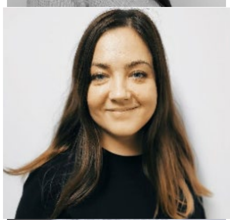
Nordic Concrete Research – Publ. No. NCR 70 – ISSUE 1/ 2024 – Article 6, pp. 99-123

sciendo	Nordic Concrete Federation
	ISSN online 2545-2819 ISSN print 0800-6377
DOI: 10.2478/ncr-2024-0004	Received: March 28, 2024 Revision received: June 20, 2024 Accepted: June 24, 2024

Repair Options for Corrosion-damaged Prestressed Concrete Bridges

Suraksha Sharma, MSc
PhD Student, Department of Structural Engineering, Norwegian University of Science and Technology (NTNU)
Richard Birkelandsvei 1A, Trondheim, Norway
suraksha.sharma@ntnu.no



Magdalena Jadwiga Osmolska, PhD
Senior Engineer, Norwegian Public Roads Administration,
Dr. Hansteins gate 13, 3044 Drammen, Norway
magdalena.osmolska@vegvesen.no

Karla Hornbostel, PhD
Chief Engineer, Norwegian Public Roads Administration &
Adjunct Professor, Department of Structural Engineering, NTNU
Trondheim, Norway
karla.hornbostel@vegvesen.no

Lise Bathen, Cand.Agric.
Senior Principal Engineer, Legislation and Regulatory Authority,
Directorate of Public Roads
Raufossvegen 40, 2821 Gjøvik, Norway
lise.bathen@vegvesen.no

Iveta Novakova, PhD
Researcher, Department of Building, Energy and Material Technology, The Arctic University of Norway
Lodve Langesgate 2, 8514 Narvik, Norway
iveta.novakova@uit.no

Mette Geiker, PhD
Professor, Department of Structural Engineering, NTNU
Richard Birkelandsvei 1A, Trondheim, Norway
mette.geiker@ntnu.no

ABSTRACT
Prestressing of bridges allows construction of long spanned bridges made from thin structural members with high flexural and shear capacity. Studies have shown that some of the existing prestressed bridges are not meeting their designed service life due to corrosion of the tendons. The main reasons are poor construction practices in combination with inadequate inspection and maintenance plans. This paper provides a summary of repair options for corrosion-damaged prestressed concrete structures with focus on the individual components of the prestressed system. The applicability of identified repair options to Norwegian conditions is discussed.

Key words: Prestressed concrete structures, corrosion, repair.

1. INTRODUCTION

According to Norwegian bridge management system [1], the Norwegian transportation infrastructure includes more than 2200 prestressed concrete bridges. Approximately 60% of these are pretensioned (tendons embedded in concrete), while the remaining prestressed bridges are post-tensioned (tendons enclosed in grouted ducts). The first post-tensioned bridge in Norway was built in 1959 and approximately 50% of the bridges are more than 40 years old. As in many other countries, a significant maintenance backlog is observed for Norwegian bridges [2]. Increasingly, the environmental impact (e.g., emissions and use of resources) is a key parameter when planning maintenance of the transportation infrastructure, including comparing the repair of existing structures vs. the construction of new structures. Depending on the overall weighting of the economic, environmental, and social impact of a structure, the decision is likely to vary. Using today's climate gas emission as the only measure, the Norwegian Public Roads Administration (NPRA) recently compared alternatives for maintaining a marine crossing and demonstrated that the repair option with cathodic protection resulted in only 10% of the emissions of a new marine bridge [3]. The gain would most likely be even less considering the structural capacity and differences in expected service life [4].

Recent investigations have shown that both pretensioned bridges and post-tensioned bridges are prone to corrosion [5]. The work presented in this paper is part of an ongoing R&D project connected to the Herøysund Bridge, which is an extensively degraded post-tensioned bridge located in the coastal area of northern Norway [6]. The Herøysund Bridge will during the coming years be replaced by a new bridge. Prior and during the demolition, the bridge will serve for testing of inspection, monitoring, and potential repair methods. Experience from the Herøysund Bridge showed that there is a lack of knowledge and overview concerning suitable repair methods for Norwegian corrosion-damaged prestressed bridges.

The purpose of the present paper is to provide a summary of internationally reported repair options for prestressed systems and to discuss their applicability to Norwegian prestressed bridges. A brief description of common pretensioning and post-tensioning systems used in Norway is given in Section 2. In Sections 3 and 4, the focus is widened to cover internationally reported experiences. Section 3 provides an overview of typical damages observed. Section 4 covers maintenance and repair options for various components of prestressing systems mentioned in technical papers and other literature in English (covering cases worldwide, but mainly Europe and the United States (US)). Section 5 discusses the applicability of the reported repair options for Norwegian bridges. Appendix A provides a list of definitions.

2. PRESTRESSING SYSTEM COMPONENTS AND TYPES IN NORWAY

Prestressing systems are classified by the types of components used, i.e., the prestressed reinforcement, the anchorage type or system, and if present, the couplings, the duct, and the filler material (typically grout), and by the method of prestressing the reinforcement. A list of definitions is provided in Appendix A. This section reviews only pretensioned and grouted internal post-tensioned systems commonly used in Norway. In addition to known issues connected to post-tensioning systems and their components, there are known errors from the building period.

2.1 Post-tensioning systems and their components in Norway

The post-tensioning systems most frequently used in Norway are summarized in Table 1. As a first installation, there are no externally post-tensioned bridges, Table 1 covers only internally post-tensioning systems. The details of each component in the system are described below.

Table 1 – Post-tensioning systems commonly used in Norway. See Appendix A for definitions.

Used in years	Post-tensioning system	Main system components			
		Prestressed reinforcement	Anchorage	Duct	Filler material
~1959 - early 1970's	Dywidag	Single bars	Nut and thread	Corrugated steel sheet	Cement-based grout
Late 1960's	Freyssinet	Parallel wires	Concrete wedge		
Late 1960's – mid 1980's	BBRV	Parallel wires	Button heads		
From 1970's	CCL	Multiple strands	Steel wedges		
From 1980's	VCL	Multiple strands	Steel wedges		
	Dywidag 6815	Multiple strands	Steel wedges		
	Dywidag 6812	Multiple strands	Steel wedges		
	Freyssinet	Multiple strands	Steel wedges		
	BBRV-656	Multiple strands	Steel wedges		

Prestressed reinforcement

In the first generation of post-tensioned bridges, mainly straight, large diameter (ø26 - ø32 mm) bars with threaded ends were used for post-tensioning [1]. These so-called Dywidag bars were made of steel grade St 80/105 (yield strength/ultimate strength in kg/mm^2 corresponding to St 835/1030 in N/mm^2) which was a hot-rolled, initially unalloyed, or low-alloyed steel with a pearlitic structure [7]. Over the years, the composition of the steel used for the Dywidag bars was improved worldwide and alloyed steels of grade St 835/1030 (in N/mm^2) and St 1080/1230 were required by the Norwegian standards [8]. Due to unknown reasons, only grade St 835/1030 (in N/mm^2) was used [1]. It should be mentioned that in addition to using the post-tensioned Dywidag bars as a main longitudinal reinforcement, the post-tensioned bars were occasionally used as a transverse reinforcement in both walls and slabs of bridge box girders, as well as reinforcement of the transverse beams in large bridges [1]. Post-tensioned reinforcement in the form of tendons consisting of parallel wires took over from the late 1960s and was in use until the mid-1980s. This type of reinforcement was part of both the sporadically used Freyssinet system and the often-utilized BBRV post-tensioning system. In the early Freyssinet system, twelve ø8 mm wires were used with steel grade St 135/160 (in kg/mm^2) [1]. The steel grade is similar to the old quenched and tempered steel grade Sigma and Neptun St 145/160 and Henningsdorf St 140/160, which is prone to stress corrosion cracking (SCC) [9, 10]. In the BBRV system, a higher number (from 22 to 72, most commonly 44 [1]) of cold-drawn and smaller diameter (ø6 mm) wires were used. The steel grade varied from St 150/175 (in kg/mm^2) to St 1600/1800 (in N/mm^2). The wires of the BBRV system were fixed on the passive side of the anchorage with cold-formed button heads. From the 1970s, tendons consisting of multistrands gradually replaced singular wires. Each strand typically consists of seven wires, six of which are helically twisted around the central wire. The strands typically have outer diameters of 12.5 or 15.3 mm and were earlier made of steel grade St 170/190 (in kg/mm^2) or St 1700/1900 (in N/mm^2) [11, 12]. Over the years steel grades with higher strength started to be used.

Anchorage and couplers

The type of anchorage used for post-tensioned reinforcement in Norwegian bridges varied depending on the system used. Couplers connect strands in the tendons between casting sections. Their design follows the chosen post-tensioned system. The typical anchorage for the post-tensioned Dywidag bars used in the 1960s and 1970s consisted of a circular steel bearing plate embedded in the concrete and steel nuts used for tightening threaded ends of the bars after tensioning. The anchorage of the Freyssinet post-tensioning system was based on the wedge principle. The anchorage device consisted of a concrete cylinder with a conical hole with corrugations on its surface and a concrete conical wedge carrying grooves on its surface. The ends of steel wires were placed closely around a conical hole. On the tensioned side, all wires were tensioned at the same time, and the conical wedge was pushed into cylinder to grip the wires. Consequently, the wires were anchored by friction forces. After tensioning, the anchor acted on the concrete. In the early BBRV system, wires were anchored individually in one steel anchor or plate by button heads at the end of the wires. The individual strands in the multistrand systems were locked with wedges in one locking steel plate in the anchoring unit.

Duct

The purpose of the duct is to provide a conduit for placing strands in the post-tensioned system and protection from external sources of water, carbon dioxide, and aggressive ions like Cl^- and SO_4^{--}. In Norway, only corrugated ducts have been used, which are manufactured from long, galvanized strips of steel. Until late in the 1990s, a very thin steel was used for duct production, which resulted in little stiffness and poor resistance to breakage during both installation and concrete casting. The ratio between the cross-sectional area of the ducts and tendons in the often used BBRV system was approximately 2.0, which is at the lower limit of today's requirements [13]. However, for bars in the Dywidag system, the ducts' diameter was only about 5 mm larger than the diameter of the bars which left very little space for grouting. In 1997 and 1998, new requirements were introduced in Norway (Norwegian Standards, NS-EN 523:1997 [14], NS-EN 524:1997 [15]) for the resistance to bending and later load, water tightness, or tensile strength of ducts Post Tensioning Institute (PTI) Acceptance Standards for post-tensioning [16]. Consequently, the ducts are expected to have higher quality in bridges built after 1997.

