HIGHWAYS DEPARTMENT

Guidance Notes on Corrosion Protection of Reinforcement in Concrete Highway Structures in Marine Environment

Bridges & Structures Division

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CONTENTS

1. INTRODUCTION

1.1 Background

1.1.1 Corrosion of steel reinforcement is a major problem with respect to durability of reinforced concrete structures.

1.1.2 Factors affecting the durability of reinforced concrete include properties of concrete, concrete cover to steel reinforcement, the presence of cracks, exposure conditions and workmanship, etc. Traditionally, the problem of corrosion in reinforced concrete is tackled through the specification of proper concrete grade/mix, cover, crack width limits and workmanship requirements with reference to relevant design manuals, codes of practice and specifications.

1.1.3 Nevertheless, well-designed and properly constructed reinforced concrete structures require regular maintenance to ensure sufficient protection against reinforcement corrosion. For coastal structures within the tidal/sub-tidal zones or exposed to sea water splash and spray, additional protection will be required. For the portion of the structures that are permanently immersed in deep water (e.g. immersed piles), where the supply of oxygen is limited, corrosion problems are in general not as serious and additional protection will generally be not required.

1.1.4 With the advance of technological and material development, numerous corrosion protection methods have been developed in an effort to enhance durability. The designer should identify suitable corrosion protection method(s) taking into account the type of structures, site conditions, cost effectiveness, etc. for their projects.

1.2 Objective and Scope

1.2.1 This document aims to provide references for designers in the selection of the four corrosion protection methods (listed out in Section 1.2.2 below), among other various corrosion protection methods available, for concrete highway structure exposed to marine environment. The corrosion protection methods, their performance from literature review, some of their limitations and selection considerations are described and highlighted. It is not intended to be a detailed step-by-step guideline on the detailed assessments of the choice of corrosion protection for particular projects. Designers are not confined to the methods described in Section 1.2.2 below. They should refer to other relevant guidelines or design manuals if the methods other than those described in these guidance notes are chosen. Project offices should seek expertise input and advice on the subject if necessary. In any case, project offices should seek comments on the proposed corrosion protection methods from the maintenance authority.

1.2.2 For steel reinforcement, the guidance notes focus on the following four methods of corrosion protection:

(a) Epoxy-coated reinforcement;

(b) Stainless steel reinforcement;

(c) Stainless steel cladded reinforcement; and

(d) Cathodic protection.

1.2.3 It should be noted that good quality concrete and adequate concrete cover can often enhance the durability of reinforced concrete structures. Moreover, consideration should be given to apply protective coating to reinforced concrete structures to prevent ingress of external deleterious agents into the concrete. Combination of different corrosion protection methods can be considered.

2. DURABILITY REQUIREMENTS IN DESIGN MANUALS

2.1 Structures Design Manual for Highways and Railways

2.1.1 The Structures Design Manual for Highways and Railways published by the Highways Department provides guidance and sets standards for the design of highways and railway structures in Hong Kong. The design working life of these structures is 120 years.

2.1.2 Amongst other requirements, Paragraph 16.1 of the Manual states that: -

(1) In the design of highway structures, due consideration should be given to durability during the service life. The materials and structures shall resist, for the target period and with regular maintenance, all the effects to which they are subjected, so that no significant change occurs in their serviceability.

(2) Maintenance cost should be considered besides the cost of capital construction.

(3) The specific durability requirements of a structure should be assessed during the design stage and measures for their achievement should be considered. Such considerations may include, but not limited to, the following:

(a) Provision of adequate concrete cover to reinforcement.

(b) Use of corrosive protection measures such as waterproofing membranes, epoxy-coated reinforcement, cathodic protection, etc. The designer is responsible for selecting the corrosion protection system which is the most appropriate to the structure. The designer should take into account technology contemporary at the time the design is prepared, the types and properties of corrosion protection system available, and the drainage characteristics of the structure.

