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Comparative analysis of protective coating on Scandinavian road bridges

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Comparative analysis of protective coating on Scandinavian road bridges

Sammenliknende analyse av beskyttende belegg på skandinaviske veibroer

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Preface

This thesis was made possible by the workers of the Norwegian Public Road Administration for giving access to their database and easily accessible standards, and by the Swedish Transport Administration for access to their database and patience with us. The weather data for Norway can be credited to the Norwegian Meteorological Institute and Kjeller Vindteknikk while weather data for Sweden can be credited to The Swedish Energy Agency and their "Vindbrukskollen" tool. We want to thank friends and family for helping us with the work and for supporting us in these trying times. Personal thanks goes to Hans Petturson and Odd Arne Våg for their e-mail correspondence about the project. We would like to thank our teachers and professors at NTNU for their contribution to our overall education. Lastly, but certainly not least, we are grateful for our supervisor Ole Øystein Knudsen for his support in writing and all of his contributions to the field of corrosion protection by methods of coating.

Abstract

Coating systems on 82 Norwegian and 32 Swedish steel bridges were studied to determine the better suited alternative for corrosion protection from a lifetime economical perspective. The studied coatings were duplex thermally sprayed zinc (TSZ) with alkyd coating, inorganic zinc (IOZ) with organic top coating and organic zinc (OZ) epoxy primer coating with top coating. The duplex coating was expected to last 69 years without repair in C2 environments, while the IOZ were expected to last 55 years and the OZ were expected to last 33 years in C2 corrosive environments based on a coating performance indicator (CPI). The performance is inversely linked to corrosivity of the environment. Maintenance cost during the bridges life was found to be the lowest for the duplex coating and the highest for OZ coating, while the data for the IOZ coatings were insufficient.

Sammendrag

Beleggsystemer på 82 norske og 32 svenske stålbroer ble studert for å bestemme hvilket beleggsystem som var best egnet for korrosjonsvern fra et livstidsøkonomisk perspektiv. Systemene som ble undersøkt var dupleks termisk sprøytet sink (TSZ) med alkydmaling, uorganisk sinkbelegg (IOZ) med organisk topstrøk og organisk sinkrik (OZ) primer maling med organisk toppstrøk. Dupleksbeleggets forventede levetid ble funnet til å være 69 år uten reparasjon, mens IOZ sin forventede levetid var 55 år og OZ var forventet til å vare i 33 år i C2 korrosivitetsmiljøer basert på coating performance indicator (CPI). Beleggytelsen er omvendt proporsjonal med korrosiviteten til miljøet. Vedlikeholdskostnadene gjennom broenes levetid var lavest for dupleksbelegg og høyest for OZ belegg, mens datagrunnlaget for IOZ var utilstrekkelig.

Contents

1 Introduction

Corrosion is the adversary of cheap and strong constructions and is estimated to consume nearly 4% of the global GDP. With this in mind; Norwegian road bridges are designed with a lifetime of 100 years, and Swedish road bridges are designed with a lifetime of 80 years. With long lifetimes like these it is important to choose a coating system with high durability to keep maintenance costs down. In this thesis the different coating systems in Norway and Sweden will be compared on maintenance cost. This was done by using the semi-publicly available database ”Brutus” from the Norwegian Public Road Administration (NPRA) and the Swedish Transport Administration’s (STA) publicly available database ”BaTMan”. In Norway the studied coating system is a thermally sprayed zinc (TSZ) duplex coating with alkyd paint. In Sweden one will find a bit more variation with inorganic zinc (IOZ) coatings, some form of TSZ duplex coating, and a zinc rich primer paint (OZ) based coating depending on the corrosivity of the environment the bridge is built in. The OZ systems are designated as ”modern” in the database.

Disclosures

This thesis is meant to continue the work of Ole Øystein Knudsen and the NPRA about corrosion protection by the use of TSZ. This work is partly funded by the International Zinc Association (IZA) whose interest in this work is to encourage an increase in the usage of zinc as corrosion protection. This thesis has not received any funding, nor had any of the authors had any direct contact with IZA. With this in mind we have tried our outmost to be objective and unbiased and our only motivation has been to produce a robust thesis.

Abbreviations

AK - Alkyd (coatings)
AY - Acrylic (coatings)
CPVC - Critical Pigment Volume Concentration
EP - Epoxy (coatings)
IOZ - InOrganic zinc (coatings)
MNOC - Minimal Number of Coats
NDFT - Nominal Dry Film Thickness
NPRA - Norwegian Public Road Administration
OZ - Organic zinc (coatings)
PUR - Polyurethane (coatings)
RUC - Chlorinated Rubber (coatings)
STA - Swedish Transport Administration
TSA - Thermally Sprayed Aluminium
TSZ - Thermally Sprayed Zinc

2 Theory

In this chapter some basic theory and necessary information for the thesis is presented.

2.1 Corrosion

Some aspects of corrosion and corrosion protection will be briefly explored in this section.

2.1.1 Corrosivity

This thesis will use the term "corrosion" as defined by the introduction of "Korrosjon og Korrosjonsvern" by E. Bardal . It defines corrosion as an "attack on a metallic material by reaction with the surrounding medium" [1]. For this thesis the surrounding medium is an outdoor North European environment with varying salinity, precipitation, temperature and wind.

Corrosivity is divided into six categories shown in table 2.1 according to ISO 9223:2012 [2]. Here the C1 category is the least corrosive, and is usually found indoors. The CX category is the most corrosive and is usually found in marine offshore environments in the so called "splash zone", just above the water surface.

Table 2.1: Categories of corrosivity of the atmosphere

Category	**Corrosivity**
C1	Very low
C2	Low
C3	Medium
C4	High
C5	Very High
CX	Extreme

The corrosivity is determined by a corrosion test specified in ISO 9226, in which a standardized test specimen is exposed for one year in the test environment [3]. To interpret the test result from the corrosion test, table 2.2 from ISO 12944-2 is used. For this project the results from Knudsen et al. [4] will be used to determine the corrosivity on different road bridges in Norway and Sweden. Their findings are presented in table 2.7

Table 2.2: Atmospheric-corrosivity categories and examples of typical environments[5]

Corrosivity Category	**Mass loss per unit surface/thickness loss** (after first year of exposure)				**Examples of typical environments** (informative only)	
	Low-carbon steel		**Zinc**		**Exterior**	**Interior**
	Mass loss g/m^2	Thickness loss μm	Mass loss g/m^2	Thickness loss μm		
C1 Very low	$\leq$ 10	$\leq$ 1,3	$\leq$ 0,7	$\leq$ 0,1	-	Heated buildings with clean atmospheres, e.g. offices, shops, schools, hotels
C2 Low	> 10 to 200	> 1,3 to 25	> 0,7 to 5	> 0,1 to 0,7	Atmospheres with low level of pollution: mostly rural areas	Unheated buildings where condensation can occur, e.g. depots, sports halls
C3 Medium	> 200 to 400	> 25 to 50	> 5 to 15	> 0,7 to 2,1	Urban and industrial atmospheres, moderate sulfur dioxide pollution: coastal areas with low salinity	Production rooms with high humidity and some air pollution, e.g. food-processing plants, laundries, breweries, dairies
C4 High	> 400 to 650	> 50 to 80	> 15 to 30	> 2,1 to 4,2	Industrial areas and coastal areas with moderate salinity	Chemical plants, swimming pools, coastal ships and boatyards
C5 Very High	> 650 to 1500	> 80 to 200	> 30 to 60	> 4,2 to 8,4	Industrial areas with high humidity and aggressive atmosphere and coastal areas with high salinity	Buildings or areas with almost permanent condensation and with high pollution
CX Extreme	> 1500 to 5500	> 200 to 700	> 60 to 180	> 8,4 to 25	Offshore areas with high salinity and industrial areas with extreme humidity and agressive atmosphere and subtropical and tropical atmospheres	Industrial areas with extreme humidity and agressive atmosphere
NOTE The loss values used for the corrosivity categories are identical to those given in ISO 9223						

2.1.2 Corrosion protection

There have been many attempts to combat corrosion throughout history with varying success. Most of the measures work by restricting the exchange of ions to and from the surface of the metal. The main groups of successful techniques are as follows:

- Correct material selection
- Change of environment
- Correct construction design
- Cathodic and anodic protection
- Use of coatings

Mainly cathodic protection, construction design and use of coatings are of interest here. Galvanic cathodic protection works by letting a metallic sacrificial anode corrode to protect the construction. Steel constructions can be protected this way with zinc. It is required that the sacrificial anode has a lower electrode potential and that the two metals are galvanically connected by electric contact and submerged in an electrolyte. For this to be effective the corrosion potential needs to be below the protection potential of steel, which is -780 mV measured against an Ag/AgCl electrode [1]. For road bridges these conditions will be fulfilled when the construction is wet and the coating is damaged down to the steel. This only holds true for small areas of damage.

Bridge construction standards has changed since the 1950's. The truss constructions that once were common has largely been outdone by box beam constructions. Truss work are made by beams of steel that are usually bolted or riveted together and the load bearing construction can be placed both under and over the roadway. This technique has some strengths in simplicity of part transportation, but leaves a large area exposed to air, many sharp edges, crevices on bolted lap joints and many "corrosion traps" wherein water can become stagnant. The new box beam constructions are made by plates welded in an enclosed profile which is used as the load bearing construction. Due to the geometry, less surface area is exposed to the environment and the design can reduce the amount of sharp edges significantly. The inside of the construction is usually climate controlled, so the environment can in the best cases be regarded as equal to an inside environment. This has reduced the amount of corrosion due to design and thus increased the overall corrosion resistance.

The use of coatings are employed to reduce the transport of ions to and from the metal surface. To successfully protect the metal, the coating need to be isolating, impenetrable to ions and chemically resistant with good adhesion to the substrate. Paint- and coating systems are more extensively explained below.

2.2 Coating systems

The selection of paint systems is usually dependent on the corrosivity of the environment, and is defined for C2 through C5 environments in ISO 12944-5 [6]. This standard outlines generic paint types and how to apply corrosion protective coatings. In this section the properties of the historically applied organic coatings will be superficially reviewed. Most paint can be subject to an application error known as "pinholes", where a small bubble may be formed under the paint and in turn cause a hole down to the layer below [4].

2.2.1 Organic coatings

Alkyds are a group of organic compounds consisting of polyesters of polyols and polybasic acids. They can be modified by substituting fractions of the polybasic acids with monobasic acids, like fatty acids, which is typically done to make paint coatings [7]. These polymers are outphased in the NPRA's standards due to their unfortunate reactions with alkaline solutions commonly found in concrete and their high content of solvents. They are also outperformed by more modern polymers. The ester groups of the polymer will be subject to saponification in contact with strong bases which one can clearly see on some bridges with alkyd painted steel beams in contact with concrete. The NPRA commonly mixed alkyds with chlorinated rubber (RUC) to improve curing time of the alkyd and to improve performance in marine environments [8].

Another group of organic binder polymers are epoxies. Epoxies are characterized their cross linked structure bound by the functional group epoxy [7]. These polymers are used for their high strength and modulus, adhesion to metallic substrates and chemical resistance. However they have a low resistance to UV-radiation and will chalk when exposed to such [6].

Due to the limitations of epoxies in outdoor environments some top coating is required and the NPRA has standardized polyurethane or polyurethane acryl as the top coating. Polyurethanes are polymers made by diisocyanates and diols [7] and, for paint and coating purposes, are characterized by high adhesion, high strength and resistance to UV-radiation when not of aromatic composition [6].

2.2.2 Organic zinc rich paints

Zinc rich paints (alternatively organic zinc coating), defined by ISO 12944-5, are organic coatings with more than 80 wt% metallic zinc particles in it the dry film [6]. The coating is easy to apply and provide corrosion protection to steel substrates. The zinc must be active and in electrical contact with the steel. Additionally Ross and Wolstenholme found that the coating must provide enough conductivity between the zinc and steel. RUC could provide the necessary conductivity due to it's ineffective wetting of the zinc, but epoxy polyamide provided too effective wetting, thereby isolating it from the steel and decreasing its galvanic action. They also found that zinc corrosion products are likely to contribute to the protection of the steel structure [9].

2.2.3 Zinc silicate coating

In Sweden organic zinc rich primers with more than 90 wt% zinc is the current standard on road bridges. Zinc silicate, also known as inorganic zinc coating or IOZ coating, was the previously used standard as primer on Swedish road bridges. This kind of coating is a glass-like ceramic coating with a high volumetric content of zinc available for corrosion protection. The coating usually cures by evaporation of solvent and hydrolysis of alkyl silicates which further react by a condensation reaction to form a cross-linked silicate polymer [10]. The zinc is usually dispersed in the coating with a higher porosity than organic zinc coatings, meaning a potentially larger area of reactive zinc is available to protect the steel substrate. Furthermore the densities between the binder (silicate or organic polymer) and the pigment (metallic zinc) are more similar for IOZ, meaning a 90 wt% pigment content translates to a higher volumetric ratio of zinc than for a 90 wt% OZ coating. Another advantage is the possibility to exceed the critical pigment volume concentration (CPVC) without severe loss of coating properties [11]. IOZ are known for their good protective properties and can be used in conjunction with organic coatings, but are notoriously hard to apply correctly, cracking if the applied layer is too thick and not curing right if the ambient temperature and humidity is not correct [12].

2.3 Thermal Spraying

Thermal spraying is a surface treatment usually employed to combat corrosion on steel parts. The process is based on thermally melting an application material and spraying the material unto a substrate. The standard process is described in ISO 2063, and several methods of heating the sprayed material is used. Common traits of the method is the porosity of the applied layer and the relatively low heat input to the substrate. Due to the low heat input the substrate will usually not experience thermally induced deformations. The porosity is usually combated with a sealant, which also can be the primer in subsequent organic coatings. Thermal spraying can be used with many materials and on many substrates.