Filler material

The main purpose of the filler material is to prevent corrosion of the tendons. The filler materials shall thus be chemically and physically stable and hinder transport of water and aggressive substances such as Cl^- and SO_4^{--} ions and carbon dioxide. Worldwide cement-based grout, grease, and oil have been used as a common filling material for injection of ducts, whereas in Norway only cement-based grouts have been used until now. The quality of the grout has, however, changed over the years. Until the early 1980s, the grout was made from water, cement, and admixtures controlling expansion and pumpability, but the mixing equipment did not provide sufficient mixing. This resulted in unstable grout with lumps of cement and clogging in the system during grouting. Since 2005 admixtures have contributed to thixotropy and eliminate water separation. From 1982, requirements were introduced for using a colloid mill when mixing grout [17], and the grout quality improved significantly. In 1997, common European standards were introduced and adopted for the quality, production, and testing of grouts (NS-EN 445, NS-EN 446 and NS-EN 447), but these had little significance until 2005 when the thixotropic grouts with high stability were developed. Test methods per NS-EN 445 were used, and a second outlet past the high point of the duct was added. In 2018, the requirement to re-establish grouting pressure 30 min after finalizing grouting was introduced. The procedure was introduced as a reply to extensive failure in filling high points of ducts in a new bridge. Most of the new solutions and innovations for improved post-tensioning are connected to the filling materials, and the technologies for grouting and monitoring during grouting, as prevention of grouting imperfections is a key factor for corrosion related durability of post-tensioned concrete structures.

2.2 Pretensioning systems and their components

Pretensioning systems in existing structural elements of Norwegian bridges consist of mainly the prestressed reinforcement, directly embedded in the concrete without ducts. Since the stress of the individual tendons of the pretensioned system is transferred to the concrete through the bond between the steel and the concrete, no additional anchorage devices are installed. The system has been used in Norway since early 1950s [18] for precast elements of bridge superstructures such as beams and plates. Since 1973 the I-shaped and inverted I-shaped pretensioned precast girders were standardized [19-21]. Design details of the girders in a historic perspective are summarized in [22]. In Norway, seven-wire high-strength steel strands are commonly used for prestressed reinforcement. The strands typically have a diameter of about 12.5-12.7 mm (0.5 inch) and were made of steel St 170/190 (in kg/mm^2) [11, 12]. Until the 1970s single wires with diameter 4 or 5 mm were allowed [23]. Although pretensioned strands are placed in concrete without ducts, some strands in structural elements might be partially unbonded using flexible sheets [11, 12]. This was done to reduce initial bursting cracking, which can occur after prestress release.

2.3 Practice on site

For many years there was a lack of good practice for storage of components on site before installation. It was not uncommon to store the post-tensioned systems on quay without any protection before they were installed. The regulation came in 1981 [24]. Also, until the 1980´s it was common that prestressing was done by the main contractor with less training and knowledge, with jacks sent from the supplier of post-tensioned systems [24]. Regulations from 1981 were the first common requirements for competence to personnel doing this job. Inlets were often not sealed, and water filled up the ducts and froze during wintertime. Several bridge decks were reported with delamination because of this. Practice of mounting spare set of ducts and anchorages often lacked drainage which led to the same freezing issues. The habit of mounting spare sets and leaving them ungrouted was not allowed by regulations that came in 1996 [25].

3. DAMAGES IN PRESTRESSING SYSTEMS

Despite the use of a high protection level in prestressing systems, especially for post-tensioning systems (Section 2), both pretensioned and post-tensioned bridges are found susceptible to damage. Understanding the possible causes of damage in each component of the system is crucial for ensuring the longevity and safety of the prestressed structure when repairing. In this section, the damage in prestressed bridges is discussed component-wise for post-tensioned bridges and with focus on the prestressed reinforcement for pretensioned bridges. It covers findings worldwide as only a few Norwegian cases of severe damage in prestressing systems have been identified. Comments are made where Norwegian practice or experience is available.

3.1 Post-tensioning systems

Prestressed reinforcement
Corrosion of the prestressed reinforcement (usually in the form of strands in post-tensioned bridges) represents the most severe form of damage that can afflict a post-tensioned bridge. Once the strands lose their required tensile strength and ductility, the structural load-bearing capacity of the entire bridge is compromised. According to a recent study conducted by the National Cooperative Highway Research Program (NCHRP), US, corrosion of the strands in post-tensioned bridges is the most significant problem faced by the construction industry [26].

Corrosion of post-tensioned strands inside ducts is a very complex phenomenon which makes it challenging to identify and to establish the acting mechanisms. Several types of corrosion can be witnessed in post-tensioned bridges: (i) As compared to ordinary reinforcement, prestressed reinforcement experiences high stress levels which accelerates pitting corrosion in the strands [27]. (ii) The twisted wire composing the strands makes it susceptible to crevice corrosion at the interface enhancing the risk of brittle failure. (iii) Furthermore, the exit points of post-tensioned tendons are also vulnerable to stray current corrosion. However, though there are very few documented cases of stray-current damage in post-tensioned bridges, the consequence is quite serious [28]. (iv, v) Other forms of damage that occur in post-tensioned strands are hydrogen embrittlement and SCC [29]. The higher the strength of the strand, higher is the susceptibility to hydrogen embrittlement. This increases the risk of potential failure [30]. In hydrogen embrittlement, the ductility of the metal is reduced due to the absorption of hydrogen atoms by the metal, whereas SCC typically occurs after hydrogen embrittlement in the presence of stress [30]. This leads to brittle failure in the steel when the steel is under tensile stress and a corrosive environment [29, 31]. A few cases of SCC and hydrogen embrittlement failures in post-tensioned bridges have been reported. A possible reason for this is that the failures have occurred in conjunction with failures due to other corrosion mechanisms like pitting corrosion [32]. Finally, in general, the large surface-to-volume ratio of prestressing strands further increases its vulnerability to corrosion.

Already during storage and construction, corrosion of the strands might initiate. During storage, failures due to SCC have occurred when strands (made of quenched and tempered steel) were stored in tightly wound coils. Such failures have only been reported in Germany and Japan, not in the US where the use of quenched and tempered steel for strands is not permitted [32]. Also during storage, the strands might come in contact with moisture or harmful contaminants (e.g., fertilizers, chlorides, or animal wastes), which can lead to the initiation of corrosion in the strands, potentially failing already during the stressing process or later in the operation phase [33]. There are known issues from several Norwegian bridges built in the era 1970s and 1980s where post-tensioning components were exposed to heavy weather conditions on site before installation. During construction, the time for finalizing the grouting procedure has been found important. As per PTI, US M55, the time limit is 7 days in an aggressive environment and 40 days in a non-aggressive environment. Investigations have shown that if grouting was performed beyond the time limits moderate corrosion with shallow pitting was visible in the strands but only when free water was present in the closed duct [34]. In addition, if the vents are not sealed after grouting it may cause water and water-borne contaminants to enter the tendons leading to the onset of corrosion [35]. In Norway, where the winter spans 4-6 months, ducts can in contrast be left ungrouted until the temperature rises above 5°C [36]. During this period, the ungrouted tendon shall be sealed properly at the ends and have closed vents, open drains, and the ducts shall be ventilated with pressurized dry air every two weeks. After the grouting is performed, checked, and accepted, the vents shall be sealed.

Anchorage and couplers

The anchorage and couplers are another common area of damage witnessed in post-tensioned bridges. Galvanic interactions can be exacerbated due to dissimilar metallic components in the anchorage zone, e.g., if incompatible materials for duct couplers and fittings are used. Also, galvanic interaction between metal ducts and anchorages lead to an increase in macro-cell corrosion in the region [30]. Poor sealing of anchorages is another factor that can result in defects in post-tensioned tendons [26, 37]. Improper grouting, resulting in voids around the anchorage region causes onset of corrosion of the anchorage and strands in the vicinity, potentially causing cracking and spalling of the surrounding concrete [38, 39]. In addition, cracking of the pour backs surrounding the anchorages can lead to intrusion of moisture in the anchorage leading to corrosion [26]. Anchors located below expansion joints and exterior member ends are especially prone to excess moisture and chlorides making them susceptible to corrosion [40]. In the US, issues with anchorage corrosion were first identified in 1971, when the damage in the anchorage blocks was observed on the old Skyway Bridge, Florida, (built in 1986) [26]. In 2000, intrusion of seawater in the anchorage zone at the top of piers led to corrosion [29]. In the Niles Channel Bridge, Florida, (built in 1983) [38] presence of voids due to bleeding in the anchor head allowed saltwater from ocean spray to ingress and cause severe corrosion of the anchorage. In Norway, there are known issues from several bridges built in the era of the 1970s and 1980s, with blocked grouting because of segregation and separation in the grout, specifically around anchorages and in couplers.

Ducts

Various incidents of corrosion of the strands have occurred due to the failure of ducts: (i) In an investigation led by Lau et al. it was found that the use of galvanised metallic ducts led to severe corrosion of the ducts which allowed ingress of aggressive ions initiating corrosion of the strands [41]. (ii) In 2012 several metallic ducts used in the Wonderwood Bridge, Florida, were investigated and were found to be severely affected by chloride-induced corrosion from chloride intrusion in the surrounding concrete [26]. (iii) In Norway, several cases of pinched metallic ducts were observed in bridges built during the 1970s and 1980s leading to issues during grouting. In addition, the vents were found to be unsealed for a certain period even after the traffic was opened. (iv) Another concern with metallic ducts is hydrogen embrittlement, and many countries have prohibited the use of galvanized ducts, despite a lack of evidence [29]. Already realizing the potential problems in 1996, the United Kingdom (UK) made encapsulation of strands in plastic ducts compulsory [42, 43]. This not only solved the concern of corrosion of ducts itself but also prevented stray current corrosion of tendons [43]. However, the utilization of low-quality plastic ducts can also introduce other issues, such as duct cracking and splitting. This problem was observed in Florida: investigations revealed that the use of brittle polyethylene ducts resulted in duct cracking, allowing the ingress of aggressive ions to post-tensioned strands [44].

Filler material

Poor grouting is frequently cited as a significant factor in causing damage to bridges, a finding substantiated by numerous case studies in the past [37]. Both detection and repair of deficient grouting are quite a challenge as the defects are potentially distributed over the entire length of ducts and are difficult to localize. Probable locations of corrosion in components of post-tensioned bridges due to insufficient grouting and the use of inferior materials are shown in Figure 1. In case of cement-based grout, prior to the year 2000, grouting issues were mostly associated with the presence of voids in grouts due to entrapped air, settlement of the grout in the duct, segregation, and formation of bleed water, and poor grouting practices in general. It should be noted that the presence of voids alone does not enhance corrosion, for significant corrosion to occur the humidity in the duct should be above 75% [45]. In general, voids are located at deflected ducts [46], higher locations inside the duct [5], and at high-point tendon anchors [43, 45] see Figure 1.

