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Cathodic Protection of Marine Prestressed Concrete Bridges – Review of Case Studies

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ABSTRACT
Reinforcement corrosion is the main deterioration mechanism in marine exposed reinforced concrete structures. Recent investigations show that not only the ordinary reinforcement, but also prestressed tendons might be affected. The present paper discusses considerations in connection with the potential application of cathodic protection (CP) systems on marine prestressed concrete bridges. It mainly addresses the potential problems associated with CP application by reviewing several case studies.

Key words: Corrosion, marine environment, prestressed concrete bridges, cathodic protection.

1. INTRODUCTION

In a study conducted by Angst [1], the direct cost of corrosion in the United States (US) is estimated to be 3.1% of the total Gross Domestic Product, amounting to approx. US$575 billion annually. Nearly half of these direct costs are attributed to infrastructure, with approx. 8% of these are associated with reinforced concrete bridges. In Europe, a substantial portion of its modern infrastructure was developed shortly after World War II. Many prestressed bridges were built during that period, and some of them now require repair to meet the structural demand and ensure their continued safety and functionality [2].

Deterioration in the prestressed bridges also depends on the construction methodology of the structure. Hence, it is important to understand the fundamental difference between the two primary systems: post-tensioned and pretensioned. In a pretensioned system, the strands are tensioned before the concrete is placed and hardened, whereas for the post-tensioned system, initially, the concrete surrounding the duct is hardened, then the strands are placed inside the duct and tensioned. Finally, a filler material is pumped inside the duct making it a bonded or un-bonded (dependent on the material) post-tensioned system. The prestressed systems, especially the post-tensioned system, provide superior corrosion protection compared to ordinary reinforced structures. To prevent corrosion, the post-tensioned tendons have multiple layers of protection; the concrete cover, the duct (metallic or plastic), and the filler material (grout or flexible fillers, e.g., grease, wax, or oil). Despite high protection levels, case studies have shown that post-tensioned structures can be prone to corrosion [3] due to the infiltration of harmful substances such as moisture, chloride, and carbon dioxide [4]. In addition to their vulnerability to chloride-induced corrosion, prestressed reinforcement exhibits an inherent susceptibility to brittle fracture due to stress corrosion cracking (SCC), e.g., induced by hydrogen embrittlement (HE) [5, 6].

According to [7], there are several potential methods to control corrosion of prestressed structures including cathodic prevention, cathodic protection (CP), and chloride removal. CP was initially pioneered by Humphry Davy in 1824 to protect metal in seawater. Since then, it has been extensively applied to metallic and buried metallic structures. The application of CP on reinforced concrete was introduced decades later, in the year 1957 in the US [8] and in Europe in 1985 [9]. Today, it is accepted that CP is an effective way to prevent corrosion in chloride-contaminated ordinary reinforced concrete structures [7, 10]. However, the applicability and effectiveness of CP on prestressed structures are yet to be confirmed. The theoretical aspects of using CP on prestressed concrete structures, especially the risk of HE, have been discussed in detail in the COST534 report [7].

The theory of CP involves using direct current to prevent or reduce the corrosion of a metal surface. Corrosion occurs when metal oxidization occurs (i.e., it releases electrons). When the electrons are intentionally supplied to the metal surface, the cathodic reaction is accelerated (consumption of the electrons), while simultaneously inhibiting the anodic reaction (releasing of the electrons) [11]. The two principal methods through which CP can be achieved are: (i) using inert anodes in combination with applying an external direct current (impressed current cathodic protection, ICCP) [12, 13] and (ii) employing less noble anodes e.g., magnesium, zinc, or aluminium [14] (sacrificial anode cathodic protection, SACP) to generate a driving current. There are also so-called hybrid systems combining the principles, where initially, ICCP is implemented for a short time to re-alkalize the corrosion sites using an anode that later works as a sacrificial anode in an SACP system to prevent corrosion in the long run [15].

In a prestressed bridge structure, CP is implemented with three primary objectives (i) to protect the ordinary reinforcement, (ii) to protect the prestressed reinforcement, or (iii) to protect both prestressed and ordinary reinforcement. In this paper, the first objective is regarded as Strategy I, whereas the second and third objectives are considered as Strategy II. The application of CP can pose several potential problems depending on the intended use (Strategies I and II) or the methods employed (ICCP, SACP, or hybrid system).

