NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 123

BRIDGE DESIGNS TO REDUCE AND FACILITATE MAINTENANCE AND REPAIR

TRANSPORTATION RESEARCH BOARD
National Research Council

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BRIDGE DESIGNS TO REDUCE AND FACILITATE MAINTENANCE AND REPAIR

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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. DECEMBER 1985

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In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to bridge designers, maintenance engineers, and others concerned with selection of materials and design details for bridges. Information is presented on materials, procedures, and methods that will contribute to the design and construction of bridges that are easier to maintain and rehabilitate.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Many of the problems of maintaining and rehabilitating bridges can be attributed to the use of materials and design details that were selected without adequate consideration of their effects on maintainability. This report of the Transportation Research Board describes how selection of durable materials and improvement of design details can make bridges easier to maintain and rehabilitate. The report also explains how better communication between bridge designers and maintenance engineers will contribute to better designs.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

BRIDGE DESIGNS TO REDUCE AND FACILITATE MAINTENANCE AND REPAIR

SUMMARY

The design and construction of bridges is continually becoming more complex. Bridge engineers are designing ever larger and more sophisticated bridges. Specifications and manuals outlining structural design criteria are constantly being updated to improve bridge performance. The systematic development of design criteria, concepts, and details can result in designs that reduce and facilitate maintenance and repair. Maintenance manuals have been developed to improve inspection and rating procedures, and to identify problem areas. However, this study finds that maintainability criteria for bridges has not been formally stated or included in standard design specifications or manuals.

Many studies, research reports, and articles have been written describing bridge deficiencies and failures. Many of these reports describe repair procedures that required alteration or removal of portions of the unaffected structure. Lack of access to component parts has required unnecessary removal. Lack of access may actually deter routine maintenance. The ease of performing repairs is generally not mentioned. Often difficult and expensive falsework is required, where additional space and details would have allowed temporary support from existing structure components.

Material selection plays an important role in designing maintainable bridges. Steel and concrete are the principal structural materials used for bridge construction. Where possible, materials inert to the elements should be used. Procedures and specifications are required to ensure quality control of all bridge materials. Particular emphasis is required in the design of details and connections. Design-related bridge deficiencies are often the result of poor design details. Deterioration from corrosion is well documented throughout the literature. Corrosion protection for bridges has mainly been in the form of paint, and other special coating systems. Some cathodic protection systems have been developed and successfully installed. Because corrosion causes so many problems, corrosion control should receive much greater emphasis.

The required continued use of a bridge while rehabilitation is performed is documented throughout the literature. Details and configuration of structure components could be designed to reduce the costs for maintaining traffic. More formal criteria specifying requirements for accessibility, corrosion protection, ease of rehabilitation, and continued bridge use while under repair should be developed. The criteria for more maintainable bridges should be formulated through cooperative effort between bridge designers and bridge maintenance engineers.

The cooperative effort required to improve maintainability will be enhanced by more effective communication channels. The decentralization that has taken place in

many departments of transportation also requires more effective communications, because decentralization should not be allowed to cause fragmented responsibility. Improved communication techniques can benefit training programs, project review procedures, funding operations, and interchange of information. Bridge administrators and engineers should be assured of receiving the current information at the right time. The development and utilization of more effective communication channels by bridge administrators is required to achieve more maintainable bridge designs.

Designers need more field experience to learn firsthand the importance of maintainability. Engineers directly supervising bridge design should be required to have field experience. Maintainability should be considered throughout the design phase, and maintenance information should be a primary data source. Inspection reports should be more effectively utilized in planning and designing for maintainability. Bridge maintenance problems should be categorized from inspection reports. By utilizing bridge inspection data, designers will be better able to address specific problem areas. Designers should prepare general maintenance instructions and procedures (in written and/or pictorial form) that are applicable to all bridges and specific instructions for bridges with complex maintenance requirements. Maintenance instructions could be in the form of standards and instructions in manuals, and/or as part of the construction plans. By defining critical inspection areas designers will assist the maintenance engineer.

Having knowledge where failures might occur should improve maintenance planning and scheduling. Bridge failures have been caused by inadequate maintenance. A primary reason for inadequate maintenance is lack of adequate funding and staffing. Administrators must recognize the importance of systematically planning and funding maintenance operations. The lack of adequate funding will cause deferral of maintenance, which will ultimately lead to more costly reconstruction.

Life-cycle costs should be evaluated. Designs based only on low first cost can result in costly and continuing maintenance charges. Design features should provide for rapid and safe performance of such routine work as light globe replacement and required lubrication of moving parts. The use of more costly material, such as stainless steel for bearing components, can be cost-effective. Initial installation of needed features, such as access and illumination facilities, increases first cost but will generally reduce life-cycle costs.

Designing for maintainability will be cost-effective and should result in longer bridge life. Although the designers can do much to improve maintainability, the bridge administrators have the greater responsibility. The develoment of communication channels that result in direct cooperative action between design engineers and maintenance engineers is of the highest priority. The prevalent perception that designers and maintenance engineers have little need for direct contact should be reversed. To achieve more maintainable bridges, administrators must ensure appropriate interaction between designers and maintenance engineers. The adoption of concepts contained in this report should lead to more maintainable bridges.

CHAPTER ONE

INTRODUCTION

BACKGROUND

The objective of this synthesis is to develop a body of information on bridge design concepts and details that will lead to reduced life-cycle maintenance costs and facilitate repair procedures. This includes accessibility, material selection, corrosion protection, ease of rehabilitation, and continued bridge use during retrofit. Concepts to increase communication among design, construction, and maintenance personnel to improve maintainability are proposed.

A literature review was made to gather information on bridge design concepts and details related to maintainability. Contact was made with bridge engineers in various states and Canada. Problem areas related to maintainability that should receive special design attention were determined. There are few reports on bridge design related directly to maintainability; however, there is a wealth of research and information related to the major problem areas. Chapters 2 through 5 present the engineering-related concerns and Chapter 6 presents the more administrative-related concerns.

Basically, all work done in the design and construction of a bridge will ultimately affect the life or maintenance of the structure. The many bridge design details affecting maintenance are too voluminous to include in this synthesis. To provide a useful synthesis it was determined that the design details reviewed during this study should be included by referencing selected biliographies to the particular subjects. The current issue of the AASHTO "Standard Specifications for Highway Bridges" (*1*) establishes minimum requirements for design. It is noted here that these specifications shall be followed, and reference to these specifications is not repeated in the selected bibliographies.

A primary intent of this synthesis is to provide thought-provoking stimulus to all those involved with bridge design. Designers must be motivated and encouraged to thoroughly understand the specifications related to each bridge they design. Research reports and articles, such as those listed in the selected bibliographies contained herein, can be effectively used. It is hoped that proposed concepts developed herein will result in improved communications. Maintenance manuals and instructions should be made more meaningful. Methods should be devised to ensure that designers are more aware of specific problems encountered by those engineers responsible for the integrity of the completed structure. Significant information from inspection reports should be given to designers. Coordinated effort should result in bridge designs that reduce and facilitate maintenance and repair.

Components of bridges that most often require repair and rehabilitation are parts normally subjected to direct impact loads, corrosive action, working loads and forces, and hydraulic action. Portions of bridges that are particularly vulnerable to deterioration are railings, roadway decks, deck joints and seals, pin-connected hangers and connections under open joints, bearings, foundation and substructure systems, and drainage systems. The failure to properly assess factors such as material toughness, repetitive loading, stress concentrators, accelerated corrosion, connections, joint details, attachments, ease of inspection, redundancy, and quality control can cause major problems. Most of the significant bridge rehabilitation projects focus on these areas.

Bridge engineers agree that improved methods of communications and technology transfer are needed. Designers need to be made aware of those details that cause problems to ensure that similar deficiencies are not repeated. Adequate staffing and funding is needed for effective design, maintenance, and inspection operations. All bridge-related operations should be organized to ensure that bridge design and bridge rehabilitation efforts are coordinated. Fragmentation of one from the other should be avoided. The importance of administrative areas of concern should not be minimized and direction must come from the administrators. Bridge designers and maintenance personnel tend to be self-sufficient. Until bridge designers have the knowledge to evaluate designs from a maintenance standpoint, impractical details will continue to be developed. The designer should be provided the means and motivation to develop maintenance evaluation. Designers should have direct contact with maintenance engineers. Designers must be willing to accept constructive criticism. Tact, mutual understanding, and administrative guidance are required to maintain effective communications within the organization.

TERMINOLOGY

Terminology assumes importance in assessing bridge designs in relation to maintenance and repairs because of various perceptions. In this synthesis bridge designers are those engineers responsible for the preparation of plans and specifications for construction; bridge construction engineers are those engineers responsible for ensuring construction to the plans and specifications; and bridge maintenance engineers are those engineers responsible for ensuring that the bridge continues to perform to the design criteria. As discussed herein these individuals should all possess a broad background of bridge engineering. Depending on organization and circumstances, they all may be required to make decisions that could affect the structural adequacy and life of bridges. Each should be aware of his or her expertise and limitations.

Routine maintenance involves the normal day-to-day operations performed to maintain the facility in a safe and clean condition and does not require engineering services. Repair, rehabilitation, and replacement are considered by many to be part of maintenance operations, but they generally do require engineering services. In some agencies these engineering services are performed by bridge designers, and in others they are performed by bridge maintenance engineers.

HISTORICAL PERSPECTIVE

History shows that all bridges require care and maintenance and nearly all will be in use beyond their assumed design life. A few bridges have survived for many centuries. According to Stephens (*2*), the oldest surviving bridge is an arch over the River Meles at Izmir, Turkey, built in about 850 BC. This bridge was constructed from very durable natural stone material. Stone masonry was used for most bridges until the 18th century. These bridges were built without engineering science as is known today. According to Bartlett (*3*), Galileo published the first book on structural analysis in 1638. Robert Hook devised the law of proportionality of stress and strain in 1678, and Mariotte and Bernoulli calculated deflections in 1694.

Cast iron bridges were constructed in the 18th and first half of the 19th centuries. Wrought iron chains were used for a suspension bridge in 1796 at Uniontown, Pennsylvania. With the advent of the Bessemer process in 1855, steel was produced leading to long-span steel, reinforced concrete, and prestressed concrete bridges. These are basically the types of bridges being designed today. Steel, concrete, and timber are the main structural materials now being used. Maintainability of bridges can be improved by using durable materials, providing better protection, providing improved design criteria and details, and improving methods for repair.

Statistics compiled through December 31, 1984 by the Federal Highway Administration (FHWA) show 574,045 bridges inventoried and classified in the United States. There were 75,198 bridges on the federal-aid system and 184,977 bridges on the off-system that would qualify for federal funds for rehabilitation or replacement based on the FHWA sufficiency rating formula. Included in these totals are 41,809 bridges on the federal-aid system and 77,558 bridges on the off-system that are classified as functionally obsolete based on the FHWA formula. Significant inventory items affecting the FHWA formulas are the built-in structural and geometric deficiencies that are due to changing traffic needs. Design trucks of 20,000 to 30,000 lb (9,000 to 14,000 kg) were used from 1920 to 1960 to design bridges that now accommodate 80,000 to 90,000 lb (36,000 to 41,000 kg) (or higher in some states) maximum weight legal vehicles. The FHWA statistics broadly define the magnitude of future bridge construction and rehabilitation, which may result in the rehabilitation and upgrading of many deficient and obsolete bridges rather than total replacement.

The "Forecast of Bridge Engineering: 1980-2000" (*4*) contains a summary of responses to a questionnaire on the future of bridge engineering. Responses were from leaders in the field of bridge engineering and construction. This summary confirms that bridge engineers, confronted with the growing problem of repair and rehabilitation of existing bridges, recognize the need to develop design and construction features that will reduce and facilitate maintenance and repair. Repair and rehabilitation will be recognized as a major activity and many designers will be diverted from designing new bridges to working on maintenance-related problems. Some engineers believe more effort will be expended toward standardizing repair procedures in strengthening or widening existing bridges. The engineering aspects of revitalizing old and deteriorating bridges will become upgraded and refined to a new level of excellence and respectability. Improved maintainability of bridges can be achieved through concerted effort to meld design, construction, maintenance, and performance into bridge design. The increasing importance and cost of bridges make this necessary. When maintainability is considered to be equal in importance to structural adequacy, more useful and cost-effective procedures will result.

Based on historical review, bridge engineers should place greater importance on bridge loadings. Today's HS-20 design truck (72,000 lb; 33,000 kg) will result in structurally deficient bridges in the future if the maximum legal weight vehicle approaches 120,000 lb (54,000 kg), as predicted by some authorities. Heavier loads will result in premature deterioration of structural components unless design loads are correctly correlated with allowed loads.

Historically, bridge construction budgets have been separate from maintenance budgets, hence the incentive has been to provide the most facilities for the least money. Designs using initial cost as the basis for selection may result in structures with much higher life-cycle costs in terms of maintenance. Administrators should require that appropriate life-cycle cost considerations be incorporated in bridge design. The importance of, and the investment in our vast and complex transportation systems mandate that there should be increased efficiency and productivity in maintaining bridges. Bridge designers should consider: What will require maintenance? When will it be required? How will it be accomplished? Who will be able to do it? Where will it be done? How much will it cost?

CHAPTER TWO

ACCESSIBILITY

Bridges that are subject to corrosion, or that require components such as expansion devices, bearings, and operating machinery or equipment, will require maintenance work. Designers should always incorporate features and details that facilitate maintenance operations. A design priority should be to reduce future maintenance work. However, because experience shows that some maintenance will normally be required during the life of a bridge, another design priority should be to facilitate future rehabilitation work. The degree of difficulty and associated costs of maintenance and repair are greatly affected by design considerations.

A prime design consideration must be access for maintenance and inspection. Accessibility to component parts that require maintenance and may require repair or replacement should be provided. Permanent structural elements of a bridge should not have to be cut or removed for replacement of component parts. All working parts, such as bearings and hinges, require access. Designers should provide access for inspection of all critical components. Designers should allow for the repair of bearings, hinges, drainage system components, and operating parts located within structural members by providing access openings of sufficient size and location to allow removal and replacement. All parts of a bridge that require maintenance, cleaning, and inspection should be reasonably accessible.

It is not enough to say that mechanical bearings require lubrication; a means must be provided to get to them. If access is not provided, the operation will be overly costly or the work will not be accomplished. Where a device requires lubrication, an oil or grease line might be brought to a more accessible location.

All bearing and hinge details should provide sufficient access and room to allow the load to be transferred to temporary supporting devices, such as jacks, to expedite repairs. Pier caps should be sized to provide reasonable placement of jacks, and designed to support the jacking loads. Also, provision must be made for a reasonable working area. The work area could be an integral part of the bridge, or it might be a temporary platform erected by maintenance personnel. In either case the design should include the access requirements.

Where closed drainage systems are required, access for cleaning and flushing the system must be provided. Drainage systems incorporating long runs with attendant bends and elbows become blocked by the solid material carried in the runoff. The time and frequency to maintain this type of system is exorbitant, and if reasonable accessibility is not provided in the design, the system will fail to perform. Maintenance personnel may solve the problem by removing objectionable portions of the system to allow a free-falling, self-cleaning operation. This may negate legitimate design concerns and result in the deterioration of other component parts of the bridge. Inlet catch basins and pipe systems designs are constantly undergoing improvement. Regardless of these improvements, drainage systems will always require cleaning. To be cost-effective (and practical) the cleanout locations must be accessible from bridge deck level or ground level.

Steel box girder and segmental concrete bridges require internal access. Many of the more critical details requiring inspection are on the inside. Stiffeners and attachments on steel box girders are areas that should be regularly inspected. Connections and joints in concrete segmental boxes should also be inspected. If these bridges have suspended spans, the hinges and bearings require access as do utility pipes and conduits. Entrance of water into closed box systems is a condition that must be known. Necessary repairs to these bridges will undoubtedly require interior access, and where access is required, provision should be made for adequate ventilation and illumination. Ventilation openings or ports should exclude entrance of unauthorized persons, water, debris, birds, or animals. Many box sections that require access are designed with only one access point and no ventilation points. When the access point is closed, the box is sealed from the outside atmosphere. To provide ventilation when access is required, the designer should provide openings at each end of a section. Both points should be opened before entering the section. Consideration should be given to illumination of enclosed access areas. This could be accomplished economically through an already existing roadway lighting circuit. If no economical power source is available, a lighting circuit might be powered by a portable generating set, and flashlights or battery-powered sources may be appropriate. To be most cost-effective, the design should include the required access facilities.

Where routine maintenance operations are required, such as servicing lights or lubricating equipment and bearings, access should be provided in the vicinity of the unit. These routine operations are best performed when they do not require walking great distances through the structure or require special equipment for getting there. However, other important factors, such as safety, clearances, vandalism, and aesthetics, should be considered. Accessibility must consider all factors, not just maintenance. Present practice generally provides for better access on major and complex bridges. Elaborate walkways, powered and hand-operated travelers, and various rail systems have been installed for inspection, painting, and maintenance work. Toll facilities normally provide more elaborate access systems, often because of requirements imposed by the bonding authority. This better access improves inspection and maintenance capability and is a factor that has generally resulted in better maintenance on these bridges. Most agencies are utilizing snoopers and cherry pickers for access to the outside and underside of high bridges. These devices have improved accessibility to these locations. Ladders, hand holds, and cables could be utilized at locations where access is required.

The Tacoma Narrows Bridge in Tacoma, Washington is a suspension bridge with a 2800-ft (850-m) main span, 1100-ft (340-m) side spans, and various steel and concrete approach spans. Figure 1 shows the power-operated traveler that provides access through the stiffening truss of the side and main spans. Figure 2 shows one of the three manually operated lower travelers that provide access below the bottom chords of the stiffening truss between the main piers. Figure 3 shows a timber walkway between the deck trusses on a major bridge in Idaho. These are examples of how access can be provided for maintenance and inspection. Such access is cost-effective if one considers only maintenance painting on the bridges. Figure 4 is an example of how access can be provided to bearings and still achieve the desired aesthetics. The view from the traveled way shows the pier face extending to the bottom of the box girder. The view from the backside of the pier shows the opening to allow access to the rollers. This configuration will allow for placement of jacks if repair or replacement is required. (Figures 13 and 14 in the Bearings section of Chapter 5 also show how access and jacking capabilities can be incorporated in truss and box girder bridges.) The North Carolina Department of Transportation Design Manual contains the following section on access:

13-11 Providing Access Facilities on New Bridges

On bridges on which accessibility to portions of the structure for inspection or maintenance work would be difficult from the bridge deck or from beneath the bridge, means of access to all parts of the bridge in the form of walkways, platforms, or ladders, shall be included as a part of the bridge contract. Detailed plans for such access facilities shall be included in the structure plans.

(a) The following criteria shall be used as a guide in determining on which bridge the facilities should be provided:
   (1) Structures on which mechanical or electrical devices that require maintenance or replacement are installed.
   (2) Bridges with exterior girder depth of any part exceeding 10.0 feet from bridge floor at gutter to bottom of girder.
   (3) Bridges having vertical underclearance of 35 feet or greater and an out-to-out deck width of 48 feet or greater.
   (4) Bridges over water or marsh land that have out-to-out width of 48 feet or greater.
(b) Final decision as to the need and type of access facility should be made in consultation with the Bridge Maintenance Unit.
(c) All access facilities shall meet OSHA requirements for structural size and safety criteria.

The above are the only accessibility criteria found during this study as written instructions to bridge designers. These types of criteria should be part of all design manuals to help create more uniform consideration of access and improve communications between bridge design and bridge maintenance engineers. Bridge designers should:

1. Provide access for cleaning and painting.
2. Provide access to all working parts.
3. Provide accessibility to parts that may require repair during the life of the bridge.

FIGURE 1 Tacoma Narrows Bridge—through traveler.

4. Provide special access for routine maintenance items, including lubrication, drainage, and lighting systems.
5. Provide access and details for jacking at bearings.
6. Provide access with walkways, ladders, travelers, rails, cherry pickers, or snoopers. How access is provided should be a part of the design process. Designers should show on an appropriate drawing the more critical points in the section where problems may occur. The access points should preferably be at each end of the structure, from areas that are easily accessible and that do not require traffic control. Access should be continuous through a girder line and openings through cross members should be a minimum of 30 in. (750 mm) in diameter.
7. Provide for internal access of closed structures, with due consideration for ventilation and illumination. The interior of box sections should be painted a light color to improve visibility.
8. Be guided by department's established criteria.

FIGURE 2 Tacoma Narrows Bridge—lower traveler.

