

The differences in bridge deck maintenance for concrete and steel due to corrosion

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1.0 Background

The innovative combination of steel and concrete has made reinforced concrete one of the world's most common building material systems. Nevertheless, the lack of awareness of concrete's long-term efficiency and the extent of the state of exposure has created serious problems. Already existing concrete bridges have shorter service life than expected due to higher deterioration levels caused by various deterioration factors such as corrosion. Such concerns have shortened the structures service life, or have required substantial maintenance, all of which come at a considerable cost. As a result of this, bridge conditions need to be reviewed on a regular basis. The main cause of the bridge's deterioration should be determined, and adequate maintenance procedures should be pursued. Despite this, the current inspection manuals focus mainly on identifying physical harm to the bridge's structure, such as delamination, cracks and spalls. If no physical harm or damage to the visible structure is found, then there will be very limited action to the maintenance. Because of the lack of knowledge of chemical deterioration within the bridge's structure due to corrosion, preventive maintenance measures are implemented without recognizing the efficiency and effectiveness of this preventive maintenance measure. On the other hand, non-destructive testing methods can be used. This will provide evaluators with the ability to assess chemical conditions of the bridge components in the concrete or steel. The data that is acquired from the non-destructive test method could be used not only to find the remaining service life of the bridge deck, but it can also be used to evaluate and determine the efficiency and effectiveness of the preventive maintenance measures.

2.0 Objectives

The main objective of this study is to demonstrate the differences in maintenance for a concrete deck due to corrosion. This study will include investigations for a better understanding for why bridges deteriorate and how this can be greatly prevented with certain types of maintenance methods. There are various types of problems that will be encountered when a bridge is constructed, from natural defects such as corrosion and high winds, to defects such as delamination, cracks and spalls. This Study will investigate how these problems can be reduced greatly, or possibly even eliminated completely with certain maintenance methods. The findings that are found in this research will be compared and a conclusion will be drawn.

3.0 Research plan

The main tasks of this research are shown as follows:

- Investigate current issues/potential problems that can occur to a bridge deck
- Research various types of maintenance methods within concrete decks.
- Find out how these methods are implemented.
- Perform a cost analysis for various maintenance measures. This includes, the unit cost, service life and the effectiveness of the maintenance.
- Find out how a bridge can have guaranteed safety after the maintenance is complete.
- Find out if these maintenance methods can be improved on for future implementation within the construction industry.

4.0 Introduction

A cost-effective bridge is a bridge in which its maintenance over its entire service is focused not only visible defects, but underlying defects such as corrosion. If corrosion mechanisms are avoided, a bridge can cost considerably less to maintain, and it can serve its maximum design service life. BS5400's provision is for all bridges to be built for a life span of 120 years at the end of which they will need replacement. By finding problems within the bridge early on and keeping it maintained, this will help the bridge reach its maximum life span. The practice of physical assessment and inadequate or delayed maintenance of damaged concrete bridges has contributed to the need for reconstruction of a significant number of bridges. The latest bridge inspection manuals focus mainly on the identification of physical harm in elements of concrete bridge decks. If no physical harm is found, such as cracks or spalls, then there will be very limited maintenance actions that are taken. Due to this, there is such a high percentage of bridges in the UK that are classed as inadequate. A post written by BBC News titled 'Hundreds of road bridges in Britain deemed inadequate' written on 18th November 2015 explains this. It states that there are more than 2,300 road bridge structures in Britain that are deemed inadequate. It would cost a considerably large sum of £328m to refurbish all the affected bridges. If these bridges were maintained more efficiently then this could have been avoided. A possible economical approach to maintain current concrete bridge decks, could include a preventive maintenance approach. A preventive maintenance approach is to work on maintaining the bridge deck periodically

when it's all in working order. Through doing so, it decreases the probability of it failing, not only that, but it makes the bridge safer because it can be maintained more efficiently. The type of environment that the bridge is constructed has a great impact on the life span of a bridge. If the bridge is constructed to cross a river or sea, then the deck of the bridge will be affected by evaporation and high winds containing high water content. Whereas if the bridge is constructed in a hillside, then it will not be affected as drastically from water but will be affected by high pressure winds blowing over the hillside. Also, the soil that the bridge sits on can affect the foundations, as high water content in the soil can render it useless for construction.

5.0 Literature Review

This research is a review on relevant literature on the corrosion of steel and concrete bridge decks and the differences in maintenance to help prevent this.

5.1 Research on Corrosion due to atmospheric elements

The reliability of reinforced concrete bridge decks is highly dependent on the reinforcing steels corrosion rate. The technology of structural health monitoring including integrated corrosion risk monitors, will significantly enhance steel corrosion risk quantification, which can lead to better structural protection, serviceability, and maintenance. The corrosion rate of reinforced steel can be highly variable, both within a given structural component and over time, due to variations in concrete materials, weather conditions and other variables. These spatial and temporal variables can be tracked and, as such, better modelled for use in a durability model by positioning several corrosion risk sensors within a structural part such as a bridge deck.

According to Czarnecki (2006) steel bridges deteriorate during their service life due to a number of different effects. Some of these effects are, the surrounding environment, for example a bridge that is located over water, comes under a lot of danger from corrosion. The high winds from the sea containing water can hit the bridge causing an accelerated effect of corrosion. Other effects of deterioration of a bridge comes from changes in live loads and structural fatigue. A steel and concrete bridge deck design requires a special consideration in respect to the deterioration of the structure due to environmental factors such as high winds, rain and evaporation which can cause corrosion damage.

The massive effect of corrosion is the loss of material section which results in a major reduction of reliability and structural load-carrying capacity. Inadequate bridges are needed to be repaired or replace. In addition to this the maintenance costs are of great importance. Therefore, it is essential and should be prioritized that a development of a procedure is in order to mitigate and eliminate the effects of corrosion.