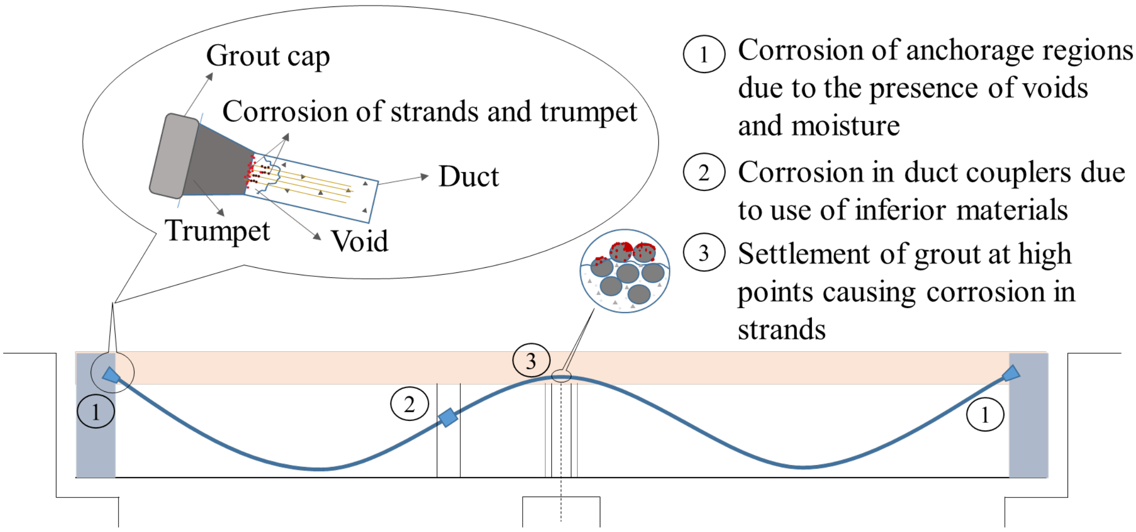


Figure 1 – Probable location of damages in internal post-tensioned tendons due to insufficient grouting and/or use of inferior materials.

Several bridges around the world have faced serious impacts, for instance, the unexpected collapse of YNS-Y-GWAS bridge (built in 1953), Wales in 1985 [46]. The main factors for corrosion were the ingress of chlorides from de-icing salts due to delamination of the waterproofing material used on the decks and high chloride levels in the dune sand used for the construction. Additional factors were poor grouting practices leading to partially filled ducts [46]. There have been other cases in parts of Europe, the US, and Asia in which improper grouting practices in combination with the use of inferior materials have contributed to severe corrosion in the tendons. [37, 38, 45, 47, 48] In the early 2000s, prepackaged thixotropic grout (zero bleed) was introduced in the US [49]. However, case studies have shown that the use of these grout led to issues such as chemically deficient grout with elevated levels of SO_4^{--} and Cl^- ions [41] and segregation of the grout into layers differing in physical appearance (soft and hardened grout) [50-52]. Only cement-based grouts have been used for Norwegian post-tensioned bridges. For several bridges built in the era of the 1970s and 1980s, there are known issues of blocked grouting caused by segregation and separation of the grout.

Due to cases of inadequate protection of prestressed reinforcement by cement-based grouts, flexible fillers such as wax, gel or grease started gaining the interest of researchers as an alternative [53]. However, until now worldwide use of flexible fillers is limited and it is quite difficult to judge their performance to date mainly due to sensitivity towards temperature during the application phase [53]. In France, wax has been used as a flexible filler in external tendons since 1999 [48] and no corrosion-related issues have been reported so far [37]. In the UK between 1970 and 2000, ten bridges used flexible fillers and reported issues of leakages [37]. In the US and Asia, the widespread adoption of flexible fillers is yet not evident in post-tensioned bridge construction. So far, it has not been used in internal tendons in any countries due to uneven transfer of stress and inability to maintain the structural capacity of the structure [54]. Hence, if these issues can be resolved, flexible fillers can be a good option in terms of both corrosion protection and easier repair, if needed [54]. They seem to be the best option for external tendons so far [54].

3.2 Pretensioning systems

Maintaining the designed level of prestress in the pretensioned elements is ensured not only by the amount of prestressing steel, but also by its sufficient bond to the concrete. Severe corrosion of prestressing strands or wires, and ordinary reinforcement placed near strands often leads to extensive cracking of the concrete cover, which reduces the bond between prestressing reinforcement and concrete, and consequently the prestress of the elements. Although the focus of this study is corrosion of the prestressing reinforcement, the impact on the concrete and ordinary reinforcement in pretensioned girders needs to be discussed.

Corrosion damage in pretensioned bridge girders was investigated in the field, both internationally [55-58] and in Norway [22]. The causes of corrosion damage in Norwegian bridges were found to be related to deficiencies in design (old girders), production or installation faults, and an aggressive exposure [22]. A majority of corrosion damage in the I-shaped pretensioned girders of bridges across the US was found in their end regions caused by chlorides from de-icing salts leaking through the bridge expansion joints or cracks in the concrete [58, 59]. Corrosion of strands and spalling of concrete corners in the bottom flange just behind the supports of pretensioned I-shaped girders [60] and severe corrosion of strands and stirrups in the girder support zone [61] were observed. Such damage may have an impact on the shear and anchorage-shear capacity.

In pretensioned I-shaped bridge girders in Norwegian coastal climates, corrosion was also found in the girder support-zones and their vicinities [22], despite continuous and crack-free bridge decks. The vulnerability of the girder support-zones to chloride induced corrosion was explained by the geometry and exposure conditions. The most severe corrosion damage with longitudinal cracking and spalling was found in the bottom and top flanges (where strands are also placed) as well as webs of the inner girders. Also, the corrosion damage extended in the shear span, which affects the shear capacity of the girders, particularly once corrosion cracking reduces the bond between strands [62]. In addition to damages in the shear zone, corrosion of exposed strands at the ends of girders was frequently reported for older bridges. This was related to lack of requirements for protecting end surfaces in pretensioned girders of bridges built until the late 1980s [22]. Damage was rather localized to the area behind and over supporting plates.

Additional design issues for older bridges are lower requirements for concrete cover thickness. The highest percentage of bridges with corrosion damaged girders in Norway was found for bridges built before 1988, and in particularly in the period 1973–1980, when the required cover was only 25 mm [22]. Similar conclusions were made in the study on pretensioned girder bridges in Japan's coastal climate [57]. Except low design concrete covers, corrosion damage due to inadequate cover thickness (often less than 10 mm) from production faults was also reported [22]. Those faults typically spread over the larger portion of the span. In Norway corrosion damage due to low concrete cover mainly affect the stirrups in the web and bottom flange rather than strands placed deeper in the concrete, but two coastal bridges were reported with severe corrosion and multiple strands breakage in several beams and locations along the span: the later strengthened Hafrsfjord bridge [22] and the Ullasund Bridge decommissioned after 27 years of service [63]. Extensive and severe chloride induced corrosion of strands along the span was also reported in New Zealand [64] and Japan [65]. Corrosion in and near the mid-span region reduces girder's flexural and flexural-shear capacity.

4. MAINTENANCE AND REPAIR OF PRESTRESSING SYSTEMS

This section describes findings worldwide as Norway has little experience with repair of prestressed bridges. Comments are made where Norwegian practice or experience is relevant. It should be noted that external post-tensioning is not common practice in Norway and is only used as a strengthening method.

4.1 Post-tensioning systems

Tendons are an integral structural part of a post-tensioned bridge. Besides structural considerations, the appropriate repair of a tendon depends on the cause, type, and location of the damage, the type of tendon (internal or external), the accessibility to anchorage and tendons, and other factors such as the availability of specialized personnel with specialized knowledge and training in the field, equipment, budget, traffic, and time constraints.

Various standards, guidelines, and manuals have been published to facilitate the repair of post-tensioned systems: for the repair of defective grout and ducts [29, 42, 52, 66-68], flexible fillers [32], and for strengthening of post-tensioned bridges and replacement of tendons [35, 48, 68-70], [48] being a State-of-the-Art report. Suggested repair methods for damaged tendon components in internally and externally post-tensioned bridges are listed in Table 2 and Table 3, respectively along with the case studies where the method has been applied. In the following sections, the applicability of the methods suggested for each tendon component is discussed.

Consideration should be given before any repair as it can lead to further damage or even failure, putting both the repair team and users of the structure at risk. Also, due to the limitations of inspection methods, the actual extent of damage will only be visible or detectable during repair.

Table 2 – Repair methods for damaged tendon components in internally post-tensioned bridges.

Component	Material	Damage / mechanism	Repair method	Standards, guidelines, manuals etc.	Bridge
Prestressed reinforcement	High strength steel	Loss of material and compromised structural capacity (corr.)	Strengthening or replacement (only for tendons placed in slabs)	[32, 48, 59, 69, 70]	1) 2)
Anchorage	Metallic	Lightly corroded	Mechanical cleaning	[52]	
		Damaged pour back	Grout cap, epoxy grout and elastomeric coat		3)
Duct	Metallic	Loss of material (corr.)	Remove corroded duct and apply hydraulic cem. grout mortar	[52]	
	Non-metallic	Cracking	Welding		
Filler material	Cement-based grout	Voids	Vacuum grouting Pressure vacuum grout. Corr. inhibiting solution	[29, 42, 52, 66-68] [48]	4)
		Segregated grout (soft, chalky grout)	Drying + corrosion inhib. Hydro-demolition		4) 5)

Note 1: Great Naab Bridge (Bavaria), Bridge Ponte De Fives (France) [69], Wonderwood Connector Bridge (Florida) [26], Sawasokogawa Bridge (Japan) [71]. Note 2: Sawasokogawa Bridge (Japan) [71], Plymouth Avenue Bridge (Minnesota) [26]. Note 3: Plymouth Avenue Bridge (Minnesota) [26]. Note 4: Wonderwood Connector Bridge (Florida) [26]. Note 5: Veteran's Glass Skyway (Ohio) [26].

Repair of prestressed reinforcement

Undamaged strands are vital for the structural integrity of the post-tensioned element and the structure in terms of both safety and functionality. Identified methods for repair of post-tensioned reinforcement include strengthening (both passive and active), replacement of tendons, and addition of new members [28, 32, 69]. No feasible repair strategies can effectively restore the reinforcement cross-section that has been compromised by corrosion [39]. In passive strengthening, the member strength is enhanced without imposing additional stress, whereas in active method, the structure is actively stressed.