2.2 Port Works Design Manual

2.2.1 The Port Works Design Manual published by the Civil Engineering and Development Department (CEDD) presents recommended standards and methodologies for the design of marine works in Hong Kong. The design working life of marine works is normally 50 years which is much shorter than that of highway structures.

2.2.2 Paragraph 6.2 of Part 1 of the Manual highlights the importance of the use of a concrete mix with high density and the required workability for adequate compaction and the provision of a large concrete cover for steel reinforcement to delay the time for ingress of chloride to the reinforcement. It also stipulates that the specification given in the General Specification for Civil Engineering Works (GS) published by CEDD for reinforced concrete in marine environment should be adopted for marine structures.

2.2.3 Protective coatings for marine concrete structures to provide additional corrosion protection and application of cathodic protection for restraining reinforcement corrosion in marine concrete structures are briefly discussed in Chapter 6, paragraphs 6.8.3 and 6.8.4 respectively. Epoxy-coated and stainless steel reinforcement are not mentioned in the manual.

3. PRINCIPLES OF CORROSION OF REINFORCEMENT

3.1 Corrosion Process

3.1.1 Reinforcing steel in concrete normally does not corrode because of the formation of a thin passive oxide film on the surface of the steel due to initial corrosion reaction. The high alkalinity of concrete pore solution (pH value about 13) stabilizes this passive film on the surface of the steel reinforcement. As long as the alkalinity is retained, this passive film remains intact and corrosion will not occur. However, corrosion can occur when the passive film layer is destroyed. The destruction of the passive film occurs when the alkalinity of the concrete is reduced or when the chloride concentration in concrete is increased to a certain level.

3.1.2 Carbonation takes place when carbon dioxide from the air diffuses through the porous concrete and reacts with hydroxides, such as calcium hydroxide, to form carbonates. This results in the reduction of pH value to approximately 8 or 9, at which level the passive film is no longer stable, causing it to breakdown. With adequate supply of oxygen and moisture, corrosion will start. The rate of carbonation primarily depends on the quality of the concrete.

3.1.3 In coastal structures, chloride ions can enter the concrete from seawater in the marine environment. Ingress of chloride ions does not cause a reduction in pH value. However, when the chloride concentration at the surface of the reinforcement exceeds a certain limit, called the threshold value, the passive film will be disrupted and corrosion will occur if water and oxygen are also available.

3.2 Corrosion Control

3.2.1 Conventional carbon steel reinforcement is susceptible to corrosion in an aggressive environment. To improve its performance in concrete, it can either be coated or replaced with a more corrosion-resistant steel material. Electrochemical method can also be used to control the corrosion of reinforcement.

4. EPOXY-COATED REINFORCEMENT

4.1 Material

4.1.1 Epoxy-coated reinforcement (ECR) was developed in the USA in the 1960s. The steel reinforcement is produced in a conventional steel mill and then passes through an additional process in which epoxy coating is applied. The principle of the protection of reinforcement by epoxy coating is that the coating acts as a physical barrier to insulate the reinforcement from aggressive agents that penetrate the concrete cover.

4.1.2 Section 15 of GS on steel reinforcement contains explicit specifications on epoxy coating to reinforcement in respect of material requirements, particulars and samples to be submitted, handling and storage, cutting and bending, repair of damaged coatings and testing. Material requirements for cover spacers, chairs, supports and spacers, tying wires, tying devices and clips are also specified in the GS. Standards cited in the GS are:

(a) BS ISO 14654:1999: Epoxy-Coated Steel for the Reinforcement of Concrete; and

(b) BS ISO 14656:1999: Epoxy Powder and Sealing Material for the Coating of Steel for the Reinforcement of Concrete

4.1.3 Section 6 of the General Specification for Building (2012 Edition) issued by the Architectural Services Department also contains similar provisions for ECR.