In the National Cooperative Highway Research Program Report 272 titled 'Performance of weathering steel in bridges', Albrecht and Naeemi (1984) conducted a study that showed the performance of weathering steel in bridges. The main discussion of this study was atmospheric corrosion attack, the causes of it, consequences and possible alternatives to mitigate the problems. The study highlights the environmental impact affecting the bridge as the main cause for corrosion deterioration. The research conducted by Naeemi and Albrecht (1988) showed that the use of de-icing salts is one of the main causes behind corrosion in steel members of the bridge. The study also talked about how an accumulation of debris is a large factor when looking into corrosion of a steel bridge as they can hold moisture and chloride with the surface of the steel for a long amount of time. In addition to this, Kolger (2012) determined that the length of time that water is on the steel has a large impact. How severe the deterioration depends entirely on how much water gets to the steel. In climates with large amounts of rainfall, the design of the bridge plays a large role as water can get trapped and retained by certain parts of the bridge. Due to this, a bridge can be designed in a way that helps mitigate water retention by designing a slope to keep the water off.

5.2 Causes of corrosion

Steel corrosion exposed to water, soil and weather is following a trend that is expected by the majority of people, for example if steel is submerged in warm water, it will corrode faster than if it was submerged in cold water, another example is that steel corrodes faster in sea water than it does in fresh water due to the salt within the water. Aside from this, similar patterns can be seen with atmospheric exposure. For example, a bridge that is constructed in a dry landscape such as Dubai, the corrosion rate will be slower than a bridge constructed in the Everglades of Florida, due to the high amount of moisture in the atmosphere. When steel is reinforced in concrete then it is a different concern. The concrete's alkalinity allows the steel reinforcement bar to behave in a similar way close to that of stainless steel. This non-corroding state is retained before adequate concentration of chloride ions from seawater or roadway de-icers enter the surface of the reinforced concrete. When this happens, the steel begins to corrode, which results in the spreading of rust which expands within the concrete causing it to crack and break.

5.3 Controlling the Corrosion

There are various amounts of measures that can be implemented into the control of corrosion for a steel and concrete deck. Steel decks can have protective coatings applied; this can extend the service life by 30-40 years. In certain environments weathering steels can be applied, this provides a similar protection but without the need of a protective coating. For a reinforced concrete deck, the right corrosion control measure must be chosen. For a steel deck to have a service life of 75 years or more, it is crucial to implement

reinforced steel within the concrete. For best results a highly impermeable concrete should be used with steel reinforced bars that must be embedded deep enough so that it can prevent the build-up of chloride at the surface of the bars which will eliminate the possibility of the steel corroding causing the concrete to crack.

The extent of damage to the bridge to corrosion increases over time. The graph below shows the deterioration of a bridge. This graph not only shows the amount of the damage caused over time, but it also shows the rate of damage that occurs to the bridge.

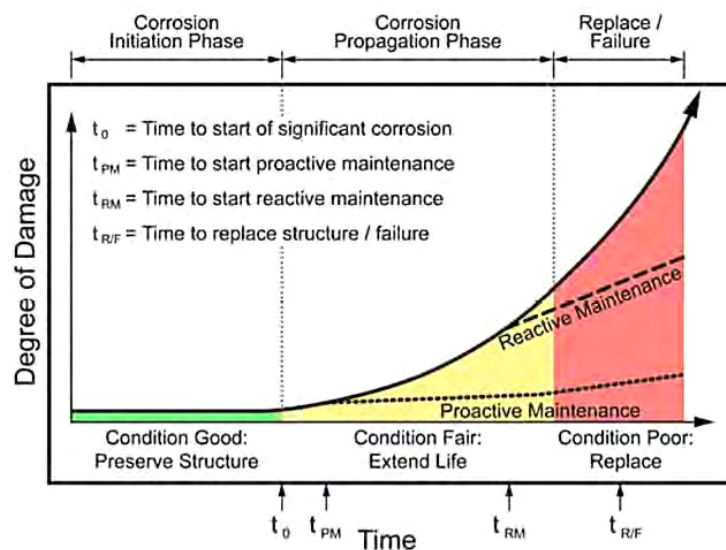


Figure 1: Graph of damage and rate of damage to a bridge over time

5.4 Damage from corrosion to the bridge

The corrosion damage to the bridge can be observed and broken down into three different factors, the corrosion initiation phase, the corrosion propagation phase, and the replacement phase. The development and progression of corrosion are also driven by environmental influences. One main environmental factor is the amount of oxygen, corrosion can only develop when oxygen is available. This explains why corrosion is less effective when concrete is submerged in water. This reliance on environmental factors for the production of corrosion will create difficulties in determining the material state, as the tests are often highly dependent on the humidity and temperature during the time at which the inspection takes place.

5.5 Corrosion initiation phase

Corrosion related damage which occurs early in a bridge's life span is typically not a concern. To enter the reinforcement, chloride ions must infiltrate the concrete from de-icers or a marine environment, and coatings are initially very safe. The duration of this phase can be increased by choosing materials that are resistant to deterioration, improving material consistency, and documenting the building. For example, if a service life of more than 75 years is required, then the use of a stainless-steel reinforcement should be taken into serious consideration. Inspection during this initial phase can provide valuable information to make accurate assumptions of the time in which corrosion will take place. By having these inspections early in the bridge's life, it can help prevent or mitigate future problems.

5.6 Corrosion propagation phase

Once corrosion has begun, it takes time before the cycle causes noticeable damage, whereas in the case of reinforced concrete it takes longer to identify using conventional sounding techniques. Measuring the corrosive potential can identify the corrosion of the reinforcement before the rust forms which will cause spalls, cracks and delamination to the bridge deck. During this initial phase, this is typically where maintenance and repairs occur. If a preventative maintenance method is in place, then repairs can be done before any cracks or spalls even occur. The use of non-destructive testing methods can be implemented which can help determine the location of erosion damage and help mitigate the problem, eliminating any dangers that can occur.

5.7 Replacement phase

In this stage there is an increasing risk of failure and to prevent danger or harm, certain measures must be taken. As shown in figure 1 above the deterioration condition of the bridge is extremely large at this stage, it can become too costly to repair and must either be replaced or taken down.

5.8 Corrosion resistance tests for reinforced steel within concrete

A seven-year site exposure test of steel reinforcement in concrete was conducted by Rashed Uz Zafar et al. They tested and evaluated the performance of corrosion resistant steels in chloride concrete. The evaluation of galvanized, epoxy coated, bare mild steel and stainless steel were examined by the embedment process within concrete with 3 variations of levels of chloride content (0.6, 1.2 and 4.8% by weight of cement) a conclusion was drawn that galvanized steel in concrete with a high level of chloride only delays the concrete failure whereas epoxy coated bars offered good corrosion resistance within low levels of chloride.