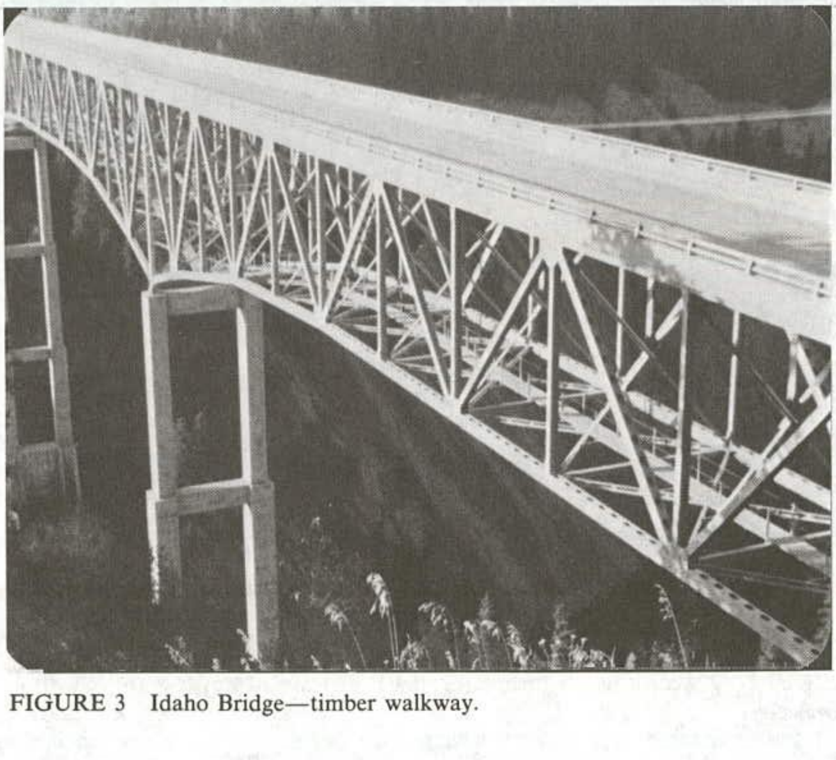
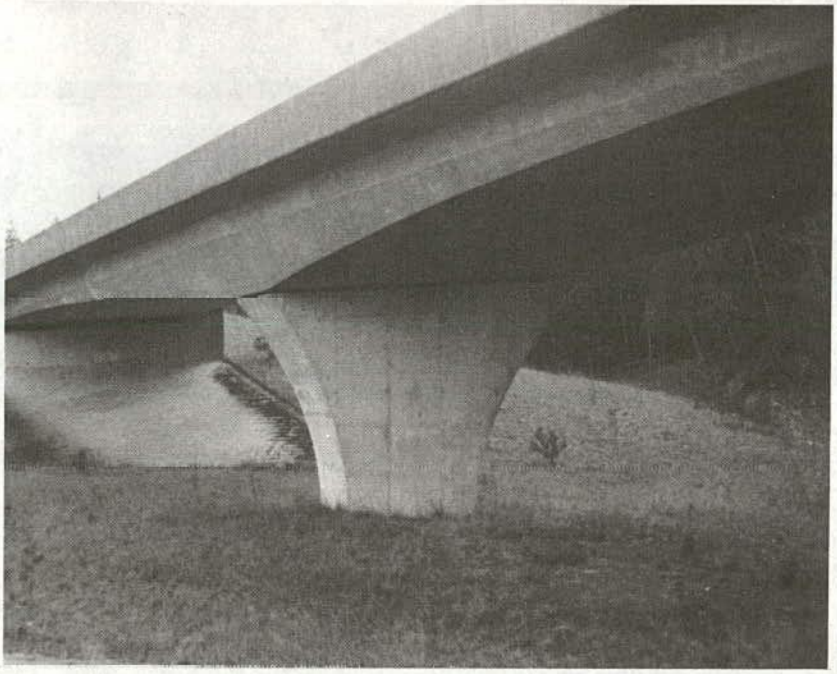
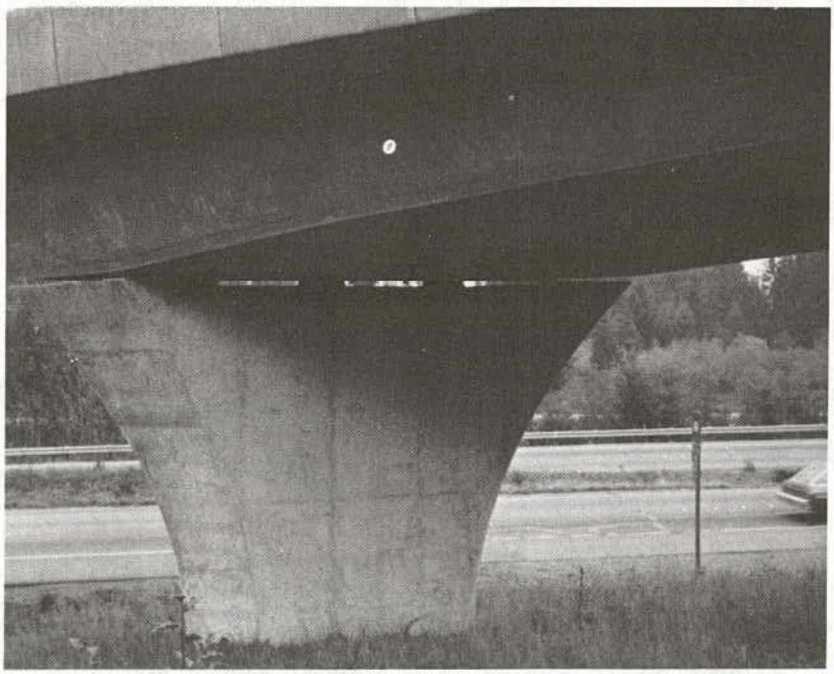


FIGURE 3 Idaho Bridge—timber walkway.



(a)



(b)

FIGURE 4 Access and aesthetics: (a) view from traveled way, and (b) view from backside.

CHAPTER THREE

DESIGN AND USE OF MATERIALS

MATERIAL SELECTION

Proper selection of materials and adequate quality assurance will reduce maintenance requirements. Bridge designs should utilize new and improved materials after they are proven to be effective in improving maintainability. Early construction used natural and available material, notably stone and timber. Many timber structures were built in this country and a number are still in use. However, bridges are currently constructed with two basic materials, concrete and steel. These two basic materials, used singly or in combination, have proven most durable and cost-effective for main structural elements. They can be shaped to desired dimensions, are capable of transmitting loads and stresses, and, when properly protected, have relatively long life expectancy. The AASHTO specifications (*1*) provide up-to-date information for correct use of materials for bridge design. Validated research is continually being incorporated into these specifications. Design criteria and quality control procedures specified by AASHTO should be fully understood by designers.

CONCRETE

Quality concrete, a mixture of cement, water, and aggregate, requires selection of good materials, correct proportion of all ingredients, and proper techniques in handling. Concrete has a relatively high compressive strength, increasing with age, and a relatively low tensile strength. Plain concrete is suitable only for structures not subject to tension. Concrete structures subject to tension require the placement of reinforcing steel within the concrete section. Quality concrete is a durable material and, when properly reinforced, is a relatively maintenance-free material for bridge construction.

One of the most important factors affecting concrete quality is the water-cement ratio. It has been common knowledge (*5*) that durability will be greatly increased by using a low water-cement ratio. For bridge decks in Kansas, McCollom (*6*) found that increasing concrete cover from 2 in. to 3 in. (50 to 75 mm) and decreasing the water-cement ratio from 0.44 to 0.34 would triple concrete deck life.

NCHRP Synthesis 57 (*7*) indicates that states were specifying water-cement ratios from 0.4 to 0.53 in 1977. With the success of low-slump concrete in retarding salt contamination and on the basis of the findings in Synthesis 57, it is recommended that a water-cement ratio of 0.4 or less be established for concrete exposed to salt intrusion. A low water-cement ratio in all concrete will reduce shrinkage cracking, increase durability, and reduce maintenance. To further enhance concrete quality, air-entrainment should be specified. Some types of sealers can be used to protect concrete surfaces, and epoxy-coated reinforcing steel should be installed in concrete subject to salt environment. Quality concrete requires nonporous, durable aggregates, proper vibration to ensure placement without voids or rock pockets, and good curing procedures.

Specifications and quality assurance should ensure proper slump and consolidation during all phases of construction. Results of on-going research indicate that quality control techniques play a most important role in underwater concrete construction. Florida and Louisiana are using prestressed concrete piles, manufactured under strict quality control to reduce concrete pile deterioration.

Prestressed and/or precast concrete has been extensively used since the early 1950s. This type of construction has produced more durable concrete, reducing maintenance and repair. However, research shows that in a salt environment all reinforced concrete is subject to deterioration from reinforcing steel corrosion. As long as chlorides are used for ice and snow removal, all concrete structures will deteriorate if the steel is unprotected from chloride. In areas where great amounts of chlorides are used, deterioration of concrete can be observed in facia beams and rails that is caused by salt spray from below and by drainage from above. Roadway drainage slots should be eliminated and drainage systems designed to eliminate drainage onto caps, girders, piers, or piles. All steel components subject to salt intrusion must be protected from corrosion to reduce maintenance costs. Various methods have been tried to protect concrete reinforcing elements. These include cathodic protection, polymerized concrete, wax-bead impregnation, low-slump or latex-modified concrete overlays, waterproofing systems, sealers, metallic-coated bars, and epoxy-coated bars.

Based on present knowledge, the use of epoxy-coated reinforcing steel offers the best and most economical technique to protect concrete from corrosive deterioration. The process of coating the bars has been developed and all states contacted are using epoxy-coated bars in bridge decks. Some are specifying only the top layer to be coated whereas others are requiring all deck steel to be epoxy coated. Protecting all deck steel will prevent corrosion from underneath and will reduce corrosion cells from forming between steel bars. In addition, all other reinforcing steel exposed to salt intrusion should be epoxy coated. This includes steel in columns, piers, retaining walls, median barriers, and bridge rails. All elements of the reinforcing system should be protected with inert materials. Bars should be cut and, preferably, bent before coating, and chairs and tie wires should be plastic coated. Handling and placement of the epoxy-coated bars must be accomplished with care to ensure that damage to the coating does not occur. This requires the development of complete specifications for the coating and placement of the steel, and quality control during the construction phase.

Design and construction of segmental concrete bridges also dictates the careful selection of materials. All steel in the portions of these structures that may be subject to salt penetration should be protected by the use of inert material coatings or continuous encasements. Because of the monolithic features of this type of design, repair and rehabilitation will be extremely difficult, if not impossible. Therefore, it seems reasonable to design the structures conservatively.

The FHWA recommends that provision be made for the installation of future additional longitudinal external post-tensioning inside the box girder. The amount of future post-tensioning is approximated at 10 percent of design prestress force. It is also recommended that transverse post-tensioning in the top flange (deck slab) be encased in polyethylene ducts. This method is used in rock-anchor work. In addition, FHWA recommends that all conventional reinforcing steel should be epoxy coated. To further protect these corrosion-critical structures, they recommend the construction of a low-slump concrete overlay of the roadway deck. Work is ongoing to determine the feasibility of using epoxy-coated prestressing steel. Only highly durable aggregates should be used in the concrete. Also, especially in areas where deicing chemicals are used, joints between segments should be carefully inspected for leakage because there is direct access to the strand where it crosses the joint.

The use of low-slump, low-permeability concrete was first developed and used in Kansas and Iowa. This type of material is still being used effectively to extend the life of bridge decks. Recent findings in Iowa indicate that this is not a permanent solution. However, through proper preparation and installation, it offers an effective means to rehabilitate a deteriorated bridge deck for an appreciable length of time. With the advent of epoxy-coated bars, it is interesting to note that Iowa is no longer specifying low-slump overlays on new construction. Many states have installed waterproof membranes under asphalt surfacing placed on concrete decks. Asphalt mats are often placed on deteriorated bridge decks to prolong deck life. Although this method has been used extensively, it has not proven to be a permanent solution. The province of Ontario, Canada installs a waterproof membrane covered with protection board and hot-mix paving on new prestressed concrete bridge decks.

Concrete Bridge Decks

The bridge problem most often mentioned today is the deterioration of concrete bridge decks. The cause is salt-induced corrosion of the reinforcing steel. The solution of the problem is to eliminate the chloride intrusion or to eliminate the corrosion of the reinforcing steel or both. Techniques and procedures have been developed that combat concrete deck deterioration. To reduce concrete deck maintenance, bridge designers should:

1. Stress importance of concrete quality control and placement of reinforcing steel on plans and in specifications. The water-cement ratio should be no greater than 0.4 and air-entrainment should be specified. The minimum clear cover to the top mat steel should be 2 in. (50 mm). To maintain this minimum, the nominal cover should probably be 2½ in. (64 mm).

2. Specify epoxy-coated bars in decks subjected to salt application. To prevent corrosion cells from forming between top and bottom mats, all reinforcing steel in the deck should be coated. The additional first cost may eliminate high repair costs later.

3. Specify high-density, low-slump concrete (HDLSC) or latex-modified concrete (LMC) with low permeability for overlays on deteriorated bridge decks. This technique will extend the bridge deck life. Research indicates that chloride intrusion will continue but at a reduced rate. With HDLSC, concrete consolidation is important. The concrete density should be no less than 98 percent.

4. Specify both epoxy-coated bars and HDLSC or LMC overlays on particularly vulnerable structures, such as segmental bridges, and on bridges carrying high-volume traffic. The inherent design features of these bridges pose very difficult repair problems. Install the post-tensioned prestressing in inert duct material, such as corrugated polyethylene, and fill duct with inert material.

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Concrete Design Details

To reduce the maintenance requirements of concrete bridges, special attention to details is important. Concrete design theory is well developed and seldom is the cause of maintenance problems. However, the location and placement of reinforcing steel within a section can be critical. Reinforcement should be sized and located to allow proper placement of the concrete. The size and durability of aggregate is important. When designing heavily reinforced members, the designer should draw the detail to a large scale to ensure that proper clearances are maintained. The desired placement of steel within the member should be determined and then the detail should ensure that the steel can be placed in that position. Designers should be aware that fabrication tolerances, especially on large-diameter bars, may preclude extremely close tolerances on bar location. Some leeway on bar placement should be allowed while still providing adequate cover.

Because cracking causes a major maintenance problem in concrete bridges, designers should pay particular attention to areas of high stress concentration. In box girder bridges, fillets are required at the intersection of webs with the top flange because of stress concentration. When stress requirements dictate a change in section thickness, this change should be accomplished by an adequate transition. Slab thickness should be increased at a rate of no more than 1 in 24 and webs should be tapered for a minimum distance of 12 times the difference in web thickness. Highly stressed bars require a larger radius of bend than hooks at bar ends. The larger radius is required to keep the radial pressures against the concrete within safe limits. The effectiveness and importance of proper reinforcement placement in concrete sections at corners subjected to bending are shown in Figures 5, 6, and 7. These representative examples show ways the designer can reduce maintenance operations.

Corners subjected to bending, as in (a), tend to crack at the reentrant corner and fail in tension across the corner. If not properly reinforced, the resisting corner moment is less than the applied moment.

Reinforced as in (b), the section will develop approximately 85% of the ultimate moment capacity of the wall. If the bends were rotated 180°, approximately 30% of the wall capacity would be developed.

Adding diagonal reinforcing steel across the corner, as in (c), approximately equal to 50% of the main reinforcing steel, will develop the corner strength to fully resist the applied moment. Extend the diagonal reinforcement past the corner each direction for anchorage. This bar will fully develop the resisting moment; thus a fillet in the corner is normally unnecessary.

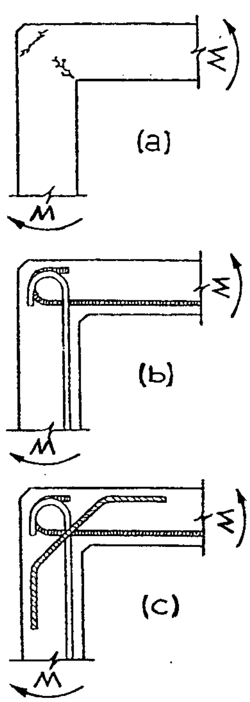

FIGURE 5 Right-angle concrete corners subjected to bending.

Side face cracking of large reinforced concrete beams can be eliminated by the addition of skin reinforcement. Precast components utilizing more prestressing result in less cracking. Bursting and spalling caused by out-of-plane pressures, curvature, inclination, and eccentricity of the prestressing steel can cause excessive cracking in the anchorage zone and at points of maximum curvature of the steel. The designer should provide additional reinforcement and utilize spiral reinforcement to contain these forces.

One detail in concrete design that reduces maintenance is continuity. Prestressed girder bridges designed continuous for live load eliminate many deck joints. Designs incorporating integral cross beams at the same level as the prestressed beams eliminate bearing devices. By eliminating joints and bearings, maintenance requirements are reduced. Designers should use epoxy-coated steel in all portions of the structure subject to salt environment.

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Like right-angle corners, the section in (a) tends to crack at the reentrant corner. The section reinforced as shown in (a) will develop the corner strength to fully resist the applied moment.

A fillet is not needed to develop the corner strength, but better resistance to cracking and better embedment of reinforcement can be accomplished with a fillet ¼ to ½ of the wall or beam thickness. Use reinforcing steel across the corner approximately equal to 60% of the main reinforcing steel.

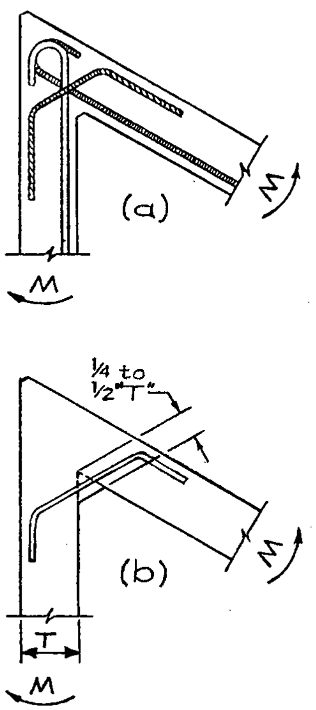

FIGURE 6 Acute-angle concrete corners subjected to bending.

Cantilever Retaining Wall

The footing near the corner (at the junction between the stem and the footing) with reinforcing as in (a) will fully develop the resisting moment as long as the toe of the footing is long enough for anchorage and the stress at "A" (bottom) is not critical.

T Joint

The forces in (b) form a tension crack at 45°. Reinforcement as shown is more than twice as effective in developing the strength of the corner than if the reinforcement were turned 180°.

"Normal" Right Corners

Corners subjected to bending as in (c) will crack radially in the corner outside of the main reinforcing steel. Smaller size reinforcing steel (similar to temperature reinforcing steel) placed in the corner as shown will distribute the radial cracking. For highly stressed steel, the radius of bend may have to be increased to keep radial pressures against the concrete within safe limits.

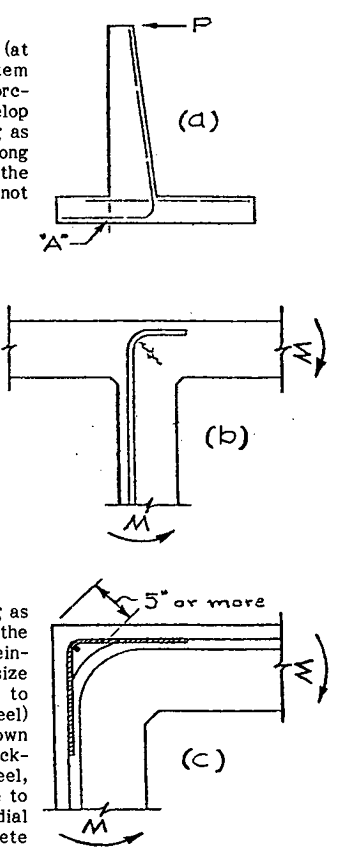

FIGURE 7 Concrete corners subjected to bending.

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STEEL

Reinforcing and structural steels are the backbone of practically all bridges being designed today. Because of the yielding characteristics of most steel, stress transfer occurs within members and joints, thus allowing steel to be an inherently forgiving structural material, particularly for static loading. However, the use of ductile steel should be assured, not assumed. Also, repeated live loads combined with stress concentrations can lead to fatigue failure.

Factors of particular importance in design are steel toughness, fatigue strength, weldability, and the effect of welding on strength, ductility, and fatigue strength. The grades of steel most commonly used for bridge construction are M 183 (A 36), M 23 (A 572), M 222 (A 588), and M 244 (A 514, A 517). The A 514 and A 517 steels are high-strength, quenched, and tempered steels and must be used with care, particularly with regard to welding and fatigue resistance. AASHTO specifications for toughness, fatigue strength, and welding should be carefully incorporated into the design process.

Steel with low toughness characteristics is subject to brittle fracture, particularly at low temperatures. Toughness is the ability of material to absorb energy under suddenly imposed stresses, such as impact conditions, by deforming plastically before fracture. The measure of this deformation ability at a high rate of loading determines impact strength. Stress concentrators, such as notches, inside corners, changes in section size, attachments, holes, weld flaws, and threads, can initiate failures. Designers must properly assess stress concentration areas and minimize their effects through good design detail, material selection, and specifications. Brittle fracture can occur at stress levels below normal design levels when steel is subjected to impact loads or stress concentrations at comparatively low temperatures. The toughness of a steel can be determined by making Charpy V-notch tests. Steel material specifications should include the supplemental impact properties as defined by AASHTO.

Because of the fracture-critical characteristics of all steels from impact and repetitive loadings, distinction is made in the AASHTO specifications with regard to redundant and nonredundant-load-path structures. A nonredundant-load-path structure is one where a single fracture can lead to a catastrophic collapse. For example, flange and web plates in one- or two-girder bridges, main one-element truss members, tie girders in tied-arches, hanger plates, and caps at single- or two-column bents have nonredundant load paths. Fracture-critical members or member components (FCMs) are nonredundant. FCMs are tension members, or tension components of members, whose failure would be expected to result in collapse of the structure. Any attachment that is welded to a tension component of an FCM shall be considered a part of the tension component and therefore fracture critical. Examples of fracture-critical members are the girders of a two-girder bridge, steel pier cap beams, tie girders of a steel tied-arch bridge, suspended-span hangers in a two-girder bridge, and other nonredundant parts supporting the superstructure.

FCMs should receive more rigorous and conservative analysis during the design process. Because FCMs are nonredundant, care must be taken to ensure that steel with adequate toughness is specified for these members. Compression members are not fracture critical and therefore fatigue stress limitations used for tensile members do not apply to compression members. Where practical and possible, multiple load paths should be designed to provide redundancy. Single-cell steel box girder and two-girder steel systems should be avoided. The introduction of a third load path would be expected to reduce the probability of catastrophic failure to near zero.

To reduce the cost of maintenance, weathering steel (A 588, M 222) has been used for many steel structures. It has been found that in a salt-corrosive environment, or in areas that do not dry readily, the desired protective oxide coating may not form on weathering steel, and it will corrode about the same as ordinary steel. Kansas has experienced corrosion problems at hinge and bearing points. Michigan has experienced problems with these bridges because of salt attack from leakage through deck joints and from traffic-induced spray. In the proper environment, the use of weathering steel will reduce maintenance costs. Thorough inspection of this material is critical to ensure that corrosion does not occur over a long period of time. Also, it will be necessary to ensure that moisture and debris are not allowed to collect on exposed steel areas. This is important for all grades of steel.

The use of weathering steel is currently being studied by the Michigan DOT. Some of their older bridges, in very corrosive environments (heavy traffic and salt use), have experienced extensive corrosive attack. Pits up to ¼-in. (6-mm) deep have developed in the steel. It has been found that commercial blasting and painting are ineffective but some "high-technology" coatings have been effective. The oldest bridges are approximately 18 years old. However, at seven years of age many bridges are showing the same types of attack that were noticed 11 years earlier on the bridges now showing significant corrosion. More recent inspections show that the corrosion is continuing at an accelerated pace. Because Michigan has utilized weathering steel extensively, they have proceeded in carefully inspecting many weathering-steel bridges on their highway system. The inspections have resulted in the halt in the use of unpainted A 588 steel. An American Iron and Steel Institute task force has made a study of weathering steel performance in bridges in the United States and concluded that when used in a proper environment and protected from chloride contamination, this method performs satisfactorily for long-term economy. The Materials Engineer for Michigan stated that current research in Japan and at the University of Maryland raised questions concerning the fatigue life of uncoated steels as well. NCHRP Project 10-22 will further evaluate the effects of corrosion pitting on fatigue behavior of weathering steel. The Michigan DOT is pursuing research in this area also, and bridge engineers should follow these studies to ensure the proper use of weathering steel in bridges.

