Received: 31 March 2022 | Revised: 11 June 2022 | Accepted: 27 August 2022

DOI: 10.1002/suco.202200297

fib CEB-FIP WILEY

ARTICLE

Corrosion-induced damages and failures of posttensioned bridges: A literature review

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Funding information
NPRA

Abstract

Corrosion of posttensioned bridges raises great concern, since the only way to safely assess the condition of the tendons is through destructive evaluation. In this scenario, this paper presents the results of an extensive literature review on reported cases of corrosion of posttensioned bridges and few prestressed structures. The aim is to increase knowledge about the structural consequences of possible corrosion-induced failure mechanisms. The cases were rated according to the increasing severity of the observed damage and consequent interventions as follows: ordinary maintenance is effective, extraordinary maintenance is necessary, and maintenance is insufficient or absent. It was found that most corrosion-sensitive structures were segmental and box section beam bridges. Most cases required extraordinary maintenance. Warning signs were often observed. The damage was mainly ascribed to design and execution mistakes that facilitated the ingress of external chlorides causing corrosion. The paper concludes with a discussion of the consequences for structural safety.

KEYWORDS

chlorides, corrosion, deficient grout, failure, literature survey, post-tensioned bridges, warning signs

1 | INTRODUCTION

When a bridge failure occurs, the loss of the structure can result in much greater economic consequences than the value of the asset itself,[1] for example, loss of human lives and traffic disruption problems. Numerous investigations have been conducted to evaluate the health of bridges and the causes of their failure in various countries.

In the period 1977–1981, a study on 150 damaged and collapsed structures around the world was carried out by Hadipriono.[2] More than one-third of the analyzed structures were bridges, the degradation of which was mostly attributable to external events (like lateral impact forces, unexpected live loads) and construction deficiencies

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(e.g., falsework and concreting faults, lack of knowledge in long-term creep and shrinkage effects on concrete).

Forty point eight percentage of the bridges present in the United States in 1988 were rated substandard by the Federal Highway Administration (FHWA).[3] One hundred and fourteen bridges failed in the period 1951–1988,[3] and over 500 bridges failed between 1989 and 2000.[4] The outcome of the investigations was that the most frequent reasons of failure were not due to design and construction fault, but due to accidents (e.g., cars or trucks colliding with the structure) and natural catastrophes like scour, earthquake, flood.[3,4]

In the early 1990s, the American Segmental Bridge Institute (ASBI) promoted a durability survey in the United States and Canada. The inspection included 96 bridges with completion dates ranging from 1966 to 1993, and highlighted that segmental constructions performed well over time.[5]

Another investigation was conducted by the FHWA in 2001, reporting that nearly 30% of bridges in the United States were rated as deficient.[6] Moreover, since 2008 the FHWA has been supporting a research project at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) with the aim of establishing reasonable bridge damage/failure models.[1]

Between 1979 and 1992 the UK Standing Committee on Structural Safety published annual reports, which included reports on suspected deficiencies of grouting of posttensioning tendons. Then, the Highway Agency in 1994 started a significant systematic series of inspections of their bridges. These activities gradually provided evidence of a growing problem with some posttensioned structures.[7]

Between 1995 and 1998, a study on the durability of prestressed concrete bridges was carried out in Switzerland.[8] Some cases of significant corrosion damages were identified. However, the study showed that prestressed concrete bridges generally behave very satisfactorily and fulfill the durability requirements, especially if they are properly maintained.

In Germany, the main part of the bridges was built between the 1960s and the 1980s, when the current knowledge about the durability of structures was not available. Therefore, despite the design lifespan of more than 70 years, bridges showed major damage after a period of 30–40 years.[9]

The results of the investigations summarized above show that bridges in general tend to perform well over time, that is, if accurate durability-based design and appropriate maintenance are conducted, bridges tend to meet their expected service life. Nevertheless, many failures of bridges are also reported, and their causes vary (accidents, natural catastrophes, external events, construction deficiencies, corrosion) and are strongly influenced by the characteristics of the bridge (like its location, environment, age, structural typology). Consequently, each country tends to orient research according to the characteristics and conditions relevant to the bridges in their territory.

In this context, in 2017 the Norwegian Public Road Administration (NPRA) promoted the "Better Bridge Maintenance' research and development program. The aim was to reduce the deterioration of national bridges by finding ways of assessing the state of the structures and identifying the most favorable maintenance methods.

According to the Bridge Management System of the NPRA, concrete bridges constitute the majority of the 18,199 bridges on national and county roads in Norway, and a significant number of them were built with prestressing tendons. Many of the bridges are in or near coastal regions with varying exposure to sea water, while nearly all of them are subject to de-icing salts during the winter. In this chloride-contaminated environment, the risk of corrosion increases, depending on age, exposure, and detailing.[10]

Corrosion (and in general damage) of bridges is very concerning since, in an increasingly connected world, the cost of damaged infrastructures represents a significant part of the gross domestic product (GDP) of a country. It is extremely difficult to estimate the indirect cost of corrosion (e.g., cost of loss of productivity, compensation for causalities and environmental pollution). However, the direct economic cost (i.e., cost of the application, operation, and maintenance of anti-corrosion technologies) is deemed calculable.[11] The global cost of corrosion was first estimated to be 2.5 trillion US dollars (3.4% of GDP) in 2013 by the National Association of Corrosion Engineers (NACE International),[12] but it was also estimated that "savings of between 15 and 35% of the cost of corrosion could be realized"[12] by using available corrosion control practices.

Corrosion is an electrochemical reaction where the steel in direct contact with oxygen (present in the air or dissolved in water) tends to return to its original form (ore) forming iron oxides on the surface (rust).[13] The volume of rust is from two to six times greater than steel,[14] and this causes the development of large tensile stresses in the surrounding concrete area resulting in cracking and spalling of the concrete, which can influence various characteristics such as the mechanical performance and load capacity of the concrete structures.[15] In specific, corrosion induces the loss of bar section, loss of concrete section (due to cracking and spalling), and a reduction of the bond between reinforcement and concrete.[16]

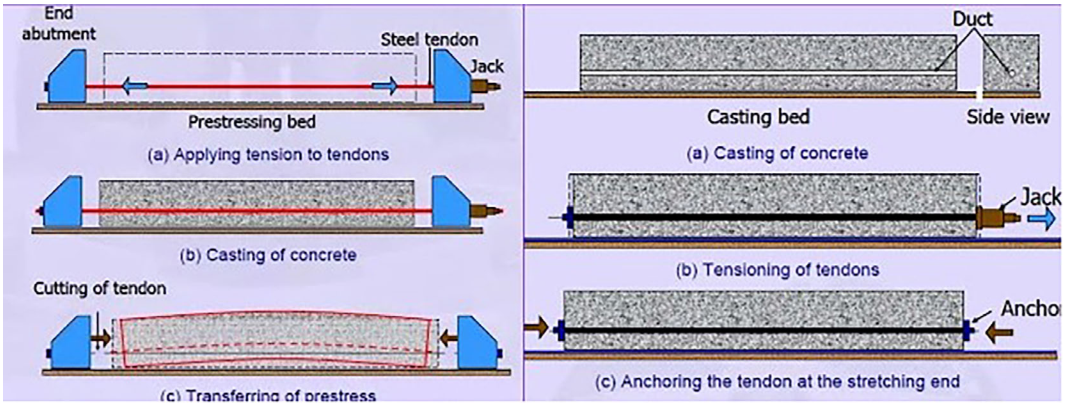

FIGURE 1 Schematic representation of the pretensioning and posttensioning methods.[20] In pretensioning (left side), the tension is applied to the tendons before the casting of the concrete. The prestress is applied to the concrete element through bond between the concrete and the tendons. In posttensioning (right side), the tension is applied to the tendons after the casting of the concrete. The tendons are enclosed in ducts, generally filled with grout after the application of the prestress. Hence, the prestress is applied to the concrete element by means of wedge actions occurring at the anchorages of the tendons, and not by bond