Table 3 – Repair methods for damaged tendon components in externally post-tensioned bridges.

Component	Material	Damage / mechanism	Repair method	Standards, guidelines, manuals, etc.	Bridge
Prestressed reinforcement	High strength steel	Loss of material and compromised structural capacity (corr.)	Replacement or strengthening	[32, 35, 48, 68-70]	6) 7)
Anchorage	Metallic	Severely corroded	Replacement	[52]	
		Damaged pour back	Grout cap, cem. grout and elastomeric coat		8)
Duct	Non-metallic	Cracking	Wrapping or half shell (permanent) Taping (temporary)	[48, 52]	8)
Filler Material	Cement-based grout	Voids	Vacuum grouting Vacuum-pressure grouting Corr. inhibiting solution	[29, 52, 66-68] [48]	9) 10) 11)
		Segregated grout (soft, chalky grout)	Drying + corrosion inhib Hydro-demolition		
	Flexible filler	Moisture inflicted grease	Dry-gas purge and regrease Injecting urethane	[32]	

Note 6: Mid Bay Bridge (Florida) [72], James B. Edwards Bridge: I-526 (South Carolina), Varina-Enon Bridge (Virginia) [26]. Note 7: Bridge W18 [69]. Note 8: Mid Bay Bridge [72]. Note 9: Mid Bay Bridge [72], Varina-Enon Bridge [26]. Note 10: Sunshine Skyway Bridge (Florida) [73]. Note 11: I-95/I-295 Interchange (Florida).

Passive method includes bonded reinforcement (using steel plates or fiber-reinforced polymers (FRP)) [32]. Active methods include installing external post-tensioning, cable stays and preflexing. Strengthening enhances the structural performance of the bridge. *fib* Bulletin 103 [70] describes preferred materials for strengthening. Materials like steel wire ropes and prestressing steel wire ropes were found suitable by Dai *et al*. [74]. To mitigate potential future corrosion-related challenges, several studies have explored the implementation of additional prestressing using FRP materials such as carbon fiber-reinforced polymers (CFRP). These materials provide similar strength as steel without the risk of corrosion [75]. In addition, FRP (in the form of both bars and sheets) adds less weight to the structure and maintains the original sectional properties of the members but has limited fire resistance. The strengthening methods are chosen according to the type of damages and condition of the bridge, type of bridge (bonded and unbonded), type of bridge structure, availability of space and clearance in the bridge, and available repair budget.

In case of damaged internal tendons, external post-tensioning is preferred because drilling an additional longitudinal or transverse duct inside an existing structure is nearly impossible. External post-tensioning is generally appropriate for box girders, slab structures, and I girder bridges [26, 69, 70]. The major execution steps during external post-tensioning are preparation of existing concrete, installation of deviator and concrete anchorage block, and duct welding followed by tensioning and duct filling [70]. While preparing the existing concrete, issues related to additional anchorages and tendon profiles can also be addressed as per [69]. A detailed description can be found in [48, 70]. However, for post-tensioned slab decks, there have been cases where the entire member or the internal tendons are replaced when prestressing force is lost due to severely corroded tendon [26, 71]. For instance, in Sawasokogawa bridge, Japan, due to the presence of severely corroded post-tensioned tendons in the slabs, lying over the intermediate piers, the entire slabs were replaced and the bridge was externally post-tensioned [71].

In case of severe damage, externally bonded or unbonded tendons can be replaced [43]. The procedure is initiated by de-tensioning of the tendons if residual force exists. This should be carefully planned and executed by specialists because the sudden release of energy during the process may lead to severe injury [43]. De-tensioning is conducted either by clamping [48], cutting, or burning of the strands [76] and the procedures for carrying out the methods are provided in detail in respective references. After de-tensioning, the tendon is pulled and removed from deviators and anchorages. Previously, bonded external tendons passed through rigid steel pipes embedded in the diaphragm and deviators [76]. As the ducts were connected to the steel pipes it was difficult to pull out the tendons from the deviators and in some cases, special jacks were used to pull the strands through the anchorages [28]. While dealing with tendons having anchor plates at joints, it is crucial to exercise extreme caution as these tendons can be challenging to remove. Tendon replacement is much simpler for the later developed double envelop concept, where the external tendons are not bonded to the concrete along the length of the tendon [76]. After removing the corroded tendon, the new tendon is placed and re-tensioned. For a detailed description of the replacement method for bonded and unbonded external tendons, [35] is referred to. Replacing the external tendons was not addressed in the US before 1988, but in France, the concept of "double duct" existed decades ago which allowed replacement of tendons with less effort [77]. Countries like Germany and Japan also have mandatory criteria for replaceable external tendons [76].

Repair of anchorage
Repair of anchorage includes repair of pour backs, grout caps, and voids around the anchorage or replacement of the entire anchorage system along with the entire tendon. Case study of Mid Bay bridge, Florida, and Plymouth Avenue bridge, Minnesota, provided the methods for repair of pour backs at anchorage [72]. During inspection, a hammer can be used to inspect the region. If a hollow response is given or corrosion is observed in the vicinity, the pour back material is removed and fitted with a non-metallic grout cap and filled with cementitious grout [72] or epoxy grout pour backs [26]. Then it is covered with waterproof/elastomeric coating [52]. Moreover, the voids can be repaired as mentioned in the repair for filler material. In case of severely corroded anchorage and strands, replacement of the entire tendon is carried out.

Repair of duct
Ducts are the first line of defence for the strands, so cracks or corrosion of ducts increase the probability of corrosion of the strands. The method of repair selected for damaged ducts depends on the material of the duct and the condition of the strands. For permanent repairs, in case of non-metallic ducts used in external tendons, wrapping is performed on the ducts using heat shrink wrap or sleeve method [52, 72, 78]. Non-metallic and metallic half shells are also used depending on the location of the repair [48]. Whereas, for permanent repair of internal tendons, for non-metallic, a new piece of the same material as of the duct of appropriate size is taken and welded on the existing duct [52]. However, for metallic ducts, the corroded part of the duct is to be removed and hydraulic cement grout mortar of approved quality is to be applied covering the exposed uncorroded strands. If the strands in external tendons are found to be corroded during inspection, temporary repairs by taping are opted. The detailed procedure for both permanent and temporary repairs for the restoration of the entire tendon has been mentioned in [52].

Repair of filler material
Repair of incorrectly filled ducts should be given utmost priority to maintain safety, integrity, and load-bearing capacity of the structure. Repair options for filler material depend on the type of filler material (cement-based grout or flexible fillers) existing inside the duct.

For cement-based grout, the appropriate repair procedure depends on the characteristics of the detected damage and its location as well as possible air leakage in the ducts. Voids present in ducts filled with cement-based grout can be repaired by pressure grouting, vacuum grouting, and pressure-vacuum grouting [73, 79]. According to Vorspann System Losinger (VSL) Report 5, voids (length <1m) can be repaired using Tremie grouting whereas voids (length >1m) are repaired using vacuum grouting [43]. In Minnesota, several bridges underwent pressure grouting repair to address small voids (around 1-4 litres in size), as well as larger void regions where duct air leakage occurred and in cases where excessive vacuum pressure was unbearable for the tendons as detailed in [80]. Based on recent investigations on economic viability, effectiveness in filling voids, and ease of implementation, the Federal Highway Administration, US, recommended pressure-vacuum grouting [33, 66, 79]. However, issues were raised when a tendon of Varina Enon Bridge, Virginia, failed (corrosion on the interface of new and old grout) already 3-4 years after repair [26]. Some argued that the corrosion in the strands accelerated due to disparities between properties of existing and new grout, others stated it was due to exposure of strands to oxygen and moisture during pressure-vacuum grouting [81], while some suggested the corrosive bleed water present at the location would have caused failure regardless [82]. Due to these uncertainties, galvanic anodes have also been used in new repair projects [83]. In Europe, polymer grouts have also been used to fill voids in cement-based grout [28].

For protecting corroded strands due to the presence of corrosive bleed water, defective and chloride-contaminated grout, and voids inside the duct, impregnation of corrosion inhibitor along the length of the tendon has shown good results in the lab [84]. The method uses interstitial spaces between the wires of each strand to disseminate the corrosion inhibitor (silicon hydrocarbon polymer) to the surrounding grout which forms a film to improve corrosion and moisture resistance [84]. The method was tested on tendons from the Ringling and I-4 Connector bridges, and also on various bridges and buildings across the US and UK [85]. However, for most of the in-situ repairs, limited information on the long-term performance is available. Additionally, a method patented by PDM/ATEAV which injects calcium nitrite solution by using an ultrasonic transducer has been used in Belgium and Luxembourg since 1994 to protect the corroded strands due to grout problems [86].

For the repair of soft grout (see list of definitions in Appendix A), Hamilton *et al*. carried out lab-tests on two remedial techniques; removal of soft grout by hydro-demolition method and drying of the soft grout [87]. Drying of soft grout was found to be more effective than hydro-demolition [87]. In the field, it can be preferred when the application of water pressure becomes impractical due to severe corrosion damage [26]. However, it was also observed that drying of soft grout with atmospheric air caused corrosion of strands and carbonation of adjacent grout, hence it was suggested to use it in combination with corrosion inhibitor [26, 87]. There are also cases where the soft grout was removed by hydro-demolition and replaced by epoxy covered with sand [26]. The methods can be chosen according to the situation of the strands in the field.

Repair methods that can be employed for moisture-inflicted greased tendons are according to ACI 222.2 [32] either a dry-gas purge in combination with regreasing or injection of low-viscosity urethane. Both methods were developed in Canada in the 1990's and have been used since [32]. In the dry-gas purge method, dry gas is injected into the system to purge free water from the tendon until the full length of the tendon is dry followed by regreasing to improve the corrosion resistance. In the latter method, urethane is injected inside the duct and water is simultaneously pressed out through the duct. Urethane forms a solid closed-cell foam protecting the strands [32].

4.2 Pretensioning systems

Based on typical damage areas in pretensioned bridge girders the methods for repairing corrosion damage are subdivided into methods for i) repairing girder end-zones and ii) repairing corrosion damage to prestressing strands in and near the mid-part of the span. Typically, methods used for repairing RC beams are also recommended for repairing pretensioned girders. However, long-term field experience is scarce.

Repair of end-zones
The commonly used method for girders rehabilitation, including girder end-zones, is epoxy sealing of cracks followed by patch repair of any loose or spalled concrete. If needed, patch repairs are also recommended prior to more advanced retrofitting techniques such as FRP wrapping [88].