This paper reviews case studies of prestressed bridges employing CP systems. In Section 2, problems potentially associated with the use of CP on prestressed structures are summarized. These potential problems are classified based on relation to prestressing steel (2.1) and those concerning the general application of CP (2.2). Section 3 brings an overview of case studies summarizing the problems observed. Both applications of Strategies I and II are addressed. Section 4 discusses the applicability of CP using either ICCP, SAPC, or a combination (hybrid) considering the impact on both the ordinary reinforcement and the prestressed reinforcement. Section 5 provides the conclusions.

2. POTENTIAL PROBLEMS ASSOCIATED WITH THE APPLICATION OF CP

2.1 Potential problems related to prestressed reinforcement

Various material aspects of prestressed reinforcement set it apart from ordinary reinforcement, making it more vulnerable to deterioration: (a) metallurgical variables [6, 8], (b) heat and mechanical treatment [6, 16, 17], (c) chemical composition [18], (d) surface texture [19], and (e) forms of prestressed reinforcement [8, 19]. These aspects complicate the application of CP on prestressed reinforcement, compared to ordinary reinforcement, resulting in several potential problems as discussed below.

Hydrogen embrittlement
One of the main problems of the applicability of ICCP on prestressed bridges is the risk of HE. HE refers to mechanical damage of prestressed reinforcement due to the absorption of adsorbed atomic hydrogen into the metal lattice, where it recombines to form hydrogen molecules forming an internal pressure [7]. This leads to reduced ductility and tensile strength in prestressed reinforcement, ultimately causing brittle failures in structures. HE can occur during the application of both Strategies I and II. For Strategy I, it can occur due to the overprotection of ordinary reinforcement in the vicinity of prestressed tendons. Overprotection refers to the excessive application of cathodic current, typically to the point where reinforcement potential drops below -900 mV_{SCE}, resulting in hydrogen evolution at the reinforcement surface [5]. For Strategy II, it can take place due to the direct application of CP on prestressed reinforcement, leading to hydrogen evolution as a cathodic reaction below a threshold potential (i.e., -900 mV_{SCE}) on the surface of the prestressed reinforcement. However, it is important to note that hydrogen evolution does not directly induce HE but increases the probability of its occurrence.

Various experimental laboratory studies showed that the potential at which hydrogen evolution occurs depends on the type of environment of the prestressed reinforcement. The investigation led by [20] indicated that hydrogen can enter the prestressed reinforcement as a result of CP. Several research groups [21-24] investigated the so-called threshold potential for HE in aggressive environments (see Figure 1).

