A FRAMEWORK FOR HISTORIC BRIDGE PRESERVATION

A Thesis

by

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ABSTRACT

In an inevitably occurring process, bridges possessing historic, artistic, and engineering significance deteriorate and must be maintained and rehabilitated in order to be kept in service. Ideally, all potentially significant bridges would be properly preserved and continue to beautify and bring character to their surroundings for years to come. However, funding is currently limited for transportation projects in general, and even more so for historic bridge preservation, which some may consider less critical in comparison to other transportation needs. Because of this limitation on resources, it is important that bridge-owning agencies use proper planning and management strategies in order to make the best use of available funding. This thesis presents a framework designed to assist agencies in this process. The framework is devised specifically for TxDOT for use in Tarrant County, Texas, but can be used as a model for agencies anywhere with some modifications to fit the inventory under evaluation. Included in the framework are a methodology for prioritization of bridges within an inventory, guidance on financial and legal procedures, identification of potential funding sources, summary and review of condition assessment practices and bridge mitigation strategies, a template for individual bridge preservation plans, and a framework for resource allocation within a bridge inventory. It can be concluded from this research that early detection of defects, preventive maintenance, condition assessment beyond routine inspection, adjustment of evaluation methodology, and use of engineering judgment when using numerical evaluation methods are critical components of proper management of historic bridges.

TABLE OF CONTENTS

Page

ABSTRACT ii
LIST OF FIGURES vi
LIST OF TABLES viii
CHAPTER
I INTRODUCTION 1
1.1 General 1
1.2 Research Objectives 2
1.3 Thesis Outline 4
II BACKGROUND AND LITERATURE REVIEW 6
2.1 General 6
2.2 Parameters and Criteria 6
2.3 TxDOT Studies 9
2.4 Preservation Frameworks in Other States 19
2.5 Summary 22
III PRIORITIZATION OF BRIDGES 23
3.1 Overview 23
3.2 Recommendations from TxDOT and Historic Fort Worth, Inc. 25
3.3 Selection Matrix 26
3.4 Quantitative Rating System 28
3.5 Final Bridge Inventory 38
3.6 Summary 48
IV GUIDANCE AND FUNDING 50
4.1 Overview 50
4.2 Procedures and Agreements 50
4.3 Funding Sources 53
4.4 Summary 61
V CONDITION ASSESSMENT AND STRUCTURAL HEALTH MONITORING 62
5.1 Overview 62
5.2 Common Defects in Concrete and Steel Elements 62
5.3 Condition Assessment of Decks 68
5.4 Condition Assessment of Superstructures 74
5.5 Condition Assessment of Substructures 81
5.6 Condition Assessment of Bearings 83
5.7 Condition Assessment of Waterways 85
5.8 In-Situ Structural Health Monitoring 87

CHAPTER Page

5.9 Summary 93

VI MITIGATION STRATEGIES 94

6.1 Overview 94
6.2 Attention to Historic Integrity 97
6.3 Regular Interval Maintenance 98
6.4 Mitigation Strategies for Reinforced Concrete Elements 100
6.5 Mitigation Strategies for Steel Elements 110
6.6 Mitigation Strategies for Bearings 119
6.7 Mitigation Strategies for Decks 121
6.8 Mitigation Strategies for Waterways 121
6.9 Summary 125

VII PRESERVATION PLANS 126

7.1 Overview 126
7.2 Guidance for Condition-Based Actions 127
7.3 Example Preservation Plans 137
7.4 Summary 142

VIII RESOURCE ALLOCATION 143

8.1 Overview 143
8.2 Listing of Available Actions 148
8.3 Assignment of Weights to Criteria 149
8.4 Criteria 150
8.5 Calculation of Benefit Score 161
8.6 Allocation of Funding 162
8.7 Review of Methodology 164
8.8 Application Example 165
8.9 Summary 181

IX SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 182

9.1 Summary 182
9.2 Conclusions 183
9.3 Recommendations for Implementation 185
9.4 Recommendations for Future Work 186

REFERENCES 188

APPENDIX A: CALCULATION OF FHWA SUFFICIENCY RATING 199

APPENDIX B: QUANTITATIVE RATING SYSTEM FOR TXDOT HISTORIC BRIDGE INVENTORY SURVEY OF NON-TRUSS STRUCTURES 209

CHAPTER Page

APPENDIX C: DEDUCTIONS FOR HISTORIC INTEGRITY IN TXDOT 1945-1965 EVALUATION METHODOLOGY 212
APPENDIX D: FLOWCHART FOR INDIANA DOT PRIORITIZATION 217
APPENDIX E: OHIO DOT NUMERICAL RATING SYSTEM FOR BRIDGES BUILT FROM 1941 TO 1950 217
APPENDIX F: PROCEDURES FOR PROJECTS INVOLVING HISTORICALLY SIGNIFICANT BRIDGES...220
APPENDIX G: MINIMUM CRITERIA FOR CONTINUED VEHICULAR USE FOR OFF-SYSTEM HISTORICALLY SIGNIFICANT BRIDGES 222

LIST OF FIGURES

Page

Figure 2-1. Selection Matrix Used in Indiana DOT Prioritization Process 20

Figure 3-1. Flowchart Depicting the Prioritization Process 24

Figure 3-2. a) All Bridges in Tarrant County; b) Final 37 Bridges 25

Figure 3-3. Selection Matrix Based on Historical Significance and Sufficiency Rating. 27

Figure 3-4. Examples of Bridge Types 32

Figure 3-5. Various Rail Types 34

Figure 3-6. Various Levels of Special Design 36

Figure 3-7. BU 287P (N. Main Street) over Clear Fork Trinity River 42

Figure 3-8. Samuels Avenue over West Fork Trinity River 43

Figure 3-9. W. Lancaster Avenue over Clear Fork Trinity River 44

Figure 3-10. SH 180 WB over Sycamore Creek 45

Figure 3-11. East Exchange Avenue over Marine Creek 46

Figure 3-12. E. Vickery Boulevard over Sycamore Creek 47

Figure 3-13. State Highway 199 (Henderson Street) over Clear Fork Trinity River 48

Figure 4-1. Savings from Flexibility Versus Level of Flexibility 60

Figure 5-1. Common Defects in Concrete Elements...65

Figure 5-2. Common Defects in Steel Elements. 67

Figure 5-3. Tension and Compression Zones in Concrete Rigid Frame 75

Figure 5-4. General Schematic of Wireless Sensor Network...89

Figure 5-5. Mote and Sensor Board 89

Figure 5-6. Installation of Distributed Sensors and Installed Distributed Sensors 91

Figure 5-7. General Schematic of a FBG Sensor Network 92

Figure 6-1. Uses of Interior Reinforcement 103

Figure 6-2. Uses of Exterior Reinforcement 104

Figure 6-3. Drilling and Plugging a Crack in a Retaining Wall....................................105

Page

Figure 6-4. Steel Jacketing of Circular and Rectangular Columns 106

Figure 6-5. Polymer Impregnation Process 119

Figure 6-6. Straightening with Hydraulic Jack and Support Beam 113

Figure 6-7. Straightening with Tie 113

Figure 6-8. Strengthening of a Plate Girder. a) Angles, b) and c) Plates, d) Plates and Grout 115

Figure 6-9. Strengthening of Truss Members with Plates, Angles, and Channels 115

Figure 6-10. Strengthening of Steel Member with Post and Bar 116

Figure 6-11. Strengthening of Trusses with "Third Chord" 116

Figure 6-12. Forces and Moments Induced by Tendons 117

Figure 6-13. Post-Tensioning Options for Trusses 117

Figure 6-14. Adjustment of Supports to Manipulate Bending Moments 118

Figure 6-15. Use of Riprap to Prevent Erosion 122

Figure 6-16. Use of Gabion to Prevent Erosion 123

Figure 6-17. Use of Spurs to Redirect Stream Flow 123

Figure 6-18. Use of Vanes to Redirect Stream Flow 124

Figure 6-19. Scour Prevention Mechanisms 125

Figure 7-1. Flowchart for Spalling, Scaling, Delamination, Pop-outs, and Reinforcing Steel Corrosion in Concrete Elements. 135

Figure 7-2. Flowchart for Cracking, Efflorescencce, and Discoloration in Concrete Elements 136

Figure 8-1. Flowchart Depicting the Resource Allocation Framework 144

Figure 8-2. Decision Matrix for *M* Alternatives and *N* Criteria 146

LIST OF TABLES

Page

Table 2-1. FHWA Sufficiency Rating..8

Table 3-1. Overview of Quantitative Rating System. 29

Table 3-2. Points Assigned for Year Built 30

Table 3-3. Points Assigned for Main Span Length and Overall Length. 31

Table 3-4. Points Assigned for Rail Type. 33

Table 3-5. Points Assigned for Special Design. 35

Table 3-6. Points Assigned for Structural Integrity 37

Table 3-7. Points Assigned for Site Integrity 37

Table 3-8. Points Assigned for Sufficiency Rating 38

Table 3-9. Final Bridge Rankings 39

Table 3-10. Top 37 Bridges by Year 40

Table 3-11. Top 37 Bridges by Type 41

Table 3-12. Top 37 Bridges by Owner 41

Table 4-1. Summary of Funding Sources..54

Table 5-1. Common Defects in Concrete Elements 63

Table 5-2. Common Defects in Steel Elements 66

Table 5-3. Condition States of Deck Overlays 79

Table 5-4. Condition States of Deck Joints 70

Table 5-5. Condition States of Concrete Superstructures 76

Table 5-6. Condition States of Steel Superstructures...78

Table 5-7. Condition States of Substructures 82

Table 5-8. Condition States of Bearings 84

Table 5-9. Condition States of Waterways...86

Table 6-1. Summary of Rehabilitation and Maintenance of Reinforced Concrete Elements 95

Table 6-2. Summary of Rehabilitation and Maintenance of Steel Elements 96

Page

Table 6-3. Summary of Rehabilitation and Maintenance of Bearings 96
Table 6-4. Summary of Rehabilitation and Maintenance of Decks 97
Table 6-5. Summary of Rehabilitation and Maintenance of Waterways 97
Table 6-6. Regular Interval Maintenance Actions 99
Table 7-1. Condition States and Corrective Actions for Deck Overlays 128
Table 7-2. Condition States and Corrective Actions for Deck Joints 129
Table 7-3. Condition States and Corrective Actions for Concrete Members 130
Table 7-4. Condition States and Corrective Actions for Steel Members 131
Table 7-5. Condition States and Corrective Actions for Substructures 132
Table 7-6. Condition States and Corrective Actions for Bearings 133
Table 7-7. Condition States and Corrective Actions for Waterways 134
Table 7-8. Summary of Current Condition (Example Bridge 1) 138
Table 7-9. Recommended Regular Interval Maintenance (Example Bridge 1) 139
Table 7-10. References for Condition-Based Actions (Example Bridge 1) 139
Table 7-11. Summary of Current Condition (Example Bridge 2) 140
Table 7-12. Recommended Regular Interval Maintenance (Example Bridge 2) 141
Table 7-13. References for Condition-Based Actions (Example Bridge 2) 142
Table 8-1. Suggested Baseline Weight Distributions 150
Table 8-2. Rating Scale for Reduction of Life-Cycle Cost 152
Table 8-3. Rating Scale for Impact on Commercial Value 156
Table 8-4. Rating Scale for Impact on Utility and Functionality 157
Table 8-5. Rating Scale for Impact on Aesthetic Value 158
Table 8-6. Rating Scale for Impact on Historic Integrity 159
Table 8-7. Rating Scale for Reduction of Risk to Structural Integrity 161
Table 8-8. for Application Example Available Sets of Actions 167
Table 8-9. Weights Assigned to Criteria for Application Example 169
Table 8-10. Ratings for Bridge 1 Actions 173
Table 8-11. Ratings for Bridge 2 Actions 174

Page
Table 8-12. Ratings for Bridge 3 Actions 175
Table 8-13. Benefit Scores and Benefit-to-Cost Ratios 178
Table 8-14. Ranking of Optimal Actions According to Benefit Score 179
Table 8-15. Ranking of Optimal Action Sets According to Cost-to-Benefit Ratio 180

CHAPTER I

INTRODUCTION

1.1 GENERAL

In an inevitably occurring process, bridges possessing historic, artistic, and engineering significance deteriorate and must be maintained and rehabilitated in order to be kept in service. Ideally, all potentially significant bridges would be properly preserved and continue to beautify and bring character to their surroundings for years to come. However, funding is currently limited for transportation projects in general, and even more so for historic bridge preservation, which some may consider less critical in comparison to other transportation needs. Because of this limitation on resources, it is important that bridge-owning agencies use proper planning and management strategies in order to make the best use of available funding.

The primary goal in historic bridge preservation is to retain the historic integrity and character-defining features of significant bridges so that they can be enjoyed and appreciated by future generations. In order to best serve this purpose, programs should first be proactive, focusing on preventing problems rather than waiting for them to occur and then dealing with the consequences. It has been proven that in general, performing proper maintenance on bridges is a more cost-effective strategy than taking action only after problems have occurred (FHWA 2011). Secondly, programs should focus on bridges with the most historic and engineering significance and public interest while also taking into account feasibility and economic considerations. In some cases, bridges possessing commendable historic and artistic qualities may be deteriorated to a point where rehabilitation is not an economically feasible option. Programs should also focus on bridge inventories as a whole, rather than on a case-by-case basis. This “big picture” approach encourages a more maintenance-based strategy and results in better planning and resource allocation.

In 2011, the bridge carrying West 7th Street over the West Fork of the Trinity River in Fort Worth, Texas was designated for replacement due to severe deterioration.

Built in 1913, the bridge possessed a great deal of historic significance and an open-spandrel concrete arch superstructure gave it a unique appearance. The decision to replace the bridge was met with concern from local historic interest groups and the general public. To help prevent similar losses of historic bridges in the future, the Texas Department of Transportation (TxDOT) Fort Worth District office sponsored a research project to develop a framework for the preservation of historic bridges in Tarrant County.

This study is aimed toward developing a historic bridge preservation framework to be used within a county bridge inventory. The framework developed in this project is devised specifically for TxDOT for use in Tarrant County, Texas, but can be used as a model for agencies anywhere with some modifications to fit the inventory under evaluation. This framework will address several areas related to historic bridge preservation that can provide bridge-owning agencies guidance toward efficiently using available funding to preserve historic bridges for years to come.

1.2 RESEARCH OBJECTIVES

This study focused primarily on the following six tasks: prioritization of the bridge inventory of Tarrant County, identification of potential funding sources, condition assessment recommendations, identification of relevant rehabilitation and maintenance techniques, guidance for formulating individual bridge preservation plans, and development of a resource allocation framework.

1.2.1 Task 1: Prioritization

The first task was to prioritize and identify the most significant bridges in the county. This task consists of narrowing the entire National Bridge Inventory (NBI) database for Tarrant County down to a final ranked list of bridges worthy of preservation. To achieve this, bridges were first eliminated based on age and type. The next step involved a selection matrix that prioritized bridges using numerical ratings assigned for historical significance and sufficiency to remain in service. Next, a quantitative rating system was used to rank and prioritize the remaining bridges. Using this rating system, a final inventory of 37 bridges was achieved.

1.2.2 Task 2: Funding and Guidance

The second task was to identify potential funding sources for the repair and maintenance of bridges. This task included researching state and federal grant and loan programs as well as public-private partnership programs such as performance-based contracts and reinvestment zones. Also included in this task was guidance regarding procedures required before rehabilitation projects can begin. Federal mandates such as the USDOT Act of 1966 and the National Preservation Act of 1966 require attention to historic integrity and character-defining features. Coordination with other involved parties such as the State Historic Preservation Officer (SHPO), TxDOT Environmental Affairs Division is also required, and local historic interest groups must be consulted. Part of Task 2 was to provide guidance regarding these and other requirements involved in rehabilitation of historic bridges.

1.2.3 Task 3: Condition Assessment Recommendations and Structural Health Monitoring

The third task was to provide recommendations for the condition assessment of historic bridges. This included primarily visual and other non-destructive methods as well as an overview several types of in-situ long-term structural health monitoring systems.

1.2.4 Task 4: Rehabilitation and Maintenance Techniques

The fourth task was to identify relevant mitigation strategies for historic bridges. This included regular interval maintenance and condition-based rehabilitation, repair, and maintenance techniques with special attention paid to preservation of historic integrity.

1.2.5 Task 5: Individual Bridge Preservation Plans

In the fifth task, guidance is provided for the formulation of individual bridge preservation plans. These plans outline the actions that would ideally be implemented on a bridge if adequate funding were available, including immediate actions based on current condition, regular interval maintenance, and condition-based actions should the bridge reach certain condition states.

1.2.6 Task 6: Resource Allocation

The sixth and final task was to develop a resource allocation framework. This methodology is designed help bridge owners choose the optimal action to take on each bridge in an inventory while taking into account factors such as monetary costs, historic integrity, commercial value, and functional value.

1.3 THESIS OUTLINE

Chapter II contains background information relevant to the current state of practice in historic bridge preservation. This includes descriptions of key parameters and criteria used to evaluate historic bridges, as well as summaries of preservation frameworks that have been previously established. Chapter III covers the prioritization process and details the methodology used to rank the bridges in the inventory for this study. Chapter IV discusses issues regarding funding and approval of historic bridge preservation projects. This includes descriptions of funding sources that could potentially be used for historic preservation projects and a summary of the procedures and agreements required for approval of projects. Chapter V presents recommendations regarding the condition assessment and structural health monitoring of historic bridges. Visual and non-destructive evaluation methods are summarized, and several structural health monitoring systems are presented. In Chapter VI, common rehabilitation, repair, and maintenance techniques are discussed. These methods are presented as a general guide to bridge owners and should not be implemented without the consultation of bridge engineers. Chapter VII provides a template for constructing preservation plans for individual bridges. This includes guidance for both interval-based and condition-based actions. Chapter VIII presents a resource allocation framework intended to help bridge-owning agencies distribute funding among bridges in an inventory. This framework includes a methodology for prioritizing actions within an entire bridge inventory based on either total benefit or benefit-to-cost ratio.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 GENERAL

Several key areas should be considered when developing a framework for prioritizing bridges for historic preservation and devising preservation plans. This chapter summarizes the current state of practice and the latest information available on historic bridge prioritization and preservation. TxDOT documents and related reports were reviewed to ensure consistency with the state-adopted approaches. In addition, frameworks used for historic bridge preservation by other state departments of transportation (DOTs) were reviewed for best practices.

2.2 PARAMETERS AND CRITERIA

Several parameters and criteria exist that are fundamental in most historic bridge preservation programs. The most common of these concepts are the National Bridge Inventory (NBI) historical significance rating, the Federal Highway Administration (FHWA) sufficiency rating, and designation criteria for the National Register of Historic Places (NRHP). In addition, Texas also considers the Texas Historic Commission (THC) recognition criteria.

2.2.1 NBI Historical Significance Rating

In the NBI database, each bridge is issued a historical significance rating, ranging from 1 to 5, depending on NRHP eligibility status. The NRHP is an official list of protected historic buildings, structures, and sites managed by the National Park Service. Only one bridge in Tarrant County is listed on the NRHP. The numerical rating indicates the following:

1: The structure is listed on the NRHP

2: The structure is eligible for listing on the NRHP

3: The structure may be eligible for listing on the NRHP or is on a state or local historic register

4: The eligibility of the bridge is not determinable at the time

5: The structure is not eligible for listing on the NRHP

It should be noted that TxDOT has used a different rating system in the past. In this system, a rating of 3 signifies that the structure has been evaluated and is not eligible for the NRHP, and a rating of 5 indicates that the structure has not been evaluated for NRHP eligibility.

2.2.2 FHWA Sufficiency Rating

Each bridge is issued a sufficiency rating by the FHWA intended to indicate the sufficiency of a structure to remain in service (FHWA 1995). The rating ranges from 1 to 100 and consists of a maximum of 55 points for structural adequacy and safety, 30 points for serviceability and functional obsolescence, and 15 points for essentiality for public use. A maximum of 13 points can be deducted based on NBI items 19 (detour length), 36 (traffic safety features), and 43 (main structure type). According to FHWA guidelines, a sufficiency rating above 80 indicates that a bridge is in acceptable condition. Ratings between 50 and 80 warrant rehabilitation, and ratings below 50 make a bridge eligible for replacement. A full description of the calculation of the sufficiency rating from the FHWA *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (FHWA 1995) can be found in Appendix A. Table 2-1 lists the NBI items that are considered in each component of the sufficiency rating of a bridge.

Table 2-1. FHWA Sufficiency Rating (adapted from FHWA 1995).

Rating Component	Percentage of Rating	NBI Items Considered	NBI Item Number
Structural Adequacy and Safety	55	Superstructure Condition	59
		Substructure Condition	60
		Culvert Condition	62
		Inventory Rating	66
Serviceability and Functional Obsolescence	30	Lanes on Structure	28
		Average Daily Traffic	29
		Approach Roadway Width	32
		Main Structure Type	43
		Bridge Roadway Width	51
		Vertical Clearance over Deck	53
		Deck Condition	58
		Structural Evaluation	67
		Deck Geometry	68
		Underclearances	69
		Waterway Adequacy	71
		Approach Roadway Alignment	72
		STRAHNET Highway Designation	100
Essentiality for Public Use	15	Detour Length	19
		Average Daily Traffic	29
		STRAHNET Highway Designation	100

2.2.3 NRHP Criteria

For a bridge to be listed on the NRHP, it must be eligible under one of the following criteria (TxDOT 1999):

- Criterion A: Bridge is associated with a significant historic event.
- Criterion B: Bridge is associated with a significant person in history.
- Criterion C: Bridge embodies the distinctive characteristics of a type, period, or method of construction or, represents the work of a master.
- Criterion D: Bridge has potential to yield information important in history or prehistory.

Criteria A and C are used most commonly, while Criteria B and D are seldom used. Bridges also must have an "area of significance", which may be transportation, community planning and development, agriculture, commerce, or politics and government.

2.2.4 THC Criteria

For a structure to be designated as a Recorded Texas Historic Landmark by the THC, it must be at least 50 years old and possess both historical significance and architectural integrity (THC 2012). Historical significance must be established by the party that nominates a structure for designation through written and photographic documentation. For a bridge to possess architectural integrity, it must "maintain its appearance from its period of historical significance and should be an exemplary model of preservation." Under this requirement, relocation in the past 50 years disqualifies a bridge from consideration.

2.3 TxDOT STUDIES

The following subsections summarize a review of several TxDOT studies focused on historic bridge preservation.

2.3.1 Texas Historic Bridge Inventory Survey of Non-Truss Structures

The TxDOT Environmental Affairs Division (1999) authored the report *Texas Historic Bridge Inventory Survey of Non-Truss Structures*. The major details of this report are as follows.

From 1997 to 1999, TxDOT conducted a project seeking to identify and evaluate the eligibility of a large group of bridges for inclusion on the NRHP. The original inventory was a pool of approximately 40,000 bridges. After narrowing down the field in three different phases of selection, it was concluded that 137 of the bridges were eligible for the NHRP, while another 102 were potentially eligible.

In Phase I of the project, the list was narrowed down using general selection criteria. First, bridges built after 1950 were eliminated because bridges must be at least 50 years old for NHRP eligibility. Second, structures under any classification other than vehicular bridges were eliminated, including tunnels and railroad bridges. Next, metal trusses and suspension bridges were excluded (due to inclusion in a previous survey), as well as timber stringers and concrete box culverts (due to low engineering significance). Fourth, all bridges that had been widened or reconstructed were eliminated, and lastly, publicly owned bridges owned by agencies other than TxDOT were excluded. After Phase I, the list was narrowed down to 5313 bridges.

In Phase II, project historians at TxDOT district offices conducted further research using files from past inspections of the bridges. This stage revealed that many of the bridges had undergone alterations not covered by the TxDOT Bridge Inspection and Appraisal database, which was the only source used when looking for modifications in Phase I. Many of these alterations reduced the engineering or historic significance of bridges, resulting in the list being trimmed to 1302 structures. In-depth photograph documentation was then conducted for each of the remaining bridges.

In Phase III of the project, the documentation of the remaining structures was examined and the field was narrowed down to 467 bridges. These bridges were then evaluated by category, using either a quantitative rating system or individual inspection. The three most common categories of bridges were steel I-beams, concrete slabs, and concrete girders. These categories were evaluated using a numerical rating system, which took the following factors into account (maximum points possible in parentheses):

- Date of construction (40): Bridges built before 1920 received a full 40 points, newer structures received increasingly less.
- Length of main span (20): A longer main span showed greater engineering expertise.
- Overall length (4): A longer overall length showed greater engineering expertise.
- Rail type (14): Bridges with early standard rails issued by the State Highway Department received a full score, other specially designed rails also earned points.
- Special design (10): Bridges designed by the State Highway Department were preferred, but any bridge showing a conscious effort toward beautifying the structural members received points.
- Structural integrity (8): Structures which had maintained the integrity of the original design, workmanship, and materials were preferred.
- Site integrity (8): Higher scores were given to bridges with unchanged surrounding environments.
- Sufficiency rating (8): Structurally sound bridges were rewarded with higher scores.

