Corrosion of Highway Bridges: Economic Impact and Control Methodologies

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Corrosion of structures has a significant impact on the economy of developed industrialized countries. Estimates, based on a 1975 Battelle-NBS benchmark study, are that the cost of corrosion in the United States alone was approximately $70 billion, which was 4.2% of the gross national product (GNP). In 1995, a limited study updating the 1975 figures estimated the total cost of corrosion at approximately $300 billion. However, that study did little more than apply a multiplication factor to the 1975 cost that was equivalent to the GNP growth from 1975 to 1995. A need was identified for a systematic study that estimates the current impact of corrosion on the U.S. economy and provides strategies to minimize the impact of corrosion.

From 1999 to 2001, CC Technologies Laboratories, Inc., conducted research in a cooperative agreement with the Federal Highway Administration (FHWA). In this study, CC Technologies Laboratories, Inc., determined the total direct cost of corrosion by analyzing five industrial sector categories: infrastructure, transportation, utilities, production and manufacturing, and government (subdivided into a total of 26 industrial sectors). This article presents a synopsis of the findings with respect to the reinforced concrete highway bridges. The complete report on this and other sectors of the U.S. economy can be found on the Internet at **www.corrosioncost.com**.

ECONOMIC IMPACT

According to the National Bridge Inventory Database, there are approximately 600,000 bridges in the United States, of which half were built between 1950 and 1994.[1] The construction materials for these bridges are concrete, steel, timber, masonry, timber/steel/concrete combinations, and aluminum. Reinforced concrete and steel bridges make up the vast majority of these structures built since 1950. Maintenance of aging bridges has become significant. In a 1998 report, the American Society of Civil Engineers (ASCE) rated the condition of bridge structures as "poor" and recognized them as being among the largest contributors to the U.S. infrastructure cost of corrosion.[2]

The present condition of bridges in the U.S. can be characterized by the significant portion of bridges that are listed as "structurally deficient" (defined as a bridge that can no longer sustain the loads for which it was designed). The nation's structurally deficient bridges, as of the end of fiscal year 1999 and the preceding 7-year period, are summarized in Table 1.[3,4] The data include all construction materials, including concrete, steel, wood, aluminum, and other materials.

Table 2 presents the 1998 data from Table 1 in more detail. This table focuses on concrete bridges constructed of materials that are subject to corrosion (conventional reinforced concrete and prestressed concrete). Of these two bridge types, conventionally reinforced concrete has the highest percentage of structurally deficient structures, followed by prestressed concrete. FHWA bridge listings for each state[3] suggest that the states with colder and damper weather have a high percentage of reinforced-concrete deficient bridges. These states include New York, Alaska, Rhode

TABLE 1:
National Bridge Inventory data—structurally deficient bridges[3,4]

	1992	1993	1994	1995	1996	1997	1998	1999
Bridges in inventory	572,633	574,191	576,472	577,919	582,043	583,207	583,414	585,947
Number deficient	118,757	111,543	107,512	103,686	101,544	98,521	93,119	88,184
Percent deficient	20.7	19.4	18.6	17.9	17.4	16.9	16.0	15.0

TABLE 2:
Structurally deficient bridges based on material of construction in 1998[5]

	Conventional reinforced concrete	Prestressed concrete	Other	Total
Bridges in inventory	235,151	107,666	240,597	583,414
Structurally deficient	21,164	3230	68,725	93,119
Percent deficient	9	3	29	16

TABLE 3:
Estimated service life for concrete bridges with different methods of construction[1]

Material of construction	Average estimate, years
Conventional reinforced concrete	72
Prestressed concrete	73

TABLE 4:
Highway Bridge Replacement and Rehabilitation Program unit costs[6]

	1995	1996	1997	1998	1999
Unit costs,* $/m²	$768	$771	$836	$855	$858

*Average between federal aid and non-federal aid projects.

Island, Pennsylvania, and Vermont. The most structurally deficient bridges in a single state are in New York, which also has a larger total bridge area for conventional reinforced-concrete and steel bridges than any other state.

The estimated service life expectancy for each of the previously mentioned bridge types is shown in Table 3. Many of the reinforced concrete bridges have reached or are approaching the end of their design service life, making bridge maintenance, rehabilitation, and replacement decisions a priority.

The impact of corrosion on highway bridge infrastructure has been estimated by several different sources using different approaches. Reconstruction of the nation's bridges was estimated to cost between $20 billion and $200 billion.[3,4] An FHWA report on corrosion protection of concrete bridges estimates that the total cost to eliminate the backlog of deficient bridges is between $78 billion and $112 billion, depending on the time required to carry out the task.[6] In addition, the average annual maintenance cost through the year 2011 (maintaining the total number and distribution of deficient bridges) is estimated to be $5.2 billion. While corrosion is not the sole cause of bridge deficiency, it is a major contributor to the costs given previously.