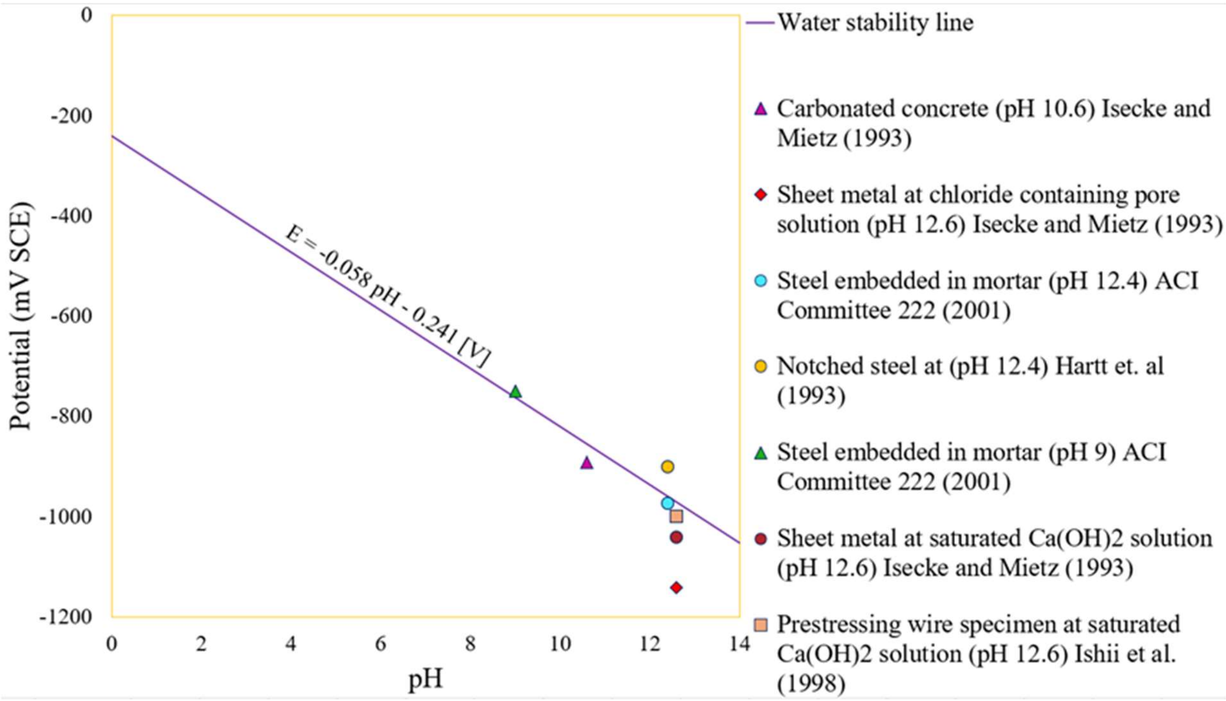

Figure 1 – Threshold potentials below which risk of hydrogen embrittlement (HE) exists as a function of pH. Data from literature as indicated.

Isecke and Mietz [21] discovered that in a chloride-exposed environment (simulated by a solution of $Ca(OH)_2$ + 3% Cl, pH 12.6), the occurrence of cathodic overprotection during the CP of prestressed strands elevated the risk of HE at potentials lower than -1141 mV_{SCE}, and an increased hydrogen activity was observed below this potential. Hartt *et al*. [24] observed that the increase in chloride content did not affect the normalized fracture load of the prestressed reinforcement. According to Funahashi *et al*. [23], for steel embedded in a mortar with either pH 12.4 or pH 9, hydrogen developed at potentials -974 and -750 mV_{SCE}, respectively. This aligns with the values mentioned by Bertolini *et al*. [5].

Full-scale testing was also conducted for the application of CP, based on the threshold potential of HE, on both post-tensioned and pre-tensioned bridges by Funahashi and Young [25]. It was observed that at -700 mV_{SCE}, hydrogen was not generated on the wires and rods of pretensioned and post-tensioned beams. However, hydrogen evolution could occur where the concrete was contaminated (lower pH). Observations were made on the potential difference between the metallic duct and the rod, which was determined to be insufficient to cause HE. Similarly, Smeltzer *et al*. [26] applied CP on concrete beams containing tendons providing protection levels of -524 mV_{SCE} to -1224 mV_{SCE} for up to three months to investigate HE. However, no loss of capacity or signs of brittle fracture were found. Li *et al*. [27] studied the effect of CP on corroded prestressed cable-stay high-strength steel wires in the atmospheric marine environment. The results from the experiment showed that the application of ICCP effectively reduced the corrosion of the steel wires and the specimens showcased no to slight corrosion; however, aspects of HE were not discussed. A recent study [28] conducted on CP of corroded pre-tensioned tendons also concluded that no signs of HE were observed between the potential of -694 mV_{SCE} and -794 mV_{SCE} for both galvanized and ungalvanized tendons. The test was conducted for 553 days for ungalvanized and 137 days for galvanized tendons. However, at -1044 mV_{SCE} to -1244 mV_{SCE}, loss of ductility was observed in galvanized corroded pre-tensioned bars, but it was solely not because of HE. The study concluded that strength, degree of corrosion, and the level of prestress appear to have more influence on the bars than the application of CP.

The disparities between the results are quite noteworthy. Full-scale tests, being closer to real-world conditions, exhibit reduced susceptibility to HE [26, 28] owing to a less aggressive environment. But this might not be true in marine-exposed environments (where chloride-induced pitting corrosion is observed), as mentioned by Bertolini *et al*. [5], who pointed out the risk for hydrogen evolution in corrosion pits (with localised acidification). This real-world condition has been overlooked in the presented studies. Consequently, the applied potential at which HE occurs in the presence of damaged prestressed tendons (active pitting corrosion) is still uncertain.

Stress corrosion cracking
Stress corrosion cracking (SCC) refers to the initiation and propagation of sharp cracks in metal leading to sudden failure from the combined action of corrosion under a specific mechanical and environmental load (externally applied or residual) [5]. As the prestressed reinforcement in prestressed bridges is in a tensioned state, they are prone to SCC. An example of SCC occurring in a floating bridge structure in a marine environment was mentioned by Hong [29]. However, the observations of the possible occurrence of SCC in prestressed reinforcement in chloride-containing environments are quite contradictory [30-32].