On the other hand, bare mild steel suffered extreme rust related damage within all three levels of chloride.

In a different test, Yeomans and Kayyali, compared black, epoxy coated and galvanized rebars that were fixed into a concrete beam that spanned a size of 1500 x 160 x 320mm. This test was carried out to evaluate the bond of coated reinforcement within concrete. The results showed that the capacity in beams of reinforced epoxy coated and galvanized bars was not much different from black steel reinforced beams.

5.9 Maintenance Research

An appropriate method of bridge maintenance can extend the service life of the bridge at a low cost if the maintenance is conducted in a routinely manner. The importance of an effective maintenance for a bridge is largely recognized. Sinha et al. (2009) showed that the service life of a bridge varies between 35-80 years, based entirely on preservation and maintenance activities. These are required to make sure that a bridge can reach its full expected service life with limited problems. “if a steel highway bridge is not maintained properly (regular cleaning, inspection, repainting, and repair) steel corrosion occurs” was an indication made by Czarnecki (2006). One recommendation from the guidelines of the Federal Highway Administration that were recommending within the document to help prevent damages to the bridge such as “Remove dirt and other deposits that hold moisture and maintain a wet surface condition on the steel. In some situations, hosing down a bridge to remove debris and contaminants may be practical and effective. Some agencies have a regular scheduled program to hose down their bridges”.

A study was conducted in 2001-2004 by the Shikoku Regional Bureau of Japan Highway Public Co. This study was based on the performance of two different weathering steel bridges under an experimental bridge washing program (Hara et al., 2005) The main investigation of this study was to analyse the effect of bridge washing as a way to remove corrosive products that develop from de-icers applied to the deck of a bridge. Throughout the study, once a year, certain points on the bridge girders were being observed and recorded to examine before and after the de-icer products were applied. For the certain points that were being observed the rust characteristics and loss of mass of the steel surface were being analysed. The research came to the conclusion that washing the steel surface had the effect of decreasing the amount of rust particles, due to the de-icer products it was a way to reduce the corrosion rate.

(Crampton et al. 2013) studied the actions of steel weathering bridge structures. The research that was conducted Investigated methods to determine the quality of the weathering steel from chloride contamination and the potential benefits of routine bridge washing. The study showed that high pressure washing the structure at around 3,500psi is an acceptable method to reduce the chloride contamination within the steel. The high pressure washing mainly removed the chlorides from the surface, but some amounts of chloride still remain under the surface. It was discovered that if the steel is washed straight

after the winter de-icing season, the bridge washing technique will be able to remove the majority of the chloride from the surface before it can move under the surface layer. The conclusion of this study was that having a consistent routine of bridge washing, the corrosion process will be mitigated. It is indicated that on this topic further study needs to be conducted.

The Federal Highway Administration conducted a study to analyse the benefits and the cost of routine washing of steel bridges (Berman et al.). The study was conducted in 2011 where certain bridges would be annually washed, while other selected bridges would not be washed. Bridge inspectors would annually inspect the bridge from the project and will document the corrosion level condition of the steel coating from both washed and unwashed bridge's the data obtained will be examined and processed annually, which will determine how cost effective it is to wash the bridge for an extended steel coating life span.

5.10 Types of maintenance

Deterioration of the bridge typically happens gradually at first which is frequently overlooked. However unexpected disastrous accidents may occur in later stages of degradation, which require prompt intervention. If proper routine preventative maintenance is performed, gradual decay may be avoided and even eliminated (Carter and kaufman 1990). Maintenance of a concrete bridge is fairly cost effective as it uses repeatable operations that either avoid or mitigate concrete life of bridge elements, or minor repairs that prolong the structural service life of the bridge. Maintenance is carried out on a concrete bridge when the structure itself is still in good condition which can then be subdivided into a preventative maintenance method.

Preventative maintenance measures are undertaken until corrosion is apparent and the concrete deck is still in good condition. This is typically prepared at the design stage. The procedure typically includes, crack repair, washing, caulking and sealing.

Active repair procedures are usually more comprehensive and are conducted in the early stages of the observable degradation, such as small cracks or spalls. Procedures require minor repairs, the development of appropriate deck drainage systems, the maintenance of deck joints and related practices to improve working life of reinforced concrete bridge decks.

Maintenance operations are most cost-effective when the concrete is still in adequate condition and is focused on concentrating on certain sections of a bridge that has to come into contact with the most extreme exposure to environmental conditions such as wind and rain. Preventative maintenance addresses the causes of likely deterioration of the bridge as opposed to actual repairs. Sealing the surface of the concrete deck for instance, eliminates chloride infiltration. Appropriate preventative maintenance can mitigate corrosion rates and extend service life while mitigating potential repair costs (Carter 1989). A responsive maintenance activity helps to keep a bridge operating safely and as efficiently as possible.

Maintenance is no substitute for sound construction and architecture. Only proper maintenance, when applied to poorly engineered and built concrete bridge structures does not yield satisfactory results. Types of improper nature include inadequate steel cover lengths, unnecessary surface splitting and bad drainage properties, such as chloride contaminated water on a concrete bridge deck.

Maintenance operations that are carried out at the correct time are highly cost-effective. Similarly, repair work that is carried out too late may be a bad investment. The incorrect time for maintenance is when significant damage has already occurred, for example once spalls and or cracks have formed then it's too late for maintenance but instead needs to be repaired. Maintenance can prevent serious damage from occurring but once its already happened then the only thing to do is to replace or repair the concrete as best as possible as concrete cannot be restored. Concrete cannot be properly repaired with more concrete or cement, it can reduce the possible damage but in time it will need to be replaced completely.

5.11 Concrete deck patching

The need to repair a concrete bridge deck is almost always the reinforcement corrosion. Deck patching is a partial fix unless all the concrete that is contaminated with chloride is removed before the deck is patched. The degradation cycle begins when only the delaminated and spalled concrete is replaced. Evidence has demonstrated that sealing and overlaying concrete contaminated by chloride cannot eliminate but will prolong, ongoing degradation and concrete decay. A deck survey is conducted to determine the concrete repair areas for permanent patching. The deck survey consists of tests that cover chloride content, delamination and reinforced steels corrosion potential. The deck survey findings are used to map regions with significant degradation and pollution of chloride, delamination's and spalls. Deteriorated areas and areas with excessive corrosion potentials and/or chloride content are marked for removal on the basis of the details gathered from the survey.

