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Durability of pretensioned concrete girders in coastal climate bridges: Basis for better maintenance and future design

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Abstract
This study was based on findings from the Norwegian Public Roads Administration's Bridge Management System and field investigations on corrosion damage in pretensioned Norwegian standard I-beam (NIB) girders in 227 coastal climate bridges. The main durability design parameters are summarized and related to regulations over the last 80 years. Environmental exposure is discussed in the light of the global, local, and micro climate. We found that 51% of the bridges have girder corrosion damage. The percentage is highest for bridges built when the cover thickness required was lowest. Cover thickness below that required (resulting from production faults) caused 74% of corrosion damage. Most of the severe chloride-induced corrosion damage in bridges was found in the inner NIB girders, particularly in the support-zones and their vicinity. This can be due to interaction between geometry and exposure. Corrosion of reinforcement in support-zones can impact structural behavior, particularly NIB girder shear performance.

KEYWORDS
bridges, coastal climate, corrosion, durability design, durability status, pretensioned girders

1 | INTRODUCTION

According to data in the Bridge Management System (BRUTUS)[1] of the Norwegian Public Roads Administration (NPRA), more than 1,100 of the national and county road bridges in Norway have pretensioned concrete girders. They are cast in reusable molds and cured in a controlled environment. The pretensioning reinforcement is anchored and pulled between two fixed bulkheads prior to casting, and released when the concrete attained the required compressive strength. After 28 days, quality approved girders are then transported to construction sites, lifted and supported on abutments and transversal beams. Pretensioned concrete girders, together with cast-in-place reinforced concrete (RC) slabs, form the typical superstructure of this type of bridge.

The BRUTUS[1] data show that 67% of the pretensioned girder bridges were built more than 30 years ago, which means that many of them may need expensive maintenance in the coming years. More than 36% of pretensioned girder bridges in Norway are located in coastal regions, with varying exposure to sea water. In this chloride-contaminated environment, the risk of corrosion increases, depending on age, exposure, and detailing. Corrosion will affect the

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

performance of both ordinary and pretensioning reinforcement and can reduce the structural capacity of the bridge superstructure. The current condition of a bridge is crucial for the estimation of its remaining service life, but this is presently assessed mainly on the basis of regular visual inspections complemented by selected measurements during major inspections.[2] More detailed surveys are performed only when significant corrosion damage has been detected. In prestressed structures, however, corrosion of strands may not produce enough rust to crack the concrete,[3] so accurate assessment of the condition of a bridge is challenging and estimation of its remaining service life is often highly uncertain.

The types of pretensioned girders most commonly used in Norway are standardized I-shaped (NIB) and inverse T shaped (NOB, NOT) girders. Their application and design have been improved over the years through modifications in the requirements and standards,[4–9] see Table 1. Data in BRUTUS[1] show that 60% of all pretensioned concrete girder bridges in Norway were built using NIB girders, so the remainder of this paper focuses on these bridges.

Nowadays, there is increasing demand for standardized, prefabricated elements. The industrialization process continues to develop and, for example, a large number of pretensioned concrete girders will be used by the Norwegian government-owned company Nye Veier AS ("New Roads AS") as part of the express road E18 between Tvedestrand and Arendal.[10]

The large number of existing and newly built pretensioned girder bridges, many located in a coastal climate, underlines the need for research on their deterioration.

The main objectives of this paper are to establish: (a) the durability status of existing NIB girder bridges in Norwegian coastal climate; (b) a basis for their optimal maintenance; and (c) a better basis for future design regulations. NIB girders are the main load-carrying elements in bridge superstructure and corrosion of their highly stressed strands can lead to bridge collapse without warning,[11] so this research focused mainly on the damage to NIB girders, though corrosion in the slabs is also briefly discussed.

2 | DETAILING AND DURABILITY DESIGN OF PRETENSIONED NIB GIRDER BRIDGES IN THE NORWEGIAN COASTAL CLIMATE

Corrosion deterioration in bridges depends on several parameters, notably environmental exposure, reinforcement detailing, cover thickness, and concrete quality. These factors vary depending on location and date of construction. This section discusses these parameters in terms of their influence on corrosion risk and the changing requirements over the last 80 years.

2.1 | Environmental exposure

The NPRA divides Norway into four climate zones for bridge climate classification.[12] Three of them relate to coastal climate, with varying exposure to sea water (see Table 2). This paper jointly defines these coastal climate zones as the global climate (see Figure 1a). Bridges located in this aggressive environment are particularly vulnerable to chloride-induced corrosion.

In addition to the global climate, the local climate also influences the chloride ingress and corrosion risk (see Section 5). This paper defines the local climate as height above sea level (see Figure 1b). Eurocode 2 and the NPRA's design criteria for bridges[13] indicate that the global and local climate determine the requirements for minimum concrete cover thickness.

Section 5 also discusses the influence of microclimate in association with wind and rain exposure. The microclimate relates to locations along the bridge spans and across the bridge superstructure (see Figure 1b).

2.2 | Reinforcement layout for NIB girders

The typical reinforcement of NIB girders consists of pretensioned strands made of high-strength steel 1700/1900 MPa (yield/ultimate strength),[8,9] and ordinary reinforcement: stirrups and additional longitudinal rebars in the web, and optionally in the flanges (see Figure 2).

Depending on the bar diameter and year of production, ordinary reinforcement is made of K400TS (KS40) or KS50

TABLE 1 Pretensioned girder types

	NOB from 1974[4]	NOB from 1983[5]	NOT from 1990[6]	NIB from 1974[7]	NIB from 1983[8]	NIB from 1989[9]
Height (mm)	400–700	400–700	500–1,000	600–1,400	600–1,800	1,030–1,830
Flange width (mm)	490	490	690	400–500	400–700	420–730
Span (meters)	6–18	5–22	10–25	~15–30	14–35	14–35

TABLE 2 Pretensioned girder bridges in Norway located in coastal climate zones

Coastal climate zones[12]		Bridges in climate zones[1]	
Climate zone	**Description**	**% of all types of pretensioned girder bridges**	**Number of NIB girder bridges**
Inner coastal	Saltwater-exposed, but well-protected areas in southwestern and southern Norway, for example, the Oslo Fjord and inner fjords of western Norway	19.6	117
Coastal	Weathered coastal areas with some shielding in the landscape, for example, coastline in southwestern and southern Norway	12.6	88
Harsh coastal	Used only for locations with extreme coastal weather conditions, for example, the outer coast areas in northern and northwestern Norway	3.9	22

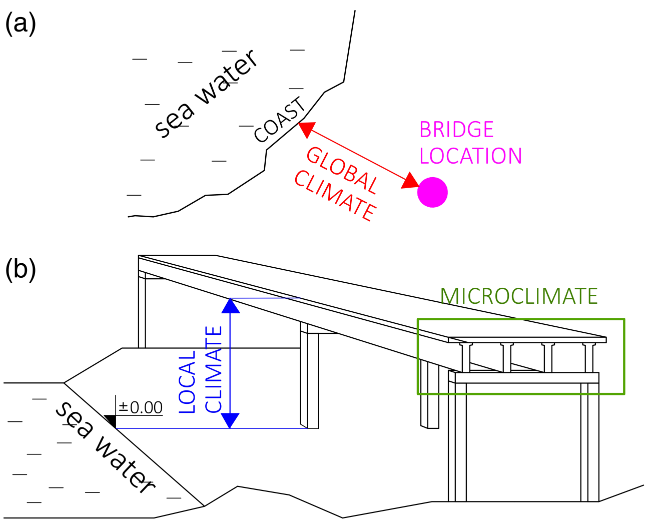


FIGURE 1 Classifications for environmental exposure (a and b)

steel, with yield strengths of 400 MPa and 500 MPa, respectively.[8,9] The arrangement of the stirrups and their center distance change with the girder size, span length, and year of production. For example, the NIB girders produced from 1983[8] have two ø12 mm stirrups in the support zone (see Figure 2a). By 1989, the arrangement in the support zone had changed to four ø12 mm stirrups (see Figure 2b), and the upper limit of the center-distance had decreased to max. 300 mm.[9] Accordingly, it can be expected that the shear capacity of girders designed before 1989 may especially be of concern.