Corrosion can appear with two different morphologies: uniform and localized (pitting) corrosion. Uniform corrosion produces a material loss distributed uniformly over the entire surface of steel exposed to the corrosive environment.[17] It is caused by the carbonation of concrete. Pitting corrosion produces a located material loss on the surface of steel creating small cavities (pits) that leads to an increase in stress concentration.[13] It is caused by chlorides partaking in the electrochemical reaction.[18] The concrete environment initially protects the steel reinforcement acting as a physical barrier with the environment because of the high alkalinity of concrete (pH $\sim$ 12.5), which creates a protective thin film at the surface of the steel bar.[13] Carbonation of concrete produces a decrease of pH in the concrete. The drop in pH at the surface of the steel bar causes the disruption of the protective film and the start of the electrochemical processes of corrosion. The corrosion reaction is accelerated if chloride ions are present. The chlorides react with the protective film, dissolving it locally.[18] Then, the dissolved iron accumulated in the pit reacts with chloride and water producing hydrochloric acid, which further accelerates the reaction.

Pitting attack is recognized as the most severe type of steel corrosion for two reasons. First, the localized nature of attack means that substantial section loss may occur prior to warning signs.[16] Second, pitting corrosion affects not only strength, but also ductility substantially reducing it.[19] This is worrisome since the current design and assessment rules are based on an assurance of adequate ductility that may no longer be applicable under pitting corrosion, and could thus be unsafe.[16]

Corrosion has more severe effects in prestressed structures, where the combination of the prestress with the cross-sectional loss of the strands due to corrosion could enhance the risk of brittle failure.[19]

The two prestressing methods (pretensioning and posttensioning, Figure 1) used worldwide can lead to different strand conditions. In the case of pretensioned bridges, the strands are placed in concrete without ducts. The prestress is hence transmitted through bond between the strands and the concrete. In contrast, strands in posttensioned bridges are located inside ducts. The prestress is hence transmitted by means of wedge actions occurring at the anchorages in the end zones of the concrete element.

The presence of ducts affect the reliability and performance of nondestructive evaluation (NDE) methods developed for ordinary reinforced concrete.[21] In fact, NDE can be used to detect corrosion of strands only if they are enclosed in a nonmetallic duct. Even if NDE methods can also be used to detect voids in the grout (where corrosion usually occurs) regardless of the duct type, the presence of voids does not always imply the presence of corrosion. This means that the only way to safely assess the presence and degree of corrosion in posttensioning strands is through destructive testing (e.g., local removal of concrete and duct), which could compromise the capacity of the bridge. As a result, surveys of posttensioned bridges are often limited to visual inspections. However, corrosion damage in posttensioned elements has been found even in situations where no external indications of the problem were apparent,[22] undermining the reliability of visual inspections.

TABLE 1 Template table of a case study description, including the description of the structure and the characterization of the failure: example for case ID-7[23]

ID-7 Mid-Bay bridge. 1992–1993 (built) – beginning of 2000 (inspection)		
Location: Destin, Florida, USA	**Reference: Venugopalan and Powers (2003)**	
Description	Failure characterization	Notes
• 141 span structure; two-lane undivided highway with shoulders on both sides. • Segmental precast concrete box girders held together by six posttensioning tendons (three on each side). The tendons span eight to nine segments and terminate at a metal trumpet type anchorage assembly. • Each tendon is comprised of 19 spirally wound 5/8 in. diameter seven-wire strands with a grouted 4 in. diameter polyethylene duct.	• Failure of individual wires was primarily due to corrosion and subsequent elevated tensile stress that resulted from the reduced cross-section. • Visual inspection of the tendon ends highlighted the presence of acid corrosion products, meaning active corrosion was ongoing. • Cracking of the polyethylene ducts is extensive, but it has not been a primary cause of tendon corrosion problems. However, if left unrepaired, the cracks will contribute in the long-term to further tendon corrosion.	• Beginning of 2000: replacing of 11 tendons after disclosing of a box girder. • Tendon corrosion associated with grout voids and bleed water is more likely to occur along the inclines rather than horizontal runs. First, since the latter location are at a lower elevation and as such exhibit fewer void. Second, because the incline from which mortar was not pumped should be particularly likely to contain both voids and bleed water.

Since visual inspections convey unreliable information about corrosion of posttensioned bridges, experience from past failures or damage reports may help in performing a better evaluation based on the type of structure, exposure, etc.[1,6] Unfortunately, it is not possible to obtain precise numbers on the incidence of serious corrosion damage in prestressed concrete structures. This is mainly because many cases are not reported and some occurrences of corrosion have not yet been detected.[22] Moreover, past surveys carried out in various countries have mainly studied the overall health of the bridges. Even when the surveys focused on corrosion-induced damage, research was limited in space (i.e., only bridges in a determined area were studied) or to a specific topic (e.g., grouting conditions).

This being the case, the lack of knowledge about corrosion-induced failures and serious damage in posttensioning tendons is alarming, mainly because it is almost impossible to anticipate these kinds of failures.

The main aim of this paper is therefore to present the results of an extensive literature review about corrosion-induced failures of posttensioned bridges conducted by the authors.[23] This paper is meant to be a more approachable and concise summary of the information and comments reported in reference 23, with the aim of reaching more people. Therefore, the details about the structures and the analyses here presented can be found in reference 23, which includes three appendices containing summary tables of the data and pictures collected for each structure in the literature review.

A number of representative posttensioned structures (especially bridges) were investigated considering possible failure mechanisms induced by corrosion in the posttensioned system. The aim was to increase knowledge about the structural consequences of these failures beyond what can be acquired through merely visual inspections. For this purpose, the following problems were addressed:

a. Is there any way to improve visual inspections to assess the development of corrosion in posttensioned structures? In other words, can the presence of warning signs be used to anticipate corrosion-induced failures?
b. How does location (climate conditions, proximity to the sea, or exposure to pollutants) affect the failure?
c. For the different types of posttensioned structures:
   - To what corrosion-induced problem are they most sensitive?
   - How severe is generally the damage when it is detected?