If the patch repair is temporary or permanent, potholes cannot be permitted if they negatively affect the quality of the bridge deck. Hard decks also raise the traffic pressure on the bridge, increasing the damage possibly leading to structural damage. Hence where the insulation of a concrete deck is not sufficiently secured against the intrusion of salt water then deck patching will be necessary.



Figure 2: Concrete bridge deck patching

5.12 Patching procedure

The following is a procedure for the patching method of a concrete bridge deck:

- Assess the area required for patching using a drag chain, areas that are delaminated will have a hollow sound.
- Outline the area that is required for patching spray paint. Allow more room for areas of delamination that might not have been detected. To ensure total coverage, the spray paint line is typically around 150mm further than the delamination that's been detected.
- Use a concrete saw to saw vertically for around 20mm around the perimeter of the sprayed outline. This provides a 'shoulder' for the patch to bear against. Extra care must be taken while doing this step as it is crucial not to cut the steel reinforcement within the concrete, it's also important to avoid cutting past the desired area as this can cause other problems such as spalling. The best results can be obtained when the number of individual patches is minimised, for example, if the patches are within 600mm of each other then they should be combined.
- Using a pneumatic jack hammer remove the concrete within the desired area at an 45-60 degrees to the deck. Periodically sound to make sure that the correct depth and area are clear of degraded concrete. Fracture lines over a supporting reinforcement bar signify that an area that is to spall should be removed.
- The area that is required to be patched should be thoroughly cleaned to remove all loose concrete, oil, rust and any debris. This is done by either water blasting or sandblasting.
- If it is found that the reinforced steel has deteriorated due to corrosion and has lost more than 20% of its original cross section, then new reinforced steel should be added by welding, mechanically connecting or lapping with the steel bar that's deteriorated.

Concrete bridge deck patching is categorised into 3 types that are based on depth

- Type A which is above the top layer of the reinforced steel.
 - Type B which is from the deck surface to a minimum of 25mm below the top mat of reinforced rebar.
 - Type C is the full depth of the deck.
-
- Type A can require different aggregate dimensions, since the rocks diameter cannot be larger than the holes depth. The problem that can occur is that the surface patch might be too thin for the asphalt, concrete or the epoxy mortar may be too thick. The maximum layer for a bridge deck repair application is a9mm-25mm.
 - Type B will have the steel reinforcements involved, as it is crucial that space is left under the steel to allow fresh concrete to flow beneath them so that no voids are left. This type of patching is typically too thick for epoxy mortar, unless it is applied in layers.
 - Type C patching will involve supporting of the bottom of the hole which will require formwork. This can be easily wired to the reinforced steel. If a patch is expected to exceed an area of 4ft x 4ft then an Engineer should be contacted, as this could have dangerously large effects on the bridge's strength.

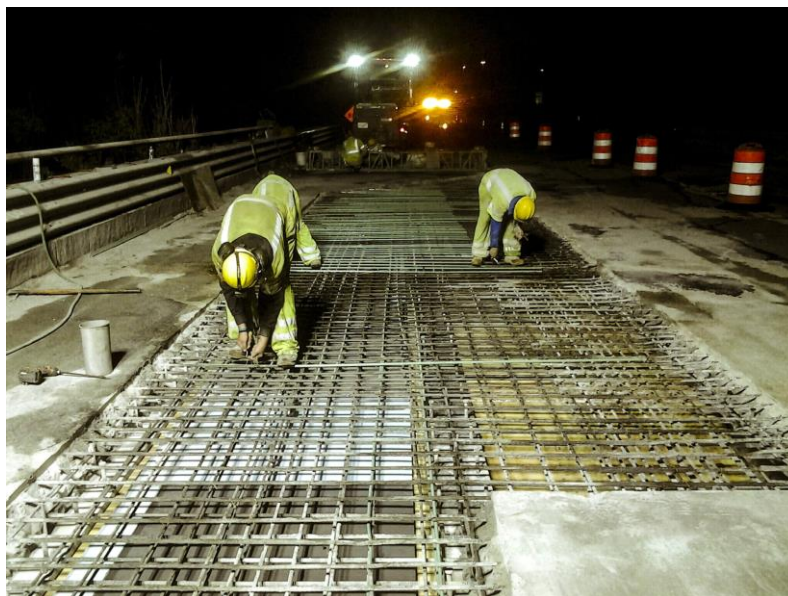


Figure 3: Patching procedure

5.13 Sealing of concrete deck

Sealing is achieved by adding a deck with a barrier to keep chloride from entering the concrete deck. Both sealer materials need penetration because of the surface coating is easily worn off by abrasion from the traffic. There are various types of sealers polymers such as epoxies and silicone. The correct application of these materials requires a dry deck surface with relatively warm atmospheric conditions. The deck surface must also be clean from any debris for the materials to be applied.

The following is a set of steps of how the sealer is applied to the deck of the bridge

- The deck must be cleaned prior to application. This is done by washing, sweeping and/or air-blasting. Sandblasting is sometimes required as some sealers have a high film thickness which can rest on the surface of the bridge deck.
- It is crucial that conditions are in check with the manufacture's specifications for the sealer to be applied. Some of these conditions are as follows:
 - Air temperatures won't fall during the application.
 - Minimal velocity of wind to mitigate drift.
 - The bridge deck is sufficiently clean with no oil or moisture.
 - Check temperatures of the deck and air prior to application.
- Areas in which the sealer is required must be marked out to the desired dimensions to ensure correct application.
- Some materials can cause a chemical reaction, so to avoid this the sealer must be prepared and mixed thoroughly.
- Apply the sealer by the use of one of the following:
 - Rollers.
 - Mechanical spray equipment.
 - Distributors.
 - Notched or un-notched squeegees



Figure 4: Concrete deck sealing

- For sealers that are on the surface, they should be immediately followed up with an anti-skid material such as sand for example. It is crucial to have this material in place because it can be imbedded in the sealer itself. On the other hand, it is not needed for sealers that penetrate the surface sand. These sealers however, typically tend to slick the deck before penetration. If traffic is using the deck, sand will be accessible if full deck penetration does not occur which involves blotting, to minimise excess content as much as possible.
- Calculate cure time of the application for adequate deck absorption and lane closures.
- Take all the correct precautions to ensure that worker safety is kept and to prevent damage to the surrounding environment.