Moreover, the pretensioned NIB girders together with cast-in-place RC slabs can be designed as a composite section. A sufficient connection between these elements is provided by extended stirrups (see Figure 2). This solution has a significant impact on the girders' shear and flexural capacity.

The pretensioning reinforcement is arranged with varying numbers of strands depending on the girder size, span length, and bridge width, with 2 to 6 in the top and 12 to 30 in the bottom flange.[9] Regarding the corrosion risk, it should be mentioned that more than 20% of the strands are located in the bottom layer of the bottom flange. In total, about 50% of the strands are located close to the concrete surface. This means that under specific conditions a large amount of pretensioning reinforcement might be particularly exposed to chloride-induced corrosion.

A design approach for dealing with anchorage failure was introduced in the third edition of Norwegian Standard NS 3473:1989.[14] This involved additional longitudinal reinforcement at the level of pretensioning, which could carry the tensile component of shear force in a cracked anchorage zone. Additional bars in the anchorage zone are therefore unusual in bridges designed according to pre-1989 regulations. Nevertheless, Hulvåg Bridge (1987) that is more in detailed discussed later in the paper, has horizontal stirrups at the bottom of the NIB girders, so there is some uncertainty about the actual anchorage reinforcement, especially in bridges designed in the period 1983–1989.

2.3 | Concrete cover thickness

The national standards and regulations on the minimum cover thickness for both ordinary and prestressed steel have changed over the years.

Concrete cover for the stirrups in NIB girders is a crucial parameter because they come closest to the concrete surface. Until 1988, the minimum required cover thickness for girders exposed to weather and moisture did not exceed 30 mm, with the lowest value (25 mm) in the years 1973–1981 (see Figure 3). Moreover, these requirements did not apply to the mounting bars, that is, supporting stirrups. This means that some bars might have 20 mm concrete

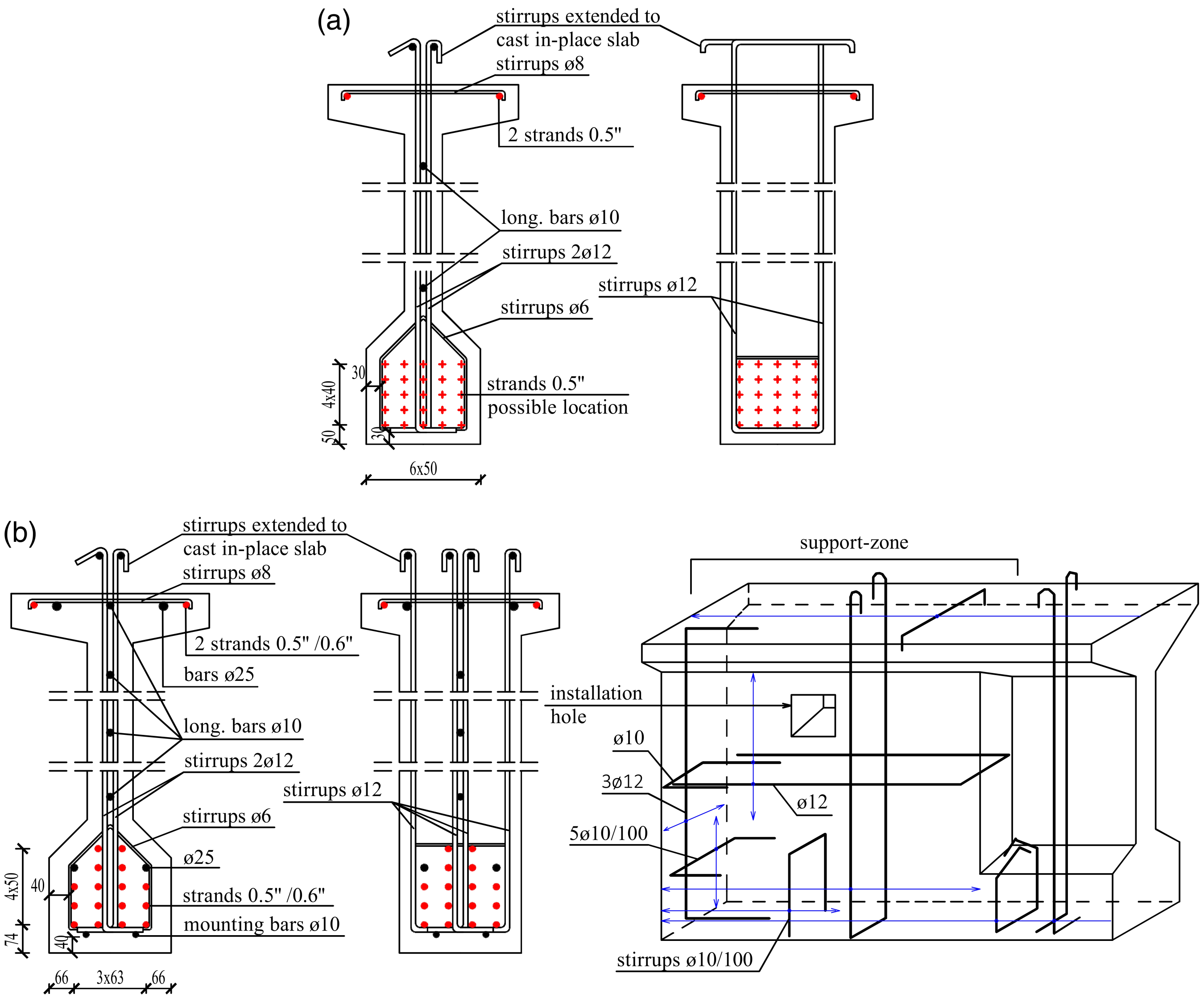


FIGURE 2 Typical reinforcement arrangements in NIB girders. (a) NIB 1400 from 1983.[8] (b) NIB 1400 from 1989[9]

cover or less, making them particularly vulnerable to chloride-induced corrosion. After 1988, NPRA regulations and standards increased the minimum cover thickness required.

The minimum concrete cover requirements for the pre-tensioning steel did not differ from ordinary reinforcement until 1989, when the minimum cover for prestressed reinforcement was increased by about 10 mm compared to ordinary bars. In the same year, requirements were introduced for the protection of end surfaces in pretensioned girders located in aggressive environments.

These changes over the years mean that bridges built before most 1988 (>30 years old) have the lowest cover thickness and are at risk for corrosion. This group accounts for 71% of existing pretensioned girder bridges in Norway (based on data in BRUTUS[1]). While we found that some bridges built just before 1988 had a higher cover thickness than required at the time (see Figure 3), there is some uncertainty about the actual cover thickness in girders, especially in bridges built in the 80s.

2.4 | Concrete quality

Several factors, including water-to-cement ratio (w/c), cement content and type, and compacting and curing, will affect the rate of chloride ingress into concrete. Because the pretensioned concrete girders were cast in a controlled environment, and required extended quality control throughout the whole production process (from 1973[21]), compacting and curing should be of less concern.