2 | METHODOLOGY

To answer the above questions, a literature survey of corrosion-induced damages and failures in prestressed structures was carried out.[23] The survey consisted in the analysis of all the publicly available documents on the topic to the authors' knowledge (papers and case-studies). A total of 52 cases where corrosion was the only cause or one of the main causes producing the damage or failure, were reported in the reviewed literature and all of them were included in this study. They mostly involved

TABLE 2 Template of summary table containing the most important details for a case study (i.e., structure and tendons description, presence of warning signs, corrosion causes and products, failure mechanism and damage description): example for case ID-7[23]

ID-7 Mid-Bay bridge					
Age at failure: 7 years	**Location: Destin, Florida**		**Prestressing system: External posttension**	**Number of spans: 141**	
Structure description: Segmental precast box girders held together by six posttensioning tendons (three on each side).	Tendon and grout description: Each tendon was constituted by 19 spirally wound 5/8 in. diameter seven-wire strands within a grouted 4 in. diameter polyethylene duct. The center lengths of the tendons were draped downward from the anchorage through deviation blocks along the length of the span.	Warning signs: Cracking of the polyethylene ducts.	Corrosion causes and products: Grout voids, bleed water and soft chalky grout in the affected areas. A variety of factors led to the failures of external tendons, including the penetration of salt water into the external tendons and the preponderance of grout voids. Acid corrosion products.	Failure mechanism: Failure of individual wires primarily due to corrosion and subsequent elevated tensile stresses that resulted from the reduced cross-section of the wires.	Damage description: Tendon corrosion mostly along the inclines, associated with grout voids and bleed water.

posttensioned bridges, but also comprised a few cases of pretensioned bridges and posttensioned structures such as slabs or cylindrical containers. This was done to make it possible to evaluate whether considerations made for structures potentially easier to assess can be applied to posttensioned bridges. The arguments can be listed as:

- Pretensioned bridges can be assessed through NDE methods.
- The assessment of simpler posttensioned structures (i.e., when compared to bridges, with shorter design working life, with smaller dimensions, and subject to smaller loads) such as slabs requires less effort than the assessment of bridges.

To manage and analyze the considerable amount of data systematically, every case was given an identification number (denoted by the symbol ID-xx). Each case was described following the same template table (see Appendix A in reference 23 for all the structures and Table 1 for an example), where characteristics about age, location, structure type, failure mechanism, and failure/damage causes were reported together with additional notes. The information gathered for each case was then summarized in another table (example shown in Table 2, complete data in Appendix B of reference 23) together with relevant keywords for every entry. The keywords were used to make graphical analyses of the case studies (see Section 3).

Finally, the cases were classified according to the increasing severity of the observed damage and consequent interventions. Not all the papers and case-studies consulted during the literature review provided specific information about how the corrosion damage of the tendons was assessed (e.g., mass-loss, cross-sectional loss—for more information see Appendix A in reference 23). Therefore, it was decided not to classify the damage according to the degree of corrosion, but to include in the lowest level all the cases in which, regardless of its severity, corrosion did not cause the failure of the tendons, the collapse of the structure, or the need for its demolition. From lowest to highest, the levels of damage were:

- *Maintenance*. Moderate damage (concrete cracking, concrete cover spalling, loss of tendon cross-section) that needs to be repaired with ordinary maintenance activities.
- *Tendon failure*. The damage included breakage of the tendons, potentially affecting the overall safety of the structure. Extraordinary operations like tendon substitution were necessary.
- *Demolition*. Serious damage affecting the overall safety of the structure and leading to demolition (extraordinary intervention).

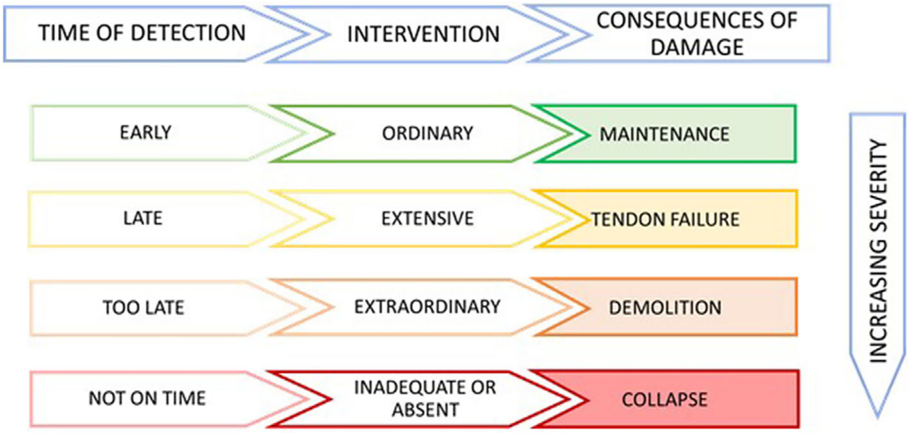

FIGURE 2 Illustration of typical relationships between how early the damage was detected, the typology and suitability of the interventions carried out, and the structural consequences in terms of increasing severity

- *Collapse*. Condition of total or partial collapse due to inadequate or absent interventions, often resulting from absence of warning signs (i.e., no detection of damage).

The adopted classification encapsulates several aspects of the problem into four categories characterized by increasing severity of the observed damage. The names chosen for the categories are not on the same level of evaluation (i.e., "maintenance" and "demolition" are consequences of the damage, while "tendon failure" and "collapse" are different types of damage). Nonetheless, the names have been chosen for their simplicity (useful in the graphical representations of the analyses) and because they are evocative of the level of damage (e.g., a damage associated with the word "maintenance" seems less severe than one associated to "tendon failure"). This system inherently also includes considerations regarding when (and if) the damage was detected and what sort of action it required. Damage could have been detected during planned inspections ("early"), when the damage had severely corrupted parts of the posttension system ("late"), when the damage was so severe that no intervention could save the structure ("too late"), or the damage was not detected in time ("not on time"). Correspondingly, each damage detection time led to intervention that could be classified as "ordinary," "extensive," "extraordinary," and "inadequate or absent." Figure 2 provides an overview of how the adopted classification relates when the damage was detected, what type of intervention was required, and the structural consequence (i.e., level of damage).

3 | RESULTS

This section reports the graphical representations of the data analyzed in this work and pertaining to the 52 case studies identified during the literature review. First, the structures were classified according to their typology. Then, the damage was characterized following the scheme introduced in Figure 2. Finally, the failure and damage causes were identified and investigated.

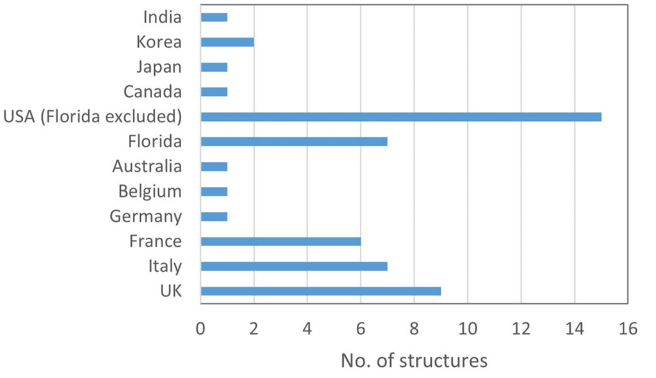

FIGURE 3 Geographical location of the case studies.