In ISO 2063 some properties of common metal alloys for thermal spraying is listed. Pure zinc is listed as an excellent choice for atmospheric corrosion protection, but also warns that coastal environments may pose a challenge. TSZ also has the best "cathodic reaction" meaning it can cathodically protect a larger area than the other listed alloys due to its ability to polarize a larger area of bare steel. Aluminium is listed as a poorer choice for general atmospheric protection, and in the case of offshore installations and accelerated corrosion tests it performs poorly in duplex coatings due to the acidic corrosion products of aluminium in chloride rich environments, and it is recommended to not cover TSA (thermally sprayed aluminium) with thick organic coatings [8].

Application errors of thermal spraying usually stems from insufficient heat input to the applied material. Due to this the spray may contain particles of incomplete melting which causes sharp protrusions through the surface. This error is also known as ”spitting”. In duplex coatings this can lead to a thin paint coat over a local peak of applied material, so the coating performance will be locally reduced. This error can reduce the lifetime of the coating system significantly [4].

2.4 Norwegian road bridges

Construction of steel bridges in Norway is described in the NPRA ”Håndbok R762” where the latest available in the time of writing is from 2018. The latest english version, ”Handbook R762E”, was published in 2014. There are some differences between the two versions regarding the coating of the bridges. Currently the coating system presented in table 2.3 has been specified as System 1. The system has been subject to small revisions since it was designated as the main system in 2007, but note that epoxies and polyurethanes have been used since the end of the 1990’s. Coating manufacturer requirements and testing standards are not discussed in this thesis. The minimum total coating thickness is specified as 285 μm at dry state. For very corrosive environments a second coat of epoxy mastic is to be applied before the polyurethane top coat, this is known as ”System 2” and has a minimum coating thickness of 410 μm.

Table 2.3: Modern Norwegian standardized coating System 1

Coat No.	**Type**	**Thickness (μm)**
1st	TSZ	>100
2nd	Two-component epoxy polyamide tie-coat sealer	<25
3rd	Epoxy mastic	100 - 125
4th	Polyurethane or polyurethane acryl	60-100

The current standard of the NPRA is not the main focus of this thesis, as the use of epoxy and polyurethane does not have the required age to be meaningfully studied here. The alkyd and chlorinated rubber specified in the 1969/1977 coating systems, have had longer exposure time and as such they are of most interest here.

Historically lead minium based paint has been the main corrosion protection utilized on Norwegian bridges. In the 1960’s duplex coating systems were introduced and in a bid to increase the durability of the coating it was advised to use TSZ duplex coating for coastal bridges in 1965. Four years later the duplex coating was a specified standard for coastal bridges and an overview of the system is presented in table 2.4. The standard was not adopted on inland bridges, which still used the older lead minium standard. Due to how long it takes for a bridge to be constructed the standard may not apply to all bridges from 1969 and onwards, so in this report it is assumed that about two years passed before the standard was common.

Table 2.4: Specification from 1967 for bridges in coastal environments

Coat No.	Type	Thickness (μm)
1	TSZ, pure Zn	100
2	Phosphoric acid wash primer	-
3	Alkyd with zinc chromate	50
4	Alkyd with zinc chromate	50
5	Alkyd	50
6	Alkyd	50

Zinc chromate was used as pigment due to its good corrosion protection properties in conjunction with metallic zinc. The change from lead minium based paint to a duplex coating system greatly improved the performance and HSE. However, chromate ($\mathrm{CrO_4}^{-2}$) is a carcinogen and thus alternatives were sought. In 1977 the zinc chromate was replaced with zinc phosphate and the new duplex coating system was standardized for all bridges in the country. The specified standard is presented in table 2.5

Table 2.5: Specification from 1977 for all bridges

Coat No.	Type	Thickness (μm)
1	TSZ, pure Zn	100
2	Phosphoric acid wash primer	-
3	Alkyd with zinc phosphate	50
4	Alkyd with zinc phosphate	50
5	Alkyd	50
6	Alkyd	50

2.5 Swedish road bridges

The coating specifications of the STA are based upon ISO 12944-5. The corrosivity of each environment is measured and a coating system is chosen based upon the corrosivity. The systems are presented in table 2.6. The least corrosive environment recognized by the STA's bridge building standards is C3.

Table 2.6: Swedish coating systems for road bridges from ISO 12944-5 [6]. The intermediate epoxy coatings are hematite pigmented

Environment	Type	Coat no.			NDTF
		1	2	3	
C3	Zn (R)	EP (Zn) 40 μm	AY 200 μm	-	240 μm
C4	Zn (R)	EP (Zn) 40 μm	EP 260 μm	PUR 100 μm	400 μm
	Galvanized	Zinc alloy 100 μm	EP 200 μm	PUR 100 μm	400 μm
C5	Zn (R)	EP (Zn) 40 μm	EP 320 μm	PUR 100 μm	460 μm
	Galvanized	Zinc alloy 100 μm	EP 240 μm	PUR 100 μm	440 μm

Table 2.6 is produced by correspondence with the STA and a report from the Nordic countries about corrosion protection on road bridges [13] and then cross referencing with NS:EN ISO 12944-5 table B.2 and B.3.

If the construction drawings in the tender does not specify a paint system the bridge is to be metallized by hot dip galvanizing and painted with one of the "galvanized" systems described in table 2.6. The specifics of the hot dip galvanized duplex system are not of high importance here, as none of the studied bridges seems to use this system.

Before the current standard, the older AY802 was used. This standard described a paint system with zinc silicate as the primer coat with a nominal dry film thickness of 70 μm, which is referred to as IOZ. A top coat of RUC was to be applied at a nominal thickness of 100 μm. In some specific case an intermediate sealer coat of modified vinyl was to be applied at 20 μm to counteract pore formation and could be measured as part of the total coating thickness. Additional edge painting could be performed, but was not mandatory. The standard was in use until 1988, but it is uncertain when it was introduced.

2.6 Coating of the Øresund Bridge

The Øresund Bridge is the bridge connecting Denmark and Sweden between the Copenhagen area and Malmö. The connection is of great socioeconomic importance for the Scandinavian countries and especially for Sweden and Denmark. These factors together with the fact that most of the economical and maintenance data is known for this bridge and its size, makes it interesting to compare to the other bridges of this thesis. The bridge does not have a page in BaTMan, but will be assessed and examined outside the databases. The Øresund Bridge has a zinc rich primer based paint system with two intermediate layers of hematite pigmented epoxy and two layers of polyurethane top coat [14]. It is uncertain if this system is in accordance with 2.6 as the thickness of each coat is unknown, it may be a fortified version to ensure low maintenance costs.

2.7 State of the Art

This section gives an overview of the work previously done by the NPRA and Knudsen et al., whose work this is a continuation of. It is therefore highly advised to read ”Experiences with thermally sprayed zinc on road bridges” [4] and ”Corrosion protection of steel bridges with thermal spray zinc duplex coatings - 50 years experience” [15]. The theoretical basis behind the methodology of these studies will be explored here.

2.7.1 Experimental basis

The methodology and findings from the afforementioned reports are reiterated here due to how integral they are to this thesis.

Corrosivity was measured on five road bridges according to ISO 9226 by three replicate samples. The studied bridges were chosen for their climatic conditions, height and availability for deployment of samples. Measurements were taken on the bridgeway, however for Gjemnessund, Hardanger and Sotra additional measurements were taken at varying intervals from 5 - 70 m above sea level along one bridge tower. After assessing the corrosion from the tests each bridge environment was labeled with a corrosion category according to ISO 12944-2. The findings are presented in table 2.7.

Table 2.7: The bridges where corrosivity was measured

Bridge Measurement site	**Climatic Conditions**			**Sailing Clearance (m)**	**Corrosivity**	
	Geography	**Temp. Avg. (C)**	**Precipitation Avg. (mm/y)**		**μm/y**	**Category**
Nessundet (A)	Inland lake	3	700	10		
Truss, west side					26	C3
Truss, middle					6	C2
Truss, east side					13	C2
Tjeldsund (B)	Shielded coast	3	1000	41		
Truss, south side					12	C2
Truss, middle					13	C2
Truss, north side					18	C2
Gjemnessund (43)	Shielded coast	7	1300	43		
Pylon, west side					11	C2
Bridgeway fence					28	C3
Under bridgeway					48	C3
Sotra (14) Pylon, west side	Exposed coast	8	1900	50	27	C3
Hardanger (C) Pylon, west side	Shielded fjord	6	1100	55	9	C2

The corrosion rate was found to be dependent upon the tested height above the sea level. It was especially evident on the Sotra bridge, which had a corrosion rate of 140 μm/year 5 m above sea level and converged at about 25 μm/year towards the road level. Gjemnessund and Hardanger did not exhibit such a dramatic dependency on height, however both show a slight increase in corrosivity towards the sea level. The findings are presented in figure 2.1. The reason for the deviation is not entirely known, but wind patterns, salt spray and precipitation may be partly responsible. The Sotra bridge is by far the bridge that experience the most precipitation of the bridges that were tested, which implies more wet days for the test sample. This data will be used to estimate the corrosivity of this thesis' bridges as a function of height above the sea.

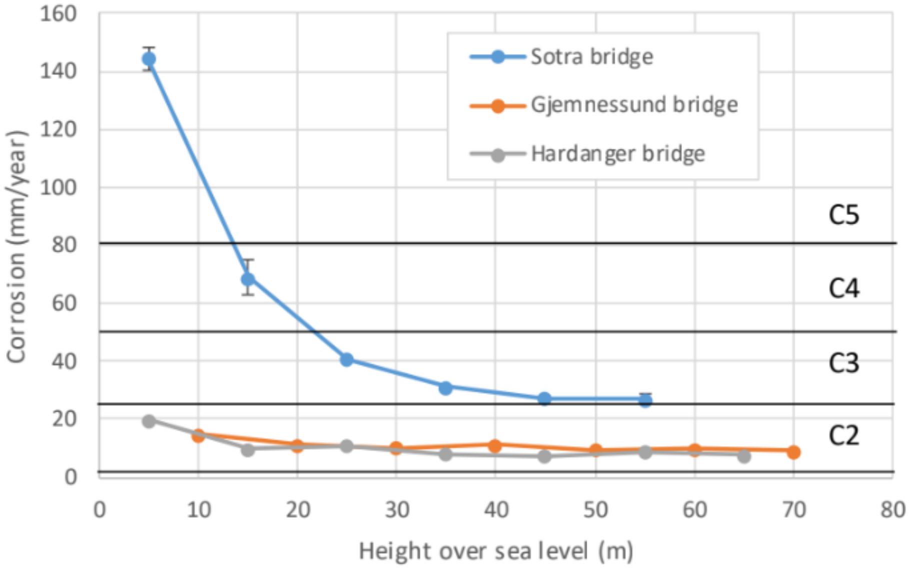


Figure 2.1: Corrosivity on three bridges as a function of height over sea level [4].

Precipitation and corrosivity has not been extensively studied, and may be a task too complex for this kind of work. Due to this the estimated corrosion class should not be considered as a fact, but an educated guess.

Inland bridges were assumed to have a corrosivity of C2. This assumption is partly based upon the fact that coastal bridges show category C2 even close to the sea in the case of Hardanger. Furthermore, the western coastal environment experiences far more precipitation than the inland environment. Annual precipitation throughout Scandinavia is presented in figure 2.2. Another aspect is the colder climates in the drier parts of the country, due to more days with below freezing temperatures the corrosivity is also assumed to be lower.

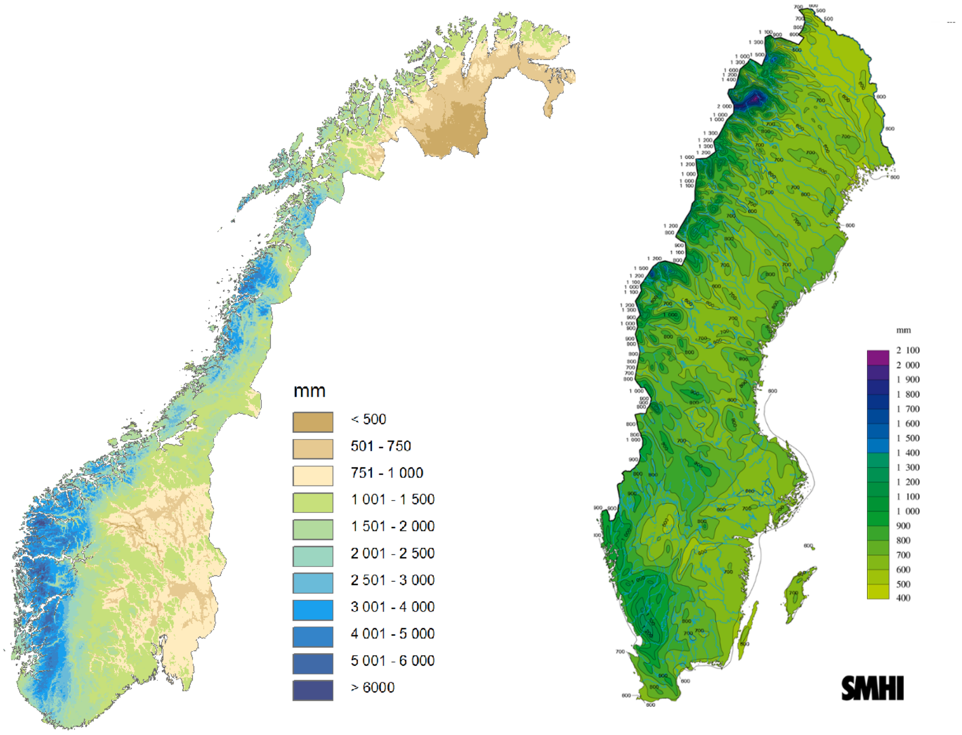


Figure 2.2: Precipitation in Norway and Sweden. The color scales are not similar. The Norwegian coasts sees significantly more rain than inland Norway and Sweden in general. [16][17]

2.7.2 Coating performance indicator (CPI)

Since many bridges in less corrosive environments had no coating maintenance a predictor for their coating lifetime was introduced by Knudsen to enable quantitative comparisons.

$$CPI = L + L \cdot \frac{S}{C} \tag{2.1}$$

L: Current age of the coating

S: The assessed condition for the coating expressed numerically. Good = 3, Fair = 2, Poor = 1, and Repaired = 0

C: The corrosivity of the environment expressed numerically. C2 = 2, C3 = 3, C4 = 4, and C5 = 5

The coating condition and corrosivity assessments are explained in chapter 3.2.1 and 3.2.2 respectively.