In both Strategies I and II, SCC can be promoted by HE if overprotection of CP is present, thereby accelerating crack growth and potentially leading to premature failure of the prestressed reinforcement.

Shielding effect
The uneven distribution of current within the prestressed reinforcement, arising from the presence of layers of reinforcement in the pretensioned system and due to the presence of ducts in the post-tensioned system, is referred to as the shielding effect.

For Strategy I: instead of acting as a problem, the shielding effect (see text above) of other layers of reinforcement and/or ducts effectively prevents the polarization of prestressed reinforcement. Also, it reduces the risks of HE in prestressed reinforcement. Whereas for Strategy II: it presents as a problem for both metallic and plastic ducts and/or a dense layer of reinforcement in front of prestressed wires in pre-tensioned structures. It significantly reduces the efficiency of CP on the strands. In a study conducted by Funahashi and Young [25] and Hope and Ip [33], it was found that the shielding effect was prominent when the metallic duct was electrically connected to the post-tensioned rods as the impressed current followed the path of the ducts. Similarly, the use of plastic ducts acted as an insulator. Shielding can also be a concern for pretensioned bridges if the anodes are not distributed uniformly in the structure. In an experiment conducted by Funahashi and Young [25] on pretensioned beams, the pretensioned wires on the opposite side of the impressed anode did not receive significant CP.

2.2 General problems related to the application of CP

There are various general problems related to the design, installation, and operation of CP. The potential problems mentioned below were observed in the case studies described in Section 3.

Inadequacy in polarizing steel by the anodes
In a CP system, poor design (specifically relating to the location, and quantity) and maintenance of anodes can result in inadequately polarized steel due to uneven current distribution. In SACP,

there might be cases where the prestressed reinforcement might not be polarized due to the inadequacy of the sacrificial anodes to generate the required current [34].

Inhomogeneous moisture condition
The inhomogeneous moisture content of the concrete may lead to varying and potentially uncontrollable protection levels. Insufficient moisture in concrete leads to conductivity issues leading to difficulties in maintaining the CP system. The presence of moisture in the concrete can be beneficial for CP as it provides conductivity in a CP system, maintaining its ability to protect the reinforcement. However, this might not be the case in the presence of high moisture loads, e.g., running water. In this case, the current chooses the low resistance path to complete the circuit leading to a short circuit in the system.

Debonding of anode
Debonding refers to the separation of the overlay or anode from the concrete to be protected. This generally happens due to incorrect installations, inadequate surface preparations, poor adhesion of coatings, or exposure to harsh environmental conditions [7, 34, 35]. A study conducted in 2009 [7] highlighted that the production of acid in the anode region can also lead to cement paste softening, ultimately causing a loss of bond.

3. FIELD EXPERIENCES OF CP

CP has been used in prestressed bridges to protect both the ordinary and the prestressed reinforcement (Strategies I and II). As per European standards (Norwegian Standards, NS-EN ISO 12696:2022) [36], by maintaining the overpotential threshold of - 900mV$_{SCE}$, CP appears to be feasible to protect ordinary reinforcement in the same structure without harming the tendons at normal operating conditions. There are also cases where CP has been used directly to protect the prestressed reinforcement.

Tables 1 and 2 provide an overview of CP systems employed in the prestressed bridges for Strategies I and II, respectively. It also includes the problems observed in the bridges, as detailed in Section 2. As mentioned in Section 2, SCC is recognised as a potential issue in prestressed bridges due to the high tensile stresses in the tendons, but this issue was not observed in any of the case studies presented. Neither shielding was mentioned in the case studies. In addition to the observed problems, the table indicates whether or not the CP system was found to be effective in the respective case studies. However, it is important to note that this assessment only covers a short duration.

Hydrogen embrittlement
From the case studies for both Strategies I and II, HE was not detected in the reported cases (no data for three of 15 case studies). In most of the case studies, the possibility of HE was discarded based on the measured electrochemical potential. For bridges in Florida and Ohio, it was found that even at zones where the potentials were more negative than the threshold potentials, HE was not observed [34]. In the first year, West 130th Bridge was overprotected in many areas, but after 28 months the potentials were maintained [34]. Also, the bridge piles in Florida containing conductive rubber showed potentials below the threshold due to inhomogeneous moisture conditions [34]. In addition to the mentioned case studies in Tables 1 and 2, 30 bridges with beam heads undergoing corrosion in ordinary reinforcement, prestressed tendons, and anchorage were protected by employing ICCP in the Netherlands [37]. After two years of installation, it was found that all components of the beam heads were well protected and as the potential was monitored

throughout, issues of HE were not observed [37]. It is generally accepted that above -900 mV_{SCE} HE does not occur. However, COST 534 [7], and Bertolini *et al.* [5] noted that in areas with pitting, hydrogen development can occur above -900 mV_{SCE} as well. HE cases may be underreported as they often coincide with other corrosion mechanisms like pitting [6], reducing the focus on further tests for HE.