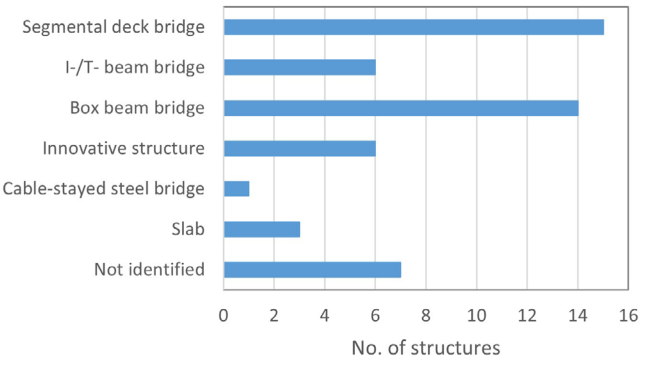

FIGURE 4 Types of studied structures

3.1 | Structure description

The selected structures were located in various countries (Figure 3), often close to the sea or to heavily polluted

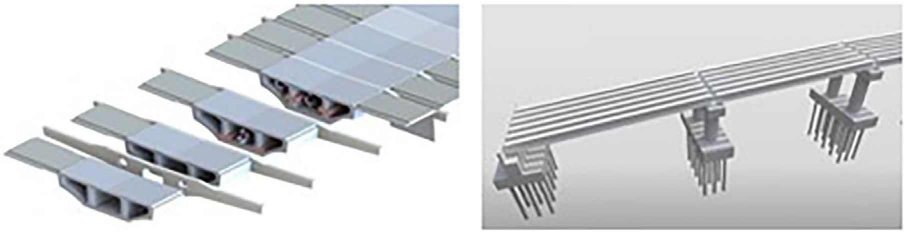

FIGURE 5 Schematic representation of a segmentally mounted bridge[24] (left side) and of a beam bridge[25] (right side). A segmental bridge is made of short transversal segments of the deck, assembled and then kept in place by posttensioned tendons. In a beam bridge, the deck is made by beams supported by an abutment or pillar at each end. The beams can be pretensioned or posttensioned

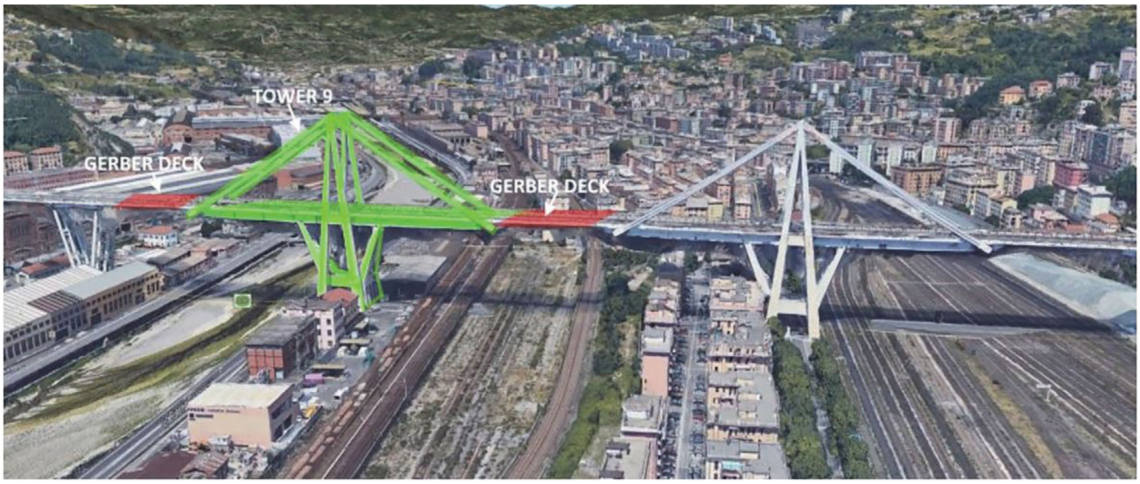

FIGURE 6 Polcevera Bridge, Ligury, Italy.[26] The peculiarity of this bridge consists in the balanced system (in green). The system comprises: the pylons from which two A-shaped structures stand (the tower); the main deck, supported at four locations by the pylons, and with no connection to the tower; four transverse link girders connecting stays and pier trusses to the deck; four concrete cable stays covering two sets of steel cables. The balanced systems are connected by two simply supported Gerber beam spans (in red)

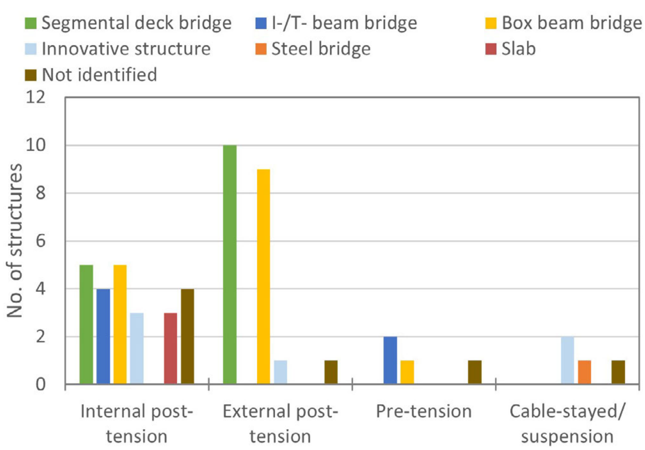

FIGURE 7 Types of studied structures divided by type of prestressing system

environment (more details in Appendix A of reference 23).

The analyses showed that most corrosion-sensitive structures (Figure 4) were segmentally mounted (precast and cast in situ) and box section beam bridges (Figure 5). Some "Innovative structures" were also included in Figure 4. They are structures with a unique design, which has rarely or never been adopted elsewhere (e.g., Polcevera Bridge, Figure 6, and Carpineto Viaduct in Italy, in Ligury and Basilicata, respectively).

The selected structures were also classified according to the type of prestressing system. There were:

- 44 posttensioned structures, of which:
  - 5 internally posttensioned structures different from bridges;
  - 18 internally posttensioned bridges;
  - 21 externally posttensioned bridges.
- 3 pretensioned beam bridges;
- 1 bridge with some pretensioned spans and some post-tensioned spans (F. G. Gardiner Expressway, Toronto, Canada);
- 3 cable-stayed bridges;
- 1 suspension bridge (Williamsburg Bridge, Williamsburg, Virginia, USA).