A full description of the quantitative rating system can be found in Appendix B. After this rating system was applied on the most common bridge categories, structures rated 62 or higher, as well as all bridges from rare categories such as masonry arches and steel girders, were further investigated. This further investigation consisted of gathering historical and technical information on each bridge and individually evaluating their eligibility for the NHRP under Criterion C (embodiment of a certain type, construction method, or period, or the work of a master), at a statewide level of significance. The five areas of eligibility under this criterion considered were type, design, representation of type or period, engineering innovation, and designer. Especially rare types of bridges such as concrete or masonry arches were given special consideration. For example, a modified railing on one of these bridges may have been considered more acceptable than on a more common type of bridge. In the end, 137 bridges were deemed eligible under Criterion C, and 102 were designated as potentially eligible.

2.3.2 On-System Historic Metal Truss Bridge Task Force Final Report

The TxDOT Environmental Affairs Division (2001) authored the report *On-System Historic Metal Truss Bridge Task Force Final Report*. The major details of this report are as follows.

In 1996, TxDOT formed the On-System Historic Bridge Task Force for the purpose of researching and evaluating options for the preservation of historic metal truss bridges. The Task Force consisted of 12 representatives from TxDOT, FHWA, and the Office of the State Historic Preservation Officer (SHPO) and was formed in response to encouragement from the SHPO and increased public interest. According to Section 106 of the National Historic Preservation Act of 1966 (US Senate 1966), state DOTs are required to coordinate all projects involving bridges greater than 50 years old with the SHPO, as well as consider input from local historical groups and the general public. Prior to the formation of the Task Force, the SHPO expressed dissatisfaction with the handling of several historic bridge projects, thus leading to the assembly of the Task Force.

The scope of the work of the Task Force was to formulate a methodology to evaluate preservation options for all metal truss bridges on state highways that were at least 50 years old, resulting in a list of 38 bridges. Of these bridges, 33 were already listed on the NRHP, but all 38 were considered in the project. Leading up to the start of the project, many of the state's metal truss bridges had been removed, and many of those remaining were in need of removal or rehabilitation.

The first category of factors that went into the decision-making process for the Task Force was technical criteria. These criteria consisted of bridge geometrics, approach geometrics, structural capacity, railing safety, and hydraulic capacity. Horizontal clearance between rails, vertical roadway clearance, and vertical clearance between the bottom chord and a lower roadway (if applicable) were the requirements considered in bridge geometrics. In the case of approach geometrics, width and alignment in relation to the rest of the road were the primary concerns. In the case of structural capacity, the Task Force focused on design load, operating rating, inventory rating, and condition evaluation. Railing safety was based on bridge railings, transitions, approach guardrails, and approach guardrail ends, each of which are included in NBI Item 36. Channel protection, waterway adequacy, scour critical status, and scour vulnerability were the factors considered for hydraulic adequacy.

The second set of factors considered for each bridge involved historic significance and public interest. It was important that any changes made to a bridge would maintain the historic integrity of the structure. Modifications were to be "visually inconspicuous" and "compatible with the historic properties of the bridge", as well as retain the original structural components as much as feasibly possible. Other considerations included how significant the bridge's location was, how many other bridges of the same type were in existence, historic designation or recognition, and feasibility of relocation.

The final category of factors was economic considerations. Several federal and state organizations were considered as funding options. The Highway Bridge Replacement and Rehabilitation Program (HBRRP) funds improvements on bridges that are determined to be structurally deficient or functionally obsolete. Bridges must be rated at a low level on one or more designated items in the NBI database in order to be eligible for HBRRP funding. According to HBRRP guidelines, bridges with an NBI sufficiency rating of less than 80 are eligible for rehabilitation, and a sufficiency rating of less than 50 constitutes grounds for replacement. Other federal funding sources included the Interstate Maintenance Program, the National Highway System Program, and the Surface Transportation Program. Funding programs at the state level included Category 8A (Farm-to-Market Rehabilitation); Category 11 (District Discretionary); and Category 14 (State-Funded Rehabilitation). Individual cost estimates for each bridge were beyond the scope of work, but generalized cost feasibility assessments were made based on past experiences of team members.

Taking all of the above mentioned factors into account, the Task Force then determined one or more recommended options for the preservation of each bridge. In many cases, the best option was not financially feasible, thus decisions were made based on both historic integrity and cost-effectiveness.

After evaluating each bridge and making recommendations for rehabilitation, the Task Force designated each bridge for one of the following preservation options (in order of decreasing desirability):

- Full vehicular use at original location: Bridges were deemed suitable for the same rate or an increased rate of traffic from its current use. Usually, improvements were necessary in order to place a bridge in this category.
- Reduced vehicular use at original location: Options included using the existing bridge for one direction of traffic while using a new structure for the other direction, using the existing bridge as only a historic turnoff while using a new structure to carry traffic, or converting the road carried by the bridge to a business route in order to reduce traffic.
- Non-vehicular use at original site: Options included bike-and-hike traffic, park or picnic area use, or access to boat ramps.
- Relocation for vehicular use: Used rarely because it is discouraged by most federal funding sources.
- Relocation for non-vehicular use: Also used rarely, but options were similar to those used for non-vehicular use at original site.
- Removal without reuse: Used only as a last resort. Archival photography and historic documentation were required before removal.

In the end, 23 bridges were designated for full vehicular service, five for reduced vehicular service, eight for pedestrian and bicycle service, one for relocation for vehicular service, and one for removal.

2.3.3 Historic Context for Texas Bridges, 1945-1965

TxDOT commissioned a study by Mead & Hunt and the resulting report was entitled *Historic Context for Texas Bridges, 1945-1965* (Mead & Hunt 2009). The major details of this report are as follows.

From 2004 to 2009, TxDOT conducted a project intended to evaluate the historic significance of each of its 14,799 existing bridges built between 1945 and 1965. Criteria A (significant events) and C (engineering design) were the only criteria considered, and bridges were evaluated at a statewide level of significance. Several laws require TxDOT to consider the historic aspects of bridges when making changes, as well as to periodically update its historic bridge inventories. The first step of the project was to conduct research on historical trends and bridge design characteristics of the period of concern. Next, a methodology to evaluate the bridges was developed and refined. The third and final step was to use this methodology to evaluate the bridges and determine the NRHP eligibility of each structure. The report details the historic context and engineering design trends used in the evaluation of bridges in this project.

Because the report focuses on a statewide level of significance, much of the historic context given is centered on how state and federal funding efforts affected bridge construction in Texas. During World War II, needs in the transportation industry increased but little funding was available. During this time, the Texas Highway Department (THD, now TxDOT) planned a large number of renovation and replacement projects to be carried out when funding became available. Combined with increased state and federal funding, this led to a boom in road and bridge construction in the postwar period. Federal-Aid Highway Acts were a main source of federal funding. The Federal-Aid Highway Acts of 1944 and 1966 authorized and expanded the Interstate system, respectively. Structures associated with these funding efforts and other successful financial programs from the same period are considered to hold a certain historic significance.

Throughout the postwar period, funding for bridges and roads increased each year. The Colton-Briscoe Act issued a significant amount of funding for farm-to-market roads, leading to the construction of many reinforced concrete slab bridges and concrete pan-formed girder bridges, which became popular after 1948. During the subject period, many bridges on farm-to-market bridges were in need of replacement, which made the Colton-Briscoe Act a significant movement in the history of Texas road and bridge construction.

Another prevalent group of bridges from the postwar period was bridges on county roads. These structures made up 18% of the extant bridges from the subject period of the project. Although there are many types of construction seen in these structures, 61% were timber stringers and steel I-beams.

One important construction trend in the bridges of the postwar period was the expansion of the Interstate system and expressways. Federal-Aid Highway Acts gave approval and funding for projects that included overpasses, underpasses, and multi-level exchanges, with much of the construction taking place in the 1950s. In 1953, the first three-level interchange in Texas was built, and in 1958 a four-level interchange was constructed. Texas was a national leader in many aspects of bridge construction, especially on the Interstate system, where it had built almost four times as many bridges as any other state. Association with the boom in Interstate and expressway construction during the postwar period is an aspect that gives bridges a special historic significance.

In the area of engineering trends, several new developments during the subject period made bridge construction more efficient. Dewitt C. Greer, the state highway engineer during the period, highly encouraged alternate design solutions, and this caused Texas to be a leading state in bridge design innovation. The emergence of prestressing technology made construction of concrete bridges quicker, cheaper, and easier. Welded connections did the same for steel bridges; however, high prices for steel during the postwar era made prestressed concrete a more attractive option for most medium-span bridges. Other significant developments included high-tensile strength steel bolts, allowing for faster construction and requiring less maintenance than rivets, and high-strength steel reinforcing bars, which required less concrete to be used in construction.

During the postwar period, aesthetics were less of a priority in bridge construction than before. Due to limited resources and a high demand for new bridges, structural efficiency was valued more than artistic design. Modernism was preferred over traditional ornamentation, and simple, clean lines and design were appreciated. Most of the bridges built during the period were beam or girder bridges, and very few were arches and trusses.

Due to improved technology in concrete and rising costs of steel during the subject period, nearly 75 percent of extant bridges built in the period were concrete. Prestressed concrete became popular in the late 1940s, making construction quicker and cheaper. Prestressed concrete girder bridges were exceptionally popular, making early versions of this type historically significant. Other types of prestressed concrete bridges, such as pan-formed girders, channel beams, and tee beams were rare, giving a special significance to all examples of these types. In reinforced concrete bridges, pan-formed girders were by far the most popular. The strength and simplicity of this construction method made it an attractive option, and because of this, nearly 25 percent of extant bridges from the subject period are pan-formed girders. Reinforced concrete slab bridges were also popular, including flat and variable depth slabs. Concrete box girders, arches, and rigid frames were less common types that are now considered historically significant due to their rarity.

As stated above, steel became a less popular option for bridge construction during the postwar era. World War II caused a shortage of steel, and delivery costs for steel were at an all-time high. However, steel bridges still make up nearly 25 percent of the extant bridges from the subject period. I-beams and plate girders were by far the most popular option in steel bridge construction, but because these bridge types were developed before the period, few of them are considered to possess a great amount of historic significance. Less common types included trusses, arches, and movable bridges such as bascules, horizontal swing bridges, and vertical lift bridges. Due to especially low numbers of extant bridges of these types from the subject period, they are considered to be historically significant.

One factor that began to affect bridge construction trends during the postwar period was the development of standard plans. The Bureau of Public Roads (BPR) defined national standards and distributed standard plans for bridges. The THD created many of its own standard plans, many of them based on national standards. In Texas, THD standards took precedence over BPR standards. Early use of certain standard plans is known to give some bridges a special historic significance.

2.3.4 Final Evaluation Methodology for 1945-1965 Bridges

TxDOT commissioned a study by Mead & Hunt and the resulting report was entitled *Final Evaluation Methodology, Texas Historic Bridge Inventory, Evaluation of 1945-1965 Bridges* (Mead & Hunt 2010). The major details of this report are as follows.

This document details the methodology used by TxDOT for an evaluation of its inventory of bridges built in the period from 1945 to 1965. The objective was to determine the NRHP eligibility status of each of these bridges. The evaluation was based entirely on Criteria A (significant events) and C (embodiment of type, method, period, or work of a master). The methodology began with evaluation of each bridge based on the two criteria and assessing a quantitative score, then subtracting points for areas where a bridge lacked historic integrity.

The first step of the methodology was to evaluate bridges under Criterion A (association with significant historic even). A bridge could receive up to eight points for being a part of a statewide initiative, such as 3- or 4-level urban interchanges or all-weather durable bridges along the Gulf Coast. Points could also be assigned for association with other significant events mentioned in *Historic Context for Texas Bridges, 1945-1965* (Mead & Hunt 2009). Bridges receiving less than eight points in this step were eliminated, while those scoring eight or higher were further investigated.

The second step of the methodology was to assess the historic integrity of the remaining bridges. In this step, specified amounts of points were subtracted from Criterion A scores for relocation, widening, and alterations to their original setting, association, aesthetic feeling, materials, workmanship, and design. The total score for a bridge after this step determined whether or not it would be deemed eligible for the NRHP under Criterion A.

After evaluating a bridge under Criterion A, the next step was to assess points according to Criterion C. Bridges could receive values of four or eight points for possessing qualities such as being built during the earliest period of use for its type, exceptional main span or overall length, displaying innovative designs and features, and embodiment of the work of a master.

In the same way as in evaluating under Criterion A, bridges receiving eight or more total points in this step were further evaluated for historic integrity. In this step, points were deducted for historic integrity in the same way as under Criterion A. Appendix C shows tables to calculate the amount of points to be subtracted for integrity for both criteria. The NRHP eligibility status of a bridge under Criterion C was then determined by the score after these deductions.

2.4 PRESERVATION FRAMEWORKS IN OTHER STATES

In addition to a review of TxDOT reports on past bridge preservation projects, bridge prioritization frameworks used in Indiana, New Mexico, and Ohio were reviewed. The following subsections describe the frameworks used in each state.

2.4.1 Indiana

In 2006, a task force from the Indiana DOT initiated a program to prioritize and preserve the historic bridges in the state in response to increased public pressure (Rathke et al. 2010). The prioritization process was based on both historic significance and engineering condition. Each of the nearly 800 historic bridges in the state was assigned both a condition score and an eligibility score. The condition score was based on functionality, safety, feasibility, and cost-effectiveness of preservation. The eligibility score was based on historic significance and integrity of defining characteristics. Each bridge was then classified as high, medium, or low in each score category. The team applied a normal distribution to the full inventory of each bridge type and classified certain percentages of each type as high, medium, or low. The bridges were then placed in a selection matrix, as shown in Figure 2-1. For example, a bridge in the medium range for eligibility score and the high range for condition score would be placed in Box 4.

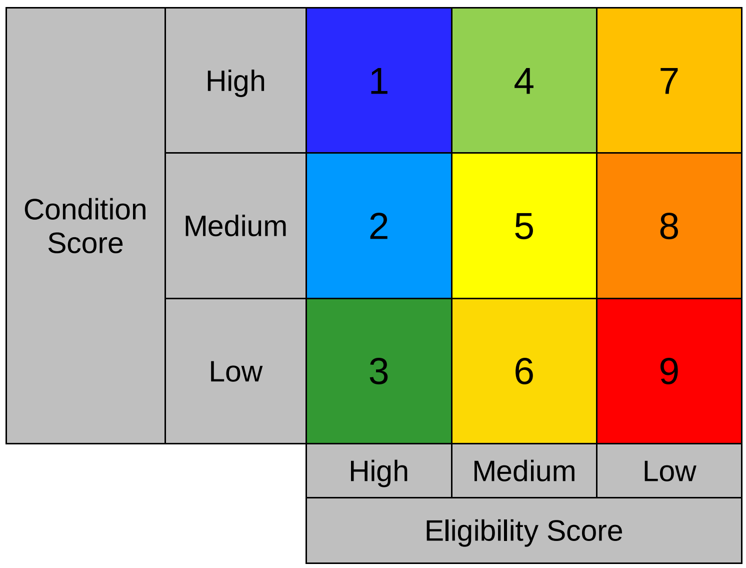


Figure 2-1. Selection Matrix Used in Indiana DOT Prioritization Process (adapted from Rathke et al. 2010).

After being placed in the matrix, each bridge was then designated as either select or non-select (Rathke et al. 2010). Bridges in Boxes 1 and 2 were determined to be select unless they were on low-volume roads (future ADT < 400) and failed to meet the Indiana DOT's Design Standards for Historic Bridges on Low-Volume Roads. Bridges in Boxes 4 and 5 were designated as select with the same exception as Boxes 1 and 2, plus an exception for post-1944 bridges. Bridges in Box 3 were subject to individual review to determine their status. The individual review consisted of five checks: superstructure and substructure condition, load capacity, geometric and functional adequacy, integrity of character-defining features, and a fifth check of several issues such as deterioration, drainage, accident rates, and detour length. Bridges in Boxes 6, 7, 8, and 9 were automatically determined non-select. A flowchart depicting the selection process can be found in Appendix D.

Regulations were different depending on whether a bridge was deemed select or non-select (Rathke et al. 2010). For select bridges, rehabilitation was required if the cost would be less than or equal to 80 percent of the replacement cost. Rehabilitation of select bridges was required to comply with the Secretary of the Interior's Standards for Rehabilitation (USDOI 1986) as closely as practically possible, and proposed plans were required to be reviewed by the SHPO. Owners of select bridges were also required to ensure adequate maintenance of the bridge for at least 25 years. In the case of non-select bridges, rehabilitation was permitted only if the initial rehabilitation cost would be less than or equal to 40 percent of the replacement cost, otherwise they were to be replaced. Non-select bridges were also ordered to be replaced if they met two or more of the following criteria:

- The waterway opening is inadequate
- The bridge has a documented history of catching debris
- The bridge requires special inspection procedures
- The bridge is classified as scour-critical
- The service lives of welded components are expected to end within 20 years
- The sufficiency rating is less than 35

In all cases, if proposed rehabilitation plans for a specific bridge could meet the Indiana DOT design standards for historic bridges on low-volume roads, rehabilitation for vehicular use was required. If this was not feasible, consideration of a bypass alternative was required. If a bypass was not feasible, then the bridge would be preserved by relocation.

2.4.2 New Mexico

From 2001 to 2003, the New Mexico DOT contracted Van Citters Historic Preservation, LLC (VCHP) to perform a survey of its bridge inventory with the intention to provide recommendations for NRHP eligibility (Van Citters et al. 2003). The VCHP team extensively researched the history of roads and bridges in New Mexico in regards to significant events and engineering trends in order to gain familiarity with the historic context of the bridges of concern. After eliminating bridges based on year built, bridge type, and maintenance responsibility, the team selected 144 bridges to be field-surveyed for further evaluation. After the surveys were conducted, the team rated each bridge based on bridge type, predominant material, overall length, main span length, and whether or not it was the oldest surviving bridge of its type. These ratings helped the team determine whether or not bridges should be recommended for NRHP eligibility under Criterion C. In the end, the VCHP team recommended 67 bridges for eligibility on the NRHP.

2.4.3 Ohio

In 1990, the Ohio DOT released a report on an evaluation of the potential NRHP eligibility of its bridges built between 1941 and 1950 (TranSystems 2010). Although the evaluation was limited to bridges of a specific time period, this document provides an example of a quantitative rating system for historic bridges. The Ohio DOT team began by field surveying all of its bridges from the select time period and providing photo documentation of each bridge. They then rated each bridge using a numerical rating system based on historic and engineering context. Half of the possible points in the rating system were dedicated to technological significance, while half were dedicated to general significance. Appendix E shows the complete rating system.

2.5 SUMMARY

In this chapter, background information relevant to a framework for historic bridge preservation is covered. Parameters and criteria commonly used in prioritization are discussed, as well as preservation efforts made by TxDOT and other state DOTs in the past. This background material lays a necessary foundation of knowledge before proceeding with the prioritization process, as discussed in the following chapter.

CHAPTER III

PRIORITIZATION OF BRIDGES

3.1 OVERVIEW

The focus of this study is on the bridge inventory for Tarrant County, Texas. The NBI database of all Tarrant County bridges was used to describe the inventory. All bridges built later than 1971 were eliminated, resulting in a list of all bridges at least 40 years old. By definition, a historic bridge must be at least 50 years old, but bridges between 40 and 50 years old were also included to make this prioritization valid for the next 10 years. Culverts were eliminated due to a general failure to exhibit any engineering or historic significance. Railroad bridges were eliminated because they are owned by railroad companies rather than the state, county, or city; therefore, they are beyond the scope of the study. Any bridges with no listing under either historical significance or sufficiency rating were also eliminated. These initial eliminations reduced the inventory from 2860 bridges to 433. The remaining bridges were then placed in a selection matrix, as described in Section 3.3. This step eliminated several more bridges, reducing the remaining inventory to 34 bridges. Further review revealed that five of these bridges had already been designated for removal, trimming the list to 29 bridges. In order to ensure a thorough prioritization, all bridges built before 1940 that were previously eliminated by the selection matrix were put under further review, resulting in eight previously eliminated bridges being returned to consideration. The final bridges (37 total) were ranked using the quantitative rating system described in Section 3.4. Figure 3-1 depicts the entire prioritization process, and Figures 3-2(a) and (b) show maps of the entire inventory and the final 37 bridges, respectively.

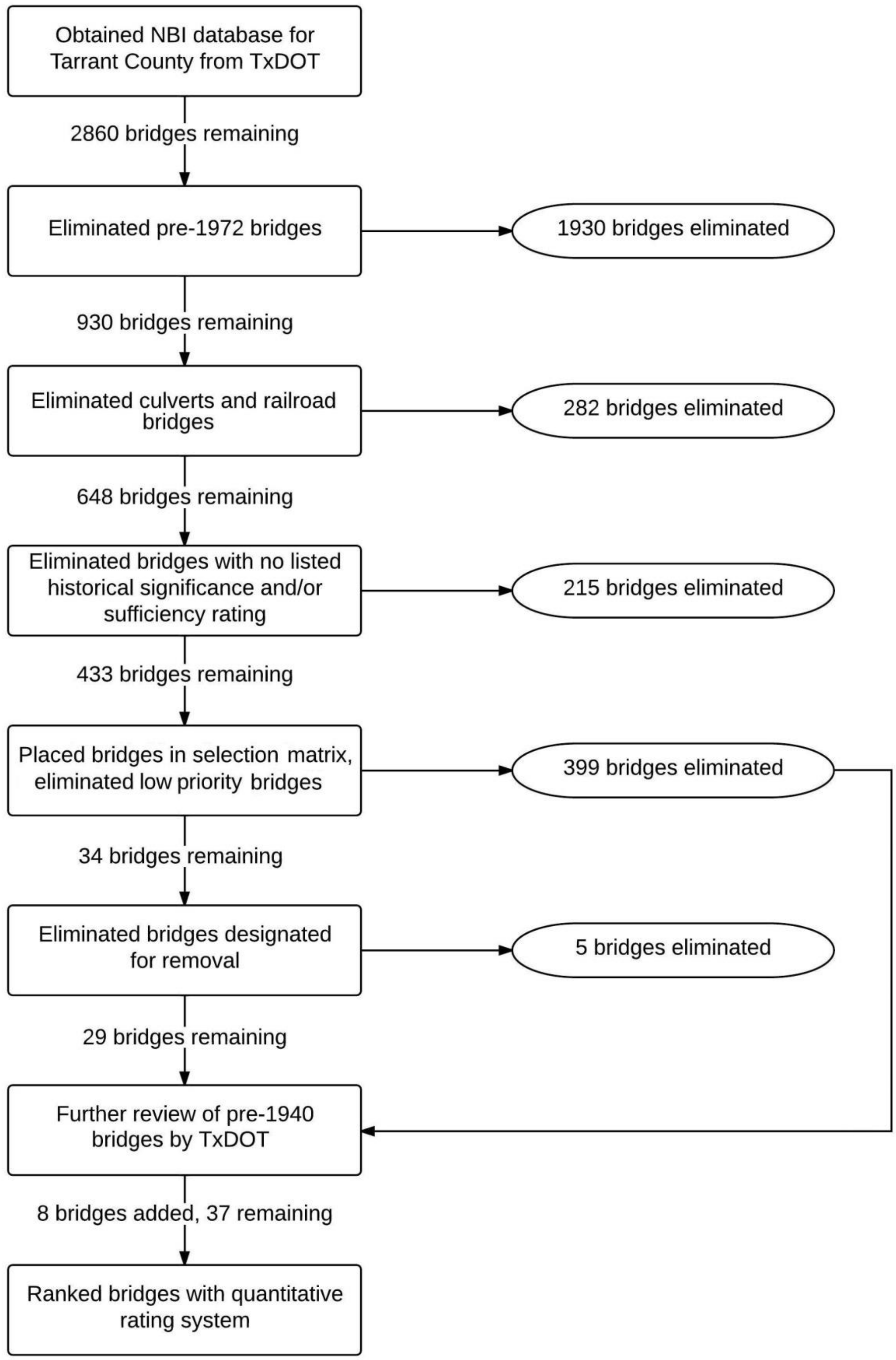
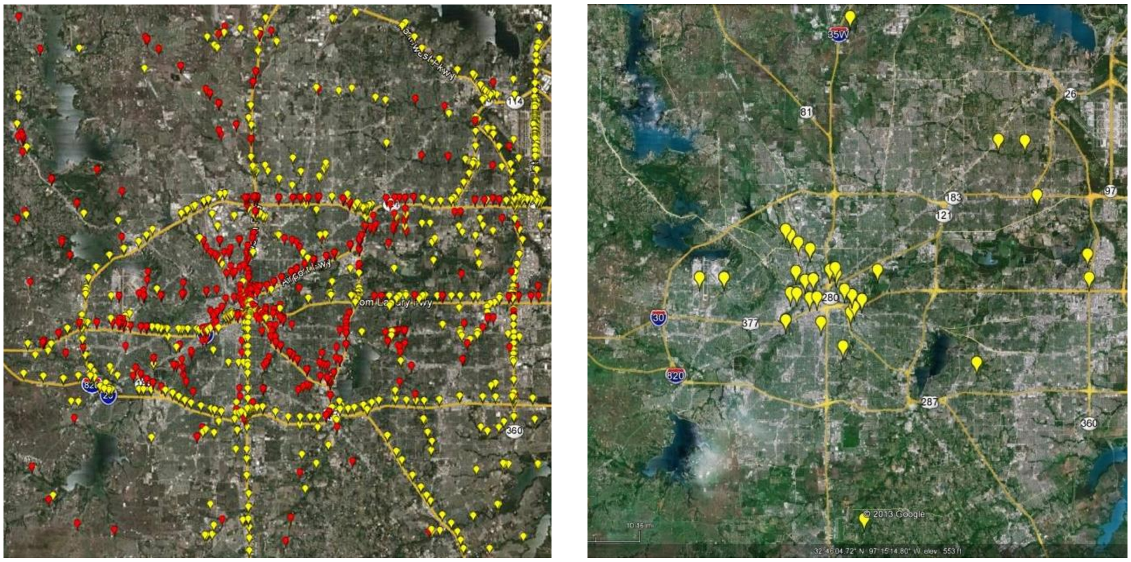


Figure 3-1. Flowchart Depicting the Prioritization Process.



a) b)

Figure 3-2. a) All Bridges in Tarrant County (pre-1972 bridges in red); b) Final 37 Bridges (TxDOT 2012).

