Monitoring and Assessing Concrete Bridges with Intelligent Techniques

Master of Science Thesis

**Student**
Name: Filippos Charavgis  
Student number: 4323300  
University: Delft University of Technology  
Faculty: Civil Engineering and Geosciences  
Master: MSc Construction Management and Engineering

**Thesis Committee**
Chairman: Prof.dr.ir. A.R.M. Wolfert  
2nd Committee Member: Ir. R.P.H. Vergoossen  
3rd Committee Member: Dr.ir. Bert-Jan Kooij  
TU-Delft CiTG  
TU-Delft CiTG  
TU-Delft EWI
Preface

The present Master thesis is the product of just over 8 months of effort. Despite the project suffering setbacks right from its initiation, it is finally nearing its completion, marking the end of my time as a student. In this preface I would like to express my sincere gratitude to all the people who assisted me in seeing this process through.

To begin with, I would like to thank my graduation committee, starting with my direct supervisor, Rob Vergoossen. Despite joining the team after the project was already underway, the feedback and advice you gave me during our meetings every week were of tremendous assistance. Secondly, I would like to thank my chairman Rogier Wolfert, who took the time from his busy schedule to help me get started with the project even after its troubled beginnings. Thirdly, I would like to express my gratitude to Bert Jan Kooij for providing the technical know-how and ideas without which all of this wouldn’t have been possible.

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Last but most certainly not least, I would like to give proper thanks to the people in my immediate surroundings who stuck with me throughout my academic and personal struggles. Firstly, to my parents, who provided me with the opportunity to spend this amazing two and a half years studying abroad in the first place, and who have always supported me in everything I have done. Secondly, to my friend Vaggelis, who was there to slap me back on my way whenever the stress would get the better of me. Finally, to my friends Leonidas, Ifigeneia and Dimitris, who provided their own support and some much needed stress relief during our time together.

I hope you will enjoy reading my thesis and hopefully it will provide some insight to whoever is interested in starting his own project in the subject matter.

Filippos Charavgis
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Summary

Asset management is often an integral part of any major industry. In the context of the construction industry, this mainly takes the form of financial or infrastructure asset management and proper management can often be crucial in both sparing hundreds of thousands or even millions of euros or ensuring the safety of end users of structures and infrastructure. It is therefore imperative to keep improving the process and looking for new ways to optimize it as much as possible, in order to make it more efficient and reliable.

The concern of the present paper is the management of infrastructure and more specifically the monitoring and assessment of prestressed concrete bridges. Constructions in general, and more so for bridges, have to perpetually weather non-constant heavy loads and changing external influences. Failure to ensure their capability to do so can lead to catastrophic results if issues are not properly dealt with in time, as this infrastructure is used by an immeasurable amount of people daily.

The current methods of bridge inspection currently involve depriving the public of access to the bridge if anything more than a visual inspection is required, while shutting down its operation often leads to costs of tens of thousands euros per hour, varying on a case by case basis. This has a discouraging effect when it is desired to do a more in-depth inspection.

This master thesis researches the possibility of employing new techniques that are currently in an experimental stage to improve the efficiency of the process. Several methods are pitted against specific requirements to determine whether they would be a good fit to use in practice on real structures. The primary research question is:

*How can the condition of a prestressed concrete bridge asset be assessed using intelligent Non-Destructive Testing (NDT) techniques?*

The requirements set forward to conclude whether each method can overall be recommended were as follows:

- The method must only involve Non-Destructive Testing (NDT)
- The required testing apparatus and miscellaneous equipment must be readily procurable or easy to create
- The amount of time that the bridge’s operation needs to be disrupted must be minimal or null
- The required equipment must be mobile and able to be used for multiple structures unless its cost is negligible
The methods this thesis focused on were ones that could be used to primarily detect prestressing steel tendons’ corrosion, fractures or loss of stress. The specific techniques that ended up being investigated were the following:

- Equipping Unmanned Aerial Vehicles (UAVs) with appropriate sensors
- Using Laser Doppler Vibrometry or acoustic methods to measure loss of stress
- Using infrared sensors to detect the heat produced by the chemical reaction that causes corrosion
- Using magnetic coil sensors to measure the loss of stress or detect local defects
- Using Electromagnetic Resonance Measurement (ERM) to detect and localize steel fractures
- Employing half-cell potential techniques to detect corrosion spots
- Employing remanent magnetism methods to detect steel fractures
- Combining thermographic methods with electromagnetic induction heating to detect corrosion
- Combining the same thermographic methods with resistance heating through direct high frequency AC excitation to detect corrosion

Of the above methods, the ones that held the most promise were the three last ones, while the magnetic coil and ERM methods are recommended to be considered when constructing new structures rather than on existing ones. Furthermore, while the half-cell potential and infrared sensors cannot stand on their own, they can be used to implement other techniques, as is evident in how the latter case is combined with others in the last 2 suggested methods.

For each of the above 3 recommended methods, a detailed test process was suggested to further determine their usefulness on the field. The recommendations included any equipment or other components that might be necessary. As the last method concerning the use of electric resistance heating to detect corrosion is the one about which the least is known, it has the most lengthy test process to implement. Furthermore, additional focus was given to it as the most promising candidate for further investigation in the future. More specifically, a few basic models were created to serve as a starting point in the actual modeling process and provide a ballpark within which the recommended current strength and test duration are expected to lie. After the model's operation was explained, sample values were given for tendon diameters common in the Netherlands, accompanied by a graph showcasing how altering the frequency would affect the final output.

The suggested test processes were then depicted step by step in flow charts involving every part of the process. The flow charts include failure checks to account for the possibility that the method does not live up to expectations, as well as the ability to adjust testing parameters to achieve a more favourable result.

Finally, the thesis concluded with a few remarks on what should be taken into account in potential future research.
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1. Introduction

This document is the final research paper of the Master Graduation Thesis of Filippos Charavgis, student of the Construction Management and Engineering programme at the Civil Engineering faculty of TU Delft. The thesis project was conducted under the supervision of Professor dr.ir. A.R.M. Wolfert, ir. R.P.H. Vergoossen and dr.ir. Bert-Jan Kooij.

1.1 Document contents

In the next section, this document will outline the research context by stating the problem definition, research question and target parameters, as they were agreed upon during the kick-off meeting.

In the following chapters, each technique that was examined so far will be described, starting with the origin of the technique or idea and followed by the primary principles it is based on and how it fares against the target parameters. Afterwards, additional comments on potential issues, solutions to them and recommendations will be given where it’s applicable.

Finally, in the discussion section the document will continue with suggestions for the steps to follow in potential future research and then conclude with a few overall recommendations in the form of flowcharts and final remarks.
2. Research Context

2.1 Problem Definition

2.1.1 Background

In the context of the construction industry, the management of assets can be a rather integral part. These assets can vary wildly in type, from financial and material, to human resources, to finished projects in the operation phase of their lifecycle. Given how necessary they are for every step of the construction process, their proper management is often vital for the success of a project.

2.1.2 Current Situation

The present research project concerns the management of one particular type of asset, namely concrete bridges. Constructions in general need to withstand heavy non-constant loads and are regularly subjected to external influences like the wind and weather. Monitoring their degradation status is required in order to ensure the safety of the people traversing them and to facilitate timely maintenance that will minimize the downtime of their use.

Currently, engineers tasked with the inspection of concrete bridges have to physically visit the structures and carry out inspections themselves. Apart from the fact that this method can be time consuming to carry out, one major issue it presents is that the structures will have locations that need to be checked and cannot be accessed easily, creating the need for specialized equipment, therefore consuming even more time and other resources. Furthermore, visual inspections alone can be entirely unreliable and often warning signs will not present themselves until it is too late to intervene in a satisfactory manner.

2.1.3 Challenges

There are several challenges that will need to be taken into account, not only within the scope of the present thesis project, but also for any potential future endeavors related to the subject matter.

Too many types of degradation mechanisms: Due to the vast number of possible degradation mechanisms, it is not possible to account for all of them in the end result, especially within the scope of a thesis project. Therefore, it will be necessary to pick and choose which ones better serve the desired purpose. While doing so, two are the most important deciding factors that should be taken into account. Firstly, how each degradation mechanism can be connected to the state of the bridge itself. Even if one of them is easy to detect, it would not be of much use if it didn't give some consequent indication of the status of the bridge. And secondly, whether there are readily available methods to detect those degradations while also fulfilling all required criteria.
The new methods may never fully replace standard inspections: It is entirely possible that the new methods may not be reliable enough to lead to completely getting rid of standard inspections. That does not render them useless however, as they could still be utilized as a cost-reducing asset through preliminary scanning, by indicating whether a standard inspection is necessary or can be postponed. One may get the most benefit out of them by employing proper time management. Assuming that some detectable parameters were set as indicators (e.g. state of the prestress cable, concrete, asphalt etc.), if at least one of them was triggered the bridge, or part of it, would need to be temporarily closed down anyway, so the opportunity could be used to carry out a full inspection of the asset. If none of the parameters was triggered, resources could be spared by postponing the full inspection up to a predetermined maximum time period.

Validation: Before any of the new methods are implemented on the field, their reliability needs to be extensively tested if they are to be trusted and employed by companies. This can only be done by cross-referencing their results with inspections that would be carried out anyway. Unfortunately, this is not something that is possible within the context of the present project, but is instead something that needs to be taken into account in future research.

2.2 Research Aim & Objectives

The aim of this study is to test the feasibility of various NDT techniques for the purpose of assessing the condition of a prestressed concrete bridge. The thesis project will focus on a few main deterioration mechanisms.

The objective is to settle on a single or a combination of satisfies the requirements set forward for the purposes of the project as much as possible. Alternatively, if none of the proposed solutions do so, potential changes to them that can make them fit will be considered.

2.3 Research Question

The main research question is:

*How can the condition of a prestressed concrete bridge asset be assessed using intelligent Non-Destructive Testing (NDT) techniques?*
In order to answer the main research question, it is broken up in the following sub-questions will have to be answered first:

1. What kind of structural degradation mechanisms exist for a concrete bridge and how can they be detected in time?
2. What actions are involved in the current process of monitoring and assessing these degradations?
3. What options are there in regards to more intelligent techniques?
4. What are the desired requirements and parameters for such a technique in this particular scenario?
5. Do any of the suggested intelligent techniques fit these requirements? If not, can they be altered in a way that makes them qualify?
6. Are the new techniques that fit the requirements more efficient than the current ones? Is any of them preferable or even optimal?
3. Target Parameters

The requirements that the examined techniques need to satisfy to the greatest possible extent in order to qualify are the following:

3.1 Non-Destructive Testing

Admittedly, the most reliable methods to accurately determine the degradation status of a concrete structure are destructive ones. However, Non-Destructive Tests (NDT) can still provide a satisfying approximation that can then indicate whether further action is required. This research project will therefore only cover techniques that fall within the context of NDT's, as the purpose is to try and avoid costs and time loss that would be incurred by the irreversible changes that destructive testing would bring forward.

3.2 Available for use

The apparatus that is required to carry out the tests needs to either be available in the market for a reasonable price or simple to construct from scratch. The reason behind this requirement is that, since the point of employing a new technique is to achieve a good combination of lower costs and increased reliability, there would be no practical use for a technique whose necessary components are incredibly expensive or are entirely unavailable and too complicated to put together.

3.3 No prolonged disruption of traffic

Preference will be given to methods that allow for the carrying out of the tests without disrupting the operation of the bridges, namely the passage of vehicles. This means methods that will not require equipment and actions which would create an obstruction on the road. However, there is some flexibility in this parameter, as methods that only disrupt the traffic for a short period of time, preferably partially, will also be considered. Alternatively, this would also include methods that can be divided into short periods over a number of days, so that they can be carried out exclusively during night hours, when traffic is at a low point.
3.4 Non-static equipment

Finally, the equipment to be utilized by the techniques needs to be mobile, so as not to require a separate set of it for each bridge. Techniques that require expensive equipment that cannot at the very least be carried between bridges within close distance of each other will be considered suboptimal. Alternatively, it would be acceptable if the methods had static components that are relatively cheap and can be installed on every location, with mobile components that would have higher tolerance levels with regards to price. It should be noted that a combination of different equipment is acceptable and also expected.

In short, in order to qualify, each solution needs to be non-destructive, available in the market or easily put together, non-disruptive to traffic and mobile.
4. Degradation Mechanisms

In this section, the major steel degradation mechanisms whose detection the present research will focus on will be summarily delineated. A more detailed description of the below mechanisms, as well as other secondary degradation mechanisms will be included in the appendix.

4.1 Corrosion

Under normal circumstances, general corrosion does not actually have a significant impact on steel’s bearing capacity. However, a local corrosion attack under certain environmental circumstances can cause a loss in that capacity in early stages through brittle fracture. Examples of such hazards include an increased accumulation of sulphates and chlorides. [Nürnberg, 2002]

4.2 Fractures

While a fracture can occur “naturally” to steel tendons due to excessive stress and fatigue, there are various causes that can make them more susceptible to it. Furthermore, while steel failure usually occurs in a ductile fashion, particular factors can cause it to be more brittle. Such factors include hydrogen embrittlement, stress corrosion cracking and tempered martensite embrittlement. Though it is often important to distinguish what the cause is, The present thesis will focus on locating fractures after the fact. [Eliaz et al., 2002]

4.3 Loss of force

Loss of prestressing tendon force is a clear, “tangible” sign of degradation that is relatively easy to express numerically, especially when it is desirable to showcase their gradual deterioration over time. There are several known causes, some of them immediate and some of them time dependent. Elastic shortening of the member, friction at the tendon-concrete interface and slip of the anchorage belong to the former category, while shrinkage and creep of the concrete and slip of the anchorage belong to the latter. [Sengupta & Menon]
5. UAV with sensors

5.1 Origin of the idea

The idea that the thesis project started with was making use of Unmanned Aerial Vehicles (UAV, also known as drones) equipped with the appropriate sensors to detect as many signs of degradation as possible.

Figure 1: Unmanned Aerial Vehicle equipped with camera

5.2 Basic Principles

The basic idea behind the concept is to make use of a UAV to carry sensors and other appropriate equipment to critical locations on the bridge. The UAV would then make sweeps of the bridge to gather all the necessary data.

