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Investigation of Chloride Induced Corrosion of Bridge Pier and Life-Cycle Repair Cost Analysis Using Fiber Reinforced Polymer Composites

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INVESTIGATION OF CHLORIDE INDUCED CORROSION OF BRIDGE PIER AND LIFE-CYCLE REPAIR COST ANALYSIS USING FIBER REINFORCED POLYMER COMPOSITES

By

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ABSTRACT

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Bridges are the long term investment of the highway agencies. To maintain the required service level throughout the life of a bridge, a series of maintenance, repair, and rehabilitation (MR&R) works can be performed. To investigate the corrosion deterioration and maintenance and repair practices in the bridge pier columns constructed in chloride-laden environment, a questionnaire survey was conducted within the 50 state Departments of Transportation (DOTs). Based on the survey data, two corrosion deterioration phases were identified. They were corrosion crack initiation phase and corrosion propagation phase. The data showed that the mean corrosion crack initiation phase for bridge pier column having cover of 50 mm, 75 mm, and 100 mm was 18.9 years, 20.3 years, and 22.5 years, respectively. The corrosion propagation phase starts after the corrosion crack initiation. The corrosion propagation is defined in a single term, corrosion damage rate, measured as percentage of area damaged due to corrosion cracking, spalling, and delamination. From the survey, the corrosion damage rate was found 2.23% and 2.10% in the bridge pier columns exposed to deicing salt water and

exposed to tidal splash/spray, respectively. For this study, two different corrosion damage rates were proposed before and after the repair criteria for minor damage repair as practiced by DOTs. This study also presents the collected data regarding the corrosion effectiveness of using sealers and coatings, cathodic protection, corrosion inhibitors, carbon fiber/epoxy composites, and glass fiber/epoxy composites as maintenance and repair technique. In this study, the cost-effectiveness of wrapping carbon fiber/epoxy composites and glass fiber/epoxy composites in bridge pier columns constructed in a chloride-laden environment was investigated by conducting life-cycle cost analysis.

As a repair work, externally bonded two layer of carbon fiber/epoxy and glass fiber/epoxy composites were installed by wet-layup method in full height of the bridge pier column stem. The damaged concrete surface was completely repaired before installing external wraps. Three different strategies were defined based on the consideration of the first FRP repair at three different corrosion deterioration phases. The strategies were to apply FRP as preventive maintenance during corrosion initiation period, to apply FRP during the corrosion damage propagation, and to apply FRP after major damage. For both composites, the strategy to repair bridge pier column at early stage of corrosion damage, which is at the age of 25 year, was observed optimum, and the use of glass fiber composite wraps resulted in lower total life-cycle repair cost. The use of carbon fiber composites in repair found to have lower total life-cycle repair cost for lower discount rate up to 6% when repair is considered at the age of 15 to 20 years.

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CHAPTER 1

INTRODUCTION

1.1 Background

The National Bridge Inventory (NBI) record shows, in 2013, there are 147,870 bridges that are deficient within the highway bridge network. This represents 24.3% of the total inventory of highway bridges. The record also shows that after 30 years of service life, about 15% of the bridges had deficiencies, either due to structural deterioration or due to functional obsolesce. Maintenance, repair, and rehabilitation or replacement requires huge investment in order to improve service condition of the bridge and to assure safety. The Federal Highway Administration (FHWA) estimated total replacement and rehabilitation cost to be about 87 billion dollars in 2012 for structurally deficient bridges within the national highway system and non-national highway system.

Chloride induced corrosion of reinforcement in reinforced concrete (RC) bridge elements is one of the major problem in the highway bridges of the U.S that causes deficiency in bridge elements (Azizinamimi et al. 2013). Concrete mainly gets contaminated due to the chloride ion present in marine water or snow and ice melt water where sodium chloride and calcium chloride have been used as deicing salts. The corrosion deterioration process continues with availability of moisture and oxygen and presence of chlorides ions in the concrete. To prevent the corrosion deterioration in reinforced concrete components, the bridge agencies are looking at newest technologies, materials, and design specifications which can save the rehabilitation and replacement cost (Darwin et al. 2007; Azizinamimi et al. 2013).

The study conducted by Azizinamimi et al. (2013) showed, in present, corrosion prevention and mitigation have been practiced by

- use of corrosion resistant reinforcement i.e. stainless steel, Fiber Reinforced Polymer (FRP) reinforcement, etc.
- use of epoxy coated reinforcement to increase the chloride threshold,
- use of corrosion inhibitors for P^H balance,
- use of cathodic protections or ion extraction methods to reduce chloride content and corrosion reactions, and
- use of concrete cover, high strength concrete, sealants, coatings, and external jackets of FRP, steel etc, to reduce the chloride ion penetration as well as moisture and oxygen diffusion.

FRP composites have been increasingly used for bridge repair and rehabilitation works. In current practice, the bridge agencies are using externally bonded FRP composites as an effective repair option to protect bridge structures from chloride contamination and corrosion. FRP composites consist of carbon fibers reinforced polymer (CFRP) or glass fibers reinforced polymer (GFRP) or aramid fibers reinforced polymer (AFRP) that are embedded in a resin matrix which binds the fibers together. The FRP composites have very high strength-to-weight and stiffness-to-weight ratios as compared to traditional material like concrete and steel. Moreover, fast construction, high durability, ease in handling and transportation, excellent fatigue and creep properties, and aesthetic make it one of the best bridge pier column rehabilitation methods. These composites provide acceptable performance to resist various environmental exposure conditions, such as alkalinity, salt water, high temperature, humidity, chemical exposure, ultraviolet light, and freezing-and-thawing cycles (Zhang et al. 2002; Green et al. 2006; Khoe et al. 2011). FRP composites act as a surface barrier to reduce chloride penetration and moisture that accelerate corrosion (Pantazopoulou et al. 2001; Debaiky et al. 2002; EI Maaddawy et al. 2006; Bae and Belarbi 2009). Due to above mentioned advantages; FRP composite jackets are effective method to preserve bridges and structures for longer service life.

The FRP composites system may vary depending on how they are delivered and installed on site. The commonly used FRP composite systems for the strengthening of structural members are wet layup systems, pre-preg systems, pre-cured systems, and filament winding (ACI 440). The wet layup systems are widely used systems due to its flexibility during installation; however it takes a relatively higher installation time and its quality is relatively lower compared to other methods.

1.2 Scope and Objective of the Study

Pier columns are the major load carrying element of the bridge, and they are frequently exposed to chloride ion either due to splash and/or spray of marine water or due to leakage and splash of deicing salt water. The loss of concrete cover due to cracking and spalling as a result of reinforcement corrosion, loss of confinement due to corrosion of stirrups, as well as loss of cross-section and surface area of longitudinal steel cause reduction in strength and ductility of pier columns.

Many studies have been conducted in the past to determine the chloride ion based corrosion deterioration process, life-cycle costing, and maintenance optimization. Almost all of the studies focused on the deterioration of bridge deck slab and beams. This study mainly focused on the investigation of corrosion deterioration profile and corrosion repair criteria for the reinforced concrete bridge pier columns, as well as maintenance and repair techniques that can be considered for the pier column. In addition, the cost effectiveness of implementing FRP composites wraps in corrosion repair of bridge pier columns at different ages after construction was investigated using total life-cycle repair cost.

The specific objectives of this study are:

- To determine the corrosion deterioration in bridge pier columns constructed in chloride-laden environment and their repair criteria.
- To investigate the different maintenance and repair practices that has been used in the bridge pier columns.
- To assess the cost effectiveness of FRP composites wraps as corrosion repair material by calculating total life-cycle repair cost.

CHAPTER 2

LITERATURE REVIEW

2.1 Corrosion Mechanism

Hansson (1984) suggested that the corrosion of reinforcement steel is an electrochemical process that consisted of anodic and cathodic reactions. The anodic reactions are responsible for loss of metal by the oxidation process and the cathodic reactions consume the electrons from the anodic reactions to produce hydroxyl ions in the availability of oxygen and water. Figure 1 shows the schematic description of corrosion process in reinforcement steel.

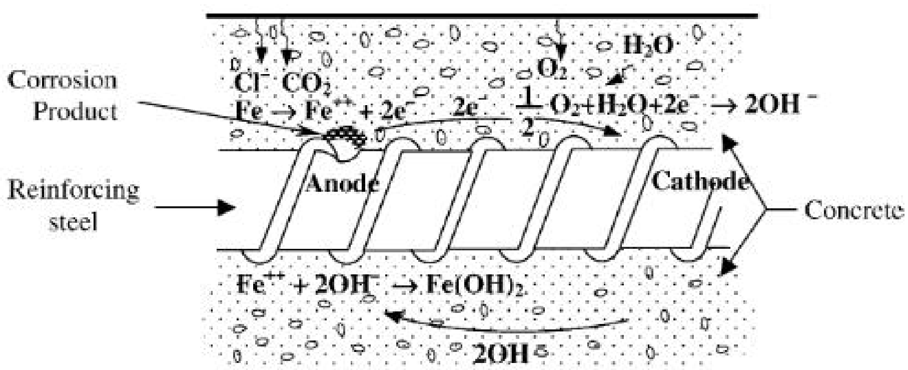

Figure 1. Schematic Illustration of Corrosion of Reinforcement Steel in Concrete as an Electrochemical Process (Ahmad 2003)

The possible anodic reactions in the embedded steel are:

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 8H^+ + 8e^-$$

$$2Fe + 3H_2O \rightarrow Fe_2O_3 + 6H^+ + 6e^-$$

$Fe + 2H_2O \rightarrow HFeO_2^- + 3H^+ + 2e^-$

$Fe \rightarrow Fe^{++} + 2e^-$

The possible cathodic reactions depend on the p^H of the vicinity of concrete and availability of oxygen.

$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$

$2H^+ + 2e^- \rightarrow H_2$

In the absence of other factors, the oxides Fe_3O_4 and Fe_2O_3 create the passive protective layer which serves to prevent the iron cations (Fe++) from entering into the concrete and also acts as a barrier to the oxygen to reach reinforcing steel. The alkalinity of the concrete reduces due to the presence of chloride ions, carbon-dioxide, oxygen, and moisture. Hence the passive layer of the steel decreases and corrosion starts to occur in the embedded reinforcement.

Wryers et al. (1993) suggested the threshold of chloride ions as 0.71 kg/m^3 of concrete in pore water to reach the corrosion initiation level. The natural rusting in the concrete contaminated by chloride ion is:

$Fe^{++} + 2Cl^- \rightarrow FeCl_2$

$FeCl_2 + H_2O + OH^- \rightarrow Fe(OH)_2 + H^+ + 2Cl^-$

$2Fe(OH)_2 + ½ O^- \rightarrow Fe_2O_3 + 2H_2O$

The free Cl^- ions continue to react with Fe^{++} cations as a spontaneous corrosion process with loss in the reinforcement steel area. The iron hydroxide reacts with oxygen ion in pore water to form rust and water. The volume of the rust is 1.7 to 6.15 times higher than the iron and hence causes expansion in concrete. If the stress on concrete exceeds the tensile strength of concrete, cracking would occur that leads to spalling and delamination of the concrete (Liu and Weyers 1998; Pantazopoulou and Papoulia 2001).

2.2 Corrosion Deterioration in Reinforced Concrete Structures

Corrosion of reinforcement is a major deterioration problem in RC bridge structures. It causes the strength deterioration and serviceability loss in the reinforced concrete element. Many studies have been conducted to define the corrosion deterioration process in reinforced concrete structures contaminated with free chloride ion (Hansson 1984; Wryers et al. 1993; Liu and Weyers 1998; Chen and Mahadevan 2008; Zhang et al. 2010). These studies found that the corrosion process mainly depends on the surface chloride content, concrete diffusion property, chloride threshold for reinforcement, concrete cover, diameter of reinforcement, and other environmental factors like humidity, oxygen, carbon dioxide, etc.

Researchers have defined the corrosion of reinforcement in terms of metal loss and corrosion current density based on Faraday's law (Liu and Weyers 1998; Vu et al. 2005; Chen and Mahadevan 2008). Corrosion current density of 1 A/m^2 is equivalent to the corrosion penetration of 1.16mm/year (Hansson 1984). Based on the experiment in RC beam , Zhang et al. (2010) found to develop empirical relation for reinforcement corrosion loss in term of corrosion attack penetration The corrosion deterioration also was explained in terms of the corrosion damage of the surface area due to cracking, spalling, and delamination (Wryers et al. 1993). The rate of damage was identified and used for the prediction of life in case of the bridge deck.