3.2 RECOMMENDATIONS FROM TxDOT AND HISTORIC FORT WORTH, INC.

In this study, lists of recommended bridges from both TxDOT and Historic Fort Worth, Inc. (HFW), a historic interest group in Tarrant County, were considered. TxDOT personnel in the Fort Worth office formulated a list of 24 bridges that they preferred to be included in the prioritization. Three of these bridges were railroad bridges and were later excluded, and one had already been designated for removal. The remaining 20 bridges from the TxDOT list were included in the final 37 bridges. HFW provided a list of what they believed to be the ten highest priority bridges in Fort Worth for preservation and maintenance, nine of which were included in the final inventory. The only bridge from the HFW list excluded from the final inventory is no longer in service or listed in the NBI database.

3.3 SELECTION MATRIX

As shown in Section 2.2.1, the Indiana DOT used a matrix based on condition score and eligibility score to prioritize its historic bridges. Using that matrix as an example, a selection matrix for this study was created using historical significance and sufficiency ratings. As was stated in Section 2.1.1.1, historical significance ratings range from one to five and each rating signifies the following:

1: The structure is listed on the NRHP

2: The structure is eligible for listing on the NRHP

3: The structure may be eligible for listing on the NRHP, or is listed on a local or state historic register

4: The eligibility of the bridge is not determinable at the time

5: The structure is not eligible for listing on the NRHP

In the TxDOT system used in the past, a historical significance rating of 3 signifies that the structure has been evaluated and is not eligible for the NRHP, and a rating of 5 indicates that the structure has not been evaluated. Sufficiency ratings, as discussed in Section 2.1.1.2, range from 1 to 100 and indicate the ability of a structure to remain in service.

Because the historical significance ratings were divided into five levels, five ranges of sufficiency ratings were formulated. Rather than creating five equal ranges of 20, the ranges were set according to FHWA guidelines regarding sufficiency ratings. The highest level ranges from 80 to 100, representing bridges in good condition according to these guidelines. The next two levels range from 65 to 79.9 and 50 to 64.9, covering the ratings that make bridges eligible for rehabilitation. The lowest two levels range from 25 to 49.9 and 0 to 24.9, representing bridges that are eligible for replacement according to FHWA recommendations.

It should be noted that in this step, seven bridges were considered to have higher historical significance ratings than their ratings listed in the NBI database. Three of these bridges were included on the TxDOT *List of National Register-Eligible Bridges* from a statewide historic bridge inventory of bridges built from 1945 to 1965 and were thus considered to have historical significance ratings of 2. The other four bridges were deemed worthy of the same rating because they possess artistic qualities, engineering design, or historic value that warrant eligibility for the NRHP. Figure 3-3 shows the selection matrix, with numbers in each box representing the number of bridges from the inventory of 433 falling in each rating region. The recommended increased historical significance ratings are reflected by these numbers.

Historical Significance						
	1	0	1	0	0	0
	2	1	3	6	2	5
	3	0	1	2	7	1
	4	0	10	23	51	26
	5	1	3	15	62	208
		0-24.9	25-49.9	50-64.9	65-79.9	80-100
		Sufficiency Rating				

Figure 3-3. Selection Matrix Based on Historical Significance and Sufficiency Rating.

As shown in the figure, the matrix was divided into green, yellow, and red regions. The green region represents the highest priority bridges, due to high historical significance ratings and relatively high sufficiency ratings. The yellow region represents the next level of priority, with high historical significance but lower sufficiency ratings.

The red region represents the lowest priority bridges due to low historical significance ratings. Bridges falling in this region were eliminated except the seven structures that were returned to consideration after further review and one that was recommended by a local historic interest group. Adding these eight structures to the 29 from the green and yellow regions made a final list of 37 bridges. Reviewing the previously eliminated bridges ensured that flaws or discrepancies in the historical significance rating did not exclude any bridges worthy of preservation. The final 37 bridges were then ranked using the quantitative rating system discussed in the following section.

3.4 QUANTITATIVE RATING SYSTEM

Using the rating system used in the report *Historic Bridge Inventory Survey of Non-Truss Structures* (TxDOT 1999) as an example, a quantitative rating system was developed for ranking bridges of all types and ages found in this study. The system used the same criteria as the TxDOT system, with changes being made where necessary to accommodate more bridge types and ages. Each bridge can receive a maximum possible rating of 112, with points distributed among criteria as shown in Table 3-1. Each criterion is discussed in the following subsections.

Table 3-1. Overview of Quantitative Rating System.

Category	Maximum Possible Points
Year Built	40
Main Span Length	20
Overall Length	4
Rail Type	14
Special Design	10
Structural Integrity	8
Site Integrity	8
Sufficiency Rating	8
Total	112

3.4.1 Year Built

Due to its importance in determining the historic and engineering significance of a bridge, year of construction was given the most weight, with 40 of 112 possible points. The point distribution for this criterion was modified in order to accommodate a greater range of years than that used in the TxDOT project. Points were assigned as shown in Table 3-2.

Table 3-2. Points Assigned for Year Built.

Year Built	Points
1900-1909	40
1910-1919	35
1920-1929	30
1930-1939	25
1940-1949	20
1950-1959	15
Post-1959	10

3.4.2 Main Span Length and Overall Length

Main span length and overall length are often used to gauge the level of engineering technology used in the construction of a bridge, hence their inclusion as criteria in this rating system. For concrete girder, concrete slab, and steel I-beam bridges, the TxDOT rating system was used (TxDOT 1999). This system assigns a maximum number of points to bridges in the top five percent of main span lengths of its particular bridge type within the state, and a lower number of points for structures in the top ten percent. Because the TxDOT report only gave a rating system for these three bridge types, a system for rating concrete arch, concrete rigid frame, steel truss, and steel plate girder bridges was developed using a similar approach. Points were assigned as shown in Table 3-3. Figure 3-4 shows examples of each bridge type.

Table 3-3. Points Assigned for Main Span Length and Overall Length.

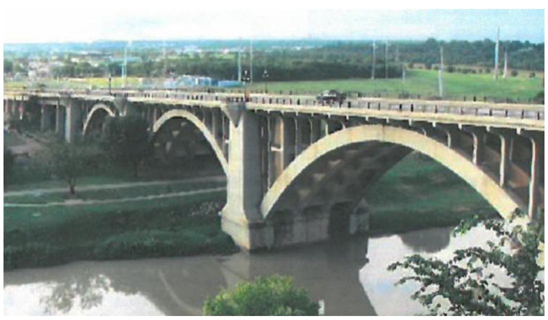
Bridge Type	Main Span Length (ft)	Points	Overall Length (ft)	Points
Concrete Girders	≥ 45	20	≥ 420	4
	40-45	10	100-420	2
	< 40	0	< 100	0
Concrete Slabs	≥ 30	20	≥ 300	4
	25-30	10	200-300	2
	< 25	0	< 200	0
Steel I-Beams	≥ 65	20	≥ 520	4
	50-65	10	340-520	2
	< 50	0	< 340	0
Concrete Arches (Closed Spandrel)	≥ 40	20	≥ 200	4
	30-40	10	80-200	2
	< 30	0	< 80	0
Concrete Arches (Open Spandrel)	≥ 120	20	≥ 750	4
	90-120	10	500-750	2
	< 90	0	< 500	0
Concrete Rigid Frames	≥ 50	20	≥ 200	4
	40-50	10	100-200	2
	< 40	0	< 100	0
Steel Trusses	≥ 100	20	≥ 1000	4
	80-100	10	300-1000	2
	< 80	0	< 300	0
Steel Plate Girders	≥ 80	20	≥ 500	4
	50-80	10	200-500	2
	< 50	0	< 200	0

a) Concrete Girder

b) Concrete Slab

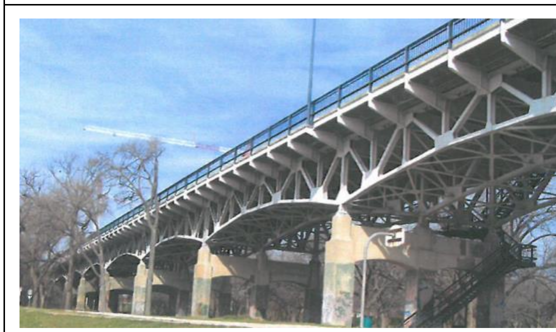
c) Steel I-Beam

d) Closed Spandrel Concrete Arch



e) Open Spandrel Concrete Arch

f) Concrete Rigid Frame



g) Steel Truss

h) Steel Plate Girder

Figure 3-4. Examples of Bridge Types (photos from TxDOT 2012).

3.4.3 Rail Type

Rails can add a decorative element to a bridge, therefore bridges were assigned a maximum of 14 points for the type of rail used. For bridges built in 1945 or earlier, the rating system used in the TxDOT evaluation was followed. Because the TxDOT project did not include bridges built after 1945, engineering judgment was used in assigning points to railings of bridges built after this date. For pre-1940 bridges, points were assigned as shown in Table 3-4. Figure 3-5 shows examples of Types H and K and specially designed rails.

Table 3-4. Points Assigned for Rail Type.

Rail Type	Points
A-J	14
Special Design	12
K, L	10
M	8
P, Q	6
R-8, R-10	4
Other post-1940 standard rail	2

a) Type H (14 points)

b) Special Design (12 points)

c) Special Design (12 points)

d) Type K (10 points)

Figure 3-5. Various Rail Types (photos from TxDOT 2012).

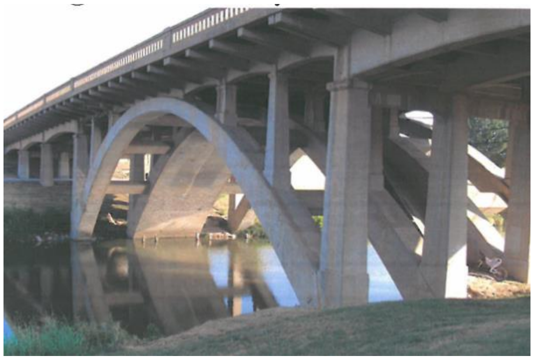
3.4.4 Special Design

Using the TxDOT rating system with no modifications necessary, bridges were assigned points based on the level of special design used in their construction. The maximum score was assigned to bridges possessing decorative elements, while bridges employing commendable engineering response received the second-highest score. Lower scores were assigned based on special design displayed in superstructures and substructures. Points were assigned as shown in Table 3-5.

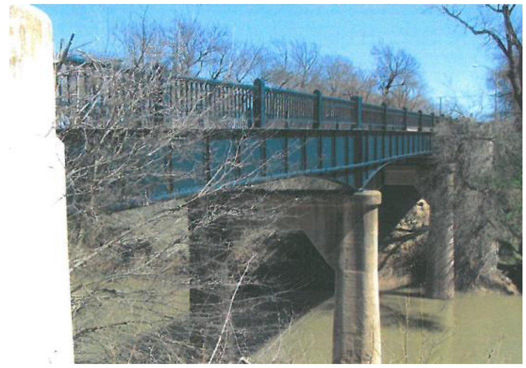
Figure 3-6 shows several examples of how bridges were scored. Figure 3-6(a) shows the bridge carrying Texas State Highway 199 over the Clear Fork of the Trinity River. This bridge received the full ten points for possessing decorative elements. The steel plate girder bridge carrying East 1st Street over the West Fork of the Trinity River, shown in Figure 3-6(b), received eight points for commendable engineering design. The variable depth tee beam superstructure and unique piers of the East Rosedale Street bridge crossing Sycamore Creek, shown in Figure 3-6(c), earned six points, and the engineering design in the superstructure of the bridge carrying State Highway 183 over Marine Creek received four points, as shown in Figure 3-6(d).

Table 3-5. Points Assigned for Special Design.

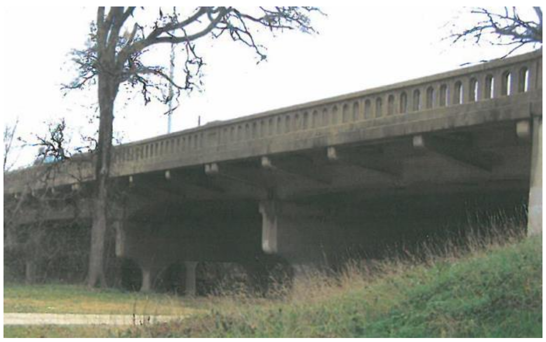
Special Design	Points
Decorative Elements	10
Engineering Response	8
Superstructure/Substructure	6
Superstructure	4
Substructure	2



a) Decorative Elements (10 points)



b) Engineering Response (8 points)



c) Superstructure/Substructure (6 points)

d) Superstructure (4 points)

Figure 3-6. Various Levels of Special Design (photos from TxDOT 2012).

3.4.5 Structural Integrity

Structural integrity is a measure of how the original features, workmanship, and materials of a bridge are retained. Damage or alteration to any of these resulted in a reduced score. Points were assigned according to the TxDOT rating system for this criterion with no modification necessary, as shown in Table 3-6. The structural integrity of a bridge is considered “excellent” if the original design, workmanship, and materials are unaltered. “Good” structural integrity implies some damage to the original features, while “fair” implies replacement of key features (TxDOT 1999).

Table 3-6. Points Assigned for Structural Integrity.

Structural Integrity	Points
Excellent	8
Good	6
Fair	4

3.4.6 Site Integrity

Site integrity is a measure of the condition of the surroundings of a bridge. It is preferred that the area surrounding a historic bridge remains unaltered, but this is not always possible. Using the rating system from TxDOT with no modifications, points were assigned according to Table 3-7. “Excellent” site integrity assumes that the surroundings of a bridge are unaltered, “good” implies minor alterations, and “fair” implies significant changes (TxDOT 1999).

Table 3-7. Points Assigned for Site Integrity.

Site Integrity	Points
Excellent	8
Good	6
Fair	4

3.4.7 Sufficiency Rating

As discussed in Section 2.1.1, sufficiency rating is a measure of the adequacy, safety, and functionality of a bridge. Bridges with sufficiency ratings above 80 are considered to be in good condition. Sufficiency ratings between 50 and 80 may warrant rehabilitation, while ratings below 50 can be grounds for replacement (TxDOT 1999). Using these ranges and following the TxDOT model, points were assigned as shown in Table 3-8.

Table 3-8. Points Assigned for Sufficiency Rating.

Sufficiency Rating	Points
80-100	8
50-79.9	6
0-50	4

3.5 FINAL BRIDGE INVENTORY

A total of 37 bridges from the Tarrant County bridge inventory were retained on the final list, with 15 coming from the first priority region of the matrix, 14 from the second priority, and eight from the third priority. Table 3-9 shows the final rankings using the quantitative rating system, as well as placement on the lists provided by HFW and TxDOT. Tables 3-10 through 3-12 summarize the bridges by year built, bridge type, and owner. The following subsections contain summaries of the top seven bridges included in the final inventory.

Table 3-9. Final Bridge Rankings.

Rank / Matrix Region	Facility Carried	Feature Crossed	Total Points (Max 112)	HFW Rank	On TxDOT List
1	BU 287P (N. Main St.)	Clr. Fork Trinity River	104	1	*
2	Samuels Ave.	W. Fork Trinity River	101		
3	W. Lancaster Ave	Clr. Fork Trinity River	95	2	*
4	SH 180 WB	Sycamore Creek	94		
5	E. Exchange Ave.	Marine Creek	93		*
5	E. Vickery Blvd.	Sycamore Creek	93		*
5	SH 199 (Henderson)	Clr. Fork Trinity River	93	4	*
8	SH 199 (Henderson)	W. Fork Trinity River	91	7	*
8	SH 180 EB	Sycamore Creek	91		
10	US 377 (Belknap)	Trinity River	87	6	*
10	E. Rosedale	Sycamore Creek	87		*
10	S. University Drive SB	Clr. Fork Trinity River	87	3*	*
10	Riverside Drive SB	W. Fork Trinity River	87	8	*
10	South Main St.	BN & SF Railroad	87		*
15	East 1st St.	W. Fork Trinity River	85		*
16	SH 180 WB	Conner Ave.	84		
17	Old Denton Rd.	Henrietta Creek	83		*
17	W. Lancaster Ave.	Foch St.	83		
19	East 4th St.	W. Fork Trinity River	77	10	
19	Jennings Ave. (MH 48)	Vickery Blvd.	77		*
21	SH 180 EB	Conner Ave.	69		
21	S. University Drive NB	Clr. Fork Trinity River	69	3*	*
21	White Settlement Rd.	Spur 341	69		*
24	SH 183	Marine Creek	68		*
25	BUS 287/LP 496	Sycamore Creek	65		

Table 3-9. Continued.

Rank / Matrix Region	Facility Carried	Feature Crossed	Total Points (Max 112)	HFW Rank	On TxDOT List
26	SH 183 WB	Pumphrey Drive	63		*
26	W. Vickery Blvd.	Henderson St.	63	5	*
28	SH 183 EB	Pumphrey Drive	61		*
29	IH 35W NB	US 377/SH 121 WB	60		
30	SH 360 NB Ftg./Watson	IH-30	59		
31	NW 30th St.	Marine Creek	56		
32	Bedford Rd.	Trib. to Mtn. Creek	55		
33	Burleson-Retta	Village Creek	53		
34	Jackson Drive	Little Bear Creek	52		
34	Marlene Drive	Trib. to W. Fork Trinity	52		
36	Mayfield Rd.	Kee Branch	50		
37	Burney Rd.	Trib. to Trinity River	40		
-	Handley-Ederville Rd.	W. Fork Trinity River	-	9**	

*Northbound and southbound bridges at same location were ranked together at #3 on HFW list.

**Bridge is no longer in service or listed in the NBI database.

Table 3-10. Top 37 Bridges by Year.

Years	Number of Bridges
1910-1919	2
1920-1929	2
1930-1939	20
1940-1949	4
1950-1959	6
Post-1959	3

Table 3-11. Top 37 Bridges by Type.

Type	Number of Bridges
Concrete Tee Beam	14
Concrete Slab	6
Steel Plate Girder	4
Concrete Rigid Frame	4
Steel Truss	3
Concrete Arch (Open Spandrel)	2
Concrete Arch (Closed Spandrel)	2
Steel I-Beam	2

Table 3-12. Top 37 Bridges by Owner.

Owner	Number of Bridges
TxDOT	15
City of Fort Worth	16
City of Arlington	2
City of Colleyville	2
Tarrant County	1
City of Euless	1

3.5.1 BU 287P (North Main Street) over Clear Fork Trinity River

The bridge carrying North Main Street over the Clear Fork of the Trinity River (Figure 3-7) is the only bridge in Tarrant County listed on the NRHP. Also known as the Paddock Viaduct, the bridge was built in 1914 and was rehabilitated in 2010. It is a concrete open-spandrel arch bridge, a member type of great historical significance. The structure is 1319 feet long with a maximum span length of 225 feet and a total of 16 spans. The bridge experiences an annual average daily traffic of 13,500 vehicles.

A sufficiency rating of 33.5 (as of 2012) and historical significance rating of 1 place the bridge in the portion of the matrix considered first priority. The bridge was included on the list of 24 bridges recommended by TxDOT and ranked as the highest priority bridge in Tarrant County for maintenance and preservation by HFW. It also received a score of 104 using the quantitative rating system, the highest in the final Tarrant County inventory.

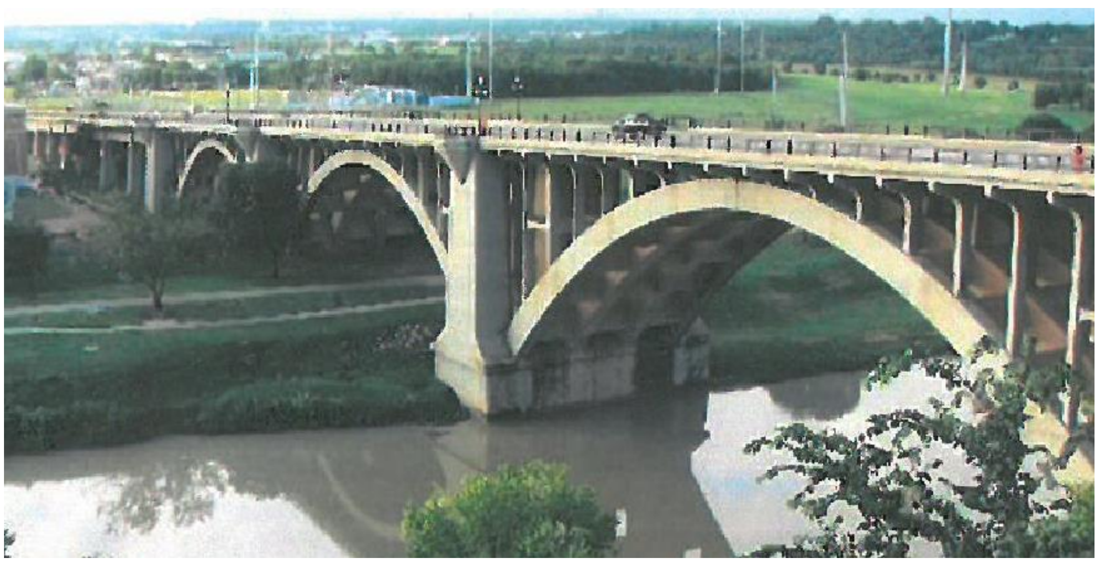


Figure 3-7. BU 287P (N. Main Street) over Clear Fork Trinity River (TxDOT 2012).

3.5.2 Samuels Avenue over West Fork Trinity River

The bridge carrying Samuels Avenue over the West Fork of the Trinity River (Figure 3-8) was built in 1914. A concrete tee-beam superstructure and Type H rails add to the historical significance. The structure is 450 feet long with a maximum span length of 50 feet and a total of nine spans. The bridge experiences an annual average daily traffic of 3990 vehicles. Several issues in the foundation were repaired in 1995.

The bridge currently has a sufficiency rating of 81.3 and a historical significance rating of 5, as listed in the National Bridge Inventory. However, the unique characteristics of the bridge make it potentially eligible for a historical significance rating of 2, placing it in the portion of the matrix considered first priority. The structure ranks second in the final Tarrant County inventory with a score of 101 using the quantitative rating system.

Figure 3-8. Samuels Avenue over West Fork Trinity River (TxDOT 2012).

3.5.3 West Lancaster Avenue over Clear Fork Trinity River

The bridge carrying West Lancaster Avenue over the Clear Fork of the Trinity River (Figure 3-9) was built in 1938. It has a continuous steel truss superstructure and specially designed rails, which add to the historical significance. The structure is 2976 feet long with a maximum span length of 133 feet and a total of 46 spans. The bridge experiences an annual average daily traffic of 12,850 vehicles. Rehabilitative actions were performed on the bearings and several steel truss members in 2009.

The bridge possesses a sufficiency rating of 80.2 and a historical significance rating of 2, as listed in the NBI database. These parameters place it in the first priority portion of the matrix. The structure was included on the list of 24 bridges recommended by TxDOT and ranked as the second highest priority bridge in Tarrant County by HFW. With a score of 95 using the quantitative rating system, the bridge ranks third in the final Tarrant County inventory.

Figure 3-9. W. Lancaster Avenue over Clear Fork Trinity River.