Steel Design Details

The design of steel bridges became more complex and critical with the advent of welded bridges. It is not practical to build welded structures that have no flaws, or to return to solely riveted or bolted construction. Therefore designers need to become thoroughly knowledgeable of steel behavior related to stress range, fatigue, stress categories, toughness, brittle fracture, welding, attachments, flaws, and stress concentration. A review of the literature indicates that the great majority of fractures in steel bridge components are caused by fatigue. Fatigue failures can occur because of inadequate design criteria, improper design detail, overloads, poor workmanship, and lack of quality control during fabrication and erection.

The tenth edition (1969) of the AASHTO design specifications related allowable fatigue stresses to a ratio of minimum stress to maximum stress, and minimum tensile strength of the steel. The lowest allowable fatigue stress for A 36 steel was above 5500 psi (38 MPa). Following extensive fatigue studies in the 1970s these specifications were revised. Allowable fatigue stress is now related to the stress range because stress range has been observed to account for nearly all of the variations in life-cycle tests of beams and details. For design purposes, fatigue strength is independent of the steel strength. Fatigue fractures can occur at a stress range below 2500 psi (17 MPa). Allowable fatigue stresses are affected by finish treatment of welds, transition details of welded splices, length of welded longitudinal attachments, and thickness of material.

Among the more important design details affecting fatigue life are cover plates, stiffeners, attachments, and splices. Designers should recognize that when an attachment is welded to a member, it becomes an integral part of the member and can adversely affect fatigue life. There have been cases where longitudinal stiffeners were welded on exterior girders in tensile areas for aesthetic reasons. Not being considered structural elements, the welds were not subjected to proper quality control procedures and cracks propagated from weld flaws to the web. Much research has been done on steel beams with welded stiffeners and attachments. Cracks occurring at stiffeners welded to the web alone initiated at the terminating weld toe of the stiffener-to-web weld. When stiffeners are welded to the web and flanges, cracks originate at the toe of the transverse stiffener-to-flange weld. Cracks can also form at the stiffener ends in the compression regions; these cracks arrest after they grow out of the residual tensile stress zone. The same stress range-cycle life relationship is applicable to stiffeners welded to the web alone and to stiffeners welded to the web and flange. NCHRP Report 147 (*8*) states that welding transverse stiffeners to the tension flange should be permitted when it is needed or desired but the effect on the fatigue life must be recognized. This weldment could be desired to prevent out-of-plane bending that can cause serious fatigue fractures.

Until the early 1970s, there were no reported or known problems with welded bridge structures that could be associated with out-of-plane displacements causing secondary web bending stresses. Since that time fractures of this type have been reported. Out-of-plane cyclic displacements in web gap regions (between end of transverse stiffener plate and flange) that exceed 0.001 in. (0.025 mm) with gap length equal to 5 times the web thickness are susceptible to fatigue cracking. A cyclic deflection that exceeds 0.01 in. (0.25 mm) results in fatigue cracking at gaps equal to 10 times the web thickness. Out-of-plane movement can occur as a result of floor beam end rotation and/or relative end movement. Designers must give careful consideration to all details that will result in out-of-plane movement inducing secondary bending stresses. At points where a flange is restrained, such as a girder flange in the concrete slab, it will likely be necessary to connect the transverse connection plate to both flanges. Fatigue cracks that were caused by vibrations from transporting have been observed at ends of stiffeners. To minimize web cracking caused by shipping and handling stresses, the end gap of transverse stiffeners should be 4 to 6 times the web thickness.

The designer has direct responsibility for two of the major and most important factors to limit and control steel fracture and thus reduce maintenance. These are the choice of detail and the stress range. If a low-fatigue-strength detail is used, every effort should be made to avoid locating it in a region of significant cyclic stress. Otherwise, the stress range must be reduced by changing the section properties to accommodate the detail. When details are located in compression stress regions and no possibility of stress reversal exists, there is no fatigue problem. (Cracks may initiate in residual-stress zones but will not propagate.) All details should be designed in accordance with the current AASHTO specifications. All designers responsible for the design and maintenance of steel bridges should be thoroughly knowledgeable of those details most susceptible to fatigue cracking. They should have a clear understanding of the importance of stress range and stress concentration and all details should be designed for the allowable fatigue stresses.

Fisher (*9*) defines the classification of details and shows examples of fatigue failures. The importance of proper design details and welding is highlighted by the fact that experience has shown that cracks have generally propagated in depth between one-fourth and one-half the plate thickness before the paint film is broken, permitting the oxide (rust) to form. Very small cracks at weld terminations are difficult to detect by nondestructive inspection (NDI) techniques. Therefore, to reduce maintenance, designers should ensure during the design stage that steel bridges will be relatively crack free. Designers should recognize that length of attachments and thickness of flange plates affect the allowable stress range. Field inspections have shown that the details most susceptible to fatigue cracking are:

1. Flanges or plates that frame into or pass through webs. The flange tips represent a very severe fatigue condition. Both field and laboratory experience suggest that this type of detail is very likely to develop fatigue cracks.
2. Cover-plated beam bridges that have experienced large number of stress cycles.
3. Gussets welded to transverse stiffeners.
4. Groove-welded flange transition with reinforcement.
5. Beam-column connections of box sections. The intersection of beams and columns, where either the column or girder must be interrupted and the flange of one is welded perpendicular to the other, results in a highly restrained joint.
6. Intersecting welds at lateral connection plates. Sometimes when lateral connection plates are attached to the girder web and the transverse stiffener, an undesirable condition develops where the welds all intersect.
7. End welds of partial-length cover plates on flanges greater than 0.8-in. (20-mm) thick. These have the lowest allowable fatigue strength (detail E). Very heavy built-up girders could experience cracking problems.

To minimize problems associated with intersecting welds, designers should incorporate details that eliminate this condition. However, one must recognize that the termination of a longitudinal weld along a stiffener or connecting plate longer than 4 in. (100 mm) results in a Category E fatigue strength detail and the allowable fatigue stress value used in the design is very low. Figure 8 shows a detail of a vertical stiffener-longitudinal stiffener connection to a web that eliminates the objectionable intersecting welds. Figure 9 shows a similar detail for a vertical stiffener-gusset plate connection to a web. Note the Category E stress conditions at the longitudinal weld terminals. Good design practice should dictate that unnecessary attachments and welds, such as longitudinal stiffeners in tension areas, will not be made. Plans and specifications should require that all attachments and welds to be made on a member be shown on the shop plans. Cross bracing should preferably be bolted, not welded, to beams. The designer should clearly define

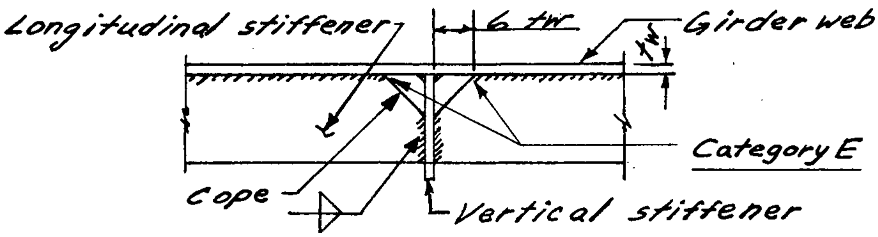

FIGURE 8 Vertical-longitudinal stiffener detail.

those members and details that are fracture critical and specify nondestructive inspection that will ensure quality workmanship. There should be a careful review of shop drawings to ensure that design is not compromised at that stage.

Steel bridge designers should have good understanding of the information contained in the following selected bibliography before design. Those engineers responsible for the maintenance of steel bridges should also become familiar with fatigue characteristics, brittle steel, and the effects of welding or heating before the initiation of repair work. If this is not done the cure may be worse than the original damage.

The third major factor affecting steel design is workmanship and quality control during fabrication and erection. Although the designer may not have direct responsibility in this area, the plans and specifications should define the procedures that are required for quality construction. Fatigue studies of bridge components and investigation of field fractures illustrate the importance and influence of welding and welded details on the life expectancy of highway bridges. The designer should prepare drawings and written procedures to supplement drawings, welding specifications, and manuals, as necessary, to fully describe the work. Fabricators should be required to fully qualify welding procedures. An example of a comprehensive manual for steel construction is the "New York State Steel Construction Manual" dated November 1, 1982. Other states have similar manuals and some states use American Welding Society (AWS) "Structural Welding Code" and the "Standard Specifications for Welding of Structural Steel Highway Bridges" by AASHTO. Supplemental specifications covering such items as lack of fusion defects and slag inclusions are required. Specifications that cover repair of faulty welds should be included.

Because of the criticality of material flaws such as delaminations, physical flaws such as nicks and gouges, and welding

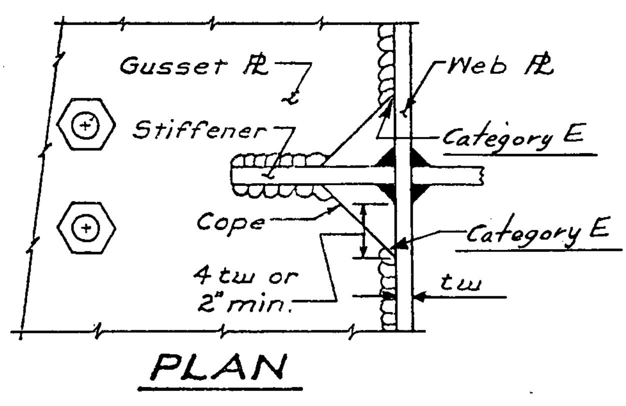

FIGURE 9 Vertical stiffener-gusset plate detail.

flaws such as cracks, the designer should be familiar with appropriate methods of nondestructive examination (NDE). Effective NDE of all steel construction is a major factor in reducing bridge maintenance. Normal inspection during fabrication, if done properly, will ensure that initial flaw sizes are small. The possibility of fatigue crack growth is very sensitive to initial defect sizes. Designers should be aware that A 514 steel is difficult to weld and cracking has occurred as a result. Preheat and interpass welding temperatures should be sufficient to prevent crack formation. A preheat temperature above 300°F (150°C) should be considered for highly restrained welds. Heat input during welding should be such that the hardness of the heat-affected zone does not exceed a Rockwell hardness of C27. Welding electrodes should be kept at 250°F (120°C) until ready to weld. Cracks detected in welds during fabrication should be removed before erection. Care must be taken to remove the crack completely. Preheat to a minimum of 150°F (66°C) before arc or flame gouging a crack. The gouged groove should then be ground smooth. The repaired area should be inspected by NDE. All welding on a bridge should be of high quality. The designer should not allow attachment welding for ease of fabrication. Extension bars and runoff plates should be used to ensure sound welds. They should be removed after welding and the surface should be finished flush by machining or grinding. Temporary or tack welds that are not incorporated into the final weld should be removed and the surface should be finished flush with the original surface. Tack welds should be avoided where possible. Thick weld sections increase the possibility of hydrogen cracking and may require special temperature control and post heating. Designers should recognize that minor discontinuities in the plane parallel to the applied stresses are generally not injurious and may best be left alone. Attempts to remove minor discontinuities may result in a condition that is worse than the original discontinuity. As stated, the designer of a new bridge may not have direct responsibility to monitor fabrication. However, indirectly the designer can help control this phase of construction by being sure the plans and specifications adequately define the work. Designers responsible for the repair of steel bridges require the same level of expertise as those designing new structures. This is most important when the repair involves heating or welding. Without sufficient knowledge, the repair could be worse than the original problem. To reduce maintenance the designer should reduce the possibility of cracking to the very minimum. Flaws should not be built into the structure. To better accomplish this goal the designer should:

1. Carefully follow the AASHTO design specifications for fatigue stresses. Reinforce these specifications by studying the

work that led to their development to ensure a clear understanding of the importance of stress range, brittle fracture, steel toughness, weldability, and the metallurgical aspects of hardening.

2. Give special attention to the details of design. Investigation clearly shows that many cracks initiate at or near connections, at points of restraint or stress concentrations, and as a result of secondary and displacement-induced stresses. Introduce redundancy, as possible, to reduce or eliminate fracture-critical members. Use bolted splices for field connections and for attaching diaphragms or wind bracing. Constantly strive to improve design techniques by studying available research and literature with regard to fracture failures.

3. Specify quality control procedures to ensure the required NDE to limit crack initiation. The designer should be responsible for defining those areas that are fatigue-stress critical. All weldments and attachments should be required to be shown on shop drawings, and these should be reviewed by the designer. Designers should thoroughly understand welding procedures and techniques because many cracks initiate from welding flaws, discontinuities, and weld repairs. Construction and maintenance engineers must recognize the importance of quality control specifications. These should not be treated as guidelines, but should be the basis for acceptance of the work.

4. Clearly show the location and define the category of critical steel design details for the bridge maintenance engineer. This information should be included on a plan sheet or in the bridge maintenance manual. Doing this during design stage will assist the designer in analyzing inspection facilities. The maintenance engineer and inspector will be able to provide more thorough inspection in less time. Communications will be improved.

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OTHER MATERIALS

Other materials often used in bridge design are timber, neoprene, polytetrafluoroethylene (TFE, sold under the trademark of Teflon) with stainless steel, bronze and other special alloys, zinc, lead, aluminum, and various plastics. With the exception of timber, these materials are generally used for special applications, such as in bearings, expansion devices, drainage systems, lighting systems, rails, and material protective systems. Most of these materials are covered by the AASHTO specifications.

Attention to details where these materials are used is important. As an example, very heavily loaded shaft bearings on a moveable bridge were designed with sintered bronze bushings, with grease fittings at the bearing tops. The excessive load plus lack of adequate lubrication caused the sintered bronze bearings to fail. To correct the deficiency, manganese bronze bushings with a spiral grease groove were designed to replace the original sintered bearings. The manganese bronze material was capable of sustaining more load, and the spiral grease groove ensured lubrication around the entire bushing.

The use of many of these materials has occurred because of their inert characteristics with respect to corrosive environments. Neoprene, TFE, stainless steel, bronze, zinc, and various plastics are not adversely affected by water and salts. They are ideally suited for use in bearings, expansion joints, and drainage systems. To reduce maintenance, designers should:

1. Specify neoprene bearings whenever the amount of motion will allow their use. Neoprene pads can be designed to allow longitudinal and transverse motions and at the same time provide for rotation. Laminated pads allow more longitudinal motion with less vertical deflection than plain pads. Neoprene pads are not only economical but allow movement without seizing. Neoprene pads also eliminate the need for routine lubrication.
2. Specify TFE bearings with stainless steel plates where larger movements preclude the use of neoprene pads and where lubrication is not provided.
3. Specify stainless steel for bearing components at locations that are not adequately protected from corrosion. Although the cost of stainless steel is high, the costs of removing a deteriorated bearing plate are much greater. The stainless steel thickness should be ⅛ in. (3 mm) minimum to allow for fastening and to prevent tearing. The use of a relatively expensive material in bearing systems will be cost-effective over the long-term bridge life.
4. Design bearing components with properly selected alloys that will adequately sustain the applied loads. If pins are used, case-hardened material should be specified and lubrication should be required, to limit corrosion.
5. Increase the use of inert materials, such as plastics and fiberglass for drainage system components. Fiberglass liners have been used for sidewalk and parapet drainage openings. The liners are extended 3 in. (75 mm) beyond the sides and top of opening on the interior and exterior face of the parapet and 3 in. below the bottom of the slab on the exterior face. Figure 10 shows a typical detail used in Maryland. This detail may still allow water to blow back on the structure.

Timber

Timber was extensively used in bridge design for many years. Most states still have many timber bridges on secondary and county road systems. However, the heavy loads of today, coupled with economic conditions, have all but eliminated timber as a principal bridge superstructure material. As highway loads increased it became more difficult to provide reliable connections, particularly in floor systems. Most nailed timber bridge decks fail long before the timber is worn out. The timber industry has developed glue-laminated and connection systems striving to overcome deficiencies.

The greatest use of timber in bridge design today is pile foundations and temporary construction. No wood is immune to marine-borer attack, so designers should select the type of wood and the method of protection most appropriate for conditions existing at the intended installation. All timber piling subject to marine-borer attack should be protected. The American Wood Preservers Standard MP-1 (AWPB-MP-1) requires

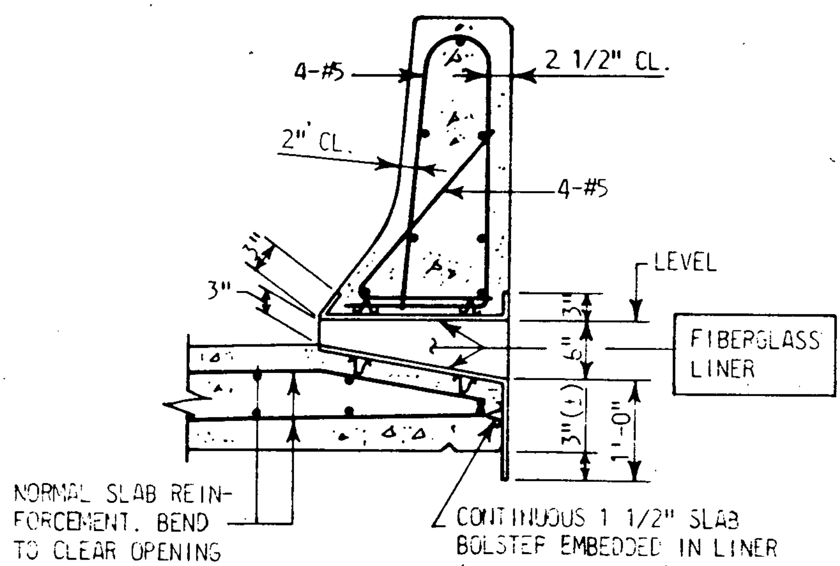

FIGURE 10 Fiberglass parapet liner.

the application of no less than 1.0 lb per ft^3 (16 kg/m^3) retention of ammoniacal copper arsenate or chromated copper arsenate and the application of no less than 20 lb per ft^3 (320 kg/m^3) retention of creosote. To be most effective the protective treatment must be thorough, the penetration as deep as possible, and the retention high. To ensure the highest retention possible the designer should specify that the piling be dried before treatment. It is best to treat piles by the full-cell process. For all but assured, short-term temporary construction, it is recommended that all timber exposed to the atmosphere be appropriately treated.

Ground contact is especially severe service; the areas immediately above and below ground line should receive special attention.

Proper protective treatment of timber and adequate connections are the best methods for reducing maintenance and repairs on timber structures. When timber is specified the designer should:

1. Specify the stress grade required to ensure structural adequacy for the intended application.
2. Clearly indicate the direction of grain of the timber in relation to the load in detail drawings (i.e., bearing perpendicular to the grain is markedly different from bearing parallel to the grain).
3. Design truss joints and other splice points to shed water to the maximum degree practicable. Joint details at truss panel points should provide definite lines of load transfer and should be simple and as susceptible as possible to definite strength analysis. Joints should be made only with fully seasoned timber. All steel connections should be galvanized.
4. Provide metal end bearings where posts or struts bear against the sides of timber members. Specify protective material to cover tops of caps and piles subject to collection of dirt, debris, and moisture.
5. Design all floor systems with positive connections to ensure that the system will not work loose. Use laminated units, preferably glue-laminates with dowels, and fasten down with bolts or deck brackets. Provide an adequate deck wearing surface. Specify that routine maintenance may be required to tighten hardware devices. Where hardware is subject to corrosion, specify hot-dip galvanizing.
6. Specify appropriate species of wood and protective treatment for the intended application to ensure long life. Once in place, inspection is difficult or impossible, and the cost to repair or rehabilitate is excessive. Fabrication should be accomplished before treatment and no degradation of the treatment should be allowed during construction. Untreated piles can be used when located below the permanent water table and not subject to marine-borer attack.

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CHAPTER FOUR

CORROSION PROTECTION

Corrosion is the deterioration or destruction of a material by reaction to its environment. The best way to achieve positive corrosion protection is to specify materials that inhibit or eliminate corrosion. Material selection, protective systems, and design details are most important to control corrosion. Because corrosion is an electrochemical process, the three basic elements necessary to cause corrosion are an anode, a cathode, and an electrolyte. These elements cause a metal to oxidize or rust, as is the case with steel. Rust is the conversion of metallic iron, through chemical or electrochemical reactions, into compound form. This compound may flake off the parent metal, and the area of the section is reduced. Corrosion of unprotected steel occurs in the atmosphere, underwater, underground, by chemical attack, and by electrolysis. The tendency of a metal to oxidize is related to its position in the electromotive force series. Steel, which is relatively high in this series, has a substantial tendency to oxidize. The structure and composition of rust varies particularly with the amount of oxygen present, and may determine the rate of further corrosion. If the rust is hard, dry, and well bonded to the metal surface it may retard corrosion, but if it is spongy and loosely bonded it will absorb oxygen, moisture, and salt and promote further corrosion activity.

The magnitude of the electrochemical potential determines the tendency of the reaction to proceed, whereas the rate of corrosion is determined mainly by resistance to the continued process set up by certain of the corrosion by-products. There are always nonuniformities in steel from the manufacturing process. These nonuniformities cause regions of lower potentials that are anodic and regions of higher potentials that are cathodic. Water or moisture acts as the electrolyte and conductivity is increased when salt ions are present. This causes the rusting process.

Designers should know and understand the following established facts regarding metallic corrosion.

1. In most cases both moisture and oxygen are necessary for corrosion.
2. The initial rate of corrosion is usually comparatively rapid, slowing as protective films form. Surface films are important in controlling the rate and distribution of corrosion.
3. Dissimilar metals in electrical contact accelerate corrosion of the one that is anodic. Galvanic action is a most active agent of corrosion. It occurs when two metals, one electronegative to the other, are placed in contact and exposed to an electrolyte.
4. The composition of ordinary iron and steel has little or no effect on their relative rates of corrosion underwater or underground. Under these conditions, the particular kind of metal is not usually as important as environment.
5. Variation in the concentration of a solution in contact with a metal tends to localize corrosion. The smaller the anodic areas in relation to cathodic areas the greater is the rate of penetration at anodic points.
6. Corrosion in crevices may proceed many times faster than at external locations.
7. Corrosion products are of greater volume than the metal consumed, and can generate high pressures. These pressures can warp, bend, and fracture adjacent metal. In enclosed spaces the increased volume may cause previously moveable connections to freeze.

Corrosion of steel elements in bridges is one of the most critical problems confronting bridge designers. Corrosion control is essential to reduce maintenance and repairs, and unless corrosion is controlled, repair and rehabilitation costs will be exorbitant. Structural design should include effective corrosion control. The relatively high first costs of materials and systems that inhibit corrosion, such as stainless steels, epoxy and high quality paint coatings, super cleaning, protective overlays, and cathodic protection, can be very cost-effective. Because water (particularly chloride-contaminated water) causes corrosion, designers should employ details that prevent water from contacting or collecting on bridge elements. Details and/or protective systems should preclude entrance of moisture between steel plates. Interplate corrosion, once initiated, is very difficult if not impossible to contain. The use of steel that forms its own protective coating (weathering steel) should be based on specific environmental factors. Various ways to control corrosion are within the domain of the designer, and designers should recognize the critical importance of corrosion control.