Service life of the RC structure depends on the corrosion deterioration phases and the acceptable damage level. Wryers et al. (1993) described chloride corrosion deterioration process for a concrete in three different stages: diffusion period or corrosion initiation, corrosion period or cracking, and corrosion propagation. The authors used these deterioration processes to determine the rehabilitation time for deck. For the natural chloride induced corrosion, the corrosion pattern was described by Zhang et al. (2010) as shown in Figure 2. The authors conducted the experiment for RC beam and observed the pattern in three phases. The first phase is corrosion initiation phase followed by cracking initiation phase and crack propagations phase. In cracking initiation phase, the local pitting corrosion was observed. The localized corrosion was observed during the first stage of crack propagation followed by general corrosion during second stage of crack propagation.

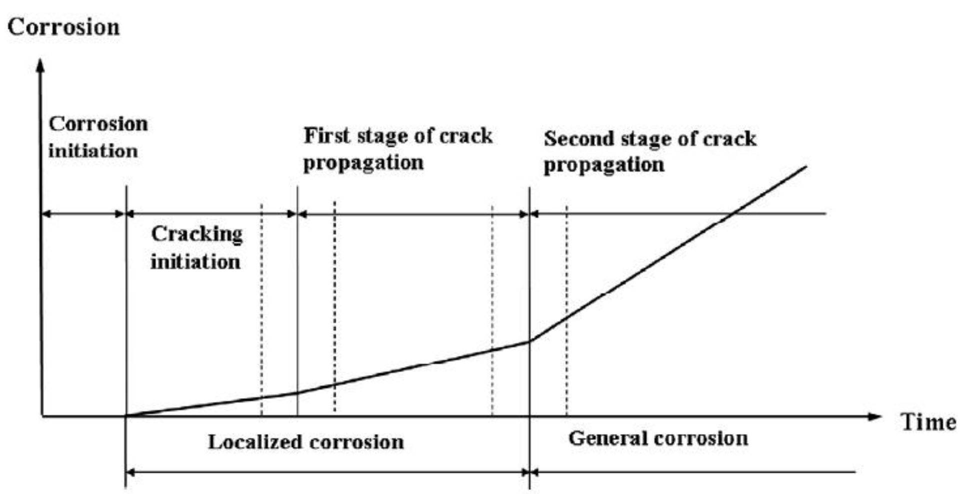

Figure 2. Corrosion Pattern under Natural Chloride-Induced Corrosion (Zhang et al. 2010).

For the bridge pier columns, the effect of corrosion damage and reinforcement loss was studied by Tapan and Aboutaha (2008). The authors mentioned that the effects of corrosion of reinforcement bars causes reduction of the strength of reinforcement, loss in bond between concrete and reinforcement, buckling of deteriorated reinforcement, loss of concrete cover, and cross-sectional asymmetry with significant reduction in load carrying capacity of the column. The authors also found that the effectiveness of reinforcement in transferring loads reach its threshold at 25% corrosion loss of cross section when length of a corroded bar exceed 35 times the diameter of corroded bar. The analytical model was based on moment – axial load (M–P) interaction diagram. Tapan and Aboutaha (2011) further studied the effect of steel corrosion and loss of concrete cover on deteriorated reinforced concrete columns. It was found that the amount of corrosion to cause cracking was dependent on the ratio of concrete cover to longitudinal reinforcement diameter. The corrosion amount was calculated in terms of % loss of cross section area. It was determined that to cause corrosion cover cracking, 5.25% and 2.25% of corrosion amount are required for cover to longitudinal reinforcement diameter ratio (C/D) of 2.5 and 1 respectively. Six cases were studied depending on the corrosion at compression bars, tension bars, left or right side bars, all bars, both compression bars and left side bars, and both tension bars and left side bars of the rectangular column. The corrosion was studied in four stages of deterioration based on the corrosion amount. The stages were at the points when the reinforcement cross section area loss was 4.25%, 10%, 50%, and 75%. The study showed that there is significant reduction in the load carrying capacity of the column at the stage of corrosion amount of 2.25% to10%. The reduction in moment capacity was observed maximum in the case of corrosion in all reinforcement bars.

2.3 Chloride Corrosion Prevention and Repair Practices

In the survey conducted by Azizinamimi et al. (2013), 84% of the DOTs mentioned to use additional cover and 74% of DOTs mentioned epoxy coated reinforcement as a protective measure they were using for bridges in chloride-laden environment. Moreover, use of the corrosion inhibitors, cathodic protection, use of stainless steel, and FRP reinforcement were also mentioned by a few DOTs. For the corrosion protection, different sealers and coating can also be used effectively; however, the use of these preventive measures highly depends on the corrosion severity, exposure type, and structure type (Wryers et al. 1993; Zemajtis and Weyers 1996; Almusallam et al. 2003). The service life of such maintenance was found to be 5 to 7 years when considered in substructure components (Wryers et al. 1993).

Different corrosion repair/rehabilitation methods can be considered for the bridge substructures. The mostly practiced method was to remove all unsound material and to replace it (Azizinamimi et al. 2013). However, the replaced concrete, or patch material should have matching property to protect it from further accelerate corrosion due to different alkalinity. The life of such repair was found to have mean 16.3 years with standard deviation 6.2 years. Moreover, chemical treatments and electro-chemical extractions were also used as the non-destructive repair of bridge elements.

2.4 FRP Composites for Corrosion Repair

Harichandran and Baiyasi (2000) carried out the experiment to study the effects of FRP composites wraps on corrosion-damaged columns. The result from the accelerated corrosion experiment showed that the use of glass and carbon fiber wraps were equally effective in reducing corrosion, and the wrapping was found to reduce the corrosion depth in the reinforcement bar by 46% to 59% after 190 days of testing. This study used three layers of glass fiber-epoxy or two layers of carbon fiber-epoxy composites to repair Michigan bridge pier columns by the wet layup method. The authors found to suggest the use CFRP if the environment is alkaline and/or humid under elevated temperature. The authors also recommended a non-destructive evaluation of the repairs every ten years to monitor the substrate concrete. This experimental study suggested that both glass and carbon fiber systems are equally effective options for rehabilitating corroded columns.

New York State Department of Transportation (NYSDOT) used double layer carbon/epoxy and three and five layer glass /epoxy composites for the repair of damaged reinforced concrete rectangular columns (Halstead et al. 2000). Based on the installation time, traffic interruption, and other effort, the authors recommended FRP composites as an effective means of bridge repair and rehabilitation; however, the life-cycle costing was not considered.

Another study carried out by Debaiky et al. (2002) found to use CFRP composites to study the effect of wrapping at an early stage of corrosion and its effects on propagation of corrosion. The test was carried out on an aggressive environment using impressed current. This study showed that the use of multiple layers of CFRP had the same effect as it had for a single layer, however the use of multiple layers found to improve the strength parameters. Epoxy resin was found to be effective in reducing corrosion acting as a barrier for chloride ion ingress rather than FRP layers. The full wrapping was found effective to reduce corrosion under well monitored installation. The authors reported that wrapping a specimen before starting accelerated natural corrosion will prevent corrosion from taking place, while wrapping the corroded specimen dropped the corrosion current density from 1 to 0.001A/m^2.

Klaiber et al. (2004) found to use single layer of CFRP and GFRP in laboratory as well as field based study in reinforced concrete bridge pier columns exposed to deicing salt water in Iowa State. The single layer of FRP composite was found effective in reduction of chloride penetration, however the test data presented were of only one year.

Green et al. (2006) also observed that FRP wrapping is effective to control corrosion if it is fully wrapped. Repair of corroded columns before corrosion initiation and after corrosion was found to have similar effects in corrosion reduction, i.e. low to moderate corrosion 0.02 to 0.1 A/m^2, and it remained up to three years after CFRP wrapping. The authors recommended two ways of repairs in which one could remove the contaminated concrete and reinforcement or without removal of contaminated concrete, but with conducting regular monitoring of corrosion activity.

EI Maaddawy et al. (2006) reported that CFRP wraps result in a significant reduction of circumferential expansion due to reduction in metal loss by 30% as compared to unwrapped specimens. The authors also concluded that CFRP wrap delays the time from corrosion initiation to visible cracking and is 20 times higher than the unwrapped specimen in chloride contaminated concrete cylinders.

Suh et al. (2007) conducted the study based on laboratory tests to examine the effectiveness of FRP composites in reducing corrosion in a marine environment. 1/3-scale model of prestressed piles were wrapped with CFRP and GFRP composites with 1 to 4 numbers of layers, and tested after the exposure of the sample on simulated tidal cycles in 3.5% salt water. The result showed that, wrapping by FRP composites significantly reduces the metal loss. Both CFRP and GFRP were found effective in reducing corrosion rate by approximately 1/3 in magnitude than that of unwrapped specimens, but were not able to stop corrosion. This study also showed that the number of layers of FRP composite will not affect the corrosion rate. The bond strength of the composite was found to be dependent on the epoxy quality and was found independent of number of layers. GFRP composites were found relatively better in bond strength reduction due to exposure.

Seven different corrosion repair alternatives were studied by Pantazopoulou et al. (2001) using GFRP as a composite wraps for a small scale sample of bridge pier columns with spiral confinement. The GFRP used in the experiment was found to have 4 mm thickness of each layer with 1.7 mm thick fabric. The postrepair performance of each repair alternative in accelerated corrosion conditions were found to be examined based on metal loss, radial strain, uniaxial testing, and failure patterns. The experimental study showed that all the repair options were better than option 1– conventional repair option with removal of damaged concrete cover and replacement by patch of low permeability concrete and then coating, in postrepair performance of corrosion control. Moreover, repair option 2– extension of option 1 with additional 2 layer of GFRP wrap over epoxy coating, and option 3 – alkali resistant epoxy coating and 2 layers of GFRP wrap over the damaged concrete without removal of cover, were found more effective in postrepair performance regarding strength recovery, deformability, as well as corrosion resistivity. However, repair option 3 was found to be easiest and simplest in installation and a cost effective option as well.

Bae and Belarbi (2009) also carried out the experimental study to examine the effectiveness of CFRP wrapping on corroded RC elements. The authors recommended the strength reduction factors for the FRP wrapped concrete columns due to the internal damages in concrete substrate and loss of steel area. The concept of effective area accounted the change in axial rigidity due to steel reinforcement corrosion.

The FRP composite wraps were found effective to reduce the corrosion rate. However, the durability of the material is still the topic under study. The deterioration of mechanical properties of FRP composite wrap system occurred after exposure to certain environments, such as alkalinity, salt water, high temperature, humidity, chemical exposure, ultraviolet light, and freezing-and-thawing cycles. Since, FRP composites are anisotropic, their responses mainly depend on selection of the constituents and the method of fabrication and installation. ACI 440 recommended that the FRP composite system should be selected based on the known behavior of the selected system in the anticipated service condition as suggested by the licensed design professional. Also, the FRP composite type and installation method must be verified by the required durability testing.

Zhang et al. (2002) studied the durability characteristics of E-glass fiber after field exposure of the adhesively bonded system and wet lay-up system used in wrapping of RC columns. The adhesively bonded system found to be failed by exposure effect on adhesive and bond-line whereas the wet lay-up system shows the resin and interface dominated deterioration. The wet lay-up system showed a greater strength reduction than the adhesive bonded system and the strength reduction was dependent on moisture induced degradation.

The study by Green et al. (2006) showed that the freeze-thaw and low temperature exposure cause sudden and brittle failure of FRP wrapped specimens, however the axial strength reduction is about 5% and 10% for CFRP and GFRP and statically insignificant. The author recommended the use of thermal insulator to get a better performance of the FRP composites.

Abanilla et al. (2006) also observed the effect of moisture on the degradation of tensile strength and lowering of glass transition temperature of carbon/epoxy wet lay-up system. The degradation was observed due to the degradation of epoxy and not due to the fabric. The deterioration was found to increase with exposure time period, ambient temperature and number of layers. The author concluded that the wet lay-up system with 2 layers of carbon/epoxy composite has a good level of durability as the time required to reach the threshold set for design tensile strength was predicted to be after 45 years of immersion in deioinzed water at 23ºC.

The effectiveness of the FRP composite wrapping in corrosion protection and durability depends on its ability to keep out both moisture and oxygen. Khoe et al. (2011) experimentally studied the oxygen permeability of FRP laminates. The study showed that the use of the epoxy improves the quality of composite against oxygen permeability. Single layer laminates were found less permeable than two-layer systems. Laminates with random orientation of fiber were found to have higher permeability. The author concluded that the FRP can slow down the corrosion, but can't stop the corrosion as the oxygen permeability coefficient has always the non-zero and positive value.

The service life of the FRP composites repair is important in optimizing the life-cycle cost. In practice, the ACI 440 recommended to use the durability parameters as suggested by manufacturers upon sufficient durability testing and verification by the licensed professionals. Further, ACI 440 recommended the environmental reduction factor for different exposure condition, and for different fiber types. In TR-55, safety factors were found to account the durability and material variability. It further recommended the service life of FRP strengthening work to be 30 years. Moreover, in both of the guidelines, periodic inspection and maintenance are recommended.