Traditionally, mortar and ordinary concrete are used for restoring the original cross-section of the girders, despite it often provides poor protection against chloride ingress [89] and spall over time due to shrinkage and weak bond to the base concrete [88, 90]. As an alternative, low shrinkage or expansive grouts, special (fast-setting) mortar and concrete or epoxy are used [88], but none of those materials alone restore the girder strength [90, 91] e.g. because of weak bonds and cracks development in the mortar patches above bearing plates [91]. The application of Ultra-High Performance Concrete (UHPC) and High Early Strength Concrete (HESC) as alternative patch repair materials of a higher strength was discussed and tested on artificially damaged bulb-tee C-shaped pretensioned beams from Iowa Department of Transportation [90]. Part of the concrete up to the reinforcement level in both the web and bottom flange near the support of the girder was saw-cut to imitate concrete delamination due to corrosion. Full-scale tests for girders repaired with both concretes showed good bonding to the beam during loading and unloading, proving the method is promising for repairing damaged girder end-zones. Consequently, further field tests were recommended on both practical applications and strengthening abilities of UHPC and HESC.

Except for restoring the original cross-section of girders, patch repair with shotcrete method was expanded for building up concrete blocks on severely corroded ends of pretensioned girders in Nebraska and Minnesota, US [88, 92]. The failure of the method was reported in terms of concrete cracking and spalling in the end-blocks just 3-4 years after repair. The repair allowed, however, restoration of the shear capacity of girders despite some cracking and delamination in the girder's web [89, 92]. Overall long-term performance of patch repairs in pretensioned concrete girders was also questioned in another study [89], even for low-permeability concretes. Additionally, it has been identified that corrosion problems may occur over time within the strands' interior due to chloride ions trapped between wires and not removed prior to repair.

For retrofitting end-zones of pretensioned girders the repair with CFRP wrappings was studied [91, 93]. The vertically applied CFRP laminates together with quick set mortar repair were tested on five AASHTO (American Association of State Highway and Transportation) prestressed girders extracted with end-region damage simulated by removing the concrete cover from web and bottom flange [91]. The method was found successful for restoring or even enhancing both the shear capacity and ductility of undamaged girders. On the contrary, CFRP fabrics of a lower strength, applied in both horizontal and vertical directions on the AASHTO prestressed girders being in service, were effective only in restraining movements in the horizontal direction while having no effects on vertical deflections [93]. Comparison between the effectiveness of CFRP sheets, glass fibre sheets, and surface-mounted vertical rods for repairing damaged girder end-zones was tested on three pre-cracked AASHTO prestressed girders [61]. The highest percentage in regaining the stiffness was found for CFRP repair, while glass fibre solution was more effective in strength recovery. Overall surface mounted rods were the most effective, but this method requires access to the top plate of the girder, which is normally not possible for girders in service.

Repair of mid-span areas

A majority of the studies on rehabilitation or retrofit in the mid-span areas of pretensioned girders concern damages caused by vehicle impact [88]. Those damages are very localized. For repairing strands corroded at multiple locations along the girder, certain methods are not suitable, e.g. splicing fractured strands [28]. Additionally, only few methods were investigated or tested on pretensioned girders with corrosion damage. However, successfully applied methods on corroded RC girders and pretensioned girders damaged with vehicle impact, are included in this review.

Similar to corrosion damage in girder end-zones, concrete rehabilitation with patch materials is used to restore concrete cross-section. Prior to placing patching material pre-loading is usually done by loading the bridge over the damaged girder [88]. Selection of the materials is the same as described for the repair of end-zones, but FRP wrapping is often provided after mechanical repairs to confine patches and prevent their potential spalling [88]. The retrofitting of pretensioned girders can be applied with passive (non-prestressed) methods, which allow for restoration of the girder's strength, or with active methods which even allow for increase in flexural strength. The retrofitting methods, both passive with CFRP strips, CFRP fabric and near-surface mounted CFRP, and active such as prestressed CFRP, post-tensioned CFRP, strand splicing, and external steel post-tensioning were reviewed in previous studies [94, 95]. Authors stated that passive repair methods are more ductile than active ones, and maximizing an active repair for a girder is not ideal. Another review [96] also mentioned a decrease in ductility with the amount of FRP strengthening, consequently limiting the use of high amounts of FRP. Limitations of the application of the above methods were also pointed out regarding girders' shape [94, 95]. In addition, it was concluded that replacing the pretensioned girder is more appropriate once 25% of the strands are ineffective.

Retrofitting of the corroded pretensioned girders with non-prestressed CFRP sheets was tested on fully-scale T-shaped beams with one pretensioned strand artificially corroded in the mid-section [97]. It was found that CFRP repair was effective in restoring the load-bearing capacity of corroded pretensioned beams and increasing the beam stiffness compared to unrepaired beam. However, the reduction in beam ductility could not have been reversed. The study was then extended to include fatigue behaviour [98]. It was found that unlike for the 10% corrosion level, the fatigue resistance of the beams with 5% of corrosion and repaired with CFRP sheets was restored to the level of the non-corroded beams.

External post-tensioned strengthening with steel bars or CFRP stripes was found to be limited by the residual capacity of the un-strengthened girder [88]. Therefore, it is considered a temporary repair in Iowa, US. Prestressed mechanically-fastened FRPs were recently used successfully as a temporary retrofit of pretensioned C-channel beams of three bridges in North Carolina, US [99]. The method allowed for extending the bridge service life by more than 23 months and was recommended also for core slab sections. Application of this method to other girder cross-sections or as a long-term solution has not been tested yet. Traditional external post-tensioning is, however, a common method for retrofitting bridges, and it was used in Norway for strengthening one pretensioned bridge with severely damaged strands [22].

Applicability of cathodic protection

Cathodic protection (CP) is widely used for limiting further corrosion in conventionally reinforced concrete structures [82]. Previously, the use of CP on prestressed concrete structures was not recommended [28]. The limitations for the use of cathodic protection include the risk of hydrogen embrittlement in prestressed steel and uncertainty of the protective effect due to shielding by the duct on post-tensioned tendons [28] and by layers of ordinary steel reinforcement on pre-tensioned tendons [100]. According to NCHRP 140, experiments and studies showed the feasibility of cathodic protection of ordinary reinforcement in prestressed structures without harming the tendons at normal operating conditions [28]. Recent studies have demonstrated the applicability of cathodic protection to slow down or prevent ongoing corrosion of pre-tensioned tendons [101]. In a sacrificial anode system, as the working potential is low, the possibility of hydrogen development is lowered. There are several cases where the system was found effective in arresting corrosion [101]. Similarly, there are also cases, where impressed current cathodic protection has been employed to arrest chloride induced corrosion in pre-tensioned bridge by obtaining uniform polarization in the member of the structure [82]. According to COST 534 [82], CP can be implemented on prestressed structures to reduce or stop corrosion. However, the potential in the structure should be monitored. The potentials should meet the criteria specified in EN-12696:2000 [102]. Notably, the report indicates that the corroded tendons inside the post-tensioned system cannot be protected with this method [82]. But more recent studies have shown that the use of sacrificial anodes inside the post-tensioned duct can be an option to protect the corroded strands inside the duct [83]. However, the method and the repair projects on which the system has been applied have not been provided in detail in the document.

5. APPLICABILITY OF REPAIR OPTIONS FOR NORWEGIAN SYSTEMS

Reported damages of prestressed bridges in Norway are mainly related to strand corrosion close to supports in pre-tensioned, prefabricated beam-bridges in marine exposure. Other damages are related to execution faults and low requirements for concrete cover thickness before 1989. An overview of damages and their causes can be found in [22] and are summarized in Section 3. Per today, just a few damages of the prestressing system of post-tension bridges in Norway are known. Reported damages are partly related to local leakages in combination with wrongly placed tendons, ungrouted ducts, or heavily exposed bridges with high chloride load in combination with fairly low cover depths of ducts. Such damages are often found in combination with ongoing rehabilitation projects, mainly unintended. There are few known cases of heavily corroding post-tensioning systems as those of Herøysund Bridge [5]. For this particular bridge, none of the above-mentioned reasons are obvious causes to the damage found. The ducts have voids, but there are no obvious leakage or ingress of chlorides and the tested chloride content in the grout is low.

Regarding worldwide reported damages and failures of post-tensioned bridges, it is reasonable to assume that also bridges in Norway can potentially have more damage than we are aware of today. To sharpen the focus of inspection of post-tensioned bridges, the NPRA has worked for several years on establishing inspection procedures and routines for these bridge types [103]. Today NPRA has methods describing the inspection of both pre- and post-tensioned bridges in its regulations [104].

So far, the only applied repair method in case of corrosion-damaged prestressed bridges in Norway is strengthening with external retrofitting methods. For Herøysund Bridge carbon fibre laminates in the main span were used to secure functionality and safety until replacing the bridge. In other cases, external tendons were used to secure the load-bearing capacity, also internal strengthening with new construction principles were tried. Retrofitting methods are mainly used in cases where damage is implying the load-bearing capacity of the structure. In other cases, where only local damages are observed, the common procedure is to verify the load-bearing capacity of the structure in case of loss of the specific single cable, assuming all other cables are well functioning. In case of sufficient redundancy in the system, the damaged cable is disregarded (considered no longer in function). Accordingly, little focus is given to the repair method.

Following an enhanced inspection regime of prestressed bridges, it is important that suitable repair methods are established and applicable. Based on the literature review presented in Section 4, there are several methods available to repair the different prestressed components in case of damage, not only to better secure load-bearing capacity but also to maintain good robustness of structures. Considering the common practice of designing and building prestressed bridges in Norway (see Section 2) certain repair methods according to Section 4 might be suitable for use, and are addressed in this section.

5.1 Potential repair options for post-tensioned bridges in Norway

In Norway, the main post-tensioned system for bridge superstructures used is based on embedded metal ducts with cementitious grouted strands. Accordingly, methods applicable to this kind of system are relevant. There are examples of rock anchors where oil or grease is used, however, this is outside the scope of this paper.

As pointed out in Section 4.1, no method can effectively restore the reinforcement cross-section. Thus, in case of loss of cross-section of prestressed reinforcement, replacing the tendons or external strengthening methods are applicable solutions. Replacing tendons is however unlikely in Norway due to the complexity of the operation. This option may only be possible for ungrouted tendons. In this case, anchorage zones must be excavated and the specific tendon and anchorage must be replaced. One may also check whether empty reserve-ducts are placed in the bridge which can be used to replace damaged tendons temporarily or permanently. Empty reserve-ducts can only be found for bridges built before 1996, as today's requirement demands filling empty ducts at the end of the building period (see also Section 2). Where replacing damaged tendons is not feasible the only option is external strengthening, methods and guidelines are available [48, 69, 70]. There is limited experience with retrofitting of post-tensioned bridges.

