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Bridge Maintenance and Management
A Look to the Future

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As the third millennium dawns, the United States is in the midst of a “bridge crisis”: Maintenance needs for older bridges have far outpaced available resources. This situation indicates the need not only for improved repair and rehabilitation techniques but also for a comprehensive approach to bridge management. Fortunately, advances in the power of microprocessors have made available personal computers and instrumentation that greatly enhance the ability of bridge engineers to manage and monitor structures, then take the proper action at the right time. In this paper, we seek to define the current state of the art in bridge maintenance and management and to look ahead to the challenges that this field will face in the 21st century.

BRIDGE MANAGEMENT SYSTEMS

Bridge owners today must make decisions pertaining to maintenance and improvements that take into account both funding constraints and the overall needs of the highway system. The states, the Federal Highway Administration, and the American Association of State Highway and Transportation Officials have been working to develop and implement automated decision-support models to assist bridge managers. Bridge management systems (BMSs) represent a unique convergence of the disciplines of structural engineering, operations research, economics, planning, and information technology. The BMS subcommittee, a focal point for research in this critical interdisciplinary area, has provided a forum for the exchange of experiential knowledge on BMSs among states through Transportation Research Board paper presentations, publications, and specialty conferences. The subcommittee works in the following areas.

Data Collection Methods

Effective support of bridge management decision making requires obtaining timely and quality data about bridge conditions, project costs, and effectiveness. Because of the expense of data collection, bridge managers must exploit new technologies and process efficiencies to continually improve data quality while simultaneously controlling the costs of data collection. Further development and evaluation of improved visual inspection procedures, innovative nondestructive testing methods, and automated methods to gather and manage data should be encouraged.

Models of Bridge Deterioration and the Effect of Maintenance Activity

One way in which BMSs assist decision makers is in forecasting the effect of agency actions on the health and economic performance of the bridge inventory. By studying the changes observed in bridge conditions over time, researchers can develop models to distinguish the effects of maintenance activity from the normal processes of bridge deterioration. State-of-the-art work in this area includes deepening our understanding of physical deterioration processes, especially the effect of structural damage on the reliability and performance of structural components.

Study of Bridge Vulnerability

Because most bridge failures in the United States result from unpredictable extreme events, such as earthquakes and floods, we must improve our understanding of the vulnerability of bridges to such events. With this understanding, we will improve strategies to reduce the risk of failure.

Developing Cost Factors

BMSs require the development of cost factors that are accurate enough to allow credible budgeting and program planning. BMS costing methods depend on an understanding of the relationships between the bridge conditions, treatment selection, and the resources (such as labor, materials, equipment, traffic control, and engineering) that are consumed in completing treatment. Regarding the current state of the practice, costing methods and data are suitable for network-level BMS models but not for project-level analysis. Additional research in this area could greatly improve the accuracy of project-level cost estimates.

Life-Cycle Economic Analysis of Project- and Network-Level Tradeoffs

Current research in this area focuses on improved optimization techniques that minimize the life-cycle agency and social costs of a bridge inventory and maximize the performance of the inventory within limited resources. By making optimization models faster and more flexible, the application of new computational techniques and paradigms can provide a means of implementing the research results with more detailed and realistic data and models.

Integration with Asset Management

Bridges are only one part of the infrastructure of a transportation agency. Increasing awareness that transportation assets are interdependent leads to the requirement that each BMS fit with other agency systems in several ways, including database navigation, geographic referencing, sharing of software components and data collection resources, and the development of common performance measures. These cooperative efforts support an integrated planning and programming process, which fosters enhanced communication and coordination among engineers, planners, and managers to promote the agency’s mission.