Study on the durability of FRP composites showed that the recommended ACI values are more conservatives in terms of strength reduction in the long term (Karbhari and Abanilla 2006). However, Marouani et al. (2012) stated that the ACI 440 underestimate the environmental aging of FRP and epoxy in long term. Moreover, considering risk of failure, the reliability study on the prediction of service life and LRFD design are being developed for FRP composite. NCHRP 665 recommends reliability index 3.5 for the externally bonded FRP design.

2.5 Life-Cycle Cost Analysis Methods

Life-cycle cost analysis (LCCA) is a technique that has been used by the bridge owners, maintenance and rehabilitation engineers, and designers to identify the cost-effective repair and rehabilitate methods based on the total life-cycle maintenance cost of the bridge (Hawk 2003). LCCA includes the set of economic principles and computational technique to determine the economically efficient strategies as well as investment options to ensure the serviceability of the bridges or bridge components. However, choice of the principle and computational technique depends on the availability of information, specific interest or requirements in the bridge network level, bridge system level, or bridge component level by bridge owners and maintenance engineers.

To maintain the serviceability and safety requirements throughout its service life, a bridge, or its components, requires inspection, maintenance, repair, rehabilitation, and replacement. Figure 3 shows the various phases, condition, and cost expended on bridge during its life-cycles (Hawk 2003).

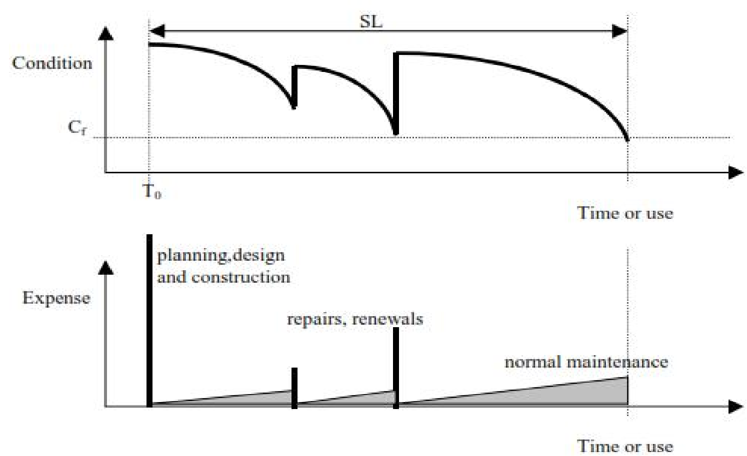

Figure 3. Life-Cycle Activity Profile (Hawk 2003)

The LCCA and optimization method varies depending on the selection of performance measure and evaluation criteria for alternatives. The LCCA includes all incurred costs and benefits throughout the life of structures. The measure of performance or condition may vary based on the owners' evaluation practices. However, in the United

States, NBI condition ratings are used to define bridge performance, which is on a scale of 0-9, where 0 being 'failed condition' to 9 being 'excellent condition'.

Mohammadi et al. (1995) developed a Value Index (VI) model in which three major variables – condition rating, bridge age, and cost were incorporated in terms of single parameter, the Value Index. The VI model was used to quantify the bridge decision making process in order to develop an optimized strategy in managing repair and rehabilitation needs of a given bridge or bridge component. The objective function which describe VI model in terms of rating (r), time (t), and cost (c) is given in Equation 1.

$$VI = r \times t/c = A_s/c \qquad (1)$$

where, A_s = area under condition rating deterioration profile

The improvement in rating and life expectancy of the bridge was expected to increase the VI, and expenditure on the bridge was expected to result in an improvement in its rating. The authors in this model suggested the iteration approach to optimize the objective function, with constraint of cost, time and target rating for different maintenance, repair and replacement (MR&R) events.

Researchers and bridge engineers also used the reliability index as a measure of performance (Frangopol et al. 1997; Stewart 2001; Liu and Frangopol 2004). Liu and Frangopol (2004) used three parameters: initial performance index, time to damage initiation, and a constant deterioration rate, to describe the deterioration performance profile of bridge under no maintenance. Each maintenance intervention, whenever considered, assumed to have effects on the deterioration profile of the bridge components. These effects were: 1) instant improvement of the performance index, 2) delay in the performance deterioration, 3) reduction in the deterioration rate, and 4) loss of functionality of maintenance after a period of effective time. The cumulative life-cycle maintenance cost was calculated as the sum of discounted cost of all maintenance interventions applied during the designated service life. Probability of failure is another important parameter used in the life-cycle cost analysis of the bridge, which accounts for the reliability of the structure as performance measure. The cost associated with the failure of bridge, i.e. cost of failure was found sensitive for the selection of repair strategies (Frangopol et al. 1997; Enright and Frangopol 1999; Stewart 2001) when optimized with targeted lifetime reliability to be greater than or equal to the acceptable reliability index at minimum expected repair cost.

Some other studies used the simulation model calculating the probability of extent of damage due to corrosion using Monte-Carlo method. The spatial-time dependent distribution of random parameters: concrete properties, concrete cover, diffusion, and surface chloride concentration were considered in a simulation-based corrosion model to obtain the probability of damage that can occur at any time (Val and Stewart 2003; Mullard and Stewart 2012). In spatial time-dependent reliability model used by Mullard and Stewart (2012) for bridge deck, the influence of maintenance strategies on the corrosion initiation and propagation time as well as crack initiation and propagation time were also integrated into Monte-Carlo simulation.

For the bridge pier columns, very limited studies were carried out that focused on life-cycle cost analysis. Engelund et al. (1999) used the probabilistic model to determine the optimal plans for repair and maintenance of bridge pier columns subject to a chloride - laden environment. It was suggested that the optimal decision could have been obtained by solving the optimization problem to get minimum cost associated with the probability of maintenance repair at any time. This probability represents the condition at any time when the damage level of structure is less than or equal to the permissible damage or targeted value of damage. The associated cost was calculated as given by Equation 2.

$$C = \sum_{i=T_d}^{T_L} P \ \ repair\ in\ year\ i \ \ C_i \qquad (2)$$

Where T_d denotes the time in years where a decision about the repair strategy is made, T_L denotes the design lifetime of the structures in years, and C_i denotes the cost of repair if it is performed in year i.

The authors studied three different strategies representing possible maintenance of pier to have service life of 50 years. The strategies were implemented if the criteria of damage were satisfied for *n* discretized elements.

- Strategy 1: A cathodic protection was installed for that area towards the tidal and splash zone and rest of the area to be painted at every 15 years. This strategy was when corrosion in the structure had initiated.
- Strategy 2: When 5% of the surface in splash and tidal zone shows minor signs of corrosion, the concrete was repaired and cathodic protection was installed.
- Strategy 3: When 30% of the surface in splash and tidal zone showed distinct corrosion damage, the complete exchange of concrete and reinforcement was done in a corroded area.

The authors conducted the deterministic and probabilistic optimization of three strategies. The strategy to implement preventive maintenance in bridge pier columns was found optimal.

2.6 Gap in Literature

The corrosion repair using FRP composites is the newly introduced concept and its long term performance profile in reducing corrosion and its service life in different exposure are still not documented, though there were many laboratory experiments carried out on those repair options. The consideration of the durability and efficiency parameter of the externally bonded FRP composite in corrosion repair of bridge pier columns in the LCCA model is the new study area.

CHAPTER 3

METHODOLOGY

3.1 Steps of Study

The study involves the following steps as shown in the Figure 4. The study scope, objectives and literature review findings were discussed in previous chapters.

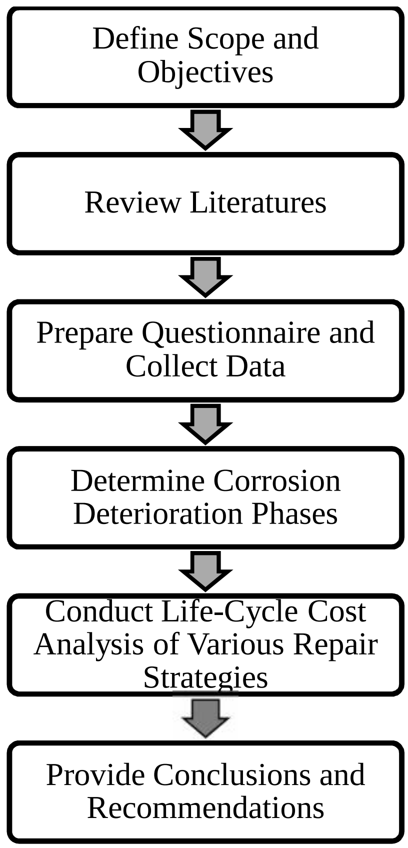

Figure 4. Research Steps

3.2 Prepare Questionnaire and Collect Data

A set of questionnaire was prepared to collect information on the repair practices of reinforced concrete bridge pier columns exposed to chloride-laden environment. The questionnaire consists of six different sections: general information, corrosion inspection and repair decision criteria, preventive maintenance, corrective maintenance, practice of externally bonded FRP composite in corrosion repair, and cost data. The questionnaire is presented in Appendix B. The survey was conducted within the 50 State DOTs of U.S. The Qualtrics Survey Software was used to collect survey responses. The survey link was send to bridge personnel in each DOT by means of email and continuous follow-ups were made by email and phone.

3.3 Determine Corrosion Deterioration Phases

Corrosion is spontaneous process that continue with availability of moisture and oxygen when free Cl^- ions continue to react with Fe^{++} cations. The process results in the propagation of corrosion through the length of reinforcement bar along with formation of expansive rust as byproduct. Once the corrosion process starts, the cracking, spalling, and delamination of concrete cover continues to occur.

In this study, the corrosion deterioration process for the bridge pier columns is presented in three phases: corrosion cracking initiation, localized corrosion damage, and general corrosion damage. This process is similar to the Zhang et al. (2010) experimental observation of corrosion pattern in reinforced concrete beam. However, it differs in the estimation of corrosion parameters. Corrosion cracking accounts the corrosion initiation phase and crack initiation phase together. The crack initiation period is obtained from the survey. The corrosion propagation is defined in a single term, corrosion damage rate, measured as percentage of area damaged due to corrosion cracking, spalling, and delamination.

Localized corrosion damage is the initial stage of chloride induced corrosion damage process (Hanson 1984; Rodriguez et al, 1997; Zhang et al. 2010). This damage is found to occur first in those areas where the chloride contamination is higher. If the localized corrosion is not cured, further extension of corrosion of reinforcement bar lead to the damage of the larger surface area. Such damage may propagate in a higher rate that leads to the ultimate failure of the structures. This phase of deterioration is defined as general corrosion damage stage. The corrosion deterioration process of the reinforced concrete bridge pier columns exposed in chloride laden environment is developed as in Figure 5. The estimation of the corrosion damage based on this proposed corrosion deterioration process is further explained in Chapter 4.

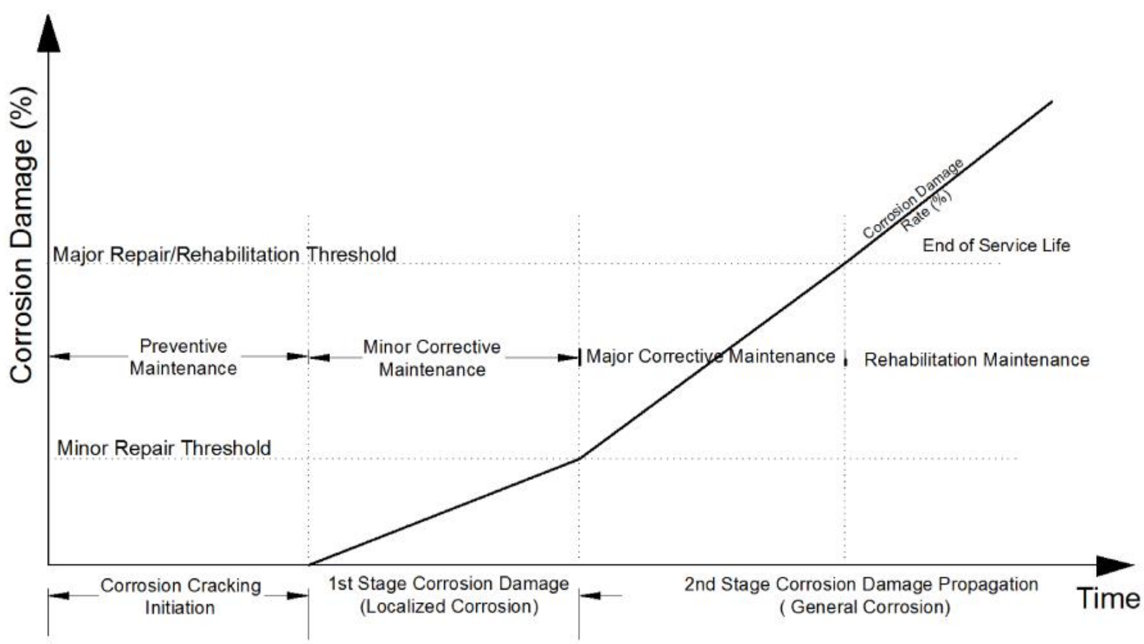

Figure 5. Proposed Corrosion Deterioration Process of Bridge Pier Columns

3.4 Life-Cycle Costing and Decision

Bridge Life-Cycle Cost Analysis (BLCCA) methodology as suggested by Hawk (2003) was modified and used for the repair strategy selection. This methodology was used in BLCCA software developed as the Bridge Management Software. The LCCA formulation given in Equation 4 is used for the life-cycle costing. For the best selected alternatives, the total life-cycle repair cost has minimum present value of all maintenance and repair cost throughout the service life. The total present value of cost is expressed as,

$$PV[C_t] = PV[C_m + C_{rep}] \qquad (4)$$

where, C_t = total life-cycle repair cost

C_m = maintenance cost

C_{rep} = repair cost

PV = represent the equivalent value at the start of analysis

$PV = FV_N / (1+R)^N$

FV_N = future value of expenditure made at time N

N = number of time units between the present and future time

R = prevailing discount rate

CHAPTER 4

SURVEY RESULTS

The corrosion problem and corrosion damage in bridge pier columns constructed in chloride-laden environment was studied through the questionnaire survey. In total, 32 responses were obtained during the survey period of 45 days. In the survey, the leakage, spray or splash of deicing salt water found to be a problem in a majority of the DOTs bridge piers, as shown in Figure 6.