PROTECTIVE SYSTEMS

The most common method of corrosion protection of steel is by application of protective coatings. Designers should be aware of the environment the bridge will be subjected to in order to specify the proper coating system. Surface preparation is most important in achieving a good protective system. All mill scale should be removed and the surface should be cleaned to near white metal before the first coat application. The surface should be dry for application and coat thicknesses should be specified and controlled. When a designer is responsible for specifying a recoat system, only those areas that are corroded, or where the coating has broken down, need to be cleaned to near white metal. In the case of repainting, the cleaned areas should be given two coats of paint, and then the entire area should be given a final top coat. The effectiveness of painting steel bridges is demonstrated by Arch (*10*) who states that the Forth Railway

Bridge is in as good condition now as when it was built more than 80 years ago. Corrosion has been controlled by establishment of an effective repainting system. To achieve adequate corrosion protection, designer specifications should include inspection procedures to ensure quality control. Details should be designed with the recognition that they must be capable of being inspected, cleaned, and repainted. (Hangar links are a good example of a poor detail in this respect.)

Cathodic Protection

Cathodic protection is widely used for minimizing steel corrosion in structures exposed to aggressive environments. This type of corrosion protection has long been used to protect underground and underwater steel structures, particularly in marine environments. Cathodic protection consists of applying a direct current to steel of such polarity and intensity as to raise the electrical potential of the cathodic areas to the potential of the anodes. When this is successfully accomplished, corrosion currents can no longer flow and corrosion cannot proceed. The current that is needed for this type of protection can be obtained from a rectifier, or it can originate from electrically connected sacrificial anodes. In either case, an electric cell is formed in which the impressed current flows in a direction opposite to the natural corrosion current. The required currents are normally quite small and the applied voltages are seldom higher than 1 or 2 V.

This brief description of cathodic protection clarifies why dissimilar metals in an electrolyte or in electrical contact accelerate corrosion. The metal that is anodic to the other is sacrificial and corrodes. Designers should eliminate contact between unprotected dissimilar metals that might be subject to galvanic action. A cathodic system must be maintained properly to prevent galvanic action. The anodes, being sacrificial, must be replaced periodically. Zinc and magnesium anodes are often used in sacrificial systems, and these anodes may often be attached with copper or brass fittings. Because copper is strongly cathodic with respect to steel, the zinc or magnesium anodes must be maintained to avoid harmful galvanic action between the copper and steel. In an impressed-voltage cathodic system, the anodes may be high-silicon cast iron or graphite. Extensive areas of steel can be protected with one installation. An impressed-voltage cathodic system requires periodic monitoring of the applied voltage to ensure adequate protection without the danger of overprotection. Overprotection can be worse than no protection.

An impressed-voltage cathodic protection system has been in place on the Hood Canal Bridge in Washington since 1962. This system has been used to inhibit corrosion of the anchor cables and has performed very well. Two sets of cables are protected through one rectifier with graphite anodes. Electrical connection to the anchor cables is made with two wires. One No. 8 (3.25-mm diameter) wire is attached to the cable inside the pontoon and one No. 2 (6.55-mm diameter) wire is attached approximately 50 ft (15 m) from the deep-water anchor. These two electrical connections provide for adequate current flow to all parts of the anchor cable. The total length of protected anchor cable in this installation is as much as 2400 ft (730 m).

Bridge designers should install more cathodic protection systems, particularly on steel portions of structures immersed in salt water. The Florida DOT has used cathodic protection on steel H piles and reinforced piles to abate corrosion. Information and schematic details of the sacrificial systems are shown in NCHRP Synthesis 88 (*11*). These installations should only be installed after a complete engineering and economic analysis has been made. The bridge designer should work in close consultation with a corrosion control engineer when contemplating the use of a cathodic protection system. Specifications for the contract work should stipulate that a cathodic system design and operating manual be furnished. An instruction period for maintenance personnel should be required, and the engineers responsible for the design and operation of the cathodic system should be made fully knowledgeable of the system before final acceptance of the project. A cathodic protection system requires periodic review and adjustment. The design should establish the monitoring intervals and procedures, provide the instruments required, and stress the maintenance requirements.

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DESIGN DETAILS

Design details should eliminate or reduce the possibility of salt, moisture, and debris from contacting unprotected steel and concrete surfaces. The collapse of a section of the West Side Highway elevated structure in New York City (*12*) was principally caused by corrosion. The drainage system became plugged and expansion joints were not watertight. To inhibit or reduce corrosion, the following design guidelines should be followed.

1. Specify positive corrosion protective systems for all steel subject to corrosion, particularly corrosion caused by salt intrusion. Effective protective systems are high-quality paint systems, epoxy coatings, zinc coatings, special overlay systems, and cathodic systems. Designers should be aware of the advantages and limitations of these different protective systems.

2. Eliminate expansion joints whenever possible, but remember that continuous design is less tolerant of differential settlements than simple-span design. Where joints are necessary, specify them to be watertight and stress the importance cf correct installation. Where water may contact the structure through deck joints, protect those portions of the structure with a protective system.

3. Install the minimum number of drains with adequate grades and cross slopes. Pipes and fittings, inlet openings, and catch basins should be oversized to ensure required capacity. Pipes should be a minimum of 6-in. (150-mm) diameter with a minimum slope of 2 percent (preferably 8 percent). Use inert materials for drainage systems where possible, and standardize components to facilitate replacement. Install numerous and accessible cleanouts in closed systems. Drain all pocket spaces and enclosed cells on all structures. Where water is discharged, install deflector and splash plates to prevent water from contacting other portions of the structure. Extend open discharge pipes a minimum of 2 in. (50 mm) below the bottoms of girders and floor beams. Locate drains to prevent water from contacting pier caps and columns. Remember that wind should not be able to blow discharged water back onto structure elements.

4. Design details to preclude the entrance of moisture between adjacent plates or shapes. Interplate or crevice corrosion is almost impossible to control once it is initiated. Welds should be continuous and paint systems should seal all joints to prevent crevice corrosion. Provide sufficient space between adjacent members for air circulation, cleaning, and painting operations.

5. Design concrete bridge caps and cross beams integral with the girders, where possible. Integral design eliminates exposed pier caps, a major area where corrosion can occur. Where exposed caps are designed, the top surfaces should be protected and sloped so that water will run off.

6. Consider how a bridge will be painted. Access for painting and inspection is required. Provide cat-walks, rail systems, and/or connection devices for temporary cables and lines for painting operations. Where interior cells require painting, provide sufficient access, work space, and ventilation, and paint interior surfaces a light color to improve visibility.

7. Ensure quality control with complete performance specifications. Proper cleaning before application of protective systems should be specified. To reduce cracking of concrete structures from porosity and shrinkage, specify high-quality, low-slump concrete with low water-cement ratio.

To reduce maintenance requirements, designers should utilize materials that are inert to the elements, whenever possible. When materials are used that are subject to corrosion, protection analysis is required in the design process. Because corrosion is known to be the source of so many maintenance problems, corrosion-prevention engineering deserves much greater emphasis, and should be particularly emphasized in the AASHTO standard specifications.

CHAPTER FIVE

DESIGNING FOR REHABILITATION AND CONTINUED USE

Designers should expend special effort to define those portions of a structure that may require future rehabilitation. Feasible and cost-effective techniques should be incorporated in the design to facilitate this work. The designer should almost never assume that a facility can be closed to traffic for repair operations. Experience shows that closure rarely occurs. User inconvenience from long detours and inordinate congestion are not normally acceptable. Designers should develop details that will allow for rehabilitation while traffic is maintained. Anticipation of possible future work should be an integral part of design. Bridge components that are normally repaired while traffic is maintained include roadway decks and rails, expansion joints, bearings, mechanical and electrical equipment, and foundation and substructure systems.

The more redundant a structure is, the easier it will be to accomplish repairs under traffic conditions. When repairs are required on a multi-stringer bridge, it is possible to direct traffic away from the affected area. Repairs can then be performed with traffic away from the work area. When the designer is unable to develop details that will allow for the repair or replacement of a bridge component without closing the bridge to traffic, this fact should be made known to the appropriate administrative authority. The decision that closure will be required should be made during the design stage.

Following the development of design details and concepts to facilitate probable future repair, the designer should document the proposed rehabilitation methods. Without documentation, the designer's efforts may be lost through lack of communication. Documenting these proposed methods should increase communications among other designers, construction engineers, and maintenance engineers; and should result in constant improvement of rehabilitation techniques. Documentation might best be accomplished by incorporating certain details and concepts on the design plans, as these plans may normally be the most permanent record. Conceptual plans for infrequent repair work for specific components of a particular bridge might best be documented in a manual prepared for the specific bridge. Rehabilitation procedures that are generally applicable to all bridges could be documented by developing a manual of standard rehabilitation procedures. Most states currently have bridge design manuals and standard rehabilitation procedures could be incorporated in those manuals. Special maintenance requirements or features could be stored in the bridge computer file. Designing to facilitate rehabilitation should result in more effective and economical repair procedures.

ROADWAY DECKS AND RAILS

Roadway decks are subject to wear and deterioration from salt intrusion. Experience shows that many roadway decks require repair or replacement during the useful life of the bridge. The bridge deck and its supporting system should be designed so that traffic can be maintained while repair work is being accomplished. The number and spacing of girders, stringers, or beams should be designed to provide the required traffic lanes and work areas. The designer should determine the repair work sequence to ensure that requirements for all stages of the repair work will be met. As a minimum, this design approach requires at least three supporting girders, with one being near the bridge centerline. Deck repair work may require replacement of expansion joints. Joints should be designed so that they can be replaced concurrently with the deck sections. Bridge rails are subject to collision damage, and should be designed for replacement. Where metal rails are used they should incorporate standard components. Rails should be designed to be removable by sections. Rails that tend to redirect traffic on impact result in less damage to the bridge as well as to the vehicle. Care should be taken to protect through-truss members from vehicular impact that could cause structural damage.

Occasionally bridges require widening to accommodate increased traffic or to provide safer structures. Generally this work is accomplished under traffic. Several agencies have made studies to better understand the effectiveness of bridge-widening techniques. Bridge widening is most effective when the new deck is attached by lapping deck reinforcement rather than using dowels; keyways are not necessary (*13*). Steel girder and precast concrete girder bridges are generally the easiest structures to widen under traffic.

Additional material and selected bibliographies pertaining to roadway decks are included in Chapter 3 under "Concrete Bridge Decks."

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DESIGN FOR BRIDGE MOVEMENTS

Bridge designs must allow for movement caused by such factors as thermal forces, loss of prestress, creep, shrinkage, rotation, centrifugal and longitudinal vehicle forces, earthquake, earth pressure, wind, and ice loads. Although movements of bridges are relatively small and deceptively slow, the forces generated when movement is restrained become very large. Where a design does not allow the required movement, the generated forces may cause a failure. The designer must allow for the freedom of motion required by the structure. Movement can be accomplished by designing flexibility into the structural system. Where possible, the structure should be designed to absorb normal movement within its elastic system. When flexibility alone does not allow the required movement, expansion joints and bearings must be added.

Deterioration of expansion devices from continually working, heavy impact loads, corrosion, and environmental conditions normally results in required repair and rehabilitation during the useful life of a bridge. The difficulty and associated costs of repairing expansion devices dictate that the number of working expansion devices should be held to the absolute minimum. Bridge expansion joints and bearings should be designed the same way that machinery parts are designed; they should require a minimum of maintenance and should be easy to inspect, clean, and repair. Expansion joints, seals, and bearings should be designed as a total system, and the designer should ensure that each will allow the proper functioning of the other.

Designers should carefully study the geometry of the bridge to determine how movement will occur. Study is particularly important in the case of skewed and curved bridges. Skew can cause longitudinal and transverse forces on joints and bearings. On curved bridges, expansion tends to be parallel to the chord between bearings rather than on the tangent to the curve. All forces that may affect expansion devices should be considered in design, including the force required to move the expansion device itself, the force required to move bearing devices, and the force required to deflect substructure units. The location and amount of movement must be accurately determined to avoid damage to expansion devices or other bridge components. Designers should provide clear and concise details in the plans to ensure proper setting of expansion devices. Permanent marks should be established on the installed devices to show their original position. Future inspections should monitor movement, and this information should be available to the designer.

The design goal where several expansion devices are installed on a bridge should be that each device will take its share of the total movement. Bearings that move the easiest will tend to take all of the movement, unless prevented in some manner. Movement can be limited by installing restrainer bolts across joints causing the distribution of movement to other joints. The tie bolts should be designed with compressible material under one end so that the required joint movement takes place before the bolt becomes tight, forcing additional movement to the next joint. Figure 11 schematically shows a simple step bearing for a concrete box girder. The joint unit will equalize movement in the opposite direction.

Devices to equalize bearing movements should not be confused with devices used to secure joints from earthquake motions. Earthquake ties must be considerably stronger than equalizing devices. One of the principal reasons for bridge failures in the San Fernando, California earthquake was that expansion joints pulled apart. Standard practice in earthquake-prone areas now is to limit the distance bridge components can separate, vertically or horizontally, by installing restrainers. Prestressing strand, steel cable, or large bolts are used to meet strength requirements. Crushable material, such as urethane foam, is placed under the bearing washers to allow the desired motion and to provide shock-absorbing characteristics. Designers should develop methods for initial construction as well as for retrofitting existing bridges. Special reference is made to NCHRP Report 243 (*14*) and NCHRP Synthesis 41 (*15*).

Expansion Joints

Bridge expansion joints must accommodate all superstructure movements and carry high impact loads while being exposed to prevailing weather conditions. Moreover, they are contaminated with water, dirt, and all manner of debris that collects on the roadway surface and, in many localities, are subjected to salt-induced corrosion. Joints should safely accommodate all traffic using the bridge and allow for snowplow operation, where required, without sustaining damage. Joints should be watertight and easily maintained. Joint assemblies should provide structural support for the adjacent deck surfacing, and the anchorage system should be maintenance free. These severe service conditions and rigorous desired characteristics cause expansion joints to be a most challenging design problem.

One of the more common defects in expansion joints is the failure of the anchorage system. The heavy impact loads cause high, localized, repetitive stresses on connections. The location of the connections and the integrity of concrete adjacent to the anchorage system are extremely important. The joint assembly should be designed to carry wheel loads with no appreciable deflection, and provide steel armoring for the ends of the concrete deck sections. The edge bulkhead plates should preferably be brought down toward the bottom of the concrete section and

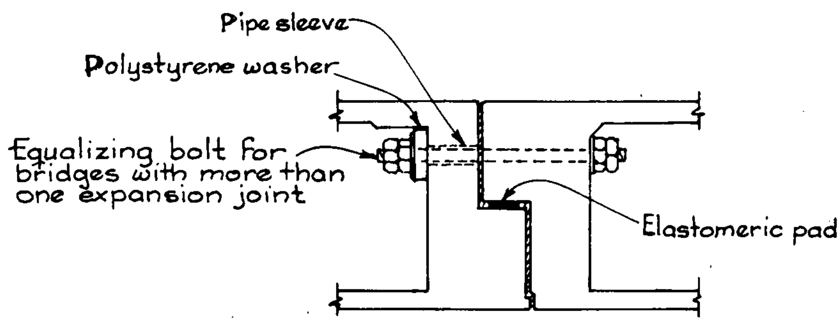

FIGURE 11 Equalizing bearing movement.

the anchors for that plate should extend into the top and bottom areas of the slab. The top anchors should be located no higher than 3 in. (75 mm) from the deck surface. These anchors should be incorporated into the main reinforcement of the structure. Design details must ensure that no looseness or working occurs in the anchorage system. Once an expansion joint starts to work, failure will occur. The designer should overdesign all structural details of expansion joint anchorage systems to reduce and possibly eliminate future repairs. Rehabilitation work on these devices is labor intensive, very costly, and extremely difficult to accomplish effectively under traffic.

The requirement that expansion joints should be watertight is a difficult criterion to achieve. For a joint to be watertight, the seal must be continuous across the entire roadway, curb, and sidewalk areas. The joint between the expansion device and adjoining concrete must also be watertight. The required continuity of the seal makes the effective repair of a damaged or worn seal difficult. The material used for seals is rubber or neoprene and is generally extruded to the required shape for the joint configuration. Fabrication and installation require the highest quality-control procedures. Installation requirements must be strictly enforced by the construction engineer.

The rubber material should not be directly affected by wheel loads, and must eject material from the joint to prevent damage to the seal and allow required movement. Expansion joints should have no projecting parts that will be subject to damage from snowplow operations. Modular joints have been designed with flexible rubber glands, held in place by supporting elements, to accommodate large movements. To limit maintenance, these joints should have a life expectancy at least equal to that of the roadway deck. When preformed seals are used, it should be possible to replace individual seals without having to remove the support elements of the expansion joint. The designer should detail procedures for accomplishing this work.

Good design practice should:

1. Reduce the number of expansion joints to an acceptable minimum. Elimination of joints may be accomplished by designing for continuity and taking advantage of the flexibility characteristics of the structural system. Precast girder bridges should be designed continuous for live load to reduce joints. Many precast girder bridges have been constructed with units up to 500 ft (150 m) between joints.
2. Use oversize expansion joints to allow for fabrication and installation tolerances and unanticipated movement. Oversize joints will compensate for movement that is difficult to calculate accurately, caused by factors such as loss of prestress, creep, and shrinkage. A conservative oversize factor should be in the range of 25 percent. Designers should furnish details and dimensions covering the possible temperature range during installation. An adequately designed joint cannot perform when it is installed incorrectly.
3. Design a joint that will experience no appreciable deflection under wheel loads and no failure to its anchorage system.
4. Strive to achieve watertight joints. When open joints are used, deflector plates should be installed to protect the bearings. The ends of girders and pier caps should be protected from corrosion. North Carolina applies epoxy coatings to prestressed girder ends, at grouted recesses of exterior girders, and at pier caps. It should be recognized that protective coatings may not be long lasting and that these areas will require routine maintenance. Open joints are subject to plugging with dirt and debris.
5. Utilize a performance specification when the joint design is the responsibility of a manufacturer. Some proprietary joints have not performed as desired or expected. Require suppliers to have successful, long-term experience. Performance specifications may result in higher initial cost, but should result in improved units. Do not compound initial and rehabilitation costs with large and complicated expansion joints just to reduce the number. Several smaller joints may be better.
6. Require the installation of relief joints at bridge ends and 30 to 50 ft (9 to 12 m) away from bridge ends to reduce force on bridge from pavement growth. In new bridge design, Illinois installs an anchor system for the approach roadway pavement to reduce the effect of pavement movement on the bridge.
7. Ensure quality control of all material, processes, and work by specifying appropriate nondestructive inspection and testing procedures.
8. Prepare complete instructions and specifications covering installation of expansion joint systems and emphasize the importance of proper installation.

When bridge movement is restrained, destructive forces may occur in bridge components. These forces can cause damaging bridge movement, jamming of expansion devices, displacement of bearings, shearing of anchor bolts, damage to pier caps and piles, damage to rail and curb sections, damage to abutments, and even damage to girders and stringers. Bridge repair will be significantly reduced by designing for ample bridge movement.

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Bearings

Bearings, whether expansion or fixed, are required to support the superstructure at a constant elevation and to safely carry loads and forces into the substructure system. Bearings must allow translation or rotation or both. Bearings can be eliminated or reduced in number by designing the superstructure continuous with the substructure. By reducing the number of bearings, continuous design can be an effective way to reduce future rehabilitation. However, reducing the number requires larger bearings and will increase the magnitude of movement at the remaining bearing points. Designers should objectively evaluate the effectiveness of the larger, and generally more complicated, bearing systems to be sure they do not compound future maintenance problems.

When the superstructure may be required to be supported or raised for repairs, jacking details should be incorporated in the design. The location for jacking and size of loads should be determined and the details should be included in the plans. Required clearances and details of the bearings should allow for removal of component parts without removal of other permanent portions of the structure. Bearing design may inherently provide jacking capability at bearing points. Some bearing stiffeners or reinforcement may be required, but reinforcement can be reduced by locating jacking points as close as possible to the permanent bearing points. Anticipating future problems can be very effective in facilitating rehabilitation.

The Washington DOT has designed jacking details for several bridges, during the design phase, to compensate for possible settlement. One is the North-Swift Ramp on I-5 in Seattle, and another is the Columbia River Bridge on State Route 2 near Wenatchee. The depth of the underlying strata of compressible material at these locations precluded the economical use of piles. The Columbia River Bridge abutments have been raised to compensate for the anticipated long-term settlement that did occur. On the Columbia River bridge project, the contractor was required to furnish the necessary jacks. The contract specifications also required that the jacking operation be successfully demonstrated as part of the original construction.

As reported in NCHRP Synthesis 41 (*15*), one bridge abutment in California was required to be raised more than 3 ft (1 m) over a period of years. The design included a jacking gallery and details for placing hardwood planks under bearings as settlement was observed. The jacking operation and placement of the shim planks could be accomplished without disturbing traffic.

Failures occur when bearings seize or are restrained from allowing required movement. Dirt, salt, and water are principal factors in bearing failures. Sliding devices tend to seize because of corrosion and are galled by dirt getting between the surfaces. Small-diameter pins used in roller or rocker assemblies tend to seize. Rollers develop flat surfaces and bearing plates develop indentations. Such bearing deficiencies may cause excessive stresses in the bearing anchorage system and in superstructure elements. The structure must somehow adjust to relieve these high stresses or fail.

The Poplar Street Bridge in St. Louis required temporary closure because of seized bearings (*16*). The failure of these bearings was caused by corrosion between the contact surfaces of the pin and the supporting saddles. The seized pin forced the girder to bend, separating the bottom flange from the bearing shoe. The resulting eccentricity caused the load to shift away from the bearing stiffener and resulted in the buckling of the end of the girder web. With respect to pin-supported bearings, the Poplar Street study recommends that double bearing stiffeners should be installed at bearing points, and that bearing pins should be case hardened and lubricated. Where lubrication is required, the designer should provide access and define the required maintenance procedures and schedules. The repair of the Poplar Street Bridge bearings was accomplished by the design and installation of elastomeric bearings. It was reported (*17*) that the repair of these bearings would cost more than three million dollars and would take a year and a half to implement.