BRIDGE EVALUATION AND INSPECTION

In the future, bridge inspection will focus on the quantitative assessments of bridge performance and conditions rather than visual inspections and condition ratings. A variety of permanent sensors on bridges will collect data at many points. These sensors will be powered by—and will report to—wireless networks. Data will be analyzed and deterioration will be detected automatically by computer workstations in central locations. When problems arise, engineers will be able to accurately analyze the structural condition and formulate timely corrective strategies. Knowledgeable, experienced engineers are the key to an accurate evaluation of the structural condition. Technology will greatly enhance their ability to make these assessments.

Sensors offer definite, unbiased, and quantitative data. These data enable engineers to use high-performance concrete and steel materials along with fiber-reinforced composite materials to increase the service life of bridges. Extensive use of sensors will become possible as advances in the miniaturization of electronic devices, increased availability of wireless communications, and lower costs for devices and communication combine to provide an array of compact, permanent, inexpensive systems.

Measurements of bridge performance will include the detection of changes in chemical and electrical properties of materials related to deterioration, aging in coatings, and changes in service environment or exposure; in addition, the response to loads will be verified periodically. Systems for measuring bridge performance may include

- Embedded sensors for measurement of corrosion potential and current,
- Load cells permanently built into bridge bearings to allow periodic verification of load paths,
- Interferometry for surface flatness to detect aging in coatings and damage in fiber-reinforced composite elements,
- Embedded fiber-optic sensors for crack detection and strain measurement,
- Permanent features in substructures for rapid mounting of laser systems for deflection measurements (permanent, dedicated mounting locations allow simple collection and comparison of response signatures), and
- Radar and infrared sensors housed in overhead bridge lighting and interrogated when weather conditions are favorable.

Because new inspection technologies will detect and measure deterioration in bridges, inspectors will have extensive quantitative data about the condition and performance of structures. Armed with this information, bridge engineers will be able to make better decisions about repairs, to redesign details that will improve durability, and to use specialized repair techniques.

The new inspection practices outlined here can be implemented. The sensors and data communication hardware exist. Hardware is costly today, and the long-term durability of sensors has not been established. However, these limitations will be overcome through research, development, and implementation.

Computational systems must be further developed to analyze data. Systems must include data interpretation, statistical analysis, evaluation of errors in measurement, identification of bridge conditions based on data, and assessment of structural reliability in its present condition. Recent work in system identification and sensitivity of system response to damage are relevant here. Overarching systems for data analysis and reporting are needed.

BRIDGE MAINTENANCE, REPAIR, AND REHABILITATION

The repair of bridges often has been a reactive activity, initiated only when deterioration threatens the safety or tolerance of the public. Now, influenced by BMSs, owners are beginning to emphasize cost-effective proactive strategies from the start, when the bridge is new. One future focus will be preventive maintenance. Agencies that take the lead in this area are reaping dividends in service life through activities such as cleaning bridge components, overlaying decks, maintaining the integrity of joint seals, and spot-painting beams.

Concrete Members

Concrete members are subject to spalling due to corrosion of the underlying reinforcement; scaling caused by freezing and thawing; and cracking caused by shrinkage, flexure, or differential settlement. Advanced materials such as polymers and high-performance hydraulic cement concretes show promise for making repairs. Various kinds of noncorroding reinforcement that are under evaluation may eliminate spalling and thus reduce the need for repair.

Because spalling is caused by corrosion of the reinforcement, which is brought on by chloride contamination, a permanent repair must halt the corrosion process. Cathodic protection—effective, but seldom used to date—is one alternative. Research on chloride ion removal from the concrete also looks promising. Improved instrumentation for detecting corrosion and controlling the cathodic protection process will expand the popularity of these techniques. Protective coatings and overlays applied in a timely manner can slow salt penetration and delay the initiation of deck corrosion. The emphasis in these applications (both now and in the future) is on rapid repairs, often performed at night to minimize user costs. Polymer concretes are effective in such applications, and very early strength latex modified hydraulic cement concretes, which can be opened to traffic in only three hours, were recently tested. Overlays and patching also can use high-performance concrete or shotcrete that contains microsilicas to decrease permeability.