5.14 Current inspection requirements

5.14.1 Inspection type

According to the bridge inspection manual that is published by (NYSDOT 2014) there are 5 various forms of inspections for a bridge and these are described below as follows:

- General inspection – this form of inspection is required for all types of bridges at an interval maximum of 24 months. Such inspections include both interim and biennial inspections as specified in the Uniform Code of Bridge Inspection (UCBI) Interim inspections during the mandatory biennial inspections are conducted during the calendar year.

- In depth inspection – this inspection is typically carried out as a follow up inspection. It is an event –driven inspection to help identify any shortcomings detected. Both forms of in-depth testing are underwater inspections and fracture-critical inspections.
- Special events – These inspections have no significant effect on the structures level of quality. Use of these types of inspections will not follow the normal workflow of quality assurance/quality control used for general and diving inspections. This group requires inspection by post-seismic inspections, flood monitors and post flood inspection.
- Special in-lieu of – This group of inspections is used for awarding and recording the special position of bridge inspections scheduled for inspection according to the intermediate criteria of the UCBI. Interim inspections shall be conducted following every biennial inspection, within one year. Bridge's that are open to motorway traffic during reconstruction, repair or rehabilitation shall be subject to interim inspection. A system of planned special inspections can be substituted with temporary inspections for a very large or unusual structure. In no case should a separate inspection position be given in seasons of back to back inspections.
- None due to construction that is being carried out - this inspection term is used for bridges that are closed to all traffic due to restoration. In fact, a general inspection will be carried out within 60 days of reopening the newly completed bridge to traffic. The inspection must then take place after the opening of the bridge to traffic, so the inspector is able to view the bridge's structural behaviour.

5.14.2 Inspection procedure

There are a few key factors when it comes to the inspection procedure, these are listed below:

- Planning stage – the inspection leader will make preparations in advance in order to keep the review organised and comprehensive. Inspection preparation is necessary for an accurate, cost effective operation, which should result in a comprehensive and full inspection.
- Preparation – these steps are needed prior to the inspection and include preparing the necessary resources and supplies, also checking the bridge construction reports and finding construction plans. The quality of the on-site inspection depends to a large degree on the effort made to prepare for inspection.
- Performing – this step is the on-site job of accessing and inspecting bridge and waterway elements, if any are present. Inspection protocols should also be practiced, as described in the NBIS

- Preparing the report – documentation is important for inspection of any kind to ensure that a detailed and accurate report is available for further use.
- Identification of repair and maintenance products and reporting of important findings – the final underlying duty is to identify, repair and maintain the bridge, in order to facilitate public safety and optimise the durability of the bridge and ensure that it has a long-life span.

5.14.3 Inspection methods

Although substantial advancements in the production of non-destructive testing methods have been made, the more common, physical and visual inspections are still the primary methods that are used to evaluate the condition of the bridge, particularly for routine inspection.

5.14.4 Physical inspection

In any case it is important to test the physical state of a bridge deck. Therefore, a suitable method of inspection to test the deck should be chosen. Physical inspections should investigate areas of concrete or reinforced steel decay which are visually detected using a hammer for the initial inspection. This hands-on action verifies the magnitude and nature of the deficit. If the concrete is struck with the hammer, a region that is delaminated will have a distinct hollow sound. A hammer that hits sound concrete will make a strong 'ping' like sound. A chain drag can also be used to conduct the test.

5.14.5 Visual inspection

Visual inspection techniques are the main methods that are used when evaluating and determining the quality of a bridge deck. The primary function for a visual inspection is to detect problems such as spalls and holes. Dirt and debris must be removed in order to obtain a high-quality visual inspection. The required special equipment and procedures should be combined with careful visual observation.

5.15 Non-destructive testing method

Non-destructive testing (NDT) methods will be the way forward for bridge deck maintenance. This method is an effective way for a company to save a lot of money and valuable time. This test help detect areas that are at risk of corrosion before they become a problem. By using this method, it will produce less waste, since the materials are not altered

in any way, they can still be used which means that a lot less samples don't have to be wasted. It is also beneficial for accident prevention. The NDT can prevent accidents from occurring which will then reduce the large costs of bridge deck repairs or even replacements. NDT is a great method for identifying areas of concern before they fail.

5.16 Accelerated corrosion tests

An accelerated corrosion test is performed in a laboratory by producing atmospheric corrosion at an accelerated rate. According to (Guthrie, 2002) there are 3 types of corrosion tests. These three are: field testing, laboratory testing, and service testing. Out of these three tests, service testing has proven to be the most reliable since it can provide actual test results from the actual in situ corrosion process. Unfortunately, the results that are obtained are limited to the short period of time in which the test lasts. Field tests are similar to this, as they can offer great results on producing corrosion but also suffer from the same limitations on time. Hence, accelerated corrosion experiments are also an acceptable option for obtaining satisfactory outcomes in a relatively short amount of time (Guthrie, 2002). The effects of accelerated research are only an approximation to fact, and are only as good as the conditions within the laboratory (Carlsson, 2006)

There are currently several common protocols for performing accelerated corrosion testing, with the most of them being developed for the automotive coating industry. The ASTM B117 procedure was originally published in 1939 and has long been used for accelerated corrosion tests. (Cremer, 1996) Since the corrosion process include many variations, certain systematic accelerated tests were developed and carried out with the intention of approaching some basic corrosion characteristics (Guthrie, 2002)

The findings have to be acknowledged with an acceptable margin of error, considering the many assumptions formed during accelerated corrosion testing. The B117 ASTM standard was applied to conduct the accelerated corrosion test to study three different types of steel, these types are: weathering steel, carbon steel and soft steel. The main goal of this research was to create a link in real environment between corrosion levels and corrosion factors, from the length of time the steel is wet, temperature and chloride deposition. By measuring the loss of weight of the specimen's in a natural and laboratory setting, (Lin 2005) identified the associations between the expected and observed thickness losses due to the atmospheric corrosion. The test findings of the experiment showed the following error margin: 37.2% for the weathering steel, 28.7% for carbon steel, and 29.0% for soft steel. Obviously, there is also a degree of uncertainty when using the accelerated test method to identify corrosion.