4.2 Performance

4.2.1 ECR has been used extensively in bridge structures in the USA for protection against corrosion brought about by de-icing salts or marine environments since the 1970s as per Griffth and Laylor (1999) and Hartt (2012). However, the adoption of ECR in the UK has been more cautious. According to Technical Report No. 61 by the Concrete Society of UK, there had been no reported cases of use of ECR in bridge construction in the UK up to 1982. No provision for the use of ECR is found in the UK Highway Agency Design Manual for Roads and Bridges. Moreover, Section 3.23 of BA 57/01: Design for Durability issued by the Highways Agency, UK stated that “ECR is not currently advocated for use in highway structures. Experience from structures elsewhere and research evidence suggest that there have been some durability problems associated with the use of ECR. It is particularly prone to coating damage, which may lead to pitting corrosion.”

4.2.2 According to the Technical Report No. 61 by the Concrete Society of UK, epoxy coating acts as an impermeable barrier to the water and oxygen necessary for corrosion. In addition, the coating is an electrical insulator and will interrupt the electrical continuity of a corrosion cell and consequently will prevent carbon-induced corrosion. Carbonated concrete has a lower pH value than normal concrete, and epoxies are more durable in environments that are more neutral. Therefore, it is considered reasonable to infer that epoxy coating should provide durability enhancement in a carbonated concrete environment.

4.2.3 However, for reinforcement in chloride-contaminated concrete, Bertolini et al. (2013) pointed out that while earlier laboratory results confirmed the effectiveness of the epoxy coating in preventing corrosion, doubts arose later about their long-term durability in very aggressive environments. The doubts were borne out by negative experience reported on structures in tropical environment.

4.2.4 A review by Hartt (2012) mentioned that corrosion induced cracking and spalling of marine bridge substructures in the Florida Keys, USA, where ECR was used occurred in the mid-1980’s, just seven years after construction and at approximately the same time as projected for conventional uncoated reinforcement. This resulted in a number of research studies for the purpose of understanding the coating failure mechanism that had occurred and projecting the long-term performance that should be anticipated with ECR. Based upon both laboratory and field studies which reported ECR coating disbondment and underfilm corrosion, the Florida Department of Transportation and the Virginia Department of Transportation had discontinued the use of ECR in 2010.

4.2.5 Although Hartt (2012) reported findings from a comprehensive field survey and laboratory analysis of 240 bar segments from 80 bridge decks with ECR in Pennsylvania and New York of age 4-18 years indicated generally good performance, some locations where the failure process had commenced were identified. Hartt further pointed out that while ECR has outperformed conventional uncoated reinforcement, the performance of ECR and the service life that can be expected in concrete exposed to chloride remain uncertain and some studies have projected an ECR service life of less than fifty years.

4.2.6 Sagues et al. (2009) also carried out a study on the corrosion performance of ECR over a nearly 30 year service life period in Florida marine bridges, which included 5 major bridges in the Florida Keys. The study found that for bridges built with permeable concrete of high apparent chloride diffusivity (D_{app} ~$10^{-7}cm^2/s$), corrosion damage was first observed at a service age of 6 to 12 years and increased until the then 25-year age of the bridges with no indication of slowdown. For bridges built with concrete of lower D_{app}, and larger concrete cover, recognizable corrosion damage began to be noticeable approximately 2 decades after construction and continued into the 3rd decade. For bridges built with very low permeability concrete having corresponding low D_{app} (~$10^{-9}cm^2/s$), no severe corrosion developed. However, there was widespread disbondment of the epoxy coating even in sound concrete locations. Although early corrosion was not observed at these locations, significant corrosion was observed at previously cracked locations of one of the bridges, giving an important warning of potentially severe local damage in the future.

4.2.7 An evaluation of the use of Scotchlite 213 ECR in Oregon coastal environment by Griffith and Laylor (1999) has been conducted based on literature documenting previous studies and the Oregon Department of Transport' s testing and evaluation conducted in 1989 and 1998. The use of Scotchlite 213 ECR for long term protection against corrosion in coastal bridges was not recommended.