The advantage of such a method would be that the drones can be guided to reach spots that would otherwise be difficult for a person to get to. In that manner it would no longer be necessary for an inspector to be present at the location, as he would be controlling it remotely to get the sensors where they need to be.

The UAV would at minimum be equipped with a high definition camera to at the very least be able to substitute for a visual inspection. With that any visible degradation could be spotted almost as reliably as it would by a person on the scene. The equipment that would be attached to it beyond that would have to be able to perform scans without direct contact and needing to be attached on the scanned object itself. There are some options that have shown promise when tested on their ability to locate defects on steel encased in concrete, among which most prevalent is the Ground Penetrating Radar
(GPR). Equipping those on a UAV, however, would require the resolution of several technical and logistical issues, rendering the suggestion unusable at this point in time.

5.3 Additional information

Drones come in a wide range of price ranges and capabilities and are highly customizable to the needs of the user. The cheapest commercial ones can be found for even as low as 50 euros to allow for low risk employee training before they move on to the models that would actually be used in practice. These typically don’t have a weight lifting capacity that can exceed 0,5-1,5 kg. As the prices go up, so do their weight lifting capabilities and control precision. The weight a drone can lift will generally depend on the number of rotors, their size and their power. It should be noted, however, that the price increase becomes exponential. As an example, the octorotor depicted below is available for professional purposes that require precision. It comes equipped with an HD camera and GPS, is rainproof and can safely lift a maximum load of 15 kg with a battery life of just below an hour. It’s currently available for sale new with a price that fluctuates and can range anywhere between 1.000 and 2.000 USD per set. [alibaba.com]

![Figure 2: UAV drone model MMC MC6-1600](source: alibaba.com)

Drones have already been used to carry out structural inspections on the field and in fact there are currently examples of inspection companies for hire that offer such services. [safescaninspections.com] Among the advantages of the method that they advertise are the capabilities to:

- Inspect any and all hard to reach areas
- Eliminate the need to shut down traffic and general access
- Detect even tiny cracks
5.4 Applying the criteria

The technique by definition qualifies as non-destructive, as the UAV would simply be making passes over certain locations and there would therefore be no alterations on the bridge. The rest of the process itself would depend on the individual sensors attached to the machine.

In addition, there are several types of drones already available for sale in the market for relatively very cheap prices. Since accuracy is a concern, the chosen model would need to be able to stabilize itself and hover on the same spot for as long as is needed for a full scan to be performed.

Since the machine has the ability to fly, it would not need to make use of roads and would therefore not disrupt traffic during its use. The only exception to that would be when the surface of the bridge itself needs to be scanned, since sensors generally cannot operate at a distance that would allow the drone to hover safely above traffic. In such a case, a human crew might as well be the ones to carry the inspection themselves.

Finally, drones are generally lightweight and capable of independent mobility, which makes it easy for them and the attached sensors to be moved from one bridge to another without too many problems. As a result, there is no need to acquire a separate set of equipment for each one. The optimal solution would be to divide the objects into areas and have a UAV corresponding to each area.

All in all, as long as the appropriate sensors are selected, the method should be able to adequately satisfy all criteria with the exception of when the surface of the bridge needs to be examined.

5.5 Issues

There are however a few concerns to be had with regards to the accuracy that such scans would be able to guarantee. These concerns are primarily raised by two factors:

Movement introduces “noise” in readings: Many of the viable detection methods would be hindered by the introduction of a mobile platform into the equation. The “noise” that an even slightly moving sensor introduces would bring forward complications when attempting to utilize the acquired data. There are several potential ways around this issue, including but not limited to:

- Taking the “noise” into account during the computation of the data, though further complicating the calculations.
- Figuring out a way to nullify the movement altogether, at least for the duration of the scan
**Distance reduces accuracy**: The majority of sensors are created with the assumption that they will be brought in contact with the subject, or at the very least within a close distance, which can be as small as a few cm. As a result, distances greater than that may introduce insurmountable inaccuracies. Whether the sensors can be brought close enough to get a reliable reading with the new methods is something that needs to be kept in mind.

### 5.6 Potential solutions

While the issue of having reduced accuracy due to not being in contact with the target is inherent to the method, it can still be mitigated by making use of a UAV with precision controls that can be kept stable as close to the target as possible.

With regards to the noise introduced by movement, one potential solution would be to have the UAV land on platforms placed on predetermined spots to be able to remain stationary while carrying out the scans.

Alternatively, both of the mentioned problems could be countered by having the drone act as a receiver for data from pre-installed static sensors. The machine itself would still be equipped with a high resolution camera for the visual part of the inspection, but for the part of the more in-depth checks it would play the role of carrier of information.

Unfortunately, both of these suggestions have the disadvantage of severely limiting the number of locations that can be checked, as placing permanent platforms or static sensors on a larger number of spots would be prohibitive cost-wise.

### 5.7 Recommendation

It should be noted that at the very least aerial drones have successfully been used on the field to replace normal visual inspections and proven to be very effective, producing faster inspection times, no need to shut down the structure during inspection and less required manpower, therefore leading to a potential significant reduction of the usual costs. This particular aspect of their performance should be kept in mind when considering their future use.

Furthermore, while employing them in combination with other sensors puts forward limitations with regards to their flexibility and accuracy, they are still limitations that have the potential to be overcome in the future.
6. Laser Doppler Vibrometry

6.1 Origin of the idea

The idea was brought up while discussing that the results of testing methods should be clear indicators of what the actual current status of the bridge is. The loss of cable stress was considered an obvious such indicator and as such this suggestion was further looked into and yielded the following results.

6.2 Basic Principles

This method has the purpose of measuring loss of stress from a cable and is based on the Taut String Theory, which can be used to calculate the natural frequency $\omega_n$ of a cable, based on the following equation:

$$\omega_n = n \pi \sqrt{\frac{T}{m L^2}}$$

Where:
- $n$ is the $n^{th}$ mode of vibration,
- $m$ is the distributed mass per unit length,
- $T$ is the cable tension and
- $L$ is the total or effective length of a cable

Taking the formula into consideration and inverting it leads to being able to calculate the cable tension $T$, as long as its physical parameters and natural frequency are known. Laser Doppler Vibrometry (LDV) can then be used to measure the natural frequency of a cable before inserting it into the formula.

A laser Doppler vibrometer is a non-destructive interferometer which emits a beam divided in two parts, one being transmitted and the other being used as a reference. The transmitting beam hits the target surface before being reflected back onto the detector and combined with the reference beam. The frequency shift between the reflected beam and the reference beam can then be measured and is attributed to the velocity the target surface had at the moment of impact because of the Doppler effect.

This process is carried out for a while until the frequency detected is the natural frequency of the cable, in which the vibrations of the cable would have the maximum displacement. [Chen & Petro, 2005]

6.3 Additional information

An approximate sketch of how the vibrometer works can be seen in figure 3.
The image demonstrates in a simple way how the initial beam is divided into 2 parts by the beam splitter, the reference and test beams. While the reference beam maintains its original frequency all the way through, the test beam passes through a Bragg modulator that shifts its frequency and differentiates it. Its frequency is further shifted once it hits the vibrating target surface due to the Doppler effect. The test beam is then reflected and guided back to the photo detector along with the reference beam, giving a reading of the frequency shift $f_d$ caused by the target. [Kaczmarek et al., 2004]

A laser Doppler vibrometer can be purchased for a price ranging between 2.000 and 5.000 USD on commercial sites.

### 6.4 Issues

Unfortunately, LDV would only work on exposed cables, as the laser beam would need to be either reflected by the target object that is to be studied or a container that vibrates in the same frequency. In the Netherlands prestressed cables are encased not only in metal ducts but then also in concrete. As neither of those is guaranteed to behave in the same manner under vibrations, the occurring results would not give any information on the cables themselves.

Acoustic methods were then proposed as an alternative. They would in theory be used as another manner with which to measure the frequency by employing impacts and without needing to have access to the entire length of the cable. However, as the cables are also grouted in place they would not be able vibrate freely and the results would again be highly skewed, making the method unusable.
In summation, these methods wouldn’t work for the purposes of a prestressed concrete bridge, but could prove useful when applied to a suspension bridge. Structural vibrations can and have in fact also been used to assess the state of other types of structures, including building connection bridges. [Dai & Huang, 2014]
7. Infrared Temperature Detection

7.1 Basic Principles

The basic idea behind this theory was that, since corrosion is a chemical reaction, it is likely to either produce or absorb heat. In other words whether it is an exothermic or endothermic reaction respectively, it would have an impact on the local temperature that could potentially be picked up by a sensor.

It is known that corrosion reactions such as the oxidation of metals are exothermic reactions, so in this particular scenario the corrosion process would produce heat, as the chemical bonds yield a net loss of energy, which escapes in the surroundings in the form of heat.

7.2 Issues

This idea was quickly abandoned as there were several problems right from the start. For one, such an emission of heat would only be present while the chemical process is taking place. Since the goal is to be able to detect the presence of corrosion in already existing structures, the method would be of no use, as any produced heat would be long gone.

In addition, even if a structure were to be constantly monitored to detect an increase in heat, the amount of it produced by the particular chemical process would not be significant enough to be able to safely attribute it specifically to corrosion and could instead have been caused by numerous other sources. To make matters worse, the heat would rapidly dissipate within the structure and have a high likelihood of not being picked up by the sensors in the first place.

However, the option of thermographic methods still exists as a possibility to combine with others in order to yield better results and will in fact be brought up again in the following sections.
8. Coil sensors for force measurement and defect detection

8.1 Origin of the method

This is part of a group of methods that have been developed by Alex Holst, Harald Budelmann and their associates for almost a decade. The earliest reference to it can be found in a paper published in 2006, with numerous contributions since. [Holst et al., 2006]

8.2 Basic Principles

The basis of this method is called the Villari effect, also known as the inverse magnetostrictive effect. The Villari effect refers to the change of magnetic properties of ferromagnetic materials when subjected to mechanical stress. As a result, the connection between these magnetic and mechanical properties can be used as a medium between sensor input and force measurement, should lead to an end result that LDV couldn't achieve.

Figure 4: (a and b) Mounting procedure of sensor assembly and (c) mounted sensor on external bridge tendons [Budelmann, Holst & Wichmann, 2013]
The instruments used in this method are cylindrical double coil sensors in varying sizes that will fit the prestressed steel samples they are to be attached to. Due to their small size, they can be mounted in places where other bulkier sensors would not be able to. The mounting procedure itself is also rather simple, as the sensor need only be pushed onto the tendon to be inspected. [Budelmann, Holst & Wichmann, 2013]

The technique has been successfully tested in practice on both a 18.5m long trial bridge and actual box girder bridges in Germany and to some extent in Japan and the US [Sumitro, Miyamoto & Jarosevic, 2011]. In all experiments surface defects were shown to have a significant effect on the magnetic parameters of the material. As an added benefit, since corrosion does affect material properties, stress distribution and magnetic parameters, the technique can also be used for its detection. The sensor is sensitive to corrosion induced modification of the cross section, making the technique’s purpose twofold.

8.3 Applying the criteria

The coil sensors only need to be mounted on the tendon in order to function. Since no alterations to the structure in question are required, the techniques does qualify as non-destructive, therefore fulfilling the first basic requirement.

However, whether it can be carried out without disrupting the bridge's traffic for a long duration of time is highly dependent on the location and accessibility of the tendons to be inspected. While it is unlikely that the sensors themselves could be placed in a problematic location, if anywhere at all, requiring equipment such as a crane to reach a normally inaccessible location would cause issues.

Moreover, while a coil sensor of these specifications is not standard issue in the market, it is described to be of simple and sturdy construction. As a result, it should not be particularly costly to put one or more together.

Finally, the coils are of relatively small size and only require a simple procedure to be mounted and dismounted on the tendons, meaning that they can easily be carried between multiple bridges to be used there. The only limitation on that regard would be the differences in the width of the tendons to be inspected and by extension the corresponding required sizes of the coils, leaving open the possibility of requiring some differently sized sensors.
8.4 Issues

Both aspects of the method, namely force measurement and defect (e.g. corrosion) detection, suffer from limitations that render them not universally applicable. More specifically, they both work comparatively, which has different ramifications for each of the two.

With regards to defect detection, the fact that the method works comparatively means that defects can only be detected locally. In other words, the coil has to be moved along the steel element to pick up on local anomalies when it is located above them and therefore free access to the entire length of the tendon is required. While that was not a major issue in Germany where the technique was developed, the majority of prestressed tendons in the Netherlands is encased in concrete, significantly decreasing the technique's useability.

As for the force measurement aspect, it only requires to be mounted on a single spot to check the entire tendon, making it somewhat less limited. However, an initial calibration of the sensor on the steel type and diameter is necessary to achieve exact results, for example during the prestressing procedure on site. This makes the method mostly useful when employed from the beginning of the lifecycle of a bridge, so that the gradual degradation can be monitored, but with reduced usefulness for existing constructions.

8.5 Recommendation

Using the method to monitor forces on a newly constructed bridge does have potential. Even if there is no exposed part of the tendon to mount the coil after the fact, it could still be built into the concrete upon construction.

In addition, there is technically a way to overcome the limitation with regards to existing constructions. The sensor primarily needs to be calibrated for steel type and diameter, so as long as an identical sample can be created it could still serve as a reference point for the method to work with.
9. ERM based on frequency domain reflectometry

9.1 Origin of the method

This is a second method developed by the same group of researchers as the previous one, with a slightly longer history going back to 2003. Both of the last 2 methods have been part of omnibus papers published by them that listed a variety of methods together. [Hariri et al., 2003]

9.2 Basic Principles

The electromagnetic resonance measurement (ERM) is a reflection measurement technique used for the detection, as well as localization, of fractures in prestressed tendons and steel cables. Its idea is based on thinking of the prestressed steel as an unshielded resonator contained within an electromagnetically lossy material.

By emitting an electromagnetic wave of variable frequency on one end of the tendon and scanning the reflection with a vector network analyzer (NWA), it is possible to record resonance frequencies of a tendon. The length of the tendon, or the distance to the fracture, is inversely proportional to the spacings between two adjacent resonance frequencies and can be calculated as long as the material's relative permittivity $\varepsilon_r$ is known.