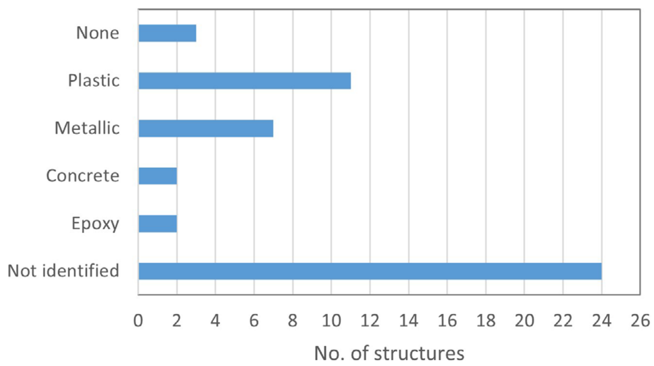

FIGURE 8 Type of ducts in the studied structures. Pretensioned structures are not included in the figure

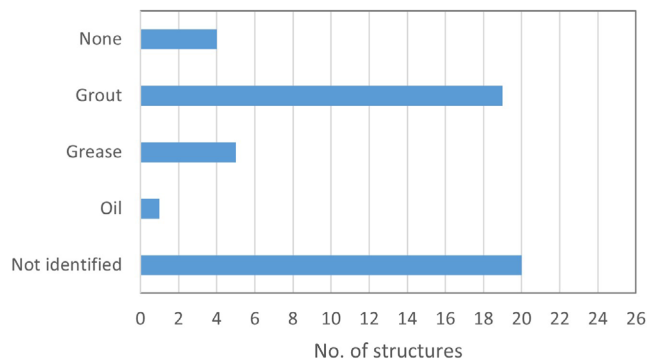

FIGURE 9 Type of duct filling in the studied structures. Pretensioned structures are not included in the figure

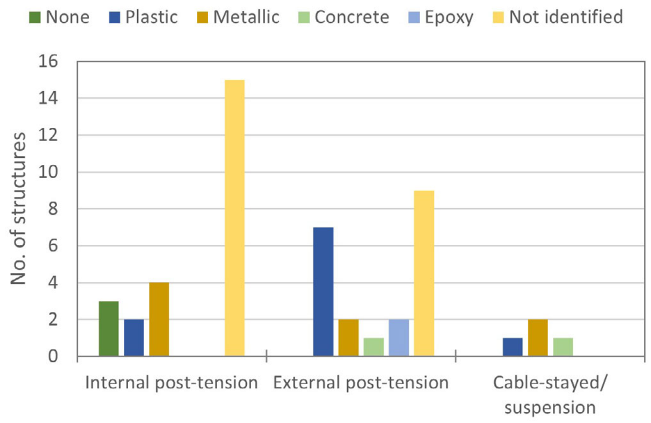

FIGURE 10 Type of ducts in the studied structures divided by type of prestressing system. Pretensioned structures are not included in the figure

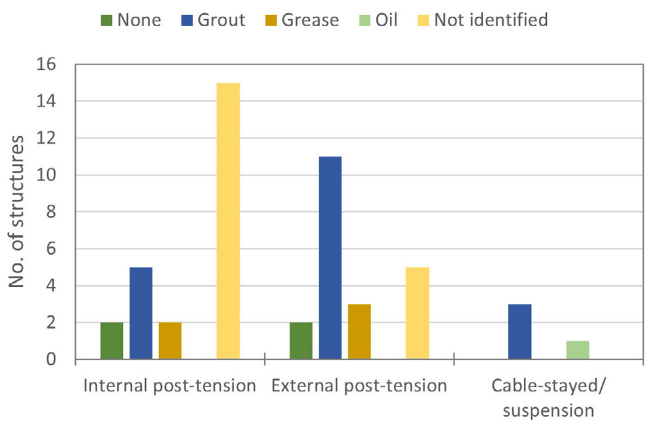

FIGURE 11 Type of duct filling in the studied structures divided by type of prestressing system. Pretensioned structures are not included in the figure.

For each structure, only the most important category was assigned. For example, Polcevera Bridge was a cable-stayed bridge with a posttensioned deck, hence it could have been enlisted as a posttensioned or a cable-stayed bridge. However, since the cables were the ones to fail, it was considered as a cable-stayed bridge. Only F. G. Gardiner Expressway presented failures both in pretensioned and posttensioned spans, so both the categories "pretension" and "posttension" were indicated, considering the bridge twice. This is why, in this paper considerations regarding the type of prestressing are always related to 53 structures instead of 52.

Detailed information about the type of tendons constituting the prestressing systems was found in the literature only for 25 out of 52 cases. Most of them consisted of spirally wound seven-wire strands with diameters ranging between 12 and 20 mm. In some cases, the strands were made with 12, 18, 19, or 27-twisted wires, while in one single case the strands were made of 12 straight wires each of 5 mm diameter.

After describing the types of structures and the types of prestressing system of the studied cases, a relationship between the two categories is shown in Figure 7.

While in pretensioning systems the tendons are bonded directly to the concrete, in posttensioning systems, both internal and external, the tendons are enclosed in ducts generally filled with grout or grease.

Figure 8 and Figure 9 report the types of duct and filling for the studied structures, respectively. These figures do not include pretensioned structures, as they do not have ducts. They also show that in most of the cases, the information included in the reviewed documents were insufficient to determine the type of duct, the type of filling, or both. This explains the existence and the difference in numbers in the entry "not identified" in the figures. Nonetheless, Figure 8 shows that most of the ducts were made of plastic, polyethylene to be precise. There were also a few cases in which the duct was made of precast posttensioned concrete blocks[27] or cast in situ mortar boxes.[24] Figure 9 shows that the majority of duct fillings in this study consisted of cementitious grout.

The type of ducts and duct fillings are related to the type of prestressing system in Figure 10 and Figure 11, respectively. Excluding the “not identified” cases, the figures show that:

- most of the external tendons were enclosed in plastic ducts filled with cementitious grout;
- internally posttensioned tendons were equally enclosed in metallic and plastic ducts filled with grout or were not provided with ducts using alternative solutions (e.g., inflatable ducts removed after grouting[28]).

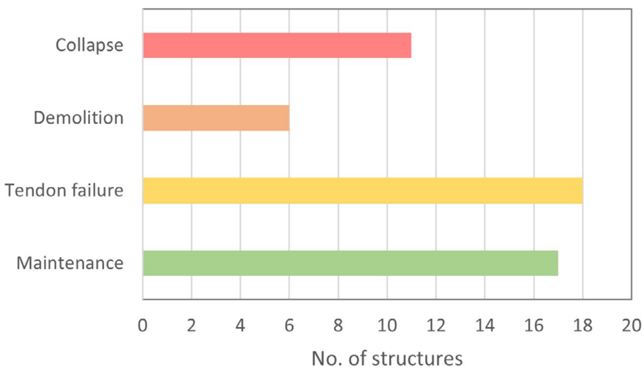

FIGURE 12 Level of damage of the studied structures

3.2 | Damage characterization

The reported cases were classified according to the increasing severity of the observed damage and consequent interventions (Figure 2).