Requirements for concrete quality in both NIB girders and cast-in-place slabs, and the internal chloride content allowed, have changed over time (see Figure 4). NIB girders used to be cast with Ordinary Portland or Rapid

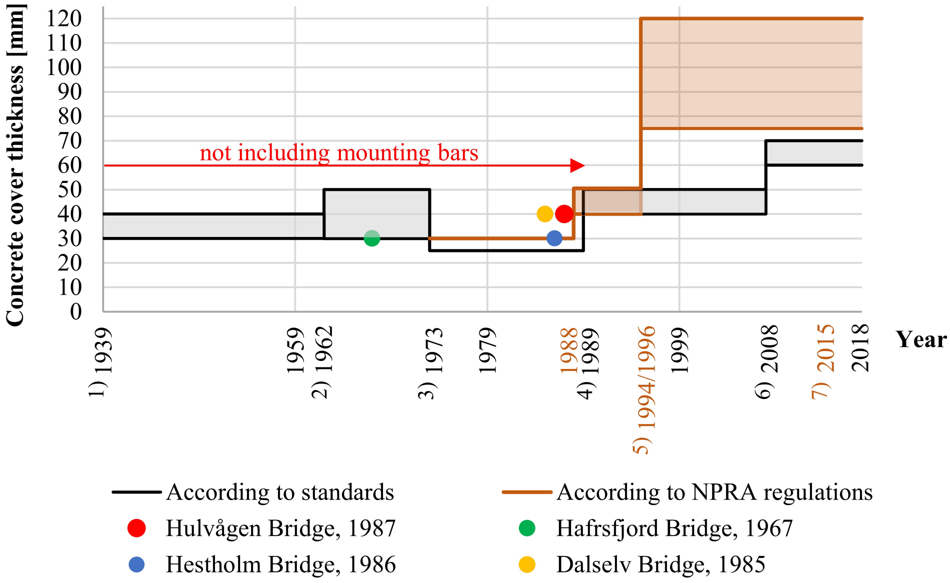


FIGURE 3 Concrete cover requirements for ordinary reinforcement in NIB girders (in coastal climate zones) versus time of design. 1) 30 mm for beams with weather and moisture exposure; 40 mm for beams exposed to waves, ice and water pressure (but not submerged)[15] 2) 30 mm for beams with weather and moisture exposure; 50 mm for beams in tide zone, splash zone and sea water vicinity[16] 3) for unprotected structures located outside[17] 4) for aggressive environmental conditions (MA): 40 mm for little corrosion-sensitive reinforcement (ordinary bars); 50 mm in the splash zone; [50 mm for corrosion-sensitive pretensioning reinforcement[14] 5) nominal cover: 120 mm in the splash zone; 75 mm up to 6 m and 12 m above the splash zone in mild and harsh marine exposure respectively; 75 mm for other elements exposed tocsalt; [55 mm for elements not exposed to salt][18,19] 6) nominal cover for 100-year design service life: 60 mm for XS1, XD3, XD2, XD1 environmental classes; 70 mm for XS3 environmental class[20] 7) nominal cover: 120 mm for marine exposure up to 6 m and 12 m above the highest astronomical tide,in mild and harsh marine exposure respectively; 75 mm for other elements exposed to salt [65 mm for elements not exposed to salt][13]

Portland Cement,[17,25] but concrete mixes containing max. 10% of pozzolanic/hydraulic materials (including 2–5% of silica fume) could have been used in years 1988–1997. New concrete mixes SV-40 and SV-30, containing 3–5% and 8–10% of silica fume, respectively, have been used in years 1997–2015.[24] Later, SV-40 and SV-30 were replaced with SV-Standard containing 3–5% of silica fume.

NIB girders are typically made of higher strength concrete (class C55, characteristic cubic compressive strength 55 MPa) than slabs. Until 1988, a higher strength class was accompanied by a lower w/c (see Figure 4). For well-hydrated cements, lower w/c results in a lower volume of the capillary pores responsible for ion transportation. This means that, in the same environmental conditions, pretensioned concrete girders in bridges built before 1988 should be more resistant to chloride ingress than cast-in-place slabs.

Since 1973, using sea water for concrete mixing or aggregate rinsing has been completely banned for concrete in contact with pretensioning steel. The same applies to using calcium chloride $CaCl_2$ as an additive, though admixtures containing only trace amounts of chloride could be added to improve concrete workability. But internal chlorides can be expected in some NIB girders of bridges built before 1973 (see Figure 4).

3 | METHODOLOGY FOR DURABILITY STATUS ASSESSMENT

Damage to the pretensioned NIB girders of 227 bridges in Norwegian coastal climate zones was investigated to assess their durability status based on data in BRUTUS[1] from September 2018. This study did not examine other structural elements, such as slabs, abutments, and so on. Among all the registered damage to NIB girders, corrosion damage was selected for further analysis (see the workflow diagram in Figure 5). Corrosion damage included: (a) lack or spalling of the concrete cover with visible corroded reinforcement; (b) corrosion cracking; or (c) corrosion stains on the concrete surface. We classified the bridge as corroded when its NIB girders showed at least one form of corrosion, regardless of its severity.

The corrosion damage was analyzed based on damage types, causes, descriptions, and photographic documentation (specified in BRUTUS[1] and the NPRA's handbook[2]). It should be mentioned that the BRUTUS data are based mainly on visual inspection and subjective engineering

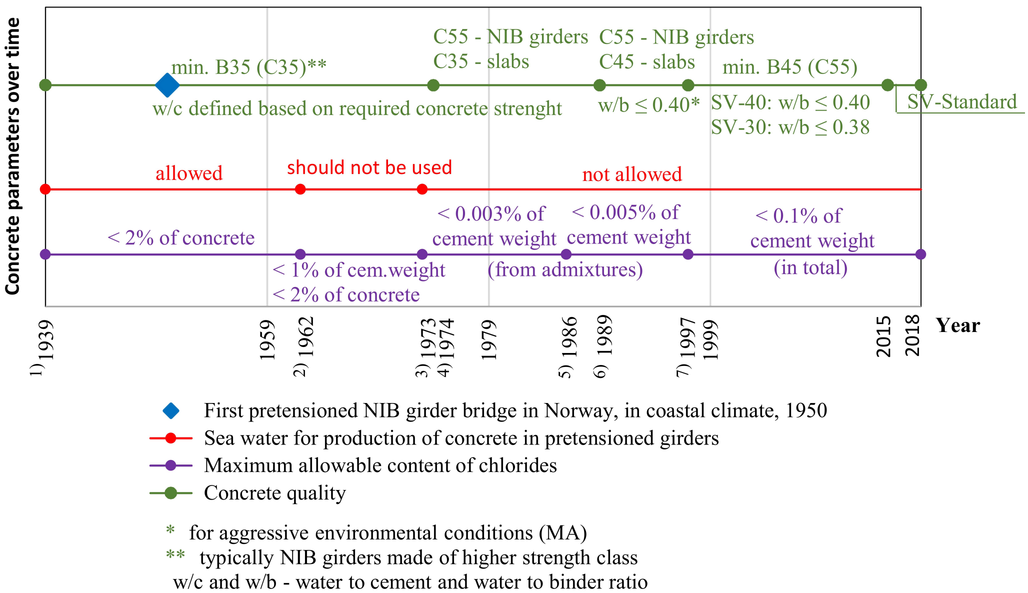


FIGURE 4 Concrete parameters versus time of design 1)[15] 2)[16] 3)[17] 4)[22] 5)[23] 6)[9] 7)[24]

judgment. We found that similar corrosion damage was registered as having different types, causes, and severity. We therefore decided to carry out a manual analysis of all the corrosion damage.

The causes of corrosion damage were assigned to one of four main categories: (1) Environmental attack, (2) Environmental attack and production/installation faults, (3) Production/installation faults, or (4) Other/unspecified (see Figure 5). These categories were introduced to make it possible to define the overall cause of corrosion damage in each NIB girder bridge (see Figure 5). Generally, the causes of corrosion damage placed a bridge clearly in one of the four categories, but two bridges showed corrosion causes in both Categories 3 and 4. For simplicity, these two bridges were classified as having Category 3 corrosion.