4.2.8 Sagues et al. (2009) in their paper proposed a corrosion development scenario for ECR which was generally in agreement with results of their investigations and surveys. Stages before and after the structure is put in service (the pre-placement in service stage and the in service stage) are considered. In summary, the corrosion was viewed as resulting from the presence of allowable (per specification prevalent at the time of manufacturing) production imperfections which were then aggravated by fabrication, handling, and a severe construction yard environment. This was followed by placing the ECR in structures exposed to a moist, warm, high chloride-level environment which was conducive to severe corrosion.

4.2.9 In summary, due to doubt on reliability, the usage of ECR is not recommended in many advanced countries including UK and USA.

4.3 Applications

4.3.1 As the effectiveness of ECR relates to the amount of defects in the coating, stringent control measures need to be put in place in the manufacturing, fabrication, handling, storage, placing and fixing of ECR if they are used. The practicality of implementing all these measures to assure absence of defects in the coating should be demonstrated by designers/contractors proposing their use.

5. STAINLESS STEEL REINFORCEMENT

5.1 Material

5.1.1 Stainless steel is defined in BS EN 10088-1 as steel that contains a minimum of 10.5% chromium, a maximum of 1.2% carbon, and have a high resistance to atmospheric corrosion.

5.1.2 Stainless steel is not a single specific grade of steel but a family of steels with a wide variety of characteristics with respect to physical and mechanical properties as well as resistance to corrosive environments. There are mainly four types of stainless steel, namely austenitic, ferritic, martensitic and duplex stainless steels. Amongst these four types of stainless steel, only austenitic and duplex stainless steels are recommended for use as reinforcement in concrete because of their high corrosion resistance.

5.1.3 Stainless steel derives its corrosion resistance from the naturally occurring chromium rich film that is present at the steel surfaces. The chromium creates an invisible surface film to resist oxidation, which helps to make the stainless steel corrosion resistant.

5.1.4 GS Clause 15.04 states that stainless steel bars for reinforcement shall be ribbed bar to BS 6744. The steel designation numbers are in accordance with BS EN 10088-1. The requirements on sampling, testing and acceptance criteria shall follow BS 6744.

5.2 Performance

5.2.1 Stainless steel is considered to be homogeneous and its properties do not vary through its thickness. The corrosion resistance is a bulk property of stainless steel. Therefore, the integrity of stainless steel is unaffected if its surface is cut or damaged during handling.

5.2.2 The corrosion resistance of stainless steel has been well-proven. Studies have demonstrated that solid stainless steel bars can provide significantly improved corrosion resistance in severely corrosive environments.

5.2.3 Bertolini et al. (2013) and Bonhi (2005) both observed that although stainless steel exhibits a great corrosion protection performance, other types of corrosions may also occur on stainless steel. Particularly, stainless steel can suffer pitting corrosion like conventional reinforcement in chloride-contaminated concrete. Pitting corrosion is the most common form of corrosion on stainless steel in concrete and is due to the interaction between chloride ions and the passive layer. The tendency towards pitting corrosion decreases with decreasing chloride concentration, decreasing temperature and rising pH value. Therefore, stainless steel is basically more resistant to corrosion in concrete (pH values about 8 – 13) than they are in atmospheric weather conditions.

5.2.4 The chloride threshold value (C_T) is the chloride concentration for passive film breakdown and active corrosion initiation of the alloy. Hartt (2012) compared the C_T of conventional steel reinforcement and two types of stainless steel reinforcement, namely UNS-S41003 (3Cr12) and A1035 (MMFX2^{TM}), and reported that the mean value of C_T for these stainless steels is approximately four times greater than that of conventional steel. The study also indicated that the time of corrosion initiation for these stainless steel reinforcements is about 63 years and concluded that a low maintenance service life of 75 and even 100 years can be expected. It is noted that the stainless steel reinforcements used in the study, i.e. 3Cr12 designated 1.4003 with 12% chromium and MMFX2^{TM} with 9% chromium, are of lower grade than the stainless steel reinforcement listed in BS 6744. Therefore an even longer service life can be expected for stainless steel grades listed in BS 6744.