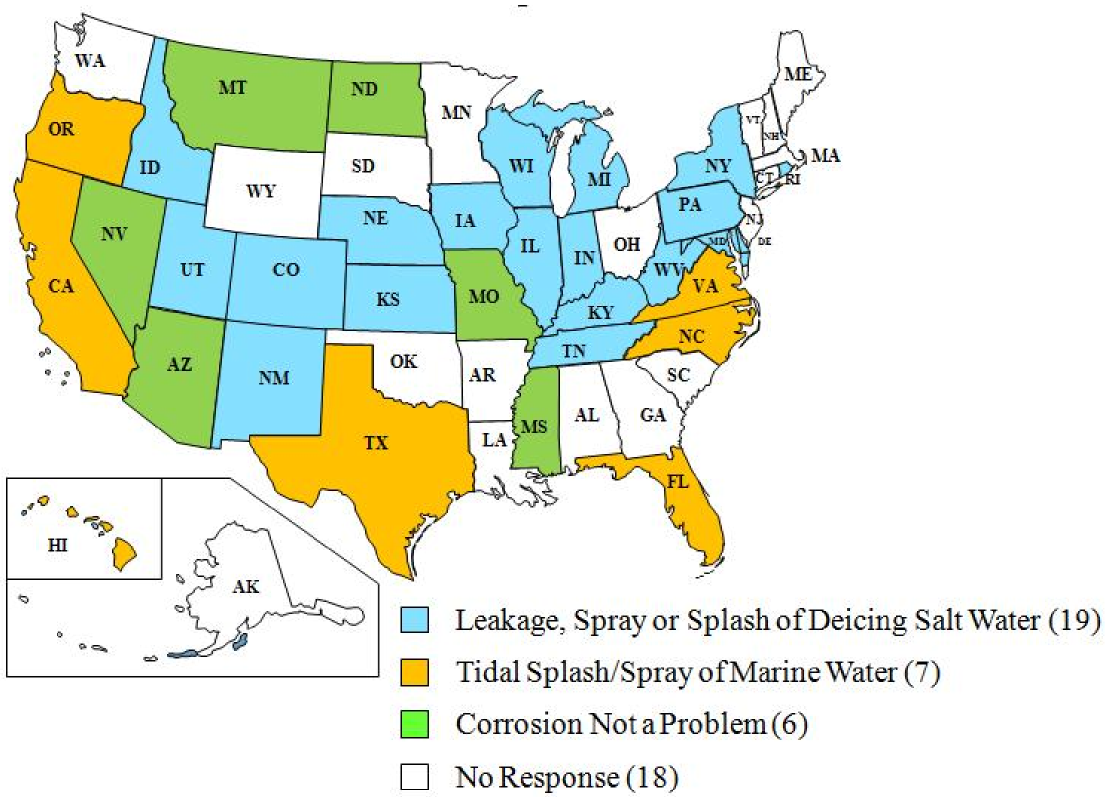

Figure 6. State DOTs with Source of Chloride Contamination Problem in Bridge Pier Columns

Thirty-two state DOTs responded to the survey, out of which, 19 states reported that the corrosion in bridge pier columns is mainly due to the leakage, spray or splash of deicing salt water, 7 states reported the corrosion problem is with the tidal splash or spray of marine water, and 6 states reported corrosion chloride induced corrosion not as a problem.

The quantity of deicing salt used in highways affects the corrosion deterioration and also has influence on the durability specification of using different concrete cover in bridge pier columns. The state DOTs indicating corrosion problem due to the deicer salt were categorized according to the Transportation Research Board (TRB) manual SHRP-S-360 (Wryers et al. 1993). The categories were based on the quantity of deicer salt used in the highways in tons per lane-mile per year.

I. State using of deicing salt < 1400 kg/lane-km/yr [ID,UT,NM,CO, DE]
II. State using of deicing salt 1400 – 2800 kg/lane-km/yr [NE,KS,IA,KY, TN,WV,PA]
III. State using of deicing salt > 2800 kg/lane-km/yr [WI,IL,IN,MD,NY,RI, MI,]

The survey result representing the use of durability specification of using concrete cover in bridge pier columns construction is presented in Table 1. The result showed that the state DOTs are practicing concrete cover thickness based on the severity of exposure environment. The concrete cover of 50 mm and 75 mm of concrete cover was practiced in bridge pier columns constructed in deicing salt water exposure area. For the tidal zone, state DOTs were found practicing higher concrete cover of 75 mm and 100 mm.

Table 1. Number of DOTs Using Various Concrete Cover in Different Exposure Environment

Exposure type	Concrete Cover		
	50 mm	75 mm	100 mm
Exposed to Deicing Salt Water			
I	4	-	-
II	6	5	-
III	4	3	2
Exposed to Tidal splash/spray	2	4	4

4.1 Corrosion Deterioration Process

The corrosion phases for the developed corrosion deterioration process were estimated from the survey data based on the DOTs practice and experiences.

4.1.1 Corrosion Cracking Period

The corrosion crack initiation time includes the corrosion initiation period as well as the corrosion cracking period. The corrosion cracking mainly depends on the surface chloride content, diffusion coefficient, and concrete cover. In this study, the crack initiation time was collected for 50mm and 75mm concrete cover as shown in Table 2.

Table 2. Corrosion Crack Initiation Period for Various Concrete Cover

Exposure type	Concrete Cover		
	50 mm	75 mm	100 mm
Exposed to Deicing Salt Water	Mean = 18.9 years SD = 3.3 years	Mean = 20.3 years SD = 3.2 years	
Exposed to Tidal splash/spray		Mean = 20 years SD = 2.3 years	Mean = 22.5 years

The result showed the crack initiation time depends on the concrete cover provided during the construction. The average corrosion crack initiation period for bridge pier columns was found 18.9 years for concrete cover of 50 mm and that is 22.5 years for concrete cover of 100 mm.

4.1.2 Corrosion Damage Propagation

This study used corrosion damage to measure corrosion in terms of percentage of surface area of bridge pier columns deteriorated due to crack, spall, and delamination. The propagation rate of corrosion represents the damage of concrete surface per year.

- The bridge pier columns exposed to deicing salt water found to have mean corrosion damage propagation rate of 2.23% per year with standard deviation of 0.96%.
- The bridge pier columns in tidal zone found to have mean corrosion damage propagation rate of 2.10% per year with standard deviation of 0.89%.

The results also showed the variation in corrosion damage propagation for each exposure categories as given below, which represents the rank value from the survey response.

- Category I: 1% to 2%
- Category II: 2% to 3%
- Category III: 2% to > 4%

The damage was higher for bridge pier columns constructed on the highways where the quantity of deicing salt use is high. To find the corrosion damage at any point of time, the proposed corrosion damage propagation rates as in Table 3 could be used.

Table 3. Proposed Corrosion Damage Propagation Rates after Corrosion Crack Initiation

Exposure type	1st Stage Corrosion Damage Propagation Rates	2nd Stage Corrosion Damage Propagation Rates
Exposed to Deicing Salt Water		
I	0.5% to 1%	1% to 2%
II	1% to 2 %	2% to 3%
III	2% to 4%	3% to 5%
Exposed to Tidal splash/spray	1% to 2%	3% to 4%

4.1.3 Corrosion Damage Repair Criteria

To identify the repair practices that DOTs follow, the respondents were asked to provide the repair criteria in terms of corrosion damage that is considered for minor repair and major repair or rehabilitation. The obtained repair criteria are shown in Table 4. It can be observed that, in tidal zones, the pier needs frequent consideration of corrosion repair than for piers exposed to deicing salt. It can be said that the continuous exposure of chloride ion in tidal zone requires the treatments more frequently than the seasonal exposure of chloride ion due to deicing salt water.

Table 4. The Corrosion Damage Repair Criteria

Exposure type	Minor Repair or Patching	Major Repair or Rehabilitation	Reinforcement Replacement
Exposed to Deicing Salt water	Mean = 10.6% SD = 4.9%	Mean = 22.9% SD = 10.84%	Mean = 16.1% SD = 6.9%
Exposed to Tidal splash/spray	Mean = 3.6% SD = 2.2	Mean = 15.0% SD = 8.16	

4.2 Corrosion Repair of Bridge Pier Columns

Most of the state DOTs mentioned that they performed regular visual inspection at every 2 years intervals along with other bridge components, however, they did not have any specific corrosion testing schedule, i.e chloride content test, half cell test, etc. for bridge pier columns. A majority of the state DOTs reported that the special corrosion test is considered for pier only when there is need of bridge replacement or rehabilitation.

Preventive maintenance is generally considered before the significant damage of the structure has taken place. Out of 26 states having corrosion problem in bridge pier columns, 14 of them said that they considered performance or need based preventive maintenance strategy, 3 of them found to consider periodic or time based preventive maintenance activities, and also 3 of them found to consider both performance based and periodic maintenance.

The survey asked about different maintenance methods used and their effectiveness when practiced in bridge pier columns. Figure 7 shows the overall responses of using different maintenance activities by 26 respondents. The use of silane/siloxane, epoxy sealers, and epoxy coatings were found mostly practiced in bridge pier columns constructed in a deicing salt exposure environment. The average expected life of such maintenance were found 6 years, 8.3 years, and 9.2 years, respectively with standard deviations of 4.4 years, 4.1 years, and 3.8 years, respectively. Also the average effectiveness in corrosion initiation delay of using silane/siloxane, epoxy sealers, and epoxy coatings were found 7.8 years, 10.5 years, and 10.5 years, respectively with standard deviations of 4.9 years, 3.3 years, and 2.7 years, respectively.

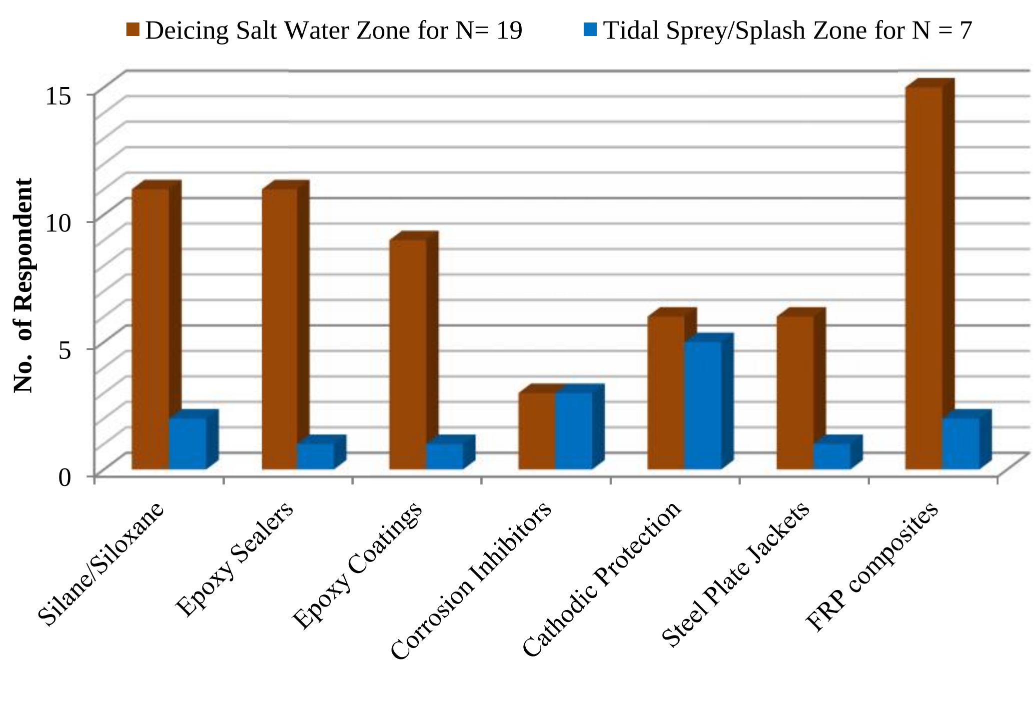

Figure 7. Maintenance and Repair Practices for Concrete Bridge Pier Columns

Cathodic protections were found to be considered in bridge pier columns in 11 states out of 26 states, and sacrificial anode was mentioned by 10 states. Only one state having corrosion problem with tidal spray/splash was found to use impressed current cathodic protection method.