The CPI of a repaired bridge will be the age of the coating at the time of repair, and for unrepaired bridges it is an indicator of how long the coating will last. As stated in the study, a correction factor should be added to the CPI formula, but determining it is outside the scope of this thesis.

2.7.3 Findings

Knudsen et al. found that the duplex coating had a very long lifetime and in C2 environments it could be expected to last for the duration of the design life, with some coatings performing just above 100 years. When discussing the more corrosive environments it became clear that no coating could reach the age requirement without maintenance. The CPI for each environment is presented in figure 2.3. These findings are suggesting that the duplex coating method has a durability fit for the stated goals of the application. It does not reach a lifetime of 100 years in aggressive environments, but has a higher durability than what is considered long lifetime in ISO 12944, until C5 environments.

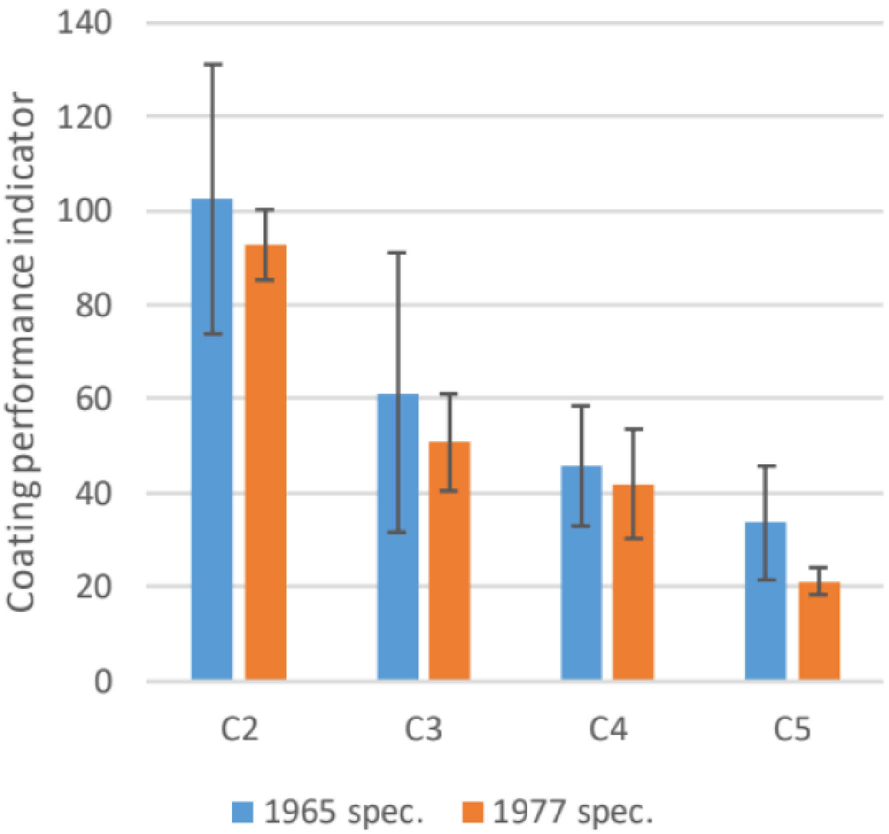


Figure 2.3: Coating performance indicator as a function of corrosivity. The bars indicate standard deviation [4].

The study concludes that due to modern advancements the lifetime of coatings will be increased. Among the improvements are:

- Box beam construction with fewer sharp edges and crevices
- Alkaline resistant epoxy and polyurethane coatings
- Coating with inherent "smartness", clearly telling the painter when sufficient paint has been applied
- Awareness of consequences and avoidance of spitting- and pinhole errors

To give a wider economical view of the coatings studied in this thesis, the coating maintenance pr area pr time from the supportive paper "Corrosion protection of steel bridges with thermal spray zinc duplex coatings - 50 years experiences" by Knudsen et al. will be used later in this thesis. [15]

3 Method

In this chapter the methodology regarding bridge selection, data gathering and data analysis is explained.

3.1 Selection process of bridges

The selection process of the bridges in this thesis was designed to exclude coating systems like lead minium paint.

3.1.1 Norway

Five selection criteria was set, partly to limit the amount of data to a small but statistical significant amount.

- The load bearing construction must be made of steel
- The bridge must be build after the year 1967 if it is located on the coast and 1977 otherwise
- The bridge must be built before 2000
- The bridge must be between 25 and 99 meters in length
- It must be a road bridge, ie. rail and pedestrian bridges are excluded
- Folding/vertical-lift bridges are excluded

The steel criteria was selected, since this study focuses on TSZ corrosion protection. The 1969-2000 cutoff is due to the Norwegian building standard pertaining to the use of TSZ as protection, which has been in use since 1969 for coastal bridges and 1977 for inland bridges. 2000 because it is assumed that no bridges will have shown any loss of protection in only 20 years. The 25-99 meter cutoff lower bound is a somewhat arbitrary limit, made to limit the number of bridges and exclude culverts, while the upper bound comes from the work already done on bridges with 100+ meters in length [4]. Folding/vertical-lift bridges are excluded because the consequences of corrosion are not comparable to static road bridges.

All bridges meeting these criteria were added to a list and evaluated. The evaluation usually revealed if the bridge had correct coatings, and where there were uncertainty the NPRA was inquired about them. The sailing clearance of the bridges was hard to come by, this information is however very important when categorizing the corrosivity. Some bridges have sailing clearance documented in Brutus, but most of the time it has been estimated from pictures of the bridges in context of their surroundings or by reviewing the construction drawings.

3.1.2 Sweden

Initially the set criteria was similar to Norway, but excluding the building years as the standards are unknown until about the 1970's. However BaTMan's search tool did not offer the same ease of filtering as Brutus. Therefore a brute force search was done, where a map over Sweden in BaTMan was searched on the 500 m scale. The European Road Network roads, E4, E6, E10, E14, E16, E18, E20, E22 and E45 was comprehensibly searched for bridges together with a selection of national roads. Mountainous and coastal areas not on the E-network was thoroughly searched for steel bridges too. In total 1300 bridges resulted from this, whereof 90 were made of steel. 20-25 or so were steel culverts, technically counting as steel bridges, but obviously outside the scope of this thesis. Some bridges were removed due to high age and insufficient records. This resulted in a list of 54 bridges, representing every county and region of Sweden. After assessing all the coatings and looking through maintenance data the list was reduced to 31 bridges, where most exclusions were due to unknown coating mostly from before 1970. A few bridges had a total coating renovation (changed from something to something more modern) and those were included if the coating could be identified. Bridges where lead minium paint had been used for protection were also excluded. This was mostly an issue on bridges built before 1979, and to determine if lead minium paint were used, inspection pictures and building plans were consulted. Lead minium paint is easily identified by its distinct orange color, which gave the American Golden Gate Bridge its distinctive colour.

3.1.3 The Øresund Bridge

The Øresund bridge has been examined by the use of Wikipedia.com to find the sailing clearance and articles in Forbes, Veier24, Reuters and Fokusoresund.com to determine the coating, maintenance costs and repaired area.

3.2 Environment- and coating assessment

In order to assess the performance of the coating some categories and criteria is needed to determine the effectiveness of the coating. The performance must also bee seen in context of the aggressiveness of the environment.

3.2.1 Coating

The coating condition has been assessed based on inspection images found in the databases. Four categories, as defined by Knudsen et al. [4], are used to assess the conditions. They are as follows:

- Good: The paint coating is in good condition and little or no degradation can be seen.
- Fair: There is some paint degradation, and zinc corrosion products (white) can be found locally.
- Poor: The steel has started to corrode and red rust is found.
- Repaired: Coating maintenance has been performed; in most cases, patch repair with a full topcoat.

As this thesis is meant to build upon the study by Knudsen et al. coating- and environment assessments have been studied. This was done in order to replicate the assessment process.

Some bridges have local damages in the coating and although red rust can be found, if it is just in a single spot, like a nut, it may be categorized as ”Fair”. If there are multiple attacks along the bridge it will weight towards being assessed as poorer. If the inspection pictures did not show enough of the steel beams to make a coating assessment the bridge was disregarded.

3.2.2 Corrosive environment

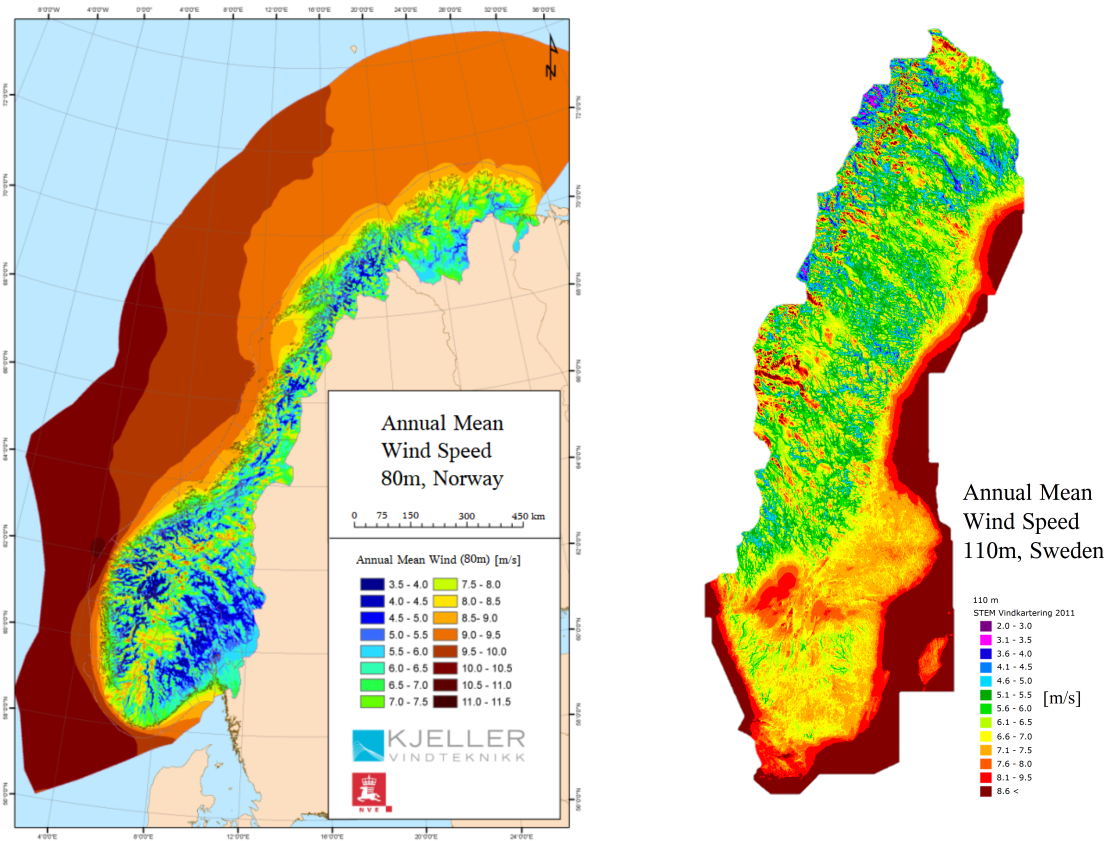
The environment of the bridges were assessed based on their height above the sea following the trend from figure 2.1 made by Knudsen et al. The following criteria need to be met to be categorized as the different environments

- C2: Most inland bridges with some height above rivers. Tall coastal bridges with little wind
- C3: Between 20 and 40 m above sea, maybe higher if high wind velocity. Some low inland bridges above water with high wind velocity and somewhat high average temperature
- C4: Between 10 and 20 m above the sea.
- C5: Up to 10 meters above the sea.

Some bridges are very hard to confidently assess. Inner city bridges may be subject to considerably more pollution and road salt than mountain bridges which may close during winter times.

The wind contributes to the aggressiveness of the environment as it circulates water and oxygen. A study performed by the Norwegian Water resources and Energy Directorate in 2009 produced a wind map of Norway at 80 m altitude which is presented in figure 3.1a. Cross referencing this with the results from figure 2.1 revealed that the difference between Gjemnessund and Sotra bridge could be explained by the wind velocity difference. Sotra experiences an average wind velocity of 7-7.5 m/s while Gjemnessund is at 5-5.5 m/s. Gjemnessund is a hard case, where the bridgeway experienced C3 corrosion, yet results show low corrosion when studying the corrosivity along a pylon down to the sea. Additionally Nessundet bridge did experience C3 corrosion on the western truss despite being over a freshwater lake. Due to this some low bridges over lakes with high wind velocities will be categorized as C3. A wind map of Sweden at the same altitude was not found, but one for 110 m was. In order to make them comparable the wind velocity was adjusted down to equivalent 80 m altitude by the wind profile power law [18]. The formula is presented in 3.1, where u is the velocity at 80 m, u_r is the reference velocity at 110 m, z is the altitude (80 m), z_r is the reference altitude (110 m) and α is an empirical coefficient dependent upon the stability of the atmosphere. Here $\alpha = 1/7$ as neutral stability is assumed.

$$u = u_r \left(\frac{z}{z_r} \right)^{\alpha} \tag{3.1}$$



(a)

(b)

Figure 3.1: Wind maps for Norway(a) and Sweden(b). Note that the scale and height is different and that these are only compilations of the wind maps used to determine the wind velocities for each bridge [19] [20]. The map descriptions has been translated from their original languages

3.3 Maintenance costs

To give a lifetime cost analysis of the bridges it is important to note the maintenance cost. In order to compare the maintenance costs on different bridges the cost per area is calculated. In Brutus the maintenance costs is listed in the "Measures" tab and it is divided on the area of the bridge to be comparable to others. The area of steel is not listed in Brutus, but a building type with related road-to-steel-area is listed. The price per unit area is calculated with the price divided by the total area of the load bearing steel. Repair costs are up to date as of April 2020. The price has been adjusted with the inflation rates for the years the repairs have been performed through an online inflation calculator [21]. In this thesis an exchange rate of 9 NOK = 1 EUR will be used as it has been stable around that rate for 15 years, however it is very wrong in the time of writing.