Elastomeric bearing pads have revolutionized bearing design. They can be used on all types of bridges. It has been stated (*15*) that probably 85 percent of the bridges built in the United States can be designed with elastomeric bearings. Elastomeric pads have no moving parts that can seize, nothing that will corrode, and do not require a lot of maintenance. They have been used for several decades and have a good performance record. They are generally used for movements up to 3 in. (75 mm) and, in combination with TFE and stainless steel, can accommodate larger movements. The primary cause of failure of these bearings has been poor material. Some elastomeric bearing pads have moved out of original position and some have exhibited excessive bulging. The designer should ensure proper quality of material by adhering to the AASHTO specifications. A durometer hardness of 55 $\pm$ 5 is most generally specified. Pads greater than 1 in. (25 mm) in thickness should be laminated and the metal laminations should be covered with ⅛ in. (3 mm) of elastomer on the edges. Pads should be designed and molded as a single unit. They should not be stacked. Pads must be free to deform to allow motion. If restrained, they can cause damage to surrounding concrete. Because elastomeric pads cannot be adjusted for the installation temperature, the design must provide sufficient flexibility for the maximum range of motion. A one-time slip for elastic shortening may be permitted. Elastomeric bearing pads come close to being the perfect bearing and should be used wherever possible.

For movements greater than 3 in. (75 mm), various types of steel bearings are commonly used. Large single rollers or rockers are often used for these large movements. Rollers should have a minimum diameter of 4 in. (100 mm) and preferably should be larger than that. Rollers and rockers must be retained in correct position with pintles or other restraining devices. Pinned rockers are a modified version of segmental rockers. One advantage of the pinned rocker is that the pinned connection keeps the bearing aligned. However, pins are susceptible to seizing. To ensure sliding and prevent seizing, sliding bearings should be designed with inert materials, such as TFE and stainless steel, between the steel elements. The sliding surfaces should be located at the top of the bearing. The stainless steel should be on top of and extend over the TFE material to eliminate deposition of sand or dust on the sliding surfaces. Deposition of deleterious material on sliding surfaces will result in seizing or galling and will lead to malfunction of the bearing.

To realize long design life, all steel bearings must be protected from corrosion. Galvanizing may be adequate for a period of years, but when the galvanizing breaks down, painting will be required. When steel bearings are galvanized they should be stress relieved before dipping, and it may be necessary to straighten them after galvanizing. Machine work should be done after welding and stress relieving. Steel bearings should be installed so that the total normal travel they experience is divided equally by the median position. On a median temperature day bearings should stand vertically. The designer should calculate expected movement from all factors (such as elastic shortening, creep, shrinkage, sidesway, and temperature) in determining the normal position of a bearing. Dimensions should then be clearly shown on the plans so that the normal position of the bearing will occur at the midpoint of the temperature range. To avoid costly repairs, bearings should be designed for approximately 25 percent more than the maximum movement that will occur. Commonly used types of bearings are shown schematically in Figure 12.

Proprietary pot bearings, and adaptations thereof, have been designed by manufacturers to provide rotation and large movements. These bearings generally utilize TFE and stainless steel plates with elastomeric pads. The pads are generally confined in a pot by a piston and allow rotation. The TFE and stainless steel are normally located at the top of the bearing and allow longitudinal or transverse motion or both. This type of bearing is normally used for heavy load applications. The elastomer must be positively confined in the pot to prevent elastomer extrusion and failure. Because of the high loads and the required confinement, these bearings are difficult to inspect and repair. Based on recent reports from the state of Washington, this type of bearing may result in serious maintenance problems. This is a complicated type of bearing system that can greatly compound future rehabilitation. When this type of bearing is used, the designer should include jacking locations to carry the load while repairs or replacement are being performed. Figure 13 schematically shows a pot bearing and possible location of jacks. The sole plate cover and cap bolts allow removal of the bearing or component parts with a minimum of jacking height. This detail is adaptable to a deck truss (as shown in Fig. 13), and similar jacking installations are applicable to other bearing types.

Figure 14 shows the design of a cast-in-place concrete box-girder section that provides inspection access and space for placement of jacks. This design is incorporated in a major bridge constructed by the Washington DOT that includes large pot bearings. Inspection and jacking space is quite restricted in this design and more clearance would have been advantageous. Because of the restricted vertical clearance, it was necessary to recess the inspection platform into the pier. The superstructure of this bridge is continuous over the interior piers, with expansion joints located at each end pier. Therefore, there should be little chance of water collecting in the recess. However, all recesses that could collect water should be adequately drained. This design should allow for the adjustment or rehabilitation of the bearings, if or when this work may be required. To facilitate the work, the design of the pot bearing should incorporate removal features similar to those shown in Figure 13.

As has been pointed out, repair of failed bearings is costly and time consuming. Considering all factors, the maintenance cost of bearings can be the most important factor in bearing design. Designers should select the type that best meets the

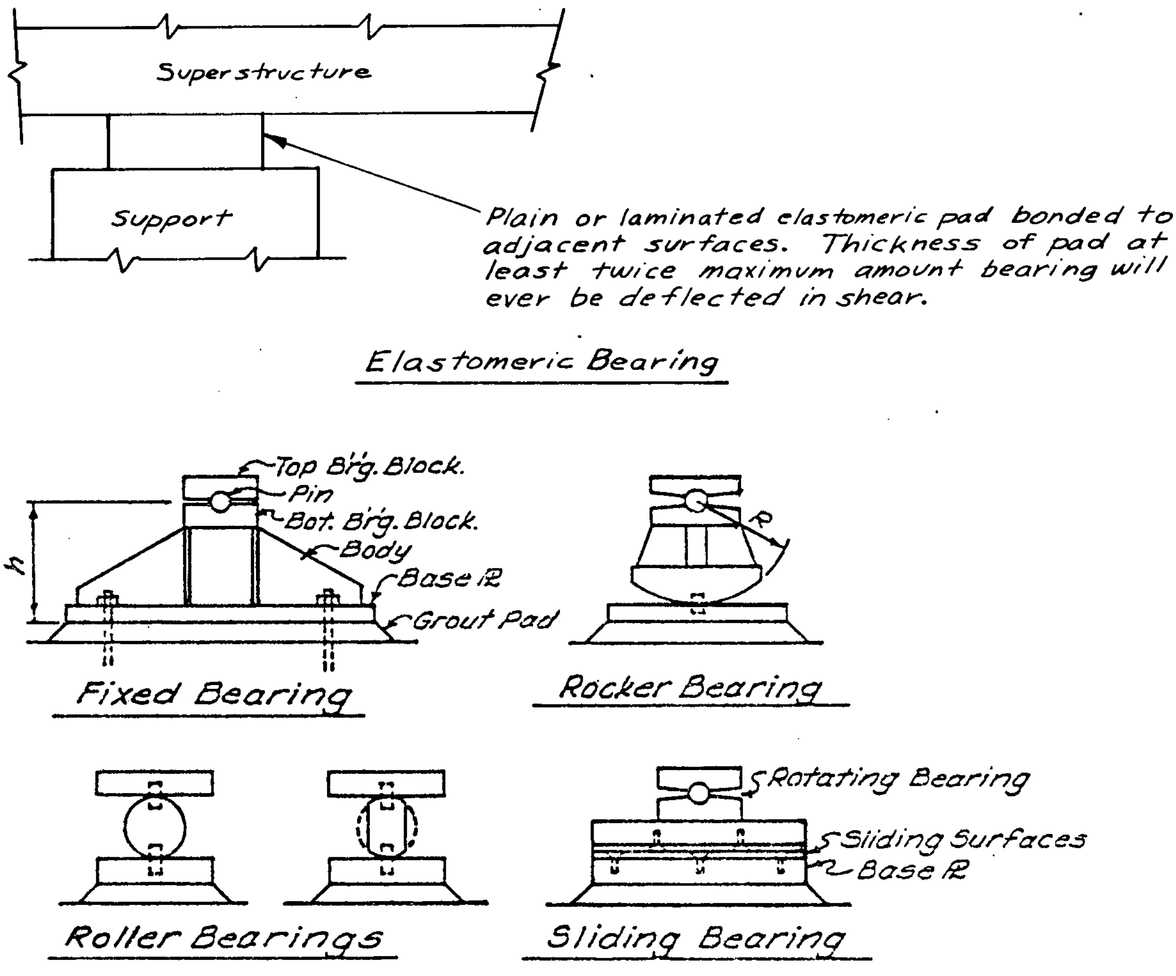
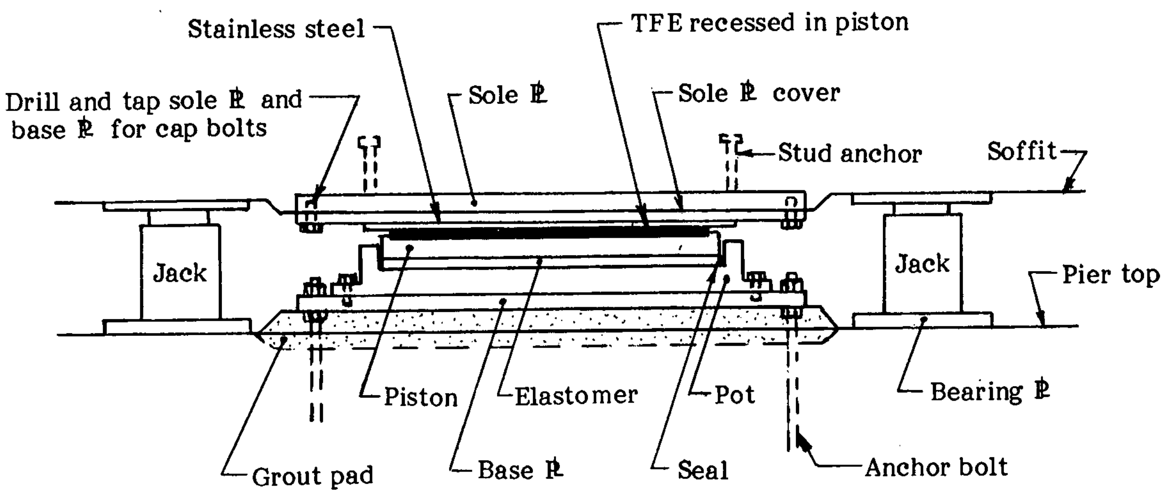
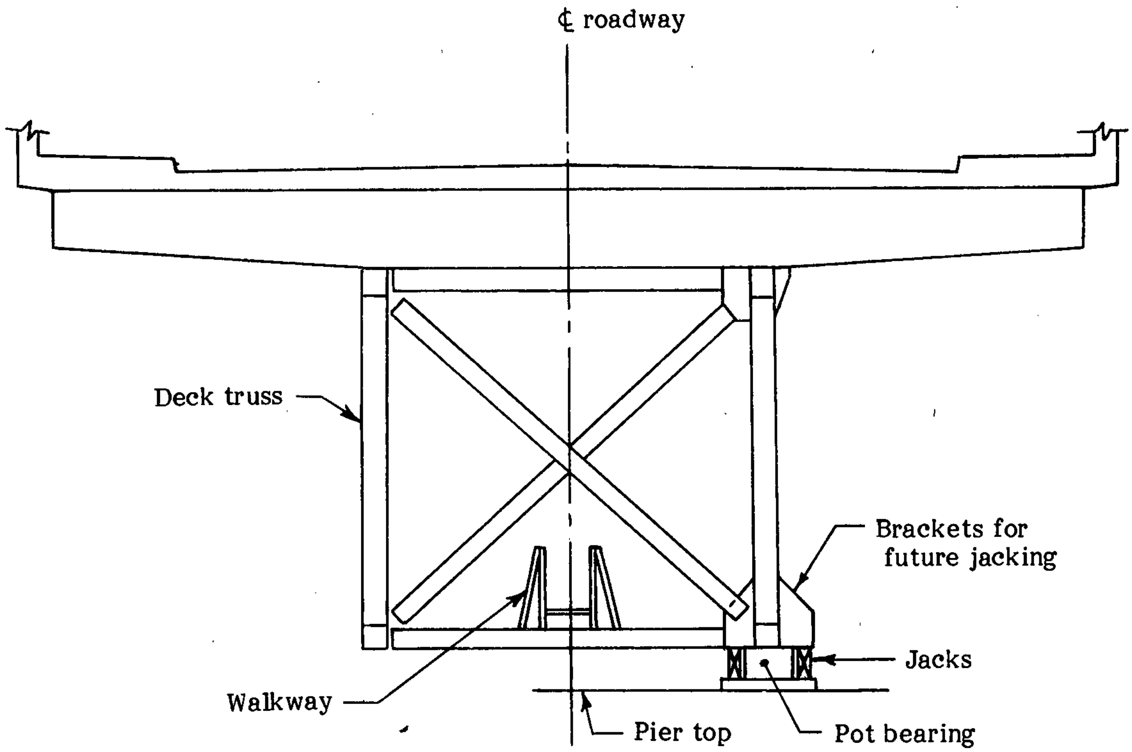


FIGURE 12 Bearing types.



Removable Pot Bearing



Jacking Brackets for Truss

FIGURE 13 Rehabilitation of pot bearings.

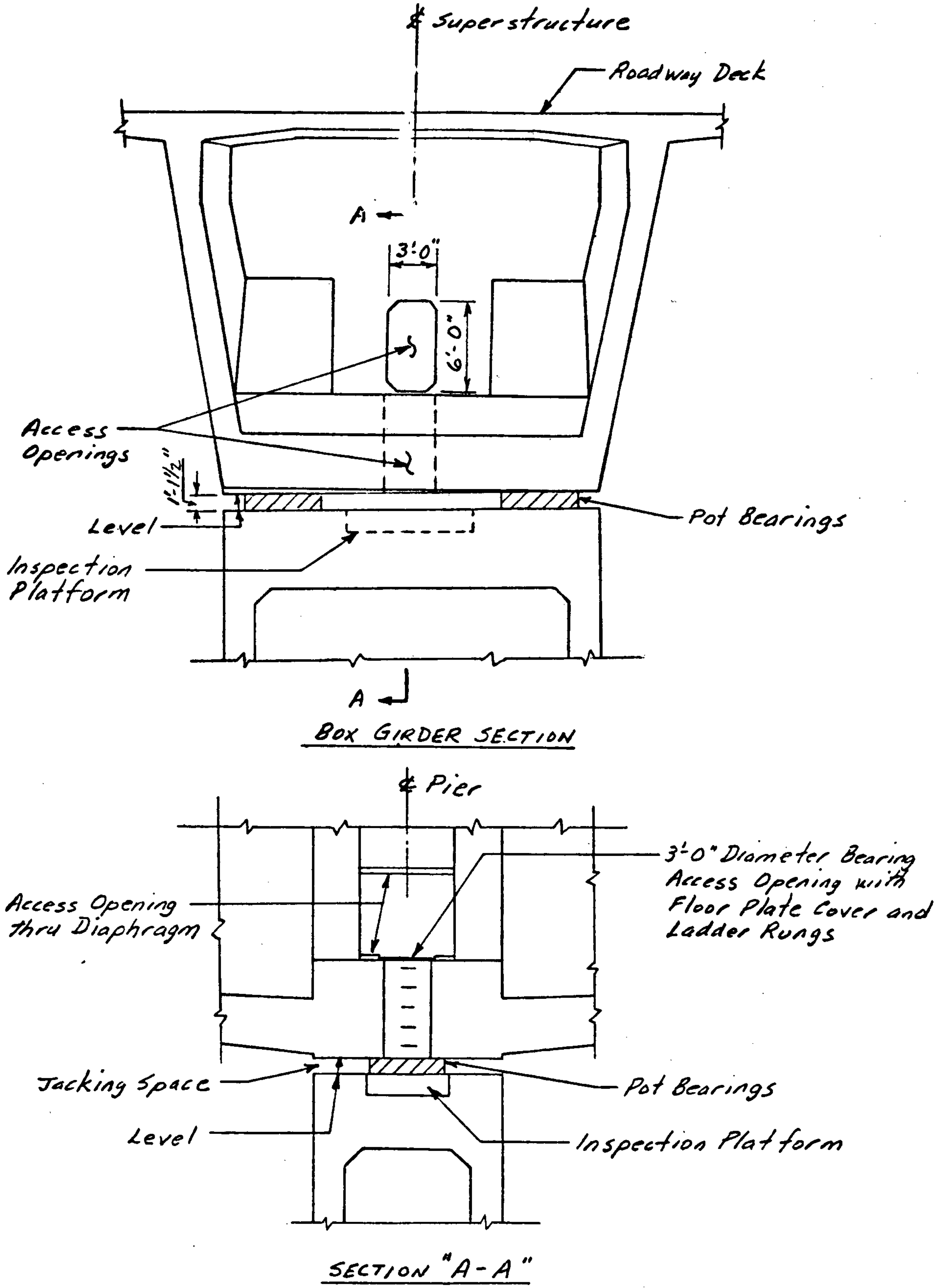


FIGURE 14 Access to pot bearings in concrete box.

design requirements and then develop details that will both reduce and facilitate rehabilitation. The following general parameters apply to all bearing design.

1. Proper alignment of bearings is most important. The base plate should be level in both directions. Setting details are critical and should be completely detailed. When aligning devices are required, they should be designed to withstand the calculated forces. Plans should require that the as-constructed location and position of bearings be permanently recorded.
2. Regardless of bearing type, the designer should incorporate features that will allow for adjustment and repair. Details should require a minimum of vertical movement to remove component parts. A minimum of 6 in. (150 mm) between support and structure soffit is required for jacking, inspection, and cleaning. Greater clearance is preferable and may be required, dependent on the jacking load. Designers should determine the size, capacity, location, and number of jacks required.
3. Use a minimum number of movable bearings, consistent with efficient expansion joint design and cost-effective maintenance requirements. Good bearing design must incorporate good expansion joint design, and both directly affect maintenance costs.
4. All bearings should be protected from dirt, roadway salt, and water. Pier caps should be sloped away from bearings, eliminating possible water pockets.
5. Sole plates and base plates must be securely anchored to the structure. Location of plate edges and anchor bolts is important to avoid spalling of concrete.
6. Rigid specifications for construction and material quality control are required. AASHTO design specifications are minimum requirements.
7. Where bearing design requires routine maintenance, such as lubrication, the designer should make this requirement known to the appropriate personnel. This would best be handled by a formal maintenance directive.

Certain types of bearings should not be used. Roller nests tend to trap dirt and moisture, leading to corrosion and failure. Bolster shoes pinned through a girder web have proven unsatisfactory. The pin seizes and locks the joint. Wheel-type bearings running on small axles are also unsatisfactory. The axles always seem to seize, locking the joint.

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MECHANICAL AND ELECTRICAL EQUIPMENT

Operating components, machinery, and electrical equipment on bridges require ongoing maintenance and repair. Because of marine and highway traffic requirements, moveable bridge rehabilitation must generally be accomplished without interruption to either traffic mode. Designers should develop preventive maintenance schedules for equipment (such as electric motors, gear reducers, trunnions and bearings, locking devices, traffic gates, and limit switches) that may require rehabilitation. The preventive maintenance schedule should show the anticipated normal time between rehabilitation work to ensure uninterrupted operation. When it is necessary to remove components for rehabilitation, consideration should be given to having spares for rapid installation while the worn part is being repaired.

The operating system should be designed with as much redundancy as possible. An example of operating redundancy is a bascule leaf normally driven by two motors through two gear boxes. A properly designed drive system would allow for the operation of the bridge leaf, at a reduced speed, if only one motor and one gear box were in service. Designers should detail temporary locking devices for moveable bridges to allow for repair of the permanent units. For example, the center locking devices on a bascule bridge will require rehabilitation. A temporary design could be accomplished by attaching pipe sleeves to each leaf and hand driving a pin through the sleeves. Lift bridge cables should be designed so that they can be individually replaced. These are only two examples of many similar situations encountered on moveable bridges, where the designer should be responsible for facilitating repair work. The installation of temporary devices may not be required at time of construction, but the designer should be responsible for the required concepts and working details at the design stage. Designers should develop preventive maintenance manuals and/or procedures for all bridges. A representative portion of a preventive maintenance manual for a moveable bridge is included in Appendix A of this synthesis.

FOUNDATIONS AND SUBSTRUCTURE SYSTEMS

Foundations and substructure systems transfer all superstructure loads into the ground. Although substructure costs vary, they represent a substantial percentage of total cost. When substructure construction is completed, a major portion of the substructure will be covered by earth and/or water. Rehabilitation and inspection below the waterline and groundline are difficult and costly. Substructure environment may be the most severe to which bridge elements are subjected. Bridge foundations in water are subjected to the fluctuating forces and actions of moving water. Timber elements are vulnerable to rot and marine organisms. Steel elements are vulnerable to corrosion. Concrete elements are vulnerable to chemical and freeze-thaw action. Structural damage to substructure systems can be the result of collision, storms, erosion, and inadequate maintenance. Structural failure can occur because of improper foundation investigation, inadequate design, poor workmanship and materials, scour, overloading, floods and storms, and inadequate maintenance. The preceding are some of the factors that cause substructure systems to be most important and most vulnerable in bridge construction.

Hydraulic factors and conditions are a major cause of foundation problems. According to Csagoly and Dorton (*18*), a recent international survey of major bridge failures showed that 66 of the 143 failures were caused by scour. Measures to reduce substructure problems should occur even before design. Whenever possible, site selection should be made so as to minimize scouring action. Straight stream alignment, right-angled bridge crossings, high-bank approaches, and narrow channels are desirable hydraulic features for bridge locations. Designers should preclude catastrophic sour by locating the bottom of footings and/or pile foundations at a conservative depth below the level of anticipated scour. Designers should recognize the need to properly design and protect all foundations from scour in a meandering stream. The proper location and configuration of piers and footings will minimize the effects of scour. Protective riprap, sheet piling, and training structures (i.e., spur dikes) should be used where applicable. Designers should review the substructure history of existing bridges on the waterway to determine the effectiveness of past designs.

Substructure problems often occur in the splash zone and adjacent to the normal waterline or water table. Deterioration generally develops in the wet-dry zone from rot, corrosion, and marine organisms. Designers should specify effective protective systems at these vulnerable locations. Because substructure systems are most difficult and costly to repair and rehabilitate, designers should rigorously follow the recommendations of the foundation and hydraulic studies. The following are guidelines that should be considered when designing foundation and substructure systems.