Even though there are several notable differences between how the two methods work, there are a lot of similarities in the limitations between this method and the force measurement method of the previous section. [Holst, Budelmann & Wichmann, 2012]
9.3 Applying the criteria

As with all methods that are examined for the purposes of this project, this method does not require any changes to be made to the structure and is therefore non-destructive. Also similar to the previous method, whether the traffic would need to be disrupted depends on where a single exposed part of the tendon can be accessed, if at all.

While a NWA is readily available for purchase in the market, its price is rather high ranging between 6.000-10.000 for a refurbished device alone. The upside is that the device is small and very easily portable and does not need to be tailored to a particular type of tendon, meaning that a single device can be used for the inspection of a greater number of bridges.

9.4 Issues

Similar to the previous technique, this one requires to be calibrated beforehand in order to measure the relative permittivity of the object, which is dependent not only on the properties of the material but also its original length. It is common for such methods to require calibration upon construction, meaning that they are generally much more useful when applied to new structures rather than existing ones, offering more limited usefulness to the latter.

Furthermore, while applying the technique in a lab is quite simple, electrical interactions within real structures complicates the measured reflection data. As a result, when it comes to for example multi-strand tendons encased in a metal duct, it is usually only possible to make a qualitative statement about whether a fracture exists or not without localizing it.

9.5 Potential solutions and alternative uses

Despite the fact that ERM is more easily usable when employed since the early stages of a bridge's lifecycle, there are ways to work around that. The tendon itself is not the only way to perform the calibration. As long as a twin tendon with similar specifications and length can be constructed, it can serve as the reference wire to which the real one will be compared. The reference wire will of course need to have no defects such as fractures or corrosion, so that deviations in the real one would indicate their presence.

Moreover, the NWA has some additional alternative uses. To begin with, while localization only works for fractures and not even in the more complex situations, studying the reflection of the wave can still indicate the presence of various other alterations of the tendon's original state, such as reduction of cross-sectional area. More importantly, it should be particularly effective in the detection of corrosion by taking advantage of what is called the skin effect. The skin effect is the tendency of alternating currents to travel through a conductor so that the current is denser closer to its surface. The higher the
frequency of the current, the thinner the “skin depth” $\delta$ through which the majority of the current travels. What this means for our purposes, by combining it with the fact that corrosion dampens the signal and first appears on the surface of a cable, is that by making use of a high frequency current corrosion should cause a significant weakening of the reflected wave, if it returns at all, giving away a strong indication of its presence.

### 9.6 Recommendation

This technique is something that should definitely be kept in mind when establishing the monitoring methods for a newly constructed bridge. It is quick and simple and can be sensitive to a wider variety of issues. The possibility of making use of it on existing structures through the creation of “twin tendons” is also worth investigating.
10. Half-cell potential

10.1 Origin of the method

This is a method that is already being used in practice to detect corrosion rather than being an experimental one. It is brought up in the present project for completion’s sake and because it can be useful to complement other methods for optimal results.

10.2 Basic principles

Reinforcing steel is normally protected from corrosion within the highly alkaline environment of concrete by a thin oxide film known as the passive film. However, this film can be destroyed when the alkalinity is lost due to chlorides penetrating the covering concrete or when it is carbonated. When it no longer has that protection, the steel is then vulnerable to corrosion, which will begin occurring in the presence of oxygen and humidity.

During the corrosion of a metal separate anodic and cathodic reactions take place at the same time, with the corroding metal acting as a mixed electrode as the reactions occur on its surface. The corrosion potential $E_{\text{corr}}$ can then be measured as potential difference, or voltage, against a reference electrode. The measured numerical value will be dependent on the type of reference electrode used and the corrosion state of the encased steel. [Elsener et al., 2003]

10.3 Applying the criteria

Where this method has the highest potential to fail the criteria is on the time aspect. Because it uses single points as representative of larger surface areas, numerous grid based measurements need to be taken in very small distances from each other in order for the results to be in any way reliable. Furthermore, multiple readings should be taken on each spot while the target concrete surface is being kept wet at all times during the survey period to ensure electrical conduction.

At best, and when there is computer assisted data acquisition and a multiple wheel measurement instrument, the technique can cover a few hundred m$^2$ per hour. This means that, depending on the size of the bridge and the number of surfaces on it that need to be measured, its application duration can by far exceed what is considered acceptable.
10.4 Recommendation

While this technique is too time consuming to be used on its own in the entirety of a bridge, it can be much more effective in localizing corrosion spots that have already been indicated to be present in a single (group of) tendon(s) by another method, such as the ERM. Dividing the bridge in sections and scanning a different one each day at low traffic hours could help further reduce the strain.

As a result, it should be kept in mind as a secondary follow-up method when the presence of corrosion has already been indicated and higher precision is required.
11. Remanent Magnetism

11.1 Origin of the method

This is yet another method with a long history that was researched and developed by Dr. Bernd H. Hillemeier, formerly of the Technical University of Berlin, and his associates for nearly 20 years. The earliest instance of a published paper documenting the method and experimental results dates all the way back to 1997, with numerous other research papers having been published since. The method has had its ability to detect prestressing steel fractures tested on actual structures and has been developed in collaboration with the construction company Hochtief. [Scheel & Hillemeier, 1997]

![Image of measurement setup](image)

Figure 6: Left: Measurement from vertical surface of beam with the magnet suspended on a flexible support system. Right: Magnetization and measurement from the surface above [Scheel & Hillemeier 2003]

11.2 Basic Principles

This method basically takes advantage of the way magnets behave to detect fractures in concrete embedded steel. Simply put, when a bar magnet is broken into pieces, all of those pieces become separate magnets and 2 poles of reverse polarity form at every point of fracture. By extension, a magnetized tendon or steel wire would behave in the same way, because the magnetic field produced by them is similar to that of a bar magnet.
As a result, locating a crack, fracture or corrosion spot on a magnetized tendon becomes as simple as locating the 2 magnetic poles that would be formed in its location by scanning for the polarization reversal. It is generally possible to detect a fracture in a single wire contained within a bundle of multiple wires. However, in a full size structure there are potentially factors that introduce complicating parameters and the depth to which the sensors can penetrate the concrete will depend on those complications. In the simplest case of a single wire with a cross section larger than 50 mm$^2$, a fracture can be detected up to 30 cm deep. In a more complex case of 40 single wires of a smaller cross section, the penetration depth could be reduced to as low as 10 cm.

Another major practical advantage of the method is that it can not only be used on horizontal bottom surfaces, but also vertical and horizontal top surfaces. Because of that, it can be employed in every situation where the tendons are relatively close to the surface without needing to in any way compromise the integrity of the concrete cover. [Hillemeier & Walther, 2007]

### 11.3 Applying the criteria

With the exception of the availability of the sensing device, the technique seems to satisfy all criteria. To begin with, it is non-destructive, as the tendons can be magnetized and then the magnetic fields be detected from the surface of the concrete, as long as they are not embedded too deep within.

The device is also highly portable and there are currently 2 versions of it. The first is a smaller version that can be carried by hand and can be seen in the images above. The second is a larger and more powerful version attached to a carrier that allows it to be towed by a vehicle in order to both transport it and scan with it.

As for the obstruction of traffic, the bridge will inevitably need to be closed to the public in order to scan the bridge deck. However, it is possible to close down only part of it and carry out the scans in strips during low traffic hours. When scanning using the vehicle-towed device, it is possible to move it with a speed of up to 5 km/h, so several passes can be made in a relatively short period of time.

Finally, with regards to the availability of the device, presently it is known to be possessed by the German company Hochtief and Professor Hillemeier of the Technical University of Berlin.

### 11.4 Recommendation

All in all, the technique definitely holds promise and is worth investigating further. Since the device is not openly available, it needs to be examined whether it would make more practical and economical sense to attempt to build a new one or make arrangements to lease the use of the existing ones.
12. Combination of electromagnetic and thermographic methods

12.1 Origin of the method

This is the last examined idea that was previously tested and has documented results based on existing research. In comparison to others, it is a relatively recent method of corrosion detection. However, the use of induction heating itself has existed for a while, including in the construction industry where it was used to determine the location of reinforcing members embedded in concrete, as is evident by a US patent owned by Dr. Bernd Hillemeier dating back to 1980. [Justia Patents, 1980]

12.2 Basic principles

This method makes use of a combination of previously examined concepts, employing both magnetic techniques and an infrared sensor for a thermographic scan. However, instead of analyzing the magnetic properties of the tendon material or magnetizing it, this technique opts to use magnetism to excite the tendon and cause it to generate heat.

The primary phenomenon it's based on is called induction heating. The device that is sued to cause it to occur consists of an induction heating coil, a water-cooling unit and power supply that provides a high frequency alternating current. As long as that current is flowing through the coil, it generates a changing magnetic field. Eddy currents are induced to any conductive object found within that field, such as a steel rebar, and its electrical resistance causes it to generate Joule heating.

Figure 7: Magnetic field and resulting heated regions during electromagnetic induction heating [Oshita, 2015]
That heating and its associated infrared (IR) radiation can be picked up by thermography with an IR camera. Because corroded points on the rebar have higher electrical resistance, spots with higher corrosion will generate a more intense peak IR radiation and heat up more quickly. On the other hand, corrosion blocks heat conduction between the rebar and the concrete cover, preventing heat from reaching the surface as easily as it would on the rest of the rebar, leading to a higher IR radiation produced by the rebar, but lower temperature concrete surface on the rest of its length, as can be seen on the left and right side of the below image respectively. [Oshita, 2015]

![Image of infrared thermography and thermographic images](image)

**Figure 8:** Left: Infrared thermography of reinforced concrete specimens with 1 inch (~2.5 cm) cover at varying corrosion levels. [Baek, Xue, Feng & Kwon, 2012] Right: Thermographic images of concrete surface above heated rebar with (a) 3 cm, (b) 5 cm and (c) 7 cm cover. [Oshita 2015]

### 12.3 Applying the criteria

With the exception of the time aspect, which will be touched upon in the next section, the method does seem to satisfy the criteria. It can be carried out with minimum or even zero direct contact to the structure, so it qualifies as non destructive.

In addition, every required apparatus is already readily available in the market. As induction heating is being used in various industry sectors, the induction coils exist in various forms. As for the power source and IR camera, they are easily obtainable common devices, with the power output required of the source being the only factor that could potentially be something to consider.

Finally, the overall apparatus is for the most part portable, with the bulkier part being the device's power source, whose size can vary greatly depending on model and the output that is required of it.
12.4 Issues

As was mentioned in the previous section, the factor of the heating process's duration could be cause for concern and is largely an unknown with regards to actual structures at the moment, as the experiment has so far only been carried out on small blocks of reinforced concrete samples with a length of approximately half a meter.

The heating period that has been reportedly used on the various papers can vary from as low as 1 minute to as high as 13 minutes. Given that those tests were carried out on such small samples, that variation can make for a huge difference when the technique is put to use on a full sized bridge. As a result, that needs to be kept in mind and any factors that can potentially increase the speed of the heating process, such as the power of the alternating current, need to be considered while also taking cost into account.

Finally, there’s one particular discrepancy between the two sources mentioned that may need to be cleared up. While corrosion causes the temperature of the reinforcement itself to rise faster, due to its thermal insulating nature the increase on the surface of the concrete should still be lower. However, in Baek et al’s paper they show that the relative IR intensity that they employ to measure it is actually higher when corrosion is present, even though it shouldn’t be possible to “see” beneath the concrete itself. Though the cause may be worth investigating, it should be pointed out that other research papers on the subject actually seem to agree with Oshita’s results, meaning that corrosion spots would appear as cold spots after all. [Kobayashi & Banthia, 2011]

12.5 Recommendation

This is yet another promising method to keep an eye out for that uses steel's electromagnetic properties to detect defects. Since this can be used to detect corrosion, it can potentially be combined with the remanent magnetism method that can detect fractures. Unfortunately, the two methods can't actually be carried out using the exact same equipment. For remanent magnetism, in order to magnetize the rebar, a Direct Current (DC) is required. On the other hand, for the purposes of induction heating, a high frequency Alternating Current (AC) needs to be flowing through the coil, as it is the only way to induce Eddy currents through the resulting magnetic field. In other words, at the very least a different power source would be required, which is a major part of the overall apparatus.

Furthermore, the technique has so far only been tested under controlled conditions in labs. Therefore, actual field tests are required before it can be fully recommended in practice.
13. Heating through direct high frequency AC excitation

13.1 Origin of the idea

This is a novel idea which, while in theory is based on solid concepts, does not as of this time have documented results to support its ability to be of use in practice. The idea is based on being an extension of the previous method, with the difference that instead of it being contactless, there would be an attempt to render stuff presence on the bridge unnecessary by making the heating be the result of a source permanently attached on the tendons.

13.2 Basic principles

The principle the idea is based is very similar to that of the previous one, with the only difference being the way in which the tendons are excited to generate heat. While in the previous method the tendons were to be excited contactlessly through the use of magnetic fields and Eddy currents, in this one an electric current generator permanently attached to one or both ends of the tendon would be used instead.

The generators would be able to be activated and controlled remotely and would present three advantages in comparison to the Eddy current method. The first is that the current would travel through the entire length of the cable, allowing it all to be heated at once instead of in small increments. The second is that the heating phase would not require the bridge to be closed down. Even if it was possible to employ the Eddy currents without the required equipment obstructing the road, the magnetic fields could potentially put the passing vehicles' engines in jeopardy. Finally, since the heating phase would not require the traffic to be discontinued in the first place, the potential exists for the thermographic part to be carried out entirely by a UAV that would be carrying the much lighter IR sensor component.

As was already mentioned, the technique should in theory work, as it is based on solid concepts. Electric or resistance heating, as it is called, is already being used in the industry for various purposes, such as welding. It takes advantage of the fact that the energy lost due to the electric resistance of a material as the alternating current passes through it is converted into heat. Corrosion and rust that has taken place on a steel rebar increases its resistance, therefore also increasing the amount of heat resulting from the current, causing it to reach higher levels more quickly.

13.3 Additional information

In contrast with induction heating, resistance heating is much more effective in heating up metal components. In the previous section it was shown that with a potential difference of approximately 50V and a heating period of several minutes, induction heating could cause a rise in temperature on the
concrete surface of a maximum of 5 degrees Celsius, with the temperature of the reinforcement inside not exceeding 80 degrees.

