnetic field.

Concrete could be seen as the skin of the rebar`s by a reinforced concrete element. The effect of the skin on the disruption of an electromagnetic field is called the skin effect. The skin effect depends on the skin depth ($\delta_s$) and the equation of the skin depth is defined as (Brooks, 2010):

$$\delta_s = \sqrt{\frac{\rho}{\pi f \mu}}$$  \hspace{1cm} (8.1)

Where:

- $\delta_s$ - skin depth \hspace{1cm} [m]
- $\rho$ - electrical resistivity of the skin \hspace{1cm} [Ω·m]
- $f$ - frequency of the covermeter \hspace{1cm} [Hz]
- $\mu$ - magnetic permeability of the skin \hspace{1cm} [Ω·s]

The skin depth provides information about how deep the electromagnetic field of the covermeter penetrates into the structure. Equation 8.1 shows that the electrical resistivity of concrete, magnetic permeability of concrete and the frequency of the covermeter has an influence on the skin depth. The influence of concrete on the measurement results are neglected by the manufacturer and this means actually that the influence of the electrical resistivity and magnetic permeability of concrete is neglected. The magnetic permeability and electrical resistivity of the specimens from the graduation project are not known. In addition, measuring this parameters for concrete structures is complicated. Therefore, the influence of concrete on the rebar diameter measurements will be analyzed by measuring a reinforcement net with air as skin.
8.1 Measuring rebar in the “air”

Test setup of figure 8.1 and 8.2 is made in order to measure the rebar diameter with air as skin instead of concrete. The test setup is actually a wooden box with a wooden bottom plate and a wooden upper plate with thickness of 20mm. The lower plate and upper plate are separated from each other with the use of four wooden blocks with thickness of 70mm. Figure 8.1 present these wooden blocks, which are located on the corners of the lower plate. The reinforcement mesh to measure is placed on the lower plate and thereafter the upper plate is placed on the wooden blocks. The space between the upper and lower plate is now filled with a reinforcement mesh and air. Aim of this test setup is to determine the influence of steel rebar’s without a concrete skin.

Table 8.1 presents the electrical resistivity and magnetic permeability of air, wood and iron (Cullity & Graham, 2008). Air and wood have a very high electrical resistivity and a very low magnetic permeability in comparison with metallic elements. Therefore, the influence of wood and air on the disruption of measurement results is negligible in this test setup. The electrical resistivity and magnetic permeability of concrete depends on the composition of concrete. Therefore, it is not easy to assign a value for the properties of concrete (Pel, 2015).

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical resistivity ($\rho$) [Ω∙m]</th>
<th>Magnetic permeability ($\mu$) [Ω∙s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$1.3\cdot10^{16}$ - $3.3\cdot10^{16}$</td>
<td>$1.256\cdot10^{-6}$</td>
</tr>
<tr>
<td>Wood (dry)</td>
<td>$1.1\cdot10^{14}$ - $1.1\cdot10^{16}$</td>
<td>$1.256\cdot10^{-6}$</td>
</tr>
<tr>
<td>Steel (electrical)</td>
<td>$4.6\cdot10^{7}$</td>
<td>$5.0\cdot10^{-3}$</td>
</tr>
<tr>
<td>Iron</td>
<td>$1.0\cdot10^{7}$</td>
<td>$6.3\cdot10^{-3}$</td>
</tr>
</tbody>
</table>
Figure 8.3 presents the detail drawing of the measured reinforcement mesh and figure 8.4 presents the measurement result of the Ferroscan PS200. The diameter of the both horizontal and vertical rebar’s of the reinforcement are 6mm Figures 8.3 and 8.4 illustrate a high degree of similarity in the center-to-center distends and the pattern of the real and measured reinforcement mesh.

Figure 8.3  Detail drawing reinforcement.  Figure 8.4  Measurement result Ferroscan.

Figure 8.5 presents the measurement results of the vertical rebar’s which are analyzed with the use of Block Analysis Method. The diameter of all verified vertical blocks are 6mm. This is for hundred percent in line with the reality.

Figure 8.5  Graph vertical rebar diameter measurement.
Figure 8.6 presents the measurement results of the horizontal rebar’s which are also analyzed with the use of Block Analysis Method. Mean value (µ) of the measurement is 6.48mm and the standard deviation (σ) is 0.86mm. Figure 8.6 shows that more than 75% of the verified horizontal blocks are in line with the real rebar diameter. Disturbance of almost 25% could be caused by the fact that these rebar’s are on the second layer of the reinforcement mesh.