6.0 Methodology

For this research paper, the author has investigated the question of ‘The differences in bridge deck maintenance for concrete and steel due to corrosion’. This question has been addressed as a lack of awareness of concrete’s long-term efficiency and the extent of the state of exposure has created serious problems. Already existing concrete bridges have shorter service life than expected due to higher deterioration levels caused by various deterioration factors such as corrosion. Such concerns have shortened the structures service life, or have required substantial maintenance, all of which come at a considerable cost. This research is a look into how a bridge can be better maintained and also how corrosion damaged can be mitigated or even eliminated in the near future due to the methods listed in this research.

In order to successfully and appropriately address the issue of corrosion within bridge maintenance, while also attempting to achieve the aims and objects stated at the start of this research a methodical approach was followed. This was to justify what was carried out throughout the project and how it was accomplished as well as not only evaluating the reliability, but also the validity of the research that has been conducted. Therefore, a qualitative methodical approach was selected and implemented into this research. The main reason for this approach is due to the fact that it allowed for a greater range of in-depth explorations and measurements through the use of case studies, articles and a questionnaire. A quantitative approach was also considered as some case studies produced some numerical values and statistics, but a qualitative approach was prioritised as it was most beneficial for this research topic, as it presents a broader picture of the use of variations of maintenance due to corrosion.

6.1 General procedure

It is crucial to have a well-structured approach to this study to ensure that it is conducted properly and professionally. In addition to this, following the correct regulations is also important. For an individual or an organisation with experience within this topic, this could be classed as common knowledge, but with an individual or an organisation with no experience on this topic secondary sources could be very beneficial. To ensure that this research was conducted correctly, further research was carried out before hand with the use of secondary sources, such as websites, previous research from articles and books. For example, National Cooperative Highway Research Program Report 272 titled ‘Performance of weathering steel in bridges’ was used as a secondary source which was used to gather relative and useful information.

The use of case studies throughout this research have helped to identify problems that can occur within a bridge deck such as cracks, delamination and spalls. These case studies then show what plans, methods and procedures are used to first identify the problem, prepare

for repairs and then carry out those repairs. The use of various maintenance methods is shown throughout this research as a basis for comparison.

A qualitative approach has been carried out for this research with the aim to gain a unique perspective of the topic through the use of case studies and data analysis. With these case studies the author is able to identify concerns with the forms of maintenance that are used which gives an insight on how these can be improved for future maintenance and how it can be carried out more efficiently.

6.2 Purpose

The purpose of this research is to collect data on how concrete and steel bridges are properly maintained due to corrosion and to analyse this data. The research that has been conducted has brought many things to light. For example, the differences on corrosion damage for various materials and how these problems are identified with the use of certain equipment and procedures. Different equipment and procedures are used for different types of damages such as delamination, and cracks. This data has been obtained through the use of various case studies and articles.

This is an interesting research topic to investigate as there are so many variations for maintenance, and by investigating the topic it helps to show how these methods could be discussed further research and potentially improved in the near future. The current inspection manuals for maintenance focus mainly on identifying physical harm to the bridges structure through visual inspection, such as delamination, cracks and spalls. If no physical harm or damage to the visible structure is found, then there will be very limited action to the maintenance. Because of the lack of knowledge of chemical deterioration within the bridges structure due to corrosion, preventive maintenance measures are implemented without recognizing the efficiency and effectiveness of this preventive maintenance measure. Corrosion can easily take place within the concretes frame. Due to chloride contamination within the steel reinforcement of concrete, rust is formed which causes the steel rebar to corrode causing a weak spot within the bridge deck which will eventually turn into a crack, which causes unnecessary damages, costs and time. If preventative measures are properly implemented these damages won't take place, as they can be prevented early on. This research shows how this preventative method has its benefits from just the correct procedure.

6.3 Discussion of possible alternative methods of data collection

An alternative approach could have been conducted for this research topic. For example, a quantitative approach could have been implemented via laboratory work. A test of corrosion acceleration could have been carried out, which uses atmospheric corrosion at an accelerated rate on concrete or steel as discussed in the literature review. This test can help to achieve numerical data which can be processed and compared with various elements to come to a conclusion. As discussed in the literature review there were three tests that were carried out on three different steels, these being: weathering steel, carbon steel and soft steel. The test findings of the experiment showed the following error margin for each of the individual steel test subjects: 37.2% for the weathering steel, 28.7% for carbon steel, and 29.0% for soft steel. Obviously, there is also a degree of uncertainty when using the accelerated test method to identify corrosion due to the lack of time that the experiment takes. This test could have been replicated in a laboratory for this research to find out if similar results could have been obtained and compared.

6.4 Advantages/disadvantages of qualitative and quantitative data collection

Qualitative data collection – There are many advantages of using this form of data collection. There is a wide array of possible paths to choose, some of these being: Focus groups, observation, interviews, existing documents and questionnaires/surveys. Each individual data collection methods has its own advantages and disadvantages but this will be focusing on qualitative data collection in general. The pros of this method are as follows:

- Qualitative data collection offers a methodology which is far more robust. If useful observations are not being obtained, then the researcher can easily adjust questions to alter the desired topic or aspect of the question to improve the response.
- Qualitative research collection helps researchers to be even more flexible on the field that they want to discuss/explore. It enables data collection to be triggered by the instinctive or positive feeling of a researcher about where to locate useful knowledge.
- Qualitative analysis can catch shifting perceptions within target group, such as a construction company or construction workers.
- Qualitative analysis methods aren't constrained by limitations like quantitative methods are. If the responses don't match the researcher's assumption, then they can easily be changed.

The cons of qualitative data are as follows:

- Bias on self-selection can occur when a business requires an employee to volunteer their opinions. If in a report, internet survey or a focus group if an HR agency asks for

applicants, there will be the problem of workers bringing out themselves. The point is that this category would eventually have limited its scope by having people volunteer themselves as opposed to having randomly selected workers.

- The amount of people chosen for this method can have a negative effect, if it is desired that you seek to give 200 employees a survey to complete from one company and 75 employees from a different company, then your data won't be as accurate as you are limiting the affective data that can be obtained by being inconsistent.
- This method can lose data as it can require multiple sessions.