The damage was mostly detected late, yielding to extensive and extraordinary operations like tendon substitution and demolition of the structure. Figure 12 highlights that the number of cases in which the structure could be brought back to safety was also significant. Still

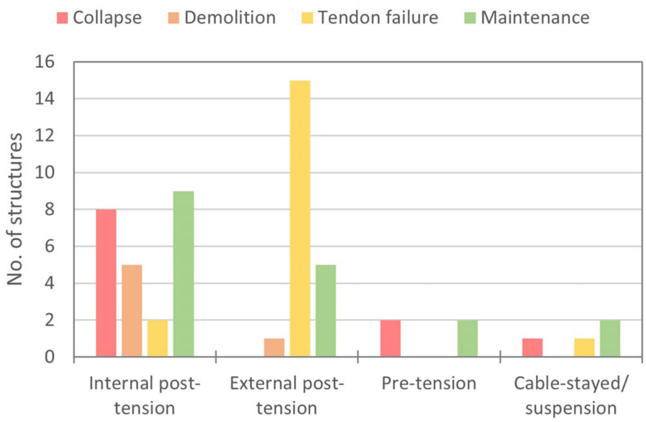

FIGURE 13 Level of damage in the studied structures divided by type of prestressing system

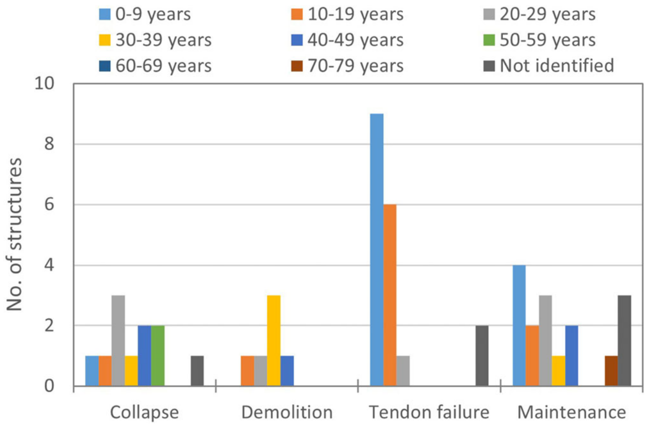

FIGURE 15 Age at damage detection of the studied structures divided by level of damage

FIGURE 14 Warning signs detected in a posttensioned bridge in the Midwest of the USA.[29] Presence of efflorescence, delamination, and spall observed on a posttensioned box girder (left side). Voids and rust at different sections of the tendon (right side)

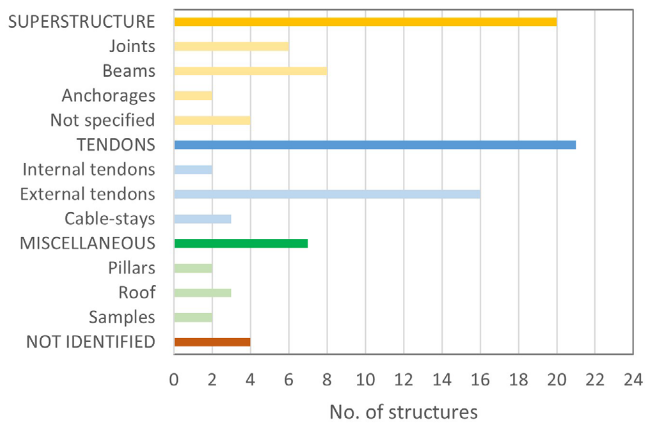

FIGURE 16 Damage location in the studied structures. The locations have been collected in the macrocategories "superstructure," "tendons," "miscellaneous," and "not identified," reported in yellow, blue, green, and brown, respectively. The entries included in the macro-categories, are reported in lighter shades of the color corresponding to the appurtenant macro-category

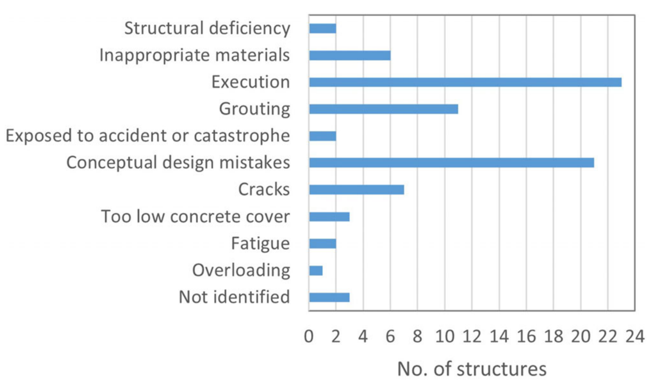

FIGURE 17 Major damage and failure causes of the studied structures

more concerning were the cases in which the collapse of the structure could not be foreseen. As shown in Figure 13, these cases mostly occurred in internally post-tensioned structures. While tendon failures were mostly detected in external posttension systems.

Warning signs such as small and large longitudinal cracks, corrosion staining, concrete cover spalling, were detected in half of the case studies (example of warning signs in Figure 14). For the other half, they were partly not detected or no information about them was reported in the literature. The analyses conducted by the authors[23] indicate that detection of warning signs can help limit and reduce the damage, provided some conditions are fulfilled:

- the damage needs to be detected early enough for the repair measures to be effective;

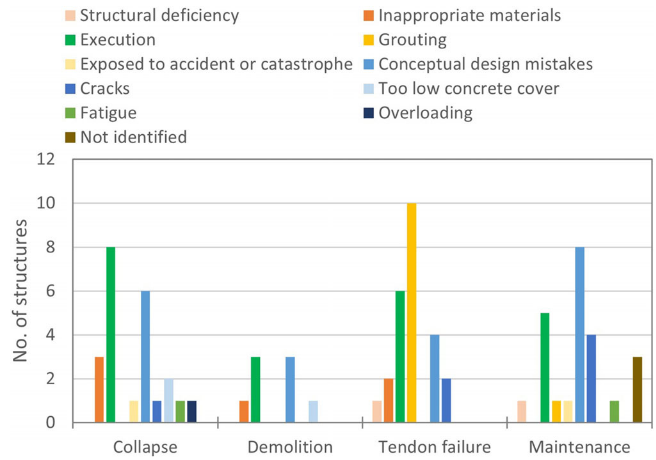

FIGURE 18 Major damage and failure causes of the studied structures divided by level of damage

- maintenance measures should be implemented as planned.

To fulfill the previous conditions, it is necessary to improve not only the frequency, but more importantly the quality of the inspections. In fact, there have been cases where a bridge collapsed even if no worrisome damage was detected during the inspections (e.g., Fossano Bridge[29] collapsed after a positive inspection occurred few hours before the failure). The problem is that, if no warning signs are reported, a bridge is not usually included in the plans for accurate and detailed evaluation. This is why in Figure 2 the first column is named "time of detection" instead of, for example, "frequency of inspections." Nevertheless, in many cases failures such as broken tendons (five cases) or the collapse of the structure (three cases) occurred without warning signs being detected. In some other cases (i.e., two cases of collapsed structures and five cases of tendon failures) presence of warning signs were not reported in the literature. This considerations highlight that the absence of warning signs does not guarantee the safety of the structure.

When it comes to the age at damage detection of the structures, Figure 15 highlights that:

- tendon failures tended to occur during the first years from construction;
- collapses and demolitions occurred mainly 20 years after construction;
- damage needing ordinary maintenance was present during the entire life span of the structures.