Cover depth of the horizontal rebar’s was 86mm and for the vertical rebar’s 80mm. Ferroscan PS200 is able to measure reliable rebar diameters up to a depth of 60mm (Hilti, 2014). Despite the fact that the cover depth does not meet the requirements of the Ferroscan PS200, the measurement results are almost perfect.

In conclusion, results from the measurement in “air” give the strong impression that concrete significantly influences the rebar diameter measurements. The measurement results of the specimens from chapter 7 show a large spread in the rebar diameter measurements. In contrast to these measurement results, rebar diameter measurement in “air” does not have any spread for the rebar’s in the first layer and a very small spread for the rebar’s in the second layer. Furthermore, analyzing the measurement results of the measurement in “air” with the Block Analysis Method results for hundred percent in the correct rebar diameter.
8.2 Influence of surface water

Water significantly disturbs the measurement results of the Ground Penetrating Radar (GPR Hilti PS1000). The influence of water on the measurement results of the covermeter (Ferroscan PS200) is neglected (Zanona, 2015). However, covermeters are largely used in situations where surface water could be present on the measured structure. For example, the covermeter is in the Netherlands largely used for measuring the cover depth and rebar diameter of gallery plates. The Netherlands has a temperate maritime climate. Therefore, it often happens that there is rainwater on the surface of the gallery plate, which has to be measured.

The influence of surface water on the rebar diameter measurement results is analyzed with the use of a reinforced concrete specimen. A reinforced concrete stair landing is measured twice with the Ferroscan PS200, namely once in a dry situation and once with water on the surface. Figure 8.6 presents the dry measurement situation. The stair landing is sprayed twice with tap water after the dry measurement. The waiting time after each spraying turn is circa one hour so that the water can sink partly into the structure. Figure 8.7 presents the wet measurement situation with water on the surface of the chair landing.

Information about the real rebar diameter and cover depth of the chair landing was not known, but this information is not of big importance for this measurement. The dry and wet measurement results will be compared on the similarities and differences in the results.

Figure 8.6  Dry measurement.  Figure 8.7  Surface water measurement.
Both dry and wet measurements are analyzed with the use of the Block Analysis Method. Figure 8.8 presents the rebar diameter measurement for the dry situation and figure 8.9 presents the rebar diameter measurement for the wet situation.

Analysis of the measurement results from figure 8.8 and 8.9 are included in annex E of the report. Table 8.2 gives an overview of the mean value ($\mu$) and standard deviation ($\sigma$) of both measurement results. Table 8.2 presents a high degree of similarity in the measurement results of the dry and wet measurement. According to these results, it can be concluded that water that is on the surface of the measured structure will not influence the measurement results.

**Table 8.2** Electrical resistivity and magnetic permeability of air and selected materials.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Horizontal mean ($\mu$) [mm]</th>
<th>Horizontal SD ($\sigma$) [mm]</th>
<th>Vertical mean ($\mu$) [mm]</th>
<th>Vertical SD ($\sigma$) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>6.43</td>
<td>0.85</td>
<td>6.03</td>
<td>0.22</td>
</tr>
<tr>
<td>Wet</td>
<td>6.41</td>
<td>0.82</td>
<td>6.03</td>
<td>0.22</td>
</tr>
</tbody>
</table>
9. Conclusions

The primary aim of the report was to determine the reliability of non-destructive testing methods by measuring the amount of rebar’s, rebar diameter and cover depth of reinforced concrete structures. Ten specimens are measured with the covermeter Ferroscan PS200 and the Ground Penetrating Radar PS1000 in order to determine the accuracy of these non-destructive testing methods. The measured amount of rebar’s of all the measurements were hundred percent in line with the real amount of existing rebar’s. Thus, the covermeter and Ground Penetrating Radar have a high precision by detecting the amount of rebar’s in existing concrete structures up to a depth of 100mm. Rebar’s deeper than 100mm are not analyzed in the report.

Cover depth measurements are carried out with the covermeter and analyzed for the measured mean value ($\mu$) and standard deviation ($\sigma$). Range of the real cover depth of all specimens were between 30 and 78mm. Accuracy of the cover depth measurements are for all specimen, except for one, about $\pm$ 3mm. The measured differences are in line with the accuracy that is provided by the manufacturer. Nevertheless, inaccuracy of $\pm$ 3mm on 30mm does not have a significant influence on the capacity calculation of a reinforced concrete structure. Furthermore, the difference in accuracy between the cover depth measurement with known and unknown rebar diameter is investigated. The accuracy of cover depth measurements significantly increases by a known rebar diameter. Moreover, the spread of the measurement results decreases for all measurements by a known rebar diameter measurement in comparison with an unknown rebar diameter measurement.