This qualitative method is what was chosen for this research project. A set of case studies and articles were researched to help find accurate data analysis and to provide the author with a questionnaire which will be linked and referenced to the literature review in 'Table 1'

Quantitative data collection – There are four main types of quantitative data research, these are: Descriptive, experimental, quasi-experimental and correlational. The variations between the four forms contribute mainly to the degree planned by the researcher for regulation of the experiment's variables. The pros of the quantitative data research are as follows:

- Data collection involving complex statistics and data analysis is considered useful and important since the complexities involved are not known by many.
- A straightforward analysis can be obtained when quantitative data is used, as numerical data can easily be observed and is less likely to contain error.
- The data that has been obtained can be checked multiple times and tested to ensure that the collection of data is accurate.

Cons of quantitative data are:

- Limited results as the research provides numerical data as opposed to a detailed narrative.
- This method relies on the experience that the researcher has.
- Difficulty when starting a research model.

A questionnaire was produced by the author to acquire further research on the topic. The questions will be listed in the table below and referenced according to the data collected from the literature review.

6.5 Questionnaire

Questions	Literature Review Referenced headings
1) Is a preventative maintenance method the best approach for a bridge deck?	Corrosion propagation phase
2) Can Non-destructive test methods for bridge maintenance replace physical and visual inspection?	Non-destructive testing method
3) Can accelerated corrosion tests help with potential problems early on in a bridge's life span?	Accelerated corrosion tests
4) Is Non-destructive test methods a cost-effective way of maintenance?	Non-destructive testing method
5) Is bridge washing a crucial method for the longevity of a bridge's life span?	Maintenance Research
6) Does epoxy coated reinforced steel provide the best protection from corrosion?	Corrosions resistance tests for reinforced steel within concrete
7) Is concrete deck patching an adequate form of repair?	Concrete deck patching
8) Out of the prevention and preservation method in maintenance, which is more beneficial and why?	Corrosion propagation phase
9) Can the onset of corrosion be controlled?	Controlling the Corrosion

Table 1: Questionnaire

6.6 Justification

These questions were chosen as it can help to further the study of this topic and provide an array of information. Each individual question stems from the literature review of this research, which has been created to conduct a survey on the differences of certain aspects when it comes to maintenance of a bridge deck, whether it be concrete or steel. In addition to this the questionnaire helps provide an understanding of how these processes and procedures are carried out, but not only that it helps to identify the advantages and disadvantages of certain materials, methods and new studies such as Non-destructive testing methods.

6.7 Review of methodology

6.7.1 Problems encountered

There weren't many problems that were encountered when conducting the methodology. One of the problems that was faced was the lack of availability on this topic on the internet. Only a few case studies and articles could be located. This problem could have possibly been avoided by better use of entering key words into the search bar. Another problem that was encountered was the lack of experimentation on this subject. Not many corrosion tests to help mitigate or prevent deterioration could be found when conducting searches online.

6.7.2 If the project were to take place again what would change to benefit the research

If this project was to be run again there are a few changes that the author could make. One of these being the use of both quantitative and qualitative research methods. By doing this not only could the author receive data collection through case studies articles and questionnaires, but numerical data could also be provided with the use of laboratory tests and studies. By doing a possible Corrosion acceleration test, this could bring data that can be examined and compared to other studies to determine the accuracy of the test subjects which in the case of this study, was different types of steel. By conducting this test method, it would help widen the research area of the project and bring a more accurate approach. Also, another test method that could be conducted would be a non-destructive test. This consists of finding defaults within a material to help prevent damage and costly repairs. This could be tested to see if it is a new and beneficial way to conduct maintenance tests with the least amount of damage, for example it could be used to detect holes and delamination without the use of a hammer, thus helping to keep maintenance free from possible damage.

6.7.3 Reliability and Validity of the research

The research that was conducted with the literature has a high reliability and validity. The case studies that were discussed were full of well-structured information and data, that has been carried over into the authors research with the use of correct referencing. The use of the qualitative data collection method helped provide a good amount of information through the use of case studies, articles, books and questionnaires. In addition to this, the British Standard codes of practice for example, BS5400 were a useful way of attaining information and data to help improve the research.

7.0 Results and discussion

7.1 Introduction

This chapter deals with the analysis of the differences in maintenance tests and procedures of concrete and steel due to corrosion. It will be a look at all the case studies and articles that were researched in the literature review to gain a better understanding of the project.

The findings of this research with the use of a qualitative research method will be analysed discussed, then brought to a conclusion. The study that was conducted by Naeemi and Albrecht (1984) was used to obtain a better understanding on the performances of weathering steel on a bridge. Also, literature from Czarnecki (2006), Carlsson (2006) and (Guthrie, 2002) were used to help gain a greater understanding on various studies throughout this research. Another useful data collection test that was used was Lin (2005) who identified the associations between the expected and observed thickness losses due to the atmospheric corrosion. The test was carried out to find the margin of error for weathered steel, carbon steel and soft steel, the findings of the experiment are as follows: 37.2% for the weathering steel, 28.7% for carbon steel, and 29.0% for soft steel. When Lin (2005) conducted these tests there was an obvious understanding that there is also a degree of uncertainty to account for when using the accelerated test method to identify corrosion.

Due to the case studies, articles and books that were researched, the author carried out a questionnaire which is listed in 'Table 2' below. The questions that were created were to achieve a better understanding of each aspect of the literature review, to determine if that possible changes could be made, any improvements, or if any form of method or procedure can be taken out of future maintenance requirements.