5.2.5 Li et al. (2017) highlighted the cost-effective use of stainless steel reinforcement in several overseas projects for increasing the service life of bridge structures.

5.3 Applications

5.3.1 According to the Technical Report No. 51 by the Concrete Society of UK, Grade 1.4301 stainless steel will provide a suitable material in many cases against corrosion. However, where chloride-induced pitting corrosion may occur in coastal environments, specifying the use of Grade 1.4436 stainless steel may be prudent. BS 6744 also gives guidance on the selection of grades of stainless steel reinforcement.

5.3.2 There is a theoretical risk of bimetallic corrosion causing accelerated damaged to the carbon steel if stainless steel reinforcement is used in conjunction with conventional steel reinforcement. However, research has shown that in practice this risk does not occur and it is unnecessary to provide electrical isolation between two different steels when both bars are cast in new concrete (BA 84/02).

5.3.3 Although stainless steel reinforcement has well proven corrosion resistance performance, its high material cost renders hesitations on the use of this corrosion protection method. Taking into account the high cost of stainless steel, Bohni (2005) considered that it is possible that stainless steel could be used only as the outer layer(s) of reinforcement (e.g. in the splash zone of the coast). The combined use of stainless steel and conventional steel reinforcement is a way to reduce project cost.

5.3.4 In the combined used of stainless steel and conventional steel reinforcement, the provision of the outer layer(s) of stainless steel reinforcement (normally crossing reinforcements in two directions) serves to provide additional concrete cover to the conventional steel reinforcement inside to delay the time of ingress of deleterious agents to the surface of the conventional steel reinforcement. Additionally, the stainless steel reinforcement layer(s) also serves to control crack width at the concrete surface and hence provide further protection. In view of the high cost of stainless steel, designers should consider minimizing the diameters of the outer layer(s) of stainless steel bars for providing additional protection to the conventional steel reinforcement, taking into account also other requirements of the design codes and guidelines such as strength and crack control etc. Normally, a total thickness of the outer layer(s) of stainless steel bars of between 30mm to 45mm may be sufficient.

Nonetheless, it should be ascertained by project-specific assessments.

6. STAINLESS STEEL CLADDED REINFORCEMENT

6.1 Material

6.1.1 Stainless steel cladded reinforcement is a core of ordinary carbon steel encapsulated in a thin stainless steel sheath for corrosion resistance. The outer stainless steel cladding is metallurgically bonded to the carbon steel core during hot rolling. It can significantly reduce the material cost and therefore it is considered to be a viable alternative to stainless steel reinforcement because of its lower material cost.

6.2 Performance

6.2.1 There is very limited local experience of using stainless steel cladded reinforcement in highway structures.

6.2.2 A study carried out by Kepler et al. (2000) concluded that the stainless steel cladded reinforcement corroded at a rate of about two orders of magnitude lower than that of conventional steel reinforcement, except in cases where the carbon steel core at the ends of the bars was exposed to the test solution, in which case the stainless steel cladded reinforcement behaved similarly to steel reinforcement.

6.2.3 Another study conducted by Lien Gong (2006) at the University of Kansas concluded that the stainless steel cladded reinforcement exhibited good corrosion resistance. No corrosion or cracking of concrete was observed in any of the stainless steel cladded reinforcement specimens tested. Although a crack in the cladding was observed using a scanning electron microscope, the crack did not penetrate the stainless steel.

6.2.4 In the above studies, intact/undamaged stainless cladded reinforcement with protected ends in general demonstrated satisfactory resistance against corrosion.

6.2.5 The combination of conventional and stainless steel cladded reinforcement could also be considered. The study conducted by Lien Gong (2006) showed that it would not increase the corrosion rate on either material.

6.3 Applications

6.3.1 Compared to solid stainless steel, a disadvantage of stainless steel cladded reinforcement is that the cladding may be damaged during shipping, handling or bending. Moreover, two ends of each bar should be capped, otherwise, if areas of carbon steel are exposed in the concrete, those areas will corrode.