The corrective maintenance is considered for the damaged bridge pier columns to restore the original condition. It can be the minor repairs by concrete patching, or the major repairs/ rehabilitation with replacing the contaminated as well as damaged concrete and reinforcement. After corrective maintenance, use of corrosion inhibitors and cathodic protection can also be considered to prevent further corrosion. For major repair, or rehabilitation, concrete jacketing, steel plate jacketing, and FRP composite jacketing can be considered.

In the survey, only 7 out of 26 states reported to use steel plates in corrosion repair and those repairs were found to have expected repair life of 20 to 35 years. Some states found to suggest that steel plates are not the best option for corrosion repair as the steel plates are also prone to corrosion damage and need periodic maintenance. Use of FRP composites wraps in corrosion repair was reported by 17 out of 26 states. Figure 8 shows the states practicing FRP composites in corrosion repair of bridge pier columns. The DOTs also reported that they do not have measured long term durability data and corrosion efficiency for the FRP repairs.

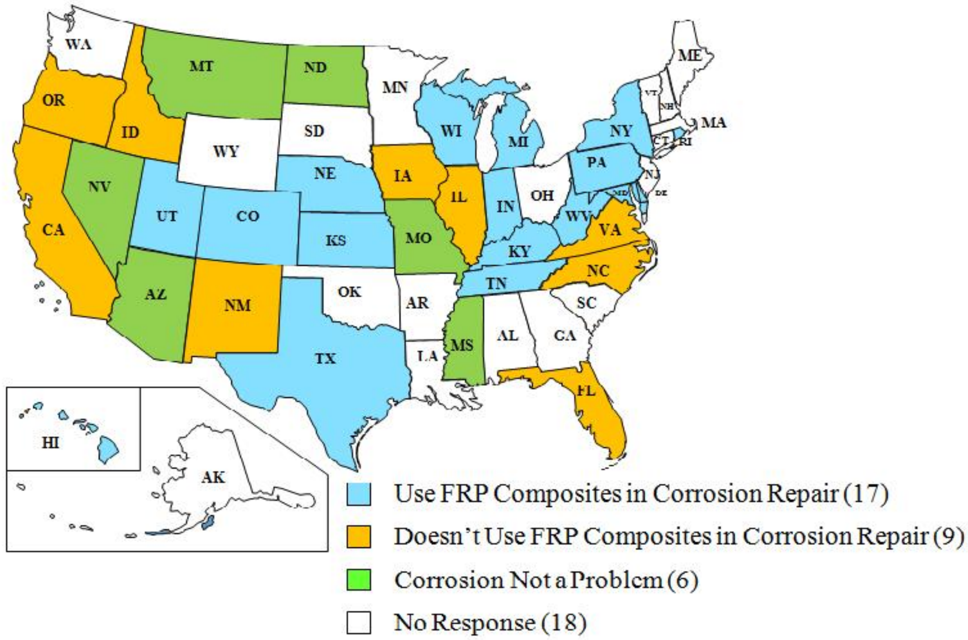

Figure 8. State DOTs Practicing FRP Composites in Corrosion Repair of Bridge Pier Columns

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The state DOTs were asked to provide data regarding number of uses, life, corrosion effectiveness, and deterioration of wet-layup installed CFRP and GFRP wraps composites with epoxy resin in order to repair corroded bridge pier columns. The survey results are shown in Table 5. The failure of the FRP repaired columns can be expected due to the failure of FRP jacket material or due to the failure of substrate. Out of 11 DOTs, 6 of them ranked that the primary cause of failure of repaired column is because of concrete substrate, and 5 of them said that the failure occurred because of failure of FRP composites. The repair criteria for the wrapped columns were also obtained from the survey result. The estimated average deterioration of strength of FRP material and concrete substrate was 25.6% and 21.6% of its original strength, respectively. The survey result showed that CFRP found to have average life of 28.7 years and GFRP found to have 22.04 years.

Table 5. Data Collected for FRP Composite used in Corrosion Repair

Description	Number of Response	Average Value	Minimum Value	Maximum Value
Projects Experience				
CFRP	7	15	1	50
GFRP	9	28	1	50
Average Expected Repair Life (weighted)				
CFRP	6	28.70 years	10 years	50 years
GFRP	5	22.04 years	20 years	40 years
Delay in Corrosion Initiation	10	10.5 years	1-5 years	15-20 years
Corrosion Current Reduction	Most of the DOTs said they do not measure this data. Only two DOTs mention its value to be 95% and 20%.			
Average Thickness and Layers	2 to 3 layers having thickness of 4 mm to 12mm			
Major repair threshold in terms of strength reduction of				
Concrete Substrate	9	21.66%	10%	50%
FRP Jackets	8	25.60%	10%	50%

CHAPTER 5

LIFE-CYCLE REPAIR COST ANALYSIS

A simple deterministic approach was used to calculate life-cycle cost of CFRP and GFRP repair in bridge pier column exposed to chloride environment. The following assumptions were made:

- These composite wraps are used only for the corrosion protection. Double layers of composite wraps are installed by wet-layup method for the full height. The use of double layer of FRP composites were assumed as mentioned by DOTs in the survey.
- The concrete is fully treated before applying composite wraps. The treatment is carried out by removing and replacing all damaged and unsound concrete up to 19 mm depth from the reinforcement. For the cost analysis, the corrosion repair area is increased by a factor of 1.5 times the corrosion damage area obtained from the developed damage profile. The corrosion damage area is increased by 50% to account for the spatial distribution of damage, removal of highly contaminated concrete, and ease of repair.
- The replacement of reinforcement is considered if there was any sign of corrosion observed during inspection.
- Cost associated with the failure of bridge pier column is not considered for this study.
- The design service life of bridge pier column was considered 75 years (AASTHO 2012).

The cost analysis was carried out for a reinforced concrete bridge pier column having diameter of 1 m and exposed stem height of 4.25 m. It has a total surface area of 13.35 square meters. This bridge pier column has a concrete cover of 75 mm. 26 numbers of longitudinal reinforcement having diameter of 28 mm was provided for this bridge pier column. The pier column was assumed to have exposure of the deicing salt water spray or splash in category type III.

5.1 Corrosion Damage

The corrosion deterioration process as discussed in the previous section was used to estimate the corrosion damage in the bridge pier column surface at different years after construction. The following data was used to obtain the damage profile as in Figure 9.

Corrosion cracking initiation = 20 years

Corrosion damage at stage I = 2% per year after corrosion cracking and will continue up to 10% of damage

Corrosion damage at stage II = 4% per year and continue up to a repair threshold of 30% damage

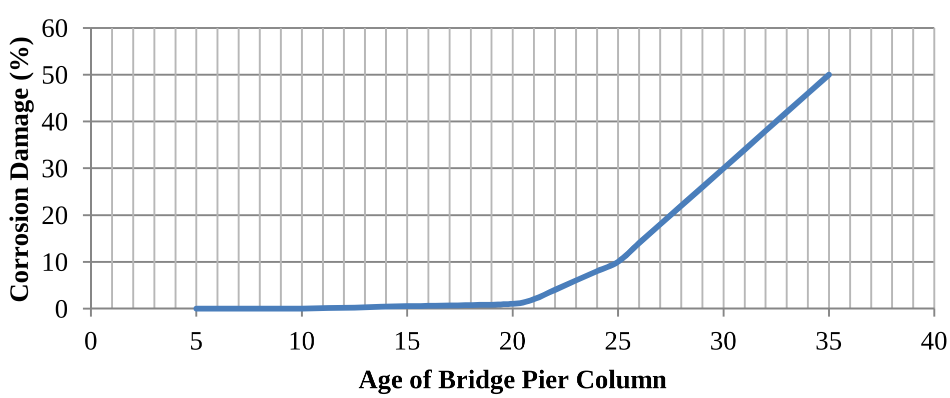

Figure 9. Corrosion Damage at Different Age of Bridge Pier Column

The preventive maintenance should be conducted up to 20 years. After that the corrosion damage starts and needs minor repairs up to 25 years. In between 25 and 30 years, the major repair should be conducted. After 30 years, the bridge pier column is considered for rehabilitation.

5.2 Corrosion Repair

The corrosion repair method includes the removal and replacement of concrete up to ¾” (19 mm) below the reinforcement layer in damaged area. The reinforcement should be replaced if any corrosion is found. Figure 10 shows the typical corrosion damage and concrete repair process.

Figure 10. (Left) Corrosion Damage, (Center) Removal of Concrete and Repair Reinforcement, and (Right) Replace Concrete (NYDOT, 2008)

After concrete repair, double layers of CFRP or GFRP composite wraps impregnated in epoxy resin are installed for the full height of pier stem by wet-layup method. Protective cover coat is also provided after the installation of FRP wraps. The method of installation should follow the manufactures' or owners' specification. The state DOT survey showed that the service life of CFRP and GFRP repair is 30 years and 25 years, respectively. A protective coat/paint is applied at every 10 years after the FRP application based on manufactures' specification.

5.3 Repair Strategy

One of the objectives of this study is to determine the optimum period of repair intervention in bridge pier column based on life-cycle repair cost for these composite materials. Three repair strategies were considered to calculate life-cycle repair cost of CFRP and GFRP composites.

5.3.1 Strategy 1: Intervention before corrosion cracking

The strategy aimed to delay the corrosion repair of the concrete and reinforcement, using these composites as the preventive-maintenance option. The repair schedule consisted of wrapping of the column at the time of corrosion cracking initiation phase up to 20 years. This strategy requires 2 to 3 repairs during the 75 years' of design service life depending upon the time of first repair. The first repair at the age of 5, 10, and 15 years represents this strategy.

5.3.2 Strategy 2: During the damage propagation period

The strategy accounted the concrete repair at an early stage of damage propagation period between 20 and 25 years. Two repairs are sufficient to keep the pier safe up to 75 years. The first repair at the age of 20 and 25 years represents this strategy.

5.3.3 Strategy 3: After major repair damage

This strategy calculated the maximum possible delay of the corrosion repair without any maintenance activities. Major repair of the concrete was considered after the repair threshold of 30% damage. This strategy also requires two repairs. The first repair at the age of 30 and 35 years represents this strategy.

5.4 Repair efficiency

Externally bonded FRP composites with epoxy resin work as a barrier to reduce the ingress of moisture, oxygen and chloride ion. The corrosion effectiveness is measured in terms of corrosion initiation delay, and corrosion current reduction. The corrosion initiation delay and corrosion current data shown below are obtained from the state DOT survey and literature review respectively.

Corrosion initiation delay = 10 years (about 50% of time that is required for unwrapped column).

Corrosion current = after repair, the corrosion current density is assumed 0.2 A/m^2 (2 $\mu A/cm^2$).

After the bridge pier column is wrapped by FRP composites, it is important to determine whether substrate repair is necessary in the subsequent repairs. To determine the time for substrate repair, Chen and Mahadevan (2008) proposed the equation based on loss of reinforcement cross section areas as shown in Equation 5.

$$\text{Loss in diameter (in m)} = 5.9 \times 10^{-11} \times i_{cor} \times \text{time (in sec)} \qquad (5)$$

The survey of state DOTs showed that the substrate repair is necessary only after the loss of reinforcement cross section area due to corrosion is greater than 16%. Using equation 5, it can be determined that it requires about 64 years after the corrosion initiation to lose 16% cross section of steel at current density of 0.2 A/m^2. That means the estimated repair time will be about 64 years plus corrosion initiation time of 30 years. The repair of the substrate concrete can be considered after 60 -90 years of first FRP repair intervention time. Hence, in this study, we do not consider any substrate repair throughout the design service life of bridge pier column when the repair is considered at the early age before corrosion initiation. However, if the repair is considered after corrosion initiation and cracking, and no concrete repair is done before applying FRP, the damage is considered at very low rate (about 0.5%) and concrete is repaired accordingly at next FRP intervention time.