3.5.4 State Highway 180 Westbound over Sycamore Creek

The bridge carrying State Highway 180 Westbound over Sycamore Creek (Figure 3-10) was built in 1928. A continuous concrete tee beam superstructure and Type H rails add to the historical significance. The structure is 122 feet long with a maximum span length of 50 feet and a total of three spans. The bridge experiences an annual average daily traffic of 7050 vehicles.

The bridge currently has a sufficiency rating of 92.2 and a historical significance rating of 4, as listed in the National Bridge Inventory. These parameters place it in the portion of the matrix considered third priority, however, TxDOT recommended including it in the final rankings due to unique design characteristics. The structure ranks fourth in the final Tarrant County inventory with a score of 94 using the quantitative rating system.

Figure 3-10. SH 180 WB over Sycamore Creek (TxDOT 2012).

3.5.5 East Exchange Avenue over Marine Creek

The bridge carrying East Exchange Avenue over Marine Creek (Figure 3-11) was built in 1930. It has a concrete arch superstructure and supports buildings on East Exchange Avenue, adding to the historical and engineering significance. The structure is 83 feet long with a maximum span length of 43 feet and a total of two spans. The bridge experiences an annual average daily traffic of 1420 vehicles.

The bridge currently has a sufficiency rating of 81.3 and a historical significance rating of 4, as listed in the National Bridge Inventory. However, the unique characteristics of the bridge make it potentially eligible for a historical significance rating of 2, placing it in the portion of the matrix considered first priority. The structure was included in the list of 24 bridges recommended by TxDOT and ties for fifth in the final Tarrant County inventory with a score of 93 using the quantitative rating system.

Figure 3-11. East Exchange Avenue over Marine Creek.

3.5.6 East Vickery Boulevard over Sycamore Creek

The bridge carrying East Vickery Boulevard over Sycamore Creek (Figure 3-12) was built in 1930. It features a closed spandrel concrete arch superstructure and Type H rails, which add to the historical significance. The structure is 116 feet long and has one span with a length of 60 feet. The bridge experiences an annual average daily traffic of 4350 vehicles.

The bridge currently has a sufficiency rating of 90.4 and a historical significance rating of 3, as listed in the National Bridge Inventory. This places it in the portion of the matrix considered first priority. The structure was included in the list of 24 bridges recommended by TxDOT and ties for fifth in the final Tarrant County inventory with a score of 93 using the quantitative rating system.

Figure 3-12. E. Vickery Boulevard over Sycamore Creek (TxDOT 2012).

3.5.7 State Highway 199 (Henderson Street)

The bridge carrying State Highway 199, also known as Henderson Street, over the Clear Fork of the Trinity River (Figure 3-13) was built in 1930. An open spandrel concrete arch superstructure and Type H rails add to the historical significance of the bridge. The structure is 796 feet long with a maximum span length of 124 feet and a total of 15 spans. The bridge experiences an annual average daily traffic of 29,000 vehicles.

The bridge currently has a sufficiency rating of 57.5 and a historical significance rating of 2, as listed in the National Bridge Inventory. This places it in the portion of the matrix considered first priority. The structure was included on the list of 24 bridges recommended by TxDOT and ranked as the 4th highest priority bridge in Tarrant County for maintenance and preservation by Historic Fort Worth, Inc. Receiving a score of 93 using the quantitative rating system, the bridge ties for fifth in the final Tarrant County inventory.

Figure 3-13. State Highway 199 (Henderson Street) over Clear Fork Trinity River (TxDOT 2012).

3.6 SUMMARY

In this chapter, the process used to prioritize the historic bridge inventory of Tarrant County is presented. After preliminary eliminations to focus the inventory on potentially historic bridges, the evaluation matrix was used to further filter the inventory, and the final rankings were produced using the quantitative rating system. A takeaway to be drawn from this process is the importance of adapting the framework to fit the inventory under evaluation. The methodology used in this chapter can be applied in a similar way to other inventories of which the owning agency possesses the appropriate background and expertise to make judgments for unique or borderline cases. In the case of this study, the evaluation matrix and quantitative rating system used in previous projects were modified to better fit the inventory of this study using engineering judgment. Also, further review of several eliminated bridges showed that additional judgment may be necessary when numerical parameters are relied upon.

Once the most significant bridges in the inventory are identified and prioritized, the next step is to identify funding sources, as discussed in the following chapter.

CHAPTER IV

GUIDANCE AND FUNDING

4.1 OVERVIEW

This chapter focuses on required procedures and potential funding sources for historic bridge preservation. Section 4.2 provides an overview of the procedures and agreements that are required before a historic bridge rehabilitation project begins. These measures are in place to help ensure that the most prudent and feasible preservation option is chosen. Procedures include coordination with federal, state, and local government agencies as well as compliance with federal and state-wide requirements. Section 4.3 covers a wider picture of potential funding programs for historic bridge preservation. Because local governments have limited resources, it is important to consider federal loan and reimbursement programs as well as public-private partnerships such as performance-based contracts and Transportation Reinvestment Zones.

4.2 PROCEDURES AND AGREEMENTS

The procedures and agreements required for the repair and rehabilitation of historic bridges differ depending on whether the bridge in question is on- or off-system and whether or not federal funding will be used on the project. The following subsections discuss the process for on-system bridges and exceptions that must be made in the case of off-system bridges. Appendix F contains a flowchart from the TxDOT *Historic Bridge Manual* (TxDOT 2010) illustrating the procedures discussed.

4.2.1 On-System Bridges

For any bridge in Texas to become eligible for rehabilitation, the proposed work must be selected by the TxDOT Bridge Division to be listed in the Unified Transportation Program (UTP), TxDOT's 10-year plan for transportation-related projects (TxDOT 2012). New projects are added to the UTP each year by the TxDOT Transportation Planning and Programming Division. In general, historic bridge projects are added to the UTP under Category 6, Structures Replacement and Rehabilitation (TxDOT 2012). This criterion requires bridges to be classified as structurally deficient or functionally obsolete and to have a sufficiency rating under 80 for rehabilitation and under 50 for replacement. (These are also the requirements for FHWA funding.) Category 6 also requires all work to conform to TxDOT design standards. The provisions of Category 6 apply to proposed work on any bridge, whether it is considered historic or not.

Once a historic bridge project is added to the UTP, the Bridge Division should provide a project manager and assemble a historic bridge team, which may include representatives from the Environmental Affairs Division, TxDOT district office, local government, and FHWA (TxDOT 2010). The historic bridge team is responsible for guiding the project manager through the project development process to ensure that the most reasonable preservation option is selected. The first task of the team is to draft a purpose and need statement that focuses on the problems with a bridge without suggesting solutions. The team should then consider preservation options, seeking the most feasible option that meets minimum design standards while maintaining the historic integrity and character-defining features of the bridge. Bridges should be kept in full vehicular service if possible, but less preferable options for on-system bridges include non-vehicular use, demolition, and in rare cases, relocation. Demolition and relocation should be avoided whenever possible.

Before proceeding, the preservation option chosen by the team must receive approval from the State Historic Preservation Officer (SHPO) and Environmental Affairs Division (TxDOT 2010). The SHPO is responsible for reviewing the proposed work and the documentation of the process. If the project is found to have too many adverse effects on historic aspects, the SHPO can define what must be changed for the project to move forward. In order to comply with Section 106 of the National Preservation Act of 1966, the team must also consult local parties that may take interest in the project (US Senate 1966). This includes the chairmen of the county historical commission and the Historic Bridge Foundation, the city landmarks commission, and any other historic preservation groups in the city or county. The team is responsible for granting these groups an opportunity to give input on the historical significance of bridges and for keeping them up to date on projects if they choose to be a part of the consultation process. The district environmental coordinator, with the assistance of the historic bridge team, is responsible for coordinating the Section 106 public involvement process.

If FHWA funding will be used for the project, the chosen preservation option must also be approved by the FHWA and conform to the provisions of Section 4(f) of the USDOT Act of 1966 (TxDOT 2010, USDOT 1966). Section 4(f) states that damage to historic properties must be prevented unless no other feasible options exist. The FHWA is responsible for reviewing the documentation submitted for Section 4(f) approval. If the bridge of concern is eligible for the NRHP but no FHWA funding will be used, the Texas Antiquities Code (Texas Legislature 1977) mandates that the SHPO review and approve any actions that may disturb a historic site.

Once the most prudent and reasonable alternative has been vetted out, the Environmental Affairs Division must coordinate with the SHPO to draft a mitigation agreement, allowing letting for the project to begin.

4.2.2 Off-System Bridges

The preservation process for off-system bridges follows the same steps as that for on-system bridges, but the following exceptions exist (TxDOT 2010):

- An off-system advanced funding agreement should be made before a project manager or historic bridge team is assigned. This agreement divides financial responsibilities for the project.
- The TxDOT district may request a historic condition assessment of off-system bridges before proceeding with funding agreements. This would help the district identify needs and preservation options and allow for a more accurate estimate of the work required.
- The design standards are less strict for off-system historic bridges to remain in service, but if a bridge falls short of the standards it must be removed from

vehicular service unless a design exception can be obtained from the Bridge Division. Off-system bridges already meeting the standards may be rehabilitated to continue carrying traffic. Minimum criteria for off-system historically significant bridges are shown in Appendix G.

- Relocation is more common in the case of off-system bridges. In this case, an agreement must be made between the involved parties before letting can begin. Parties may include the state, the local government, and a third-party recipient. This agreement states the specific parties that are responsible for certain tasks involved in the preservation of a bridge, including submittal of documents, obtainment of clearances, letting, and funding of design, construction, and maintenance.

4.3 FUNDING SOURCES

The following subsections provide an overview of federal and state programs as well as private grant and partnership methods that may be considered by owners seeking funding for preservation of historic bridges. For the purpose of this study, the Tarrant County bridge inventory may be divided into three groups consisting of bridges crossing the Trinity River, downtown Fort Worth bridges crossing features other than the Trinity River, and peripheral bridges outside of the downtown Fort Worth area. Table 4-1 summarizes all funding sources. The third column of the table defines whether or not each program applies to on-system bridges, off-system bridges, or both. The fourth column depicts whether or not bridges are required to be eligible for listing on the NRHP. The three succeeding columns identify bridge groups that could be eligible for funding from each program, and the final column gives the percentage of project costs covered by the programs.

Table 4-1. Summary of Funding Sources.

Program Type	Program	On/Off-System	NRHP Eligibility Required	Downtown Bridges	Trinity River Bridges	Peripheral Bridges	Percent Federally Funded
Federal Reimbursement	STP	Both	No	Yes	Yes	Yes	80
	Transportation Enhancements	Both	Yes	Yes	Yes	Yes	80
	TIGER Grants	Both	No	Yes	Yes	Yes	80
Federal Loan	National Infrastructure Bank	Both	No	Yes	Yes	Yes	50
	TIFIA	Both	No	Yes	Yes	Yes	33
State Grant	THC Trust Fund Grants	Both	No*	Yes	Yes	Yes	N/A
Public-Private Partnership	Performance-Based Specifications	Both	No	Yes	Yes	No	N/A
	TRZs/TIRZs	Both	No	Yes	Yes	No	N/A

*NRHP eligibility not required, but structures should possess some historical significance to qualify.

4.3.1 Federal Reimbursement: Surface Transportation Program

The Surface Transportation Program (STP) is a FHWA program that provides funding for many types of transportation enhancements, including "bridge projects on any public road" (FHWA 2011). Both on- and off-system bridges can qualify for funding, but bridges must be classified as structurally deficient or functionally obsolete and have a sufficiency rating under 80 for rehabilitation or under 50 for replacement. The STP absorbed the FHWA Highway Bridge Program in 2012 (FHWA 2012). Federal funding from this program generally pays 80 percent of project costs and leaves the remaining 20 percent to be paid by state and local governments (FHWA 2011). In the case of relocation, funds only cover up to the estimated cost of demolition, leaving the remaining cost to be paid by the recipient of the bridge. The program contains no specific provision for historic bridges and does not require NRHP eligibility.

4.3.2 Federal Reimbursement: Transportation Enhancements Program

The FHWA Transportation Enhancements Program provides funding for projects that enhance surface transportation through any of 12 eligible activities, one of which is Historic Preservation (FHWA 1999). Bridges must be eligible for the NRHP (and thus have a historical significance rating of 1 or 2) in order to qualify under this provision (TxDOT 2010). Funds from the program cover up to 80 percent of project costs, leaving 20 percent to be paid by state and local governments.

4.3.3 Federal Reimbursement: National Infrastructure Investments (TIGER Discretionary Grants)

National Infrastructure Investments is a United States DOT program that offers grants for large infrastructure projects with "a significant impact on the nation, a metropolitan area, or region" (USDOT 2012). The program is also known as the TIGER (Transportation Investment Generating Economic Recovery) Discretionary Grants Program. Grants usually range from $10 million to $200 million, but can be as low as $1 million for projects located in rural areas. The eligibility requirements are similar to those of the STP, allowing for both on- and off-system bridges to be funded, provided that they are either structurally deficient or functionally obsolete and meet the sufficiency rating requirements. The program also does not require bridges to be NRHP-eligible. Funding from the program usually covers 80 percent of project costs, with local and state governments being responsible for the remaining 20 percent. Grants from this program are currently scheduled to be awarded through September of 2013 (USDOT 2012).

4.3.4 Federal Loan: National Infrastructure Bank

The National Infrastructure Bank provides long-term, low-interest loans for large-scale infrastructure projects (Compton 2011, Plumer 2011). For a project to qualify for funding, total costs must be greater than $100 million, or $25 million for rural projects. The Bank provides up to 50 percent of the loan, while the remaining portion comes from private investors or local governments. Projects are then expected to produce a method of generating revenue, such as tolls, to pay back the loan. Both on- and off-system bridges are eligible for funding through the National Infrastructure Bank, and NRHP eligibility is not required. In this particular study, all bridges requiring work may be eligible, provided that the project cost is high enough to meet minimum requirements and a repayment method is available.

4.3.5 Federal Loan: Transportation Infrastructure Finance and Innovation Act

Loans financed by the Transportation Infrastructure Finance and Innovation Act (TIFIA), an FHWA program, are similar to those from the National Infrastructure Bank. Projects with costs upwards of $50 million are eligible to receive loans and credit assistance from this program (FHWA 2012). As of September 6, 2012, the interest rate on TIFIA loans was 2.74 percent. Similar to the National Infrastructure Bank, projects funded by TIFIA are expected to generate revenue to repay the loan. Repayment terms on direct loans are flexible and can be distributed over as many as 35 years. Federal funding from TIFIA can cover up to 33 percent of project costs, and both on- and off-system bridges can qualify. Bridges are not required to be NRHP-eligible to receive funding (FHWA 2012). Similar to the National Infrastructure Bank, this program could be a funding option for any bridge with a sufficiently high project cost and a repayment method.

4.3.6 State Grant: Texas Preservation Trust Fund Grants

The THC Texas Preservation Trust Fund provides grants for projects on a much smaller scale than the programs listed above. Grants usually range from $5000 to $30,000, and totaled $515,000 on 25 projects in the year 2009 (Texas Historical Commission 2012). Both on- and off-system bridges can qualify for these grants. NRHP eligibility is not required, but bridge owners seeking grants must make a case for the historical significance of the bridge. The program has been suspended for the years 2012 and 2013 due to legislative budget cuts.

4.3.7 Public-Private Partnerships

Public-private partnerships (PPPs) represent an "umbrella" term often used to describe a project delivery method in which the public and the private sector share both the risk exposure and the potential benefits associated with the project. They can be used to deliver new facilities or to maintain and operate the facilities. In structuring PPPs, key considerations include ownership of the facility; funding and reimbursement mechanisms; control over design, construction, and maintenance; and service performance standards. Private finance initiatives (PFIs), performance-based specifications, Transportation Reinvestment Zones (TRZs) and Tax Increment Reinvestment Zones (TIRZs) are types of PPPs that could be of significance for this project. PPPs should be considered as an option for bridges located near businesses, especially in urban areas.

4.3.7.1 Private Finance Initiatives

The private finance initiative (PFI) is a PPP-based concept in which the private sector provides funding and delivers public facilities and infrastructure to meet output and performance specifications. Under a PFI, the public sector does not own the facility, but reimburses the private partner with a stream of committed payments for the use of the facility over a time period specified in the contract (Allen 2001). These payments are conditional on the ability of the private partner to meet the performance specifications, which address the strategic needs of the facility owner and occupants and focus on results rather than how the needs are met.

4.3.7.2 Performance-Based Specifications

Bridge and highway maintenance have traditionally been either performed by the owning agency or outsourced to contractors by means of job-specific contracts. Historically, in-house maintenance was the preferred method of delivering work at the beginning of the roadway network development, while outsourcing maintenance contracts became an important method of delivery with the expansion of the roadway network as agencies struggled to provide needed resources. Outsourcing maintenance contracts is currently the prevalent method of delivering maintenance work (Dlesk and Bell 2006).

As previously mentioned, early maintenance outsourcing contracts were primarily job-specific and based on the procedures to be performed, materials to be used, or a combination of both (Ozbek 2004). In such contractual settings, the contractor is limited by the prescribed procedures and material specifications. Once the project is accepted by the owner, the contractor is waived of any legal responsibility in regards to the future performance of the facility as long as the prescribed procedures and material specifications have been followed; hence, the risk associated with future performance is fully retained by the owning agency.

An alternative approach to outsourcing maintenance services is through the application of performance-based maintenance contracts (PBMCs). In contrast to the previously mentioned prescribed outsourcing contracts, PBMCs grant contractors the freedom to select construction methods, material specifications, and timing of maintenance actions under the condition that managed sections meet the performance specifications over a period of time. Hence, in PBMCs, the contractor absorbs the performance risk, rather than the agency. Reported benefits of PBMCs include flexibility for contractors to exploit advances in methods and materials without the need to renegotiate the contract terms, transfer of knowledge of innovative practices from the contractors to the agencies, and a decrease in construction time that results in a decrease in the impact of maintenance actions on commuters and freight transport.

Since the 1980s, PBMCs have become a valuable part of pavement management plans in many agencies. In 1988, highway departments in Canada began implementing performance specifications in some road maintenance contracts. Currently, all of the provincial highways in British Columbia and Alberta are maintained through contracts that are either completely performance-based or contain a combination of traditional and performance-based features. In Australia, after two successful implementations of short-term pilot contracts, Sydney highway officials let the first long-term contract in 1995. This contract had a 10-year duration period, covered 450 kilometers of urban roads, and resulted in a significant reduction in the cost of managing the network (World Bank 2006). Further, a significant increase in asset condition, reported with implementation of this contract, indicated that cost savings were not the result of cheaper designs, but due to more efficient designs and timely application of rehabilitation actions. In this case, the private sector was able to achieve savings and earn profit by managing highways more efficiently.

The results of a study by the Second Strategic Highway Research Program (SHRP 2) state that the benefits of using performance-based specifications come from solving the following four problems: inefficient budgeting in the public sector, poor quality control mechanisms, lack of innovation incentive due to the general risk-averse nature of agencies' project executives, and lack of uniformity of project objectives among stakeholders (Damnjanovic and Anderson 2009). To fully utilize the savings from inefficient budgeting and innovation, it is essential that performance-based contracts are long-term. Better budgeting efficiency and innovation cannot produce significant payoffs in a short contract period. This is also true from the perspective of the project size. Only relatively large projects can produce significant savings that can be passed to the owner. Figure 4-1 illustrates this concept. In this figure, the level of flexibility is represented as the sum of contract duration and flexibility in design and construction, two primary economic drivers in projects. As shown by the figure, the savings acquired due to flexibility are amplified by the size of projects. In other words, relative increase in savings increases as a transition occurs from small size projects to larger size projects ($S_{BC} >> S_{AB} > S_{OA}$). There also exists anecdotal evidence that the relationship is highly nonlinear, implying that larger contracts yield a greater percentage of savings. It is important to note that agencies can bundle projects together to achieve the required size. In the context of this project, performance-based specifications could provide financing to the owners, as the cost of major rehabilitation could be spread over the contract duration, which is typically longer than five years.

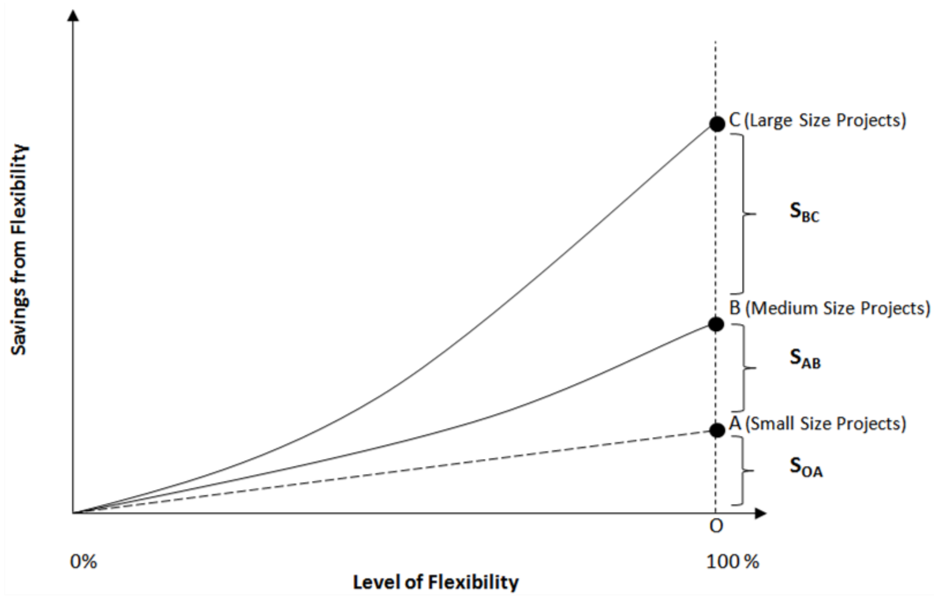


Figure 4-1. Savings from Flexibility Versus Level of Flexibility (Damnjanovic and Anderson 2009).

4.3.7.3 Transportation Reinvestment Zones and Tax Increment Reinvestment Zones

Transportation Reinvestment Zones (TRZs) and Tax Increment Reinvestment Zones (TIRZs) are similar strategies that provide funding for rehabilitation and maintenance of transportation facilities by raising the value of an area of land and collecting additional revenue due to an increased tax rate on that land (Vadali et al. 2011). Once a region is designated as a TRZ or TIRZ, a local government teams with private investors to fund improvements on the facilities in the region. The improvements cause the appraised value of the land to increase, which requires land owners to pay a higher tax rate. In some situations, the improvements also lead to increased economic activity in the area, resulting in more income tax revenue. The additional revenue from the elevated tax rate and economic activity is then used to pay back investors and fund rehabilitation and maintenance of transportation facilities in or out of the zone. Reinvestment Zones are meant to be a long-term investment and are typically set up for periods of 20 years of more.

4.4 SUMMARY

In this chapter, the topic of funding for historic bridge preservation is covered. First, the necessary steps for funding and approval of on- and off-system bridge projects are presented. Because of the number of procedures required, the proposal process should be begun by bridge-owning agencies as soon as possible, as any additional delay to actions may lead to harmful deterioration. Next, potential funding sources are listed and summarized, including federal and state reimbursement and loan programs and public-private partnerships.

CHAPTER V

CONDITION ASSESSMENT AND STRUCTURAL HEALTH MONITORING

5.1 OVERVIEW

The following sections contain a review and summary of common practices for the condition assessment and structural health monitoring of bridges. Reliable inspection and monitoring methods lead to earlier identification of problems, which leads to better planning and use of funding. Section 5.2 describes common defects found in concrete and steel elements. Sections 5.3 through 5.7 cover assessment of decks, superstructures, substructures, bearings, and waterways. These sections include overviews of routine visual inspection methods according to the *National Bridge Inspection Standards (NBIS) Bridge Inspector's Reference Manual* (Ryan et al. 2006). Because visual inspection relies on personal judgment and is subject to human error, other methods are often necessary in the assessment of bridges. This chapter also discusses advanced non-destructive evaluation (NDE) methods. For concrete elements, these methods include infrared thermography and ground-penetrating radar, and for steel elements, methods such as eddy current and ultrasonic testing are covered. Section 5.8 discusses in-situ structural health monitoring methods. These methods involve the installation of measurement devices that continuously transmit information to bridge owners regarding the structural behavior of bridges.

5.2 COMMON DEFECTS IN CONCRETE AND STEEL ELEMENTS

Tables 5-1 and 5-2 list common defects that occur in reinforced concrete and steel elements, respectively. Figures 5-1 and 5-2 illustrate examples of each defect.

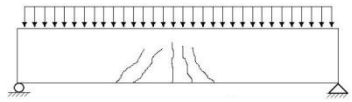
Table 5-1. Common Defects in Concrete Elements (adapted from Ryan et al. 2006).