With resistance heating on the other hand, a voltage of 20V is all it takes to bring forward a temperature rise measured in the hundreds degrees with a heating period measured in seconds, as is shown in the graph below. [Karunasena, Greene & Chen, 1978] As such an extreme difference could be severely detrimental to a material under stress, a much lower voltage might be more appropriate if this method were to be tested, which will likely need to be modeled and calculated beforehand.

![Graph showing results of resistance heating](image)

**Figure 9:** Results of using resistance heating on a rectangular stainless steel sheet blank. [Karunasena, Greene & Chen, 1978]

Fortunately, the flow of electricity and resulting heating complies to known circuit and thermodynamic laws. It can be seen that the theoretical temperature was able to be calculated relatively accurately through equations beforehand. It should be noted, however, that this was a simple example with known or controllable variables and would not necessarily be as simple in practice.

At the very least, it should be possible to predict the flow of electricity by creating a model of the interconnected prestressing steel tendons of a girder and applying Kirchoff’s circuit laws a large number of times to calculate the electric current passing through each section. The produced heat would then be equivalent to the square of the current multiplied by that section’s resistance, which can be useful when having a baseline to work comparatively.
13.4 Applying the criteria

As this is so similar to the Eddy currents method, the same comments apply with regards to the criteria, with one major difference. Should the overall method be feasible, the factor of time that bogged down the other method would no longer be an issue.

13.5 Issues

The primary issue with employing electric heating as an alternative is the number of unknown factors with regards to its feasibility. The method has to be tested from scratch by future research in order to verify its ability to be effectively used on the field. Should those tests be able to be successfully carried out with promising results, that would open the way to solving numerous issues when combining this method with others.

There is however another factor that can cause major issues and needs to be taken into account. That is a phenomenon called hydrogen embrittlement, to which high strength steels like prestressing steel are particularly vulnerable. It’s a phenomenon that occurs when hydrogen is brought in contact with the surface of a metal and then the atoms of the former are subsequently diffused through the latter. While a high temperature is not necessary to propagate the situation, it can further exacerbate the diffusion of hydrogen, which is another reason special care needs to be taken when calculating the proper voltage to achieve the desired temperature change.

Furthermore, there is one more reason that could potentially render this method unusable due to the existence of hydrogen embrittlement. Because of the use of electric current, it is possible that hydrogen atoms will be collected on the cathode and be transferred to the prestressing steel, causing it to become a vulnerability point for it. Those atoms can originate from something as simple as moisture, so it could be tricky to defend against. [Li et al, 2015]

13.6 Recommendation

Despite how efficient this method would be if it could be made to work, the sheer number of unknown factors and potential safety issues can make it hard to recommend. Those issues need to be resolved if it is to be put to use on the field.

As a result, extensive testing from the ground up needs to be carried out first. There are questions that need to be answered before even considering the matter of hydrogen embrittlement, such as whether corroded spots would react sufficiently differently to be detectable as they did when induction heating was employed.
Another question concerns what the optimal set-up to attach the electrodes is. Obviously it is not possible to drill holes for every tendon, but the fact that the tendons are brought to electric contact with each other through rebar can be taken advantage of. A set-up would still need to be determined that would allow all desired locations to be sufficiently heated without risking overheating another one.

Finally, the potential of inadvertently causing hydrogen embrittlement introduces a safety concern that needs to be addressed. If the method carries a high risk factor with it, putting it to use on the field is likely never going to happen.
14. Discussion

In this section there will be a discussion of which of the examined methods have shown promise and are worth investigating further. For each of them, should further experiments be required, the components and overall setting necessary to carry them out will be described. Finally, which methods compliment each other well and which stand above the others will also be commented upon.

The methods will be listed in an order of descending relevance.

14.1 Heating through direct high frequency AC excitation

Of all the ideas mentioned, the last one to be brought up holds the greatest potential to be the most efficient in practice, should it prove to be feasible. However, it is also the one about which the least is known, as this direction has yet to be investigated and tested. As a result, it should be a priority when deciding what to experiment on for future research.

Since there is so little information to go on, its feasibility needs to be tested from the ground up, starting from simple lab tests and moving up to full scale tests on actual structures. In the paragraphs below, a general outline will be suggested with regards to the components and set-up of each of the steps of this process. Since this will for the most part go through the entire spectrum of the testing process, it will potentially be used as a reference for similar suggestions for the rest of the methods that will be brought up in this section.

14.1.1 Modeling

The first part of the process would be an attempt to create simulation models to gain a better understanding of the situation. As Karunasena et al.’s study showcased, it is in theory possible to achieve a good approximation of the temperatures resulting from the electric current flowing through metal. Relevant equations can be found in the appendix.

However, simulating the case of an actual structure would obviously be far more complicated than the simple scenario used in their study. For the time being, the primary interest would lie in simulating the case of the samples that will be used for the lab tests. The question that needs to be answered before any testing happens is how much current is required to achieve the desired safe temperatures in an amount of time that is neither long enough to delay the overall process, nor short enough to cause the temperature to reach undesired levels before any significant surveying can be carried out.

The more complex full scale simulation of the bridge will be carried out through the use of appropriate programmes after the method has been confirmed to work on test samples. An example of the simpler model will be given here. The primary aim of this model is to determine the appropriate ballpark for the
current’s frequency and how much thermal energy is produced by how much current. For that purpose, an Excel spreadsheet was created that allows for the user to input non-constant parameters and get the relevant results.

The spreadsheet is divided into 3 different tables. The purpose of the first table, an example of whose can be seen below, is to calculate a frequency that would make good use of the skin effect for the purposes of the experiment.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected corrosion ratio</td>
<td>1 %</td>
</tr>
<tr>
<td>Desirable skin depth $\delta$</td>
<td>0,1 mm</td>
</tr>
<tr>
<td>Magnetic permeability $\mu$ (steel)</td>
<td>1,26 $10^{-4}$ H/m</td>
</tr>
<tr>
<td>Electrical resistivity $\rho$ (steel)</td>
<td>1,69 $10^{-7}$ $\Omega$.m</td>
</tr>
<tr>
<td>Suggested frequency $f$</td>
<td>42,69 kHz</td>
</tr>
</tbody>
</table>

Figure 10a: Model for calculating an appropriate frequency

In this case, the user input is the diameter of the reinforcement or tendon, either as a whole or down to its individual wires. In addition, an expected or tolerable corroded percentage of the diameter is also required. Normally, 10% would be considered fully corroded, so this value really shouldn’t be above 5%. For the purpose of demonstration, values of 20 mm and 1% respectively were selected.

From those values, the desirable skin depth so that the current would flow through that 1% is selected. Since 1% would include both of its ends, the value is also divided by 2. Now all that is required is the material’s electromagnetic parameters. However, those parameters are not always constant even for the exact same material and can be affected by a number of outside factors, such as temperature. For the sake of simplicity in order to make this calculation possible, it is assumed that this deviation can be ignored. Some standard values of those parameters that can be found for steel were then input into the table to be used for the final calculation.

$$d = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

This is the equation that was used for that calculation and is further explained in the appendix, keeping in mind that the resistivity $\rho$ and conductivity $\sigma$ are reciprocal and can therefore be easily deduced from each other. The equation was solved for the frequency $f$ and the resulting one was then inserted into the spreadsheet.

For the input values chosen, the final result of the whole process was a suggested frequency of 42,69 kHz to make full use of the skin effect. The spreadsheet makes it easy to fiddle with the input values to
quickly get another result for different limitations. For example, let’s assume we have a power source than can only reach 50 kHz and want to check whether it would also be viable for a 18 mm diameter.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>18 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected corrosion ratio</td>
<td>1 %</td>
</tr>
<tr>
<td>Desirable skin depth δ</td>
<td>0,09 mm</td>
</tr>
<tr>
<td>Magnetic permeability μ (steel)</td>
<td>1,26 $10^{-4}$ H/m</td>
</tr>
<tr>
<td>Electrical resistivity ρ (steel)</td>
<td>1,69 $10^{-7}$ Ω.m</td>
</tr>
<tr>
<td>Suggested frequency f</td>
<td>52,71 kHz</td>
</tr>
</tbody>
</table>

Figure 10b: Model for calculating an appropriate frequency

As can be seen, the suggested frequency is now 52,71 kHz, which is just above the desired upper limit. However, the skin depth only exceeds the desired value by 0,002 mm, so it’s up to the individual researcher to decide whether that is an acceptable deviation.

As a final example, the corrosion ratio will now be made a bit more flexible and be raised to the 5% value mentioned earlier. Without changing the diameter, the final output becomes significantly lower and falls to a value of a “mere” 2,11 kHz.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected corrosion ratio</td>
<td>5 %</td>
</tr>
<tr>
<td>Desirable skin depth δ</td>
<td>0,1 mm</td>
</tr>
<tr>
<td>Magnetic permeability μ (steel)</td>
<td>1,26 $10^{-4}$ H/m</td>
</tr>
<tr>
<td>Electrical resistivity ρ (steel)</td>
<td>1,69 $10^{-7}$ Ω.m</td>
</tr>
<tr>
<td>Suggested frequency f</td>
<td>42,69 kHz</td>
</tr>
</tbody>
</table>

Figure 10c: Model for calculating an appropriate frequency

After several repetitions, the new minimum value for the diameter is found, while keeping the power source’s limitation unchanged. It is found that it is now viable for a wire as thin as 4 mm. Reducing that value further by even a single mm would considerably raise the required frequency to 75,9 kHz.

The second table is much smaller, because it makes use of the same electromagnetic parameters without including them by borrowing them from the previous one. It is used to calculate the real skin depth by using the frequency that was eventually settled upon as input and the original equation as it was already solved for δ. For this example, it is assumed that the previously mentioned theoretical power source was set to its maximum value of 50 kHz.
Actual frequency $f$ | 50 | kHz  
|-----------------|----|-------|  
| Skin depth $\delta$ | 0,09 | mm  

Figure 11a: Model for calculating the actual skin depth

Finally, the third table begins by calculating the amount of power that would be converted from electrical to thermal energy due to the material’s resistance, thanks to the Joule heating phenomenon. That is measured in Joule/sec and per meter of examined conductor. It should be noted that corrosion spots usually have a much shorter length than that, even down to 1 cm. However, while length has an effect on resistance, that effect is removed again for the final result of temperature shift due to dividing by the mass. The table then proceeds to also calculate the resulting temperature increase. In addition to the previously required input, there is extra information that is required for this model to work.

To begin with, the resistivity value $\rho$ for the corrosion product is needed. For iron and steel, that is typically an iron oxide, otherwise known as rust, with its most common naturally occurring form being Fe$_2$O$_3$. Like before, while the value can fluctuate due to outside factors, a single representative constant value was chosen. [Shinde et al., 2011]

Next is the cross-sectional area $A$, calculated for a circle by the simple formula of $A = \pi d^2/4$. However, the total area of the conductor is not the only one needed, but also the ones of the rings formed by the corrosion depth and skin depth.

Finally, the effective resistance of the conductor needs to be calculated, when taking into account that the current only flows through a small part of it and therefore does not make use of the full cross-sectional area. This value is governed by the following equation.

$$ R = \rho \frac{\ell}{A} $$

Since the final result is meant to be expressed per meter, the section’s length is set to a default value of 1 m, but the spreadsheet allows for changing it to fit each specific scenario. As can be seen in the final table below, that value is several orders of magnitude larger for the corroded section in comparison to the uncorroded one, since rust is not a good conductor of electricity. That attribute is what comprises the basis of this method, as higher resistance leads to higher heat losses. All that’s missing to solve the next equation is the current’s strength $I$, which is left as input for the user. For this example, a value of 100 Amp was selected.

$$ P = IV = I^2 R = V^2 / R $$
That equation can take several forms, based on the fact that $R = V/I$. For this model $P = I^2R$ was employed, as it makes use of the current strength that the experimenter can directly control.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>20 mm</td>
</tr>
<tr>
<td>Expected corrosion ratio</td>
<td>1 %</td>
</tr>
<tr>
<td>Frequency f</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Current strength I</td>
<td>100 Amp</td>
</tr>
<tr>
<td>Skin depth δ</td>
<td>0.09 mm</td>
</tr>
<tr>
<td>Corrosion depth</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Total area Atot</td>
<td>314.16 mm	number</td>
</tr>
<tr>
<td>Corroded area Acorr</td>
<td>6.25 mm^2</td>
</tr>
<tr>
<td>Effective area Aeff</td>
<td>5.78 mm^2</td>
</tr>
<tr>
<td>Electrical resistivity ρ (rust)</td>
<td>280.000 \times 10^{-7} Ω.m</td>
</tr>
<tr>
<td>Length of section</td>
<td>1 m</td>
</tr>
<tr>
<td>Effective resistance Rcorr</td>
<td>4.844.97 Ω</td>
</tr>
<tr>
<td>Effective resistance Runcorr</td>
<td>0.029 Ω</td>
</tr>
<tr>
<td>Thermal energy Pcorr</td>
<td>48.449.715.69 Joule/sec</td>
</tr>
<tr>
<td>Thermal energy Puncorr</td>
<td>292.43 Joule/sec</td>
</tr>
<tr>
<td>Specific heat c (steel)</td>
<td>600 J/kg.K</td>
</tr>
<tr>
<td>Specific heat c (rust)</td>
<td>650.64 J/kg.K</td>
</tr>
<tr>
<td>Density (steel)</td>
<td>7.850 kg/m^3</td>
</tr>
<tr>
<td>Density (rust)</td>
<td>5.242 kg/m^3</td>
</tr>
<tr>
<td>Overall mc (corr)</td>
<td>1.471.57 J/K</td>
</tr>
<tr>
<td>Overall mc (uncorr)</td>
<td>1.479.69 J/K</td>
</tr>
<tr>
<td>Temperature increase ΔT (corr)</td>
<td>32.923.90 K/s</td>
</tr>
<tr>
<td>Temperature increase ΔT (uncorr)</td>
<td>0.20 K/s</td>
</tr>
</tbody>
</table>

Figure 12a: Model for calculating the produced thermal energy and temperature increase

Since the released heat is directly proportional to the resistance, it stands to reason that it would also be significantly higher for the corroded section. However, the value itself is highly unrealistic for the corroded section, as a significant simplification was made to make this calculation possible for demonstration purposes, which becomes obvious when looking at the final results for the temperature’s increase $ΔT$. The simplification will be discussed after the remaining calculations are explained.