Rebar diameter measurements of the graduation project are also carried out with the use of the covermeter PS200. Measurement preconditions for covermeter devices are provided in the manual of these devices. Nevertheless, information about how to analyze the cover depth and rebar diameter measurement results is not given in the manual and in addition there is no protocol in the Eurocode. This leads for a lot of confusion by the consultants, because there is not one method for analyzing the rebar diameter measurement results. Therefore, several test cases are measured in cooperation with several NDT consultants in order to determine the analysis methods that are used in practice for rebar diameter measurement analysis. The so-called Quick Analysis Method, Line Analysis Method and Block Analysis Method are compared with each other. According to this comparison, the conclusion is drawn that the Block Analysis Method is the most accurate method for rebar diameter measurement analysis.
Therefore, the measurements of the graduation project are analyzed with the Block Analysis Method in order to determine the accuracy of the Ferroscan PS200. Accuracy of the Ferroscan PS200 for rebar diameter measurements is given in the manual as ± 1 European trade size for structures with cover depth smaller or equal to 60mm (Hilti, 2013). The so-called European trade sizes for rebar diameters are given as: 6, 8, 10, 12, 14, 16, 20, 22, 25, 28, 32 and 40mm (Hilti, 2013). The Block Analysis Method results are in line with the given accuracy of ± 1 European trade size. However, the inaccuracy of ± 1 European trade size has a large influence on the capacity calculation of a reinforced concrete element. One European trade size is at least 2mm and the rebar diameter is squared in the capacity equation for reinforced concrete. This means that the inaccuracy will be squared in this equation. In addition, the inaccuracy of the rebar diameter measurement increases by a rebar diameter of 20 and 25mm in comparison with the accuracy for diameter of 6,8,10 and 12mm. This is in contradiction with the rebar detecting theory of covermeters, because a rebar with larger diameter should be better detectable for a covermeter in contrast to a rebar with smaller diameter. The difference of one European trade size for a rebar with the diameter of 20mm or 25mm is not the same as the difference of one European trade size for a rebar with a diameter 12mm, when the difference is expected in millimeters. Therefore, the fact that the measurement results are presented in European trade sizes instead of in mm could cause the larger inaccuracy of the covermeter when measuring a rebar with diameter of 20 or 25mm.

Nevertheless, the standard deviation of all rebar diameter measurements is significantly large. The standard deviation of all 2961 verified rebar diameter blocks is 1.30 European trade size. Expressing the standard deviation in mm gives 3.06mm and expressing in relative difference gives 25.82 percent. The large standard deviation is caused by the neglected influence of concrete on the rebar diameter measurement results. Measuring the diameter of a rebar in “air” provides almost perfect measurement results. In addition, water on the surface of the structure to measure does not affect the rebar diameter measurement results.

Finally, partly destructive testing the measured structure provides substantial local insight into the rebar diameters and cover depth. If the design documents of the analyzed structure are not present, than non-destructive measurements should be combined with partly destructive testing in order to verify the measurement results. This partly destructive testing could be a gap of 40x40mm² on the place where the horizontal and vertical rebar`s cross each other. Even if the design documents of a structure are present then partly destructive testing could be helpful in order to verify the information on the design documents.
10. Recommendations

Most unexpected conclusion of the project is the large spread of the rebar diameter measurement results. As a result of the “air” measurement result, the conclusion is drawn that concrete has an “unexpected” influence on the rebar diameter measurement results. The influence of concrete on the rebar diameter measurements is neglected by the manufacturers of covermeters (Zanona, 2015). A follow-up study should identify the exact influence of concrete on the measurement results. Reinforced concrete specimens could be made with three different types of cements, namely Portland cement, blast furnace cement and aluminous cement. Subsequently, the magnetic permeability and electrical resistivity of these specimens could be measured in cooperation with Department of Applied Physics (Pel, 2015). These measurement results should provide clarity about the influence of concrete and especially the influence of the aggregate material on the measurement results. The obtained information could be used in order to make an attempt to calculate a safety factor for incorporating the information of non-destructive testing methods in structural calculation of reinforced concrete structures. Influence of the magnetic permeability and electrical resistivity can be used as a variable in the safety factor.

Furthermore, a new analyzing method for rebar diameter measurements could be examined with the measurement results from the annex of the report. A disc is included in the annex with all data of the measurements. The Ferroscan PS200 contains seven coils and the magnetic field of the fourth coil should be the strongest, because this coil is in the middle of all seven coils (Zanona, 2015). During the measurement, it must be taken in to account that the fourth coil is located exact in the middle of two perpendicular rebar’s. Figure 10.1 presents a measurement whereby the fourth coil is in the middle of two perpendicular rebar’s.