Defect	Description
Structural Cracking [Figures 5-1(a), 5-1(b)]	• Cracking caused by flexure and shear imposed by loading • Flexural cracking occurs parallel to loading in tension zones • Shear cracking occurs diagonal to loading near supports • Normal occurrence in reinforced concrete, but becomes a concern when excessive crack widths develop
Nonstructural Cracking [Figure 5-1(c)]	• Cracking caused by nonstructural means such as temperature changes and shrinkage • Hairline cracks (less than 0.0625 in.) insignificant, larger cracks may be a cause for concern
Scaling [Figure 5-1(d)]	• Loss of cement layer from the surface of concrete • Caused by the bond between cement and aggregate being chemically broken • Can range from light (coarse aggregate slightly exposed) to severe (coarse aggregate lost)
Spalling [Figure 5-1(e)]	• Loss of surface concrete to outermost layer of steel • Can be caused by reinforcing steel corroding and thus expanding • Can also occur as a result of tension in an overloaded member • More of a concern when caused by overloading than corrosion
Delamination	• Stage of damage before spalling, caused by the same issues • Fully detached delaminated concrete is considered a spall • Usually cannot be detected visually
Efflorescence [Figure 5-1(f)]	• White surface deposit caused by calcium carbonate and other compounds being leached out of cement • Can be a sign of excessive cracking

Table 5-1. Continued.

Defect	Description
Reinforcing Steel Corrosion [Figure 5-1(g)]	• Caused by penetration of moisture and chloride ions through cracks or diffusion • Leads to loss of tensile strength and expansion of reinforcing steel • Expansion can cause cracking, spalling, and delamination • Can be detected by rust-colored stains before serious issues occur
Honeycombing [Figure 5-1(h)]	• Construction defect involving separation of coarse aggregates from cement and fine aggregates
Pop-outs [Figure 5-1(i)]	• Small cone-shaped pieces of concrete that separate from the structure due to shattered aggregates • Can be caused by expansion of aggregates exposed to moisture, reactive aggregates, and high alkali content in cement
Abrasion [Figure 5-1(j)]	• Deterioration of concrete due to outside forces such as sediments in flowing water • Occurs most often on piers and pilings
Wear [Figure 5-1(k)]	• Deterioration of concrete caused by traffic • In extreme cases, exposed aggregates can become polished and can be a safety hazard when wet
Collision Damage	• Cracking and spalling in components struck by traffic
Overload Damage	• Excessive cracking and spalling caused by overstressing of a structural element • Includes cracking and spalling in tension zones and diagonal cracking in shear zones

a) Shear Cracking (Ryan et al. 2006)



b) Flexural Cracking

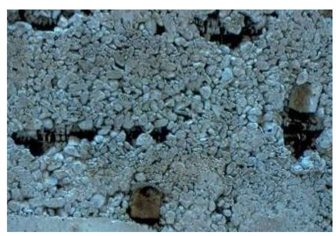
c) Shrinkage Cracking (ACI 2012)

d) Scaling (Ryan et al. 2006)

e) Spalling (Buell 2009)

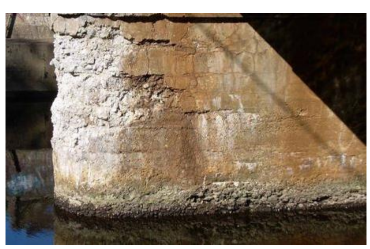
f) Efflorescence (Ryan et al. 2006)

g) Reinforcing Steel Corrosion (NASA 2012)



h) Honeycombing (ACI 2012)

i) Pop-out (ACI 2012)



j) Abrasion (Fox 2011)

k) Wear (Goodrich 2012)

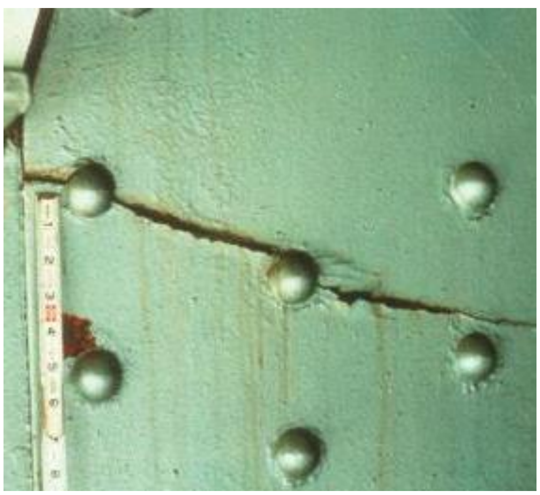
Figure 5-1. Common Defects in Concrete Elements.

Table 5-2. Common Defects in Steel Elements (adapted from Ryan et al. 2006).

Defect	Description
Corrosion [Figure 5-2(a)]	• Oxidation of steel most commonly caused by environmental means such as moisture and deicing salts • Also caused by bacteria in stagnant water, tensile stress, and vibration of tightly fitted parts • Normal occurrence in steel components, but becomes a concern when section loss occurs
Paint Failure [Figure 5-2(b)]	• Can be triggered in a variety of ways, but should be mitigated as quickly as possible to avoid corrosion and section loss
Fatigue Cracking [Figure 5-2(c)]	• Cracking caused by repeated stress below the material's yield stress • Can lead to sudden failure of members and should be carefully monitored, especially in fracture critical bridges
Overload Damage	• Plastic deformation caused by loads greater than design load • Signs include elongation and necking of tension members and bowing of compression members • Extreme cases include buckling and fracture
Distortion [Figure 5-2(d)]	• Deformation of a steel member's intended plane of bending • Caused by collision, heat exposure (at temperatures in excess of 400 ^{o}F), and out-of-plane stresses transmitted from secondary members • Can cause cracking in webs of rolled members

a) Corrosion (Ryan et al. 2006)

b) Paint Failure (Ryan et al. 2006)



c) Fatigue Cracking (Ryan et al. 2006)

d) Distortion (Kozy 2011)

Figure 5-2. Common Defects in Steel Elements.

5.3 CONDITION ASSESSMENT OF DECKS

Because historically significant bridges rarely have steel or timber decks, only cast-in-place reinforced concrete decks are discussed. Both visual and non-visual inspection techniques are effective in the condition assessment of decks.

5.3.1 NBIS Routine Inspection

All of the common concrete defects listed in Section 5.2 may be present in concrete decks (Ryan et al. 2006). More specifically, a thorough deck assessment should include checking for the following defects:

- Wheel ruts due to wear
- Ponding water, delamination, and spalling in drainage areas
- Leaking joints
- Flexure cracks at midspan on bottom of deck and above supports on top of deck
- Cracking, delamination, and spalling of overlay
- Debris, corrosion, and spalled edges in joints
- Debris in drains

Tables 5-3 and 5-4 provide descriptions of condition states of overlays and deck joints, respectively. In general, "Good" and "Fair" conditions are acceptable while "Poor" and "Failed" components require attention.

Table 5-3. Condition States of Deck Overlays (adapted from Ryan et al. 2006).

Condition State	Description
GOOD	• No signs of wear, smooth driving surface • Full protection of concrete deck
FAIR	• Minor wear, adequately smooth driving surface • Some cracking • Adequate protection of concrete deck
POOR	• Significant wear and cracking • Spalling and delamination • Moderately rough driving surface • Moisture infiltrating concrete deck
FAILED	• Significant wear, cracking, spalling, and delamination • Rough driving surface • Failure to protect concrete deck

Table 5-4. Condition States of Deck Joints (adapted from Ryan et al. 2006).

Condition State	Description of Condition
GOOD	• Expansion and contraction of superstructure uninhibited • No leakage of closed joints or clogging of open joints
FAIR	• Expansion and contraction of superstructure uninhibited • Some debris buildup • Minor leakage of closed joints
POOR	• Expansion and contraction of superstructure restricted by debris buildup • Leakage of closed joints • Clogging of open joints • Corrosion of steel joint components • Spalling of concrete edges
FAILED	• Restriction of superstructure movement threatens structural integrity • Leakage of closed joints • Clogging of open joints • Corrosion and section loss in steel joint components • Significant spalling and deterioration of concrete at edges

5.3.2 Advanced NDE Methods for Decks

Problems that cannot be easily detected by routine visual inspection may exist in bridge decks. For example, delamination or chloride contamination may exist but could be overlooked by a strictly visual inspection. However, methods exist that can detect these problems, and these methods should be put to use by agencies responsible for preserving historic bridges.

In a 2012 study at Michigan Technological University, twelve advanced NDE methods used for the condition assessment of bridges were evaluated (Vaghefi et al. 2012). Each method was rated under several criteria that measured effectiveness, availability, cost, level of traffic disruption, and ease of implementation. This study concluded that three-dimensional photography methods, light detection and ranging (LiDAR), and infrared thermography were the most effective methods for detecting defects on a deck surface, while remote acoustics, ground-penetrating radar (GPR), and other radar methods worked best for detecting problems beneath the outer surface. The following subsections cover several NDE methods.

5.3.2.1 Ground-Penetrating Radar (GPR)

GPR is a relatively simple and low-cost evaluation method that uses either air- or ground-coupled radar to scan deep images of bridge decks (Saarenketo and Scullion 2000). These images can be used to detect concrete defects such as voids, moisture, cracking, corrosion, and delamination. GPR can be used for assessment of existing concrete or for quality control when replacing concrete components. Air-coupled GPR evaluations can be performed at normal driving speeds with a vehicle carrying an antenna suspended approximately one foot above the deck surface. Ground-coupled GPR requires the antenna to be in contact with the bridge deck and must be performed at slower speeds but is capable of reaching greater depths than air-coupled systems. This method is capable of reaching up to 5 inches below the surface of the concrete (Chen et al. 2010). Other types of radar such as synthetic aperture radar have also achieved similar results.

5.3.2.2 Chain Dragging

Chain dragging is another nondestructive method used primarily to detect delamination in bridge decks (Yehia et al. 2008). Chains are hung from a bar and dragged across decks, and inspectors determine where delaminated spots are by listening for differences in the sound made by the chains. This method depends on the judgment of inspectors and because of this, can be inaccurate. The main advantage of the method is that it is simple, cheap, and requires little equipment.

5.3.2.3 Infrared Thermography

Infrared thermography uses an infrared camera to detect shallow defects in concrete decks (Stimolo 2003). Temperature differentials occur where voids and delamination are present, and this method detects the defects by locating the changes in temperature. The method can be performed by passive heating, using heat from sunlight, or active heating, which uses infrared radiation to apply heat (Maser 2004). In general, active heating is known to be more reliable but also requires more labor and time because heating of the deck must be done at a speed of approximately one foot per second. Limitations of infrared thermography are the inability to detect cracking or to reach depths greater than three inches.

5.3.2.4 Remote Acoustics

Remote acoustics refers to a class of inspection techniques that use sound waves to analyze the condition of concrete. The impact-echo method physically sends waves through concrete and measures responses to detect defects (Carino 2001). A mechanical impactor, commonly a steel ball, is used to strike the concrete surface, and a nearby receiver observes and records the response of the material. The method is capable of detecting a variety of concrete defects including voids, delamination, honeycombing, and cracking, and can reach sufficient depths to be used on any concrete element. The main drawback of the impact-echo method is that it is a slow process that only covers small surfaces at a time. Ultrasonic methods such as tomography, pulse-velocity, and pulse-echo can also be used to detect concrete defects such as cracking, honeycombing, voids, and delamination (White et al. 2012). Each of these methods use transducers to emit ultrasonic pulses into concrete and measure the pulses reflected from the material (Im et al. 2010). Ultrasonic methods usually provide images in relatively good detail but can be more time-consuming than other methods.

5.3.2.5 Three-Dimensional Photography

Three-dimensional photography methods can be used to provide images of bridge decks (Vaghefi et al. 2012). These images can be useful in analyzing surface defects such as spalls because of the ability to detect height and depth. Three-dimensional photogrammetry uses overlapping images taken by digital cameras from separate angles to form an accurate high-resolution image. The images can be taken from a moving vehicle, making it an easily implemented method. Another method known as "StreetView-style" photography (named after Google's StreetView) can also be used to obtain three-dimensional images of bridge decks. This method forms a 360^{o} image using collections of photographs and allows bridge owners to easily assess bridges in between scheduled inspections. This method also uses images taken from cameras on a moving vehicle. The main advantage of three-dimensional photography methods is that bridge owners can accurately monitor the condition of a bridge in between scheduled inspections without the need to travel to the bridge.

5.3.2.6 Light Detection and Ranging (LiDAR)

LiDAR is a remote sensing method that uses lasers to form images of surface defects (Chen et al. 2010). A transmitter sends a pulse of light to the target and a receiver captures the light reflected back. A signal processing unit then analyzes either the travel time or the phase shift of the reflected light and uses this to form a three-dimensional image and calculate the area and volume of defects. LiDAR equipment carries a high initial cost but allows for quick and easy scanning of a bridge deck.

5.4 CONDITION ASSESSMENT OF SUPERSTRUCTURES

The superstructure of a bridge consists of members directly supporting the deck. Sections 5.4.1 and 5.4.2 discuss reinforced concrete and steel superstructures, respectively.

5.4.1 Concrete Superstructures

5.4.1.1 NBIS Routine Inspection

All of the common concrete defects listed in Section 5.2 may be present in concrete superstructures (Ryan et al. 2006). More specifically, a thorough assessment should include checking for the following defects:

- Cracking, delamination, and spalling near bearings
- Transverse cracking near supports (shear zones)
- Flexure cracking, efflorescence, discoloration, spalling, and delamination near midspan (tension zones)
- Delamination, spalling, and scaling near drainage areas
- Flexure and shear cracking in secondary members (if applicable)
- Collision damage, exposed rebars, and corner spalling in areas exposed to traffic
- Previously repaired areas

Because concrete rigid frame and arch superstructures differ structurally from most concrete bridge types, several other points should be considered when assessing these types (Ryan et al. 2006). In addition to all defects and assessment points listed above and in Section 5.2, an assessment of a concrete rigid frame superstructure should include checking for the following problems (as shown in Figure 5-3):

- Diagonal cracking in legs initiated from footing
- Flexure cracking, efflorescence, discoloration, spalling, and corrosion of reinforcement in tension zones (bottom of midspan, outside corners, and inside faces of legs)

- Delamination, spalling, and scaling near compression zones (top of midspan, outside faces of legs, interior of interface between deck and legs)

An assessment of a concrete arch superstructure should include checking for the following problems:

- Loss of rebar cross-section at spalls, longitudinal cracks in arch, and horizontal cracks in columns near bearing area
- Transverse or lateral cracking near compression zones

Table 5-5 provides descriptions of condition states of concrete superstructures. In general, “Good” and “Fair” conditions are acceptable while “Poor” and “Failed” components require attention.

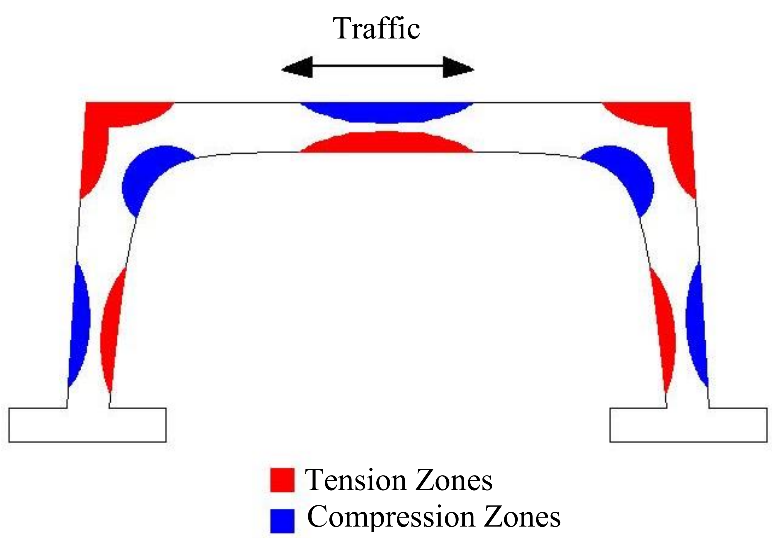


Figure 5-3. Tension and Compression Zones in Concrete Rigid Frame (adapted from Ryan et al. 2006).

Table 5-5. Condition States of Concrete Superstructures (adapted from Ryan et al. 2006).

Condition State	Description of Condition
GOOD	• Minimal cracking in shear and tension zones • No spalling, scaling, or delamination
FAIR	• Some cracking in shear and tension zones • No spalling • Some scaling and delamination
POOR	• Significant cracking; discoloration and efflorescence at cracks • Spalling, exposed rebar • Some scaling and delamination • Signs of overloading • Deterioration of concrete in drainage areas
FAILED	• Excessive cracking; discoloration and efflorescence at cracks • Major spalling, exposed rebar, section loss in rebar • Major scaling and delamination • Signs of overloading • Deterioration of concrete in drainage areas

5.4.1.2 Advanced NDE Methods for Concrete Superstructures

Many of the NDE methods used on decks (Section 5.3.2) may also be used on concrete superstructures (Vaghefi et al. 2012). LiDAR and infrared thermography can be used effectively to detect surface defects on concrete girders. Beneath the outer surface, remote acoustic methods can be used to detect defects such as voids, delamination, and cracking, and GPR and other types of radar can identify problems such as corrosion and chloride contamination.

5.4.2 Steel Superstructures

5.4.2.1 NBIS Routine Inspection

All of the common steel defects listed in Section 5.2 may be present in steel I-beam, plate girder, and truss superstructures (Ryan et al. 2006). More specifically, a thorough assessment should include checking for the following defects:

- Web cracks, section loss, buckling, corrosion of bearings, and debris buildup in bearing areas
- Section loss or web buckling near supports
- Corrosion, section loss in flanges, flexure damage to flanges, local buckling of compression flange, and failure of cover plate welds near midspan
- Loose fasteners, cracked welds, corrosion, and distortion in secondary members
- Debris buildup on horizontal surfaces (bottom flanges, diaphragm connections, gusset plates for lateral bracing)
- Cracks, section loss, and distortion in areas exposed to traffic

When assessing steel superstructures, it is important that special attention is paid to fracture critical members (TxDOT 2002). For the bridge inventory considered in this study, potentially fracture critical members include the girders of steel two-girder superstructures and tension members of trusses. Defects found in fracture critical members should be given high priority and repairs should be considered more urgent than in a structure with no fracture critical members. Cracks, broken welds, and rust in tension areas are signs of overstressing of fracture critical members and should be dealt with as quickly as possible.

Table 5-6 provides descriptions of condition states for steel superstructures. In general, “Good” and “Fair” conditions are acceptable while “Poor” and “Failed” components require attention. In the case of a distorted member (Special Case 1), repair or replacement is also required.

Table 5-6. Condition States of Steel Superstructures (adapted from Ryan et al. 2006).

Condition State	Description of Condition
GOOD	• No paint defects or corrosion • No section loss • All connections intact • No fatigue cracking
FAIR	• Some paint defects, light rust • Minor section loss in some members • All connections intact • No fatigue cracking
POOR	• Significant paint failures and corrosion • Section loss in some members • Some broken welds, bolts, or rivets • Some fatigue cracking
FAILED	• Major paint failures and corrosion • >40% section loss in some members • Broken welds, bolts, or rivets • Fatigue cracking significantly reduces capacities of members
Special Case 1	• Member is distorted

5.4.2.2 Advanced NDE Methods for Steel Superstructures

Flaws in steel elements can lead to sudden failure and are not always able to be detected by a visual inspection. Non-visual inspection methods such as eddy current, radiographic testing, ultrasonic testing, acoustic emissions testing, magnetic particle testing, and dye penetrant inspection can be used to provide further detection of flaws in steel elements and welds.

Eddy current is a relatively low-cost inspection method that uses a probe coil to locate cracks and stresses in steel elements and welds (Bader 2008). The probe induces a circular electromagnetic current in the test material and observes the impedance of the material. The current is disrupted when it meets defects and this disruption is used to locate cracks. Significant expertise is required in calibrating the frequency of the current according to the material being tested. Research on eddy current at the FHWA Non-Destructive Evaluation Center has shown the method to be effective even on materials coated with nonconductive materials, although the sensitivity decreases proportionally to the thickness of the coating (FHWA 2000). The method also showed good accuracy when the magnetic properties of the test material varied throughout a specimen

Radiographic testing is a method that has been used for crack detection in welds for decades. This method exposes the test material to radiation and forms a black and white x-ray image (Bader 2008). Cracks in the material show up as dark spots in the image and allow for subjective interpretation. It is a relatively simple method but is not capable of indicating the depth of cracks. Another drawback is the health risk that radiation exposure poses to inspectors. The required safety precautions add to the cost of the method and complicate the setup of the testing.

Ultrasonic testing has been researched and developed in recent years to serve as an alternative to radiographic testing (FHWA 2005). This method uses a transducer to send an ultrasonic pulse through the test material and a processing unit to observe and process how the pulse propagates through the material. Disturbances in the velocity of the pulse indicate the presence of cracks. A third instrument tracks and records the location of the device so that defects can be localized. After the data is processed, a three-dimensional image is formed. The main advantage of this method is the ability to measure both the length and width of cracks without requiring any human judgment. It also poses less of a health risk to operators in comparison to radiographic testing. An automated scanning system has been developed but requires a significant amount of calibration. One drawback of ultrasonic testing is that it is a slower process than other methods. The amount of equipment required for testing also makes it more difficult to set up and transport.

Acoustic emissions testing has been used to detect and locate flaws in various engineering materials, including steel, since the 1970s (Kosnik 2009). When steel members are stressed, energy is released in the form of acoustic waves (Nair and Cai 2010). These waves propagate through the test material and irregularities in the waves occur in the presence of a material flaw such as a crack. This method uses sensors placed on the material to observe the waves and thus locate cracks in steel members. Most of the complications with the method come from tuning out background noise, which requires experienced operators and often several trial test sessions.

Magnetic particle testing is a method used for detecting cracks and discontinuities in welds and steel members (Breen et al. 2010). The method sends an electric current into the material to induce a magnetic field, then applies small magnetic particles, either as a dry powder or a liquid solution. The particles line up according to the magnetic field in the material, and disturbances in the formation indicate flaws in the test material. This method is relatively fast and inexpensive and uses little equipment. It can also be used an any steel surface, painted or unpainted. The primary drawback is that it requires the judgment of an experienced operator.

Dye penetrant inspection is a simple method of detecting cracks in unpainted steel members. After the material is cleaned, dye is applied to the testing material, then wiped off (Hartle et al. 2006). Cracks retain some of the dye, allowing inspectors to locate and measure them. The main advantages of the method are affordability and simplicity. Limitations include the ability to be used only on unpainted surfaces and the requirement of pre-cleaning.

5.5 CONDITION ASSESSMENT OF SUBSTRUCTURES

Substructures consist of abutments and wingwalls at each end of a bridge, and in the case of multi-span bridges, piers or bents in between (Ryan et al. 2006). Abutments support the superstructure and retain the soil of the embankment. Wingwalls also provide support for the embankment but are only considered a part of the substructure when they are directly connected with an abutment without an expansion joint or construction joint. Piers and bents provide intermediate support for the superstructure between abutments. All bridges in the inventory under consideration have concrete substructures, therefore steel and timber substructures will not be discussed.

5.5.1 NBIS Routine Inspection

In general, the same concrete defects existing in concrete superstructures (listed in Section 5.2) may also exist in substructures (Ryan et al. 2006). The difference in substructures is that because they are in contact with soil, global movement can be an issue. In addition to the common concrete defects, a thorough condition assessment of a concrete substructure should include checking for vertical, lateral, and rotational movement, scour and undermining of the foundation, and damage to high-stress areas.

Settlement in the soil underneath a bridge can cause vertical movement of substructure elements (Ryan et al. 2006). If all abutments, piers, and bents settle approximately equally, it is usually not a serious issue. If differential settlement occurs, however, it can cause high levels of stress in the superstructure and lead to structural damage. Uneven deck joints, cracking of substructure elements, and improperly aligned railings are signs of differential settlement.

Because abutments and wingwalls are responsible for retaining the soil around a bridge, they are vulnerable to lateral earth pressure that can cause the substructure to move horizontally (Ryan et al. 2006). Piers and bents can also be susceptible to lateral movements due to scour and undermining. Lateral displacement of bearings, improper alignment of deck joints, wingwall joints, and railings, exposed footings, and unusual cracking or spalling are signs that lateral movement may have occurred in the substructure of a bridge.

Substructure elements are also susceptible to rotational movement, or tipping, due to lateral earth pressure, settlement, scour, and undermining (Ryan et al. 2006). Signs of rotational movement include improper vertical alignment of substructure elements, reduced or increased spacing between simply supported beams, exposed footings, and unusual cracking or spalling.

Table 5-7 provides descriptions of condition states of substructures. In general, "Good" and "Fair" conditions are acceptable while "Poor" and "Failed" components require attention.

Table 5-7. Condition States of Substructures (adapted from Ryan et al. 2006).