1. Substructure design should be based on a thorough foundation, soils, and hydraulic analysis. Design should be conservative to ensure structure safety.
2. Select structure configuration and alignment to minimize scour conditions. The effects of scour can be minimized by location and configuration of piers and footings. Footing elevation and size should be designed so that the design-flood scour depth will not cause undermining. Design all foundations in a meandering stream for possible scour conditions. Use riprap, sheet piles, and training structures where applicable.
3. Pile foundations should be used when expansive or compressible soils extend for a considerable depth. Removal of unsuitable material beyond a depth of 10 ft (3 m) may be uneconomical. Because of very deep compressible material, it may not be possible to design the substructure system so that it will not experience excessive settlement. In those rare cases, the designer should design a viable jacking system for future adjustment. Pier-cap width should be increased when using battered piles. [Minnesota requires a minimum cover of 9 in. (230 mm)]. Battered piles are normally driven at abutments.
4. Sufficient time must be allowed for the settlement of fill and underlying material before substructure construction to avoid settlement of, or downdrag forces on, the substructure.
5. Steel piles can be protected with coatings. All coatings will deteriorate and recoating steel piles is generally costly and difficult. Cathodic protection systems will protect immersed steel. Weathering steel performs no better than regular steels in the immersed and splash zones and should not be used unprotected in those locations.
6. All concrete placed under water must have aggregates and cement that do not react to each other or with water. Cement content should be high with a low water-cement ratio. Adequate concrete cover should be specified and strictly controlled during construction. Concrete should not be placed in running water or allowed to fall through water. Aggregates should be free of fines and other material that might cause laitance. Underwater concrete should always be discharged into previously placed concrete and placement should be continuous. New concrete should not be exposed to running water for at least four days and preferably longer. No steel should be left protruding from the finished concrete. When concrete is placed in the dry, laitance and foreign materials must be removed from contact surfaces of previously placed concrete, and the contact surface should be damp before placing additional concrete.
7. Concrete piles must have adequate cover over the reinforcement. Epoxy-coated bars should be used in salt environments. Plastic sleeves might be effective in salt splash zones. (They have been used by Iowa for repair of damaged piles.) Some sealing materials may be effective in retarding salt intrusion.
8. Timber piles must be properly treated for their environment to have an acceptable service life.
9. Void or hollow abutments should be provided with access.

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INNOVATIVE REHABILITATION

Most rehabilitation and repair will be required long after the design and construction period. However, when rehabilitation work requires engineering services, an engineer competent in bridge design should be responsible for plan preparation. Some of the most challenging design work is needed to repair or rehabilitate a deteriorated bridge, and often this challenging work is accomplished by maintenance engineers. To repair or rehabilitate a bridge, it is first necessary to provide adequate access with sufficient work space, illumination, and ventilation. Then it is often necessary to transfer load, remove and replace or repair components, and very likely try to improve corrosion protection. Where deterioration has occurred because of poor material or inadequate design details, the repair will require the introduction of another material and/or improved design details. This repair or rehabilitation work must be accomplished with as little disturbance to traffic as possible, and closure of the bridge is almost unthinkable. These factors require and result in innovative repair techniques.

The correct time for the development of innovative repair techniques is at the time of design. Components of a bridge that may require repair should be given maintainability consideration. The design should include details compatible with removal and replacement of component parts. The design for replacement of structural-critical components, or components that require a scheduled maintenance replacement, should be included in the design plans. The development of the most effective repair plans will be accomplished when the design engineer and the maintenance engineer share their knowledge and work together. The general lack of structured guidance for bridge maintainability results in hurried decisions under stress, greater expenditure of funds than necessary, possibly inadequate communications between involved parties, and general frustration. These factors may lead to a perceived lack of responsibility. Bridge designs that address maintainability will include innovative plans and details for most emergent situations.

Published literature related to rehabilitation projects points out the importance and need for comprehensive design-stage planning. The number and magnitude of rehabilitation projects that are the result of corrosion points out the need for more emphasis on corrosion prevention. Almost all rehabilitation projects speak to the need for accomplishing work while maintaining traffic. All 14 lanes of the George Washington Bridge between New York and New Jersey (*19*) were kept in service for peak-hour traffic while the bridge was redecked with prefabricated panels. The state of Maryland (*20*), the Pennsylvania Turnpike Commission, and the Santa Fe RR (*21*) have used precast units to reduce construction time and allow maximum use during construction. Details of future reconstruction of roadway decks should be part of the design process.

External post-tensioning has been used to upgrade and repair bridges. This technique is applicable to most types of bridges. NCHRP Report 226 (*22*) shows several post-tensioning methods to repair damage. Provisions for future rehabilitation of a segmental box girder bridge over the Kentucky River at Frankfort, Kentucky (*23*) were included in the original design. Ducts were installed through diaphragms and anchorage blocks were constructed for future tendons. An existing bridge crossing the Welland Canal in Canada (*24*) was rehabilitated by installing external post-tensioned tendons. The canal was de-watered from December 19, 1967 to March 15, 1968, and all major construction activities had to be completed in that time period. External post-tensioning can be cost-effective and will minimize construction time and traffic interruption.

Extensive rehabilitation and retrofit has been required on bridges in earthquake zones. Before the 1971 San Fernando earthquake, bridges in California experienced only minor seismic damage (*25*). The San Fernando earthquake resulted in the initiation of a bridge retrofitting program to increase seismic resistance of existing bridges. Many of the details developed for retrofitting could be adapted to new bridge designs.

A recent major rehabilitation project was the replacement of the cables on the Lake Maracaibo Bridge in Venezuela. The Maracaibo bridge was the first modern prestressed concrete cable-stayed bridge in the world. It was built in 1962 and is still one of the longest. Corrosion of the cables was detected (*26*) in early 1978. The bridge is located in a very saline environment with the humidity ranging from 70 to 80 percent. No concrete deterioration was evident but the condition of the supporting cables indicated possible collapse. The original design had not provided for cable replacement. In February 1979 one cable failed, and in 19 days an auxiliary cable system was designed, fabricated, and installed. Placement of light, auxiliary saddles was accomplished by helicopter. All cables were replaced at a cost of $50 million in a two-year period. The rehabilitation design resulted in a system that will make future cable replacement simple, and routine maintenance has been eased. The installation of a viable replacement system is a valuable investment for the future.

Another major rehabilitation project was the total replacement of cables and suspenders on the U.S. Grant suspension bridge (*27*) between Portsmouth, Ohio and South Shore, Kentucky in 1979. The center 70 percent of the main-span roadway was removed in reusable sections. Each end span was supported on temporary bents. The cantilever portions of the main span, which were not removed, were supported by cables from the towers and end spans. This bridge was built in 1928. Unusual as this replacement is, this was the second time the cable system required replacement. In 1940, as in 1979, severe corrosion required total replacement of the cables and suspenders. Triple-dipped galvanized wire was used in the 1979 replacement. The cost to the Ohio DOT for replacement in 1979 was approximately six million dollars. Both of these major rehabilitation projects were required because of corrosion of main fracture-critical members. Positive corrosion prevention methods should be included in the design of such critical members.

The selected bibliography, including the referenced examples, illustrates the challenging design effort required to maintain and repair bridges. At present there are few references in the literature or few plans indicating that future repair and rehabilitation requirements are considered during initial design. Effective designs to reduce and facilitate maintenance and repair must include details and plans for rehabilitation.

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CHAPTER SIX

EFFECTIVE ORGANIZATIONAL COMMUNICATION

INTRODUCTION

A principal administrative concern of all organizations should be the establishment of an effective communication system. Communications play an important role in designing bridges to reduce and facilitate maintenance and repairs. Those responsible for bridge design have recognized this concern. Through annual regional meetings of bridge engineers, AASHTO continually updates design specifications and defines specific research needs. The AASHTO Standards Specifications for Highway Bridges (*1*) is a comprehensive example of effective communications. Compilation of these technical specifications started in 1921 and were first formally published in 1931. The specifications have led to safer, more standardized, and more durable bridges through improved technical design criteria and quality control of materials and construction. They allow highway agencies to achieve more uniform design, regardless of the design agency.

Development of design criteria and material specifications has been predicated on structural adequacy and long useful life, with the least possible maintenance and repair. Because maintenance and repair costs are ongoing and can be of great consequence, bridge engineers attempt to achieve the elusive ideal of a maintenance-free bridge. Striving for the maintenance-free bridge can emasculate a more realistic design philosophy, which is to design a bridge for maintainability. A bridge should be designed so that needed maintenance can be economically accomplished.

AASHTO has published manuals for maintenance inspection (*28*) and bridge maintenance (*29*). The Manual for Maintenance Inspection of Bridges was first published in July 1970. The Manual for Bridge Maintenance was first published in February 1976. Both manuals provide information for bridge designers and maintenance personnel. A review of the maintenance manuals provides basic insight into maintenance-related bridge problems.

The Manual for Maintenance Inspection includes guidelines for inspection and rating of bridges. The preface to the manual states: "This manual has been prepared to serve as a standard and to provide uniformity in the procedures and policies of determining the physical condition and maintenance needs of highway bridges. The procedures for correcting known deficiencies are outside the scope of this manual and no attempt has been made to cover this field." This manual is technical in nature and does include specifications for rating bridges and for checking capacities of existing bridges.

The Manual for Bridge Maintenance develops a common frame of reference to be used in the discussion of the maintenance and repair of highway structures. It recognizes that the manual may be used by individuals with a wide variety of backgrounds, ranging from structural engineers to personnel with no formal engineering training. The preface to this manual states in part:

> This manual has been prepared to serve as a guide for all bridge engineers to use as a single source reference which represents input from select State maintenance engineers. It is not intended to set national standards because of the varying conditions, limited resources of manpower, equipment and materials, and various State programs. In fact, the recommendations contained in the manual to some extent may conflict with present State policies or goals. We intend the manual to solely identify a problem area and make recommendations that are considered to be effective operation and efficient management methods directed toward solving the problem (*29*).

The stated goal of the manual is to provide guidelines for the proper maintenance of highway bridges. Although it contains useful information for bridge designers, it is primarily directed toward maintenance personnel. In addition to AASHTO specifications and manuals, most agencies have developed bridge design manuals for their specific use. However, the basic maintainability concerns discussed in this synthesis are not adequately covered in any of these manuals.

The technical specifications and design manuals set minimum standards for acceptable design practice. They contain little, if any, specific reference to maintainability. Rather, the design criteria and material specifications have been developed to include and thereby produce serviceability, which will reduce future maintenance. The inspection manual establishes procedures to determine physical condition and maintenance needs. The bridge maintenance manual identifies problem areas and makes recommendations directed toward solving the problems. The recommendations in the bridge maintenance manual are directed to field maintenance personnel, rather than to the bridge designer. The AASHTO design specifications and bridge manuals do not establish criteria or specifications specifically related to accessibility, corrosion control, ease of rehabilitation, and continued bridge use during rehabilitation. Establishment of minimum standards in these areas is recommended to improve maintenance and repair. Effective collaboration of bridge designers and bridge maintenance engineers is required to reduce life-cycle costs and facilitate repair procedures. AASHTO bridge design specifications should include minimum standards for bridge maintainability. To be effective, these standards must be developed with input from bridge maintenance engineers. Bridge maintenance engineers have not been as effectively utilized as they might have been in the development of the various AASHTO publications.

Areas where administrative planning could help open communication channels include job training and experience, preconstruction review, and funding for maintenance activities.

Increased communications could lead to the development of more standard maintenance instructions, and methods for exchange of maintenance-related information.

Adoption of maintainability concepts would resolve a lament expressed by one bridge maintenance engineer. This engineer observed that maintenance and repair instructions are furnished to the customer purchasing a lawn mower, but a bridge maintenance engineer feels fortunate to receive a copy of the bridge plans, let alone any mention of preventive maintenance.

COMMUNICATION CHANNELS

The communication policy for efficient management should ensure that the right information is getting to the right place at the right time. This should be accomplished within all types of organization structures, and should be achieved with a minimum amount of effort. A carefully planned cohesive communication policy is required to ensure that responsibility remains within the appropriate jurisdiction.

Most state bridge functions are now organized as an integral part of a DOT. The expanded responsibilities of the DOT have generally increased the trend toward decentralization, which can tend to fragment administrative responsibility. It is observed that, regardless of organization structure, bridge adequacy and safety are the ultimate responsibility of the office of the Bridge Engineer.

The office of the Bridge Engineer should be responsible for establishing and monitoring technical bridge procedures and policies. Where department organization results in bridge maintenance functions being separate from the Bridge Engineer's office, procedures should be established to ensure proper and adequate direction from the Bridge Engineer's staff. Administrative direction is required to ensure that effective communication channels are in place and are being used. All problems that can affect structural adequacy should be the direct responsibility of the Bridge Engineer's office. Department procedures should ensure the required interaction between separate offices.

Productive communications should occur between engineers responsible for design and those engineers responsible for field performance. Communication interface, obtained from effective communications between the generally more theoretically oriented design engineer and the generally more practically oriented field engineer, can pay large dividends. Individuals who have working experience in all phases of bridge engineering tend to exhibit a more tolerant understanding of problems associated with these diverse areas. Clear distinction should be made between routine maintenance, and repair or rehabilitation maintenance. Routine maintenance should not require engineering services. Rehabilitation maintenance may require engineering services that are as important to the structure as the engineering required in the original design.

Training and Experience

Bridge administrators should implement methods to provide meaningful training and experience for bridge designers and bridge maintenance engineers. More maintainable bridge designs will be achieved if designers have actual working experience in maintenance and inspection. Conversely, the effective bridge maintenance engineer should have design experience. Those engineers who are responsible for bridge design or bridge maintenance should be required to have achieved an adequate experience level in both areas, in addition to traditional technical training. Job assignments of bridge engineers should be made systematically to ensure effective cross-training.

One effective way to provide designers with field experience could be through the bridge inspection program. Transportation departments regularly inspect bridges on the highway system. These inspections are normally performed by at least two persons. Inspection by some agencies is accomplished by engineers, whereas other agencies train inspection specialists for this work. The inspection program should be under the direct responsibility of a structural engineer. Where inspection is an integral part of the Bridge Engineer's office, designers could be assigned to inspection teams for part of the inspection season. Where bridge inspection is the responsibility of another office, designers could assist in the more complex in-depth inspections on selected bridges. This type of interaction would be beneficial to both the designer and inspector. Designers should have an opportunity to inspect some of those bridges they designed. An actual hands-on working experience for designers should pay big dividends. The designer should come to appreciate the importance and value of adequate access. The importance of describing special structure features and noting their locations on the plans, or in maintenance directives or manuals, should become evident. Through the inspection process, designers would see the effects of corrosion. The designer could provide the inspector with information and knowledge of the design process. Maintenance engineers could learn more about fatigue failure and have a better idea of where inspection should be concentrated.

An effective way for designers to gain construction experience could be through a consulting relationship with bridge project construction engineers. Involvement would vary from job to job and would be governed by the complexity of the project. Designers should have sufficient opportunity on construction projects to gain a clear understanding of the complexities and importance of quality control. Other than for general training experience, designer time at a job site could be minimal, limited to those times when specific technical advice is required. Through a consulting relationship with the project construction engineer, the designer will become aware of design details that may complicate bridge construction. Improved conformance to plans should be obtained through an established consulting relationship. Improved communications should ensure more construction uniformity.

Designers should be made aware of problems and deficiencies in bridges they design. Bridge inspection reports should be utilized as a communications channel. Design-related problems and deficiencies should be clearly defined on inspection reports. The designer could assist the bridge maintenance engineer with the field investigation and the assessment of the problem. Repair and rehabilitation design projects could be accomplished through joint working effort of bridge maintenance engineers and those engineers normally assigned to new bridge design. Designers could gain appreciation for the innovations required in bridge maintenance, and bridge maintenance engineers would not lose sight of the constraints encountered by designers.

Regardless of the organizational structure, methods need to be developed to ensure comprehensive training for bridge engineers. Training and experience is needed to produce designs that reduce and facilitate maintenance and repair. Implementation of a comprehensive training system will increase and improve communications.

Preconstruction Review

Most transportation departments attempt to have construction and maintenance personnel review bridge design plans before the advertising date. A common method is by forwarding plans to the appropriate offices stipulating the required approval date. Often the review time is too short, the reviewing office may not have personnel available, and past actions taken with reference to other review comments may result in a perfunctory review. Perfunctory reviews are a waste of time and proliferate paper work. Appropriate communication channels should be established that provide for ongoing communications between the designer and construction and maintenance engineers. The designer should be able to initiate these communications. Design plans and details should be shared throughout the design phase to accomplish the most from the joint participation. The establishment of acceptable design standards to meet maintenance and construction requirements could reduce or eliminate many review requirements.

When a joint review is desirable, an open and frank meeting is most productive. Participants should be adequately prepared to be in a position to defend their recommendations. Participants should include a representative number of individuals involved with the details of the project. This review by personnel from design, construction, and maintenance should be sufficiently in advance of the advertising date to allow for the incorporation of revisions. It should be made clear that decisions will be made at this joint review and that endless discussion will not be tolerated. Preconstruction review would afford meaningful communications between personnel responsible for the various facets of bridge engineering.

Funding

One of the most effective means of communicating concern for bridge maintenance is through adequate funding. Time should be provided so that designers can develop plans on the basis of life-cycle costs, rather than on lowest first cost. Future maintenance costs should be given consideration during the design stage. Life-cycle cost analysis should produce designs that reduce and facilitate maintenance and repair. Those engineers responsible for bridge maintenance should plan repair and rehabilitation work in advance of the need. Funding should then be budgeted to accomplish the work in the most timely and cost-effective manner. Orderly planning of maintenance needs will produce preventive-type maintenance rather than emergency-type repairs. Deferred maintenance will become reconstruction.

Concepts used in the management of toll facilities have generally resulted in more efficient and cost-effective bridge maintenance. On toll facilities maintenance is usually a specified requirement. Normally the bonding or insuring authority requires yearly in-depth inspection and maintenance reports and records. To protect the bonded indebtedness, a standard of maintenance is stipulated, and generally insurance on the structure is required. These stipulations and requirements, in conjunction with the physical size of the facility, may result in the permanent assignment of maintenance personnel to the facility. Being a toll facility, the owner is normally able to provide necessary maintenance funds by adjusting the tolls. The managing authority for the toll facility prepares budgets on the basis of planned work during each budget period. Work is planned and budgeted on a systematic basis, and the required maintenance funds are made available. The fact that maintenance costs will affect tolls may cause engineers to develop more cost-effective designs. Toll-bridge designs normally provide special access features for maintenance. Because closure would result in lost revenue, repair and rehabilitation procedures are important to ensure continued bridge use. As observed in Civil Engineering (*12*), New York City toll bridges and tunnels are in relatively good shape. Being toll facilities, adequate revenues have been provided to keep the facilities well maintained. The maintenance level and consequently the condition of bridges are directly related to funding.

COMMUNICATION TECHNIQUES

Maintenance Standards

Examples of good communicating techniques are the AASHTO specifications and manuals, and bridge design manuals. Bridge design manuals and/or AASHTO criteria should be expanded to include specific maintenance guidelines for bridge designers. Bridge maintenance engineers should have an active role in the development of maintenance-related design criteria. Minimum standards should be adopted that formally establish access requirements, corrosion control, design features required for rehabilitation and routine maintenance, and the agency policy regarding continued bridge use. The adoption of maintenance-related standards for bridge design will reduce and facilitate bridge maintenance and repair. By including maintenance standards with the technical design standards, all bridge engineers will know they belong to the same team.

Maintenance Instructions

To ensure that maintenance is performed as contemplated by the designer, appropriate direction must be communicated to maintenance personnel. The designer should initiate this action through maintenance instructions. Maintenance instructions could be included as part of the plans, in the form of a maintenance directive, or by the development of a maintenance manual. The format for maintenance instructions will depend on the complexity of the required maintenance operations. Many maintenance operations could be included in a manual for standard maintenance procedures.

To develop maintenance instructions, the designer should address maintenance concerns throughout the design process. The designer should determine how inspection, repairs, and maintenance can be accomplished. Details that may require special attention should be noted. Maintenance requirements for components, such as lubricated bearings, should be clearly defined. Special design features to facilitate maintenance should be described. Documentation of all design features that will require maintenance, or will facilitate maintenance operations should be clear and complete.

Bridges with complex maintenance requirements require comprehensive maintenance manuals. The Washington State DOT has prepared a "Preventive Maintenance Manual" for each moveable bridge on its highway system. These manuals were prepared to assist maintenance forces in establishing effective and systematic preventive maintenance programs. The goal is to reduce unscheduled maintenance, leading to improvements being made on a planned basis and a budgeted program. Included in each manual is a maintenance schedule giving the required frequency for the various maintenance operations. A selected portion of the manual for the Deep River Bridge is included in Appendix A.

Information Exchange

The following techniques could be effectively used to exchange information related to bridge design and maintenance. Methods to report inspection and repair of bridges are widely used. Methods to communicate concerns and innovative concepts are not as well established. Continued development of communication techniques will enhance bridge engineering.

1. State highway bridge organizations have adopted, with variations, inspection report forms based on FHWA recommendations. These forms are used to record the findings of the inspection teams, and show condition ratings for the various bridge components. The data from these forms are used to establish sufficiency ratings for bridges on the national highway network. Good inspection reports describe the type and extent of bridge deterioration. Deviations or modifications from the contract plans should be noted. These inspection reports are used to formulate corrective action. The bridge maintenance engineer is normally responsible for review of the bridge inspection reports. The bridge maintenance engineer should use information from these reports to increase communications with bridge designers. Where defects or deficiencies are found to be design related, this information should be made known to the bridge design engineer. Deficiencies should be reported immediately to avoid repetitive use of a deficient detail. Direct personal contact, in addition to written advice, would be beneficial to the communicating process.

Bridge inspection reporting may need to be revised to be an efficient communication tool between maintenance and design engineers. The information should be concise and related to the maintainability features that should be an integral part of design. A general maintainability rating could be established based on accessibility, material selection, corrosion protection, ease of rehabilitation, and continued bridge use during repair. It is proposed that satisfactory-unsatisfactory (with explanation) ratings be used. Accessibility, ease of rehabilitation, and continued bridge use ratings could be objectively established during the initial inspection. Material selection and corrosion protection ratings may be more subjective, and might be given no rating over several inspection periods. This general maintainability rating system could be used when reviewing design plans, before construction. As shown in the proposed format in Figure 15, each component part of a bridge that is rated unsatisfactory should be listed with a concise explanation of the deficiency.

Maintainability rating information, such as the above, could be stored in computerized information systems. The retrieval of the information could be in the form of individual reports for each bridge, or in various summarized reports to show the extent of overall problem areas. The implementation of this system of rating maintainability should be immediately effective in defining specific areas that should receive design attention.

2. Bridge repair reports should be used by maintenance per-

	GENERAL MAINTAINABILITY RATING	
Item	Satisfactory	Unsatisfactory (with explanation; list each unsatisfactory component or feature)
Access		
Material		
Corrosion Protection		
Ease of Rehabilitation		
Continued Bridge Use		

FIGURE 15 Possible form to report maintainability rating of a bridge.