![Figure 10.1 Location of the fourth coil.](image)

Finally, the research could be repeated with a covermeter from another manufacturer. The Profometer PM-600 of Proceq could be used as covermeter. The Profometer PM-600 presents the measured rebar diameter in millimeters instead of in European trade sizes.
Bibliography


Q: How are the tables about the accuracy of the PS200 substantiated?
A: We did a lot of experiments in order to determine the accuracy of the cover depth measurements. We are always in connection with our customers and we consider the findings of them. Our devices are used for cover depth measurement for years and we are always working to improve our devices. The Ferroscan PS200 is not our first edition for cover depth measurements. However, the Ferroscan PS200 is our first device for measuring the rebar diameter. The accuracy of the rebar diameter measurement are determined with experiments.

Q: What kind of experiments are used for the rebar diameter accuracy?
A: We have boxes where we put the steel rebar’s in and measure the thickness with the covermeter. Only ribbed steel rebar’s are measured in order to determine the accuracy of the PS200.

Q: What is the influence of concrete composition on the measurement results?
A: We have never researched if concrete has influence on the measurement results. I don`t think that concrete will have an influence on the rebar diameter measurements. However, we are interested in a possible research concerning this topic.

Q: How does the PS200 determine the diameter of the rebar? Is this a data match or Algorithm?
A: There is a very sophisticated Algorithm, which translates the information from the disturbed electromagnetic field into measured diameter.

Q: Why are the diameters only presented in a fixed range of diameter (DIN 488)?
A: The diameters in DIN 488 are the most common sizes, which are used in Europe. Every manufacturer could make their own sizes. However, with the PS200 we focused on the European trade sizes of steel rebar’s. We are thinking of developing a new device in which the measurements are presented in mm instead of European trade sizes.
Q: How can a welded reinforcement net measurement be analyzed?

A: It is required to conduct a partly destructive test when measuring a welded reinforcement net with the PS200. These results are used as input data in the software Hilti Profis. This program calculates a factor that multiplies the results of the PS200. In this way the PS200 could be used to measure welded reinforcement. The PS35 can also be used to measure welded reinforcement net. This device calculated the results directly.

Q: There isn’t any directive for analyzing of the results of the quickscan. Has Hilti a protocol for the analyses?

A: No, Hilti has no protocol for the analyses of the measurements. Measurement technics of the Ferroscan are still in development for the rebar diameter measurements. You are right that we should have a directive for analyzing the rebar diameter measurements as we have a direction for concrete cover depth analysis. Therefore, we are very interested in the results of this study. In your report you describe three analyzing methods, namely Quick Analyses Method, Line Analyses Method, and Block Analyses method. A fourth method could be that you look at the measurement results of the middle coil. The Ferroscan PS200 contains seven coils. The magnetic field of the fourth coil should be the strongest. Therefore, I think that the measurement of the fourth coil should be most accurate. In addition, the fourth coil must be located as far as possible from other rebar’s. You have to carry out the measurements with the Ferroscan in such a way that the fourth coil is in the middle of two perpendicular rebar’s. Although there is no protocol, we are aware that one is needed for analyzing the rebar diameter measurement results.
Q: Are you familiar with techniques of covermeter devices?
I did some research about the used methods after your request for this conversation. I know that the eddy-current principle with pulse induction is used. I was also involved in a project whereby a huge magnet is made in order to orientate the position of steel fibers in a concrete mixture.

Q: Has concrete an influence on the magnetic field of the covermeter?
Concrete could have an influence on the magnetic field of the covermeter. The skin depth of concrete is important for the magnetic permeability. The neglected magnetic permeability of concrete could be the reason for the large spread of your measurement results. If you look at the formula of the skin depth, you can see that the electrical resistivity of concrete and the frequency of the device could have an influence on the measurement results. The frequency of the device is of importance for the strength of the created magnetic field.

Q: Is it possible to measure the magnetic permeability of concrete?
Magnetic permeability is not easy to measure. However, there are researchers in the faculty of physics that are willing to measure it. If you want to see the influence of concrete, than you have to make test pieces with different composition of concrete. Think about three specimens which differs in type of cement. You can make reinforced concrete specimens with three different types of cements, namely Portland cement, blast furnace cement and aluminous cement. Subsequently, the magnetic permeability and electrical resistivity of these specimens could be measured in cooperation with Department of Applied Physics.

Q: Could water disturb the magnetic field of the covermeter?
I think that water could have an influence on the magnetic field of the covermeter. However, I am not sure if surface water will have a large impact. Salt water will have an influence on the magnetic field.