The temperature increase is governed by the following formula:

$$Q = mcΔT$$
Where \( m \) is the overall mass, \( c \) is the material’s specific heat and \( Q \) is the produced heat. Normally, \( Q \) would be measured in Joules and be equal to the released thermal energy \( P \) multiplied by the duration of the current flow. However, since the final result is meant to be the temperature increase per second, for this scenario it is assumed that they are one and the same. Furthermore, when multiple materials with different specific heats are involved, it needs to be taken into account that the aggregate result occurs from \( mc = (m_1c_1 + m_2c_2 + \ldots + m_nc_n) \).

The new data required is therefore the specific heat \( c \) and, to calculate mass \( m \), the density of both steel and rust, which are all readily available from various sources and are depicted in the table. Since all relevant cross-sectional areas have already been calculated it is easy to get the desired volume by multiplying them with the length and then the mass by multiplying the result with the density. It is assumed that the produced heat would spread uniformly to the entirety of the steel’s mass before being shared with the concrete. Solving the above formula for \( \Delta T \) will then give the desired final result.

As was already mentioned, getting an increase of 32.924 K/s in comparison to 0.20 K/s for an uncorroded section is extremely unrealistic. That result occurred because it was assumed that, thanks to the skin effect, the entirety of the current would flow throw the rust, even though it is a bad conductor of electricity and a path of much less resistance is readily available. In truth, the vast majority of the current would still flow through the uncorroded steel.

Before concluding the model, to get a somewhat better approximation, the ratio of the current that flows through the rust itself can be found by first recalculating the skin depth, while substituting the electrical resistivity with that of rust. When keeping the frequency at 50 kHz as previously, the following result occurs:

<table>
<thead>
<tr>
<th>Actual frequency ( f )</th>
<th>50 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin depth ( \delta )</td>
<td>37.61 mm</td>
</tr>
</tbody>
</table>

Figure 11b: Recalculation of the skin depth for rust

The division of current flow between the steel and rust in an effective corroded cross-section will then be calculated by making use of the formulas for the electric field and its boundary conditions, as well its relation to the current density by making use of the equations depicted below:
Where:  
\( J \) is the current density in \( \text{A/m}^2 \) (here used with \( \text{A/mm}^2 \))  
\( \sigma \) is the conductivity and equal to \( 1/\rho \)  
\( E \) is the electric field in \( \text{V/m} \)  
\( E_0 \) is the electric field produced by an uncorroded section before the division

In this scenario, \( E_0 \) can be found by treating it as the \( E \) of the upper left formula and calculating it through the known conductivity of steel and the initial current density, which can be inferred from the effective cross-sectional area and initial current strength. That is then substituted in the lower left formula, along with the corrosion depth for \( d \) and rust skin depth for \( \delta \). The resulting \( E \) is the parallel electric field at the point of contact of the two materials, which according to the boundary condition is equal on both sides of the border. All that’s left to do is reverse the first formula to calculate \( J_{\text{parallel}} \) for the steel, then extrapolate the current that flows through it an subtract it from the initial current to find the current that flows through the rust. The resulting number of all of the mentioned calculations can be seen in the table below. It should be noted that it keeps all input data the same as has been used so far and that a 0 subscript denotes a characteristic of the initial current flow, while 1 and 2 denotes one of the divided current that flows through the rust and steel respectively.

<table>
<thead>
<tr>
<th>( J_{\text{par}0} )</th>
<th>17,3035</th>
<th>( \text{A/mm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{par}0} )</td>
<td>2,9243</td>
<td>( \text{V/m} )</td>
</tr>
<tr>
<td>( E_{\text{par}1,2} )</td>
<td>2,9165</td>
<td>( \text{V/m} )</td>
</tr>
<tr>
<td>( J_{\text{par}2} )</td>
<td>17,2575</td>
<td>( \text{A/mm}^2 )</td>
</tr>
<tr>
<td>( I_2 )</td>
<td>99,7345</td>
<td>( \text{A} )</td>
</tr>
<tr>
<td>( I_1 )</td>
<td>0,2655</td>
<td>( \text{A} )</td>
</tr>
</tbody>
</table>

Figure 13: Parameters added to improve the approximation of the model in figure 12.
By substituting the value that was initially used with the value of I1 that was just calculated, the table of figure 12a now becomes as follows:

<table>
<thead>
<tr>
<th>Diameter</th>
<th>20</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected corrosion ratio</td>
<td>1</td>
<td>%</td>
</tr>
<tr>
<td>Frequency f</td>
<td>50</td>
<td>kHz</td>
</tr>
<tr>
<td>Current strength I</td>
<td>100</td>
<td>Amp</td>
</tr>
<tr>
<td>Skin depth δ</td>
<td>0,09</td>
<td>mm</td>
</tr>
<tr>
<td>Corrosion depth</td>
<td>0,1</td>
<td>mm</td>
</tr>
<tr>
<td>Total area A_tot</td>
<td>314,16</td>
<td>mm^2</td>
</tr>
<tr>
<td>Corroded area A_corr</td>
<td>6.25</td>
<td>mm^2</td>
</tr>
<tr>
<td>Effective area A_eff</td>
<td>5.78</td>
<td>mm^2</td>
</tr>
<tr>
<td>Electrical resistivity ρ (rust)</td>
<td>280,000</td>
<td>10^-7 Ω.m</td>
</tr>
<tr>
<td>Length of section</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>Effective resistance R_corr</td>
<td>4,478,73</td>
<td>Ω</td>
</tr>
<tr>
<td>Effective resistance R_uncorr</td>
<td>0,029</td>
<td>Ω</td>
</tr>
<tr>
<td>Thermal energy P_corr</td>
<td>315,74</td>
<td>Joule/sec</td>
</tr>
<tr>
<td>Thermal energy P_uncorr</td>
<td>292,43</td>
<td>Joule/sec</td>
</tr>
<tr>
<td>Specific heat c (steel)</td>
<td>600</td>
<td>J/kg.K</td>
</tr>
<tr>
<td>Specific heat c (rust)</td>
<td>650,64</td>
<td>J/kg.K</td>
</tr>
<tr>
<td>Density (steel)</td>
<td>7.850</td>
<td>kg/m^3</td>
</tr>
<tr>
<td>Density (rust)</td>
<td>5.242</td>
<td>kg/m^3</td>
</tr>
<tr>
<td>Overall mc (corr)</td>
<td>1,471,57</td>
<td>J/K</td>
</tr>
<tr>
<td>Overall mc (uncorr)</td>
<td>1,479,69</td>
<td>J/K</td>
</tr>
<tr>
<td>Temperature increase ΔT (corr)</td>
<td>0,21</td>
<td>K/s</td>
</tr>
<tr>
<td>Temperature increase ΔT (uncorr)</td>
<td>0,20</td>
<td>K/s</td>
</tr>
</tbody>
</table>

Figure 12b: Reconfigured model for calculating the produced thermal energy and temperature increase

The two output numbers are now much closer to each other, though one should bear in mind that $P_{corr}$ is how much more thermal energy a corroded section releases than an uncorroded one, as it only takes into account the amount of current that flows through the rust. Still, since one can argue that energy produced by rust is the only one that has a chance of escaping its insulating properties, the proximity of the two numbers could be seen as an issue. However, this can easily be resolved by dialing up the frequency, which will be demonstrated in a graph soon. For now, it should be enough to mention that raising it to 150 kHz would turn the above temperature increase numbers into 0,34 K/s and 0,64 K/s for an uncorroded and corroded section respectively.

It should also be noted that even this approximation is based on the assumption of a homogeneous current distribution. A much more detailed model using the actual COMSOL programme would be required in order to produce an accurate result.
To make a heating time estimation, we’ll take into account that in Oshita’s experiment the internal temperature at the surface of the steel (not the external surface of the concrete) peaked at a maximum of around 80°C. Assuming that the starting point is an environmental temperature of 20°C, when using the latest numbers for a frequency of 150 kH, it would take approximately 94 seconds, just over 1.5 minutes, for a corroded section to reach that maximum temperature, at which point an uncorroded section should be at around 52°C. Because the result is dependent on the square of the current strength, doubling that to 200 A would quadruple the produced thermal energy and cut that time down to only 23.5 seconds. It is likely that after those intervals the power would need to be disconnected, though there would still be time to continue scanning before the heat dissipates uniformly. A full thermal conductivity analysis would be needed to calculate what the duration of that cooldown period would be.

That analysis would also be necessary to produce the time that it would take for the heat to reach the concrete surface, which is what really matters for the purposes of the experiment, bearing in mind that even a difference below 1°C is detectable by an IR camera. Furthermore, it would be able to take into account the fact that rust is a strong thermal insulator. Depending on the source, the thermal conductivity of steel can take values between 51 and 54 W/m·K [Gillie], while the equivalent value of rust is a mere 0.1-0.6 W/m·K [Laaidi et al, 2011]. As a result, if the surface of a corroded area is completely covered in rust, the heat would not be able to reach the concrete surface, which would appear as a cold spot instead. In theory, hotter spots should appear later adjacent to the corrosion’s location, as the heat gets time to dissipate. It also remains to be seen how a circumference that is only partially covered would affect the overall visibility.

Now that the process of how the spreadsheet operates has been detailed, it will be repeated a couple more times to produce results for various different diameters representative of those used in the Netherlands. Only the most relevant numbers will be shown, with the intermediate parameters being skipped. Since the wires/strands of a cable are in close contact with each other, based on the image of their cross-section it is assumed that they are a single entity of approximately 3.5 times the diameter of the individual piece when there are 12 of them (rounding up) and 3 times when there are 7 of them. So the assumed effective diameter would be 26 mm for small cables (12 7-mm strands) and 42 mm for large cables (7 strands consisting of 12 4-mm wires each). Since the rest of the duct containing them is filled with grout, for the purposes of this calculation the duct itself is not considered to be contributing to the effective diameter. However, it would have to be taken into account for a consequent heat dissipation model, particularly if it is heavily corroded. With that in mind, the occurring results are listed in the following table:
<table>
<thead>
<tr>
<th>Diameter</th>
<th>26 mm</th>
<th>42 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion ratio &amp; depth</td>
<td>1% (0,13 mm)</td>
<td>1% (0,21 mm)</td>
</tr>
<tr>
<td>Suggested frequency &amp; actual</td>
<td>25,26 kHz (150 kHz)</td>
<td>9,68 kHz (125 kHz)</td>
</tr>
<tr>
<td>Skin depth</td>
<td>0,05 mm</td>
<td>0,06 mm</td>
</tr>
<tr>
<td>Current strength</td>
<td>100 A</td>
<td>175 A</td>
</tr>
<tr>
<td>Temperature increase (uncorroded)</td>
<td>0,16 K/s</td>
<td>0,10 K/s</td>
</tr>
<tr>
<td>Temperature increase (corroded)</td>
<td>0,38 K/s</td>
<td>0,37 K/s</td>
</tr>
<tr>
<td>Time from 20 to 80°C</td>
<td>375 s / 158 s</td>
<td>600 s / 162 s</td>
</tr>
</tbody>
</table>

Figure 14: Sample configuration values for tendon diameters used in the Netherlands

One more thing that is left to do is make a showcase of how the system responds to the alteration of frequency, in order to better demonstrate the overall effect that the skin effect has on the final output. This can best be achieved with a line graph that directly depicts the correlation between the two variables. The numbers used to create it were given as output by the present model and can be found in the appendix.

Figure 15: Line graph showing correlation between frequency and temperature increase rate

The parameters that were considered constant were taken from the first column of the above table and are depicted next to the graph. As can be seen, with the sum of the assumptions that has been made, there is a clear linear correlation between the two factors, whether the sample is corroded or not. Since the temperature increase rate is connected to thermal energy by a single mixed parameter that remains constant as long as material composition and volume does not change, the same linear connection can be inferred between frequency and energy.
To sum up, before concluding this chapter, the overall assumptions that were employed and considerations or issues that need to be taken into account when moving forward will be recounted in a concentrated list. With regards to the former, to make the analysis possible it was assumed that:

- Electromagnetic parameters (e.g. electrical resistivity $\rho$) remain constant regardless of shifts in temperature.
- The result of corrosion is typical $\text{Fe}_2\text{O}_3$ rust and has its physical and electromagnetic characteristics.
- The current distribution is homogeneous.
- Initially it was assumed that the current would flow through the same skin depth regardless of the corrosion status of the conductor.
- For a more realistic approximation it was then assumed that the amount of current flowing through rust could be found by comparing the rust's skin depth to its actual depth.
- The produced thermal energy spreads uniformly to the entirety of the conductor’s cross-sectional area before dissipating away.
- Wires and/or strands of a cable behave as a singular entity as far as the current is concerned
- The cables start from a default temperature of 20°C.
- The steel duct does not contribute to the effective diameter of the conductor. This can be seen as a conservative assumption, as normally the propagation of corrosion on it would predate that of its insides and would essentially “signal boost” its presence.

Finally, the most major factor that had to be neglected to make this calculation possible but needs to be taken into account when creating a more detailed model is how the materials behave with regards to thermal conductivity. The surface temperature of the steel cables was used here as the basis to determine heating time, but in reality the time it would need to reach the surface of the concrete cover and become discernible would play the most important role. This is particularly important cause of rust’s low thermal conductivity, making it likely that the amount of heat produced would be rendered irrelevant if it can’t reach the surface.

An additional consideration is whether the cables are in sufficient electrical contact with their ducts and whether they are then in sufficient contact with the perpendicular rebar to allow the current to spread throughout an entire girder. This plays a significant role, as not having to electrify each cable independently is a necessary requirement for the method to be practical.