Anchorage zones are cast in concrete. After stressing, the wedge plate in the anchorage zone is closed with a grout cap to seal the anchorage before grouting. When grouting is finalized, and the result is accepted, the whole area is supposed to be closed with a cast-on. Due to that reason, they are normally not accessible for inspection. However, for bridges with missing or damaged cast-on, and where local leakages or outer exposure conditions have led to damages in the anchor zones, the methods described in Section 4.1 (Repair of anchorage) may be applicable.

Metallic ducts are prone to corrosion in cases where external exposure can lead to the penetration of e.g., chlorides or carbonation. To ensure a long service life of the tendons it is advisable to repair any duct parts observed with damages. Repairs should be applied immediately after observation to avoid any further damage of the tendon. To avoid subsequent corrosion in a chloride environment one might consider removing the part of the corroded duct, cleaning, and applying hydraulic cement mortar over the exposed areas as mentioned in Section 4.1 This method can potentially also be applicable in Norway.

The assumable most common defect for Norwegian post-tensioned structures is insufficient grouted ducts. Any methods restoring or ensuring grouting with cementitious materials is therefore relevant for Norwegian bridges. In Section 4.1, it is shown that there exist, both on a European level as well as in the US, guidelines on how to refill ducts [29, 33, 52, 66-68, 79]. As there is no experience with these methods in Norway all use must be considered as initial testing and accordingly should be documented and monitored (for example by a sensor-system) to ensure that the repair is well-functioning for Norwegian conditions. For cases, in which tendons are considered not necessary to ensure load-bearing capacity and safety of the bridge, there are good opportunities to test these methods. Experience with these kinds of repair methods can prove to be very valuable in the future for Norwegian bridges.

5.2 Potential repair options for pretensioned bridges in Norway

Corrosion of prestressing tendons in pretensioned bridge girders is reported in Norway [22], mainly due to external chloride exposure. Accordingly, these damages can potentially be repaired with mechanical repairs (patch repairs) and cathodic protection.

When applying mechanical repair for prestressed structures one must assure not to remove sound parts of concrete which provide bond to the prestressing strands along prestress development length in and near girder end-zones, and thus prestressed to the concrete and sufficient shear and anchorage capacity. Only loose or delaminated parts of concrete should be removed. Materials used for restoring the concrete cross-section of the girders should preferably be low-permeability, high strength concrete with a non-shrink additive. For patch repairs in and near the mid-span areas, preloading should be considered. Also, UHPC is a promising material for patch repairs of increased impermeability, strength, and bonding to the existing concrete. Girders, for which severe cracking, spalling, and delamination are found, can be used for testing both applicability of UHPC in the field including its long-term performance. This can be particularly useful for girders with damage above load-bearing plates, where lifting (to apply the CFRP sheets) should be avoided to not damage the continuity of the concrete deck above the supports. As far as the authors of this article know, mechanical repair on Norwegian pretensioned girders has been carried out to a limited extent, mainly in the bottom flanges near supports. Only one extensive repair was used on the girders with corrosion in the mid-span areas. It is thus important to document and report any repair attempts, including following up on functionality. In Norway, there is experience in retrofitting the pretensioned girder bridge with external post-tensioning [22]. CFRP strengthening method has also been used but on post-tensioned bridge girders. Methods with externally bonded CFRP-stripes or sheets as mentioned in Section 4.2 can potentially be used in the future to a larger extent, as they are proven to increase or even restore girders' capacity (both in shear and flexure) and are relatively fast to install comparing to other strengthening methods. Since ductility of the elements decreases with increasing amount of FRP strengthening, strengthening should be carefully designed. Also, in terms of its tensile strength, and bond to the concrete.

CP, either with impressed current or sacrificial anodes, can be a repair option for pre-tensioned tendons (see Section 4.3). Both methods have been tried in other countries but not in Norway. CP is a common repair method for ordinary reinforcement in Norway, and there is a good level of expertise in the country. Trial repairs with CP on pre-tensioned bridges are, therefore, feasible and should be conducted when possible. As for all other new repair methods, it is essential to well document the execution, experiences, and long-term functionality for future applications.

6. CONCLUSIONS

Durability issues have been present in prestressed bridges since their inception. Hence several advancements have been made in design and construction to ensure durability and long-term performance of these bridges. Various repair options for prestressed bridges have provided increased service life for structures with design and/or construction defects. However, long-term experience with repair options for prestressed systems is limited. The main conclusions drawn for the available repair methods are as follows:

- For severely corroded internal tendons, external post-tensioning is often the preferred method whereas, replacement of tendons is recommended for highly compromised external tendons
- In case of repair of voids in the grout, filling the voids using the pressure-vacuum grouting method appears to be the most effective method. Impregnation with corrosion inhibitors along with drying appears suitable for repairing soft grout.

The recently published State-of-the-Art Report *fib* 110 summarizing strategies of individual road administrations highly recommends that repair options be based on local strategies and conditions. For post-tensioned bridge systems in Norway, repair methods applicable for embedded metal ducts with cement-based grout and strands are required:

- External strengthening and tendon replacement (only for tendons present in the deck slab) are viable options for restoring sections with severely corroded tendons
- Corroded anchorage regions can be repaired
- Corroded parts of metallic ducts can be removed, and hydraulic cement mortar can be applied to cover uncorroded strands
- Defective grouting, the internationally recommended methods need to be considered as initial testing in Norway due to limited experience.

Pretensioned bridges in Norway are prone to corrosion mainly due to chloride exposure. Accordingly, these damages can potentially be repaired with mechanical repairs (patch repairs) and cathodic protection. For both pretensioned and post-tensioned, passive carbon fibre reinforced polymer (CFRP) strengthening hold potential for future use.

7. ACKNOWLEDGEMENT

The first author acknowledges funding by Norland Fylkeskommune and the Norwegian Public Roads Administration through the Norwegian R&D project Herøysundbru tilstandsevaluering, Herøy FoU (Condition assessment of Herøysund Bridge) and support from the project known as Green Management of Structures for Infrastructure, known as EXCON (Research Council Norway project number 340843).

REFERENCES

1. Norwegian Public Roads Administration: "Bridge Management System (Brutus)". Available from: https://www.vegvesen.no/fag/teknologi/Bruer/Bruforvaltning
2. Geiker, M.R., A. Michel, H. Stang, H. Vikan, and M.D. Lepech: "Design and Maintenance of Concrete Structures Requires Both Engineering and Sustainability Limit States". *Proceedings,* Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision, Ghent, Belgium, 2018, pp. 3110.

3. Hornbostel, K.: "Air Conditioning Gas Emissions for the Rehabilitation of Concrete Bridges, Case Study: Cathodic Protection". Internal Note, Norwegian Public Road Administration, Oslo, Norway, 2022.
4. Geiker, M.: "Sustainability Verification of Deteriorating Concrete Infrastructure". Keynote Lecture, 6th International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2022). 2022: Cape Town, South Africa.
5. Menga, A., T. Kanstad, D. Cantero, L. Bathen, K. Hornbostel, and A. Klausen: "Corrosion-Induced Damages and Failures of Post-Tensioned Bridges: A Literature Review". *Structural Concrete*. Vol. 24, No.1, 2023, pp. 84-99.
6. Johnsen, R.: "Herøysund Bru, Korrosjon Av Etterspent Armering". Statens vegvesens rapport nr. 843, Norway, 2022, 64 pp. (In Norwegian).
7. *fib* Bulletin 26: "Influence of Material and Processing on Stress Corrosion Cracking of Prestressing Steel". TR, 2003, 44 pp.
8. Norwegian Association of Civil Engineers: "Dimensjonering Av Spennbetong". Sandefjord, Norway, 1980. (In Norwegian).
9. Bundesministerium für Verkehr Bau und Stadtentwicklung: "Handlungsanweisung Zur Überprüfung Und Beurteilung Von Älteren Brückenbauwerken, Die Mit Vergütetem, Spannungsrisskorrosionsgefährdetem Spannstahl Erstellt Wurden (Handlungsanweisung Spannungsrisskorrosion)". Germany, 2011. (In German).
10. Wilhelm, T.: "Wasserstoffinduzierte Spannungsrisskorrosion Ein Beitrag Zur Beurteilung Der Zuverlässigkeit Von Spannbetonbrücken Mit Hennigsdorfer Spannstahl". (PhD Thesis), Technische Universität Dresden, Dresden, Germany, 2014. (In German).
11. Norwegian Public Roads Administration: "Bridge Design-08: Nib-Bridges: Norm". Handbook 100, Oslo, Norway, 1989. (In Norwegian).
12. Norwegian Public Roads Administration: "Bridge Design-08: Nib-Bridges: Norm". Handbook 100, Oslo, Norway, 1983. (In Norwegian).
13. *fib* Bulletin 20: "Grouting of Tendons in Prestressed Concrete". 2002, 48 pp.
14. NS-EN 523:1997: "Steel Strip Sheaths for Prestressing Tendons-Terminology, Requirements, Quality Control". Oslo, Norway, 1997.
15. NS-EN 524-1:1997: "Steel Strip Sheaths for Prestressing Tendons-Test Methods-Part 1: Determination of Shape and Dimensions". Oslo, Norway, 1997.
16. Post-Tensioning Institute: "Acceptance Standards for Post-Tensioning Systems". 1st Ed, Arizona, USA, 1998, 64 pp.
17. Norsk Betongforening: "Grouting". Publ. No. 13, Oslo, Norway. (In Norwegian).
18. Nordgård, L., "Betongkonstruksjoner:Dimensjonering. 2.Spennbetong". Universitetfolaget, Oslo, Norway 1972. (In Norwegian).
19. Norwegian Concrete Association Bridge Committee: "Normalized I-Cross Section «NIB» ". Publ. No. 4, Oslo, Norway, 1974. (In Norwegian).
20. Norwegian Concrete Association Bridge Committee: "Normalized Inverted T-Cross Section «NOB»". Publ. No. 3, Oslo, Norway, 1974. (In Norwegian).
21. Norwegian Public Road Administration, "Bruhåndbok Prosjektering (001)". 1st ed. Part 1- 4. Oslo, Norway, 1973. (In Norwegian).
22. Osmolska, M.J., T. Kanstad, M.A.N. Hendriks, K. Hornbostel, and G. Markeset: "Durability of Pretensioned Concrete Girders in Coastal Climate Bridges: Basis for Better Maintenance and Future Design". *Structural Concrete*. Vol. 20, No.6, 2019, pp. 2256-2271.
23. "Norsk Vegtidsskrift". Vol. 4S nr 9, 7, Teknisk Ukeblad, Oslo, 1967. (In Norwegian).
24. Norwegian Public Road and Administration: "Prosesskode 2: Standard Beskrivelsestekster for Bruer Og Kaier, Hovedprosess 8: Retningslinjer". Håndbok 026, Oslo, Norway. (In Norwegian).
25. Norwegian Public Road Administration: "Prosjekteringsregler for Bruer: Normaler ". Håndbok 185, Oslo, Norway, 1996. (In Norwegian).
26. National Academies of Sciences Engineering and Medicine: "Repair and Maintenance of Post-Tensioned Concrete Bridges". NCHRP Synthesis 562, Washington, D.C., USA, 2021, 68 pp.
27. Cavell, D.G. and P. Waldron: "A Residual Strength Model for Deteriorating Post-Tensioned Concrete Bridges". *Computers & Structures*. Vol. 79, No.4, 2001, pp. 361-373.