Similar materials can be used to repair scaling, but the best approach remains the specification of air entrainment, which is very effective in preventing the onset of distress. Cracks are filled with an appropriate material that is inserted, poured, or pressure-injected into the opening. Specific repair methods depend on the number and size of the cracks and movement. High molecular weight methyl methacrylate, a low-viscosity material, can successfully seal shrinkage cracks. However, an effective method for sealing “working” cracks has not yet been found.

Steel Members

Damage to steel members typically results from corrosion, fatigue, and impact. If the damage from any of these causes is extensive, either a portion or the entire member may have to be replaced. Often, however, such a drastic remedy can be avoided by research findings in the following areas:

- The application of paint management systems, now under development, should greatly extend the service lives of coatings, as will research into better coating systems.
- Prompt detection of fatigue cracks through health monitoring of bridge members, a promising area of research, will facilitate the identification and repair of cracks at an early stage.
- The application of heat straightening, a technique that continues to benefit from ongoing research, may eliminate the need to replace an impacted member.

Scour and Settlement

Scour, undermining, or settlement of bridge substructure supports is the most common cause of bridge failures and the most expensive kind of damage to repair. The method of repair depends on the extent of or the potential for future damage, but it usually involves filling the void with concrete and armoring the slope. Future work involves developing both prediction models and monitoring instruments for the early detection of scour at critical sites, to warn bridge engineers and motorists of impending hazards.

Strengthening and Retrofitting of Existing Bridges

Bridge engineers have bonded carbon fiber reinforced plastic laminates to aging or damaged beams to supplement or restore load-carrying capacity. Although the lightweight carbon-fiber laminates are expensive, relatively small amounts are required, and they can be handled easily, reducing construction costs.

Composite materials are gaining in popularity for retrofitting damaged columns or enhancing the ductility of those members. The columns are wrapped in either glass or polymer-impregnated sheets that are reinforced with glass or carbon fibers; the sheets can be field-cut to fit any cross section and length. (Fibers of other materials also are being evaluated.) A coating of ultraviolet inhibitor paint completes the installation and enhances aesthetics.

Composite wraps effectively prevent damage to columns during seismic activity. Seismic isolation bearings, which minimize the effects on superstructures, and shock transmission units, which temporarily freeze bridge bearings to maximize resistance during seismic events, also are under evaluation to mitigate earthquake damage. Widespread attention to seismic vulnerability can be expected.

Deck and Superstructure Replacement Systems

Innovations in construction technology—for example, prefabricated systems that use conventional materials such as concrete, steel, and aluminum along with fiber-reinforced plastics and other emerging materials—are changing rehabilitation strategies. Although some of the systems are relatively costly, all of them offer the rapid replacement of decks or entire superstructures. As the concepts of life-cycle cost analysis and user costs are included in the replacement algorithm, acceptance of the often proprietary and expensive systems certainly will increase.

Deck Systems

Segmental Concrete Construction

To rehabilitate the decks of heavily traveled bridges, prestressed concrete panels often are placed transversely on the supporting girders and posttensioned longitudinally. Portions of a deteriorated deck can be removed during night operations and the panels installed in time to open the structure to morning traffic. Other deck systems offer similarly rapid construction with the advantages of reduced dead load and enhanced durability.

Advanced Composite Deck Panels

Fiber-reinforced plastic (FRP) panels offer light weight, superior corrosion resistance, and ease of erection. Several systems—most of which are composed of conventionally pultruded triangular or tube sections with deck and bottom plates and polymer concrete riding surfaces—are under evaluation at this time. Among the issues being investigated in the development of these structures are environmental concerns other than corrosion, connections for the members and the supporting beams, and the attachment of crashworthy barriers.

Proprietary Systems

Numerous proprietary deck and superstructure replacement systems are being marketed or evaluated at this time. Although the specifications of the following proprietary systems may present problems for public agencies, they do represent the current state of the art. Other systems may be available, because the field is evolving rapidly.