To assess the durability status of the bridges, they were quantified in the above categories and distributed by coastal zone and time of construction (see Figure 6). The bridge construction periods correspond to time during which the required minimum thickness of the concrete cover did not change significantly (cf. Figure 3).

Finally, we carried out a detailed analysis of the corroded NIB girder bridges in relation to individual overall cause of corrosion damage. Here, the bridges in the combined Category 2, are included in both Categories 1 and 3. In addition, NIB girder damage specified in BRUTUS[1] as spalling due to workmanship faults or honeycombs and rock pockets in uncorroded bridges is quantified and categorized as falling in Category 3.

In addition to the data from BRUTUS,[1] results from three field investigations are included. The inspections were carried out on a total of 13 pretensioned NIB girder bridges located coastal zones, mainly on the basis of visual assessment and selected measurements.

4 | DURABILITY STATUS OF THE NIB GIRDER BRIDGES

4.1 | Data collected from BRUTUS

We found that 51% of the bridges investigated have registered corrosion damage in the NIB girders, which includes damage since repaired. The percentage of bridges with corroded NIB girders decreases the more recent the year of construction. This trend is observed for both the coastal and inner coastal zones (see Figure 6). For the above zones, we found that the highest percentage of corrosion-damaged bridges were built in the years 1973–1980, when the concrete cover thickness required was lowest (see Figure 3). It should be mentioned that the number of NIB girder bridges built in this period in coastal zones was about 60% higher than in the previous period. Such an increase in the production volume of NIB girders could have affected production quality, leading to increased bridge corrosion due to production/installation faults (see Figure 7).

The number of NIB girder bridges in the harsh coastal zone is significantly lower than in the other coastal zones (see Figure 6), but the percentage of bridges with registered corrosion damage is much higher here (82%) than in the coastal and inner coastal zones (51% and 44%, respectively).

Overall, most of the corrosion damage in NIB girders was related to production or installation faults (see Figure 6).

To show the severity of the corrosion damage, the impact of the damage on the bridge performance and/or

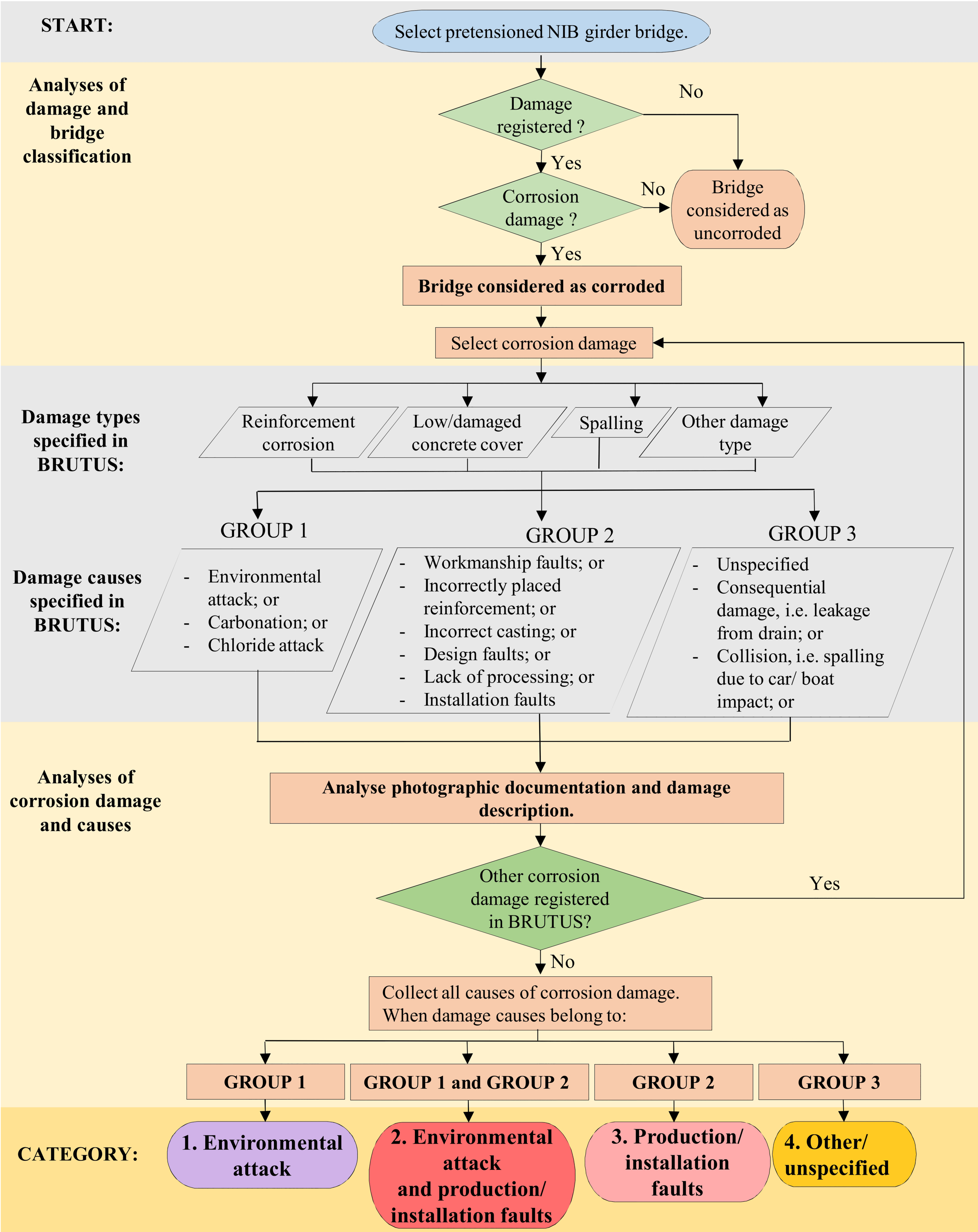


FIGURE 5 Workflow diagram for analyzing data in BRUTUS for pretensioned NIB girder bridge

maintenance registered in BRUTUS[1] was assessed in accordance with the NPRA Handbook for the Inspection of Bridges[2] (see Figure 8). The majority of bridges with damage impacting maintenance costs required repairs within 4–10 years, and about 20% of the corroded NIB girder bridges have little damage and, according to the NPRA handbook,[2] do not require repairs. It should be mentioned that no flexural cracks were reported in BRUTUS[1] for any of the bridges, and only one shear crack was found (in the NIB girder of a bridge located in inner coastal zone).

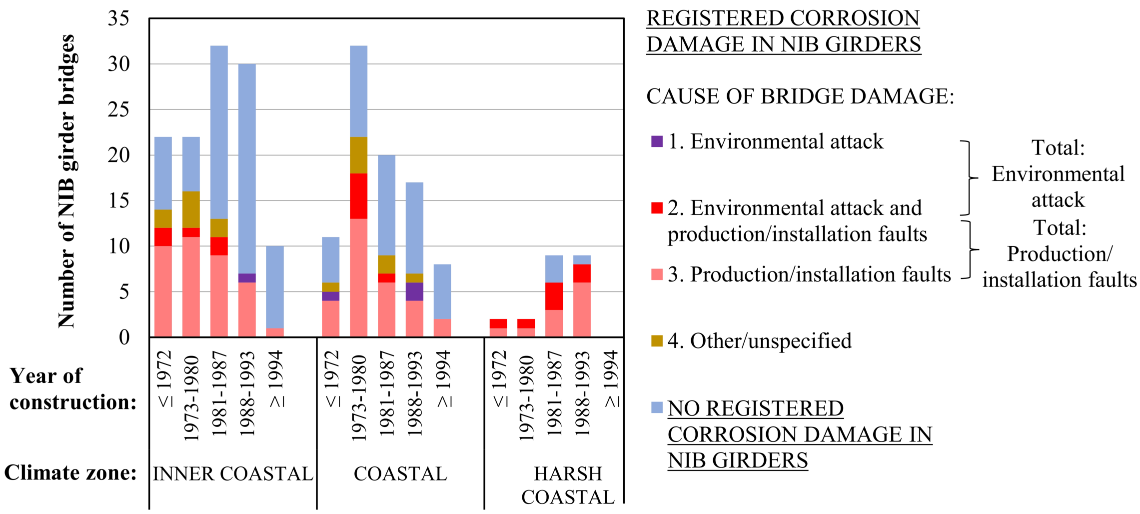


FIGURE 6 Durability status of the NIB girder bridges in Norwegian coastal climate zones. Causes of corrosion damage versus time of construction