A discussion with proposed explanations about the age of the structures and the related damage is included in Section 4.

FIGURE 19 Examples of execution and conceptual design mistakes found in Ynis-y-Gwas bridge.[32] On the left side, void in the centre of a longitudinal tendon, due to execution mistakes. Helical coil was used to space the wires apart in the image. On the right side, cardboard tube across a transverse joint. This represents a conceptual design mistake because the joint (i.e., a region in which the tendons are not protected by the concrete against the external environment) is protected by mere cardboard, which is not even waterproof

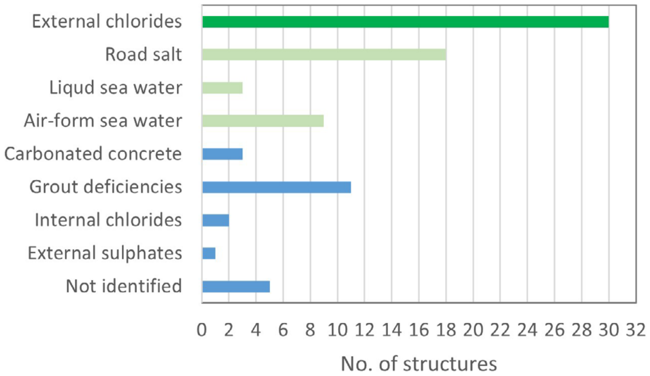

FIGURE 20 Major corrosion causes of the studied structures. The entry "external chlorides" (in green) is the sum of the sub-entries "road salt," "liquid sea water," and "air-form sea water" (in a lighter shade of green). The sub-entries specify the origin of the external chlorides

The locations where the damage associated to the failures was observed are listed in Figure 16. The damage was mainly observed along the tendons and in the bridge superstructure at joints or anchorages, where water could penetrate.

3.3 | Damage and failure causes

All the cases included in this work presented damage and/or failure caused by corrosion alone, or by a combined effect of corrosion and other factors (e.g., overloading, fatigue[13,30]).

Figure 17 presents a list of the major damage and failure causes which created the conditions for corrosion to occur, and their frequency for the case studies. Contrary to previous analyses (concerning, e.g., type of structures, type of ducts, presence of warning signs), this figure includes up to three entries for each structure. This is because past investigations (e.g.,[31]) highlighted how it is unlikely that damage, but especially failure can be caused by one of the insufficiencies alone. In fact, failures are usually the result of a combination of factors that arise over time.

To better understand how the causes produced the observed damage and failure, they are reported in Figure 18, classified according to the level of damage. This figure demonstrates the importance of accurate design and careful execution in preventing failure (Figure 19). It also highlights that tendon failures were caused mostly by grouting problems. This information is valuable because, as previously discussed (Figure 13), tendon failure occurred in almost all the externally post-tensioned bridges included in the survey. This means that those bridges were extremely sensitive to corrosion due to grouting problems, more than to execution or design mistakes.

In addition, Figure 18 shows that cracks have some importance in cases where monitoring and ordinary maintenance could be performed. Cracks can be considered as a result of corrosion (due to the stress generated by the presence of corrosion products with increased volume compared to uncorroded steel). Taking this into account, some studies have also started to use cracks as an indicator for the degradation of bond and load-bearing resistance due to corrosion of reinforcement.[33–35] However, cracks are also a cause of corrosion. This can be considered when cracks are produced not only by design and execution mistakes, but also by various other factors

FIGURE 21 Example of whitish segregated grout embedding corroding strands in an Italian bridge[37]

like for instance, shrinkage and thermal effects. This confirms that corrosion is induced not only by issues in the planning and construction phases, but also by events during the structure's service life.

To cause the chemical reaction called corrosion the presence of determinate elements (namely water, oxygen, and chlorides—this last is not required in case of carbonation-induced corrosion) is needed. In this paper the words "corrosion causes" are used to indicate the sources of the aforementioned elements. Both corrosion causes and damage and failure causes (see Figure 17) contributed to the onset of corrosion in the studied cases. Specifically, damage and failure causes created the conditions (e.g., presence of cracks, weak points) and corrosion causes provided the elements for corrosion to occur (i.e., water, oxygen, chlorides).

Figure 20 lists the major corrosion causes detected in the survey. Only one corrosion cause (i.e., the one that seemed to be the most relevant in enabling corrosion) is associated to each structure. External chlorides, mainly coming from de-icing salts, were the main corrosion cause in the analyzed structures. Other origins of external chlorides were liquid and air-form sea water.

4 | MAJOR CAUSES FOR CORROSION

This section presents the discussion on the results presented in Section 3. The discussion focuses on the two more common and dangerous causes of corrosion encountered in this study: external chlorides penetration and presence of deficient grout.

4.1 | External chlorides penetration

In places with cold climates it is common practice to spread salt on the roads to prevent them from icing. However, chlorides contained in de-icing salts could penetrate inside the structure through pores in the concrete or worse, through openings at joints, anchorages, or tendon deviation points not properly designed or constructed. Moreover, the above reported analysis showed that other sources of external chlorides are sea water in the liquid and air-form state (see Figure 20).

Most of Norwegian bridges are located in coastal regions, and climate in Norway is notoriously cold. Taking this into consideration, the simultaneous presence of both road salt and external chlorides coming from the sea aerosol raises great concern. Even more since chlorides generally induce pitting corrosion. In fact, pitting corrosion creates localized holes and cavities in steel tendons, it is more destructive than uniform corrosion, and results in reduced capacity, especially under repeated loads.[18,19] It is also more difficult to detect, since its occurrence is local, subjecting the tendons to high levels of stress concentration.[36] Therefore, a more detailed analysis on corrosion induced by road salt and external chlorides is needed.

The analyses currently conducted[23] showed that most failures were attributed to design and execution mistakes that facilitated the ingress of external chlorides leading to corrosion damage. Since chlorides usually need time to penetrate the concrete cover, these failures generally occurred after the structure was at least 10 years old. Design mistakes associated with these kinds of failure mostly concerned the inadequacy of the drainage system, the joints, and the position of the ducts' vents or of the anchorages, allowing water infiltrations inside the ducts. On the other hand, execution mistakes induced mainly incorrect grouting operations, which resulted in the presence of voids in the ducts and/or vents not fully sealed.

Consequently, design and execution mistakes resulted in:

- tendons that were not adequately protected by the grout-duct system;
- ducts not adequately protected by concrete in sensitive locations like joints, anchorages, and tendon deviators.

Voids in the duct mean that tendons are surrounded by air instead of grout. Hence, once chlorides penetrate inside the duct, they react with the air and trigger corrosion of the tendons. Since air is lighter than grout, voids tend to be situated at higher locations inside the duct. For this reason, the strands generally corroded more severely along the top and sides.[28]

In pretensioned bridges, the technology to apply prestress forces does not involve the grout-duct system. The absence of this system:

- reduces possible mistakes related to grouting operations;

- makes NDE possible because there is no duct interfering with the evaluation.