5.5 Cost Data and Price Adjustment

The cost data were collected from DOTs, and then averaged to get the unit price as given in Table 6. The cost of the FRP material with installation was also collected from two of the FRP suppliers, Fyfe Co., and DowAksa USA. The fiscal year 2013/14 was used as the base year for the analysis. The costs presented in the Table 6 incorporate the material cost, labor cost, and installation cost. The time adjustment is done as per Engineering News Record (ENR) price index. The index data from year 1990 to 2013 are used to obtain the adjustment rate of 3.15% per year. After time adjustment of all future investment, the discount rate is applied to account the time value of money. Discount rates of 4%, 6%, 8%, and 10% are used to calculate the sensitivity in investment decisions. The calculation for 6% discount rate is shown in Appendix A as base case.

Table 6. Bridge Pier Column Repair Cost Data for the Base Year of 2013/14

S.N	Activity	Unit	Average Unit Cost
1	Removing and replacing corroded concrete and reinforcement	SM	$ 1087.10
2	CFRP + Epoxy composite by wet layup	SM /Layer	$314.50
3	GFRP + Epoxy composite by wet layup	SM /Layer	$233.87
4	Applying protective coating	SM	$ 26.88

5.6 Result and Discussion

The life-cycle repair costs incurred during 75 years of design service life of the bridge were obtained for CFRP and GFRP composites. Repair activities were scheduled from the first FRP repair at which the age of bridge pier column is 5 year, 10 year, 15 year, 20 year, 25 year, 30 year, and 35 year, respectively.

5.6.1 CFRP composites Repair

The total life-cycle repair cost for CFRP composites are presented in Table 7. The result showed that the implementation of Strategy 1 at the age of 15 year was found cost effective. The Strategy 2 representing the first repair at the age of either 20 year or 25 year showed comparable result in both case however the repair at the age of 25 year showed relatively lower total life-cycle cost. For the Implementation of Strategy 3, the repair at the age of 30 year found cost-effective than to repair column at 35 year. While comparing all three strategies in case of CFRP, optimal repair age found to vary with discount rate. The implementation of Strategy 2 at the age of 25 years was found cost effective at discount rate up to 8% whereas implementation of Strategy 3 at the age of 30 years was found cost effective at the discount rate of 10%.

Table 7. Total Life-Cycle Repair Cost of using CFRP Composites

Strategies	Age of Pier at First FRP Repair (year)	Number of FRP Repair	**Cost/SM at Discount Rate**			
			4%	6%	8%	10%
Strategy 1	5	3	$ 1,579.76	$ 1,005.10	$ 734.09	$ 585.75
	10	3	$ 1,464.65	$ 823.30	$ 544.53	$ 398.70
	15	2	$ 1,141.01	$ 668.85	$ 426.46	$ 290.05
Strategy 2	20	2	$ 1,131.20	$ 597.55	$ 344.34	$ 212.49
	25	2	$ 1,126.91	$ 575.08	$ 317.13	$ 185.00
Strategy 3	30	2	$ 1,310.91	$ 636.14	$ 329.76	$ 179.20
	35	2	$ 1,707.97	$ 789.09	$ 384.93	$ 194.81

5.6.2 GFRP composites Repair

The result of the life-cycle repair cost for GFRP composites are presented in Table 8.

Table 8. Total Life-Cycle Repair Cost of using GFRP Composites

Strategies	Age of Pier at First FRP Repair (year)	Number of FRP Repair	**Cost/SM at Discount Rate**			
			4%	6%	8%	10%
Strategy 1	5	3	$ 1,228.37	$ 779.06	$ 562.45	$ 443.83
	10	3	$ 1,164.58	$ 676.43	$ 446.19	$ 321.61
	15	3	$ 1,181.28	$ 623.12	$ 370.97	$ 241.25
Strategy 2	20	3	$ 1,171.36	$ 559.68	$ 301.70	$ 177.93
	25	2	$ 896.15	$ 468.57	$ 260.17	$ 151.38
Strategy 3	30	2	$ 1,115.54	$ 553.50	$ 289.43	$ 157.45
	35	2	$ 1,504.47	$ 709.36	$ 348.36	$ 176.74

The implementation of Strategy 1 at the age of 10 year resulted in lower life-cycle repair cost at 4% discount rate and for higher discount rates, repair at the age of 15 year was found cost effective. The implementation of Strategy 2 was observed to have different scenario than it was in the case of CFRP since the repair at the age of 25 years showed minimum cost with higher cost different than the case of repairing column at the age of 20 year. In case of Strategy 3, the GFRP resulted in lower life-cycle cost repair at the age of 30 year. While comparing all three strategies, optimal GFRP intervention time found for implementation of Strategy 2 at the age of 25 years for discount rate up to 10%. At 10% discount rate, the repair of column at the age of 25 year showed comparable life-cycle repair cost with the case of considering repair at the age of 30 year.

5.6.3 Comparison of CFRP and GFRP Composites Repair

At discount rate of 8% or higher, the use of GFRP in corrosion repair found to be cost effective than use of CFRP. At 6% discount rate, between 15 and 20 years, both composites showed comparable total life-cycle cost as shown in Figure 11. At 4% discount rate as shown in Figure 12, CFRP composites were found cost effective for repair intervention at 15 and 20 year.

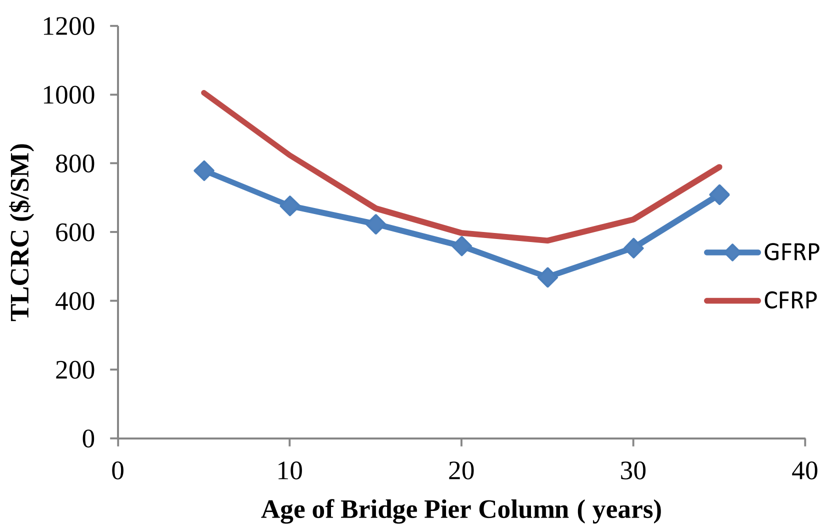

Figure 11. Cost comparison of CFRP and GFRP Composites Repair at 6% Discount Rate

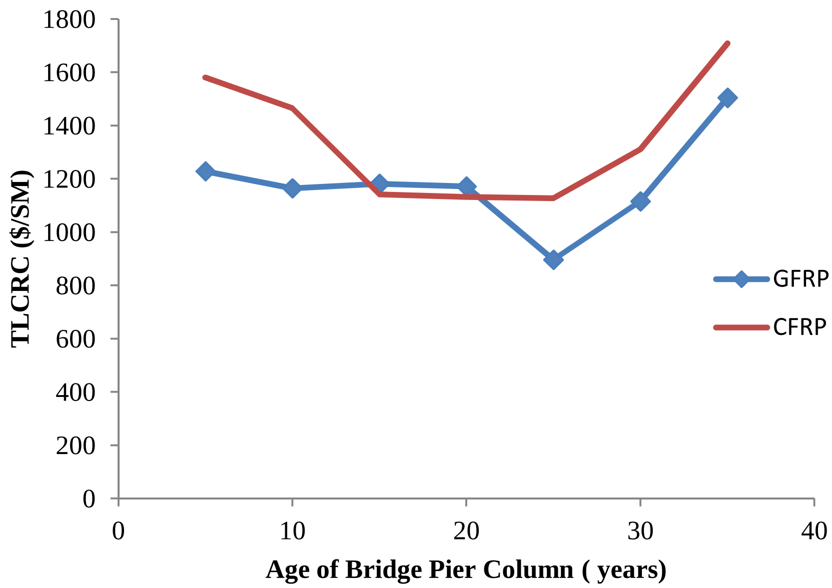

Figure 12. Cost comparison of CFRP and GFRP Composites Repair at 4% Discount Rate

In overall, The Strategy 1 showed higher life-cycle repair cost due to early investment, and more number of FRP repairs needed throughout the design service life than other Strategies. Also Strategy 3 was found to result in lower life-cycle cost for higher discount rate of 10% or more. It can be inferred that, the major repair or rehabilitation of bridge pier column is cost effective than preventive as well as corrective maintenance at a higher discount rate. For a lower discount rate, the Strategy 2 with repair at early stage of damage is found economic which utilizes the corrosion reduction capacity of concrete cover in initial days, and also it utilizes the corrosion reduction properties of FRP composites by minimizing damage propagation and further corrosion of reinforcement bar. In this analysis, we considered the design service life of bridge pier column to be 75 years, however, when FRP composite wraps are used for corrosion repair, the actual service life of the bridge pier column can be extended up to 100 years. The use of GFRP composite wraps provides a more cost effective solution than CFRP composite wraps; however the decision to go with each type of composite depends on durability requirement based on the exposure environment and owner's choice.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the chloride ion based corrosion problem in bridge pier columns and its corrosion repair methods by conducting the survey with 50 state DOTs in the U.S. The corrosion problem in bridge pier column due to leakage and spray of deicing salt water was mentioned by majority of the state DOTs. The state DOTs' experiences were used to identify the two different corrosion deterioration phases – corrosion crack initiation phase and corrosion propagation phase. The mean corrosion crack initiation found to lie between the age of 18 years and 22 years for concrete cover of 50 mm to 100 mm. The corrosion damage propagation rate were 2.23% and 2.10% in the bridge pier columns exposed to deicing salt water and exposed to tidal splash/spray, respectively. Two different corrosion damage propagation rates were proposed for different corrosion exposure condition based on minor repair criteria. By using the repair criteria and the corrosion damage rate, as provided by the state DOTs, the damage level at different deterioration phases of bridge pier columns can be evaluated.

The use of silane/siloxane, epoxy sealers, and epoxy coatings were found mostly practiced in bridge pier columns exposed to deicing salt water. Corrosion inhibitors were found practiced in piers constructed in tidal zone. Also, sacrificial anode is the most practiced cathodic protection in bridge pier columns exposed to deicing salt water as well as exposed to tidal spray or splash. Corrosion repair of bridge pier columns using FRP wraps composites with epoxy were mentioned by majority of the state DOTs. However, they were found to implement CFRP and GFRP wraps in less than 50 projects.

Three different repair strategies were evaluated comparing the total life-cycle repair cost for CFRP and GFRP repair interventions that are considered at different phases of corrosion deterioration. The strategy with repair at early stage of damage is found economic which utilizes the corrosion reduction capacity of concrete cover in initial days. The use of GFRP composite wraps found to be the cost effective solution than CFRP composite wraps, however the decision to go with each type of composite could depends on durability requirement based on the exposure environment and owner's choice.

Externally bonded fiber reinforced composites could be the best alternative repair and protective measure of corrosion problem in bridge pier columns constructed in chloride environment. It could reduce the frequency of the concrete repair works as well as reduce the need of rehabilitation or replacement works in bridge pier column as a result of severe corrosion damage with minimum repair effort and cost. The findings from this study could be further supported by:

- The study on long term durability of repair with single layer of FRP composites wraps based on laboratory or field test, which could provide more economical repair solution.
- The study on benefits of using FRP composites wrap at the time of construction by considering concrete filled tube column or by considering its effectiveness in the reduction in concrete cover of bridge pier column.