7.2 Results

Questions	Answers
1) Is a preventative maintenance method the best approach for a bridge deck?	Yes – 82% No – 18%
2) Can Non-destructive test methods for bridge maintenance replace physical and visual inspection?	Yes – 12% No – 88%
3) Can accelerated corrosion tests help with potential problems early on in a bridge's life span?	Yes – 93% No – 7%
4) Is Non-destructive test methods a cost-effective way of maintenance?	Yes – 88% No – 12%
5) Is bridge washing a crucial method for the longevity of a bridge's life span?	Yes – 66% No – 34%
6) Does epoxy coated reinforced steel provide the best protection from corrosion?	Yes – 98% No – 2%
7) Is concrete deck patching an adequate form of repair?	Yes – 58% No – 42%
8) Out of the prevention and preservation method in maintenance, which is more beneficial and why?	1 Example: A preventative approach would be classed as more beneficial as it helps eliminate potential problems that could arise early on in the deck of the bridge. By finding these issues early on it can mitigate destructive damage causing costly bridge repairs or even replacements, thus saving money, time and effort.
9) Can the onset of corrosion be controlled?	Yes – 87% No – 13%

Table 2: Questionnaire Results

7.3 Discussion

With the results that have been obtained by the author, they are able to be cross-referenced to what has been researched in the literature review. Each example of this will be listed below as follows:

- For question one, the author was able to obtain results from the case studies that were present in the section of the 'corrosion prorogation phase' of the literature review. In this phase it talks about the measuring of the corrosive potential which can identify the corrosion of the reinforcement before the rust form which will cause spalls, cracks and delamination to the bridges deck with the use of a preventative maintenance method. This question was created to help support the author with research into preventative methods and how this can benefit the construction industry in the future.
- With question two, the author was able to support the findings of the research within the literature review by investigating non-destructive test methods. This question is referenced to the non-destructive testing methods part of the literature review. The results were able to provide evidence of the benefits of non-destructive testing methods, but also provide a foundation to how not only one method can be beneficial when it comes to inspection for maintenance, as the importance of maintaining a bridge requires a wide array of methods and procedures.
- Question three is referenced to the accelerated corrosion test of the literature review. The main aim for this question was to provide a foundation for the benefits of testing corrosion potential for a bridge early on in the bridge's life span. With 93% of people who took the survey answering yes to the question, this gives evidence to the benefits of corrosion testing to mitigate problems in the future.
- With question four, this question was provided to analyse the potential benefits of how cost effective a non-destructive test method is.
- Question 5 asked the question of how crucial bridge washing is for the life span of a bridge. This provided the author with a deeper insight into how bridge washing is important for the longevity of a bridge, but also how it isn't crucial. Bridge washing is an important factor for bridge maintenance, but it isn't the only method that is required as various methods must be used in conjunction to provide the best outcomes for the longevity of a bridge.
- Question six was an interesting topic. This question is in reference to 'Corrosions resistance tests for reinforced steel within concrete' within the literature review. It provides substantial evidence of the benefit of using epoxy coating for reinforced steel. 98% of people that participated in the questionnaire agreed that epoxy coating is the best method to provide protection of corrosion for reinforced steel.
- Question 7 looks at if concrete deck patching is an adequate form of repair. The results from the questionnaire provide a divided opinion and require a further in-

depth investigation on the question at hand. This question is a reference to the research of 'concrete deck patching' in the literature review.

- Question 8 was an open-end question, which provided substantial evidence for how a preventative maintenance approach was best suited for when it comes to maintaining a bridge deck. It discusses the benefits of using this method in the form of saving money, time and effort.
- Question 9 was an investigation into the controlling of corrosion. The majority of people who took part in this questionnaire answered yes to 'can the onset of corrosion be controlled'. 87% of people agreed that it is possible to be able to control corrosion. Corrosion can't be permanently stopped as of yet, but there are methods and procedures that can help to mitigate the effects of corrosion and slow the corrosion process down, such as the corrosion acceleration test, which was also a question within the questionnaire which helps provide a foundation for this question.

8.0 Conclusion and recommendation

To conclude, this research was aimed to advance the understanding of the differences in bridge deck maintenance for concrete and steel due to corrosion. The aims and objectives were met and followed for the completion of this project. This research provides an in-depth analysis of previous case studies on corrosion within concrete and steel bridge decks.

The main aspects of this research looked into the following subjects:

- Preventative maintenance types.
- Causes of corrosion and how to handle them.
- Main methods and procedures for undertaking bridge maintenance due to corrosion.
- Bridge inspection methods and procedures.
- Accelerated corrosion test analysis.
- Deck patching procedures.
- Deck sealing procedures.
- Corrosion resistance tests such as epoxy coating.

To conclude this research. The author has investigated different aspects within the desired subject area and has completed a questionnaire to help provide a stable foundation for the research. These findings have shown that a preventative maintenance approach is best

suited when it comes to maintaining concrete and steel bridge decks. The use of non-destructive test methods (NDT) is a great way to accomplish bridge maintenance as an environmentally friendly method which produces minimal waste. In addition to this corrosion tests are necessary to find problems early on in a bridge's life span, as these tests can provide substantial evidence to what causes corrosion within the structure. Epoxy coated reinforced steel is another great benefit to helping prevent corrosion within the structure which will help mitigate future problems.

8.1 Recommendations for future study

The current service life of a bridge design ranges from 75-100, some even ranging to 120 years. Crucial maintenance work is required throughout the entire service life of the bridge. The cost of this is a large amount, but if a cost-effective maintenance program is implemented such as a preventative maintenance technique then the price of this will decrease incredibly. The aim of effectiveness is to implement the preventative maintenance method, this method relies on stopping concrete and steel bridge decks from physically degrading due to corrosion and other factors. This could be done by identifying the problem early on and to mitigate the effects of destructive chemical reactions. To investigate the chemical condition of the concrete or steel deck, this would require the method discussed to be used to stop the corrosive damage to the bridge before physical damage begins.

A good tool to use would be to also implement the use of non-destructive test methods. This is crucial to estimate the process of corrosive deterioration and to mitigate the effects by predicting the condition of the concrete or steel used for the deck. These non-destructive test methods should be used on all parts of the bridge deck, even the parts that are in great visible condition, not just the issues that are visible as this can help predict and prevent future issues that are underlying.

A test for chloride content can also be carried out, as the extent of deterioration can be used to determine the cause of corrosion. This will come under the preventative maintenance method. In addition to this test the steel and concrete properties should be evaluated and tested to ensure that the compressive strength of these materials is in adequate condition. The permeability and porosity of these materials should also be taken into consideration to achieve the maximum potential of preventative maintenance. The non-destructive test method can be used in these tests to attain numerical results from the chloride test.

By taking advantage of these methods, when it is time for inspection, the bridge inspector can examine and identify potential decay prior to significant physical deterioration. Once this is done the correct maintenance method can be selected and implemented to begin work on repairing the deck.

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