14.1.2 Lab tests

Since the method is so similar in concept to the one that is based on electromagnetic induction heating and Eddy currents, the proposed setup for the lab tests will be partly based on the equivalent ones that were carried out for that method.
The next step of the process would be to perform the test on samples of small reinforced concrete blocks whose corrosion level is known in order to test the validity of the idea on a basic level. The purpose of this step is to also gain some important practical information, like:

- How strong the employed current actually needs to ideally be
- How much energy needs to be expended for the rebar’s temperature to reach and sustain the desired levels
- How long the overall heating process takes
- How close the IR camera needs to be to get usable readings
- What the maximum temperature is before it becomes detrimental to the structure, and
- Most importantly, whether the presence of corrosion affects the results as predicted.

One of the most important parts of this step is creating the concrete samples themselves. For the first phase of testing, simple reinforced concrete blocks with regular rebar will be used to confirm whether the method actually has any potential. The composition of the concrete and rebar needs to be noted down. There also need to be several samples with differing adjustable variables in order to account for various possibilities. The most important variables in that regard are the corrosion level, starting from 0% for uncorroded rebar, and the depth of the concrete cover. The relevance of the former is obvious, as the effect of corrosion on the occurring results is one of the basic questions that needs to be answered. As for the latter, it serves the purpose of finding out how deep inside the concrete the IR sensor can see and still be able to clearly distinguish the differences between the corroded and uncorroded rebar, if there are any.

The corroded samples will need to be created through a method of accelerated corrosion. A commonly used method to achieve that in concrete lab tests is through the impressed current technique. Such a technique is necessary to ensure that tests can be carried out within a reasonable time frame. In this method, corrosion is achieved by applying an electrochemical potential between the steel rebar and a cathode. To cover all desired reference points it is suggested to create samples with 0%, 1%, 5% and 10% corrosion ratios. [Maaddawy & Soudki, 2003]

![Example of a test specimen’s arrangement](image)

Figure 16: Example of a test specimen’s arrangement [Oshita 2015]
As was already mentioned, it is important to make use of several test samples to account for a variety of factors, one of the most important ones being the depth of the concrete cover. Ideally, the cover depths used should be at minimum equal to ones used in practice. As a suggestion, some good reference points would be 65 mm, 75 mm and 120 mm. Those would give information with regards to how the clarity of the readings is affected as the depth they need to reach gradually increases.

All in all, at least 12 different samples need to be created to cover all possible combinations based on the above suggestions. An additional possibility would be having samples with multiple distinct corrosion spots and observing whether they react differently under the same circumstances.

Next in line to acquire are the rest of the instruments necessary to carry out the experiment. Most notable of those are the power supply and infrared camera. The power supply will need to be able to provide a high frequency alternating current and also give the capability to adjust its output voltage and currents through controls, in order to allow the researcher to settle on an optimal one. As an example, the supply model depicted in the image below, which has been used in an induction heating experiment, is able to offer an output frequency of 50 kHz and control of the output current within a range of between 200 A and 600 A. However, it is unlikely that the current for the resistance heating case will need to be as strong, so a weaker power supply will need to be acquired instead, likely with a maximum capacity of 300 or 400 A. It should still be noted that the high frequency is crucial however. Being able to achieve at the very least 50 kHz is a primary requirement for the power generator. Having the ability to go beyond that to see how the result would be affected would also be a boon. A supply that can achieve frequencies in the vicinity of 500 kHz would be optimal for that purpose.

Figure 17: Power supply [Baek, Xue, Feng & Kwon, 2012]
As for the IR camera, it needs to be able to detect heat and IR radiation emitted by the rebar within the concrete and digitally record the footage to be studied afterwards. The final set-up of the experiment would look similar to the one depicted below, plus the cables connecting the edges of the rebar to the power supply.

![Infrared camera and Heating object (rebar)](image)

Figure 18: Experiment set-up [Baek, Xue, Feng & Kwon, 2012]

The first and foremost output of the test should be whether it is indeed possible to tell the corroded rebar apart from the uncorroded ones through the intensity of the radiation they emit or the temperature level on the concrete surface. If it is, records should be made of the rest of the information that occurred, such as the output voltage and current of the power supply, the power that was expended and of course the heating time it took for the specimens to reach detectable ranges. It should once again be noted that the desired outcome is not the heating up of the steel, but the detection of differentiations in its behavior based on its health state, regardless of whether the deteriorated areas, or rather the concrete surface above them, experience expedited or delayed temperature increase.

This should in theory be possible thanks to the nature of high frequency alternating current. Due to the skin effect, the higher the frequency of the current that travels through a conductor, the larger the part of it that will travel through its surface. At high enough frequencies, such as the 50 kHz one that was suggested earlier, the majority of the current will be flowing through the “skin” of the tendons, where corrosion will be making its appearance first. Consequently, it will encounter the higher resistance of rust and corroded steel, causing the production of a greater amount of heat that should be visible through the IR camera.

Should the initial test prove successful, the next step would be to test other limitations of the method. This would be done through the use of a steel rebar specimen as long as can be procured, not
necessarily encased in concrete this time. Using a similar set-up, the purpose of this stage of the process would be to figure out whether:

- The entire length of the rebar heats uniformly
- Corrosion far from the power source can be detected as well as in the smaller sample
- The expended power increases in accordance to the length increase
- The duration of the heating period increases in accordance to the length increase

The final step of the lab tests would be to acquire samples comprising of actual prestressing steel to work with. The makeup of these specimen should be as close to the ones used in practice as possible. In the Netherlands, what is primarily used is post-tensioning with cables consisting of up to 27 7-wire strands of a diameter of 12 to 16 mm. The configurations used in the model of the previous chapter (12 7-mm strands or 7 strands consisting of 12 4-mm wires each) is from a real example, so it is a worthwhile suggestion. Their concrete cover is 75 mm and 66 mm respectively. The cables are placed in steel ducts grouted in place and encased by concrete cover. As this is a far more complex setup, whether it would be feasible to view and interpret the shift in temperature needs to be investigated.

Before moving on from the lab tests, the samples can also be used in a couple potentially destructive tests to investigate possible detrimental scenarios. To begin with, the potential of hydrogen embrittlement needs to be accounted for, since high strength steel is particularly susceptible to it. ASTM International lists several standard tests methods to determine the thresholds and susceptibility of steel and metals in general to this phenomenon. [ASTM F1624 - 12 & ASTM G142 - 98] Furthermore, if the power supply can reach frequencies nearing 500 kHz, it should be investigated whether those heights can cause dissipation within the concrete with harmful effects due to dielectric heating. While in normal circumstances dielectric heating is achieved by inducing microwave electromagnetic radiation, it can also occur due to high frequency electric fields if they approach the HF level of the radio spectrum. Still, that scenario is somewhat unlikely at our proposed levels, as the HF spectrum begins at 3 MHz, with the US patent for methods of dielectric heating proposing a minimum of 10 MHz.

14.1.3 Field tests

After the successful conclusion of the lab tests, coming up next would be carrying out the experiment on an actual bridge, to ensure that the method would work as successfully in practice. A location that will be available for that purpose in the near future would be the Hollandse Brug, which will in the following months become closed to traffic anyway.

Before carrying out the field tests themselves, optimal locations to connect the power source(s) need to be determined. Now that the feasibility of the method will have been confirmed, it is time to move forward and attempt to simulate the steel “grid” of an actual girder and the circuit it forms. The setup will need to be such that every part of the circuit can be sufficiently heated without causing other parts to overheat. It is likely that multiple access points will be required to achieve that.
There are various reliable simulations programmes that are capable of achieving that analysis in order to produce a desirable setup. A recommended option is COMSOL Multiphysics, which is a finite element analysis software package that has been used in the past to simulate the outcome of a similar experiment. It should be noted that COMSOL makes use of add-on software modules that need to be activated separately in order to expand the programme’s capabilities. The minimum required modules for this simulation are “AC/DC Module” from the Electrical category and “Heat Transfer Module” from the Mechanical category. [Tanaka et al., 2014]

The field tests would then be divided in two parts. The first part would be similar to the lab tests, only on a much larger scale. Its purpose would be to make sure that the method translates well to an actual bridge and can be as successful there. Readings will be taken from the prestressing tendons, moving the IR camera along their entire spans.

It should be noted that, since this process can take some time and heating can scale up rapidly when current is applied on metal, the whole process should be carried out in small increments of time with a set maximum duration calculated from the model, allowing for cooling periods in between. The cooling periods need to be long enough for the previously produced heat to entirely dissipate so that the higher resistance corrosion spots can be distinguishable once again.

Another matter of import to keep into consideration is the clarity of the results. While the current in practice would flow individually in each wire, all that will be able to be picked up by the sensor is a relatively vague area with differing temperature cause of heat that was conducted to the surface. And as can be seen from Oshita’s experiment, the deeper the cover the fuzzier the image will become. Consequently, at best the measurement can be carried out on a cable by cable basis.

The second part and final step of the process would be to check the possibility of completely eliminating the human element that would have to be on the actual bridge during future assessments. The way that would be done would be by installing a smaller model of an IR camera on a UAV and see if the readings can be as accurate that way. The UAV would make fly-bys following the length of the rebar.

This final test would be marked as a success if the UAV mounted camera can detect any corrosion spots that were detected in the previous step. Furthermore, in the case where the top of the deck needs to be scanned, it needs to be determined whether the range of the camera is long enough to allow the drone to perform it from a safe height that would keep it out of the way of potential incoming vehicles, if the road is to remain open during future assessments.

14.1.4 Safety considerations

Given that this method relies on the flow of current throughout a steel “grid”, it’s the only one that can have hazardous effects on places where no equipment is located. Since the effect of electricity and its potential for harm can vary greatly depending on a number of circumstances, one should always assume
the worst case scenario when accounting for matters of health and safety, especially for field tests and potential application in practice later on.

A major factor to consider is the possibility of existence of electrical contact between the grid and a conductive surface that is accessible to the public, such as a handrail. Even if no such contact was intended, it is always better to lean on the conservative side of safety factors. Because time is no longer a factor if this method’s application is fully successful, a first consideration would be to reduce the current strength to non-dangerous levels. However, the natural resistance of the human body can be affected by so many unpredictable factors and vary so greatly, from 1 MΩ in the best case scenario to 100 Ω in the worst, that this is not practically possible. The table below showcases that all it takes is 37 mA for high frequency AC to become painful and 50 mA to cause loss of muscle control, a threshold which cannot realistically be adhered to. [Kuphaldt, T.R.]

<table>
<thead>
<tr>
<th>BODILY EFFECT</th>
<th>DIRECT CURRENT (DC)</th>
<th>60 Hz AC</th>
<th>10 kHz AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight sensation</td>
<td>Men = 1.0 mA</td>
<td>0.4 mA</td>
<td>7 mA</td>
</tr>
<tr>
<td></td>
<td>Women = 0.6 mA</td>
<td>0.3 mA</td>
<td>5 mA</td>
</tr>
<tr>
<td>felt at hand(s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold of perception</td>
<td>Men = 5.2 mA</td>
<td>1.1 mA</td>
<td>12 mA</td>
</tr>
<tr>
<td></td>
<td>Women = 3.5 mA</td>
<td>0.7 mA</td>
<td>8 mA</td>
</tr>
<tr>
<td>Painful, but voluntary muscle control maintained</td>
<td>Men = 62 mA</td>
<td>9 mA</td>
<td>55 mA</td>
</tr>
<tr>
<td></td>
<td>Women = 41 mA</td>
<td>6 mA</td>
<td>37 mA</td>
</tr>
<tr>
<td>Painful, unable to let go of wires</td>
<td>Men = 76 mA</td>
<td>16 mA</td>
<td>75 mA</td>
</tr>
<tr>
<td></td>
<td>Women = 51 mA</td>
<td>10.8 mA</td>
<td>50 mA</td>
</tr>
<tr>
<td>Severe pain, difficulty breathing</td>
<td>Men = 90 mA</td>
<td>23 mA</td>
<td>94 mA</td>
</tr>
<tr>
<td></td>
<td>Women = 60 mA</td>
<td>15 mA</td>
<td>63 mA</td>
</tr>
<tr>
<td>Possible heart fibrillation</td>
<td>Men = 500 mA</td>
<td>100 mA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Women = 500 mA</td>
<td>100 mA</td>
<td></td>
</tr>
</tbody>
</table>

Figure 19: Bodily effects of various levels of electric current [Textbook for “Lessons in Electric Circuits”]

As a result, the only practical solution when there is a chance that, for instance, a handrail might be electrified, is to close access to the pedestrian sidewalk only. At the very least, vehicle traffic is very unlikely to be hindered by such a scenario, as the only materials coming in contact with each other are asphalt and tire rubber, both of which are electrical insulators.

The other safety factor to consider is of course any detrimental long term effects the current might have on the structure itself, such as the potential embrittlement that was mentioned earlier.
14.2 Combinations of electromagnetic and thermographic methods

While this method had been tested in the lab and been shown to work with documented results, the issue as far as the purposes of this project are concerned is that it has only been tested for specimens reinforced by plain rebar. Since prestressing steel comprises of a different chemical composition from regular rebar, the same procedure needs to be carried out for new specimens containing an actual prestressing tendon that emulates the 27 strand one that is being used in the Netherlands and with thicker concrete cover to approximate the condition of the actual structure. To date the maximum concrete cover for which the induction heating technique has been tested is 70 mm, while in certain real cases in the Netherlands it can even exceed 120 mm.

As a result, the experiments need to be repeated but, unlike in our previous case, without for the most part having to find out whether the technique actually works, but rather how the parameters change when put in a scenario that more closely resembles reality. Namely, for the previous tests we have the output voltage, current and frequency that were produced by the power source, as well as the electric power that was consumed. What is more, we have the properties of the materials used for the samples, the duration of the heating period and by how much the temperature of the reinforcement was raised. This information can all be seen in the tables of figure 20 below.

![Figure 20](image)

Figure 20: Characteristics of electromagnetic induction heating and experimental conditions of the 3 reinforced concrete specimens used in the past experiment [Oshita 2015]
All of the above parameters need to be redefined for the prestressing steel scenario. Since the setup for the resistance heating method was based on the experiments that have already been carried out for induction heating, the setup, which can be seen in figures 17 and 18, won’t be too different. The primary difference will be that the power source won’t be attached directly to the steel itself, but rather to a coil that will generate the magnetic field to heat up the steel through Eddy currents. Subsequently, the required equipment will also be the same, with the addition of the coil, for whose shape a suggestion is depicted below in order to ensure uniform heating in a region.