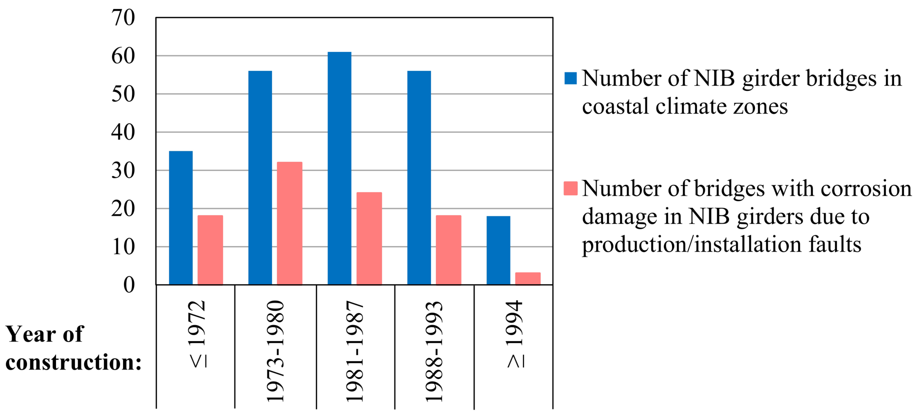


FIGURE 7 The total number of NIB girder bridges and number of bridges with corrosion damage due to production/installation faults versus time of construction

Corroded areas in NIB girders are usually repaired mechanically with sprayed mortar (patch repairs). Nevertheless, the BRUTUS data[1] show that many NIB girders have corrosion cracking in places previously repaired, which suggests this type of treatment is ineffective. Moreover, in pretensioned girders, removal of the concrete cover irreversibly reduces the bond between strands and concrete and can lead to a reduction in the girder's pretensioning.

So far, only 11 Norwegian pretensioned girder bridges have been demolished, of which five had registered corrosion damage in the NIB girders.[1] Ullasund Bridge was demolished after only 27 years in service due to heavy corrosion and ineffective repairs in pretensioned NIB girders.[26]

4.1.1 | Production/installation faults

In corroded NIB girder bridges, the percentage of bridges damaged due to production/installation faults is rather constant over the years (see Figure 9). In uncorroded bridges, it increases the more recent the year of construction. This suggests poor quality production and/or installation of NIB girders and potential damage increase in the coming years.

In each construction period, some 63–86% of the corroded bridges have corrosion damage caused by having less concrete cover in the NIB girders than the minimum required (see Figure 9). This is associated mainly with incorrectly placed reinforcement.[2] In several bridges, the registered local thickness of the concrete cover was less than 10 mm.

Photographic evidence from BRUTUS[1] showed that in 40% of the 85 bridges with corrosion damage due to insufficient concrete cover in the NIB girders, the damage was local to the vertical stirrups (see Figure 10). The loss of stirrup cross section and concrete spalling in the web might decrease the girder's shear capacity. Corrosion damage in the horizontal part of stirrups in the bottom flange does not pose a direct risk of reducing girder capacity, though it may indicate corrosion in the pretensioning strands located just above the shear reinforcement.

Corrosion damage in the top flanges (see Figure 10), is mainly registered in BRUTUS[1] as spalling caused by

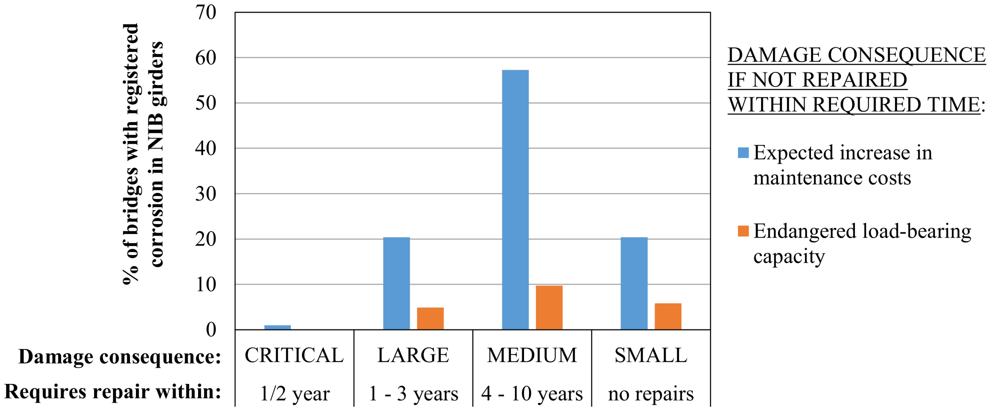
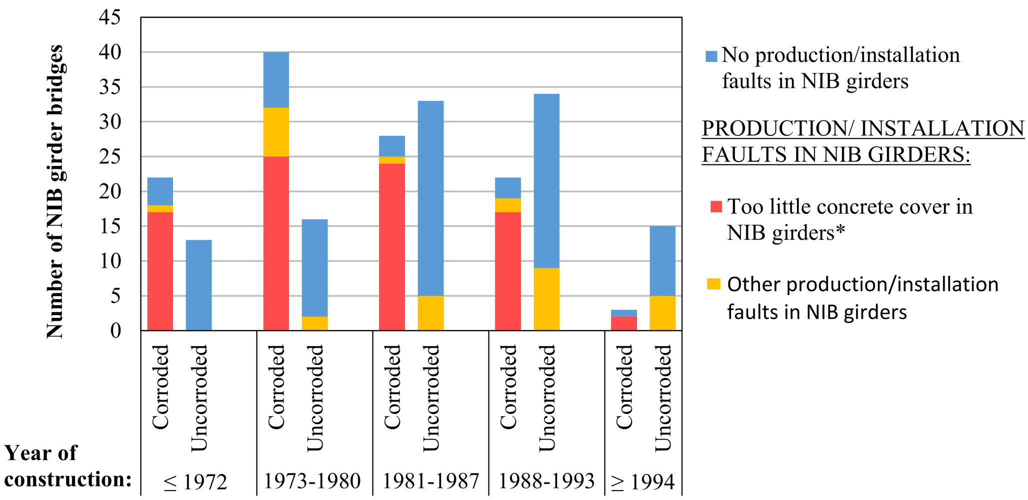


FIGURE 8 Consequences of corrosion damage in pretensioned NIB girder bridges



*sometimes combined with poor quality concrete cover

FIGURE 9 Bridges with NIB girders damaged due to production/installation faults

corrosion of reinforcement with too little cover. However, we found spalling in some bridges without visual corrosion signs, so in some cases the actual cause of top flange damage is uncertain and the influence of other parameters, for example, cyclic freezing and thawing, needs further investigation.

About 16 bridges are registered with little or no concrete cover on the girder-ends, resulting in visible strand corrosion. In a few bridges, especially in the harsh coastal zone, severe corrosion has caused local cracking and spalling of the concrete in the strands' anchorage zone.