28. Manning, D.G.: "Durability of Prestressed Concrete Highway Structures". NCHRP Synthesis of Highway Practice 140, Washington, D.C., USA, 1988, 75 pp.
29. Salas, R.M., Schokker-AJ, J. West, J.E. Breen, and M. Kreger: "Conclusions, Recommendations and Design Guidelines for Corrosion Protection of Post-Tensioned Bridges". Texas DOT, Texas, USA, 2004.
30. Yoon, I.-S., T.H.-K. Kang, and H. Shin: "Corrosion Protection Method and Performance for Prestressing Strands". *HERON*. Vol. 64, 2019.
31. Schupack, M. and M.G. Suarez: "Some Recent Corrosion Embrittlement Failures of Prestressing Systems in the United States". *PCI Journal*. Vol. 27, No.2, 1982, pp. 38-55.
32. ACI Committee 222: "Corrosion of Prestressing Steels". ACI 222.2R-01, Farmington Hills, MI, USA, 2001, 43 pp.
33. Trejo, D., S.B. Im, R.G. Pillai, M.B.D. Hueste, P. Gardoni, S. Hurlebaus, and M. Gamble: "Effect of Voids in Grouted Post-Tensioned Concrete Bridge Construction: Inspection and Repair Manual for External Tendons in Segmental, Post-Tensioned Bridges". Texas Transportation Institute, Texas, USA, 2009, 62 pp.
34. Sagues, A.A., F.C. Karins, and K. Lau: "Corrosion Characteristics of Post-Tensioning Strands in Ungrouted Ducts". University of South Florida, Florida, USA, 2011.
35. *fib* Bulletin 97: "External Tendons of Bridges". State of the art report, 2020, 108 pp.
36. Norsk betongforening: "Spennarmeringsarbeider". No.14, Oslo, Norway, 2016. (In Norwegian).
37. *fib* Bulletin 15: "Durability of Post-Tensioning Tendons". 2001, 277 pp.
38. Corven Engineering: "New Directions for Florida Post-Tensioned Bridges". Florida Department of Transportation (FDOT), Tallahassee, USA, 2002.
39. Theryo, T., P. Garcia, and R. Powers: "Investigation Findings of Sunshine Skyway Bridge Post-Tensioned Columns Tendon Corrosion and Repair Methods ". *Proceedings,* The 3rd International Conference on Current and Future Trends in Bridge Design, Construction and Maintenance, 2015, pp. 534-546.
40. West, J.S.: "Durability Design of Post-Tensioned Bridge Substructures". (PhD Thesis), The University of Texas at Austin, Texas, USA, 1999.
41. Lau, K., I. Lasa, and M. Paredes: "Update on Corrosion of Post-Tensioned Tendons with Deficient Grout in Florida". *Proceedings,* Corrosion 2014 (NACE), Texas, USA, 2014.
42. The Concrete Society: "Durable Bonded Post-tensioned Concrete Bridges". TR No. 47, Slough, UK, 1996.
43. VSL International: "Grouting of Post-Tensioning Tendons ". Switzerland, 2002, 46 pp.
44. Berg, K.M. and A.J. Schokker: "Development of Best Practices for Inspection of PT Bridges in Minnesota". University of Minnesota Duluth and MDOT, Minnesota, USA, 2012, 213 pp.
45. Lau, K. and I. Lasa: "Corrosion of Prestress and Post-Tension Reinforced-Concrete Bridges". Chapter No. 3, "Corrosion of Steel in Concrete Structures", A. Poursaee, Editor, Woodhead Publishing, Oxford, UK, 2016, pp. 37-57.
46. Woodward, R. and F. Williams: "Collapse of Yns-Y-Gwas Bridge, Glamorgan". *Proceeding of the Institution of Civil Engineers*. Vol. 84, No.4, 1988, pp. 635-669.
47. Kamat, N.: "Thirty Years after Mandovi Bridge Collapse", in The Navhind Times. 2016.
48. *fib* Bulletin 110: "Management of Post-Tensioned Bridges". 2023, 143 pp.
49. Hamilton, H.R., A. Piper, A. Randell, and B. Brunner: "Simulation of Prepackaged Grout Bleed under Field Conditions". University of Florida, Florida, USA, 2014.
50. Lau, K., I. Lasa, and M. Paredes: "Corrosion Failure of Post-Tensioned Tendons in Presence of Deficient Grout". *Proceedings,* Corrosion 2013 (NACE), Florida, USA, 2013.
51. Bertolini, L. and M. Carsana: "High pH Corrosion of Prestressing Steel in Segregated Grout". *Proceedings,* Modelling of Corroding Concrete Structures, Madrid, Spain, 2011, pp. 147-158.
52. Teddy S. Theryo, W.H.H., and Piotr Paczkowski: "Guidelines for Sampling, Assessing, and Restoring Defective Grout in Prestressed Concrete Bridge Post-Tensioning Ducts". FHWA-HRT-13-028, Federal Highway Administration, Virginia, USA, 2013.
53. Abdullah, A.B.M., J.A. Rice, R. Bhatia, N.R. Brenkus, and H.R. Hamilton: "A Thermal Analysis of Flexible Filler Injection for Unbonded Post-Tensioning Tendons". *Construction and Building Materials*. Vol. 126, 2016, pp. 599-608.

54. PTI Technical Notes: "Selection of Filler Material for Multistrand PT Tendons". *Post-tensioning Institute*. No.19, 2015.
55. Bruce, S., P. McCarten, S. Freitag, and L.M. Hasson: "Deterioration of Prestressed Concrete Bridge Beams". *Proceedings,* Land Transport New Zealand, Wellington, New Zealand, 2008.
56. Pough, K., D. Mayhorn, G.S. Prinz, and R. Floyd: "Evaluation and Repair of Existing Bridges in Extreme Environments". SPTC14.1-58-F, School of Civil Engineering and Environmental Science, University of Oklahoma, Oklahoma, USA, 2016, 199 pp.
57. Tanaka, Y., H. Kawano, H. Watanabe, and T. Nakajo: "Study on Cover Depth for Prestressed Concrete Bridges in Airborne-Chloride Environments". *PCI Journal*. Vol. 51, No.2, 2006.
58. Song, G. and S. Ahmad: "Corrosion of Steel in Concrete: Causes, Detection and Prediction". A State-of-the-Art (Review Report 4), ARRB Transport Research Ltd, Melbourne, Australia, 1998.
59. American Concrete Institute Committee 222: "Report on Corrosion of Prestressing Steels". ACI, Farmington Hills, MI, USA, 2014.
60. Murray, C., B. Cranor, R. Floyd, and J.-S. Pei: "Experimental Testing of Older AASTHO Type II Bridge Girders with Corrosion Damage at the Ends". *PCI Journal*. Vol. 64, No.1, 2019, pp. 49-64.
61. Ramseyer, C. and T.H.K. Kang: "Post-Damage Repair of Prestressed Concrete Girders". *International Journal of Concrete Structures and Materials*. Vol. 6, No.3, 2012, pp. 199-207.
62. Osmolska, M.J., T. Kanstad, M.A.N. Hendriks, and G. Markeset: "Numerical Investigation into the Effects of Corrosion on the Shear Performance of Pretensioned Bridge Girders with Cast-in-Place Slabs". *Structures*. Vol. 46, 2022, pp. 1447-1468.
63. Austnes, P. and R. Kompen: "Resistant Concrete Structures, Subproject 3: Maintenance Methods, Report 3.3: Cathodic Protection of Prestressing Steel in Chloride Contaminated Concrete". The Research Council of Norway, Oslo, Norway, 1999. (In Norwegian).
64. Rogers, R., L. Wotherspoon, A. Scott, and J. Ingham: "Residual Strength Assessment and Destructive Testing of Decommissioned Concrete Bridge Beams with Corroded Pretensioned Reinforcement". *PCI Journal*. Vol. 57, 2012, pp. 100-118.
65. Tanaka, Y., T. Shimomura, and T. Yamaguchi: "Experimental and Numerical Study on the Residual Strength of Deteriorated Prestressed Concrete Bridge Beams Affected by Chloride Attack". "Concrete Repair, Rehabilitation and Retrofitting III*"*, CRC Press, UK, 2012.
66. Corven, J. and A.J. Moreton: "Post-Tensioning Tendon Installation and Grouting Manual". FHWA-NHI-13-026, Federal Highway Administration, Washington D.C., USA, 2013, 184 pp.
67. *fib* Bulletin 102: "Guide for Protection and Repair of Concrete Structures". 2021, 291 pp.
68. *fib* Bulletin 33: "Durability of Post-Tensioning Tendons". Recommendation, 2005, 71 pp.
69. Transport Infrastructure Ireland: "Strengthening, Repair and Monitoring of Post-Tensioned Concrete Bridge Decks". Dublin, Ireland, 2014, 28 pp.
70. *fib* Bulletin 103: "Guide for Strengthening of Concrete Structures". 2022, 316 pp.
71. Toshihiko, N. and T. Takeharu: "Replacing the Deck Slab on a Post-Tensioned, Prestressed-Concrete Composite Girder Bridge in Japan". *Proceedings of the Institution of Civil Engineers - Forensic Engineering*. Vol. 172, No.1, 2019, pp. 3-10.
72. Corven Engineering: "Mid-Bay Bridge Post-Tensioning Evaluation". FDOT, Florida, USA, 2001.
73. Dickes, G.: "Vacuum Grouting Repairs for Existing Post-Tensioned Structures and New Construction". *Proceedings,* PCI Convention, 2008, pp. 15.
74. Dai, L., L. Wang, M. Deng, B. Wu, R.W. Floyd, and J. Zhang: "Strengthening a 20-Year-Old Post-Tensioned Concrete Box Beam with Double-Layer Prestressed Steel Wire Ropes". *Journal of Bridge Engineering*. Vol. 23, No.11, 2018.
75. MacDougall, C., M. Green, and L. Amato: "CFRP Tendons for the Repair of Post-Tensioned, Unbonded Concrete Buildings". *Journal of Performance of Constructed Facilities*. Vol. 25, No.3, 2011, pp. 149-157.
76. Ledesma, T.: "Replaceable Grouted External Post-Tensioned Tendons". FHWA-HIF-19-067, Federal Highway Administration, Washington D.C., USA, 2019, 47 pp.
77. L. C. Powell, J. E. Breen, and M. E. Kreger: "State of the Art Externally Post-Tensioned Bridges with Deviators". FHWA/TX-89+365-1, Center for Transportation Research, University of Texas at Austin, Texas, USA, 1988, 63 pp.