The same approach proved to be hard with BaTMan, which does not have a uniform way of reporting maintenance cost on the bridges. Due to this the Swedish bridges could not be compared in the same way as the Norwegian ones. The cost of maintenance per area is a constant in Sweden put at 230 EUR/m^2 for the measure "bättringsmålning" or "improvement painting". This is the only clue to what a repair on Swedish bridges actually cost. An exchange rate of 10 SEK = 1 EUR is used in this thesis. Although the Øresund bridge is mostly in Swedish territory, it is not listed in BaTMan, however sufficient records were available in the mainstream media.

In order to compare the maintenance cost during the lifetime of the bridges the maintenance cost is divided on the area of the bridge times the years of service. The formula is presented in formula 3.2. LMC means the Life Maintenance Cost. L is the lifetime of the bridges, A is the area and C_m is the maintenance cost.

$$LMC = \frac{C_m}{A \cdot L} \tag{3.2}$$

The maintenance cost will be divided by the average age of the bridges for each environment when presenting how well the coating performed. This is due to the fact that some bridges have had no coating maintenance at all.

4 Results

The locations of all the bridges examined are presented in figure 4.1. The numbers are map numbers (leftmost number) from the tables 4.1, 4.2 and 4.3. Areas of clustered bridges are presented in zoomed maps. Finland and Russia have been removed for clarity.

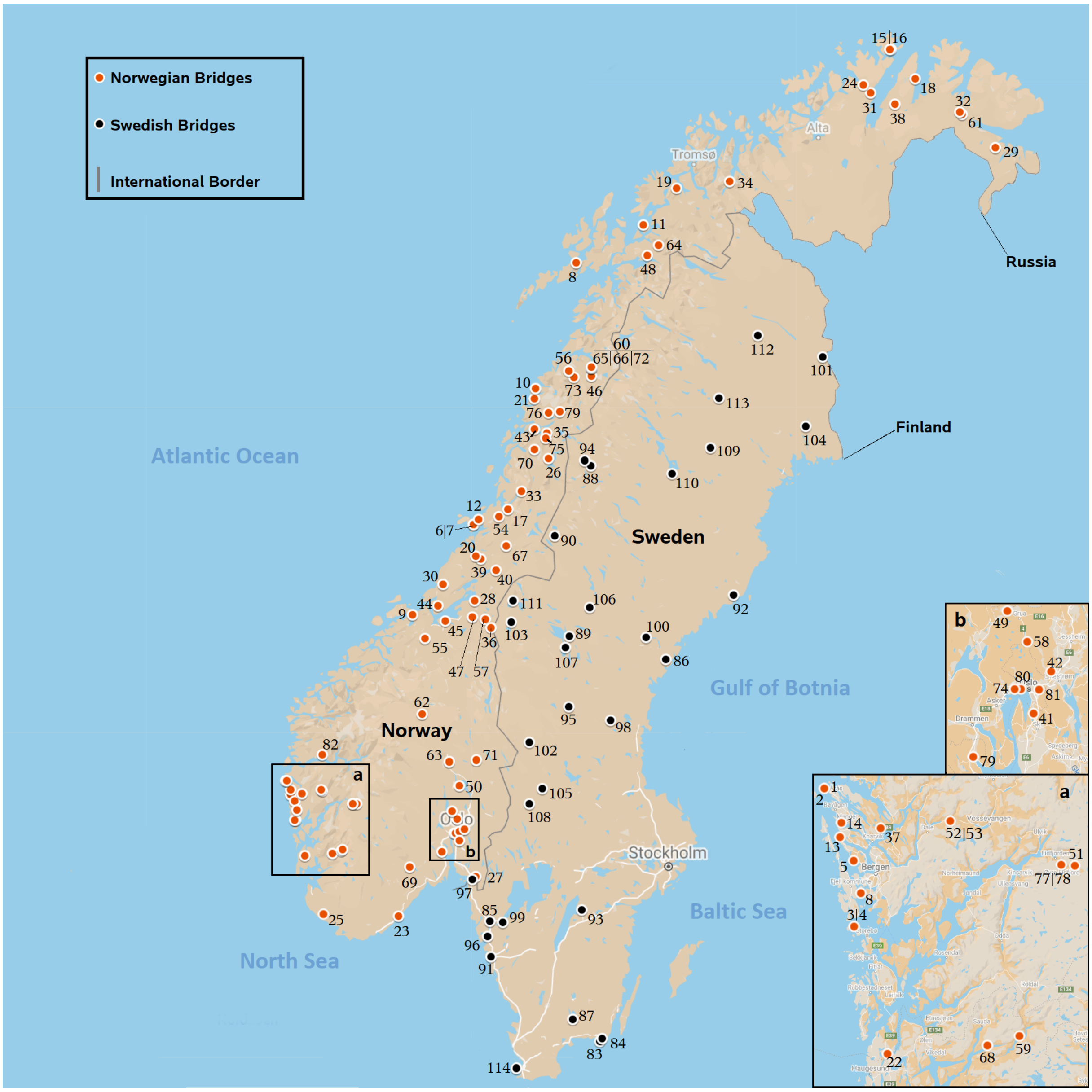


Figure 4.1: Location of the examined bridges corresponding to the map number from tables 4.1, 4.2, 4.3

4.1 Norwegian bridges

The examined Norwegian bridges are presented in the tables 4.1 and 4.2.

Table 4.1: The coating lifetime on briges in C3 - C5 environments in Norway. CPI is the coatingperformance indicator.

	Name	**Corrosiv. [C]**	**Built**	**Clearance [m]**	**Condition [S]**	**Maintenance**	**Lifetime [years]**	**CPI**
1	Lauvøystraumen	C5	1990	8	poor	-	30	36
2	Sævrøysundet		1996	6	fair	-	24	33,6
3	Navøybrua		1999	12	poor	-	21	25,2
4	Spissøybrua		1999	9	poor	-	21	25,2
5	Marholm		1993	7	poor	-	27	32,4
6	Ottersøy Sør		1983	5	repaired	1997	14	14
7	Klungvik		1983	10	poor	-	37	44,4
8	Årnøysundet Bru		1994	5	poor	-	26	31,2
9	Hemnskjelbrua		1994	8	poor	-	26	31,2
10	Åmnessund		1981	2	repaired	2001	20	20
11	Hestvik		1978	5	repaired	2010	32	32
12	Åndervåg		1980	5	repaired	2001	21	21
13	Herdlesundet	C4	1969	17	poor	-	51	63,75
14	Toskasundet		1989	16	poor	-	31	38,75
15	Kjelkevik		1998	3	poor	-	22	27,5
16	Sarnespollen		1998	5	fair	-	22	33
17	Flostrømmen		1986	2	poor	-	34	42,5
18	Veidnes		1984	3	poor	-	36	45
19	Rossfjordstraumen		1979	7	fair	-	41	61,5
20	Bangsundbrua		1984	5	repaired	2010	26	26
21	Strømdalselv Bru	C3	1992	7	poor	-	28	37,33
22	Fjon II		1992	10	good	-	28	56
23	Hammeren		1987	6	good	-	33	66
24	Russelvfoss		1981	2	poor	-	39	52
25	Hovland I		1977	5	poor	-	43	57,33
26	Tustervasstraumen bru		1983	5	fair	-	37	61,67
27	Vaterland		1997	5	fair	-	23	38,33
28	Langåsdammen		1988	3	fair	-	32	53,33
29	Klokkerelv		1993	5	poor	-	27	36
30	Årnesbrua		1986	8	poor	-	34	45,33
31	Smørfjord		1981	7	fair	-	39	65
32	Masjohka		1995	5	fair	-	25	41,67
33	Storelvbrua		1995	4	good	-	25	50
34	Furuflaten bru		1995	3	poor	-	25	33,33
35	Bjerka Nye Bru		1994	3	good	-	26	52

Table 4.2: The coating lifetime on briges in C2 environments in Norway. CPI is the coating performance indicator.

	Name	**Corrosiv. [C]**	**Built**	**Clearance [m]**	**Condition [S]**	**Maintenance**	**Lifetime [years]**	**CPI**
36	Kluksdal 1		1990	2	good	-	30	75
37	Lyngholmsundet		1992	15	fair	-	28	56
38	Vieksa		1982	4	fair	-	38	76
39	Sandåbrua		1989	3	good	-	31	77,5
40	Strindmoelv		1988	3	good	-	32	80
41	Tverrveien		1991	not above water	good	-	29	72,5
42	Åros		1999	6	good	-	21	52,5
43	Bardalselv Bru		2000	10	fair	-	20	40
44	Fossbrua		1980	5	fair	-	40	80
45	Kystadbrua		1996	10	fair	-	24	48
46	Sauelva Bru		1998	8	fair	-	22	44
47	Sona		1986	5	fair	-	34	68
48	Storelva Bru		1999	10	fair	-	21	42
49	Engen		1994	6	good	-	26	65
50	Hekshus		1994	14	good	-	26	65
51	Vøringsfoss II		1978	5	good	-	42	105
52	Storevik II		1978	15	fair	-	42	84
53	Storevik I		1978	15	fair	-	42	84
54	Sagelv		1992	5	good	-	28	70
55	Granmo		1980	6	fair	-	40	80
56	Moldjord		1979	2	fair	-	41	82
57	Nustad		1992	5	fair	-	28	56
58	Strekan		1993	9	fair	-	27	54
59	Lalid	C2	1978	100	good	-	42	105
60	Langvad Bru		1978	3	good	-	42	105
61	Luftjohka		1994	7	good	-	26	65
62	Rostbrui		1983	8	poor	-	37	55,5
63	Brufoss		1993	7	fair	-	27	54
64	Langmyra		1977	15	fair	-	43	86
65	Nestby Overgangsbru		1992	7	fair	-	28	56
66	Sundby Sør Vegovergang		1992	7	fair	-	28	56
67	Aurstadbrua		1984	not above water	good	-	36	90
68	Bjerga II		1992	8	good	-	28	70
69	Østerå bru- Nye		1996	6	good	-	24	60
70	Lynghaug		1988	5	poor	-	32	48
71	Rena bru		1978	5	poor	-	42	63
72	Sundby Nord Overgang		1993	7	poor	-	27	40,5
73	Tollå Bru		1996	5	repaired	2002	6	6
74	Lysaker-Søndre Bru		1991	3	good	-	29	72,5
75	Leirelva		1978	3	good	-	42	105
76	Glomåga		1982	5	good	-	38	95
77	Steinberg		1989	6	good	-	31	77,5
78	Veig		1990	3	good	-	30	75
79	Blakkåga Bru		1977	7	poor	-	43	64,5
80	Frøyas Gate O/Nsb		1994	above train tracks	poor	-	26	39
81	Haraldrudveien		1987	above train tracks	poor	-	33	49,5
82	Hjetland		1977	3	poor	-	43	64,5

Of the 82 Norwegian bridges examined most of them where in an inland C2 environment. An overview of the average age of the bridges are presented in figure 4.2. A statistical overview of the wind for the bridges environments are presented in figure 4.3

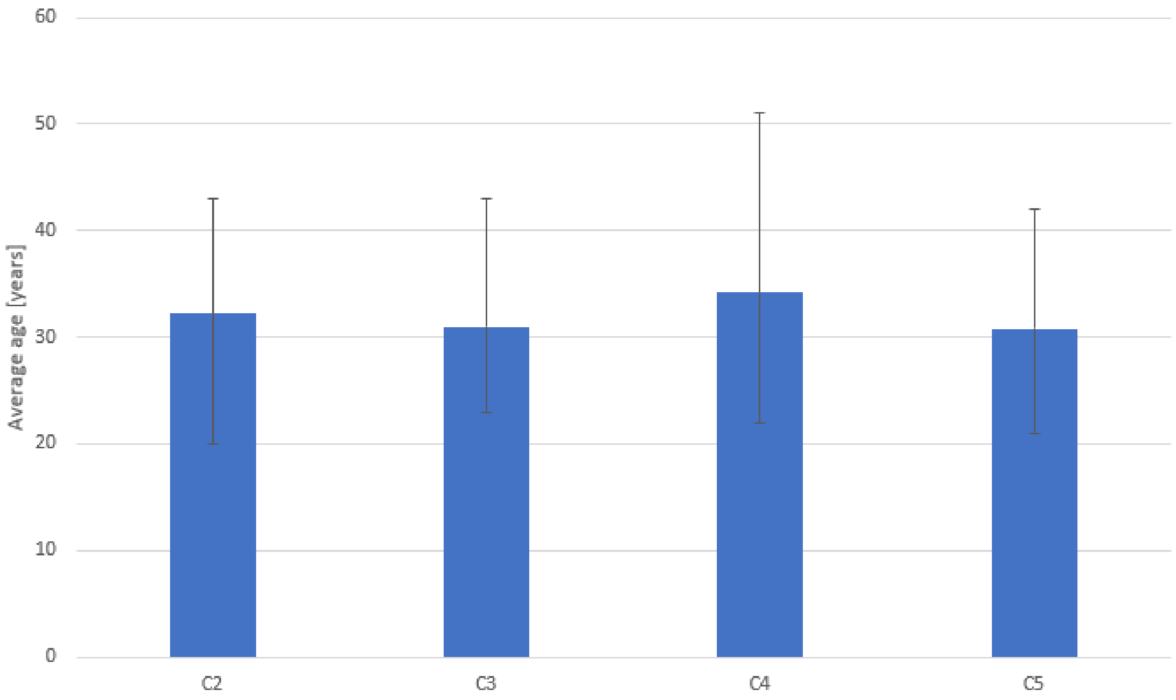


Figure 4.2: Average age of Norwegian bridges by corrosivity. The deviation lines show the highest and lowest values.