![Figure 21: Example of outline of induction coil shape](image)

After the tests have been conducted, the values for the parameters listed above need to be documented. Afterwards, the images produced by the IR camera need to be used to confirm whether the corrosion spot are still distinguishable from clean ones despite the new circumstances.

Finally, it’s once again time for the field tests. Since personnel will need to be present on the bridge itself for this technique to be carried out anyway, the second part of the process with the UAV that was suggested for the previous method is obsolete and the primary question that needs answering is whether the method is fit to be used on the field.

Other than whether the readings are reliable, the factors that will provide the answer to that question is how long the heating period needs to be and how big the area that can be covered within that time is. Since traffic will need to be closed down for the real application of the technique, carrying out the entire pressure is under a time pressure and needs to be as quick and efficient as possible.
In summation, the tests of this technique would be labelled a success if both of the below statements are true:

- Corrosion spots can be detected on the actual structure, and
- The process can be carried out in a satisfyingly timely manner.

### 14.3 Remanent magnetism

The rest of the recommended methods have already been tested both in a lab setting and on an actual bridge. As a result, the only reason to test them further is to check for any issues that differences between the environment the previous experiments were carried out in and the Netherlands may cause. In this case, the past experiments have been carried out by German researchers and Germany has a tendency of using box girder bridges that offer easier access to their prestressing tendons.

With remanent magnetism, the primary concern with employing the method both for the purposes of testing and for actual use is procuring the necessary apparatus. Currently there is one known to be in the possession of the German construction company Hochtief and the professor who originally developed the method over the last decade, Bernd Hillemeier of the university of Berlin. There is a smaller version of the apparatus that can be carried by hand and a larger that is meant to be dragged by a vehicle to scan the deck of the bridge. In other words, the apparatus will have to be negotiated over with the current owners or constructed from scratch with permission, specifications and schematics also acquired from them.

After the apparatus has been successfully acquired, it is only a matter of setting it up to slide over the surfaces to be examined at an appropriately slow speed, as most of the equipment it requires to operate is already installed on a single carriage. The criteria to label the experiment a success would be similar to before:

- Fracture spots can be detected on the actual structure, and
- The process can be carried out in a satisfyingly timely manner.

### 14.4 Electromagnetic Resonance Measurement (ERM)

ERM based on frequency domain reflectometry has also been tested under controlled conditions as well as on the field and it is somewhat plausible because it requires a single access point in order to properly function. However, that would mean an access point for each tendon to be tested, which might not be entirely practical. Additional hindrances are added by the fact that the exact specifications of the tendon need to be known in order for the device to be properly calibrated, preferably with a twin tendon to calibrate it with.
The recommendation for this method is on one hand to keep it in mind for bridges to be newly built in the future, while on the other hand re-review it on a case by case basis for structures where the access and calibration limitation would not present a major issue.

14.5 Coil sensors

This final technique to be recommended is another one that has been extensively tested both in a lab and on the field, but carries with it the same issues. The fact of the matter is, access to the bridge tendons is somewhat easier in Germany and this method’s capabilities are severely limited by that.

As a result, this method loses part of its usefulness for the purposes of this research. Normally it can be used to detect both loss of force and local defects. However, the latter requires the coil to be installed on the tendon and located directly above the defects, which just wouldn’t be possible in a Dutch bridge. That limits its usefulness to being used only for force measurement, which carries its own limitations. The coil needs to be calibrated in order to provide any useful information, which means that it is more easily applicable when initial measurements are taken upon construction of a bridge. So like the ERM, the usefulness of the coil sensors would be limited depending on circumstances.

Therefore, the recommended procedure for this technique is to also take it into account in the planning stage of a new structure.
15. Overall Recommendations

This section will depict the overall recommended processes in flowcharts, starting with the most lengthy procedure.

**Phase A: Modeling 1**

**Step 1:** Use thermodynamic equations to create initial model

**Step 2:** Settle on acceptable current strength and heating period

**Step 3:** Settle on representative sample composition

**Step 4:** Create initial reinforced concrete samples

**Step 5:** Simulate accelerated corrosion w/ impressed current

**Step 6:** Acquire instruments (IR camera, electrodes)

**Phase B: Lab tests**

**Step 7:** Select appropriate power supply (high freq.)

**Step 8:** Connect electrodes to 2 ends of rebar

**Step 9:** Setup IR camera to record procedure

**Step 10:** Activate power supply

**Step 12:** Observe results

**Step 11:** Take readings and complete test

**Step 13:** Create prestressed concrete samples

**Step 14:** Repeat experiment

**decision:** Redefine parameters?

**check:** Is corrosion observable?

**check:** Are results acceptable?

**Step 15:** Carry out hydrogen embrittlement tests

**End process (failure)**

**Flowchart B**
**Phase C: Modeling 2**

- **Step 16**: Acquire COMSOL programme
- **Step 17**: Install AC/DC and Heat Transfer modules
- **Step 18**: Create model of actual bridge
- **Step 19**: Run simulation
- **Step 20**: Repeat until optimal electrode setup found
- **Step 21**: Gain access to bridge
- **Step 22**: Setup electrodes according to optimal setup
- **Step 23**: Activate current with cooling periods inbetween
- **Step 24**: Take readings in increments

**Phase D: Field tests**

- **Decision**: Redefine parameters?
- **Check**: Is corrosion observable?
- **Step 25**: Acquire appropriate UAV
- **Step 26**: Mount camera on it
- **Step 27**: Repeat experiment
- **Step 28**: Determine maximum reliable reading distance

**End process (failure)**

**No**

**Yes**

**End process (success)**

---

Figure 22a: Recommended process flow chart (electric excitation)
Step 1: Settle on representative sample composition

Step 2: Create prestressed concrete samples

Step 3: Simulate accelerated corrosion w/ impressed current

**Phase A: Lab tests**

Step 4: Acquire instruments (power supply, IR camera, induction coil)

Step 5: Setup IR camera to record procedure

Step 6: Activate power supply and heat prestressing steel w/ coil

Step 7: Take readings and complete experiment

Step 8: Note down heating time and current strength/freq.

Check: Is corrosion observable?

Decision: Redefine parameters?

Step 9: Gain access to bridge

Step 10: Divide bridge in appropriately sized areas along tendons

Step 11: Heat tendons with coil

Step 12: Take readings and note down process speed

Step 13: Mark method's degree of success

**End process (failure)**

**Phase B: Field tests**

**Finish process**

---

*Figure 22b: Recommended process flow chart (induction heating)*
Begin process

Step 1: Negotiate for testing apparatus

Step 2: Run cost benefit analysis

Decision: Preferable course of action

Step 3a: Lease existing testing apparatus

Step 3b: Assemble new testing apparatus

Step 4: Gain access to bridge

Step 5: Setup device to slide along tendons

Step 6: Slide device over them at appropriate speed

Step 8: Determine if fractures are satisfyingly visible

Step 7: Take readings

Step 9: Note down testing duration

Step 10: Mark method’s degree of success

Finish process

Remanent magnetism

Figure 22c: Recommended process flow chart (remanent magnetism)
16. Conclusion

This thesis project investigated a number of techniques that allow for the assessment of the condition of a concrete bridge. It then examined how those techniques hold up when judged in accordance to certain criteria to determine their usefulness in practice. From the pool of techniques, a number of them that potentially hold promise and are worth investigating further were put forward.

As a starting point for future research, for each of the techniques that were deemed worth researching further an overall testing process was suggested to ensure their usefulness and practicality on the field. These suggestions include not only the sequence of actions to perform in order to check aspects of their performance that has not yet been tested, but also the equipment that would be required for those actions.

As a final reminder, the criteria that have been and should be used to determine a certain method’s practicality are the following:

- It needs to include only non-destructive testing when it is to be carried out on the field.
- It needs to only require equipment that can reasonably be obtained by a company through some means.
- It preferably needs to not require the entire traffic to be shut down, but in case it does it cannot be for prolonged periods of time.
- Should some equipment need to be permanently attached on a specific structure, it needs to be relatively cheap so that the method can for the most part be considered mobile and not have to devote a huge sum of resources for a single structure.
17. References


Portland Cement Association (2002). Types and Causes of Concrete Deterioration. PCA R&D Serial No. 2617


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Appendix A – Overall degradation mechanisms of concrete

Corrosion

Corrosion of the reinforcing steel is one of the most prominent causes of concrete deterioration. Because rust, the product of corrosion, ends up having a larger volume than the reinforcement, its appearance causes tensile stress to the surrounding concrete, which can consequently cause cracking or spalling, as concrete in general is vulnerable to tensile forces.

The corrosion process occurs because steel is not a naturally occurring material and, like most metals, is thermodynamically unstable under normal atmospheric conditions, as it tends to release energy that was stored within it during its production and revert to its natural state, which is an iron oxide, commonly known as rust.

In order for corrosion to take place, there need to be 2 spots at different energy levels, an electrolyte and a metallic connection between them. Those conditions can be quite common in reinforced concrete, as reinforcement tends to have separate areas at different energy levels, concrete acts as the electrolyte and several metallic components can act as the connection.

Despite steel’s natural tendency towards corroding, it is usually protected by the alkaline environment of concrete. Because of the high alkalinity, a thin oxide layer forms that protects steel from corrosion, not by stopping it entirely, but by bringing it down to a practically negligible level.

However, that protection can be circumvented by the presence of chloride ions or the air’s carbon dioxide. Chloride ions, being the most extensively documented cause of corrosion in reinforcing metals, are normally found in deicing salts and seawater and can begin corrosion propagation as long as oxygen and moisture are also present to sustain it. Carbon dioxide on the other hand reacts with hydroxides and brings down the alkalinity to a level that destabilizes the previously mentioned protective film. The process, called carbonation, takes place at a generally slow rate, though it can be increased by, among other things, a higher water-to-cement ratio. As an added “bonus”, by destabilizing the protective film carbonation also lowers the chloride ion threshold to begin the propagation of corrosion.

Freeze-Thaw Deterioration

Water’s volume typically increases when it freezes. As a result, the freezing of water in wet concrete introduces pressure inside its pores. Should that pressure exceed the relatively low tensile strength of concrete, it can cause ruptures. A repeated succession of a freeze-thaw cycle can cause significant to the concrete in the form of cracking, scaling and crumbling. Ways to combat this risk include making use of entrained air and low permeability concrete that can resist the penetration of water.
Particularly freshly mixing concrete must be protected from freezing, as it has not yet built up its resistance and can incur a strength loss of even up to 50% if the freezing occurs within a few hours. If this has happened only once concrete can normally be restored through sufficient curing, but it will no longer be as watertight or resistant to weathering as it would otherwise.

**Sulfate attack**

Concrete generally has adequate resistance to chemical exposure. However, there are some that can cause swift deterioration, such as strong acids that can cause extensive damage to any type of concrete. One particularly damaging type of chemical compounds is sulfates, which react with the hydrated compounds of hardened concrete. The various types of sulfates react differently, but overall they tend to result in loss of strength by introducing pressure that disrupts the cohesion of the cement paste.

Environmental conditions can greatly influence the extent of sulfate attacks, particularly when the concrete is exposed to continuous cycles of soaking and drying, as the evaporation of water allows sulfates to concentrate on the concrete surface. Ways to combat the threat include once more making use of low water-to-cement ratios, as well as pozzolans or fly ash.

**Alkali-Silica Reaction**

While aggregates tend to be harmless to concrete, there are some which can cause reactions when in contact with the hydroxides in the highly alkaline cement paste. The most prominent of those reactions is the Alkali-Silica Reaction (ASR). ASR results in a gel that can expand by absorbing water, which then introduces enough pressure to damage the concrete, causing cracking and sometimes even spalled surfaces.

In short, the elements required for an alkali reaction are:
- High alkaline content (hydroxides)
- A chemically reactive aggregate, most prominently containing silica
- Moisture

As a result, a readily available way to contain the damage is keeping the concrete dry. However, this is not always practical or even possible, particularly in the presence of seawater. Some admixtures known to reduce the reaction are silica fume, fly ash, ground-granulated blast furnace slag and lithium compounds.
**Abrasion**

Abrasion occurs typically in the presence of excessive rubbing and friction that the concrete surface is unable to properly sustain. When the outer paste is worn out, the contained aggregate are exposed and additional degradation occurs affecting the aggregate-to-paste bond strength and hardness of the aggregate.

As this degradation mechanism revolves around, friction, it stands to reason that one of the most prominent causes would be traffic-induced friction, particularly when it comes to vehicular traffic. Increased compressive strength is the most effective factor known to reduce this kind of damage, along with the use of harder wear-resistant aggregate.

Another example of when this friction damage can occur is hydraulic structures. Dams, spillways and tunnels may have to sustain damage not only from the friction of the water itself, but also from carried debris that might grind against their surface. As before, strong concrete and harder aggregates can be used to contain this kind of damage.

**Fire**

While concrete is exceptionally resistant to temperatures encountered in most situations, exposure to fire or similarly high temperatures can be highly detrimental. Stiffness and loss of flexural and compressive strength are the most prominent symptoms of such an exposure. Concrete is particularly susceptible to cycles of increased and reduced temperatures. The heat durability it has under constant temperatures does not entirely carry over. This is most likely because of differing dimensional changes between the cement paste and aggregate.

**Volume Change Restraint**

Volume change can take place in concrete for a variety of reasons, most commonly related to fluctuations in moisture and temperature. Restricting these changes can cause cracking if the produced tensile stress exceeds concrete’s tensile strength. To provide a couple examples, the inevitable loss of water will cause local shrinkage in parts of a structure, which will be resisted by other parts that lean towards maintaining their volume. Furthermore, thermal fluctuation introduces expansions and contraction that will also differ locally in the various parts of the structure.
Overload and Loss of Ground Support

This category involves damage that is caused by circumstances that go beyond the predicted scenarios during the design of a structure. A properly designed structure should be able to withstand the loads that its use is expected to bring forth. However, a change in its use or increase in its traffic that is accompanied by an unexpected rise in loads should be accompanied by an appropriate structural upgrade. Another scenario that can be listed in this category are earthquakes. Earthquake damage is a classic example of structure overload even when its possibility has been accounted for during design.