78. VDOT Structure and Bridge Division: "General Requirements for the Usage, Design and Specification of Post-Tensioned Bridge Superstructures". IM-S&B-91, Virginia,US, 2016, 204 pp.
79. Im, S.B.: "Inspection, Assessment, and Repair of Grouted Ducts in Post-Tensioned Bridge". (PhD Thesis), Texas A&M University, Texas, USA, 2009, 326 pp.
80. Chauvin, M.R.: "Considerations for Development of Inspection and Remedial Grouting Contracts for Post-Tensioned Bridges". Wiss, Janney, Elstner Associates, Inc. and MDOT, Minnesota, USA, 2017.
81. Sprinkel, M.M.: "VDOT Experience with Grouts and Grouted Post-Tensioned Tendons". *PTI Journal*. 2015, pp. 51-61.
82. COST 534: "New Materials System, Methods and Concepts for Prestressed Concrete Structures". Electrochemical Maintenance and Repair Methods-Part 4, COST, Brussels, Belgium, 2009, 32 pp.
83. Liao, H., J. Vukotic, and D. Whitmore: "Post-Tensioning Investigation and Corrosion Mitigation in Voided Slab Bridges". *Proceedings,* 11th International Conference on Short and Medium Span Bridges, Toronto, Canada, 2022.
84. Whitmore, D., G. Fallis, H. Liao, S. Strombeck, and I. Lasa: "Tendon Impregnation Technology Mitigates Corrosion and Protects Post-Tensioned Tendons". *PTI Journal*. Vol. 2014, pp. 17-21.
85. Whitmore, D., T. Arnesen, and B. Pailes: "Investigating and Resolving Bridge Grouted Pt-Strand Corrosion Problems ". *Proceedings,* Structures Congress, ASCE, 2017 pp. 68-75.
86. Gilles, I.P.: "Internal Post-Tensioning Tendons: Many Problems and Sometimes Solutions". Public Service of Wallonia, Belgium.
87. Hamilton, H.R., S.R. Patil, and E. Torres: "Evaluation of Techniques to Remove Defective Grout from Post-Tensioning Tendons". University of Florida and FDOT, Florida, USA, 2020, 222 pp.
88. Kodsy, A., G. Morcous, and R.L. Wood: "Synthesis of Repair Practices of Damaged Precast/Prestressed Concrete Girders". University of Nebraska, Lincoln, USA, 2020, 151 pp.
89. Nagi, M., D. Whiting, and H. Tabatabai: "Laboratory Evaluation of Repairs to Pretensioned Concrete Bridge Members". *Proceedings,* 10th International Conference and Exhibition-Structural Faults and Repair Conference 2003, London, UK, 2003.
90. Shafei, B., B. Phares, and W. Shi: "Beam End Repair for Prestressed Concrete Beams". No.IHRB Project TR-715, Institute for Transportation, Iowa State University, Iowa, USA, 2020, 76 pp.
91. Andrawes, B., I.D. Shaw, and H. Zhao: "Repair & Strengthening of Distressed/Damaged Ends of Prestressed Beams with FRP Composites". Center for Transportation, Illinois, USA, 2018, 94 pp.
92. Shield, C. and P. Bergson: "BR27568-Experimental Shear Capacity Comparison between Repaired and Unrepaired Girder Ends ". MDOT, Minnesota, USA, 2018, 144 pp.
93. Choo, C.C., A. Peiris, and I. Harik: "Repair of I-65 Expressway Bridges Using Carbon Fiber Reinforced Polymer (CFRP) Composites". KY Transportation Center, Kentucky, USA, 2013.
94. Harries, K.A., J. Kasan, and J. Aktas: "Repair Methods for Prestressed Concrete Girders ". FHWA-PA-2009-008-PIT 006, Pennsylvania DOT, Pennsylvania, USA, 2009.
95. Harries, K.A., J. Kasan, R. Miller, and R. Brinkman: "Updated Research for Collision Damage and Repair of Prestressed Concrete Beams.". NCHRP Project 20-07(307), NCHRP, Transportation Research Board, Washington, D.C., USA, 2012, 228 pp.
96. Ghaffary, A. and M.A. Moustafa: "Synthesis of Repair Materials and Methods for Reinforced Concrete and Prestressed Bridge Girders". *Materials*. Vol. 13, No.18, 2020, pp. 4079.
97. Menoufy, A. and K. Soudki: "Flexural Behavior of Corroded Pretensioned Girders Repaired with CFRP Sheets". *PCI Journal*. Vol. 59, 2014, pp. 129-143.
98. Menoufy, A.E.: "Flexural Fatigue Behaviour of Corroded Pretensioned Beams and Their Repair Using Carbon Fibre Reinforced Polymer Sheets ". (PhD Thesis), University of Waterloo Ontario, Canada, 2015, 251 pp.
99. Lin, S.-H., B.C. McCoy, G.W. Lucier, R. Seracino, and N.A. Pierce: "Rapid Prestressed Concrete Retrofit with Prestressed Mechanically-Fastened Fiber-Reinforced Polymer: Field Performance and Observation for a Deteriorated Prestressed Concrete Bridge". *Transportation Research Record*. Vol. 2678, No.4, 2023, pp. 804-818.
100. Funahashi, M. and W.T. Young: "Cathodic Protection of Prestressed Bridge Members-Full-Scale Testing". *Transportation Research Record*. Vol. 1561, No.1, 1996, pp. 13-25.

101. Whitmore, D. and C. Ball: "Galvanic Corrosion Protection of Prestressed/Post-Tensioned Structures". *Proceedings,* Structure Congress: New Horizons and Better Practices, 2007, pp. 1-13.
102. NS-EN ISO 12696:2022: "Cathodic Protection of Steel in Concrete ". Oslo, Norway, 2022.
103. Norwegian Public Road Administration: "FoU-Programmet Bedre Bruvedlikehold 2017-2021". Sluttrapport, No.865, Oslo, Norway, 2022. (In Norwegian).
104. Norwegian Public Roads Administration: "N-V441 Bruinspeksjon". Oslo, Norway, 2023. (In Norwegian).
105. *fib*: "*fib* Model Code for Concrete Structures 2010". 2013.
106. Eurocode 2: "Design of Concrete Structures-Part 1-1: General Rules and Rules for Buildings, Bridges and Civil Engineering Structures". FprEN 1992-1-1:2022 (E), 2022, 410 pp.

APPENDIX A

The definition of prestressed components in this paper are in accordance with *New Directions for Florida Post-Tensioned Bridges, Florida Department of Transportation* [38], *fib Bulletin 97* [35], *fib Bulletin 33* [68], *Replaceable Grouted External Post-Tensioned Tendons, Federal Highway Administration, US* [76], *fib Model Code* 2010 [105], *Repair and Maintenance of Post-Tensioned Concrete Bridges, National Cooperative Highway Research Program* [26] and *Draft of Eurocode 2: Design of concrete structures-Part 1-1* [106]. (See reference list in main manuscript.)

Anchorage: An assembly of various hardware components that secure a tendon at its ends after it has been stressed and imparts the tendon force into the concrete.
Bonded construction: In bonded construction, the tendons directly transfer stresses to the structure. Grout is injected to fill the void between the tendon and the duct.
Coupler: Mechanical devices to connect the end of a tendon that has been tensioned first, to a second tendon placed as an extension of the first, and which will be tensioned in a second stage.
Damage: Physical disruption or change in the condition of a structure or its components, brought about by external actions and influences, such that some aspect of either the current or future functionality of the structure or its components will be impaired.
Deficiency: Lack of something, possibly arising because of an error in design, specification, or construction, eventually affecting the ability of the structure to function as it is intended to, either now or in the future. Often concerned with the durability of the structure.
De-tensioning: Allowing the prestressing force in a tendon to be relieved without damaging the existing members.
Deviator: Interface between tendon and deviation block and deviation points
Duct: Enclosure in which all tensile elements of the tendon are placed.
External tendons: Tendons are most frequently used in cellular sections and must be unbonded or partially bonded at intermediate deviators.
Filler material: Material used to fill the space between post-tensioning strands and tendon duct. The most common filler material used is grout, but grease or wax are also used.
Grout: Cement-based filler material.
Internal tendons: The tendons installed inside the concrete are termed as an internal tendon.
Post-tensioning system: Complete system of components, which is used for tensioning tendons after the concrete has gained minimum required strength. The system used for post-tensioned construction is generally classified as bonded or unbonded.
Pour-back: Material cast to cover the anchorage or vent assemblies of post-tensioned tendons after injection of filler.
Prestressed reinforcement: Reinforcement made of strands, wires, or bars subjected to a prestressing process, where not specified otherwise, it is made of prestressing steel. Prestressed reinforcement covers both pretensioned and post-tensioned reinforcement.
Prestressing system: System for prestressing reinforcement which has European Technical Approval and is used in prestressed reinforced concrete. Designation for the complete system of components necessary for the execution.

Pretensioning system: Complete system of components, which is used for tensioning tendons before and during concrete casting and hardening to the required strength. In the system used for pretensioned construction, prestressed reinforcement is bonded directly to the concrete.
Soft grout: Grouts that were inadequately mixed or contained excess water, resulting in the separation of solids and liquids to form jelly-like substance which retains water and does not harden.
Strand: An assembly of several high strength steel wires wound together. Strands usually have six outer wires wound in long-pitch helix around a single straight wire of a similar diameter.
Tendon: Complete assembly consisting of anchorages, prestressing steel (strand, wire, bar), and sheathing with coating for unbonded applications or ducts with grout for bonded applications. In pretensioned applications, the tendon is an individual element of prestressed reinforcement.
Unbonded construction: In this type of system, the tendons transfer stress to the structure only at the anchorages. The duct is filled with grease or wax to fill the void between the tendon and the duct.
Wire: A single, small diameter, high strength steel member which is typically the basic component.