6.3.2 A set of comprehensive design standards and specifications for stainless steel cladded reinforcement in Hong Kong is currently not available.

7. CATHODIC PROTECTION

7.1 Basic Principle

7.1.1 Cathodic protection is a technique to minimize corrosion of a metal surface (e.g. steel reinforcement) by applying a small amount of direct electric current to the metal from an external anode through an electrolyte (e.g. concrete) such that the metal becomes cathodic.

7.1.2 There are two types of cathodic protection system, namely impressed current system and sacrificial anode system.

7.2 Impressed Current System

7.2.1 The system employs an external power source and applies an electrical current between an anode and the reinforcing steel to be protected. The reinforcing steel is forced to become cathodic and the anode material is consumed at negligible or controlled rate. Cathodic protection is accomplished by providing an external current source connecting to the corroding steel where localized corrosion cells occur. The current leaves an auxiliary inert anode and enters both the cathodic and anodic areas of the corrosion cells through the electrolyte (concrete) and return to the external electrical source by the metallic path (steel reinforcement). When the cathodic areas are polarized by external current to the open circuit potential of the anodes, all steel surfaces are at the same potential and local current will no longer flow. The steel does not corrode so long as the external current is maintained.

7.2.2 Visual inspection and regular checks at the power supply to ensure proper operation of the impressed current system are required. The regular checks should entail measurement of the voltage and current for each anode zone. The most important operating parameter is to ensure that the supply of direct current from the rectifier to the structure is in accordance with the operation and maintenance manual. Remote monitoring systems may also be incorporated to facilitate monitoring of the rectifier.

7.2.3 According to the study carried out by Nash et al. (1994), reduction of the life of the anode and hydrogen embrittlement can occur if a structure is overprotected by impressed current cathodic protection systems.

7.3 Sacrificial Anode System

7.3.1 Steel is connected to a sacrificial anode, usually made of zinc, magnesium or aluminum in an electrolyte. The anode corrodes, giving up electrons to protect the steel which behaves as the cathode because the anode is more active in terms of electrochemical potential.

7.3.2 The system requires no external source of power and only needs low maintenance activities such as routine checks on the potentials achieved.

7.3.3 The protection current in a sacrificial anode system decreases with time so that the anodes eventually become passive and the system is no longer effective. System life can be extended by installing replacement anodes. Unforeseen areas of high current demand can be accommodated by the installation of extra anodes close to the affected areas.

7.4 Performance

7.4.1 Polder et al. (2013) assessed the performance of cathodic protection systems on 150 concrete structures in Netherlands. The study showed that working lives of cathodic protection systems without major intervention of ten to twenty years have occurred in practice; corrosion and related damage to concrete has been absent in all documented cases. When intervention was necessary, it was mainly related to defective details such as local leakage or poor electrical isolation. Survival analysis of 105 documented cases suggests that minor interventions are increasingly necessary with increasing age.

7.4.2 In accordance with the Port Works Division (2009), some embedded components such as ribbon mesh anodes of Impress Current Cathodic Protection systems could have service life in excess of 50 years. However, the electrical power supply and monitoring system needs replacement at about 20 to 25 years. With proper inspection/regular checks and maintenance of the protection systems, the service can be further extended.

7.5 Applications

7.5.1 As per Kepler et al. (2000), cathodic protection can effectively stop corrosion in contaminated reinforced concrete structures and can reduce the concentration of chloride ions at the surface of protected reinforcement.

7.5.2 However, cathodic protection is not recommended for prestressed concrete structures with non-uniform resistivity, as it is difficult to obtain sufficient protection at locations where resistivity is high without generating hydrogen in areas of low resistance.

7.5.3 In Hong Kong, highway structures are designed for a 120-year service life. The cost of continuous operation of the system as well as data monitoring over the long service life can be a significant outlay. Furthermore, repairing of the system can be difficult and time-consuming, for example, in identifying the causes of defects, determining the defective locations and extents, rectifying problems related to electrical connectivity, etc. Therefore, specialist inputs in the system design, installation, maintenance, operation and data monitoring are necessary to ensure the effectiveness in the application of cathodic protection.