Table 1– Overview of observed problems for Strategy I (see text)

Bridge	Damaged component	Type of CP & anode	Time of evaluation (yrs)	Problems observed				E
				HE	IM	De	IPS	
Overpass of I-74, IL[1]	Abutment & pier cap (Pre)	SACP & Zn hydrogel	1, 2, 3	NA	Yes	Yes	No	No
I-55 over Sugar Creek, IL[1]	Abutment (Pre)	SACP & Zn hydrogel	1, 2, 3	NA	Yes	Yes	No	No
Neerbossche Bridge, NL[2]	Segment 1 & 2 (Post)	SACP & Zn	3, 4	No	Yes	Yes	No	Yes
Saint-Cloud Viaduct, FR[3]	Abutments & junction (Post)	ICCP & Ti	3	No	No	No	Yes	Yes

Note 1: Gawedzinski [38] 2: Van den Hondel *et al.* [35] 3: Ducasse-Lapeyrusse *et al.* [9] HE: hydrogen embrittlement, IM: inhomogeneous moisture, De: debonding, IPS: inadequate steel polarization, and effectiveness (E) of CP system applied on prestressed bridges Strategy I (see text). Pre: pretensioned, Post: post-tensioned, NA: data not available.

Inadequacy in polarizing steel by the anodes

The SACP on the Abbey Road Bridge was unable to generate enough current, and the system was shifted to ICCP after a few months [34]. Similarly, for the bridge over I-474, the sprayed-on zinc anode was not able to develop enough current to arrest corrosion and the installation was terminated. In the case of the viaduct in France, ICCP was used to protect the ordinary reinforcement by creating subzones [9]. The anodes were omitted in the zones where post-tensioned tendons were present. The results after three years showed that the top inside, central, and bottom zones were successfully protected. However, at the top outside zone (near the tendon), high current demand was observed, and the potential decay criteria were not met. This discrepancy was explained by the presence of ducts and high chloride content in the region.

Inhomogeneous moisture condition

A SACP system was installed on prestressed concrete I beams in Illinois using sprayed-on metalizing anodes [38]. After a year of installation, the effectiveness of the sacrificial anodes was evaluated and no reduction in corrosion potentials was observed. The areas with more water had high corrosion potential leading to the ineffectiveness of anode to drive potential. Similarly, for both bridges in Ohio, due to inhomogeneous moisture content, it was difficult to maintain the polarization decay criteria [34]. In the Neerbossche Bridge, Netherlands [35], both current output and potential decay decreased after three to four years of application, due to drying of concrete.

Debonding of anode

The early (two months) signs of debonding of conductive paint anodes in the form of blisters were observed in 5% of the total area of the West 130th Street Bridge [34]. Initially, debonding was also observed in Neerbossche Bridge [35].

Table 2– Overview of observed problems for Strategy II (see text)

Bridge	Damaged component	Type of CP & anode	Time of evaluation (yrs)	Problems observed				E
				HE	IM	De	IPS	
Twin structure over I-474, IL[1]	Abutment (Pre)	SACP & sprayed Zn	1	No	No	No	Yes	No
Willoughby Bay Bridge on I-64, VA[4]	Piles (Pre)	SACP & Zn grout jacket / Al-Zn-In	1.2	No	Yes	No	No	Yes
Howard Frankland Bridge, FL[5]	Beam Piles (Pre)	SACP & Zn	3.2	No	No	No	No	Yes
		ICCP & Ti mesh	3.2	No	No	No	No	Yes
		Cond. Rubber	0.1, 2.7	No	Yes	No	Yes	Yes
Abbey Road Bridge, OH [6]	Soffit of box beams (Pre)	SACP/ ICCP & metalized Zn	0.6, 3.1	No	Yes	No	Yes	No
West 130th St. Bridge, OH [6]	Soffit of box beams (Pre)	ICCP & conductive coating	2.4	No	Yes	Yes	No	No
Route 37 Bridge, NY [7]	Box Beam (Pre)	SACP & embedded galvanic anodes	2	NA	No	No	No	Yes
Kyle of Tongue Bridge, UK [8]	Beam (Pre)	Hybrid & hybrid anodes	1.6	No	No	No	No	Yes
North-South Viaduct, BE [9]	Column head and deck (Pre)	ICCP & Ti strips	0.1	No	No	No	No	Yes