Condition State	Description of Condition
GOOD	• Minor cracking in tension zones • No spalling • No vertical, lateral, or rotational movement
FAIR	• Minor cracking in tension zones • Some delamination, no exposed rebar • Negligible movement, no differential settlement
POOR	• Significant cracking in tension zones; discoloration and efflorescence at cracks • Some spalling and delamination • Significant earth movement, some differential settlement
FAILED	• Excessive cracking in tension zones; discoloration and efflorescence at cracks • Major spalling, section loss in rebar • Earth movement and differential settlement threaten structural integrity

5.5.2 Advanced NDE Methods for Substructures

NDE methods exist for detecting concrete defects in substructures and global movement of a bridge. Several of the methods discussed as inspection methods for decks in Section 5.3.2 could also be used to inspect the concrete of substructures. LiDAR and infrared thermography could be employed to detect surface defects, and radar could be used to find problems deeper inside members. The three-dimensional photography methods discussed previously can be used on a larger scale for detection of global movement such as settlement or rotation but would require the cameras to be mounted on an aerial vehicle (Vaghefi et al. 2012).

Digital image correlation has been proven to be useful in detecting global movement of substructures. This technology detects displacements by comparing images of a structure taken at different times from the same position (Yoneyama et al. 2006). This method requires high-resolution cameras to be placed in secure locations to continuously capture images of a bridge. These images are then processed by software that can observe the displacement and rotation of certain features between images. This method avoids disruption of traffic and has been found to be useful in detecting settlement and transverse movement of bridges (Vaghefi et al. 2012).

5.6 CONDITION ASSESSMENT OF BEARINGS

Whether a bridge is supported by steel or elastomeric bearings, spalling or crushing of the concrete seat and improper alignment are two problems that may exist (Ryan et al. 2006). Regardless of the condition of the bearing itself, crushing or spalling of the concrete seat holding the bearing can be a cause of serious structural problems and should be monitored closely. Improper alignment, whether in the longitudinal or transverse direction, can also be a problem. Most bearings are designed to be centered when the exterior temperature is 68 ^{o}F, allowing for expansion or contraction caused by changes in temperature. If the sole plate (attached to superstructure) and masonry plate (attached to seat) are not properly aligned, stresses higher than certain components are designed for may be induced, leading to structural damage. In addition to a check of alignment and the condition of the concrete seat, a thorough condition assessment of steel bearings should include checking for loose fasteners, broken or cracked welds, sheared fasteners, and corrosion of steel.

In the case of elastomeric bearings, a condition assessment should include checking for excessive bulging (greater than 15% of the original thickness), splitting or tearing, and broken bonds between the bearing pad and masonry plate (Ryan et al. 2006).

Table 5-8 provides descriptions of condition states of bearings. In general, "Good" and "Fair" conditions are acceptable while "Poor" and "Failed" components require attention. The three special cases listed would also require repair or replacement.

Table 5-8. Condition States of Bearings (adapted from Ryan et al. 2006).

Condition State	Description of Condition
GOOD	• Rotation and/or translation uninhibited as designed • No corrosion or section loss • No debris buildup
FAIR	• Rotation and/or translation uninhibited as designed • Minor corrosion, no significant section loss • Some debris buildup
POOR	• Intended movement restricted by corrosion or debris • Some section loss due to corrosion
FAILED	• Intended movement restricted by corrosion or debris • Significant section loss due to corrosion
Special Case 1	• Bearings out of alignment
Special Case 2	• Concrete seat significantly deteriorated
Special Case 3	• Elastomeric material deteriorated or cracked

5.7 CONDITION ASSESSMENT OF WATERWAYS

Scour is the primary problem that occurs in waterways, and can lead to harmful changes in the stream, settlement, and most importantly, undermining of the foundation (Ryan et al. 2006). General scour degrades the channel nearly uniformly across a section along a certain length of the stream and leads to increases in the grade and velocity of the stream. Contraction scour is caused by acceleration of the stream near a contraction in the waterway. Contractions can be caused by erosion of banks, debris buildup, placement of abutments, among other factors. Local scour occurs where the stream hits an obstruction, usually a pier or abutment, and forms vortices. In general, undermining is a bigger concern in the case of spread footings than footings founded on piles. Scour poses the largest threat to bridges with shallow foundations and in channels containing fast-moving water and cohesive soils, sand, or gravel. Exposed footings, erosion, changes in stream slope, and depressions around piers are among the most common signs of scour.

Other problems that may occur in waterways include typical concrete defects, erosion, and damage to hydraulic control structures (Ryan et al. 2006). In the case of concrete piers and abutments, stream flow may cause abrasion, scaling, delamination, and spalling. These defects can reduce the strength of the structure in the same way as in other concrete elements. Erosion of embankments can also be a problem. Along with being a sign of scour, erosion can also cause the stream to shift or contract. Shifting of the stream can cause water to collide with parts of the substructure at angles for which they are not designed, leading to scour and structural damage. Contraction of the stream causes an increase in flow velocity, which causes scour. In general, it is important to note changes in the channel from one inspection to the next, such as water depth, velocity, slope, and scour depth. Significant changes in these characteristics can be a sign or a cause of other problems. Inspectors should also check for damage to hydraulic control structures such as riprap, spurs, and gabions, which are often used to prevent scour and shifting of the stream. Damage to these structures can cause the stream to migrate or flow faster than intended, leading to scour and other waterway deficiencies.

Table 5-9 provides descriptions of condition states of waterways. In general, "Good" and "Fair" conditions are acceptable while "Poor" and "Failed" components require attention.

Table 5-9. Condition States of Waterways (adapted from Ryan et al. 2006).

Condition State	Description of Condition
GOOD	• Minimal scour, no undermining of foundation • No erosion of banks • No abrasion, delamination, or spalling from flowing water • No shifting or contracting of stream
FAIR	• Some scour and undermining, no exposed footings • Minimal erosion of banks • Minimal abrasion from flowing water, no spalling or delamination • No shifting or contracting of stream • Some debris buildup
POOR	• Scour and undermining, some exposed footings • Erosion of banks • Some delamination, spalling, and loss of concrete aggregates due to flowing water • Shifting and contracting of stream resulting in increased stream velocity • Possible damage to hydraulic control structures • Some debris buildup
FAILED	• Major scour and exposed footings • Erosion of banks causing contraction of stream • Significant loss of concrete cross-section due to flowing water • Excessive spalling and rebar section loss • Possible damage to hydraulic control structures • Debris buildup causing contraction of stream

5.8 IN-SITU STRUCTURAL HEALTH MONITORING

Keeping historically significant bridges in service often requires continuous structural health monitoring that goes beyond scheduled inspections. In-situ structural health monitoring (SHM) consists of mechanisms permanently installed on bridges that continuously take measurements of properties such as acceleration, displacement, and strain at certain locations. These measurements are then processed and analyzed and can give bridge owners consistent reports on the condition of bridges in between scheduled inspections. In general, SHM detects problems globally rather than locally (Ahlborn et al. 2011). Most SHM methods are designed to detect changes in the behavior of the structure as a whole, such as vibration frequency or mode shapes. Detection of these changes shows when problems exist but does not localize them.

SHM is not required or widely used but could be instrumental in providing information that can help keep aging historic bridges in service. For certain cases, it can be the best way to detect problems early on and allow owners to mitigate them before significant damage occurs. Considering that most systems cost less than $50,000 to install, implementation of SHM is often a proactive and economical investment that saves money in the long-term (Inaudi 2010). The following subsections discuss several SHM methods that could potentially be of use in this study.

5.8.1 Wireless Sensor Networks

SHM is most commonly employed in the form of sensor networks (Ahlborn et al. 2011). Small sensors are placed at various locations on a bridge, and measurements taken at these locations are compiled to form a representation of the behavior of the entire structure. Accelerometers, fiber-optic sensors, electromechanical strain gages, and temperature sensors are the most common types of sensors used in networks. This subsection discusses wireless sensor networks, which are likely to be more practical for the purpose of this study.

Reyer et al. (2013) designed a wireless sensor network using sensors that detect magnetic field, temperature, and acceleration. This network uses individually powered and independently operating motes with attached sensor boards to extract measurements from different locations and process them into meaningful results. Each mote contains a sensor board, micro controller, radio transmission hardware, and memory storage. Figure 5-4 shows a general schematic of the system, and Figure 5-5 shows a mote and sensor board. The sensors take time-stamped measurements and send them via radio waves to an on-site base station. If the base station is within the range of the motes, measurements are sent directly (known as a level one hop). If motes are out of range of the base station, measurements must be sent to other motes in range, then from the intermediate motes to the base station (known as multi-hopping). Figure 5-4 shows a level two hop in which signals from the out-of-range motes are relayed by intermediate motes closer to the base station. Higher levels of hopping can be achieved but networks should use as few levels as possible. The base station collects the data from the sensors and transmits data files to a computer through an internet connection. The data is then processed and analyzed to form a representation of the behavior of the entire structure. The main advantage of this method is that it can be configured and modified after installation. Sensors can be moved or added at any time, making it a flexible and practical method. The primary drawbacks are energy consumption and complications related to multi-hopping and time synchronization between sensors.

In general, the wireless sensor network developed by Reyer et al. (2013) is representative of most that have been developed. Minor differences between systems exist, such as the type of sensors and data processing software used, but most networks follow the same general schematic.

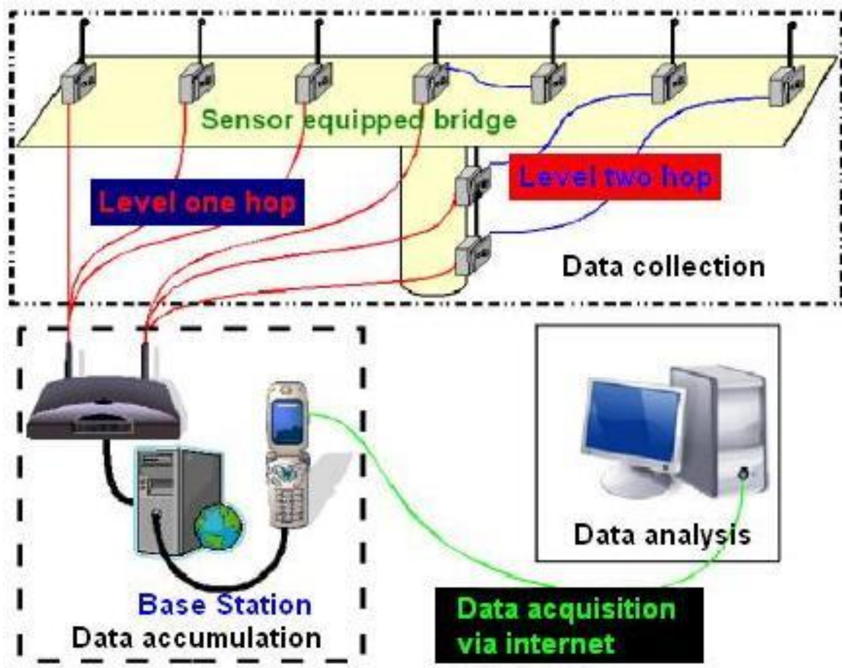


Figure 5-4. General Schematic of Wireless Sensor Network (Reyer et al. 2011).

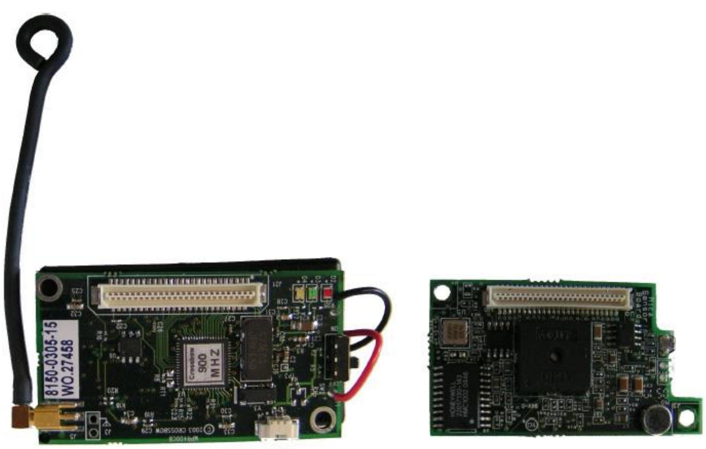


Figure 5-5. Mote (left) and Sensor Board (right) (Reyer et al. 2011).

5.8.2 Fiber-Optics

Fiber-optic wires can measure strain, displacement, and temperature by observing changes in the transmission of propagating light (Chang 2012). They are practical for use as sensors because they are suitably sensitive and have a long lifetime. Common types of fiber-optic sensors include Michelson interferometric sensors, fiber Bragg grating (FBG) sensors, and distributed sensors. Michelson interferometric sensors are small point sensors that use two coupled fibers, a reference fiber and a sensing fiber. Deformation causes a change in the length of the sensing fiber, and this change in length causes interference in the light propagated through the fibers. This interference is observed and used to measure the strain in the material. FBG sensors are also point sensors. When fibers are subjected to environmental changes such as acceleration, strain, or temperature changes, the frequency of the propagating light changes. FBG sensors detect these changes and use them to measure properties at a location such as strain, acceleration, and temperature. Arrays of FBG sensors can be used as a quasi-distributed sensor but cannot distinguish between thermal and mechanical strain. Distributed sensors consist of long fibers continuously attached to members to measure strain and temperature (Glisic and Inaudi 2010). These sensors provide measurements at every cross-section and avoid the need for algorithms to connect information from various sensors.

Glisic and Inaudi (2010) highlight the advantages of distributed sensors over point sensors and present an SHM system using distributed tape sensors. The main advantages that distributed sensors carry are easier and cheaper installation and operation than point sensors. This is mostly due to the fact that a distributed sensor requires only one connecting cable to the reading unit, while a network of point sensors requires cables from each sensor. Distributed sensors also have the ability to accurately localize strain and cracks. When installing distributed sensors, a good bond between the material and the fiber is important because slippage can cause inaccurate strain measurements. However, when cracking of the material occurs, the bond should break to avoid damage to the fiber. The SHM system presented by Glisic and Inaudi was employed on a continuous steel girder bridge built in the 1930s in Sweden. Fatigue cracking had been found in the girders and was the primary reason for the implementation of the system. The sensors consisted of polyimide coated fiber embedded in a composite tape and were available in lengths of 295 ft. This type of sensor is known to have good sensitivity to strain and cracking in relation to other available distributed sensors and cost approximately $7 per foot in 2010. Three sensors could feasibly be connected in series, so each cable had an effective length of 885 ft . The tape sensors were glued to the girders with a wider strip of aluminum tape on top, and a parallel cable was installed with each sensor to detect and compensate for temperature-induced strains. The system has the ability to detect and localize cracks and unexpected strains in girders and transmits measurements every two hours. The system can also detect malfunctions and has an expected service life of at least 15 years. Figure 5-6 shows the installation process and fully installed sensors.

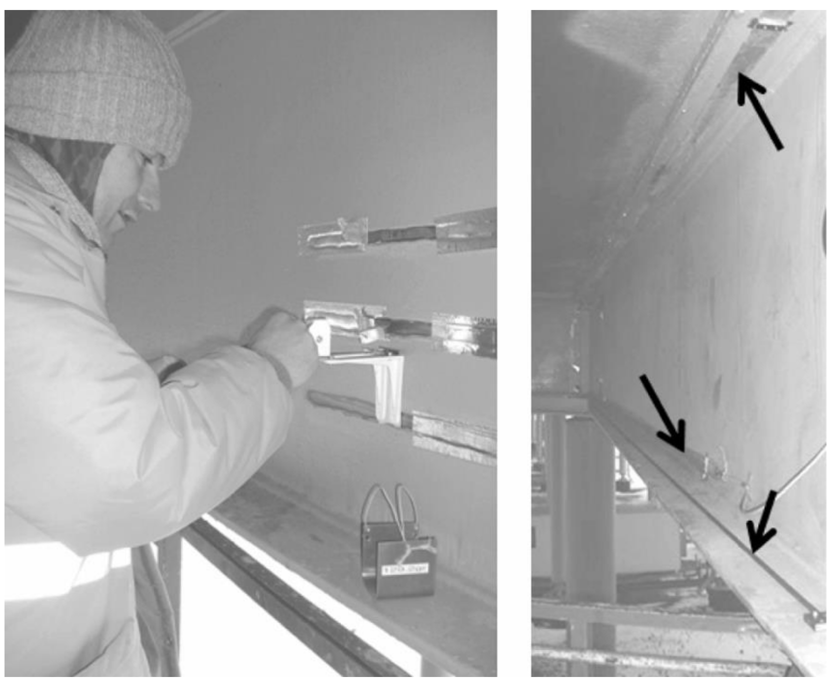


Figure 5-6. Installation of Distributed Sensors (left) and Installed Distributed Sensors (right) (Glisic and Inaudi 2010).

A 2012 study at California State University at Long Beach compared FBG point sensors and distributed sensors for measuring strain, temperature, and deformation (Chang 2012). Both sensor types were shown to have better accuracy than conventional sensors but FBG sensors significantly outperformed distributed sensors. Chang recommends an FBG sensor network and concludes that further developments should be made in distributed sensors before they are widely used in the field. In the proposed FBG sensor network, strategically placed sensors would transmit signals to a nearby optical node. The optical node collects the measurements and transmits the data to a computer for processing and analysis. Figure 5-7 shows a general schematic of the network.

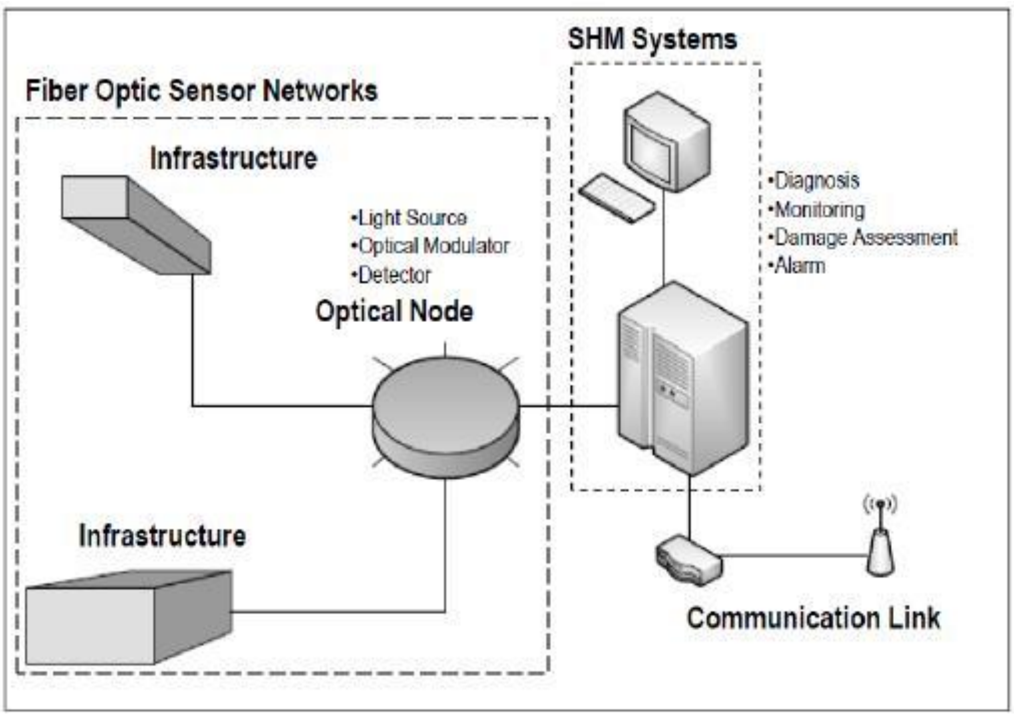


Figure 5-7. General Schematic of a FBG Sensor Network (Chang 2012).

5.8.3 Global Positioning Systems (GPS)

GPS technology has become increasingly reliable for SHM purposes in recent years (Ahlborn 2011). In general, GPS-based SHM methods are best suited for measuring long-term absolute displacements, such as global movements of bridges caused by earth movements. GPS receivers are placed at target points on a structure, and the displacements of these points are monitored and compared with nearby stationary reference points. Some GPS methods have achieved accuracy within a few millimeters. Meng et al. (2007) recommend an SHM system that combines GPS with accelerometers. This system utilizes two measurement types in an attempt to mask the deficiencies of each method and showed good accuracy compared to a finite element model. Accurate measurements of vertical and horizontal displacements on a suspension bridge in Tampa Bay, Florida were achieved by placing GPS receivers at the tops of the two towers and at the center of the main span (Schenewerk et al. 2006).

5.9 SUMMARY

This chapter reviews and summarizes methods used for the condition assessment and structural health monitoring of historic bridges. In most bridges of old age, deterioration occurs at an accelerated rate, making inspection a vital element of the preservation process. In many cases, advanced non-destructive evaluation and long-term structural health monitoring may be necessary in addition to regularly scheduled visual inspections. These methods can help bridge owners preserve bridges by detecting defects early on, including those that exist beneath the surface and go unnoticed by visual inspection. Once problems are identified by condition assessment methods, mitigation strategies should be considered, as covered by the next chapter.

CHAPTER VI

MITIGATION STRATEGIES

6.1 OVERVIEW

One of the primary objectives of this project is to help bridge-owning agencies prevent the replacement of historic bridges by recommending feasible methods of preservation. Bridge preservation consists of rehabilitation, repair, and maintenance. This includes both regularly scheduled and condition-based actions. In most cases preventative maintenance is the more cost-effective way to preserve bridges (FHWA 2011). This chapter provides an overview of methods used to mitigate and prevent problems commonly seen in bridges. First, the issue of historic integrity is discussed, including an overview of legislation requiring consideration of historic aspects during rehabilitation. The next section covers regular-interval maintenance that should be performed at a consistent frequency rather than when bridge elements reach certain condition states. Next, rehabilitation, repair, and maintenance of reinforced concrete elements are covered. This includes methods for mitigating common concrete defects such as corrosion of reinforcing steel, section loss, and cracking. The next section presents methods used on steel elements, including techniques for corrosion prevention, deformation repair, fracture repair, and structural strengthening. Methods used on bearings, decks, and waterways are also discussed. Tables 6-1 through 6-5 summarize methods used for rehabilitation, repair, and maintenance of concrete elements, steel elements, bearings, decks, and waterways.

It should be noted that the purpose of this chapter is to familiarize the reader with common practices and available options. Further research should be conducted and licensed engineers consulted before employing any of the methods discussed in the following sections.

Table 6-1. Summary of Rehabilitation and Maintenance of Reinforced Concrete Elements.

Problem(s)	Mitigation / Preventive Measures	Section(s)
Corrosion of Reinforcing Steel	Manual Removal	6.4.1
	Cathodic Protection - Galvanic - Impressed	6.4.8.1
	Chloride Elimination Methods - Electrochemical Chloride Extraction - Electrochemical Alkalization - Zinc Anode - Hydrophobic Impregnation - Polymer Impregnation	6.4.8.2
	Surface Treatments	6.4.9
Spalling Delamination Scaling Honeycombs Collision Damage Pop-outs	Patching	6.4.2, 6.4.3
	Jacketing	6.4.7
Structural Cracking	Interior Reinforcement	6.3.4, 6.4.6
	Exterior Reinforcement	
	Drilling and Plugging	
Non-Structural Cracking	Drypacking	6.4.5
	Gravity Soak	
	Shotcrete	
	Epoxy Injection	
	Routing and Sealing	
	Patching	6.4.2, 6.4.3
	Jacketing	6.4.7
Efflorescence	Manual Removal	6.4.10

Table 6-2. Summary of Rehabilitation and Maintenance of Steel Elements.

Problem(s)	Mitigation / Preventive Measures	Section
Corrosion	Manual Removal - Mechanical - Chemical - Heat	6.5.1
	Paint / Coating	
Distortion	Flame Straightening	6.5.2
	Mechanical Repair	
Inadequate Structural Strength	Enlargement or Strengthening of Existing Members	6.5.3
	Addition of Members	
	Post-tensioning	
	Adjustment of Supports	
	Shear Connectors	
	Replacement of Members	6.5.4
Cracking	Mechanical Methods	6.5.5
	Welding	6.5.5

Table 6-3. Summary of Rehabilitation and Maintenance of Bearings.

Problem(s)	Mitigation / Preventive Measures	Section(s)
Corrosion	Clean and Paint	6.6
Frozen Bearings	Regular Lubrication	6.6
Misalignment	Jack Structure and Realign	6.6
Deterioration of Concrete Seat	Jack Structure and Patch	6.6, 6.4.2
Significant Section Loss (Steel Bearings) Broken Seals (Pot Bearings) Cracked Pad (Elastomeric Bearings) Damaged Sliding Surface	Jack Structure and Replace	6.6

Table 6-4. Summary of Rehabilitation and Maintenance of Decks.

Problem(s)	Mitigation / Preventive Measures	Section(s)
Cracks in Overlay	Apply Waterproof Sealant	6.7
Spalling Delamination Scaling Honeycombs Pop-outs	Patching	6.4.2, 6.4.3
Rough Driving Surface Excessive Moisture Penetration	Replace Overlay and/or Waterproof Membrane	6.7
Leaks in Closed Joints	Apply Waterproof Sealant	6.7
Lack of Drainage in Open Joints	Remove Debris	6.7
Excessive Damage to Joints	Replace Joints	6.7

Table 6-5. Summary of Rehabilitation and Maintenance of Waterways.