BRIDGE STANDARDS COMMITTEE ACTION RECORD

Proposed: ______

Purpose: ______

Submitted by: ______ Date: ______

COMMITTEE ACTION:

1) Approved for immediate implementation ______
2) Study and consider at next meeting ______
3) Obtain additional information ______

4) Reject for following reasons: ______
5) Other action (define): ______

The above action by Committee Members— Date: ______

Comments: ______

FIGURE 16 Form used to submit ideas concerning bridge designs (Minnesota).

Research Pays Off

Kansas DOT Saves Its Bridges —and $1 Million Besides

What do you do when you discover that your "bridges may come falling down"? When annual inspections in Kansas uncovered cracks in some of the state's concrete bridges that could lead to failure, a research project was formulated to determine the cause and find a remedy. The cracks proved to be the result of shear, the remedy was post-reinforcement, and the application of the research effort paid off in savings of more than $1 million.

PROBLEM

Between 1955 and 1965, the Kansas Department of Transportation (KsDOT) built many bridges on its highway network by using two-girder continuous reinforced concrete construction. When inspections revealed shear cracks present in some girders that could result in failure, the KsDOT decided to investigate repair techniques rather than go the route of tearing down the bridges in question and building new ones. This approach was KsDOT's application of the "frontier" philosophy of repair, use up, wear out, make do, and innovate—and it worked! With a budget of $50,000 provided by KsDOT and the Federal Highway Administration through its Highway Planning and Research Fund, research began in 1976 on a repair technique called post-reinforcement.

SOLUTION

The post-reinforcement method was developed by KsDOT researchers and engineers Wayne Stratton, Roger Alexander, and Bill Nolting. It involves (a) locating and sealing all of the girder cracks with silicone rubber, (b) marking the girder centerline on the deck, (c) locating the transverse deck reinforcement, (d) vacuum drilling 45° holes that avoid the rebars, (e) pumping the holes and cracks full of epoxy, and (f) inserting reinforcing bars into the epoxy-filled holes. This process makes bridges stronger than when they were first built. Although the original design followed the 1957 AASHO Bridge Specifications, the shear-carrying capacity at certain points in the girders was as much as 36 percent below the 1981 AASHTO Specifications, but that of the repaired girder is 46 percent greater than the as-built condition and now exceeds the 1981 Specifications. Even greater strength is possible by closer spacing of the reinforcing bars.

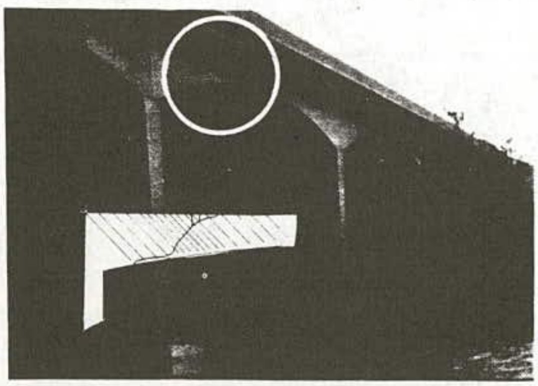

Diagram shows how reinforcing bars were placed to repair bridge girder circled in photo.

APPLICATION

During this study, 19 girder-halves were repaired under the supervision of the KsDOT researchers. After this work demonstrated the merit of post-reinforcement, a developmental phase (funded at less than $50,000) was initiated in 1980 to train bridge maintenance personnel and to continue refining the repair procedure. Another 11 girder-halves were repaired during this phase, and KsDOT engineers worked with industry to develop a durable, high-speed, vacuum drilling rig that would be capable of producing straight, small-diameter, dust-free holes in reinforced concrete to a depth of 8 or 9 ft. The equipment, which is highly maneuverable and able to drill holes at a 45° angle, was subsequently field tested and is now available for heavy-duty repair operations.

The repair method has been adopted by KsDOT as a standard procedure. Plans and specifications are available, and a contractor has successfully completed rehabilitation of two bridges that included post-reinforcement of the concrete girders.

BENEFIT

Both time and money were saved as a result of this research effort. A total of 30 girder-halves were repaired at an average cost of less than $2500 each. Removal and replacement would have cost about $40,000 for each girder-half—not including costs associated with construction detours and loss-of-service time. KsDOT calculated savings in excess of $1.1 million as a result. Not a bad return on an R&D investment of less than $100,000!

Kansas has more than 80 bridges on which the post-reinforcement method can be used. Thus, the major benefit of this effort is still to be realized. However, given the magnitude of bridge repair problems across the nation, the potential for savings through the application of this process in other states could reach many millions of dollars.

For further information, contact Carl Crumpton or F. Wayne Stratton, KsDOT, 2300 Van Buren Street, Topeka, KS 66611, telephone 913-296-7410.

FIGURE 17 Example of TRB "Research Pays Off" report.

sonnel to communicate with the bridge maintenance engineer. This report may originate from a district bridge maintenance engineer or from other maintenance personnel. The bridge repair report should factually describe the work accomplished. There should be reference to prior communications or directives that initiated the repair. There should be a remarks section for reporting other information that might be useful to the bridge maintenance engineer.

3. Bridge engineers should encourage and motivate all personnel in the organization to communicate their concerns and ideas. Some of the most useful ideas may originate from persons having little technical training. Minnesota has developed a system to promote a wide communication network. All personnel can submit proposed ideas on a form titled "Bridge Standards Committee Action Record," shown in Figure 16. Proposed ideas are reviewed monthly by a committee composed of design, con-

MAINTENANCE TECHNICAL BULLETIN

Washington State Department of Transportation

NO. T-00-00-001

July 15, 1981

MAINTENANCE AND OPERATIONS GROUP
Highway Administration Building
Olympia, Washington 98504

I keep six honest serving-men
(They taught me all I knew)
Their names are WHAT and WHY and WHEN
and HOW and WHERE and WHO.

\- Rudyard Kipling

The Maintenance and Operations Group will be preparing technical bulletins to provide technical information to maintenance employees. These bulletins will answer to the six serving men and will answer the questions:

- WHAT WORK IS TO BE DONE? WHY?
- WHERE IS THE WORK TO BE DONE? WHY?
- WHEN IS THE WORK TO BE DONE? WHY?
- WHO IS TO DO THE WORK? WHY?
- HOW IS THE WORK TO BE DONE? WHY?

Information on any aspect of maintenance and operations may be covered. Bulletins on the maintenance and repair of buildings, equipment, and radios will also be issued.

These bulletins are intended to supplement, not replace, the new materials and work methods described in the Maintenance Newsletter. Because they will be limited to a single sheet of paper they can be quickly printed and distributed. This will provide the information to those interested in a very short time.

The numbering system will relate each bulletin to a maintenance function such as Roadway Surface, Landscape Management, etc. Special groupings have been developed for the areas of Equipment, Radio, and Capital Facilities which are not based upon maintenance operations. This will enable bulletins on like subjects to be grouped together. The numbering system will be explained in detail in the next Technical Bulletin.

During the next few months about fifteen Technical Bulletins will be issued every month. If you have any constructive comments please submit them to the Headquarters Maintenance and Operations Staff. Also, if you have suggestions for bulletin subjects, please let us know. Complete texts would be acceptable and appreciated.

FIGURE 18 Example of Washington DOT Maintenance Technical Bulletin.

struction, and maintenance engineers. All proposals require formal action, and the person making the proposal is notified of the action taken by the review committee. The effectiveness of this program is enhanced by the knowledge that action will be taken.

4. A nationwide communication network for reporting and categorizing bridge design and maintenance information could be established. Bridge engineering personnel continually develop innovative solutions for specific problems. Too often an effective technique may be known to only a few. When a similar problem occurs elsewhere, effort is again expended to solve the problem.

Information retrieval systems for searching published literature and research are available. These retrieval systems are organized so that information can be located on related subject topics. The amount of material that may have to be reviewed to obtain desired information is great. More effective utilization of information and ideas might be achieved in two ways.

First, a system could be developed to disseminate useful and innovative concepts that have not been published. The reporting format should be brief, requiring a minimum of time. Preferably, the pertinent data could be confined to one sheet. The report could briefly state the problem, the solution, the application, and the benefit. The Transportation Research Board (TRB) has developed a reporting system to demonstrate the effectiveness of transportation research. Figure 17 is one of the TRB reports. The Maintenance and Operations Group of the Washington State DOT has developed a reporting system for their operations. Figure 18 shows the bulletin that outlines the intent and scope of this communication method. A nationwide communication network for sharing unpublished innovative bridge rehabilitation techniques, incorporating concepts similar to those used by TRB and Washington DOT, should be developed.

Second, a system could be developed to systematically communicate and categorize published information for structure inspection, maintenance, repair, and rehabilitation. A format to categorize bridge-related information was adopted by TRB Committee A3C06, "Structures Maintenance." The format is contained in a table of contents for one-page bibliographies. The proposed "Bibliography Subject List" is included in Appendix B. A bibliography format would be good for capturing and exchanging information. This same format could, of course, be used for unpublished information.

The development of an effective communications network is not easy. Good communication requires strong commitments, and is difficult to achieve on a voluntary basis. Administrative concern and direction is required to bridge any perceived gap in communication.

CHAPTER SEVEN

CONCLUSIONS

Bridge designs to reduce and facilitate maintenance and repair can be improved. Much has been done to continually improve and standardize technical design specifications. Research is conducted to substantiate and update the design criteria. Design and material specifications are developed to promote long bridge life. Published studies and reports describe bridge problems and failures when they occur. Technical specifications, research, and knowledge gained from study of bridge deficiencies are all used to reduce maintenance and repair. The ideal design would be a maintenance-free bridge, attained through technical specifications and quality control.

A maintenance-free bridge is not attainable. Striving for it may tend to reduce the consideration of designing for maintainability. To facilitate maintenance and repairs, the maintainability of bridges should have as high a priority as the technical design. Comprehensive design specifications should be developed to establish minimum requirements for accessibility, corrosion protection, ease of rehabilitation, and continued bridge use during rehabilitation. Although maintainability may be given general consideration by many agencies, there are few formal criteria for designers. The establishment of more formal criteria is needed.

Designers should recognize that most bridge deficiencies are caused by the details of design. Failure caused by such factors as stress concentration; corrosion of component parts; lack of quality control; undermining of foundations from scour; cracking of concrete sections; steel fracture caused by fatigue, brittle fracture, and out-of-plane bending; cracks and flaws from improper welding procedures; lack of redundancy; and failures of connections and joints are more related to details of design than to the structural design calculations. Because corrosion causes so much deterioration, special emphasis should be placed on providing adequate corrosion protection. It is recommended that corrosion engineers be utilized more in the bridge design process. Wherever possible, material inert to the environment should be specified.

Planning for maintenance and repair should take place throughout the design phase. The designer should determine what may require repair or replacement, and then define how the work can be accomplished. The repair work should not require the removal of other structural components.

Maintenance and repair procedures should be developed for each bridge. Where those procedures are complex, they should be jointly reviewed by the designer and the bridge maintenance engineer. Procedures should be formalized on plans, in manuals, or by directives.

A clear perception of maintenance is required. All maintenance is important to the structure. Routine maintenance involves work that does not require technical engineering services. Repair and rehabilitation may require engineering services equal to those required for the original design.

Designers should have the opportunity to gain a working knowledge of bridge construction and maintenance. Engineers responsible for supervising bridge design should be required to have such experience.

Deferred maintenance becomes reconstruction. Planning for maintenance and rehabilitation should be based on need and budgeted accordingly. Preventive planning will reduce emergency repairs. Adequate funding at the right time will reduce life-cycle costs. Life-cycle costs need to be determined to design for the lowest overall costs.

Effective communication channels are necessary to ensure that the right information is received by the appropriate jurisdiction at the right time. Good communications require strong administrative commitment. Decentralization of an organization should not result in fragmented responsibility or lack of communications. Bridge inspection reports should include maintainability ratings for bridges, which would be useful to designers and administrators. A nationwide system to exchange and categorize information related to bridge maintainability would be beneficial. In particular it could be used to communicate techniques and concepts that are not in published form.

Bridge engineers, over many years, have developed techniques and procedures resulting in useful, efficient, and aesthetic transportation structures. Advancement has been accomplished by individual contributions, and more significantly by cooperative efforts through organizations such as AASHTO. The many structures on our highway system represent the cumulative effort of a tremendous number of individuals. It is not surprising that the greatest emphasis in bridge construction has been on the development of technical design and material specifications. Correct technical design and materials are essential ingredients for efficient bridges. Also, because of organization development, it is not surprising that design and maintainability have not been more closely coordinated. However, to develop bridge designs to reduce and facilitate maintenance and repair, a closer working relationship between designers and maintenance engineers is essential. The maintenance engineer knows the field problems, and can best explain what is being done to resolve those problems. By working together, the designer and maintenance engineer can eliminate many of the problems during the design stage. Improved solutions will also be developed for existing problems. Bridge administrators are responsible for implementing the programs and procedures to improve bridge maintainability. At this stage of bridge development, maintainability should be given greater importance. Improving coordination of design with maintainability will continue the established pattern of ever-better bridge design.

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APPENDIX A

EXCERPTS FROM THE PREVENTIVE MAINTENANCE MANUAL FOR DEEP RIVER BRIDGE (WASHINGTON)

PREVENTIVE MAINTENANCE MANUAL

for

DEEP RIVER BRIDGE
State Route Bridge Number 4/102
Control Section 3504
District Number 4

Washington State Transportation Commission
Department of Transportation
Olympia, Washington

C.S. GLOYD, Bridge & Structures Engineer

March 1983

Prepared by the Bridge & Structures Branch, Project Development

Distribution List

1 - Project Development Engineer
1 - Maintenance & Operations Engineer
3 - District 4 Administrator
3 - Bridge & Structures Branch, Project Development

FOREWORD

This publication has been prepared primarily as a technical manual to assist on the job maintenance forces in establishing an effective and systematic preventive maintenance program on the Deep River Bridge. This publication describes the minimum preventive maintenance activities that need to be performed in order to sustain the bridge in an excellent working condition. In addition, the manual outlines the necessary maintenance records which must be kept by maintenance forces and the necessary reporting to headquarters.

The manual may be used as a base for training and indoctrinating new personnel or retraining existing personnel. The maintenance manual, however, is not a panacea; it will not replace competent managers and a skilled maintenance force. On the other hand, Transportation Department policy must be emphasized - bridge maintenance remains the responsibility of the District Administrator. The Bridge & Structures Branch, Project Development will, at all times, be available to render assistance to the district when so desired or when requested.

A. D. ANDREAS
Assistant Secretary for Highways

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*Added January 1980

I. GENERAL PREVENTIVE MAINTENANCE INSTRUCTIONS

1. SCOPE

a. Preventive maintenance on the Deep River Bridge involves:

(1) Cleaning, lubricating, painting and adjusting the structure and equipment to secure good operation under all conditions.

(2) Periodic inspection and testing of structural, mechanical and electrical parts in such a way that defects are recognized and problems are anticipated.

(3) Observation of the action of the structure and equipment under various conditions of operation in order to increase knowledge and understanding of the bridge.

(4) Performing all maintenance on a scheduled basis to prevent or slowdown deterioration and/or wear and to reduce breakdown as much as possible.

(5) Replacing items or parts on a schedule that will ensure preventable deterioration or wear will not be the cause of failure and unscheduled shutdown.

(6) Proper record keeping and maintenance status reporting.

b. Preventive Maintenance as required by this manual does not include unscheduled repair and replacement nor does it include improvements which may, at times, be made to improve operation safety or reduce maintenance costs.

c. The goal of Preventive Maintenance is to reduce unscheduled maintenance. Unscheduled repairs and replacements may be required by the disclosures of scheduled inspections and tests made under the Preventive Maintenance Program. In practice Preventive Maintenance properly reported will lead to improvements being made on a planned basis and a budgeted program.

d. Maintenance personnel may find that some instructions in this manual are inadequate or incorrect. The manual is in loose leaf form and .it is desired that inadquacies or errors be reported. After investigation and discussion a better instruction will be issued to replace that one found to be faulty.

e. Many regular maintenance jobs are not put on a schedule in this manual, because they are of a housekeeping nature, for example: washing windows, cleaning the operator's house, minor spot painting, replacing light bulbs, removing debris, repairing minor damage, etc. Nevertheless, this work is important. Well kept, neat and clean equipment and surroundings result in better performance of scheduled inspection and maintenance and in safer working conditions. It should be diligently attended to.

2. PERSONNEL SAFETY

a. It is desired that all maintenance work be performed in a manner that is safe for personnel and property. The Safety Standards for Construction Work by the Department of Labor and Industries and the instructions of the Department of Transportation, Safety Division should be observed.

b. The following precautions and instructions are of special importance for work in this bridge:

(1) Before doing repair or service work on motorized equipment, place the disconnect switch in the "off" position. Tie a tag, with the name of the man responsible for the work, to the disconnect handle. Never return the switch to the "on" position until all personnel are in the clear and the equipment is in condition to be operated. The man responsible for the work is personally responsible for placing the tag and removing it.

(2) Inspect ladders, platforms, scaffolds, etc., regularly and maintain them in good condition. Provide adequate temporary installations when necessary.

II. STRUCTURAL ITEMS

Annually inspect all structural bridge components. This yearly inspection is primarily an in-depth visual inspection.

11. STRUCTURAL CONCRETE

a. Included in the structural concrete components are roadway slab, pier, and counterweight.

b. Visually inspect concrete components for scaling, cracking, spalling, joint spalls, pop-outs, and mud-balls. Visually check for rust stains from exposed steel.

c. Visually check for scour and erosion or any evidence of movement of settlement. Check bearing seats for cracking and spalling, especially near the edges.

D. Inspect roadway slab for scaling, spalling, cracking. Note deck condition due to weathering and traffic wear.

12. STRUCTURAL STEEL

a. Included in the structural steel components are truss top and bottom chords; truss veticals, diagonals, laterals and struts; floor beams; sway frame; counterweight frame; anchor column; carrying girder; bearings.

b. Visually inspect steel components for rusting and condition of paint. Check for deterioration due to fumes, animal wastes, galvanic action. Inspect for cracks in steel (report cracks immediately), buckles and kinks. Check for stress concentration, observe the paint around connections at joints for fine cracks which are indications of large strains due to stress concentrations. Check for loose or sheared rivets and bolts. Check for cracks in welds.

c. Check bearings for corrosion and debris, proper alignment, rattles under live load. Check anchor bolts for looseness or missing nuts.

d. Check chords, diagonals, verticals, laterals, struts, floor beams, sway frame, etc. for rust, corrosion and deterioration. Check for slippage around rivets and bolts, examine welds. Visually check for signs of distress or stress concentrations. Check general alignment, waves, wrinkles, or cracks in flanges or webs. Check stiffeners for buckling. Determine whether any unusual vibration or excessive deflection occur under passage of heavy loads. Listen for unusual noises with the passage of live loads.

e. Spot paint and clean yearly as necessary.

f. Paint all structural steel every 9 years.

g. A problem may exist in expansion at the center line of the channel during hot weather. Inspect this condition during hot weather.

13. STRUCTURAL TIMBER

a. Annually inspect stringers, caps, piles, timber fenders for decay, insect attack, weathering, mechanical wear. Check timber fenders for collision from marine navigation. Check bolts for rust and looseness. Test soundness with an ice pick or drill.

b. Replace timber fender component parts as necessary or schedule complete replacement every 16 years.

III. MECHANICAL EQUIPMENT

21. MAIN DRIVE ASSEMBLY

a. The main drive assembly consists of the following equipment: 2 HP electrofluid gearmotor with a ratio of 6.2 to 1, size 7.4 fluid coupling, H-72-9 Sterns motor mounted brake with automatic hand release and a 70:1 gear reducer. See electrical machinery section for electrical motor maintenance. There is one main drive assembly located at the pivot pier.

b. Every 6 months inspect visually the main drive assembly in detail. This inspection is to be made with the assembly in the stationary position and also during operation. With the assembly in the stationary position check for rust and condition of paint. Look for signs of distress in the metal such as bends or cracking of paint. See that all bolts have the proper tightness. Check for oil leakage from the reducer case. Check and clean off excess grease, dirt, wood chips. See that all keys are in their proper position. Check the oil level in the reducers and see that all bearings have adequate grease.

   With movable span in operation check for backlash of gears, ease of functioning of parts, excess vibration, unusual noises such as scraping of gears or grinding. Check for excess wear and looseness of mating parts. Unusual noises may be checked with an industrical stethoscope.

c. Monthly lubricate all bearings, gears and racks.

d. Flush out the reducers and change oil every year. Inspect old oil for contaminants. Inspect gears.

e. Spot paint as necessary.

f. Repaint every 9 years.

22. MAIN CENTER BEARING

a. The main center bearing consists of a base, bronze bushing, cap, anchor bolts, cap bolts. The swing span pivots on this bearing.

b. Lubricate every month.

c. Inspect in detail every 6 months. Inspect while stationary and during opening operation. See paragraph 21. b. for items to be inspected.

d. Spot paint annually as necessary.

IV. ELECTRICAL MOTORS AND BRAKES

31. GENERAL ITEMS

Inspect every 6 months during routine inspection of motors.

a. See that shaft is free of oil and grease from bearings.

b. Check for leakage around bearings.

c. See that end play of shaft is normal.

d. Inspect and tighten connections on motor.

e. During running, examine drive critically for smooth running and absence of vibration.

f. Check all bolts for tightness.

g. Check motor and bearing for overheating during running.

32. DIELECTRIC STRENGTH

The megger test must be performed on motors to check insulation once a year. These values must be recorded. Caution: the megger test must be performed only by qualified personnel; there is danger of damage to the tested equipment if improperly tested.

On 440 or 480 volt motors, readings should be made using a 500 volt hand cranked or battery operated megger. New or replacement motors testing at megohm values of 7.5 or less shall not be installed. Overlhaul shall be scheduled for motors in place when megohm values are projected to reach 2.0 or less. If the megohm value reaches 1.0 then overhaul is mandatory. Megger phase to ground and between phases.

33. MAIN DRIVE ASSEMBLY 2 HP (AC) ELECTRIC MOTOR

a. The motor is a General Electric 1200 RPM type KR frame size 215Y 3 phase 60 cycle 220 volt motor. This motor provides the power to turn the swing span.

b. Maintenance:

(1) Monthly check general condition during the monthly lubrication of the bridge.

(2) Every 6 months inspect in-depth the general items. (Paragraph 31)

(3) Megger the motor annually. Record values. Spot paint.

(4) Repaint at 9 year intervals with repainting structural steel. Do not paint name-plates.

(5) Give the motor a basic overhaul by commercial electrical repair personnel every 10 years. See the appendix for definition of basic overhaul.