The installation faults in Figure 9 are linked to damage specified in BRUTUS[1] as spalling, which occurs due to impacts during the transportation, lifting, or installation of the NIB girders. Typically, spalling damages the concrete cover, which could lead to reinforcement corrosion.

The other production faults in Figure 9 generally relate to poor quality concrete cover. Poor concrete compaction and/or curing conditions led to the formation of rock pockets, honeycombs, porous, and/or cracked concrete cover.[2] Poor compaction might be due to workability problems during casting of concrete that is too stiff (low w/c), especially in the heavily reinforced bottom flanges of the girders. This can result in the formation of macro-voids trapped inside the concrete. Their presence near the steel surface reduces the chloride threshold level,[27] so that reinforcement corrosion might occur faster. Unfortunately, we could not clearly document the influence of poor concrete quality due to insufficient data in BRUTUS.[1]

4.1.2 | Environmental attack

As expected, we found the highest percentage of bridges with corrosion damage due to chloride attack in the harsh coastal zone and the lowest in the inner coastal zone (see Figure 11), which shows the influence of global climate on corrosion vulnerability.

Concrete carbonation rarely occurs in bridges located in a coastal climate,[28] so the number of bridges with corrosion damage caused by carbonation is rather low (see Figure 11).

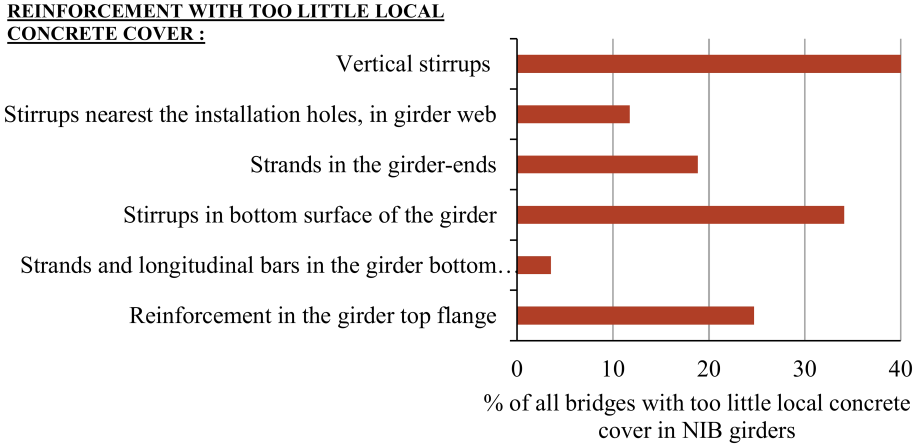


FIGURE 10 Reinforcement registered with too little local concrete cover in NIB girders

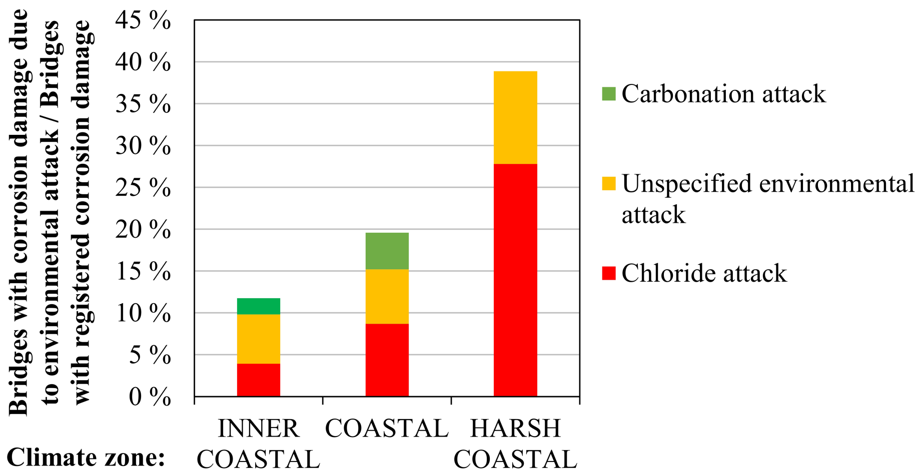


FIGURE 11 Bridges with environment-induced corrosion damage in NIB girders, in the three coastal climate zones

Typically, measured carbonation depth is 5 mm or less and therefore negligible for rebars deeper in the concrete.

The unspecified environmental attacks in coastal climate zones come from chlorides, carbonation, or sulfates, depending on the bridge location, concrete cover thickness, and reported damage type.[2]

4.2 | Results from field investigations

Our inspection of NIB girder bridges revealed corrosion in NIB girders, for both stirrups and pretensioning strands. Most of the damage we saw corresponded well to the damage reported in BRUTUS[1] for these and other bridges. Examples of typical corrosion damage are shown in photos taken on four bridges (see Figure 12). Corrosion of the shear reinforcement with very low concrete cover (0–5 mm) was probably induced by carbonation or an atmospheric exposure. It extended to a considerable length of the bars and along a great part of the girder span (see Figure 12a,b). The remaining ordinary reinforcement with too little concrete cover is probably corroded due to high chloride content. Lack of concrete cover on the NIB girder-ends led to strand corrosion and concrete spalling just behind the support plates (see Figure 12c).

Generally, we found that the concrete cover thickness over the stirrups could differ considerably from the requirements according the valid standards for the design year. For example, the measurements taken on stirrups in Hafrsfjord Bridge girders revealed a cover thickness as low as 40% of the design requirement (see Figure 13a). In Dalselv Bridge, about 77% of measurements detected inadequate cover thickness (see Figure 13b). The concrete cover over pretensioning strands should vary less because they are anchored in fixed positions before casting.

The visual damage caused by chloride-induced corrosion was in localized areas, mostly in the bottom flange of the NIB girders (see Figure 12d–f). The most severe corrosion damage was on the inner NIB girders, typically on the second and third ones from the windward side (see Figure 12d,f). Corrosion stains, cracking, and concrete cover spalling were also seen in the bottom surface of the outermost NIB girders. Moreover, most of the corrosion damage was usually in the girder's support-zones and their close vicinity (see Figure 12d–f). This suggests high corrosion risk in these areas.

FIGURE 12 Typical visual corrosion damage in pretensioned NIB girders (a–i)

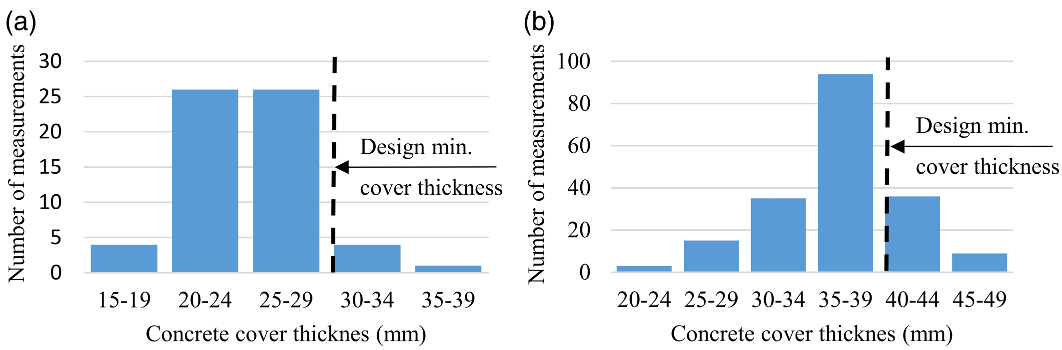


FIGURE 13 Variation in the concrete cover thickness over stirrups in the NIB girder webs. (a) Hafrsfjord Bridge. (b) Dalselv Bridge

In girders produced without additional mounting bars supporting the stirrups, corrosion of the strands closest to the concrete surface produced rather horizontal and relatively short cracks. These cracks followed the location of pre-tensioning reinforcement and were not accompanied by extensive corrosion stains on the concrete surface (e.g., in Hafrsfjord Bridge) (see Figure 12e,g [upper photo]). The concrete cover was removed at several places on selected girders and corrosion on strands and stirrups was detected (see Figure 12g [lower photo]). Moreover, when we removed the concrete cover in areas with no visual signs of corrosion, we still found wide-shaped pitting in some of the stirrups. This means that corrosion can occur in pretensioned NIB girders with little or no sign visible on the concrete surface.