An additional estimate of the total corrosion costs related to the replacement of structurally deficient bridges is possible using the National Bridge Inventory data for December 1999.[3] Table 4 gives the unit costs for bridge replacement calculated by taking the mean for all states.

The overall area of structurally deficient bridges (conventional reinforced concrete, prestressed concrete, and steel) is 34.2 million m² (370 million ft²). Assuming that these structural deficiencies are largely attributable to corrosion (obsolete bridges were not included), and using the average unit cost data ($858 per m² [$80 per ft²]), the total cost of replacing the structurally deficient bridges is estimated to be $29.3 billion (34.2 million m² x $858 per m²). Hence, the overall dollar impact of corrosion on highway bridges is considerable.

The annual direct cost of corrosion for highway bridges is estimated to be between $6.43 billion and $10.15 billion: $3.79 billion to replace structurally deficient bridges over the next 10 years; $1.07 billion to $2.93 billion for maintenance and cost of capital for concrete bridge decks; $1.07 billion to $2.93 billion for maintenance and cost of capital for concrete substructures and superstructures (minus decks); and $0.50 billion for the maintenance painting cost for steel bridges. This gives an average annual cost of $8.29

billion. Life-cycle analysis (see **www.corrosioncost.com**) estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion. In addition, it was estimated that employing "best maintenance practices" versus "average practices" can save 46% of the annual corrosion cost of a bridge deck reinforced with black steel, or $2000 per bridge per year.

CORROSION CONTROL AND PREVENTION IN NEW CONSTRUCTION

Despite their aggressive nature, the use of deicing salts is not likely to be discontinued. In fact, it has been reported that salt use actually increased in the first half of the 1990s after a period of "leveling off" in the 1980s. Therefore, bridge designs and concrete mixtures must be resistant to chloride-induced corrosion. This can be accomplished by: preventing chlorides from getting to the steel surface (physical barriers at the concrete surface, coating the reinforcement, or low chloride-permeable concrete); making the concrete less corrosive at specific chloride levels (inhibitors or admixtures); or making the reinforcement resistant to corrosion (corrosion-resistant alloys, composites, or clad materials).

Corrosion-resistant reinforcement

Over the past 20 years, there has been a trend in new construction toward using higher quality concrete and more corrosion-resistant reinforcement. Longer bridge service life is currently achieved by using epoxy-coated reinforcing steel in the majority of new bridge construction, with the limited use of stainless steel-clad or solid reinforcement in more severe environments.

At present, epoxy-coated reinforcing steel (widely used since the late 1970s) is the most common corrosion protection system and is used by 48 state highway agencies. To date, there are approximately 20,000 bridge decks using fusion-bonded epoxy-coated reinforcement as the preferred corrosion protection system. This represents roughly 95% of new deck construction since the early 1980s. Data from the Concrete Reinforcing Steel Institute (CRSI) shows that more than 3.6 billion kg (4 million tons) of epoxy-coated reinforcing bars were used worldwide as of 1998, with 79% installed in the last 10 years.[7] CRSI estimates that the increase in the total cost of a structure due to coating both mats of reinforcement is typically between 1 and 3%.[8]

A number of metallic coatings, metallic claddings, and reinforcement alloys have been tested. The most promising are galvanized (zinc-coated) reinforcement, stainless steel-clad reinforcement, and solid stainless steel reinforcement.[6] Stainless steel reinforcement has been used in several projects in the U.S., including projects in Michigan and Oregon.[9] The Oregon DOT estimates that the higher cost of stainless steel reinforcement (Type 316LN, Nitronic 50) leads to an overall cost increase of 10 to 15% when used in the deck and superstructure, and another 5% if used in the substructure. The expected service life of a structure using stainless steel reinforcement was stated to be 120 years.

One way to minimize the cost of the stainless steel reinforcement is to use stainless steel-clad reinforcement. It has been estimated that the cost increase to construct the deck using stainless steel-clad reinforcement is 6%, with an expected service life of 50 years.[6]

Alternative means of protection

In addition to the use of coated or alloy reinforcement, other approaches to mitigate corrosion of reinforcing steel in bridge structures include using high-performance concrete, corrosion-inhibiting admixtures, or a combinations of these.