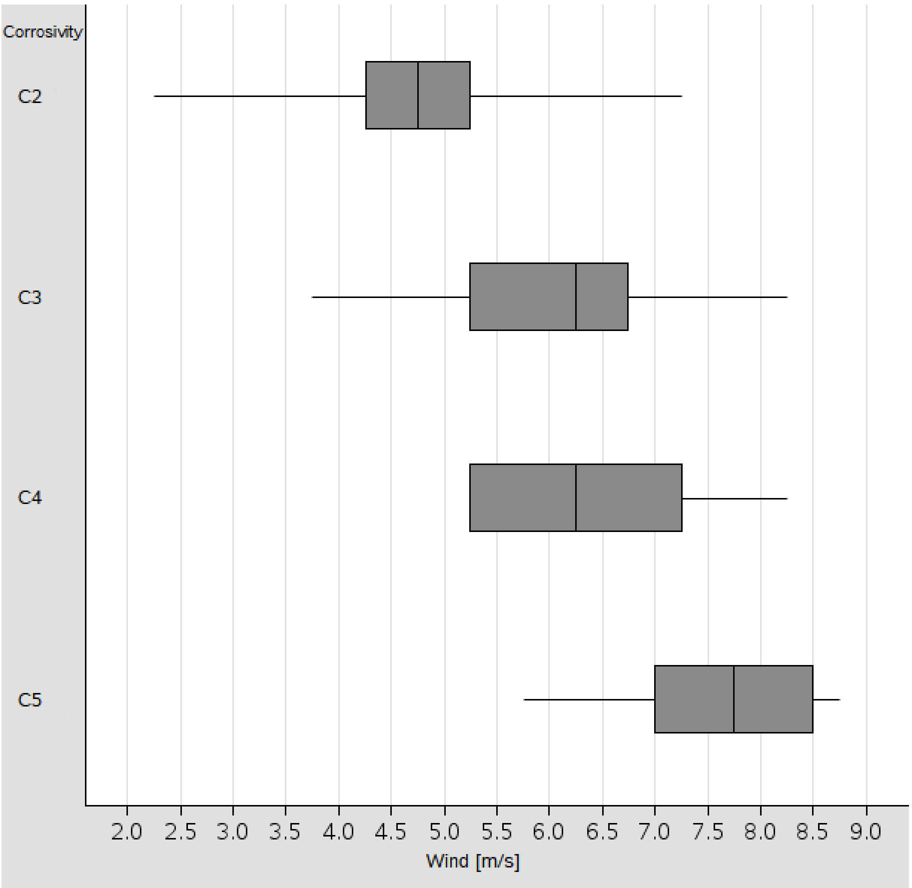


Figure 4.3: Average wind speed by corrosivity, Norway. There's a noticeable correlation between mean wind speed and corrosive environment. This can be attributed to a number of reasons which will be discussed in 6.4

The bridges examined here showed more coating degradation than the longer bridges which were explored by Knudsen et al. [4]. The condition of the coating in each environment is presented in figure 4.4

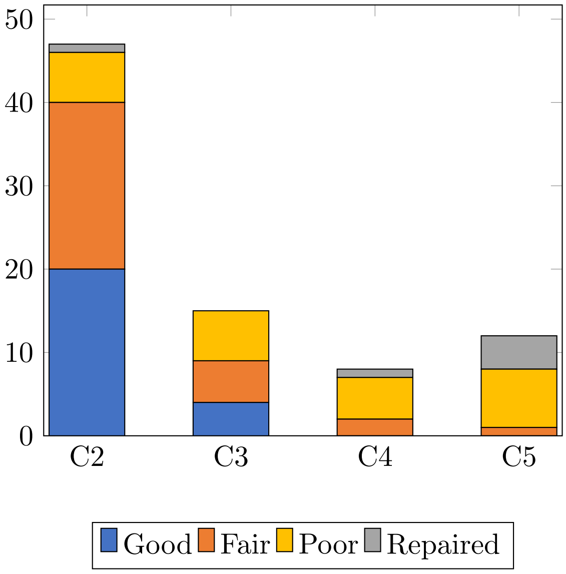


Figure 4.4: The coating condition for Norwegian bridges in different environments.

Most of the bridges were in fair or good conditions, however, most of the bridges were in kind environments as well. The more aggressive the environment the more bridges are either poor or repaired.

The CPI for each environment is presented in figure 4.5. From this it should be possible to estimate an expected lifetime for each coating type. Note that although Herdlesundet bridge is not of the same specification as the rest of them, it is still included in the C4 category here. Herdlesundet bridge has zinc chromate pigmented intermediate layers in the coating as it is the 1969 spec.

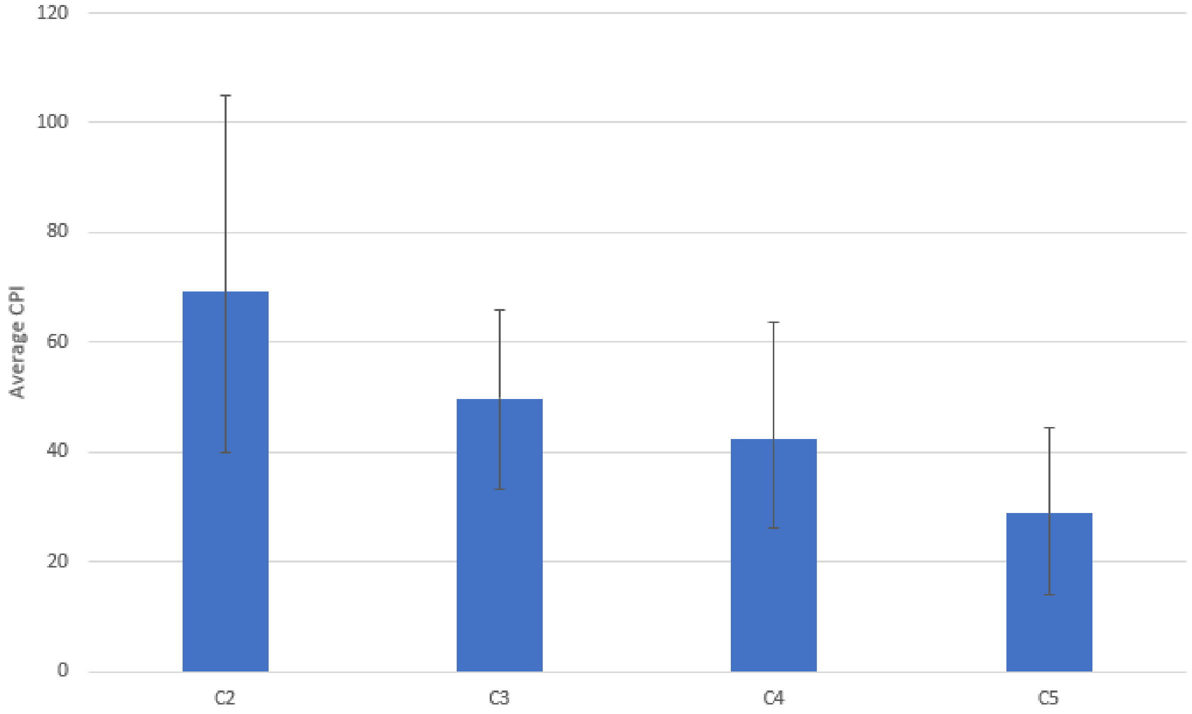


Figure 4.5: Average CPI of Norwegian Bridges by Corrosivity. The deviation lines show the highest and lowest values.

It is clear that the CPI of Norwegian bridges are inversely proportional to the aggressiveness of their environment.

4.2 Swedish bridges

Table 4.3: The coating lifetime on Swedish bridges. CPI is the coating performance indicator. *These bridges had a change in coating a few decades after being built

	Name	Corrosiv. [C]	Built	Clearance [m]	Coating System	Condition [S]	Maintenance	Lifetime [years]	CPI
83	Bro o Djupasund i Karlskrona	c5	1959	1,5	modern	poor	1993	27	32,4
84	Bro o Möcklösund(!)	c4	1998	17	modern	poor		22	27,5
85	Uddevallabron	c3	2000	45	modern	repaired	2015	15	15
86	Höga Kustenbron		1997	40	modern	repaired	2015	18	18
87	Bro o Mörrumsån		1994	2	modern	poor		26	34,66667
88	Bro över Ume älv Tärnaforsen	c2	1990	2	modern	repaired	1995	5	5
89	Vallsundbron		1998	19	modern, polyuretan	repaired	2004	6	6
90	Bro o Blåsjöälven		1988	8	IOZ	repaired	1999	11	11
91*	Älvsborgsbron		1966	45	Duplex	repaired	2007	12	12
92	bro o ume älv sofiehem		2001	10	modern	repaired	2014	19	38
93	Vätterbron		2013	22	modern	fair		7	14
94*	Bro o Ume älv v Björkfors		1954	2	Duplex	repaired	2000	15	15
95	bro o. Ljusnan v. Älvros		1988	2	modern	repaired	2003	15	15
96	Bro o. Askeröfjorden		1981	43	modern	repaired	2003	22	22
97	Nya Svinesundsbron		2005	55	modern	poor		15	22,5
98*	bro o. Ljusnan v. Ljusdal		1964	5	Duplex	repaired	2013	24	24
99	Stallbackabron		1981	28	IOZ	repaired	2012	31	31
100	Bro över Ångermanälven vid Rösta i Sollefteå		2003	21	modern	fair		17	34
101	Pajalabron o Torne älv		1995	7	modern	poor		25	37,5
102	bro o. Sund		1998	2	modern	fair		22	44
103	Bro o. Tångböleströmmen		1994	3	modern	fair		26	52
104	Bro o Kalix Älv Svartbyn		1994	4	modern	fair		26	52
105	Bro o Västerdalälven		1985	3	IOZ	poor		35	52,5
106	Bro o Hammerdalssundet		1993	2	modern	fair		27	54
107	Sannsundsbron		1981	15	IOZ	fair		39	78
108	Bro o Klarälven		1979	8	IOZ	poor		41	61,5
109	Bro o Pite älv vLjusselet		1989	2	IOZ	good		31	77,5
110	Bro o Skellefte älv v. Slagnäs		1989	3	modern	fair		31	62
111	Bro o sund i Anjan		1994	4	modern	good		26	65
112	Bro o Kalix älv Lappesuando		1974	2	IOZ	poor		46	69
113	Bro o. Lule älv Akkatsfallen		1983	11	IOZ	good		37	92,5
114	Øresundsbron	C3	2000	50	sinkepoksy	repaired	2020	20	20

The age of the examined Swedish bridges are presented in figure 4.6. Note that this is just the age of the bridge, and not the age of the coating, which will be used in the CPI-chart in figure 4.9.

In order to say anything qualitative about the Swedish coatings they have been divided into three charts, one for modern coatings presented in figure 4.8a, one for IOZ presented in figure 4.8b and one for TSZ duplex in figure 4.8c. It is important to note that ”modern coatings” in Sweden can be very different from one another and with the information available it was not possible to differentiate them from one another.

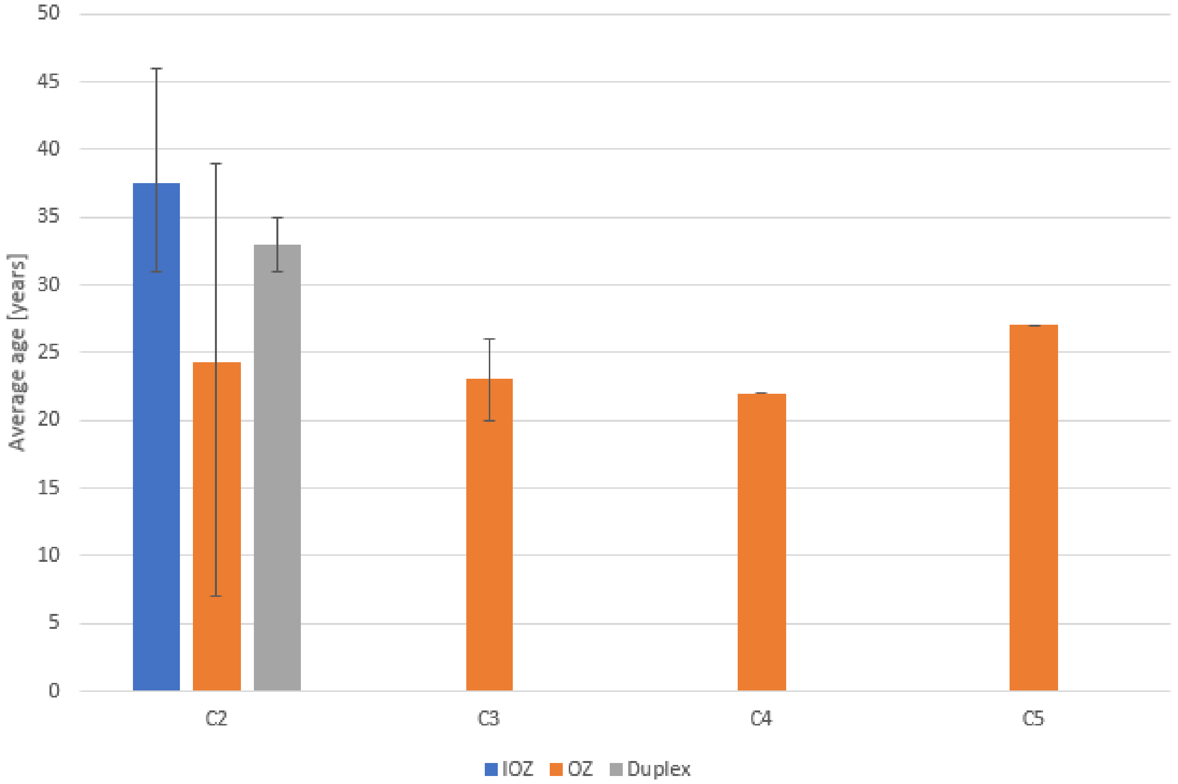


Figure 4.6: Average age of Swedish bridges by corrosivity. The deviation lines show the highest and lowest values.