In girders with horizontal mounting bars, corrosion attacks these first (see Figure 12h). The corrosion usually produces two cracks following the location of the bars, and slightly more widespread rust stains on the concrete surface. Nevertheless, the visual damage is still rather local and mostly limited to the girder's support-zones.

In heavily corroded NIB girders, corrosion damage was also found in the girder spans. During the Hafrsfjord Bridge investigation made by NPRA,[29] large amounts of corrosion were detected in stirrups and the bottom layer of strands close to the mid-span location. Some of the wires in the strands were already fractured. Bridge was strengthened with posttensioning system. During our bridge inspection, we found newly formed corrosion-induced cracks in the girder bottom flange close to the mid-span region. The cracks were about 1.5 mm wide and relatively short (about 400 mm).

While investigating Hulvåg Bridge, we found severe corrosion damage on parts of the bridge slab. Corrosion stains were also detected in connections between slabs and top flanges of the NIB girders. Moreover, a large amount of efflorescence was observed on the bottom surface of slabs (see Figure 12i). The efflorescence product (white powder) was investigated by X-Ray diffraction and found to consist mainly of aragonite (a crystal form of calcium carbonate $CaCO_3$), which can form on concrete surfaces in contact with sea water. Although Hulvåg Bridge is located in the harsh coastal zone, with its superstructure close to sea level, the bottom of the superstructure is protected by wooden panels. The presence of sea water could then be explained as leakage from the top of the insufficiently protected deck, which has overflowed during storms, or condensation of moisture built-up behind the wooden panels. This type of efflorescence suggests a high probability of chloride contamination in the slab, as well as carbonation lowering the pH in the concrete pore solution. Both factors favor corrosion initiation and propagation, including the reinforcement providing composite action with the NIB girders.

The corrosion in the slab of Hulvåg Bridge was found by the NPRA in earlier inspections and treated with patch repair (see Figure 12i). During our inspection, we found new large areas in close proximity to the repairs with corroding reinforcement (marked with white lines in Figure 12i). This confirms that repassivated reinforcement in the repaired areas might accelerate corrosion in adjacent, unrepaired places.[30]

5 | DISCUSSION

5.1 | Influence of local and microclimate on corrosion observed during field investigations

The influence of global climate on corrosion is well-documented and supported by this study, with the harsh coastal zone being most aggressive (see Figures 6 and 11).

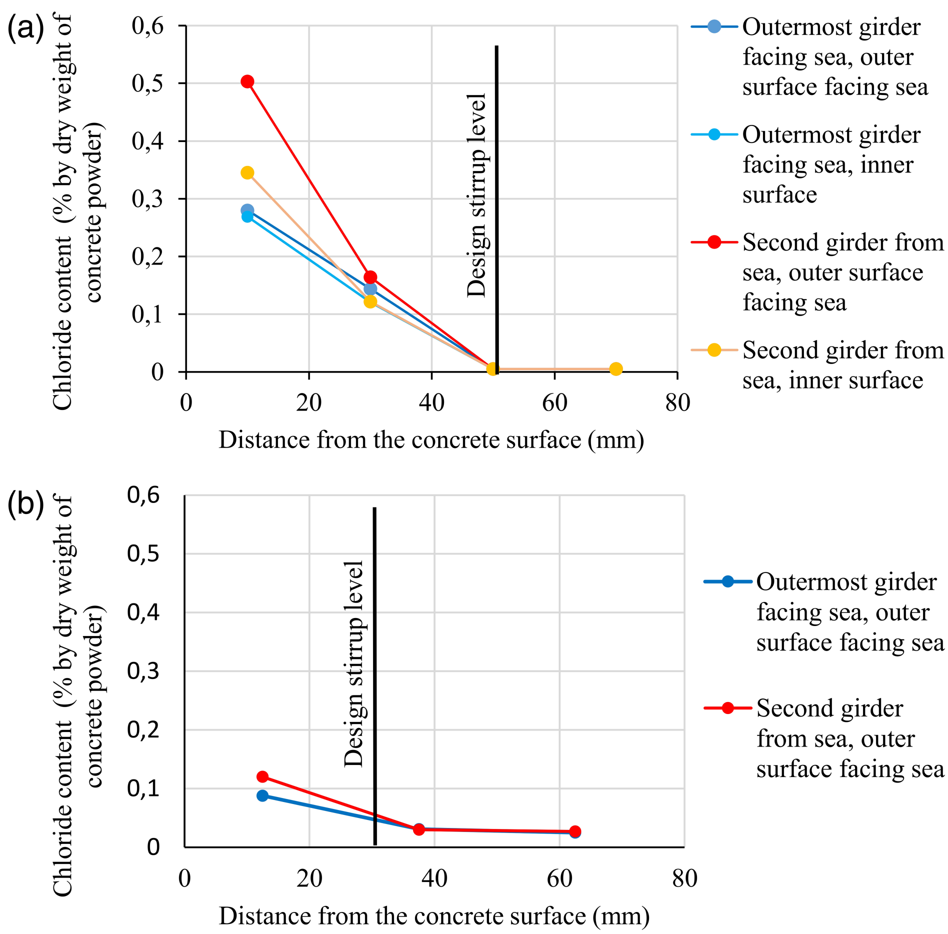


FIGURE 14 Chloride profiles of NIB girder webs of two bridges at different heights above sea level located in the harsh coastal zone.
(a) Hulvåg Bridge: NIB girders at about 5.8 m above sea level.
(b) Hafrsfjord Bridge: NIB girders at about 12.0 m above sea level (based on NPRA data[28])

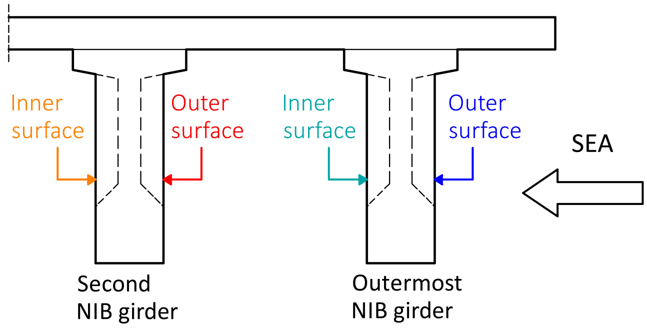


FIGURE 15 Location of chloride samples for the Hulvåg Bridge

The local climate has also been shown to have significant impact on the availability of chlorides and corrosion.

For instance, chloride surface concentrations are well-documented on bridges and quays located in Norway's coastal climate, and they show that chloride concentrations decrease with increasing height above sea level.[31–33] Figure 14 shows an example of a difference in chloride content in NIB girders for bridges in the harsh coastal zone but at different heights above sea level (comparing chloride contents between parts a and b). At Hulvåg Bridge, concrete powder samples for chloride analysis were taken from webs of the outermost and second NIB girder facing the sea, but close to an abutment (see Figure 15). The results were compared with chloride profiles based on data collected by the NPRA from similar locations next to a supporting pillar at Hafrsfjord Bridge.[28] The bridges were of similar age at the time of sampling: Hulvåg with 30 and Hafrsfjord with 29 years of exposure. However, the NIB girders in the Hulvåg Bridge had been coated with hydrophobic paste for the first 13 years, and protect later with wooden panels. Because the hydrophobic surface treatment has proven to have a good effect in slowing chloride ingress, it can be assumed that chloride ingress in Hulvåg Bridge had been considerably reduced over those years. Nevertheless, the chloride content was significantly greater in the Hulvåg Bridge than in Hafrsfjord Bridge (see Figure 14), despite the treatment. This shows that corrosion in NIB girders with the same cover thickness is more likely in bridges less elevated above the sea level, supporting earlier findings on the impact of height above sea level on chloride ingress.