8. CHOICE OF CORROSION PROTECTION MEASURES

8.1 Selection Considerations

8.1.1 In selecting a corrosion protection method, designers should take into account the purposes, constructability and specific environment of the project as well as the cost effectiveness of the method. In particular, the applicability of the corrosion protection method with respect to the specific environment should be carefully considered. There are various corrosion protection methods available and designers are not confined to the options described in these guidance notes. Moreover, combination of different corrosion protection methods can be considered.

8.1.2 Epoxy coated reinforcement: Local experience in the use of ECR in highway structures is very limited. Overseas experience and studies show that the performance of ECR against corrosion remains uncertain. Its performance is related to the amount of defects in the coating and therefore stringent control measures have to be implemented from the manufacturing to construction to ensure its reliability against corrosion. As there is always a risk of damaging the coating of ECR during manufacturing, delivery and construction even under stringent control, the use of ECR in coastal highway structures within the tidal/sub-tidal zones or exposed to sea water splash and spray is not recommended. If ECR is adopted in other parts of highway structures, its use should be well justified by detailed project-specific assessments based on the latest knowledge and data available.

8.1.3 Stainless steel reinforcement/stainless steel cladded reinforcement: Stainless steel reinforcement exhibits satisfactory corrosion resistance in aggressive environment. However, in view of its high material cost, detailed project-specific assessments based on the latest knowledge and data available should be carried out to justify the use of stainless steel reinforcement and, in particular, to substantiate how the saving in maintenance and repair costs etc. can outweigh the initial cost. Where the use of stainless steel is necessary, designers may consider adopting a combination of stainless steel and conventional steel reinforcement or stainless steel cladded reinforcement in structural detailing to reduce the overall cost. It should be noted that like ECR, intact/undamaged stainless steel cladded reinforcement with protected ends is important to ensure satisfactory resistance against corrosion.

8.1.4 Cathodic protection system: The system can effectively stop corrosion of reinforcement in concrete if it is properly designed/installed. However, this method is still not common in Hong Kong and good practices have yet to be developed. Besides, long-term monitoring and maintenance issue have to be addressed. Designers should note that the efficiency of the system can be affected by poor electrical continuity and the associated repair cost is high. Therefore, the electrical continuity has to be checked carefully in structural detailing during design stage and steel fixing prior to concreting during construction stage. Designers may consider adopting the cathodic protection at the later stage of the working life of the structure when the external deleterious agents is about to reach the surface of the steel reinforcement. To achieve this, provisions have to be allowed in the design of the concrete structure to apply the cathodic protection system and regular monitoring of chloride ingress into the concrete should be carried out to ensure timely application of cathodic protection. Specialist input is required on the design, construction, operation, data monitoring and maintenance of the system.

8.1.5 Apart from the above mentioned measures for steel reinforcement, the use of a concrete mix with high density and with adequate concrete cover for steel reinforcement together with the application of protective coatings, such as epoxy coatings, polyurethane coatings, etc., on the concrete surface may be able to provide more cost effective alternative for enhancing the durability under the circumstances considered. In this connection, the specification given in Appendix 21.2 of Section 21 of the GS for reinforced concrete in marine environment should be adopted. Designers should also consider including the requirement of rapid chloride ion penetration test (RCPT) in accordance with Section 19 of Construction Standard CS1, together with the RCPT compliance criteria adequate to the structures. Reference should be made to Clause 6.8.3 on “Protective Coatings for Concrete” in Port Works Design Manual Part 1 with regard to the application of these measures for corrosion protection in marine structures. Designers should also refer to relevant documents for the latest information on protective coatings.

8.1.6 For those concrete highway structures within the tidal/sub-tidal zones or exposed to normal sea water splash and spray, such as the pile caps, a more promising and reliable corrosion protection method, like the use of stainless steel reinforcement, should be adopted in view of the difficulty in applying/renewing protective coatings and the high cost to be incurred in carrying out inspection, maintenance and repair works in the sea.