Exodermic Bridge Decks

The Exodermic bridge deck system is a composite modular system that is lightweight and strong. It consists of a reinforced concrete slab on top of, and composite with, an unfilled steel grid. Because a steel grid is used instead of a full-depth concrete slab, Exodermic decks typically are only 50–65 percent as heavy as conventional reinforced concrete decks. Superior economy and durability are claimed.

Aluminum Bridge Decks

Reynolds Metals developed a bridge deck system that offers rapid installation with only a light crane as well as the proven durability and light weight of aluminum components. The deck is only 25 percent as heavy as a concrete deck, thus allowing for a significant increase in live load capacity. Penalized initially because of its high cost, the system may prove viable when its advantages are considered in selecting a design for high-volume locations.

Precast Concrete Sections

In 1990, Jean Muller International introduced a new segmental system called the Channel Bridge System. The channel cross section, in which the supporting beams serve as traffic barriers above the deck, increases the underclearance. Longitudinal and transverse prestressing provide strength and durability by maintaining compressive stresses in the concrete when loaded. Segments 2.5 meters long can be connected to form spans 35 meters long.

Prefabricated Steel Systems

The Quadricon system, which originated in India, is currently under evaluation by the Highway Innovative Technology Evaluation Center (HITEC). Identical components can be combined to form a variety of bridge structures that have a range of span lengths and carrying capacities. Quadricon bridges claim the advantages of light weight and high material efficiencies.

Coatings

Experience with the handling of lead-based paint, which constitutes a hazardous material when removed, has forced a management approach to coatings. Coatings management encompasses three considerations:

- Selection of coating systems,
- Technologies for the removal of existing coatings, and
- Replacement strategies (including monitoring systems).

Coating Systems

The paint systems emerging as "the longest lasting" incorporate zinc-rich organic and inorganic primers with urethane-based midcoats and top coats using moisture-cured media. This kind of system is becoming more popular because of its tolerance to application under both low-temperature and high-humidity conditions. Recent research indicated that these systems yield favorable results.

However, the coating system with the best indicated life expectancy is not paint. Metallization with 100 percent zinc or 85 percent zinc/15 percent aluminum produces a coating that protects bridge steel longer than any paint system currently available. Life-cycle cost analysis gives a very positive argument for using this technology, especially on new construction. Although its use on older steel is increasing, it is not as successful at present.

Removal Technologies

Older paints that contain lead-based components must be removed cleanly and with the greatest respect for the environment and for worker health. New technologies often reduce the volume of hazardous waste and ease containment requirements. Abrasives blasting with traditional and new materials completely removes the paint and provides a mechanical anchor profile for the new paint system. Depending on the combination of materials used, the lead-based paint debris may be stabilized so that it can be disposed of as a nonhazardous material.

Several paint removal technologies under development may provide viable, cost-effective options to owners and contractors for handling the lead-based paint. These technologies include

- Electrochemical, debonding paint via low-voltage direct current;
- Plasma jet, ablating paint without distressing substrate; and
- Bioingestion, using paint-eating bacteria.

Management Strategies

Effective management systems provide owners with practical and economically sound choices for coatings maintenance. Up-to-date information about the kind of paint, its application, and whether an overcoat is feasible is important to the owner in making replacement and renewal decisions. It also plays an increasingly important role in a BMS.

LOOKING AHEAD

The approach to bridge maintenance is increasingly influenced by emerging management systems. Other trends that probably will influence future developments and practices in this field include increased attention to life-cycle cost analyses and the incorporation of user costs into maintenance decisions.

Certainly, bridge maintenance engineers will use an array of increasingly sophisticated instruments, procedures, and systems to evaluate, repair, and rehabilitate structures. Research into materials also will continue, with an emphasis on products such as noncorroding reinforcements, more impermeable concrete, and superior coatings that will drastically reduce maintenance requirements when used in new construction.