APPENDIX A

COST CALCULATION

A.1 Calculation of Total Life-cycle Repair Cost using CFRP at 6% Discount Rate

Strategy 1: 2-Layer CFRP Composite Repair at 5 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	5
FRP Maintenance 1	10
FRP Maintenance 2	20
FRP Repair 2	30
FRP Maintenance 1	40
FRP Maintenance 2	50
FRP Repair 3	60
FRP Maintenance 1	70

Total Surface Area of Pier Column (Square Meter) = 13.35

Price adj% 3.15 Discount Rate 6%

*Base Year 2013 Expected Life upto 2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2018	$ 9,805.69	$ 7,327.38
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2023	$ 489.33	$ 273.24
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2033	$ 667.26	$ 208.05
FRP Repair 2	SM	26.7	$ 314.50	$ 8,397.15	2043	$ 21,291.63	$ 3,707.09
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2053	$ 1,240.74	$ 120.63
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2063	$ 1,691.89	$ 91.85
FRP Repair 3	SM	26.7	$ 314.50	$ 8,397.15	2073	$ 53,986.58	$ 1,636.57
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2083	$ 3,145.99	$ 53.25
							$ 13,418.06
						Per SM	$ 1,005.10

Strategy 1: 2-Layer CFRP Composite Repair at 10 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	10
FRP Maintenance 1	20
FRP Maintenance 2	30
FRP Repair 2	40
FRP Maintenance 1	50
FRP Maintenance 2	60
FRP Repair 3	70

Total Surface Area of Pier Column (Square Meter) = 13.35

Price adj% 3.15 Discount Rate 6%

*Base Year 2013 Expected Life upto 2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2023	$ 11,450.49	$ 6,393.90
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2033	$ 667.26	$ 208.05
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2043	$ 909.89	$ 158.42
FRP Repair 2	SM	26.7	$ 314.50	$ 8,397.15	2053	$ 29,033.62	$ 2,822.71
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2063	$ 1,691.89	$ 91.85
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2073	$ 2,307.09	$ 69.94
FRP Repair 3	SM	26.7	$ 314.50	$ 8,397.15	2083	$ 73,617.01	$ 1,246.14
							$ 10,991.01
						Per SM	$ 823.30

Strategy 1: 2-Layer CFRP Composite Repair at 15 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	15
FRP Maintenance 1	25
FRP Maintenance 2	35
Concrete Repair	45
FRP Repair 2	45
FRP Maintenance 1	55
FRP Maintenance 2	65

Surface Area of Pier Column (Square Meter) = 13.35

Price adj%	3.15	Discount Rate	10%
*Base Year	2013	Expected Life upto	2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2028	$ 13,371.20	$ 3,200.96
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2038	$ 779.19	$ 71.92
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2048	$ 1,062.51	$ 37.81
Concrete Repair	SM	1.34	$ 1,087.10	$ 1,451.27	2058	$ 5,859.56	$ 80.39
FRP Repair 2	SM	26.7	$ 314.50	$ 8,397.15	2058	$ 33,903.72	$ 465.13
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2068	$ 1,975.69	$ 10.45
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2078	$ 2,694.08	$ 5.49
							$ 3,872.15
						Per SM	$ 290.05

Strategy 2: 2-Layer CFRP Composite Repair at 20 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	20
FRP Maintenance 1	30
FRP Maintenance 2	40
Concrete Repair	50
FRP Repair 2	50
FRP Maintenance 1	60
FRP Maintenance 2	70

Surface Area of Pier Column (Square Meter) = 13.35

Price adj%	3.15	Discount Rate	6%
*Base Year	2013	Expected Life upto	2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2033	$ 15,614.09	$ 4,868.55
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2043	$ 909.89	$ 158.42
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2053	$ 1,240.74	$ 120.63
Concrete Repair	SM	2.0	$ 1,087.10	$ 2,176.91	2063	$ 10,263.66	$ 557.20
FRP Repair 2	SM	26.7	$ 314.50	$ 8,397.15	2063	$ 39,590.73	$ 2,149.32
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2073	$ 2,307.09	$ 69.94
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2083	$ 3,145.99	$ 53.25
							$ 7,977.30
						Per SM	$ 597.55

Strategy 2: 2-Layer CFRP Composite Repair at 25 year

Schedule of MR& R activity	Age of Pier
Concrete Repair	25
FRP Repair 1	25
FRP Maintenance 1	35
FRP Maintenance 2	45
FRP Repair 2	55
FRP Maintenance 1	65
FRP Maintenance 2	75

Surface Area of Pier Column (Square Meter) = 13.35

Price adj%	3.15	Discount Rate	6%
*Base Year	2013	Expected Life upto	2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
Concrete Repair	SM	2.0	$ 1,087.10	$ 2,176.91	2038	$ 4,726.85	$ 1,101.35
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2038	$ 18,233.19	$ 4,248.31
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2048	$ 1,062.51	$ 138.24
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2058	$ 1,448.86	$ 105.26
FRP Repair 2	SM	26.7	$ 314.50	$ 8,397.15	2068	$ 46,231.68	$ 1,875.50
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2078	$ 2,694.08	$ 61.03
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2088	$ 3,673.69	$ 46.47
							$ 7,677.34
						Per SM	$ 575.08

Strategy 3: 2-Layer CFRP Composite Repair at 30 year

Schedule of MR& R activity	Age of Pier
Concrete Repair	30
FRP Repair 1	30
FRP Maintenance 1	40
FRP Maintenance 2	50
FRP Repair 2	60
FRP Maintenance 1	70

Surface Area of Pier Column (Square Meter) = 13.35

Price adj%	3.15	Discount Rate	6%
*Base Year	2013	Expected Life upto	2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
Corrosion Inspection	LS	0	$ 200.00	$ -	2043	$ -	$ -
Concrete Repair	SM	6.0	$ 1,087.10	$ 6,530.73	2043	$ 16,559.18	$ 2,883.12
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2043	$ 21,291.63	$ 3,707.09
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2053	$ 1,240.74	$ 120.63
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2063	$ 1,691.89	$ 91.85
FRP Repair 2	SM	26.7	$ 314.50	$ 8,397.15	2073	$ 53,986.58	$ 1,636.57
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2083	$ 3,145.99	$ 53.25
							$ 8,492.51
						Per SM	$ 636.14

Strategy 3: 2-Layer CFRP Composite Repair at 35 year			
Schedule of MR& R activity	**Age of Pier**		
Concrete Repair	35	Surface Area of Pier Column (Square Meter) =	13.35
FRP Repair 1	35		
FRP Maintenance 1	45		
FRP Maintenance 2	55		
FRP Repair 2	65		
FRP Maintenance 1	75		

				Price adj%	3.15	Discount Rate	6%
				*Base Year	2013	Expected Life upto	2088
Activity	**Unit**	**Quantity**	**Unit cost**	**Total Cost ***	**Year of Investment**	**Price adjustment**	**Discounted Cost**
Concrete Repair	SM	13.35	$1,087.10	$ 14,512.74	2048	$ 42,970.72	$ 5,590.71
FRP Repair 1	SM	26.7	$ 314.50	$ 8,397.15	2048	$ 24,863.09	$ 3,234.82
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2058	$ 1,448.86	$ 105.26
FRP Maintenance 2	SM	13.35	$ 314.50	$ 4,198.58	2068	$ 23,115.84	$ 937.75
FRP Repair 2	SM	26.7	$ 26.88	$ 717.70	2078	$ 5,388.16	$ 122.06
FRP Maintenance 1	SM	13.35	$ 314.50	$ 4,198.58	2088	$ 42,982.76	$ 543.69
							$ 10,534.29
						Per SM	$ 789.09

A.2 Calculation of Total Life-Cycle Repair Cost using GFRP at 6% Discount Rate

Strategy 1: 2-Layer GFRP Composite Repair at 5 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	5
FRP Maintenance 1	13
FRP Maintenance 2	21
FRP Repair 2	30
FRP Maintenance 1	38
FRP Maintenance 2	46
FRP Repair 3	55
FRP Maintenance 1	63
FRP Maintenance 2	71

Surface Area of Pier Column (Square Meter) = 13.35

Price adj% 3.15 Discount Rate 6%

*Base Year 2013 Expected Life upto 2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
FRP Repair 1	SM	26.7	$ 233.87	$ 6,244.33	2018	$ 7,291.75	$ 5,448.82
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2026	$ 537.04	$ 251.79
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2034	$ 688.28	$ 202.46
FRP Repair 2	SM	26.7	$ 233.87	$ 6,244.33	2043	$ 15,832.98	$ 2,756.68
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2051	$ 1,166.11	$ 127.39
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2059	$ 1,494.50	$ 102.43
FRP Repair 3	SM	26.7	$ 233.87	$ 6,244.33	2068	$ 34,379.02	$ 1,394.67
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2076	$ 2,532.05	$ 64.45
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2084	$ 3,245.08	$ 51.82
							$ 10,400.50
						Per SM	$ 779.06

Strategy 1: 2-Layer GFRP Composite Repair at 10 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	10
FRP Maintenance 1	18
FRP Maintenance 2	26
FRP Repair 2	35
FRP Maintenance 1	43
FRP Maintenance 2	51
FRP Repair 3	60
FRP Maintenance 1	68

Surface Area of Pier Column (Square Meter) = 13.35

Price adj% 3.15 Discount Rate 6%

*Base Year 2013 Expected Life upto 2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cos
FRP Repair 1	SM	26.7	$ 233.87	$ 6,244.33	2023	$ 8,514.87	$ 4,754.66
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2031	$ 627.13	$ 219.71
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2039	$ 803.73	$ 176.67
FRP Repair 2	SM	26.7	$ 233.87	$ 6,244.33	2048	$ 18,488.81	$ 2,405.49
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2056	$ 1,361.72	$ 111.16
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2064	$ 1,745.18	$ 89.38
FRP Repair 3	SM	26.7	$ 233.87	$ 6,244.33	2073	$ 40,145.76	$ 1,216.99
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2081	$ 2,956.78	$ 56.24
							$ 9,030.29
						Per SM	$ 676.43

Strategy 1: 2-Layer GFRP Composite Repair at 15 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	15
FRP Maintenance 1	23
FRP Maintenance 2	31
Concrete Repair	40
FRP Repair 2	40
FRP Maintenance 1	48
FRP Maintenance 2	56
FRP Repir 3	65

Surface Area of Pier Column (Square Meter) = 13.35

Price adj%	3.15	Discount Rate	6%
*Base Year	2013	Expected Life upto	2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cos
FRP Repair 1	SM	26.7	$ 233.87	$ 6,244.33	2028	$ 9,943.16	$ 4,148.93
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2036	$ 732.32	$ 191.72
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2044	$ 938.55	$ 154.16
Concrete Repair	SM	1.34	$ 1,087.10	$ 1,451.27	2053	$ 5,017.86	$ 487.85
FRP Repair 2	SM	26.7	$ 233.87	$ 6,244.33	2053	$ 21,590.12	$ 2,099.04
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2061	$ 1,590.13	$ 97.00
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2069	$ 2,037.92	$ 77.99
FRP Repir 3	SM	26.7	$ 233.87	$ 6,244.33	2078	$ 46,879.81	$ 1,061.95
							$ 8,318.64
						Per SM	$ 623.12

Strategy 2: 2-Layer GFRP Composite Repair at 20 year

Schedule of MR& R activity	Age of Pier
FRP Repair 1	20
FRP Maintenance 1	28
FRP Maintenance 2	36
Concrete Repair	45
FRP Repair 2	45
FRP Maintenance 1	53
FRP Maintenance 2	61
FRP Repair 3	70

Surface Area of Pier Column (Square Meter) = 13.35

Price adj%	3.15	Discount Rate	6%
*Base Year	2013	Expected Life upto	2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cos
FRP Repair 1	SM	26.7	$ 233.87	$ 6,244.33	2033	$ 11,611.02	$ 3,620.37
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2041	$ 855.16	$ 167.30
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2049	$ 1,095.98	$ 134.52
Concrete Repair	SM	2.0	$ 1,087.10	$ 2,176.91	2058	$ 8,789.34	$ 638.55
FRP Repair 2	SM	26.7	$ 233.87	$ 6,244.33	2058	$ 25,211.65	$ 1,831.63
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2066	$ 1,856.86	$ 84.64
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2074	$ 2,379.76	$ 68.06
FRP Repair 3	SM	26.7	$ 233.87	$ 6,244.33	2083	$ 54,743.43	$ 926.66
							$ 7,471.72
						Per SM	$ 559.68

Strategy 2: 2-Layer GFRP Composite Repair at 25 year

Schedule of MR& R activity	Age of Pier
Concrete Repair	25
FRP Repair 1	25
FRP Maintenance 1	33
FRP Maintenance 2	41
FRP Repair 2	50
FRP Maintenance 1	58
FRP Maintenance 2	66

Surface Area of Pier Column (Square Meter) = 13.35

Price adj% 3.15 Discount Rate 6%

*Base Year 2013 Expected Life upto 2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
Concrete Repair	SM	2.00	$ 1,087.10	$ 2,176.91	2038	$ 4,726.85	$ 1,101.35
FRP Repair 1	SM	26.7	$ 233.87	$ 6,244.33	2038	$ 13,558.65	$ 3,159.15
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2046	$ 998.61	$ 145.98
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2054	$ 1,279.82	$ 117.38
FRP Repair 2	SM	26.7	$ 233.87	$ 6,244.33	2063	$ 29,440.65	$ 1,598.28
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2071	$ 2,168.33	$ 73.86
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2079	$ 2,778.94	$ 59.39
							$ 6,255.39
						Per SM	$ 468.57

Strategy 3: 2-Layer GFRP Composite Repair at 30 year

Schedule of MR& R activity	Age of Pier
Concrete Repair	30
FRP Repair 1	30
FRP Maintenance 1	38
FRP Maintenance 2	43
FRP Repair 2	55
FRP Maintenance 1	63
FRP Maintenance 2	71