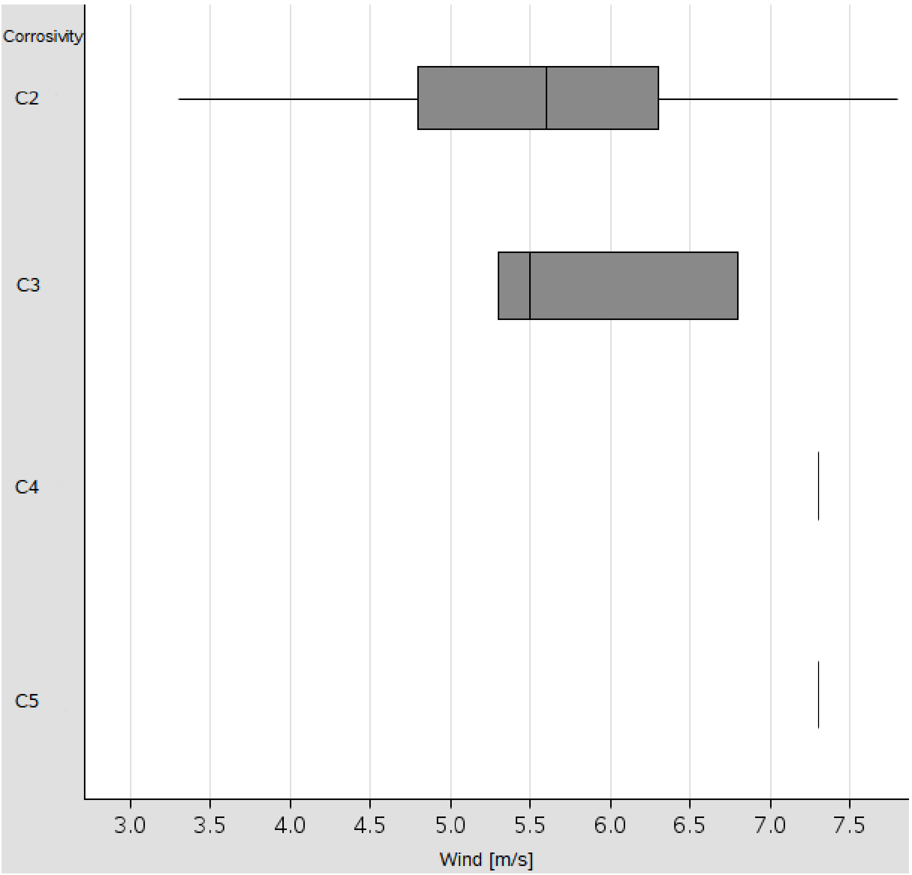
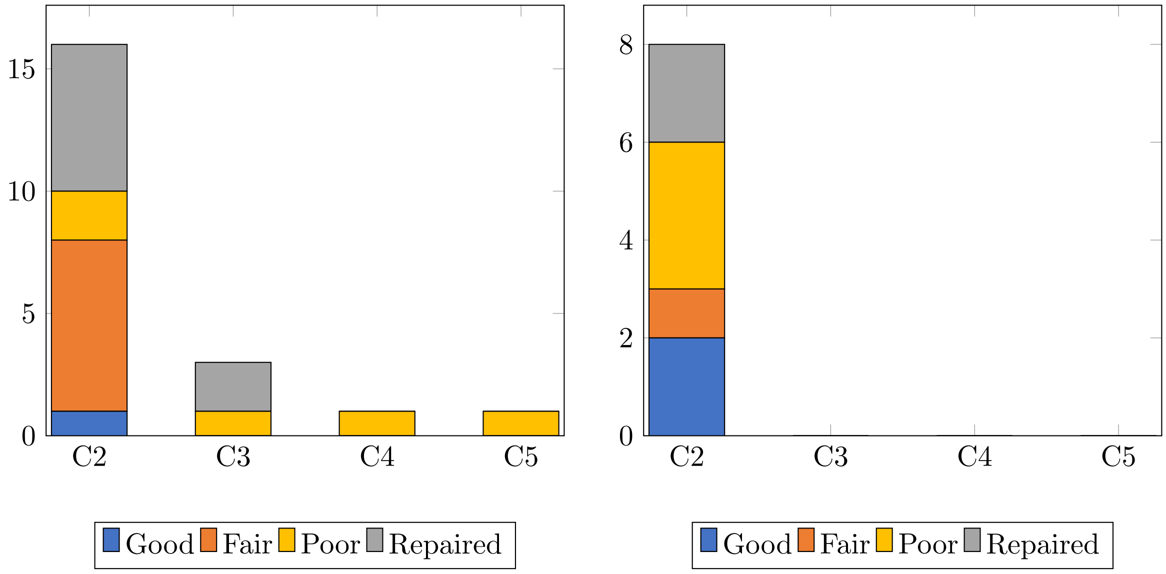
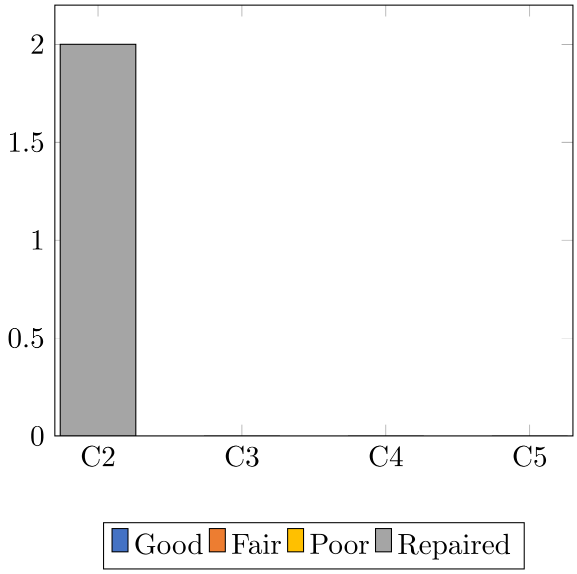


Figure 4.7: Average wind speed by corrosivity, Sweden



(a) Swedish OZ coatings (b) Swedish IOZ coatings



(c) Swedish TSZ duplex coatings

Figure 4.8: Swedish coating conditions for different coatings and environments

The CPI for each coating in each environment is presented in figure 4.9. The sample size outside of C2 environments is very low (5), meaning the results can be very difficult to interpret accurately. From figure 4.9 it is clear that the IOZ coatings are performing best on average, however with a huge variance ranging from 11 to 93 years. The OZ coatings had a lower variance, from 65 to 5 years, while the duplex coatings had the least, with 24 years being the highest to 15 years being the lowest.

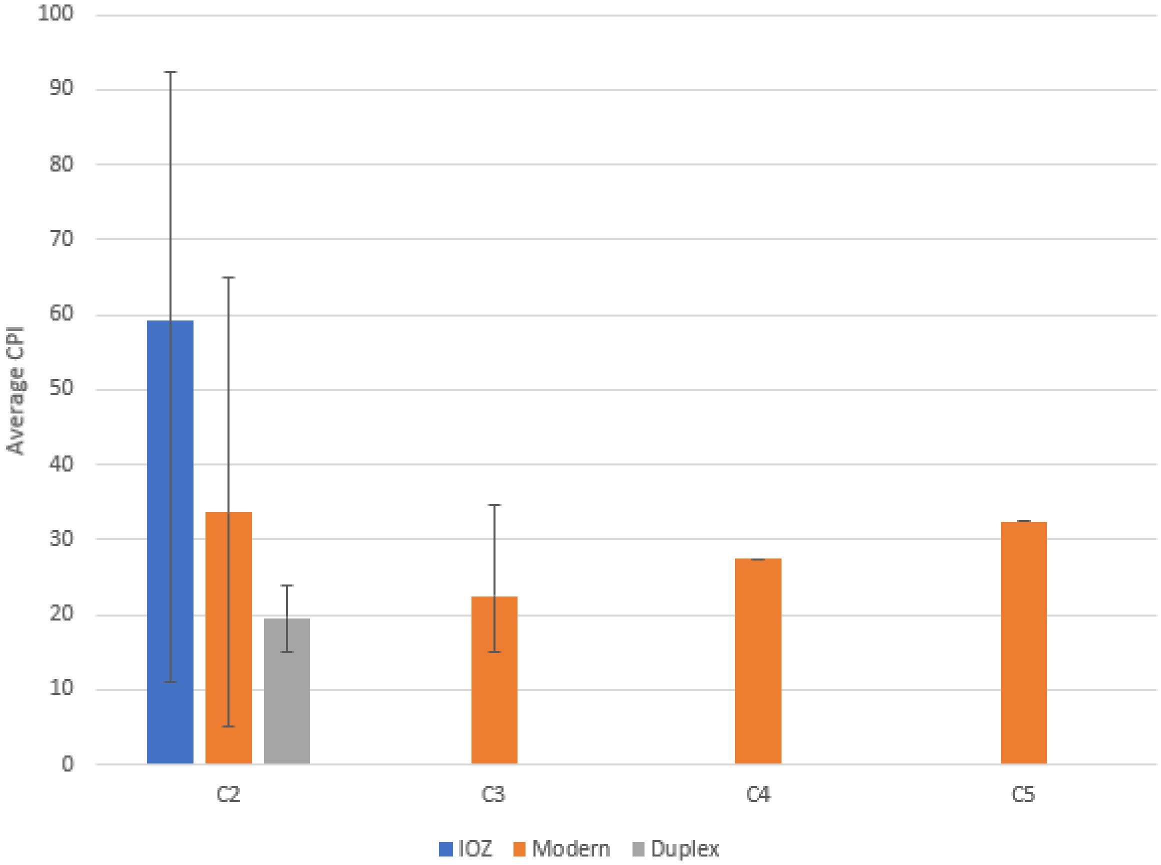


Figure 4.9: Average CPI of Swedish bridges by corrosivity. The deviation lines show the highest and lowest values.

4.3 The Øresund Bridge

The Øresund Bridge has a sailing clearance of 57 m at the highest, however the bridge has a mean height of between 30 and 40 m. This would put the bridge in a C3 environment in this thesis. Reuters are claiming 300 000 m^2 are to be painted, and it is scheduled to take 13 years [22]. News report from Forbes claims the bridge will be maintained for 226 000 000 SEK or 22 600 000 EUR [23]. This means the bridge will be maintained for 75 EUR/m^2. However the original estimate was 420 000 000 SEK, or 42 000 000 EUR [24]. Using the CPI with L equal to the maintenance starting date, the Øresund Bridge would be put at 20 years. However using the average age of the coating when it was replaced would put the CPI at 26.5 years given that the paint job has a linear progression during the 13 years of maintenance.

4.4 Maintenance cost comparisons

The performance of the coating may not be the most important factor in the choice of coating. Maintenance cost is of high importance when choosing long life coating systems.

4.4.1 Maintenance of Norwegian bridges

Figure 4.10 Shows the price per area per year found by Knudsen et al. [15], but readjusted for inflation and exchange rate. This figure shows the average of each specification in the different environments. This figure shows that the maintenance cost increases with corrosivity. Figure 4.11 shows the price per area per year for all bridges in this study and Knudsen's study together, along with an average for all bridges in both studies in a third column. This figure also shows that the maintenance cost increases with corrosivity, but not as much for the 1977 specification in C5 environments.