However, our analyses confirmed that, as with internally posttensioned bridges, attention needs to be paid to joints, anchorage regions, and other locations sensitive to mistakes in both phases of design and execution in pretensioned bridges as well. In this research only a reduced number of pretensioned cases were explored, so for further detail on durability of pretension structures please refer to other studies, for instance that by Osmolska et al.[10]

4.2 | Presence of deficient grout

The current study showed that in structures that exhibited failure of tendons, corrosion was mostly enabled by problems in the grout. In all these cases, the grout remained unhardened, with a whitish and soft appearance (Figure 21). High pH, low levels of chlorides, and high levels of sulfates were detected inside the chalky grout, while corrosion would manifest as "deep and localized attacks that resembled the form of pitting attacks."[37] It is important to highlight that no corrosion attacks were found in the areas where the tendons were embedded in a regular hardened cement grout.[38]

These grouting problems mean that the usual causes of steel corrosion in concrete (chlorides and/or carbonation) could not be responsible for the corrosion attacks in the prestressing tendons:

- high pH excludes the possibility of carbonation-induced corrosion;
- low levels of chlorides exclude the possibility of pitting corrosion;
- plastic ducts exclude the possibility of water and air infiltration (in the absence of cracks due to design or execution defects).

The typical grout used through the 1990s was made of cement, water, and an expansion agent, and in some cases a gelling agent that made the grout thixotropic[39] (i.e., a property of certain gels and emulsions of becoming fluid when agitated and then setting again when left at rest).

When corrosion of tendons coincided with the presence of voids, the corrosion cause was generally identified as external chlorides penetration through inadequately protected anchorages, grout, and vents. However, in some cases the observed corrosion was due to excessive accumulation of bleed water.[39] Hence, in 1989 the FHWA (United States) commissioned a study to evaluate the performance of grouts for posttensioned bridge structures. The study demonstrated that conventional grout was susceptible to develop significant levels of bleed-water under normal handling conditions. It was also shown that, although the bleed-water eventually dissipated, significant corrosion developed on the strand at the grout-water interface. Moreover, one particular commonly used grout, containing an aluminium based expanding admixture, experienced the highest amounts of bleed-water development and subsequent corrosion.[39]

In France, controls on grouting began in 1995. Laboratory testing in tilted transparent tubes showed a phenomenon of exudation combined with a settlement of the grout. The exudation phenomenon (i.e., the discharge of a liquid or viscous gel-like material through a pore, crack, or opening in the surface of concrete) was amplified by the presence of a superplasticizer. At the end of the test, in the higher part of the tube, a layer of whitish paste topped by a yellowish liquid was produced. The liquid itself was topped by a space filled with air. Mineralogical analyses carried out at the "Laboratoire Central des ponts et chaussées" (LCPC) on the various products reported that[40]:

- The whitish paste, which hardened quickly in contact with the air, was primarily made up of ettringite (40%), portlandite (20%), and calcite (20%). Calcite was coming mainly from the carbonation of the portlandite. The remainder of the paste presented an enrichment in admixtures and sulfates.
- The yellowish liquid presented a composition close to the interstitial solution of a cement paste with a very strong alkalinity (pH of 13.8). This admixture could present in some cases an incompatibility with the cement, causing an instability of the grout during the dormant phase of the set.
- The air was saturated with water (100% of relative humidity).

Under these conditions, combined with the effect of variations in temperature, a pure water condensation could occur. The water would condense either on the interior wall of the duct, or on the parts of the prestressing wires exposed to this air saturated with water, triggering the onset of corrosion. Moreover, the high levels of sulfates detected in the chalky grout might destabilize the growth of the passive film around the steel facilitating its corrosion.

Therefore, under these conditions, the cause of corrosion was identified with the processes of exudation, bleeding, and segregation due to variation in temperature. This leads to rapid formation and diffusion of corrosion, which explains why tendon failures have been reported in the first years from the construction of the structure.

5 | CONCLUDING REMARKS

This paper presents the results of an extensive literature review on reported cases of corrosion of posttensioned tendons in bridges.

The questions raised in Section 1 can be answered based on the review:

a. Detection of warning signs can help limit and reduce the damage, provided that these conditions are fulfilled:
   - the damage needs to be detected early enough for the repair measures to be effective;
   - maintenance measures should be implemented as planned.

   Nevertheless, the absence of warning signs does not guarantee the safety of the structure. An accurate program of inspection and maintenance activities throughout all the life span of the structure is necessary. Particular attention should be paid to the quality, more than to the frequency of the inspections, even in the absence of warning signs. In this regard, the authors suggest developing a classification system for the all the bridges in the network to assess their robustness against tendon failures.

b. Since all the cases with chalky grout problems were observed in places with high-temperature climates (e.g., Florida, Italy), it is the authors' opinion that grouting-induced failures are more probable in locations where temperatures of 30°C are commonly reached. On the other hand, the analyses confirmed that in cold climates the structures are more sensitive to the penetration of external chlorides (mainly coming from de-icing salts).

c. Various types of structures were analyzed in the current work, showing that:
   - Internally posttensioned bridges can show all levels of damage, and that they appear in the superstructure at various locations (joints, anchorages, and other structural details). Warning signs are not always present. On the contrary, damage and failure may occur without showing any warning signs.
   - Internally posttensioned slabs show damage mainly at tendon anchorages.
   - In externally posttensioned bridges, the damage usually consists in failure of external tendons. In cable-stayed/suspension bridges, the damage can be due to the exposure of the external tendons/cables, which carry the main load globally. On the other hand, frequent inspections and easy access mean warning signs are usually observed earlier in external tendons than in internal tendons.
   - In pretensioned bridges, damage mostly involves the superstructure, particularly affecting joints, tendon deviation points, and anchorages.

To conclude, the conducted review[23] showed that pretensioned bridges and internally posttensioned bridges share some similarities related to where the corrosion-induced damage occurs (e.g., joints, tendon anchorages, and deviation points). This observation highlights once more the importance of correct design and execution, especially in these specific locations. In fact, joints, tendon anchorages, and deviation points are known to be vulnerable to corrosion attacks since they represent the place where the continuity of the element is broken. This is particularly true for pretensioned bridges, generally consisting of simply supported precast prestressed beams separated by joints. On the other hand, in case of internally posttensioned bridges the tendons and the ducts continue throughout the joint between two adjacent segments. However, at joint locations we expect voids in the grout due to the grout composition, and corrosion of internal tendons is often associated with voids in the grout.

ACKNOWLEDGMENTS

The present research project was mainly conducted between September and November 2020, at the Department of Structural Engineering at NTNU in Trondheim, Norway. The study was supported by the 5-year research and development program for bridges and ferry quays of steel and concrete "Better Bridge Maintenance," established by the Norwegian Public Road Administration (NPRA) in February 2017.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Menga A, Kanstad T, Cantero D, Bathen L, Hornbostel K, Klausen A. Corrosion-induced damages and failures of posttensioned bridges: A literature review. Structural Concrete. 2022. https://doi.org/10.1002/suco.202200297