Surface Area of Pier Column (Square Meter) = 13.35

Price adj% 3.15 Discount Rate 6%

*Base Year 2013 Expected Life upto 2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
Concrete Repair	SM	6.0	$ 1,087.10	$ 6,530.73	2043	$ 16,559.18	$ 2,883.12
FRP Repair 1	SM	26.7	$ 233.87	$ 6,244.33	2043	$ 15,832.98	$ 2,756.68
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2051	$ 1,166.11	$ 127.39
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2056	$ 1,361.72	$ 111.16
FRP Repair 2	SM	26.7	$ 233.87	$ 6,244.33	2068	$ 34,379.02	$ 1,394.67
FRP Maintenance 1	SM	13.35	$ 26.88	$ 358.85	2076	$ 2,532.05	$ 64.45
FRP Maintenance 2	SM	13.35	$ 26.88	$ 358.85	2084	$ 3,245.08	$ 51.82
							$ 7,389.28
						Per SM	$ 553.50

Strategy 3: 2-Layer GFRP Composite Repair at 35 year								
Schedule of MR& R activity		**Age of Pier**						
Concrete Repair		35		Surface Area of Pier Column (Square Meter) =			13.35	
FRP Repair 1		35						
FRP Maintenance 1		43						
FRP Maintenance 2		51						
FRP Repair 2		60						
FRP Maintenance 1		68						
				Price adj%	3.15	Discount Rate		6%
				*Base Year	2013	Expected Life uptc		2088

Activity	Unit	Quantity	Unit cost	Total Cost *	Year of Investment	Price adjustment	Discounted Cost
Concrete Repair	SF	13.35	$ 1,087.10	$ 14,512.74	2048	$ 42,970.72	$ 5,590.71
FRP Repair 1	SF	26.7	$ 233.87	$ 6,244.33	2048	$ 18,488.81	$ 2,405.49
FRP Maintenance 1	SF	13.35	$ 26.88	$ 358.85	2056	$ 1,361.72	$ 111.16
FRP Maintenance 2	SF	13.35	$ 26.88	$ 358.85	2064	$ 1,745.18	$ 89.38
FRP Repair 2	SF	26.7	$ 233.87	$ 6,244.33	2073	$ 40,145.76	$ 1,216.99
FRP Maintenance 1	SF	13.35	$ 26.88	$ 358.85	2081	$ 2,956.78	$ 56.24
							$ 9,469.97
						Per SM	$ 709.36

APPENDIX B

SURVEY QUESTIONAIRE

This survey is prepared to collect data regarding the maintenance, repair and rehabilitation (MR&R) practices considered by state DOTs for RC bridge pier columns constructed in chloride exposure environment. The collected information will be used to study the MR&R strategies considering the life-cycle cost of RC bridge pier column. Please provide the data being specific to the chloride corrosion repair of RC bridge pier having conventional carbon steel as reinforcement. The data can be based on your field observation, experience, current practice, and research findings. Please provide this information as fully as possible. Your detailed responses will help us to select MR&R alternatives that can be implemented in chloride contaminated environment to extend the service life of RC bridge pier, and also to carry out the life-cycle cost analysis to know the cost effectiveness. The estimated response time to complete the survey is about 20-25 minutes.

Please provide the following details.

	Title (1)	State DOT (2)	Contact Phone or Email (3)
Respondent (1)			

Q.1 Please select the chloride ion exposure environment that your DOT experienced major corrosion problem in RC bridge pier column.

- ❍ Leakage, spray or splash of deicing salt water (1)
- ❍ Within marine/brackish water body (2)
- ❍ Tidal splash/spray of marine water in coastal area (3)
- ❍ Corrosion due to chloride ion is not a problem (4)

Bridge pier inspection and repair decision

Q.2 Please provide the special corrosion inspection interval e.g. chloride content test, half-cell potential test, core test that your DOT practices to detect corrosion in RC bridge pier ?

- ❍ Every 2 yrs (1)
- ❍ Every 5 yrs (2)
- ❍ Every 10 yrs (3)

- Other, please specify (4) ____________________

Q.3 Please specify the average age of bridge pier column at which the first crack due to corrosion is observed for different concrete cover thickness.

	0-4 yrs (1)	4-8 yrs (2)	8-12 yrs (3)	12-16 yrs (4)	16-20 yrs (5)	>20 yrs (6)	Not Applicable (7)
50 mm cover (1)	❍	❍	❍	❍	❍	❍	❍
75 mm cover (2)	❍	❍	❍	❍	❍	❍	❍
100 mm cover (3)	❍	❍	❍	❍	❍	❍	❍

Q.4 Please estimate the corrosion induced cover crack width used to define corrosion damage?

- < 0.2 mm (1)
- 0.2-0.4 mm (2)
- 0.5 -0.7 mm (3)
- 0.8 -1.0 mm (4)
- Other, please specify (5) ____________________

Q.5 Based on your experience and practice, estimate the threshold of damage i.e. crack/spall/delamination area (% of total pier column area) that is considered for localized corrosion repair.

- < 4% (1)
- 4-8% (2)
- 8-12% (3)
- 12-16% (4)
- 16-20% (5)
- Other, please specify (6) ____________________

Q.6 Based on your experience and practice, estimate the threshold of damage i.e. crack/spall/delamination area (% of total pier column area) that is considered for pier column rehabilitation (full concrete surface repair).

- < 10% (1)
- 10-20% (2)
- 20-30% (3)
- 30-40% (4)

- >40% (5)

Q.7 Based on your experience, please estimate the rate of damage per year after corrosion initiation (% spall/delamination area per year) for RC bridge pier in chloride ion exposure without any maintenance.

- < 1% (1)
- 1-2% (2)
- 2-3% (3)
- 3-4% (4)
- Other, please specify (5) ____________________
- Not applicable (6)

Q.8 Based on your experience, estimate the threshold of % section area loss of longitudinal reinforcement that is considered for reinforcement replacement.

- < 5% (1)
- 5-10% (2)
- 10-15% (3)
- 15-20% (4)
- Other, please specify (5) ____________________

Preventive maintenance of RC bridge pier column

Q.9 Please specify the preventive maintenance strategy that you use for RC bridge pier.

- Periodic or time based (1)
- Performance or need based (2)
- Both (3)
- Not applicable (4)

Q.10 Please estimate the following sealers and coating's average life.

	< 2 yrs (1)	2 -4 yrs (2)	5-7 yrs (3)	8-10 yrs (4)	>10 yrs (5)	Not practiced (6)
Silane/siloxane (1)	❍	❍	❍	❍	❍	❍
Epoxy sealers (2)	❍	❍	❍	❍	❍	❍
Epoxy coating (3)	❍	❍	❍	❍	❍	❍

\Q.11 Please estimate the delay in major repair/rehabilitation of RC bridge pier due to application of following sealers and coating.

	< 2 yrs (1)	2 -4 yrs (2)	5-7 yrs (3)	8-10 yrs (4)	>10 yrs (5)	Not practiced (6)
Silane/siloxane (1)	❍	❍	❍	❍	❍	❍
Epoxy sealers (2)	❍	❍	❍	❍	❍	❍
Epoxy coating (3)	❍	❍	❍	❍	❍	❍

Corrective maintenance of RC bridge pier column

Q.12 Please estimate the delay in corrosion initiation time due application corrosion inhibitor in chloride contaminated environment.

	Not Practiced (1)	Not effective (2)	<3 yrs (3)	3-5 yrs (4)	5-7 yrs (5)	7-9 yrs (6)	9-11 yrs (7)	11-13 yrs (8)	Not applicable (9)
Calcium Nitrate based (1)	❍	❍	❍	❍	❍	❍	❍	❍	❍
Organic based (2)	❍	❍	❍	❍	❍	❍	❍	❍	❍
Other, please specify (3)	❍	❍	❍	❍	❍	❍	❍	❍	❍

Q.13 Based on your experience, how would you estimate the corrosion current reduction efficiency due to the application of corrosion inhibitor?

	Not Practiced (1)	Not effective (2)	<3 yrs (3)	20-40% (4)	40-60% (5)	60-80% (6)	80-90% (7)	90-100 % (8)	Not applicable (9)
Calcium Nitrate based (1)	❍	❍	❍	❍	❍	❍	❍	❍	❍
Organic based. (2)	❍	❍	❍	❍	❍	❍	❍	❍	❍
Other, please specify (3)	❍	❍	❍	❍	❍	❍	❍	❍	❍

Q.14 Please indicate the effectiveness of cathodic protection method in case of RC pier column in chloride exposure.

- ❍ Impressed current (1)
- ❍ Sacrificial anode (2)
- ❍ Cathodic protection found not effective for pier (3)
- ❍ Not practiced (4)

Q.15 Please estimate the service life of steel plate jacketing for corrosion repair/rehabilitation.

- ❍ Not practiced (1)
- ❍ < 20 yrs (2)
- ❍ 20-35yrs (3)
- ❍ 35-40 yrs (4)
- ❍ 40-50yrs (5)
- ❍ Other, please specify (6) ____________________

Q.16 Please provide the average thickness of steel plate used for the corrosion repair.

- ❍ < 2 mm (1)
- ❍ 2-4 mm (2)
- ❍ 4-6 mm (3)
- ❍ Other, please specify (4) ____________________

Q.17 Based on your experience, how would you estimate the corrosion current reduction efficiency due to the application of steel plate jackets in chloride contaminated environment?

- In % reduction (1) ____________________
- Not Applicable (2)

Externally bonded FRP composites for corrosion repair of RC bridge pier column

Q.18 Does your DOT use FRP composite for RC bridge pier corrosion repair/rehabilitation?

- Yes (1)
- No (2)

Q.19 Please estimate the number of RC bridge pier repair or rehabilitation cases in which you choose following externally bonded FRP composites.

______ CFRP + Epoxy by wet layup method (1)

______ GFRP+ Epoxy by wet layup method (2)

Q.20 Please provide the number of layers and overall average thickness of FRP composite that your DOT most frequently considers as a chloride contaminated corrosion repair.

	Number of layers (1)	Overall thickness of FRP composite (Inches) (2)
CFRP+Epoxy by wet layup method (1)		
GFRP+Epoxy by wet layup method (2)		

Q.21 Please estimate the observed or design service life of FRP composite repair (In years).

______ CFRP + Epoxy by wet layup method (1)

______ GFRP+ Epoxy by wet layup method (2)

Q.22 Based on your experience, how would you estimate the corrosion current reduction efficiency due to the application of full height FRP wraps in chloride contaminated environment?

- In % reduction (1) ____________________
- Not Applicable (2)

Q.23 Please estimate the delay in corrosion initiation time due to application of full height FRP wraps in chloride contaminated environment.

- Not effective (1)
- 1 -5 yrs (2)
- 5 -10 yrs (3)
- 10 -15 yrs (4)
- 15-20 yrs (5)
- Other, please specify (6) ____________________

Q.24 Based on your past field installation, please rank the reason causing end of service life of the FRP repaired column (wet layup with epoxy resin)

______ Deterioration of FRP jacket material (1)

______ Deterioration of substrate concrete due to further corrosion (2)

Q.25 For a corroded and FRP jacketed column, please estimate the level of strength reduction from original strength at which another major repair would be conducted.

______ Tensile strength of FRP (1)

______ Strength of substrate (2)

Q.26 How do you consider the durability/environmental factor for FRP composite while estimating service life? Please specify the deterioration rate, or environmental deterioration factor, or deterioration profile, or please upload any helpful documents as per your current practice.

Q.27 Does your DOT has any established design/durability guidelines and inspection/repair guidelines for FRP repaired elements? If yes please provide the link or upload the file.

Cost data

Q28 Please estimate the total install cost (material, labor and equipment) for the given repair related job based on the historical construction cost data. Please be specific to the corrosion repair of bridge pier column. Cost price unit is in Square feet of bridge pier surface area. If unit is different, then please type at respective column at right.

	Unit Price in Dollar	Unit
Special corrosion inspection, sampling and testing (1)		
Surface preparation (2)		
Epoxy sealer application (3)		
Epoxy coating application (4)		
Silane/siloxane treatment (5)		
Removing corroded concrete and reinforcement & patching with normal concrete (6)		
Removing corroded concrete and reinforcement & patching with concrete containing Calcium Nitrate based corrosion inhibitor (7)		
Removing corroded concrete and reinforcement & patching with concrete containing organic based corrosion inhibitor. Please specify the product name if possible (8)		
CFRP-Epoxy composite wrapping by wet layup method per layer (9)		
GFRP-Epoxy composite wrapping by wet layup method per layer (10)		
Concrete jacketing. Please specify average thickness if possible (11)		
Steel plate jacketing. Please specify plate thickness if possible (12)		
Cathodic protection (Impressed current) (13)		
Cathodic protection (Sacrificial anode) (14)		
Annual maintenance cost for cathodic protection (15)		

Sugestion

Q.29 Please post your valuable suggestion or information that you want to provide in addition to the above survey regarding the RC bridge pier MR& R strategies in chloride exposure environment.

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