34. CENTER WEDGE ASSEMBLY ½ HP (AC) ELECTRIC MOTOR

a. The motor is a General Electric 900 RPM type KR frame size 213Y, 3 phase, 60 cycle 220 volt motor. The motor provides the power to draw the center wedges.

b. Maintenance:

(1) Monthly check general condition during the monthly lubrication of the bridge.

(2) Every 6 months inspect in-depth the general items. (Paragraph 31)

(3) Megger the motor annually. Record values. Spot paint if necessary.

(4) Repaint at 9 year intervals with repainting structural steel. Do not paint name-plates.

(5) Give the motor a basic overhaul by commercial electrical repair personnel every 10 years. See the appendix for definition of basic overhaul.

35. END WEDGE ASSEMBLY 2 HP (AC) ELECTRIC MOTOR

a. The motor is a General Electric 1800 RPM type KR frame size 213 Y, 3 phase, 60 cycle 220 volt motor. There is a motor at each end of the swing span that powers the end lift assembly.

b. Maintenance:

(1) Monthly check general condition during the monthly lubrication of the bridge.

(2) Every 6 months inspect in-depth the general items. (Paragraph 31)

(3) Megger the motor annually. Record values. Spot paint if necessary.

V. ELECTRICAL CONTROL APPARATUS

51. LIMIT SWITCHES

a. Function: Limit switches are switches which provide control of electrical circuits. They are turned off or on mechanically by the motion of a machine or piece of equipment.

b. Description: Limit switches normally consist of a metal enclosure securely anchored in position. A lever or plunger inside or outside of the enclosure is operated mechanically by the motion of another piece of equipment. The lever opens or closes contacts, inside the metal enclosure, which open or close an electrical circuit. Springs may be present to return the contacts to the normal position.

c. Maintenance: Ever six (6) months the following items should be checked and corrected on the limit switch:

(1) Collections of dirt, gum, or grease.

(2) Excessive heating of parts - evidenced by discoloration of metal part, charred insulation, odor, or blistering.

(3) Freedom of moving parts (no bidding or sticking).

(4) Corrosion of metal parts.

(5) Check contact tips.

(6) Tighten loose mountings and connections.

(7) Condition of flexible shunts.

(8) Condition of arc chutes or barriers.

(9) Worn or broken mechanical parts.

(10) Condition of gaskets if present.

(11) Voltage to the limit switch.

(12) Moving parts should be lightly oiled with WD 40 cleaner and lubricant (apply drops with a toothpick to bearing surfaces).

(13) Clean the interior of limit switches with LPS Contact Cleaner.

(18) Operation - including proper functioning of timing devices, sequencing of devices, etc.

(19) Condition of heating element.

(20) Clean relays with LPS Contact Cleaner.

60. MECHANICALLY OPERATED DEVICES (SWITCHES)

a. Function: Switches are devices for making, breaking, or changing connections in an electric circuit under the conditions of load for which it is rated. They are not designed for interruption of a circuit under short circuit conditions.

b. Description: Switches are of various types, some of the more common are: master switches, drum controllers, push buttons, selector switches, knife switches.

c. Maintenance: Check and correct the following conditions every six (6) months:

(1) Collections of dirt or gum.

(2) Excessive heating of parts - evidenced by discoloration of metal parts, charred insulation, odor, or blistering.

(3) Freedom of moving parts (no binding or sticking).

(4) Corrosion of metal parts.

(5) Remaining wear allowance on contacts.

(6) Proper contact pressure.

(7) Tighten loose mountings and connections.

(8) Condition of flexible shunts.

(9) Condition of arc chutes or barriers (if present).

(10) Worn or broken mechanical parts.

(11) Excessive arcing in opening circuits.

(12) Condition and level of oil (if oil-immersed). Check for presence of sludge.

(13) Check amount of spring pressure.

(14) Conditon of gaskets (for oil-immersed, dust-tight or water-tight units).

(15) Clean switches with LPS Contact Cleaner.

(16) Lubricate with WD 40 Cleaner and Lubricant (Apply drops with a toothpick to bearing surfaces).

61. METERS AND INSTRUMENTS

a. Function: Various ammeters, voltmeters, indicating lights, etc. are in use to monitor electrical apparatus.

b. Description: Most of these instruments operate in shunt off of the main line they are metering.

c. Location: Most instruments will be found in control consoles, panelboards, or cabinets.

d. Maintenance:

(1) Observe the functioning of these instruments during operation.

(2) Every six (6) months, check and correct:

(a) Loose connections.

(b) Corrosion of metal parts.

(c) Inspect for cracks, broken cases, or cover glass.

(d) Clean collections of dirt, gum and grease with LPS Contact Cleaner or equivalent.

(e) Replace damaged units with new units.

62. SOLENOIDS

a. Function: Solenoids are used to perform work through a straight line motion. The operating force is obtained by means of an electro magnet which actuates a plunger.

b. Description: Control of the solenoid may be any form of switch mechanism for opening and closing the circuit to the magnet coil For manual operation, a snap switch, knife switch or similar device may be used. For automatic operation, a magnetic contactor which is controlled by means of a push-button, limit switch or other similar device may be used.

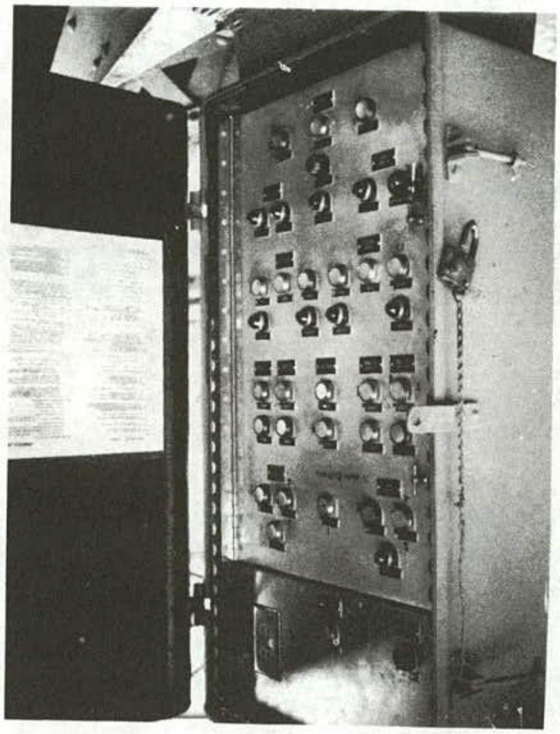

FIG. 1 Operation Station Panel

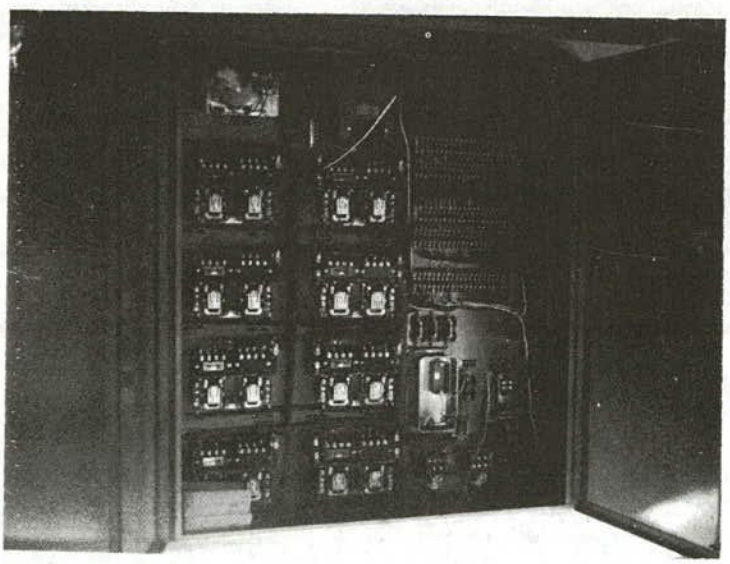

FIG. 2 Control Console

FIG. 3 Centerlock Drive End Lock Similar Except 2 HP Motor Used

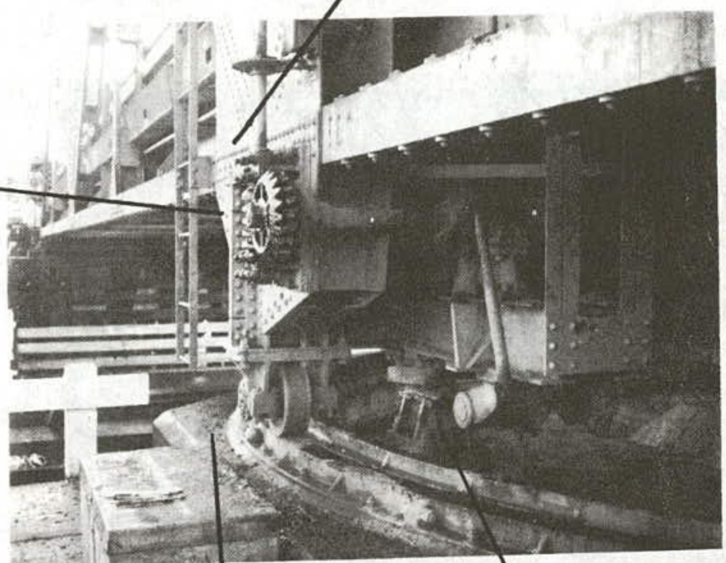

FIG. 4 Centerlock Drive Shaft and Gears

M 23-27 (HB)

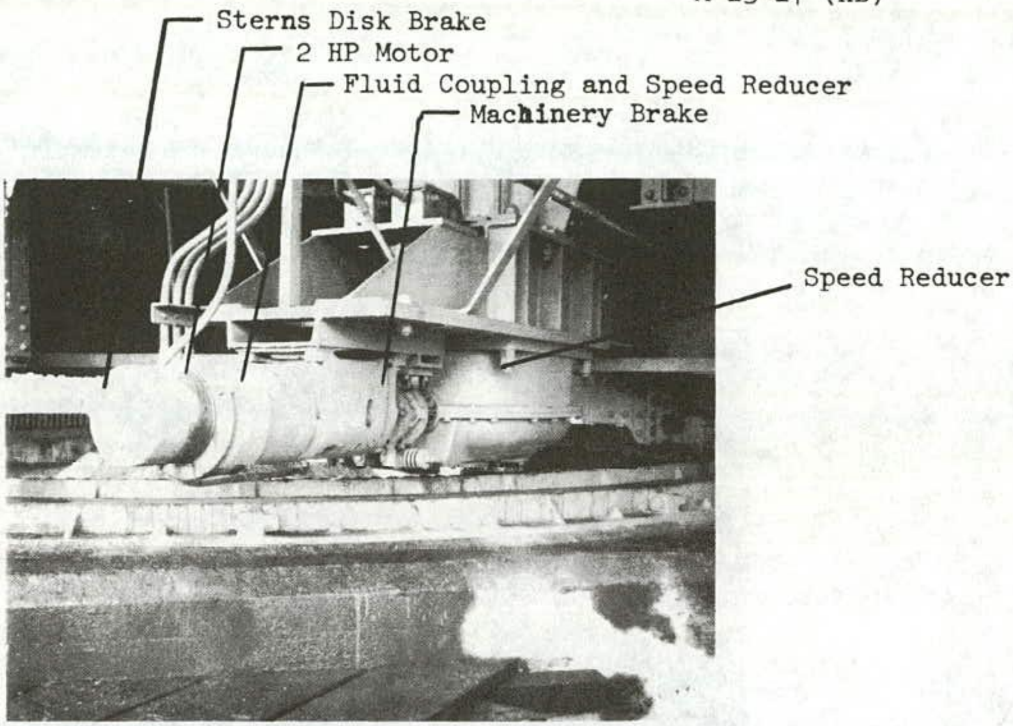

FIG. 5 Main Drive Assembly

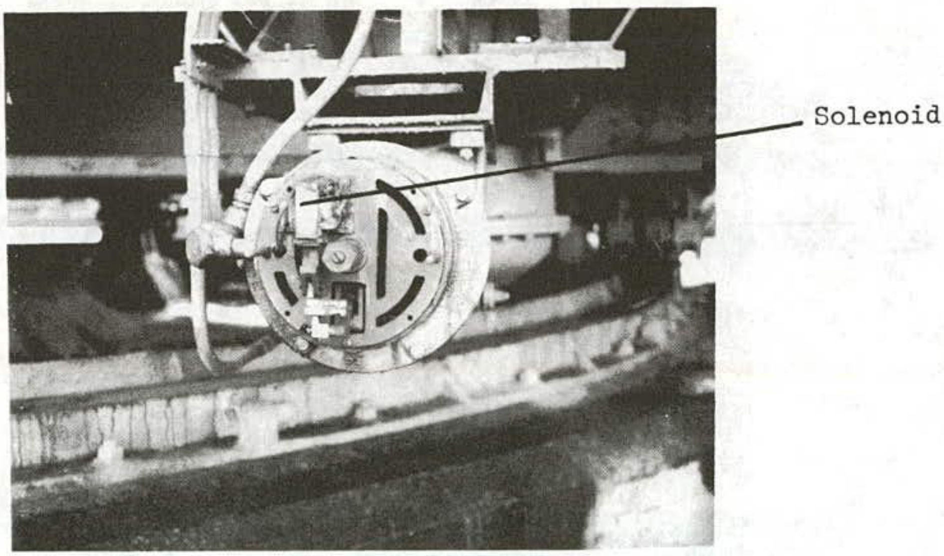

FIG. 6 Sterns Disk Brake

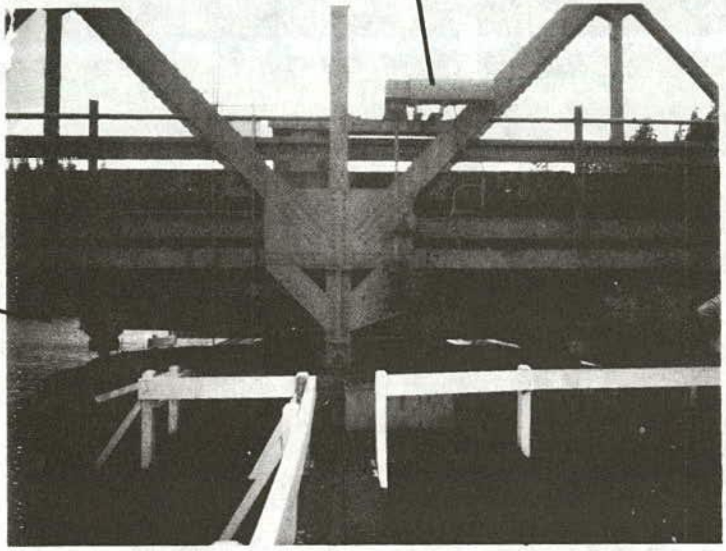

FIG. 7 Pivot Pier

FIG. 8 Center Bearing

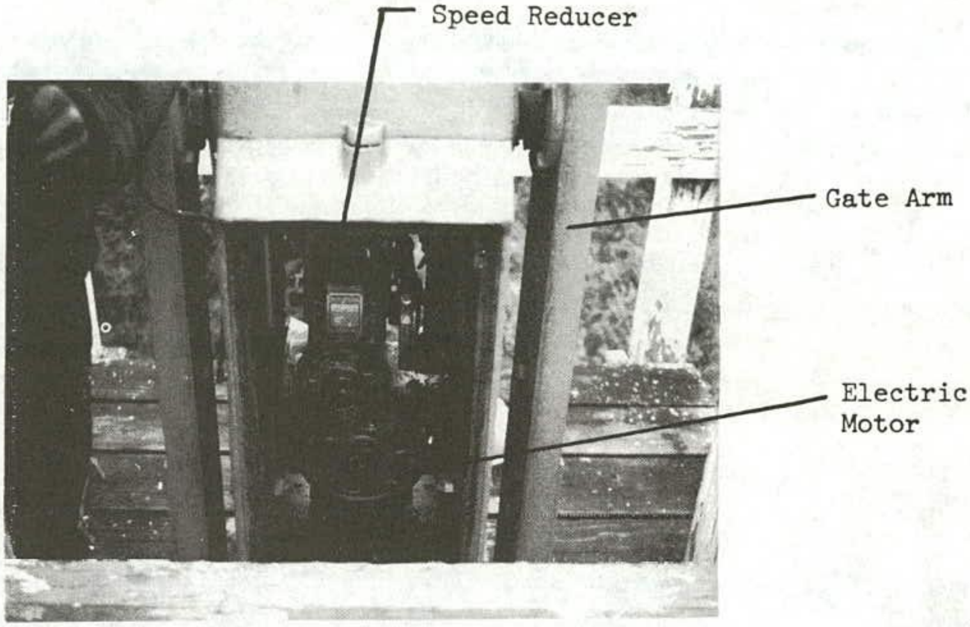

FIG. 9 Gate Machinery and Housing

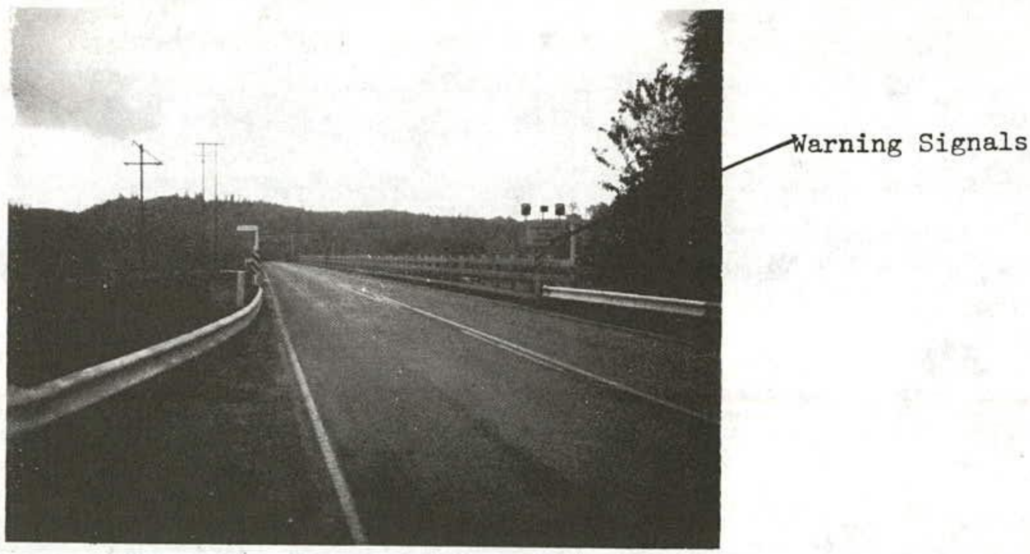

FIG. 10 Deep River Bridge

VII. APPENDIX

91. NONDESTRUCTIVE TESTING

a. Fatigue Stresses: Some machine parts on moveable bridges are subject to repeated variations or reversals of stress. These stresses are called fatigue stresses. Numerous repetitions of fatigue stresses will cause minute surface cracks in metal. Continued application of fatigue stresses will cause the cracks to grow until the uncracked section becomes so small that it is unable to withstand the applied load. Then complete failure will occur suddenly.

b. Preventive Maintenance: Parts subject to fatigue stresses should be replaced before failure occurs, but the exact time of failure is unpredictable. The parts which are subject to fatigue stresses shall be tested by non-destructive tests to find any fatigue cracks are found, a part is considered good for another period unless its calculated fatigue life expectancy is used up.

Parts which are found to have fatigue cracks and those which have been in use for their designed life expectancy shall be scrapped.

92. GENERAL ELECTRICAL MOTOR, GENERATOR, REBUILD (BASIC OVERHAUL)

a. Disassemble.

b. Steam clean.

c. Inspect.

d. Turn collector rings and polish.

e. Dip and bake windings and varnish (epoxy). *

f. New bearings if necessary.

g. Assemble.

h. Test and paint.

* Note: Rewind may be necessary if the unit is in very bad condition.

IX PREVENTIVE MAINTENANCE SCHEDULES

Item numbers refer to paragraph numbers of maintenance instructions.

Additional work necessary for preventive maintenance of the equipment and systems should be reported to headquarters for inclusion in the manual.

Check off items on the Maintenance Schedules and record unsatisfactory conditions on the back of the schedule sheet or on supplementary sheets attached to the schedule.

Date and sign or initial all reports.

If warranted, make an immediate verbal report to the foreman.

Record and report preventive maintenance operations on standard forms.

M 23-27 (HB)
IX-2

MAINTENANCE SCHEDULE FOR THE YEAR 19

Under "Item" reference is made to a paragraph in the Maintenance Instructions. Upon completion of work on a unit, initial the appropriate blank space below.

M = Monthly
A = Annually
Y = Years

MAINTENANCE OPERATION	ITEM	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	FREQUENCY	SCHEDULE NEXT IN
CENTER WEDGE ASSEMBLY	23														
Lubricate	23c													M	
Inspect	23d													6M	
Change oil in gearmotor	23e													A	
Spot Paint	23f													A	
Repaint	23g													9Y	
END LIFT ASSEMBLY	24													M	
Lubricate	24c													M	
Inspect	24d													6M	
Change oil in gearmotor	24e													A	
Spot paint	24f													A	
Repaint	24g													9Y	

APPENDIX B

TRB BIBLIOGRAPHY SUBJECT LIST

1 Inspection
- .1 Type and Frequency
- .2 Equipment
- .3 Procedures
- .4 Training

2 Structure Evaluation and Rating
- .1 Foundation
- .2 Substructure
- .3 Superstructure

3 Repairs - Superstructure
- .1 Framing System
  - .11 Steel
  - .12 Concrete, mild reinforced
  - .13 Concrete, prestressed or post-tensioned
  - .14 Other
- .2 Decks
  - .21 Overlays
  - .22 Patching
  - .23 Drainage
  - .24 Joints
  - .25 Protection systems
  - .26 Other
- .3 Bearings

4 Repairs - Substructure
- .1 Steel
- .2 Concrete
- .3 Timber
- .4 Masonry
- .5 Other

5 Repairs - Foundations

6 Rehabilitation
- .1 Member Strengthening
- .2 Deck Replacement

7 Structural Railing Systems
- .1 Increase Capacity
- .2 Other

8 Movements

9 Approach Appurtenances
- .1 Slabs
- .2 Relief Joints

10 Preventive Maintenance

11 Structure Maintenance Management
- .1 Inventory
- .2 Routine Maintenance Activities
- .3 Organization

12 Corrosion

13 Protective Coating Systems for Metal
- .1 Cleaning
- .2 Coatings
  - .21 Painting
  - .22 Cladding
- .3 Cathodic
- .4 Quality Control

14 Substructure Protection System

15 Scour

16 Waterway Navigational Aids

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