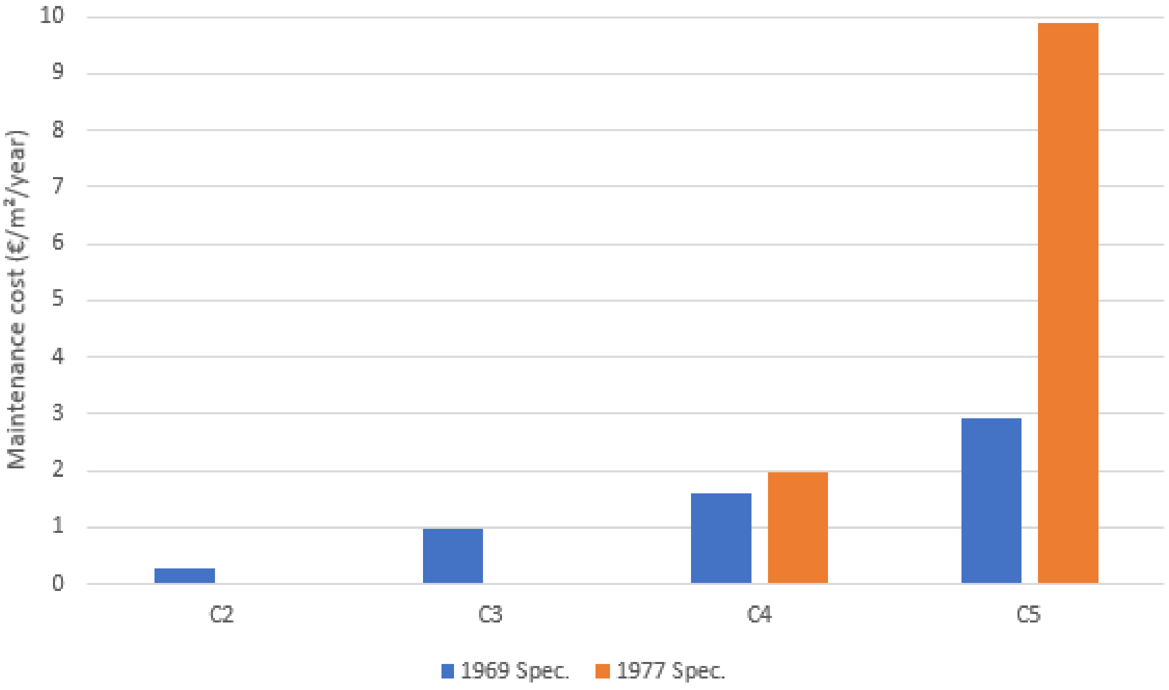


Figure 4.10: Average cost of repaired bridges per area per year by environment from the supporting study by Knudsens et al. [15]. with adjusted inflation rate and exchange rate

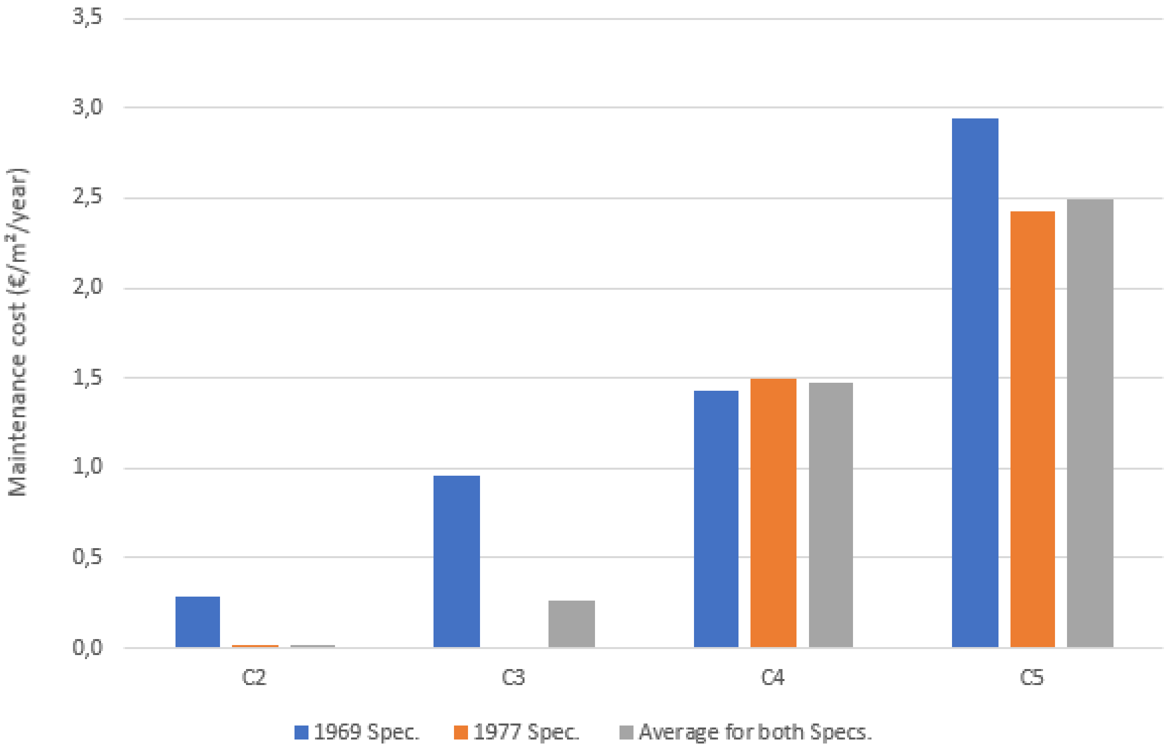


Figure 4.11: Average cost per area per year by environment for both specifications, with an average for both specifications together. All bridges studied here and by Knudsen et al. compiled together

4.4.2 Maintenance of Swedish bridges

It is very hard to make a good graphical overview of maintenance cost on Swedish bridges. This is mostly due to the fact that many of them are listed as ”Repaired - entire bridge”, ”Changed load-bearing beams” or ”improvement painting”. However it is not listed how much the maintenance costed in any case or the scope of the repair. The two IOZ coatings that were repaired lasted 11 and 31, thereby averaging 21 years. The OZ coated bridges were repaired after an average of 12 years, where the lowest was 5 years and the highest was 24 years. The most durable OZ coated bridge in Sweden were 31 years old and was assessed as fair, indicating that the coating has a possibility of lasting for a long time.

Using the average life maintenance cost for both Norwegian specs in the environments and assuming the maintenance cost per square meter of the Øresund bridge is representative of OZ coatings in C3 environments figure 4.12 is obtained.

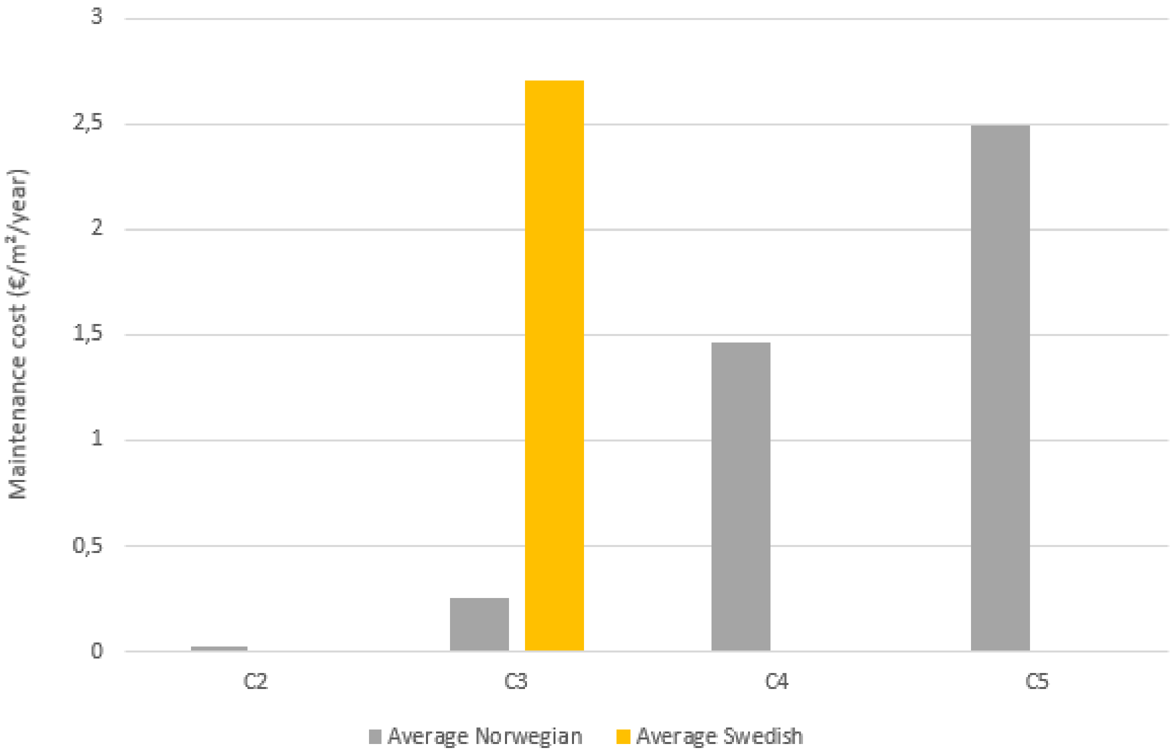


Figure 4.12: Maintenance cost comparison of the Norwegian bridges and the Øresund bridge representing OZ coatings

5 Discussion

In this chapter the findings and the uncertainties of the results are discussed. The study by Knudsen et al. [4] will also be discussed and compared to the findings in this thesis.

5.1 Assessments

As there are some uncertainties in both corrosivity and coating assessment this will be explored firstly.

5.1.1 Corrosivity

The corrosivity assessments are based on trends from tall and long bridges over the sea down to 5 m above the water. However, the shorter a bridge is, the lower it usually is too, meaning many of this study's bridges are lower than 5 m. Most of them are inland bridges and no tests have been performed to assess corrosivity in inland environments. To validate the assessed corrosivity a test in accordance to ISO-9226 should be performed for bridges over rivers and waterfalls.

Wind velocity is of importance when considering corrosivity as wind will transport the underlying water into the air and thus unto the bridge. It is uncertain how big the impact on corrosivity is. The bridges studied in by Knudsen et al. [4] showed that Nessundet bridge experienced low C3 corrosivity despite being an inland bridge over a fresh water lake. However the samples down to sea level of the Hardanger bridge only showed C2 corrosivity despite experiencing more wind, having a higher average temperature and being over salt water (a fjord bridge). The corrosivity may be explained by road salt, a factor which has not been studied here.

Although coating selection for Swedish bridges is based on an assessment of corrosivity, this has not been used to categorize the corrosivity of their environment in this thesis. The Øresund Bridge was initially assessed as either C4 or C5 judging by the use of paint system. However it is the bridge with the highest sailing clearance here, and judging by the corrosivity by height in figure 2.7, it should be between C2 and C3 at the top point and about C4 at the abutments. The middle ground of C3 was chosen due to this. Similarly the Vallsund bridge, another Swedish bridge, had a polyurethane top coat, meaning it was designated as at least C4 by the STA. Due to its location far from the sea (map number 89) and the low mean wind velocity it was designated as C2 in this thesis.

Some bridges may have been categorized wrong as the air quality is unknown in many places. Especially the bridges in city centers may be subject to much pollution that they should be C3 categorized. The atmospheric corrosivity of for example Oslo is not known. Bridges over train tracks are also interesting to note, as the total impact of the exhaust gases from trains on corrosivity is unknown.

5.1.2 Coating condition

The coating condition is not always easy to assess. Some bridges only had corrosion on I-beam edges, which is expected when the edges are sharp. If the degradation was only one local strip of corrosion along the edge it could be assessed one category better. The following three figures illustrates the state of the coating and their assessed conditions. Figure 5.1 shows the worst case acceptable good condition, figure 5.2 shows a bridge on the verge of good, yet assessed as fair, and figure 5.3 shows an example of a poor condition bridge on the verge of fair.

Figure 5.1: Example of the coating (IOZ) on a bridge assessed as good. Few areas of this kind of top coat flaking is accepted

Figure 5.2: Example of the coating of a bridge assessed as fair. Pinhole application errors with zinc oxide visible over large areas can make the bridge assessed as fair

Figure 5.3: Example of the condition of a bridge assessed as poor. Widespread areas of visible ferric corrosion through the coating

Corrosion or mechanical degradation?

Some bridges bore marks of damages from contact with other objects. A couple of bridges had impact damage from either trailer trucks or boats, scraping away substantial areas of coating. One bridge in Western Norway had rock- and landslides on it resulting in a boulder resting on the bearing construction as seen in figure 5.4. Such damages were not taken into consideration when assessing the coating condition.

Figure 5.4: Boulder on bridge beam

5.2 Coating performance

The strength and weaknesses of the coatings as well as the uncertainties of the assessments are discussed here.

5.2.1 Norway

8% of the Norwegian bridges in this thesis were repaired.

The findings of this thesis shows that the bridges in C2 environments performed worse than the previous study by Knudsen et al. [4]. However, the trends in figure 4.5 is similar to what was found in that study. Interestingly C2 bridges deviated from the previous results by nearly 25 years in CPI. As the C2 bridges in this thesis are on average 5 years younger than those of the previous study, the CPI may be affected by as much as 10 years if the condition doesn't worsen in 5 years. This difference can be partly explained by the fact that 1995 was the cutoff year for that study (here it is 2000) and there were comparatively more of older C2 bridges. Another possibility is that the assessment has become more strict in this thesis, but an update of the coating conditions on the bridges with some doubts proved to only increase the average CPI by 5 years. If the condition was raised by 1 for each bridge in C2 and the age was 5 years higher the average CPI would be about the same as what was found by Knudsen et al. [4]. Any deviation outside of that can not be confidently explained, but handling of parts, standards of local companies and similar circumstances around construction could be of importance other than corrosivity. The bridges in the other environments showed similar CPI to what was found by Knudsen et al. The CPI for C3 environments was here found to be 50 years, for C4 environments it was found to be 42 years and for C5 it was found to be 29 years. This is a deviance of 0, 0 and +9 years respectively from the study by Knudsen et al. The higher CPI for C5 bridges is probably due to the fact that more C5 bridges have been studied here and the two that were studied by Knudsen et al. are known to have application errors in the coating, thus reducing the durability.

Tollå bridge seems to not have been top coated during construction, but may have been so 6 years after. Due to this kind of treatment it has been excluded from figure 4.5. It was however interesting to note the costs of maintenance to get a representative number for a 1977 spec duplex coating in the C2 environment of Norway.

Hestvik bridge is interesting to note due to preventative maintenance. The bridge seemed to be in fair condition in 2007, which is illustrated in figure 5.5. The reasoning behind the painting was to stop corrosion early as some white rust had been observed and the bridge is in a very aggressive environment. The maintenance contract for this bridge also covered multiple other bridges of different sizes, which Hestvik and Bangsund were of the longer ones. The company responsible for the paint job claimed the price they charged was 155 EUR/m^2, which made the jobs on the larger bridges very profitable, but also that they lost money on smaller bridges with the same price. This points towards the project starting costs, involving project planning and mobilizing of equipment and personnel. These costs don't scale much with the size of the bridge and becomes a smaller fraction of the maintenance cost when the relevant bridge is longer.