Based on published data, construction cost increase associated with the use of a high-performance concrete containing silica fume is estimated to be 0.9%.[10] Silica fume provides an increase in expected life of 10 years beyond that provided by black steel reinforcement in conventional concrete.[11] In the past decade, the use of corrosion-inhibiting concrete admixtures has emerged as a promising method for delaying the onset of corrosion of prestressing and conventional reinforcing steel.[12] Berke, Pfeifer, and Weil discussed the cost of calcium nitrite (one of the most commonly used corrosion-inhibiting admixtures) with and without the addition of silica fume; they estimated the cost increase to construct a deck using calcium nitrite inhibitor is 1.1%.[10] It is estimated that the use of inhibitors may provide an increase in expected life of 20 to 25 years beyond that provided by black steel reinforcement and conventional concrete.[13]

Table 5 gives the costs of new construction alternatives for bridge structures and includes the expected service lives.[6,10,14,15] There are many choices for corrosion prevention, and careful life-cycle cost analysis and risk assessment are required to select the most appropriate one for any given application. In addition, the alternatives are not mutually exclusive (combinations of corrosion-inhibiting admixture and silica fume or epoxy-coated reinforcement and corrosion-inhibiting admixture have been used).

REHABILITATION

Although the positive effect of adoption of corrosion protection measures can already be seen on individual structures, there are thousands of existing bridges constructed without the latest corrosion control methods. Therefore, repair and rehabilitation of bridge structures, and the mitigation of existing corrosion, will be a major activity for bridge engineers for years to come.

TABLE 5:
SUMMARY OF COSTS AND LIFE EXPECTANCY FOR NEW CONSTRUCTION ALTERNATIVE[6,10,14,15]

Corrosion control practice	Cost of bar, \$/kg	Bar weight per deck area, kg/m²	Cost per deck area, \$/m²	Increase in comparison to baseline, \$/m²	Percent increase	Estimated service life, years
Black steel (baseline)	\$0.44	26.4	\$11.60	NA	—	10
2-layer epoxy-coated reinforcement	\$0.66	26.4	\$17.40	\$5.80	1.2%	40
2-layer solid SS reinforcement	\$3.85	26.4	\$101.64	\$90.04	18.6%	75 to 120
2-layer SS-clad reinforcement	\$1.54	26.4	\$40.66	\$29.00	6.0%	50
Calcium nitrite CIA	—	—	—	\$5.40	\$1.1%	30
Silica fume	—	—	—	\$4.30	0.9%	20

Many rehabilitation methodologies, designed to extend the service life of bridges that have deteriorated due to corrosion of the reinforcing steel, have been developed and put into practice within the past 25 years. These include: application of surface barriers for chloride ingress (overlays and sealers); control of electrochemical reactions at the reinforcement/concrete interface (cathodic protection); and modifying the environment to make it less corrosive (electrochemical chloride removal).[6] Although each of these methods has been shown to be successful, continuing developments are necessary to improve their effectiveness and increase the life extension provided by these methods.

Surface barriers

The application of an overlay of low-slump concrete, latex-modified concrete (LMC), high-density concrete, polymer concrete, or bituminous concrete with a membrane on existing concrete provides a barrier that impedes continued intrusion of chloride ions, moisture, and oxygen that are necessary for corrosion to continue. Traditionally, greater than 90% of rehabilitation jobs use low water-cement ratio concrete or LMC overlay as the preferred barrier method. FHWA Report FHWA-RD-98-088 indicated that state highway agencies estimate the life of applied surface barriers to be around 15 years.[6] Table 6 summarizes the costs associated with different overlay and patching options.[16]

Cathodic protection

Cathodic protection (CP) is a corrosion control method that imposes an external voltage on the steel surface, which forces the steel to become cathodic (reduction reactions are favored and anodic reactions, which result in metal loss, are decreased), thereby mitigating corrosion. Selection of the proper anode material for the application is critical because anode failure results in CP system failure. For a variety of reasons, CP systems are seldom installed on a newly constructed bridge; however, CP is installed on newly constructed bridge pilings exposed to marine and brackish waters where corrosion is known to be a severe problem. Presently, CP remains an under-used technology for corrosion protection of steel-reinforced concrete structures. Table 7 summarizes the costs and the service life of CP systems using impressed current and sacrificial anode.

Electrochemical chloride removal

Electrochemical chloride removal (ECR) is a technique similar to CP, except it uses much higher currents and applies them for a relatively short period of time. Field data, so far, show that ECR is an effective method for stopping corrosion for at least 8 years. FHWA predicts that ECR technology will extend the life of bridges by as much as 20 years.[17] To date, there has been approximately 372,000 m² (4 million ft²) of concrete worldwide that has been treated. Table 8 summarizes the costs and the service lives associated with ECR.

OPPORTUNITIES FOR IMPROVEMENT AND BARRIERS TO PROGRESS

A typical bridge management dilemma is how to allocate the (often insufficient) funds for construction, rehabilitation, and maintenance. Compounding the problem is that funding typically comes from city, state, and federal sources and there are spending restrictions based on the funding source. This makes allocating the funds to optimize construction, rehabilitation, and maintenance decisions difficult.