Problem(s)	Mitigation / Preventive Measures	Section
Scour Erosion Contraction or Shifting of Stream	Riprap	6.8
	Gabions	
	Spurs and Vanes	
	Slots	
	Collars	

6.2 ATTENTION TO HISTORIC INTEGRITY

Careful attention should be paid to preserving the historic integrity and character-defining features of bridges when considering rehabilitation and repair methods. Although safety and adequacy are always the most important factors to be considered when making decisions regarding bridge rehabilitation, historic integrity should be preserved whenever possible. Work performed should not alter the character-defining features of a bridge unless it can be determined that no other feasible alternatives can bring the bridge to an acceptable condition. Several legislative items encourage or require attention to historic integrity. According to Section 4(f) of the United States Department of Transportation Act of 1966, all projects on historic sites must be planned so that they "minimize harm to the property" in order to qualify for federal funding (USDOT 1966). Section 106 of the National Historic Preservation Act of 1966 states that in projects dealing with structures eligible for the NRHP, all proposed work must be approved by the State Historic Preservation Officer and that the entity proposing alterations must show that no alternative solutions are feasible (US Senate 1966).

6.3 REGULAR INTERVAL MAINTENANCE

Some maintenance actions should be performed at regular intervals regardless of the condition of the bridge. These actions can lengthen the service life of a bridge while also saving money for the bridge-owning agency over time. Studies have shown that bridge maintenance is less expensive for bridges in good condition than for bridges in poor condition (Rossow 2011). Therefore, it is economically beneficial to perform routine maintenance regularly in order to keep a bridge in the best condition possible.

Deck drains should be cleaned frequently because they are designed to direct the flow of water from the deck away from other members. If drains are clogged, unwanted drainage may occur in other areas and cause deterioration in superstructure or substructure members. Deck joints should be maintained because they allow the bridge to expand and contract without causing structural damage and in some cases, act as a drainage route. Cracks in the deck or overlay should be sealed to prevent moisture and chemicals from penetrating and damaging the concrete. The deck surface should be cleaned and sealed periodically because infiltration of water and chlorides can lead to serious deterioration. Bearings should be kept clear of debris and properly lubricated in order to allow for free expansion and contraction. Areas of spot rust on steel members should be cleaned before they develop into further corrosion and section loss. Horizontal surfaces in the superstructure and substructure should be kept clear, especially in the case of steel members, because debris often holds moisture. Debris should also be removed from waterways because it can cause irregular stream flow, which can lead to scour.

Table 6-6 shows recommended intervals for several routine maintenance actions. These recommendations are made using engineering judgment based on a review of several FHWA publications. The recommended intervals are generally conservative but in the case of historic bridges, aggressive maintenance is often necessary.

Table 6-6. Regular Interval Maintenance Actions (Rossow 2011, FHWA 2011).

Action	Frequency
Remove debris from deck drains	6 months
Remove debris from deck joints	6 months
Seal cracks in deck or overlay	12 months
Repair loose connections in deck joints	12 months
Pressure wash deck	12 months
Apply waterproof sealant on deck after cleaning	36 months
Clean and lubricate bearings	24 months
Remove spot rust and repaint affected areas on steel members	36 months
Remove debris from superstructure and abutments	12 months
Remove debris from waterway	24 months

6.4 MITIGATION STRATEGIES FOR REINFORCED CONCRETE ELEMENTS

The following subsections provide an overview of available rehabilitation, repair, and maintenance techniques for reinforced concrete elements.

6.4.1 Concrete Removal

Removal of concrete is often required when repairing or rehabilitating concrete bridge elements but should be done only where absolutely necessary when dealing with historic structures. Concrete is most commonly removed by a powerful water stream, known as hydrodemolition (Lachemi et al. 2007). This process in known to be the fastest and easiest to perform and causes the least unwanted damage. Concrete may also be removed by jackhammer or saw.

6.4.2 Patching

Concrete patching is usually used as a temporary repair method. For small repairs, mortar is often used, while concrete is used when larger portions are needed (Radomski 2002). In order to preserve the historic integrity of a bridge, repair material should match the color of the existing material and should be as inconspicuous as possible. For compatibility reasons, the patching material should have similar properties to the existing material, such as shrinkage effects and thermal expansion characteristics. It is also advisable to choose a material with a low chloride concentration, as chloride ions from the patching material can contaminate the existing concrete and cause corrosion in the reinforcing steel.

In addition to traditional cement-based mortar or concrete, polymer cement concrete, polymer concrete, non-shrink mortar, and epoxy mortar may be used as patching materials. Polymer cement concrete is slightly more expensive than regular cement-based concrete, but has been proven to be a high-strength alternative with high resistance to environmental effects and better bonding abilities (ACI 2008). Polymer concrete contains resin-based binding materials and carries the same advantages as polymer cement concrete, but is also more expensive. Non-shrink mortar is used where quick setting is required (such as deck joints) and is useful for shrinkage cracks and spalls (Xanthakos 1996). Epoxy mortar contains epoxy resin and is known to have high strength, good bonding characteristics, and high resistance to environmental effects, impact, and abrasion.

6.4.3 Repair of Spalling and Delamination

Spalled and delaminated areas may be repaired by hand with mortar (Ball 2005). Patching methods covered in the previous subsection should be followed. In the case of delamination, it is recommended that the affected area be cut out short of the first layer of reinforcement, then patched with mortar. In the case of spalling, the exposed steel is usually corroded, so all concrete around the exposed bars must be removed. After all corrosion is removed from the affected area, the mortar is applied. Vibration may be used to ensure that all spaces between the reinforcement layers are filled. A hand trowel is then used to smooth the patch. As mentioned in the previous subsection, the chosen repair material should match the visual and material properties of the existing material as much as possible in order to preserve historic and structural integrity.

6.4.4 Repair of Structural Cracking

Cracking can reduce the flexural, shear, torsional, and axial capacities of concrete elements, making crack repair an important aspect of bridge rehabilitation (ACI 1996). Structural cracking is caused by flexure and shear and is to be expected in reinforced concrete. Excessive cracking can be caused by overloading and other structural flaws. The most common ways of repairing cracks in reinforced concrete are interior and exterior reinforcement. Interior reinforcement is installed by drilling a hole perpendicular to a crack and inserting a reinforcing dowel held in place by a bonding agent. Dowels are usually stainless or galvanized steel and sometimes coated in epoxy mortar. The length of the dowel being used should depend on the required strength of the bond. Figures 6-1(a)-(d) show various uses of interior reinforcement.

Exterior reinforcement can be used in several ways. Steel plates can be applied across shear or flexural cracks as shown in Figure 6-2(a) (ACI 2007). Tension ties can be anchored on opposite sides of a crack as in Figure 6-2(b) and (c), applying a compressive force that holds the crack together and post-tensions the member. Near-surface reinforcing, or pinning, involves cutting a slot into the surface of the concrete perpendicular to a crack and placing a reinforcing bar with a bonding agent in the slot to act as additional tensile reinforcement. Exterior reinforcement can also be applied as shown in Figure 6-3(d). When rehabilitating historic bridges, exterior reinforcement should be used sparingly due to its potential to detract from the visual appearance of bridges.

Polymer impregnation can also be used to repair cracks (ACI 2007). When a low-viscosity monomer is injected into a crack, it is eventually polymerized and becomes a solid which can adequately repair cracks.

Another method of crack repair is drilling and plugging (ACI 2007). Figure 6-3 shows an example of drilling and plugging in a retaining wall. This technique uses grout inserted into a drilled hole along the length of the crack. It is most effective on cracks that are in a relatively straight line.

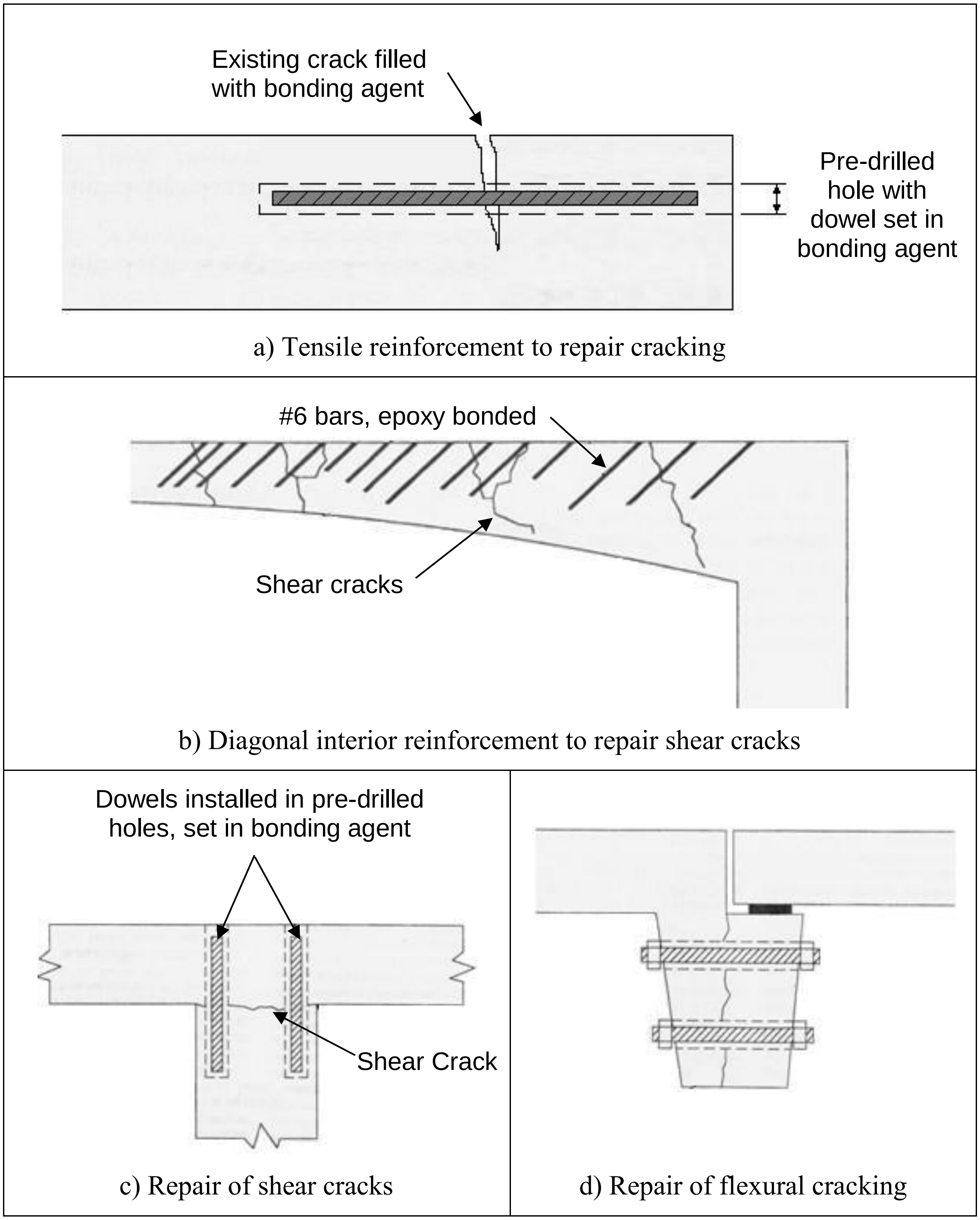


Figure 6-1. Uses of Interior Reinforcement (adapted from ACI 1996).

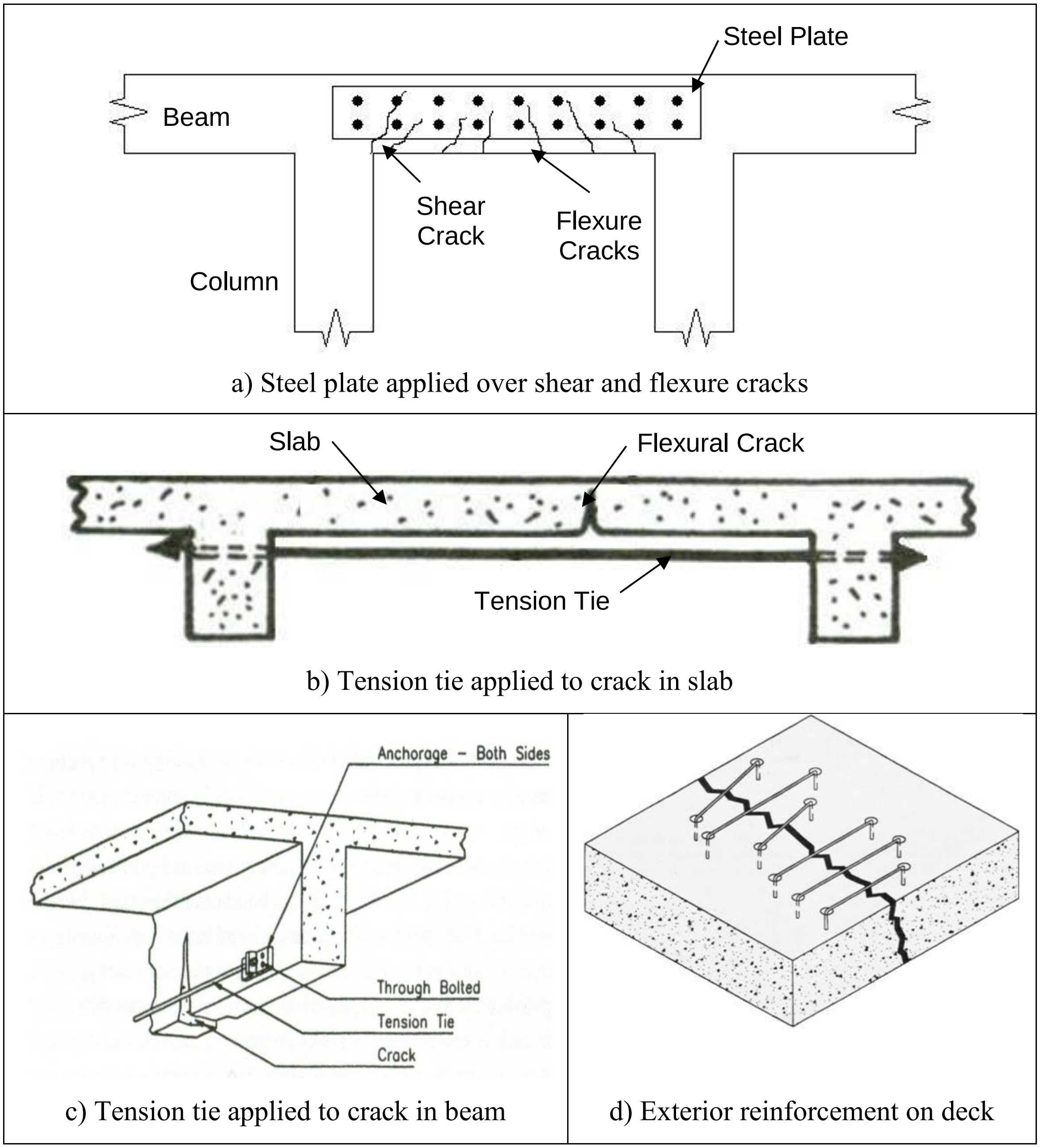


Figure 6-2. Uses of Exterior Reinforcement (adapted from ACI 1996).

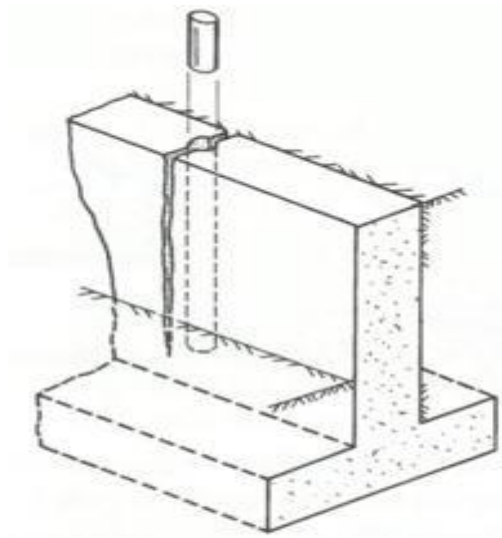


Figure 6-3. Drilling and Plugging a Crack in a Retaining Wall (ACI 2007).

6.4.5 Repair of Non-Structural Cracking

When repairing cracks caused by non-structural means such as shrinkage and temperature changes rather than by structural means, different methods are used. One method of repairing non-structural cracks is drypacking (Woodson 2009). This method uses mortar with a low water content and is useful for deep and narrow cracks. Another method, the gravity soak, uses a liquid monomer to keep moisture from entering small cracks. The solution is poured over the affected area, usually a bridge deck. Epoxy injection has also been proven to be a successful method of non-structural crack repair (ACI 2007). This technique consists of inserting an epoxy sealant into intermittently spaced entry points drilled into cracks. Non-structural cracks can also be patched with Portland cement grout or chemical grout. Grouting has been successful in keeping moisture out of cracks but adds little structural strength. Low-slump shotcrete is another commonly used method for repairing small cracks (Grantham 2011). It is especially useful for vertical and overhead surfaces due to its ability to remain suspended after application.

6.4.6 Addition of Reinforcement

In the case that reinforcement must be replaced or added, several types of bars exist as alternatives to traditional carbon steel. Stainless and galvanized steel bars are more expensive than traditional steel but also provide better resistance to corrosion, and therefore last longer (Bertolini et al. 2004). Epoxy coated bars are less expensive than stainless or galvanized steel but do not provide the same level of protection from corrosion.

6.4.7 Jacketing

For concrete piers and bents damaged by cracking, spalling, delamination, and abrasion, jacketing can be an effective rehabilitation technique. Steel, concrete, and fiber-reinforced polymers have all been used effectively as jacketing material (Endeshaw et al. 2008). Both rectangular and circular columns can be jacketed, as shown by the example of steel jacketing in Figure 6-4. Jacketing has been shown to improve concrete confinement and thus increase the shear and flexural strength of columns (Itani and Liao 2003). Historic integrity is a concern when using this method, especially in the case of covering rectangular members with round jackets.

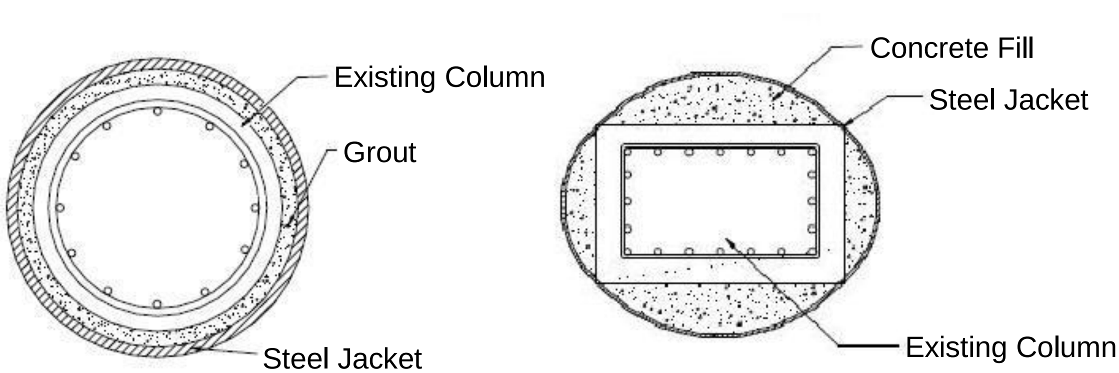


Figure 6-4. Steel Jacketing of Circular and Rectangular Columns (Itani and Liao 2003).

6.4.8 Repair and Prevention of Reinforcing Steel Corrosion

Corrosion reduces the capacity and cross-section of reinforcing steel while also causing expansion that may lead to spalling and cracking of concrete (Brinckerhoff 1993). The manual removal process requires all surrounding concrete to be removed from potentially corroded steel, then cleaning of the steel. The steel may then be coated to increase the cross-section, then the removed concrete is replaced. The following subsections cover corrosion prevention methods.

6.4.8.1 Cathodic Protection

In a naturally occurring chemical process known as the anodic reaction, reinforcing steel loses electrons, and after several other reactions, corrosion is formed (Broomfield 2007). In another naturally occurring process, the cathodic reaction, hydroxide ions are formed near the surface of the steel. These ions protect the steel from corrosion. Depending on the chemical environment of the concrete, one of these reactions may be favored.

The objective of cathodic protection is to prevent corrosion by inducing an electric field which promotes the cathodic reaction and deters the anodic reaction (Sohanghpurwala 2009). Cathodic protection systems are permanently installed in bridges, some embedded in repair material and some externally. Impressed cathodic protection systems externally apply an electric current through the reinforcing steel through an anode connected to the bridge, while galvanic systems impose an electric field by placing a material of higher electronegative potential than steel (usually zinc) near the steel. The difference in potentials causes an electric current that flows from the anode material to the steel. In the case of historic bridges, cathodic protection systems should be installed in discrete locations that do not detract from the visual qualities of bridges.

6.4.8.2 Chloride Elimination Methods

One important step in preventing corrosion is to eliminate chloride ions from concrete before they reach the first layer of reinforcing steel (Bertolini et al. 2004). One available method of chloride elimination is a localized cathodic protection system using an anode covered with mortar and lithium hydroxide. After removing all of the corrosion from the area of application, the anode is placed so that it is directly in contact with the steel. The steel may also be covered with a layer of mortar or chemical coating to resist chlorides before placement of the anode.

Electrochemical methods can also be used to eliminate chloride contamination. Electrochemical chloride extraction uses a titanium or steel mesh as an anode, temporarily placed on top of a layer of concrete (Bertolini et al. 2004, Polder and Hondel 2002). After a calcium hydroxide solution is applied to the mesh, an electric current is induced. As the current flows between the anode and the reinforcing steel, chloride ions are removed from the steel while hydroxide ions, which help prevent corrosion, are developed at the surface of the steel. Electrochemical re-alkalization uses different chemical processes, but works similarly to extraction (Odden 1994).

Overlays are commonly used to physically prevent chloride infiltration on bridge decks (Broomfield 2007). This is an effective method, especially in regions of less traffic and in warm climates where the use of deicing salts is not prevalent. Varieties of overlays include waterproof membranes and several different types of concrete overlays. Waterproof membranes have been shown to be effective in keeping chloride ions out of concrete, but blistering can be an issue when the membrane is exposed to changes of temperature and atmospheric pressure (ACI 2001). Types of concrete used in overlays include polymer, silica fume-modified, Portland cement, and latex-modified concrete.

Another way that chloride removal and prevention can be achieved is through impregnation methods. When executed correctly, impregnation makes concrete less permeable and more durable. Hydrophobic impregnation involves application of a water repellent solution consisting of various silicates at the surface of the concrete (BRE Centre for Concrete Construction 2000). The solution penetrates the concrete and can reduce the number of chloride ions present. Polymer impregnation is a multi-step process that can prevent chloride contamination (ACI 2001). The first step of this process is to remove all air and water from the voids in the concrete. The next step is to saturate the voids with monomers, which then transform into solid polymers. Figure 6-5 shows the steps of the polymer impregnation process. Application of surface treatments can also prevent chloride infiltration (in addition to other functions), and is discussed further in the following section.

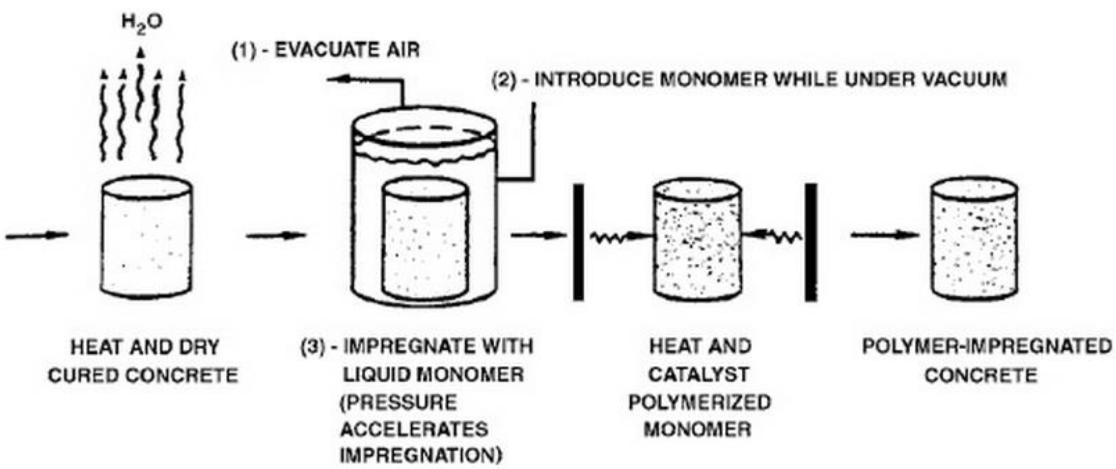


Figure 6-5. Polymer Impregnation Process (ACI 2009).