Note 1: Gawedzinski [38] 4: Clemeña and Jackson [39] 5: Bennett and Schue [34], Virmani and Clemeña [40], Vinik and Duncan [41] 6: Bennett and Schue [34], and Virmani and Clemeña [40] 7: Whitmore and Ball [42] 8: Christodoulou and Kilgour [15] 9: COST 534 [7]. HE: hydrogen embrittlement, IM: inhomogeneous moisture, De: debonding, IPS: inadequate steel polarization, and effectiveness (E) of the CP system applied on prestressed bridges Strategy II (see text). Pre: pretensioned, Post: post-tensioned, NA: data not available.

4. APPLICABILITY OF CP ON PRESTRESSED BRIDGES

Potential problems anticipated from Sections 2 and 3 are provided in Table 3. These potential problems necessitate careful consideration in the design, construction, and maintenance of CP systems on prestressed bridges to ensure their safety and longevity.

Table 3 – Summary of potential problems anticipated on prestressed bridges applying Strategies I and II

	HE	SCC	Shielding	CP problems
Strategy I	X	X	X	X
Strategy II	X	X	X	X

Considering the observed problems and effectiveness (Tables 1 and 2, Section 3), CP is found to be applicable for pre-tensioned bridges. However, the direct application of CP on corroded post-tensioned tendons appears inadvisable [7]. A study by Liao *et al*. [43] mentioned the use of sacrificial anodes in tendon repair projects for post-tensioned bridges in 2012 in the US after the issues of grout dissimilarity causing failure in the repair of corroded tendons; unfortunately, documentation related to it was not found. According to Manickam and Pillai [44], an experimental study indicates that protecting strands in anchorage regions using sacrificial anodes in combination with regrouting seems to be a viable option. The study showed that the galvanic anode connected to the strand end of the anchorage was sufficient to protect the strands inside the anchorage region. Preliminary numerical analyses were performed to check the effectiveness of ICCP on an initially passive strand in a post-tensioned tendon where an anode was employed as a middle strand in a helically twisted seven-wired strand. The preliminary results are promising, however, more research is required and also corroded wires should be taken into account to consider the risks of HE. Few case studies on the application of hybrid systems on prestressed bridges indicated effective application [15]. However, more studies and documentation on the practical application of hybrid systems are required to measure their long-term effectiveness.

As a summary, Table 4 provides an overview of today's experience with CP application on prestressed bridges exposed to the marine environment.

Table 4 – Applicability of CP in the form of impressed current (ICCP), sacrificial anodes (SAPC), or a combination (hybrid)) on prestressed bridges considering both the ordinary reinforcement (OR) and prestressed reinforcement (PR)

Type of prestressing	Reinforcement type and state		
	OR (corroded)	PR	PR (corroded)
Pretensioned	Well-established: ICCP, SACP Limited experience: Hybrid	Well-established: ICCP, SACP Limited experience: Hybrid	Well-established: ICCP, SACP Limited experience: Hybrid
Post-tensioned	Well-established: ICCP, SACP Limited experience: Hybrid	Limited experience and research required: all	Research required: all

5. CONCLUSIONS

Case studies revealed that CP presents different potential problems when intended for ordinary reinforcement (Strategy I) and for prestressed reinforcement and ordinary reinforcement (Strategy II):

- For Strategy I, hydrogen embrittlement can be a problem if the potential is low. However, shielding limits the polarization of the prestressed reinforcement.
- For Strategy II, both hydrogen embrittlement and shielding are potential problems.

In addition, for both Strategies I and II, general problems related to the application of CP are encountered, including inhomogeneous moisture conditions, debonding, and inadequacy in polarizing the reinforcement.

Concerning the application of CP:

- For Strategy I, ICCP and SACP appear feasible for all prestressed structures on the condition that potential limits are not exceeded.
- For Strategy II, ICCP and SACP appear feasible for prestressed reinforcement in pretensioned bridges. For post-tensioned bridges, more research is needed and especially ICCP as per today is not advisable.

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