TABLE 6:

Cost (adjusted to 1998) and life expectancy for overlay and patching options for concrete bridges[16]

Type of maintenance	Average cost, \$/m²	Range of costs, \$/m²	Average expected life, years	Range of expected life, years
Portland cement concrete overlay*	\$170	\$151 to 187	18.5	14 to 23
Bituminous concrete with membrane	\$58	\$30 to 86	10	4.5 to 15
Polymer overlay/sealer	\$98	\$14 to 182	10	6 to 25
Bituminous concrete patch	\$90	\$39 to 141	1	1 to 3
Portland cement concrete patch	\$395	\$322 to 469	7	4 to 10

*Includes latex-modified concrete (LMC).

TABLE 7:

Summary of costs and life expectancy for cathodic protection systems

Type of maintenance	Average cost, \$/m²	Range of costs, \$/m²	Average expected life, years	Range of expected life, years
Impressed-current CP (deck)	\$114	\$92 to 137	35*	15 to 35
Impressed-current CP (substructure)	\$143	\$76 to 211	20	5 to 35
Sacrificial anode CP (substructure)	\$118	\$108 to 129	15	10 to 20

*Current technology.

TABLE 8:

Summary of costs and life expectancy for electrochemical chloride removal

Type of maintenance	Average cost, \$/m²	Range of costs, \$/m²	Average expected life, years	Range of expected life, years
Electrochemical removal (deck)	\$91	\$53 to 129	15	10 to 20
Electrochemical removal (substructure)	\$161	\$107 to 215	15	10 to 20

Cooperation among these different funding agencies is required to permit allocation of resources to achieve the best cost benefit.

An increased need for bridge inspection has placed additional drains on maintenance funds. An economic analysis showed that monitoring bridge conditions, and subsequent maintenance based on that information (information-based maintenance), is the most cost-effective maintenance strategy. The economic analysis further suggests that capital funding for the higher quality construction materials (epoxy-coated reinforcement) results in lower annualized costs due to postponement of repair expenses incurred by the owner. The analysis also indicated that user costs (traffic delays during maintenance) are significant and can be 10 times greater than the direct costs to the bridge owner. This places a premium on the selection of construction materials that minimize maintenance over the bridge service life. It also highlights the importance of careful planning for traffic control and alternative routes during bridge maintenance and rehabilitation activities.

Additionally, the use of technological advances among bridge owners has not been uniform. This can, in part, be explained by the difference in funding and technical staffing between the agencies. Because of the perceived high costs of certain corrosion control methods, these methods go unused. With the general tendency to reduce the maintenance departments' size and budget, corrosion control becomes the responsibility of personnel who may not have the experience to understand the problems or the knowledge of available solutions. There remains a significant need for life-cycle cost analysis to aid in the selection of repair, rehabilitation, and replacement decisions.

RECOMMENDATIONS AND IMPLEMENTATION STRATEGY

Technological advances provide the opportunity for newly constructed bridges to last considerably longer than the bridges that were constructed 20 to 30 years ago (having projected service lives in excess of 75 years). However, newly developed construction materials and corrosion control methodologies must be employed properly over the entire bridge project (both design and construction phases).

These improvements, however,

will not assure that the problems with corrosion on highway bridges will disappear soon. The percentage of deficient bridges, while declining, still remains high. At the same time, the costs of bridge repair and rehabilitation are steadily increasing, thereby offsetting any potential savings. Some of the bridges owned by state and city agencies simply cannot be replaced due to their historic value and/or the enormous strain on the traffic resulting from a bridge closure (for example, the New York City East River bridges and the Oregon coastal U.S. Highway 101 bridges). These bridges are maintained and rehabilitated even at high costs.

There is an urgent need for allocation of greater funding so that the bridge engineers can properly maintain structures based on timely inspections, thereby optimizing maintenance practices. At present, maintenance personnel are forced to make choices while restricted by inadequate funds, which will ultimately lead to a less-than-optimal cost/benefit ratio.

Despite appreciation of corrosion-related issues in the bridge community, there is still a need for raising awareness and the transfer of the advanced methodologies for efficient corrosion protection to the end-users. The FHWA, which has amassed considerable research and field application data on corrosion protection methods for concrete bridges, has served as an effective conduit for dissemination of such information through periodic demonstration programs and educational seminars. These demonstration programs have been successful and should be continued with increased staffing and funding levels.

There also remains a considerable necessity for additional research in innovative construction materials such as corrosion-resistant alloy/clad reinforcement (metallic and nonmetallic) and more durable concretes with inherent corrosion-resistant properties. In addition, research and development is needed in rehabilitation technologies that can mitigate corrosion with minimal maintenance requirements, such as sacrificial cathodic protection systems.

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Selected for reader interest by the editors.

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