The chloride content at the reinforcement level in Hulvåg Bridge was close to zero, so corrosion is not expected in the NIB girders, which corresponds well to our field observations.

The occurrence of severe corrosion damage in the inner NIB girders can be explained by the varying microclimate across the bridge cross section. Bruce et al.[34] found that variation in chloride profiles between girders may occur due to varying micro exposure. In research on a posttensioned bridge,[33] it was found that chloride contamination was significantly greater on the leeward surfaces, to which chlorides are transported by wind turbulence and underpressure, but cannot be washed away by rain. Chloride levels in 20-year-old prestressed girders[35] were also found to be higher in inner girders, in this case due to traffic-spread chloride-contaminated mist or spray.

In NIB girder bridges located in coastal climate zones, the wind and rain usually comes from the sea and may create low-pressure zones with recirculating airflows (wakes) between girders (see Figure 16). Due to cyclic washing and drying, the sea-facing surfaces of the outermost NIB girders will have lower chloride levels than shielded inner girders where chlorides accumulate. Examples of higher chloride content (as much as 25 mm below the surface) in inner girders are shown in Figure 14a,b.

The reason for corrosion in NIB girders close to support zones is not yet well understood and needs further investigation. Chloride-induced corrosion on girder-ends has been explained by the leakage of chloride-laden water through expansion joints and cracks in the concrete overlay.[36–38] However, because the slabs in the bridges we investigated are continuous over the middle supports and no cracks were observed in the deck surface, other explanations should be investigated.

Varying microclimate close to support zones has been observed in a posttensioned, box-girder bridge.[33,39] The chloride content close to supports at depths 0–10 mm below the concrete surface was 3.5 times higher than in mid-span. Because the height of the bridge superstructure varied along the span, this was explained as due to the size/shape of the surfaces exposed to atmospheric conditions. However, NIB girders have constant cross section height along the span length, so corrosion damage close to the support zones might be associated with wind flow affected by the vertical supports acting as barriers. Turbulent wind flow around pillars and abutments could cause accumulation of moisture and chlorides and therefore increased chloride ingress.

Because the corrosion location strongly depends on both environmental exposure and geometry, we suggest replacing the term "microclimate" with the more descriptive term "Geometry Exposure Interaction" (GEI). Although current standards and design rules do not consider such effects, GEI has shown to have a decisive influence on chloride ingress and corrosion occurrence.

Corrosion of strands in the girder support-zone might also be influenced by possible micro-damage at the steel-concrete interface (SCI), which can occur when strands are released and the prestressed load is transferred by bond stresses to the hardened concrete. Although SCI condition is one of the main parameters affecting the durability and corrosion behavior of reinforced concrete structures,[27,40] the influence of bond-

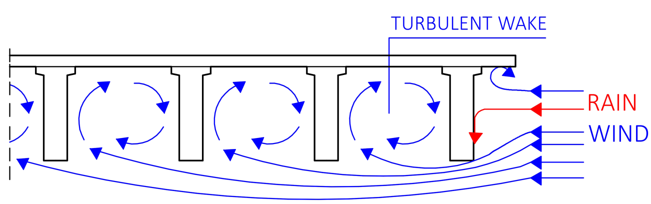


FIGURE 16 Schematic view of wind and rain direction in the NIB bridge cross section

induced damage is challenging to assess and more research is needed, especially in relation to pretensioning strands.

5.2 | Consequences of corrosion

Corrosion of vertical stirrups in the support-zones and their vicinity (caused by both production faults and chlorides) can reduce the shear capacity of the girders and lead to the formation of diagonal shear cracks. Corrosion of strands in the support-zones (propagating from unprotected girder-ends or caused by chlorides) can reduce the bond between concrete and pretensioning reinforcement in the most critical anchorage zone and finally lead to strand slippage. This effect can be even more pronounced for girders designed without additional reinforcement at the level of the pretensioning strands. Corrosion of reinforcement in bridge slab, providing composite action with the NIB girders, might consequently affect the structural performance of NIB girders related to the composite action between girders and slab, and particularly their shear capacity. The shear and anchorage capacity of corroded NIB girders should therefore be carefully evaluated. Corrosion of pretensioning reinforcement outside the support-zone can reduce the flexural capacity of NIB girders. Considering a large amount of strands located close to the concrete surface (see Section 2.2), corrosion outside the support-zone may lead to sudden and brittle failure of the girders in flexure. Effect of corrosion on load bearing capacity and failure mode may be even more pronounced when stirrups are corroded (i.e., due to production faults), hence the flexural and flexural-shear capacity of NIB girders should also be assessed.

The remaining NIB girder capacity can be analyzed with Finite Element Method, including concrete degradation, decreased reinforcement cross section, mechanical properties (mainly ductility) and bond. Nevertheless these parameters depend on corrosion degree, which cannot be deduced from the above observations. Therefore, parametric investigations of corrosion severity and location need to be carried out, with respect to typical damage reported in this study.

6 | CONCLUSIONS AND FURTHER WORK

Using data from the NPRA's Bridge Management System (BRUTUS) and field investigations, we report the durability status of 227 NIB girder bridges in Norway's coastal climate. We found that:

1. Fifty-one percent of these bridges have registered corrosion damage in their NIB girders.
2. The highest percentage of bridges with corrosion-damaged girders was found for bridges built before 1988, probably due to lower requirements for cover thickness than in later standards. This effect is most pronounced for bridges built in the period 1973–1980, when the required cover was only 25 mm, that is, lower than for bridges built before 1973.
3. Most corrosion damage in NIB girders is related to production/installation faults resulting in the inadequate cover thickness registered in 85 of 115 corroded bridges.
4. Girder support-zones are particularly vulnerable for chloride-induced corrosion. This can be explained by the interaction between geometry and exposure, here denoted the GEI effect, a parameter which should be considered in design.
5. Current design principles do not sufficiently differentiate the cover thickness requirements for various global and local climates.
6. The only structural damage observed in any of the NIB girders was one diagonal shear crack in a bridge in the inner coastal zone.
7. Extensive strand corrosion in the girder support-zones can weaken their bond in the most critical prestress-transfer region. Considering also reported corrosion in stirrups and possible loss of the composite action with bridge slabs, the shear and anchorage capacity of the NIB girders might be significantly reduced. This could be even more pronounced in older girders with insufficiently anchored pretensioning reinforcement when installed. Corrosion damage also occurred outside the support-zones, which means that the girders' flexural and flexural-shear capacity should also be evaluated.

NIB girders should be designed and produced more carefully, taking into account the above findings. We also recommend the establishment of more detailed guidelines for the interpretation and determination of damage properties in the BRUTUS database. Despite the large amount of data available in BRUTUS, such analysis cannot be performed automatically.

While investigating NIB girders, particular attention should be paid to girders condition near the support-zones, as well as areas with too low or damaged concrete cover. Because reinforcement corrosion in NIB girders may result in little or no visual signs on concrete surface, it is suggested to systematically carry out detailed inspections for detecting corrosion risk. It is also recommended to revise the cover requirements by providing more detailed principles for varying global and local climate, possibly including GEI parameter.

Further research is needed to assess the extent to which observed local damage influences the bearing capacity of the NIB girders. This could be done by using numerical modeling for parametric study of corrosion variables, mainly its location and degree.

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CONFLICT OF INTERESTS

The authors declare no potential conflict of interests.

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