Finally, loss of ground support can occur because of a variety of reasons, the most common being the settling of soil. The differential settling of soil can lead to issues ranging from cracking to even structural failure. Slab curling is another problem relevant to this category. It is a rise in a slab’s corners and edges caused by a differing temperature or moisture content. This is also another example of volume change restraint and can result in loss of contact between slab and subbase, cracking, slab deflection and joint deterioration. [Portland Cement Association, 2002]
Appendix B – Prestressing tendon types

The tendons employed to create prestressed concrete can take different forms and can also be classified in categories based on several parameters.

The forms a tendon can take are as follows, arranged in an ascending order of size:

- Wires
- Strands
- Tendons
- Cables
- Bars

Typically, they take the form of individual wires, wires spun together helically to form strands, or bars. The concepts of pre-tensioning and post-tensioning will be further explained below, but for now it should be mentioned that for pre-tensioning the wires, strands or bars are commonly placed separately to allow the concrete to bond directly to them, while for post-tensioning they are grouped together in order to decrease the number of required ducts and anchorages. In this case, each group is usually referred to as a cable.

In other words, most of the above categories are sub-divisions of another. In short, wires are the smallest subdivision and are basically single units, strands consist of several wires wound together, tendons consist of a group of either wires or strands and cables are formed by tendons grouped together in a duct. Bars are a separate case, with a single bar being used to form a tendon, and their diameter greatly surpasses that of a wire. [Abeles & Bardhan-Roy, 2003]

The rest of the parameters according to which tendons are categorized are:

- Pre-tensioning vs. post-tensioning
- Nature of concrete-steel interface (bonded vs. unbonded)
- Location of tendon with respect to concrete (internal vs. external)
- Source of pre-stressing force
- Shape of the member
- Amount of pre-stressing force
- Direction of member

Pre-tensioning vs. Post tensioning: This is the most relevant classification and is based on the sequence of applying tension to the tendons and casting the concrete.

With pre-tensioning, strand are tensioned first and potentially depressed for non-linear tendon profiles. Concrete is then cast so that the tendons are contained within the structural object. After the hardening of the concrete, the forms are removed and the strands are cut at their ends. The forces of pre-compression are transmitted from the steel to the concrete through the bond and elastic shortening
takes place. After the process is over, long term losses because of creep, shrinkage or steel relaxation begin to occur.

For post-tensioning, concrete is cast first with duct openings and allowed to harden. Tendons are then passed through the ducts, then tension is applied to them and they get anchored. The anchorage device at the end blocks is what transmits the pre-compression to the concrete. Finally, the tendons might be grouted, at which point long term losses again begin to take place.

Nature of concrete-steel interface: This division is based on whether there is an adequate bond between concrete and the prestressing tendon, rendering the tendon either bonded or unbonded. Pre-tensioned tendons are always bonded, while whether a post-tensioned tendon is bonded depends on whether the grouting procedure took place at the end. A post-tensioned tendon that was never grouted is considered unbonded.

Location of tendon: This is based on whether the tendons are placed within or outside the concrete member. A tendon located inside is considered internal, while the latter is called external. Most pre-tensioning applications make use of the internal variety. External prestressing is comparable to unbonded post-tension tendons, with the difference that external ones attach to the concrete at various distinct locations, including anchorage points. It is typically seen in bridges or the strengthening of buildings.

Source of prestressing force: Based on the method through which the prestressing force is generated, tendons can be divided into mechanical, hydraulic, electrical or chemical. Mechanical prestressing is the one employed when it comes to mass production. It can involve weights, geared transmission in conjunction with pulley blocks, screw jacks and wire-winding machines. Hydraulic prestressing is the simplest one and can produce large forces, making use of a hydraulic jack that comprises of calibrated pressure gauges which indicate the magnitude of the force. Electrical prestressing, also known as thermo-electric prestressing, has the wires heated electrically and then anchored before casting the concrete into the molds. Finally, chemical prestressing is used by introducing an expansive component into the concrete mix, whose expansive potential consequently stretches the reinforcement.

Shape of member: Prestressed members can be either straight or curved in the direction of prestressing. These are called linear and circular prestressing respectively. Examples of the former category are beams, pies, poles and slabs. It should be noted that the profile of the tendon in this case can still be curved. Examples of the latter category include circumferential prestressing of tanks, silos and pipes.

Amount of prestressing force: Prestressing can be defined as full, limited or partial based on the amount of force that is applied. In the case of full prestressing, no tensile force can be allowed to affect the concrete under service loads. For limited prestressing the tensile stress under service loads does not exceed concrete’s cracking stress. Finally, for partial prestressing, the width of any crack that might occur under service load can be within a certain allowable limit.
Direction of member: For this category, tendons can be divided into uniaxial, biaxial or multiaxial. This classification depends entirely on the number of axes that the tendons are placed parallel to, namely one, two or more than two respectively. Uniaxial is the typical prestressing that is used for a beam. Examples of biaxial and multiaxial prestressing can be found in the prestressing of slabs and domes respectively. [Sengupta & Menon]
Appendix C – Distribution of bridge types in the Netherlands

Several years ago Rijkswaterstaat carried out an inventory of older engineering structures in the Netherlands, which included bridges, along with tunnels and viaducts, in order to determine whether they are still safe to operate despite the drastic increase in traffic that has occurred in the intervening decades. While the inventory table produced was not exhaustive, as it included only structures built prior to the year 1975, it can still provide some useful information about the distribution of the types of bridges that are generally employed in the Netherlands.

23 types of main structures were differentiated in total, which were then further grouped together into 5 wider categories, excluding tunnels:

- Slab category
- Beams category
- Box girder category
- T-profile category
- Box shaped structure category

The resulting inventory can be seen in the table presented below:

<table>
<thead>
<tr>
<th>Category</th>
<th>Box girder</th>
<th>Beams</th>
<th>Slabs</th>
<th>T-profile</th>
<th>Box-shaped structure</th>
<th>Tunnels</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWN, transportation axis (RW)</td>
<td>14</td>
<td>76</td>
<td>113</td>
<td>43</td>
<td>16</td>
<td>2</td>
<td>264</td>
</tr>
<tr>
<td>HWN, no transportation axis (in RW)</td>
<td>48</td>
<td>131</td>
<td>312</td>
<td>31</td>
<td>24</td>
<td>4</td>
<td>550</td>
</tr>
<tr>
<td>HWN over the RW</td>
<td>17</td>
<td>75</td>
<td>159</td>
<td>10</td>
<td>7</td>
<td></td>
<td>268</td>
</tr>
<tr>
<td>National water ways/water systems</td>
<td>4</td>
<td>9</td>
<td>48</td>
<td>23</td>
<td>8</td>
<td></td>
<td>92</td>
</tr>
<tr>
<td>HWN, next to RW</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>83</strong></td>
<td><strong>290</strong></td>
<td><strong>638</strong></td>
<td><strong>108</strong></td>
<td><strong>54</strong></td>
<td><strong>6</strong></td>
<td><strong>1180</strong></td>
</tr>
</tbody>
</table>

Figure 23: Inventory of engineering structures dating to before 1975 [Rijkswaterstaat 2007]

A observation of note to make relevant to the present thesis is that box girder bridges constitute a rather minimal proportion of the structures relatively to the rest of the types. This is important to keep in mind, as several of the experimental methods carried out in Germany took place within box girder bridges, where prestressing tendons tend to be exposed and easier to attach equipment to, in contrast with the encased Dutch ones. [Rijkswaterstaat, 2007]
Appendix D – Electric & thermodynamic equations

The following is the equation employed by Karunasena et al. in their research in order to pre-emptively calculate the theoretical temperature increase in the steel sheet blanks they applied direct resistance heating to during their experiment. There are however 2 important notes to make regarding the assumptions they used in arriving to this equation and their relation to the present thesis project:

1. As their project used a low frequency AC of 50 Hz during their experiment, the skin effect was ignored cause it would have negligible influence on that level. It would, however, be more prevalent in the higher frequencies recommended by the present paper.
2. There is a temperature gradient normal to the x axis because of the heat loss from the sheet surface, which is small enough to neglect in comparison to the variation of temperature along the x axis for thin strips. This is not necessarily the case for other shapes such as bars. [Karunasena et al., 1978]

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial \theta}{\partial x} \right) + \frac{l^2 \rho}{A^2} - \frac{P}{A} h (\theta - \theta_0) - \frac{eP}{A} (\theta^4 - \theta_0^4) = C_p d \frac{d\theta}{dt}
\]

Where:
- \( x \) is the distance along the strip in m,
- \( \lambda \) is the thermal conductivity in W m\(^{-1}\) oC\(^{-1}\),
- \( \theta \) is the instantaneous temperature of the strip in K,
- \( I \) is the heating current in A,
- \( \rho \) is the electrical resistivity in \( \Omega \cdot m \),
- \( A \) is the cross section area of the strip in m\(^2\),
- \( P \) is the contact load in N,
- \( h \) is the convective heat transfer coefficient in W m\(^{-2}\) oC\(^{-1}\),
- \( \theta_0 \) is the ambient temperature in K,
- \( e \) is the radiation heat transfer coefficient in W m\(^{-2}\) K\(^4\),
- \( p \) is the perimeter of the strip in m,
- \( C_p \) is the specific heat in J Kg\(^{-1}\) oC\(^{-1}\) and
- \( d \) is density in kg m\(^{-3}\)
The following is the equation that expresses the skin effect caused by high frequency AC and can be used to calculate the so called “skin depth”:

\[ d = \sqrt{\frac{1}{\pi f \mu \sigma}} \]

Where: 
- \( d \) is the skin depth,
- \( f \) is the frequency,
- \( \mu \) is the magnetic permeability and
- \( \sigma \) is the conductivity.

Finally, the equations presented below are the governing equations of the heat transfer and electric modules of the COMSOL Multiphysics programme, whose use was suggested for use in future research. The first equation expresses general heat transfer. [Tanaka et al., 2015]

\[ \delta_{ts} \rho C_p \frac{\partial T}{\partial t} - \nabla (k \nabla T) = Q \]

Where: 
- \( \delta_{ts} \) is the time scaling coefficient,
- \( \rho \) is density,
- \( C_p \) is the specific heat capacity,
- \( T \) is the temperature,
- \( k \) is the thermal conductivity and
- \( Q \) is the heat source.
The other two equations express the analytic formula of electric and induction currents.

\[ -\nabla (i\omega \sigma - \omega^2 \epsilon_0 \epsilon_r) A - \sigma V \times (\nabla \times A) + (\sigma + i\omega \epsilon_0 \epsilon_r) \nabla V - J^e = 0 \]
\[ (i\omega \sigma - \omega^2 \epsilon_0 \epsilon_r) A + \nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times A) - \sigma V \times (\sigma + i\omega \epsilon_0 \epsilon_r) \nabla V = J^e \]

Where:

\( \epsilon_0 \) is the electrical conductivity of the air,
\( \epsilon_r \) is the electrical conductivity of the conductor,
\( A \) is the magnetic field,
\( \mu_0 \) is the magnetic permeability of the air,
\( \mu_r \) is the magnetic permeability of the conductor,
\( V \) is the electric potential,
\( v \) is velocity and
\( J^e \) is the current's density
Appendix E – Excel model

This section will list the exact formulas that were inserted into the Excel spreadsheet in order to create the model, so that it can be readily reproduced. It is assumed that the exact same cells will be used as the ones named below and that all tables are located in the same spreadsheet, so that they can borrow numbers from each other. Any cell that requires user selected input will be marked appropriately.

<table>
<thead>
<tr>
<th>Cell #</th>
<th>Label</th>
<th>Input Value</th>
<th>Unit</th>
</tr>
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<td>mm</td>
</tr>
<tr>
<td>E5</td>
<td>Corrosion</td>
<td>[User input]</td>
<td>%</td>
</tr>
<tr>
<td>E6</td>
<td>$\delta$</td>
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<td>mm</td>
</tr>
<tr>
<td>E7</td>
<td>$\mu$ (steel)</td>
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<td>$10^{-4}$ H/m</td>
</tr>
<tr>
<td>E8</td>
<td>$\rho$ (steel)</td>
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<tr>
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</tr>
<tr>
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<td>$f$</td>
<td>[User input]</td>
<td>kHz</td>
</tr>
<tr>
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</tr>
<tr>
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<td>mm</td>
</tr>
<tr>
<td>E15</td>
<td>Corrosion</td>
<td>[User input]</td>
<td>%</td>
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<tr>
<td>E16</td>
<td>$f$</td>
<td>[User input]</td>
<td>kHz</td>
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<tr>
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<td>$I$</td>
<td>[User input]</td>
<td>Amp</td>
</tr>
<tr>
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<td>mm</td>
</tr>
<tr>
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<td>Cor. Depth</td>
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<td>mm</td>
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<tr>
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<td>Atot</td>
<td>=PI()*(E14/2)^2</td>
<td>mm^2</td>
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<tr>
<td>E21</td>
<td>Acorr</td>
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<tr>
<td>E22</td>
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<td>m</td>
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<tr>
<td>E25</td>
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<tr>
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<td>Runcorr</td>
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<td>Joule/sec</td>
</tr>
<tr>
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<td>Puncorr</td>
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<tr>
<td>E32</td>
<td>D (rust)</td>
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<td>K/s</td>
</tr>
<tr>
<td>E36</td>
<td>$\Delta T$ (uncorr)</td>
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<td>K/s</td>
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<td>Input Value</td>
<td>Unit</td>
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<td>---------</td>
<td>----------------------------------</td>
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</tr>
<tr>
<td>J14</td>
<td>Jpar0</td>
<td>=E17/E22</td>
<td>A/mm²²</td>
</tr>
<tr>
<td>J15</td>
<td>Epar0</td>
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</tr>
<tr>
<td>J16</td>
<td>Epar1,2</td>
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<tr>
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<td>Jpar1</td>
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<td>I2</td>
<td>=J18*E22</td>
<td>A</td>
</tr>
<tr>
<td>J20</td>
<td>I1</td>
<td>=E17-J19</td>
<td>A</td>
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Appendix F – Frequency’s effect on output

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<th>ΔTcorr (K/s)</th>
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