Figure 5.5: Hestvik bridge in 2007. Together with some pictures of rusty bolts this would be considered fair by this thesis standards

5.2.2 Sweden

More Swedish bridges than Norwegian showed corrosion traps under examination, which if avoided could increase the lifetime of the coating. A corrosion trap found on a Swedish bridge is shown in figure 5.6. The presence of these reduces the lifetime of the coating and construction significantly. 39% of the Swedish bridges were repaired, compared to 19% of the Norwegian bridges studied here and by Knudsen et al.

Figure 5.6: Corrosion trap on a Swedish bridge

Swedish OZ

The Swedish bridges in C4 and C5 environments are difficult to draw any conclusions from as the sample size is too small. The CPI is very high for these bridges, yet both bridges are in very poor conditions. The Djupasund bridge (C5) had extensive paint degradation and areas of red rust and the Möcklösund bridge (C4) had multiple points of ferric corrosion, possibly stemming from pinhole application errors. Due to the this it would not be appropriate to base any conclusions on them.

There are three C3 bridges (excluding the Øresund bridge), all with the same coating type, which is a small sample size, but since two of them are repaired it would seem natural to use them to substantiate a conclusion. The two repaired bridges lasted about as long as what is expected by what ISO 12944-1 defines as "high durability" which is 15 to 25 years. Due on this the coating could be considered to reach the durability goals by the standard they are based on. The Bridge over Mörrumsån had not been repaired and had an age of 26 years. It was assessed as poor as it had many coating damages down to the steel, but due to little ferric corrosion as of 2015 it could be expected to last some more years without maintenance. This bridge increased the CPI from 17 to 20 years.

The modern coatings in C2 environments are numerous and shows high performance for a paint system. The average durability is what would be considered "very high" in ISO 12944-1, despite some low outliers that were repaired. The worse performing coatings could be due to numerous unforeseen consequences throughout the lifetime of the bridge, and ISO 12944-1 does indeed state that there is no good correlation between guaranteed lifetime and durability range. 38% of the OZ coatings had been repaired and 40% of C2 bridges were repaired.

Wolstenholme and Ross points to epoxies being too effective at wetting zinc particles as an explanation for the lower current supplied to the steel substrate compared to RUC. It is hard to solve this problem as the reason the epoxy is "too effective" at wetting the zinc particles is the same reason as to why it is desirable to use as paint on the steel substrate in the first place, namely the strong adhesion. The obvious answer to this concern is to apply a layer of metallic zinc before applying organic coating.

Comparing the OZ coating in Sweden with the duplex coating in Norway shows that the duplex system outperforms the OZ system significantly. The Norwegian bridges with '77 spec only had 1.6% of the C2 bridges repaired while 40% of the Swedish OZ C2 bridges were. It is not entirely comparable as the Swedish bridges are on average 9 years younger than the Norwegian bridges and there are only 16 bridges in the Swedish selection and 62 bridges in the Norwegian selection.

Swedish duplex

The Älvsborgs bridge was originally covered with a TSZ duplex system. Another two bridges in Sweden were coated with TSZ duplex coating in part of a major maintenance operation. It is unknown exactly how extensive this operation was, but it is believed to be removal of lead minium paint and application of duplex coating. These bridges coatings performed poorly compared to the NPRA standards, and the reason is not well known. It could be that the applied coating is not to the same standard as in Norway, for example if the bridges were repaired on site the coating job could be considered flawed as application and quality control is best done in a workshop. Especially spitting application error is a common pitfall when utilizing TSZ. It is hard to assess what causes the poor performance of these bridges as the inspection pictures doesn't show any obvious signs of TSZ application errors. One of the bridges also seem to have been repainted without removing all rust from the steel. The documents describing the coating specifics were not found.

Swedish IOZ

Since the ratio of repaired IOZ bridges is less than the ratio for OZ coating bridges there are doubts about the superiority of OZ coatings, but it is uncertain if this is due to demolition of old bridges or better performance. The CPI for IOZ coating was the highest for the Swedish bridges at 55 years, but with a variance ranging from 11 (repaired) to 93 (unrepaired) years. The enormous span in the performance of IOZ bridges can be explained by the difficulty of application for IOZ coating. It would be interesting to examine the application process for these bridges, but it is probably not feasible as that information may not have been recorded at all. 25% of the 8 IOZ bridges were repaired compared to the 38% of OZ bridges.

Due to their higher age and less maintenance it is strongly indicated that IOZ coatings have a higher potential for long lifetime corrosion protection than OZ coatings. This could partly be explained by Wolstenholme and Ross' findings on epoxy being to effective at wetting the zinc so that it doesn't get enough galvanic contact with the steel. Given that the IOZ bridges examined here are representative of the performance of IOZ the coating seems to be the second best performing alternative for corrosion protection based on CPI, the best performing being the NPRA duplex coatings. However this could be survivorship bias if the amount of demolished IOZ bridges are high and in this thesis only the ones that were good enough to not be demolished were studied. Only 8 IOZ bridges were examined in this thesis. It was possible to gather that approximately 2600 Swedish bridges have been demolished, however, to find out which were steel constructions, not to mention what kind of protection was used, would have amounted to anything from 10 000 - 20 000 individual reviews of documents, to be done manually.

5.2.3 CPI

CPI is a somewhat unreliable way to tell how long a coating will last, and has yet to be validated. The call to start maintenance is made by different people in different offices with different budgets and thus some bridges get a somewhat postponed maintenance date and others get an early maintenance. Since the CPI is a factor of lifetime it can get abnormally high due to this. For young bridges there are some problems too, as however great a coating may be and however kind the environment may be it hasn't gotten the age to prove it. This points to the need for a correction factor to make CPI a more reliable way to estimate the lifetime of the coating, giving young bridges an increased score and older bridges in poorer condition a reduction. However that is outside the scope of this thesis. CPI should in theory show some correlation to coating performance.

5.3 Maintenance cost analysis

The maintenance costs of repaired bridges in Norway and Sweden were supposed to be compared to analyze economic benefits of different coating systems. But to do this reliable data, and sufficient data points is very important to get accurate results with statistical significance. With this study and with the study by Knudsen et al. we get a decent amount of data points for the Norwegian bridges, but for some of the repaired bridges in that study the maintenance cost is an estimate. Of the bridges covered in this study there are 7 that are repaired in Norway shown in table 4.1 and table 4.2. In Sweden there are 12 repaired bridges shown in table 4.3. Seven with OZ coating systems, three with duplex coating, and two with IOZ coating. To analyze the Norwegian bridges the bridges from "Corrosion protection of steel bridges with thermal spray zinc duplex coatings - 50 years experiences" [15] were included, as shown in figure 4.11.

The coating on Norwegian bridges may be expected last between 69 to 90 years in C2 environments based on this thesis and the study by Knudsen et al. respectively. As the bridges are designed for 100 years of service, the coating in C2 environment can match this lifetime about 21% of the time without repair based upon CPI from this thesis and the paper by Knudsen et al. combined. However, the more aggressive the environment the more often the coating needs repairs during its service. It is important to note that the coating is not expected last 100 years without maintenance by the NPRA.

From figure 4.11 the Norwegian bridges show maintenance costs up to 0.3 $EUR/(m^2 \cdot year)$ for C2 bridges. For bridges in C5 environment the maintenance cost is up to 2.9 $EUR/(m^2 \cdot year)$ at the highest with the 1969 specification, and at 2.4 $EUR/(m^2 \cdot year)$ with the 1977 specification and 2.5 $EUR/(m^2 \cdot year)$ on average for both specifications. The repair done on Hestvik, the most expensive C5 bridge in this thesis, with a maintenance cost of 5.8 $EUR/(m^2 \cdot year)$, was more of a preventative measure rather than a strictly necessary one, as the only damage was some rusty bolts and some areas with zinc corrosion products, which may explain the high cost per year.

Swedish bridges are designed to last for 80 years. The IOZ coatings could be expected to last about 55 years without coating maintenance and 25% could be reaching the bridge design lifetime without coating maintenance both based on the CPI. This is the most durable of the Swedish systems. For OZ coatings the expected lifetime was found to be 33 years and decreasing with corrosivity based on the experiences with the coating in C3-environments and excluding the C4 and C5 bridges. This does not seem to reach the design lifetime as the maximum CPI was 65 years and it seems like no OZ coated steel bridge will be able to be operational for 80 years without coating maintenance. This is not expected by the STA, but it means that there is almost a guarantee that their current standard will need more maintenance than both their previous standard and the NPRA's standard.

As the repair frequency for Swedish bridges with the OZ coating systems seems to be every 23rd year (+/- 8 years) in C3 environments some prediction about the costs can be made. Due to limitations in information in the databases the scope of repairs are not known. This would help predict the time of repair and a realistic cost estimate. Since the area of repair and the maintenance cost is not listed in the BaTMan, knowing what fraction of paint area degradation is considered in need of repair is not simple. The repair frequency is very hard to determine for the C2 environment, but it may seem to be very similar to what was found for C3.

The Øresund bridge was found to have a maintenance cost of nearly 4 $EUR/(m^2 \cdot year)$. Since the maintenance cost information from other Swedish bridges are lacking this is the only representative for what it costs to maintain an OZ system on road bridges. The Øresund bridge is very long and, as discussed on about the Hestvik bridge, this means the maintenance costs approach that of the painting costs alone. This means the cost per unit area can be regarded as a best case scenario for coating maintenance costs.

Since the Øresund bridge may be a best case scenario for the maintenance cost per area, it is desirable to compare it to the Norwegian bridges. As none of the studied Norwegian C3 bridges with 1977 spec have been repaired this comparison will be done with the 1969 spec instead. The cost per area per year for the duplex system approaches 1 EUR/m^2/year as seen in figure 4.12, which is 1/4 of the equivalent cost for the Øresund bridge. Considering the fact that two out of the three other OZ coated bridges in C3 environments are repaired, the real cost per area per year may be somewhat different. Figure 4.12 points towards OZ coatings being much more expensive than TSZ/alkyd duplex coatings. The maintenance cost of the OZ coating is even higher than the duplex cost for C5 environments. Now, it is also important to note that the coating of the Øresund bridge is considerably more modern than the duplex specs from these Norwegian steel bridges, and the alkyd paint used from 1969 is not as durable as the modern polyurethane and epoxies in employment now.

Norwegian maintenance cost issues

Determining the costs on bridges of different length is hard even though the maintenance costs are well documented. This is due to the fact that most bridges are repaired in bulk by companies winning a tender which should present profitability on the bulk. This way a price of 150 EUR/m^2 could turn a profit for a company even though they lose money on the smaller bridges in the bulk, while the larger bridges could be repaired for a cheaper rate, thus muddling the water somewhat when analyzing the listed maintenance costs.

Swedish maintenance cost issues

A problem arises when trying to compare the maintenance cost in Sweden to Norway due to how costs are reported in BaTMan. As the maintenance cost is set to be 230 EUR/m^2 while the coating on the Øresund bridge is repaired for 75 EUR/m^2 there is uncertainty in how high costs one can actually expect from the maintenance. It is desirable to produce a formula for the maintenance cost by the length of the bridge, but as the lower boundary is unknown and there are no representatives in the mid range it seems like the curve may be misrepresenting the situation, but claiming that the maintenance cost for coatings on bridges start at around 230 EUR/m^2 and approaches somewhere in the realm of 75 EUR/m^2 is not unreasonable. We can speculate that the high price of 230 EUR/m^2 may be due to the experiences with IOZ coating maintenance and not just the OZ coatings as the application of IOZ is known to be harder.

This way companies in the know may be able to charge a somewhat higher rate due to less competition than for OZ coating repair.

6 Conclusions

The Norwegian system of TSZ and alkyd duplex coating seems to be a more economical choice as the coating has a very high durability and low maintenance frequency compared to the alternative of zinc rich paint. The durability is expected to be 65 to 90 years in C2 environments, and in some cases the coating seems to be able to last nearly 100 years without repair based on CPI. However, the alkyd paint reduces the durability compared to the more durable epoxies and polyurethanes in current employment. The duplex coatings require less maintenance than their zinc rich primer counterparts, but have a very similar maintenance cost when they need it. Zinc rich paint is expected to last around 30 years in C2 environments without repair and some seemed to reach 69 years based on CPI. Given that the IOZ bridges examined are representative of the performance for IOZ-coating they were expected to last 55 years, with one reaching 90 years based on CPI. IOZ is however the coating with the highest uncertainty of performance. The durability decreases when the environment becomes more aggressive. In any case CPI is not a validated measurement, and should not be understood as more than an indicator. When planning bulk maintenance it is highly advised to issue contracts on bridges of similar length to get the most representative price per unit area for that kind of maintenance, although we realize that might be hard or in some cases economically unsound.

7 Further thoughts

After looking through the databases, it becomes evident that the full potential of the archiving system is not being used. There should be more information stored about why maintenance was done, like an assessment or evaluation. It is important to know why some bridges were repaired for very high costs when no pictures showed any obvious signs of damage and no reasonable assessment indicated the need for reparations, like the Hestvik bridge. Specifically, for BaTMan the real maintenance costs should be noted in the database. Both Brutus and BaTMan should standardize how information is logged and reported. For example in BaTMan very few bridges had listed any reasonable amount of repairs. One post said ”Improvement painting - 1x” which makes it very hard to understand the scope of the repair and, due to the fact that the cost is calculated from the repair type and scope, the maintenance cost. The issue with survivorship bias was mentioned. In Brutus, searching for demolished steel bridges according to the search criteria, was done in less than a minute. However when it comes to BaTMan this proved to be unfeasible due to it lacking a criteria based search engine. In any case both the NPRA and the STA should look to each other’s databases for inspiration, as most of the weak points of one are the strong points of the other.

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Appendix

Risk assessment

Populærvitenskapelig artikkel

NTNU
Kunnskap for en bedre verden