8.2 Cost Comparison

8.2.1 The costs of various corrosion protection methods vary from one application to another. Designers should make use of up-to-date cost data and take into account the conditions of the structure in cost evaluation. The cost information given in the paragraphs below can serve as a rough indication of the relative order of cost for different corrosion protection methods discussed.

8.2.2 According to Technical Report No. 61 by the Concrete Society of UK, the price of ECR is approximately 20-35% more than the price of equivalent uncoated reinforcement, inclusive of supply and installation.

8.2.3 Study conducted by Kepler et al. (2000) indicated that with respect to normal steel reinforcement, the in-place cost of stainless steel reinforcement is about 5 times higher. Bertolini et al. (2013) mentioned that with respect to normal steel reinforcement, use of ECR costs about twice as much and the cost of stainless steel is about 5 to 10 times higher.

8.2.4 Only limited references can be made to the cost of stainless steel cladded reinforcement. In accordance with Lien Gong (2006), the in-place cost of cladded reinforcement is about twice that of the normal steel reinforcement.

8.2.5 The above overseas references indicated that if the in-place cost of using normal steel reinforcement is 1, the cost of using ECR is about 2, stainless steel reinforcement about 5 to 10 and stainless steel cladded reinforcement about 2. Available contract rate data from previous local contracts for ECR and stainless steel reinforcement also indicate similar price ratios.

8.2.6 For cathodic protection, the in-place cost and subsequent operation, maintenance, replacement and data monitoring costs over the service life should be considered. To optimize the cost of cathodic protection, designers with agreement of the maintenance authority, may consider adopting the cathodic protection at the later stage of the working life of the structure when the external deleterious agents is about to reach the surface of the steel reinforcement. In this regard, provisions should be allowed in the design to monitor the ingress of deleterious agents in the concrete and allow timely application of cathodic protection during the working life of the structure when necessary.

8.2.7 On the use of a concrete mix with high density in marine environment with adequate concrete cover together with the application of protective coatings on the concrete surface, designers should look into this alternative in detail for structures above the tidal and normal sea water splash zones as it may be able to provide a more cost effective design for enhancing the durability of reinforced concrete if its reliability can be affirmed.

8.2.8 In any case, project office should seek comments on the proposed corrosion protection method from the maintenance authority in order to ensure that the proposed corrosion protection method can fully satisfy the durability requirements and maintenance considerations.

8.3 Life-Cycle Costing

8.3.1 The life time cost of a concrete structure is a combination of construction, operation and monitoring, maintenance and repair costs occurring within the service life of the structure.

8.3.2 The use of Net Present Value (NPV) can be adopted to estimate the present cost of future maintenance, repair, operation and monitoring. The total life-cycle cost of a structure is initial cost plus the sum of the NPV of all future costs over the service life.

8.3.3 Designers should evaluate the life-cycle costs of the structure taking into account various options of corrosion protection methods before determining which method to be adopted.

8.3.4 Life-cycle cost analysis (LCCA) of reinforced concrete structures exposed to marine environment involves prediction of time to onset of corrosion of the reinforcing steel, prediction of time for corrosion to reach an unacceptable level, determination of repair schedule after first repair, and estimation of the initial construction cost, future inspection, maintenance and repair costs etc. A number of computer software for LCCA have been developed and some are available on a commercial basis or for free download from the internet. References could be made to their user manuals for the details of the approaches, procedures and considerations involved in the carrying of such analysis.

8.4 Corrosion Monitoring

8.4.1 Designers, with the agreement of the maintenance authority, may consider the installation of corrosion monitoring devices at strategic locations to check the corrosion conditions of concrete and to assess the effectiveness of the corrosion protection control measures. Such monitoring systems shall be designed by qualified specialists. The diagnosis data collected can also provide early warnings on structural durability and guide the maintenance strategies as early as possible.

9. ENQUIRES

9.1.1 Any enquiry on these guidance notes can be directed to the B&S Division of HyD.

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