6.4.9 Surface Treatments

In general, surface treatments are applied to concrete to act as a barrier to protect against moisture and aggressive agents such as chlorides and acids (The Concrete Society 1997). This can slow and prevent deterioration and abrasion of concrete as well as corrosion of reinforcing steel. Some surface treatments penetrate the pores in the surface of concrete, while others block the pores or seal the entire surface. This section gives an overview of the many available types of surface treatments.

Pore-lining treatments include silicon-based penetrants, stearates, and drying oils (The Concrete Society 1997). These substances provide a water-resistant film inside the pores of concrete and, in general, are effective in preventing moisture infiltration but ineffective against chloride ions. Advantages of pore-lining treatments include their inconspicuous nature, as they are usually colorless, and ease of use, as they require minimal surface preparation prior to application. Stearates and drying oils are effective for up to five years and silicon-based penetrants can remain effective for up to 20 years, but it is recommended that all pore-lining treatments be re-applied every four to five years.

Pore-blocking sealers protect concrete by blocking pores from the outside (The Concrete Society 1997). Sealers such as silicates and silicoflourides react with concrete to form a pore-blocking substance, and others such as acrylics, epoxies, and polyurethanes physically block the pores. These substances usually provide protection against moisture, chemical attack, and abrasion. Like pore-lining treatments, pore-blocking sealers are usually colorless and require little or no surface preparation.

Surface coatings include cementitious materials, thermoplastics, rubbers, bituminous materials, and thermosetting polymers (The Concrete Society 1997). These coatings are more effective in protecting concrete than pore-lining or pore-blocking treatments but can be more expensive and difficult to apply, and are not always colorless. Surface preparation required before application of surface coatings usually includes leveling, smoothing, and priming.

6.4.10 Removal of Efflorescence

Efflorescence is prevented by eliminating moisture from concrete. Savage (2007) recommends removing efflorescence with a wire brush, then using a pressure washer to rinse the surface. If efflorescence still exists, diluted vinegar may be used to chemically remove the remains.

6.5 MITIGATION STRATEGIES FOR STEEL ELEMENTS

Most damage to steel bridge elements can be classified as corrosion, fatigue damage, or mechanical fracture (Radomski 2002). Certain preventive maintenance methods should be performed regularly, but some damage cannot be prevented. When steel elements become deteriorated or damaged, problems should be identified according to Chapter V with special attention given to fracture critical members, then repair methods considered. The following sections discuss various methods for rehabilitation, repair, and maintenance of steel elements.

6.5.1 Removal and Prevention of Corrosion

Corrosion is the most common cause of problems in steel bridges (Brinckerhoff 1993). Due to exposure to oxygen and moisture, all steel bridge elements are susceptible to corrosion, but it can be slowed or prevented. Removal of corrosion should always precede any other repairs. This can be done by hand, heat, chemical methods, or blasting. For small areas, manual removal methods such as brushing and scraping are the most practical but in most cases, blasting has been proven to be the most efficient method. Flame cleaning can also be used, but can cause damage to thin elements. Inorganic acids such as phosphoric acid have also been used, most commonly on smaller areas (Radomski 2002). When removing paint from old bridges, it should be noted that the paint may contain lead, making containment and disposal of waste important measures to be implemented (Chong and Yao 2007).

Painting is the primary method of corrosion prevention. In order to preserve historic integrity, any paint applied to a structure should match the original color as closely as possible. When applying paint to steel elements, preparation of the surface is an important operation because it affects the durability of the new coat (Brinckerhoff 1993). All existing corrosion and the previous coating should first be removed. After surface cleaning, the steel is usually covered first with a prime coating and a finish coating (Xanthakos 1996). Typical prime coatings are classified as either inhibitive or galvanic (also known as sacrificial) primers. Inhibitive primers chemically and mechanically protect steel from moisture and oxygen, while galvanic primers contain a material of lower electronegative potential than steel (usually zinc) that becomes an anode and creates an electric field that helps to prevent corrosion. Finish coatings keep out water, oxygen, and harmful ions, and can be metallic (inorganic) or non-metallic (organic). Non-metallic coatings include paints, lacquers, tar, and epoxy. For small areas, these coatings should be applied by hand because this achieves the best bond, but spraying is the most commonly used method. Metallic coatings include cathodic materials such as copper, nickel, and lead, and anodic materials such as zinc, cadmium, and aluminum. Anodic materials are more commonly used because they do not require a complete seal in order to be effective. Specific types of anticorrosion coatings are so numerous that it would be impractical to discuss all of them within this thesis, but a choice of coating application method should be made based on a number of factors including environmental conditions, coverage area, and budget (Radomski 2002).

6.5.2 Repair of Deformed Members

When steel members become plastically deformed beyond acceptable levels but replacement is not necessary, repairs can be made mechanically or thermally (Radomski 2002). When choosing a repair method, the strength and other properties of a member should be taken into consideration. For example, if a member is made of weldable steel, flame straightening is recommended. As with any repairs, any corrosion found on the deformed member should be removed before repairing the deformation and the member should be coated after the deformation is repaired. Regardless of which repair method is used, it should be noted that the yield point of the member will be reduced after repairs. Because of this, a thorough structural analysis should be performed beforehand to ensure that the weakened member will be adequate in carrying the design load after being repaired.

Mechanical repair is the most common method used for straightening deformed steel members (Radomski 2002). In small members, hand tools such as hammers are used, while larger members require jacks, winches, and hydraulics. In most cases, mechanical repair is aided by heat applied with an oxy-acetylene torch. All forces should be applied nearly statically to avoid impact and sustained for at least 15 minutes. Figure 6-6 shows the straightening of a deformed truss member using a support beam and hydraulic jack, and Figure 6-7 shows a tie anchored at a joint to straighten a truss member.

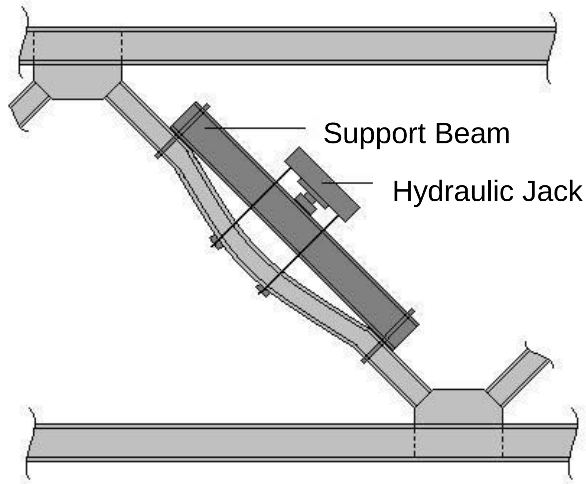


Figure 6-6. Straightening with Hydraulic Jack and Support Beam (adapted from Radomski 2002).

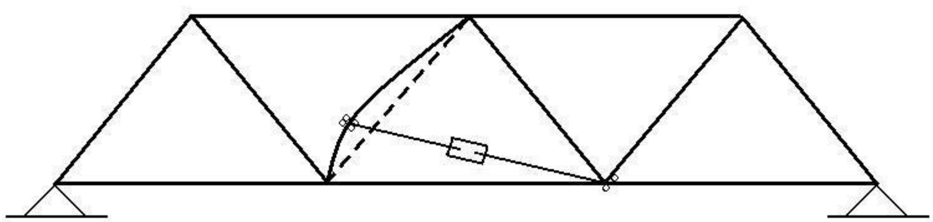


Figure 6-7. Straightening with Tie (adapted from Radomski 2002).

Repairing a deformed member using only heat is not as common as mechanical straightening but can be an economically advantageous method in some situations (Connor et al. 2008). An oxy-acetylene torch is used to heat the affected area until thermal plastic deformation occurs, then the member straightens. This method is most effective in steel with a low carbon content and requires experienced technicians due to its delicate nature (Radomski 2002). Heat straightening should not be used on fracture critical members or at the same location more than twice, as repeated heating can cause a decrease in fatigue life (Thiel et al. 2001, Connor et al. 2008).

6.5.3 Strengthening of Steel Structures

In general, strengthening of a steel structure consists of either enlarging existing members, installing additional members, external post-tensioning, changing the support system, or a combination of these methods. It should be noted that a redistribution of forces will occur after strengthening methods are performed on a structure (Radomski 2002). Before execution of these methods, a structural analysis should be performed to ensure that all members have adequate strength to withstand the redistributed forces. Another matter to be considered prior to strengthening is jacking the structure to release dead load deformation. If work is performed without jacking, the rehabilitation will only carry live loads (Xanthakos 1996). It is also recommended that any steel added to the structure have similar properties to the existing steel. When the electronegativity of the repair steel is much higher or lower than that of the existing steel, corrosion can occur (Brinckerhoff 1993). When the chemical properties of the old and new steel differ significantly, welding can be difficult, especially on old bridges built with wrought iron. Discrepancies in the stiffness of the materials can lead to an unequal distribution of stresses, which may cause overloading of members (Thiel et al. 2001).

The most commonly used method of strengthening steel structures is enlargement of existing members (Radomski 2002). This can be an expensive operation, but can be an effective and simple way of increasing the capacity of members where necessary. It can also be done in a relatively inconspicuous manner, preserving the artistic integrity of bridges. Figures 6-8 and 6-9 show several ways that plate girders and truss members can be strengthened using plates, angles, channels, and grout.

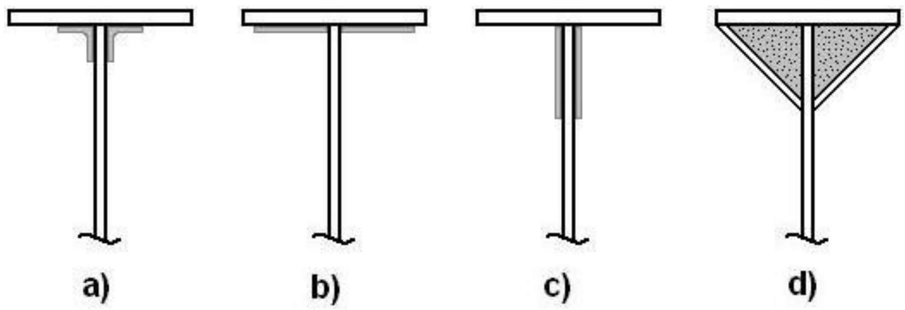


Figure 6-8. Strengthening of a Plate Girder. a) Angles, b) and c) Plates, d) Plates and Grout (adapted from Radomski 2002).

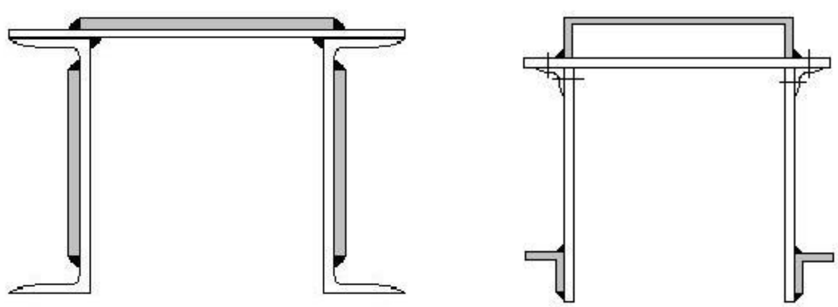


Figure 6-9. Strengthening of Truss Members with Plates, Angles, and Channels (adapted from Radomski 2002).

Another option for strengthening a steel structure is the addition of members (Radomski 2002). This is also an expensive process and construction may be difficult and time-consuming, but it has been proven to be successful in redistributing stresses to relieve overstressed members. Historic integrity is a concern when using this method, as newly added members can detract from the aesthetic appeal of bridges. Figure 6-10 shows how a bar and post can be used to strengthen a plate girder or rolled I-beam, and Figure 6-11 shows various ways that trusses can be strengthened using a “third chord.”

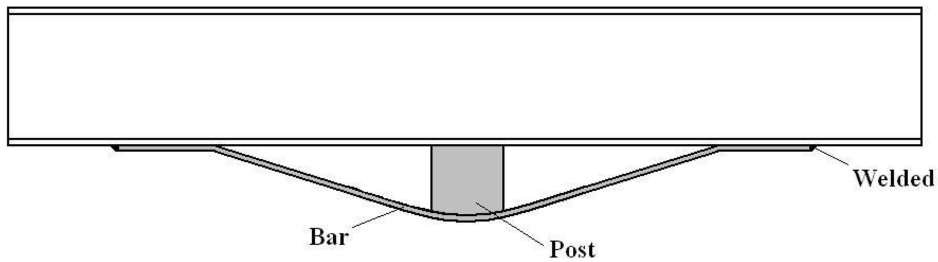


Figure 6-10. Strengthening of Steel Member with Post and Bar (adapted from Radomski 2002).

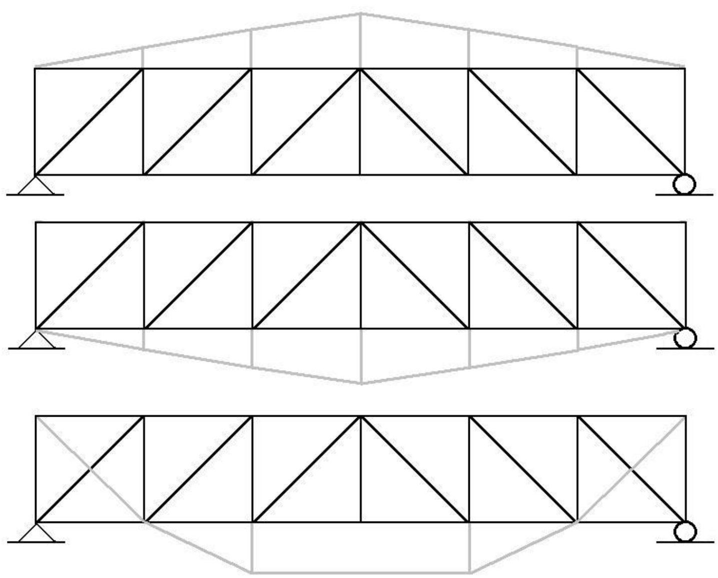


Figure 6-11. Strengthening of Trusses with "Third Chord" (adapted from Radomski 2002).

Post-tensioning can also be an effective method of strengthening steel structures (Xanthakos 1996). It can be used locally to strengthen members individually as shown in Figure 6-12, or on a larger scale to strengthen an entire structure as shown in Figure 6-13. The disadvantage of post-tensioning is that it can cause high localized stresses where tendons are anchored. Historic integrity is also a concern, and because of this, post-tensioning should be used sparingly on historic bridges.

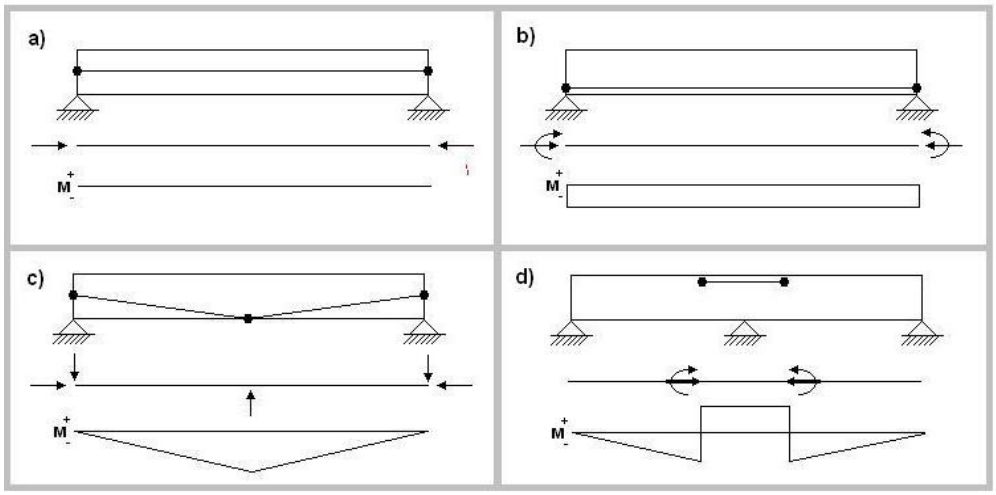


Figure 6-12. Forces and Moments Induced by Tendons. a) concentric tendon, b) eccentric tendon, c) polygonal tendon, and d) eccentric tendon in two-span member (adapted from Xanthakos 1996).

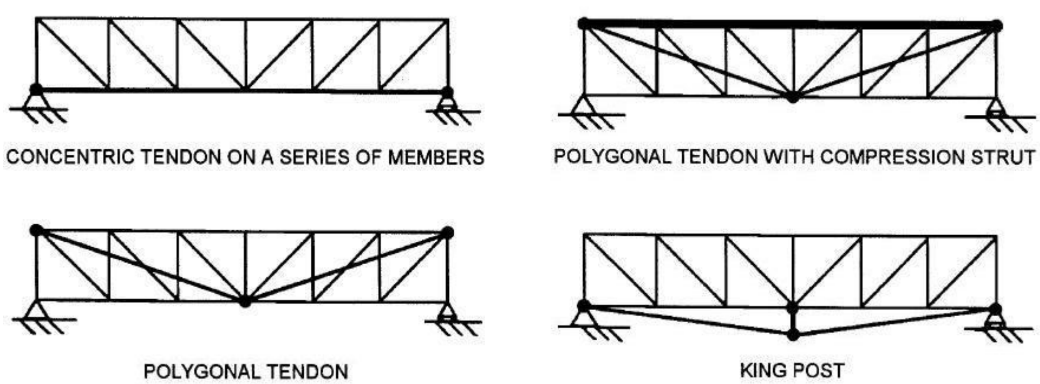


Figure 6-13. Post-Tensioning Options for Trusses (adapted from Thiel et al. 2001).

In the case of continuous span structures, adjusting a bridge's support system can be used as a method of manipulating positive and negative moments (Radomski 2002).

Figures 6-14(a)-(d) show various ways that this can be done. Figures 6-13(a) and (b) show how negative moments can be reduced by raising the end supports and lowering the intermediate supports, respectively. The configurations shown in Figures 6-13(c) and (d) reduce positive moments by raising the intermediate supports and lowering the end supports, respectively.

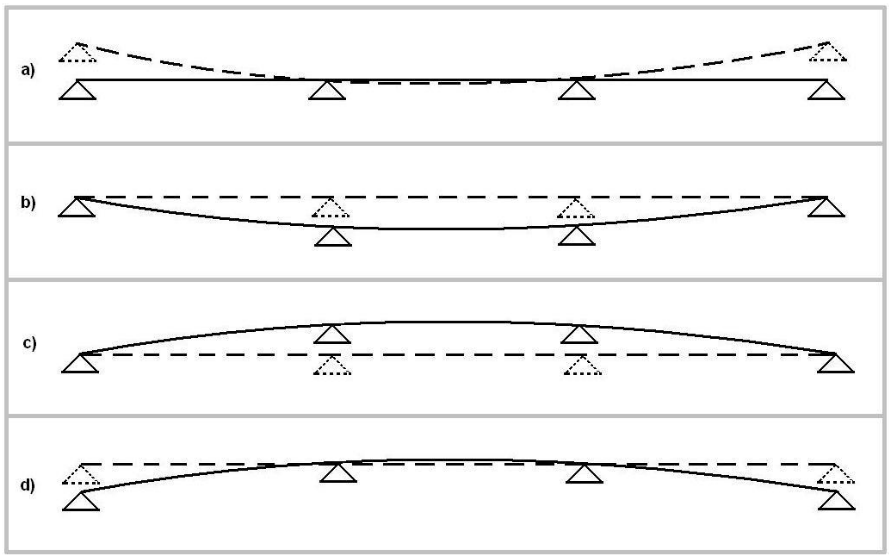


Figure 6-14. Adjustment of Supports to Manipulate Bending Moments (adapted from Radomski 2002).

In the case of steel girder bridges with concrete decks, shear connectors can increase bending capacity (Thiel et al. 2001). The connectors allow shear to be transferred between the deck and girders, causing them act as a composite member that is stronger than the girders alone. This can be done by drilling through the deck, anchoring connectors to the top flanges of girders, and filling the holes with grout.

When rehabilitating a steel structure, an important decision that must be made is which type of connections to use (Xanthakos 1996). Bolting is usually the preferred method, especially on fracture critical members, but welding can often be just as effective. In the case of riveted bridges, replacing rivets with high-strength bolts can increase the strength of the structure, but historic integrity must also be considered. Riveted connections add to the aesthetic quality of many historic steel bridges and should be preserved if possible.

6.5.4 Replacement of Members

In some cases, members may become damaged to a point where replacement is a more economical or safe option than repair. For example, it is recommended that members with greater than 40 percent section loss be replaced (Thiel et al. 2001). When replacing members of a steel structure, many of the same considerations should be made as when strengthening a structure. New members should consist of steel with properties similar to the steel of the existing structure for weldability and to avoid corrosion and harmful stress redistribution. Before removing members, stresses on remaining members should be calculated and temporary reinforcement should be installed if necessary (Radomski 2002). New members and connections should remain consistent with existing members in order to preserve historic integrity.

6.5.5 Repair of Cracks

All steel members are susceptible to fatigue cracking (Xanthakos 1996). Small cracks (one inch long and 3/32 inches deep or smaller) can be removed by mechanical methods such as grinding and no other repair is necessary. For repairing larger cracks, welding is typically used. Heat can cause a crack to propagate further, so a hole should be drilled at the end of the crack being repaired before heat is applied. This hole is usually 0.5 to 1.25 inches wide, depending on the thickness of the steel. The crack should then be grooved, either mechanically or by air carbon arc gouging, then filled in by welding.

6.6 MITIGATION STRATEGIES FOR BEARINGS

If bearings are not maintained properly, a variety of problems can occur (Radomski 2002). Debris and corrosion can cause bearings to freeze, leading to negative moments for which girders and slabs are not designed. Misaligned bearings can lead to high stress concentrations, which can cause damage to the concrete seat or the bearing itself. Lack of lubrication can restrict a bridge from expanding or contracting during temperature changes, leading to unexpected compressive or tensile stresses.

One of the most common problems encountered in bearings is corrosion, usually caused by leakage from deck joints (FHWA 2011). When corrosion has occurred, steel bearings should be cleaned and painted. If blasting is required, keeping the contact areas on the sole plate and masonry plate protected is important. To prevent corrosion and freezing, bearings should be lubricated regularly, preferably with a lubricant that includes a corrosion inhibitor (Brinckerhoff 1993). The FHWA Bridge Preservation Guide (FHWA 2011) recommends lubricating bearings on regular intervals of two to four years.

Other common problems in bearings include misalignment and deterioration of the concrete seat (Brinckerhoff 1993). Mitigating these issues requires jacking of the superstructure, which can be an expensive and difficult operation. For this reason, the cause of the problem should be identified and engineers should ensure that the problem will not be repeated after being repaired. The most common method of realigning bearings is to jack the superstructure and move the masonry plate to the correct position. Repairing deterioration of the concrete seat also requires jacking and can be performed according to the methods discussed in Section 6.4.

In some cases, replacement of bearings may be a more optimal choice than repair, for either functional or economic reasons (Brinckerhoff 1993). It is recommended that steel bearings with significant section loss caused by corrosion, pot bearings with broken seals, elastomeric bearings with cracked or deteriorated material, and sliding bearings with significantly damaged surfaces be replaced. When choosing replacement bearings, factors such as environmental conditions and required height should be considered.

6.7 MITIGATION STRATEGIES FOR DECKS

In this particular study, all bridges of concern possess reinforced concrete decks. In general, concrete decks can be treated in the same way as any other concrete element (Section 6.2), but having joints and an overlay makes them somewhat unique.

Overlays are designed to protect the concrete deck from moisture and to provide an adequately smooth driving surface (Xanthakos 1996). They typically consist of bituminous concrete (asphalt) or cement concrete. Asphalt overlays are easily penetrated by moisture, so a waterproof membrane is usually added between the bridge deck and overlay. Cement concrete overlays are relatively impenetrable and do not require a membrane. Cracks in overlays can be repaired by applying a waterproof sealant, while spalling, scaling, and delamination can be repaired using methods similar to those used in other concrete elements. If a wearing surface becomes significantly worn or deteriorated and can no longer serve its purpose, replacement is recommended. Cement concrete overlays may last 20 to 25 years, while asphalt overlays typically last 10 to 15 years but are easier to construct and repair (FHWA 2011, Radomski 2002). Waterproof membranes should be replaced whenever the asphalt above them is replaced.

In the case of deck joints, most actions consist of adding or replacing sealant, removing debris, and repairing damaged concrete (Xanthakos 1996). Closed deck joints that do not properly seal out water should be repaired with waterproof sealant or, in the case of excessive damage, replaced. Open joints that do not properly allow drainage should be cleared of debris. Spalled concrete near edges should be patched according to the methods discussed in Section 6.4.2.

6.8 MITIGATION STRATEGIES FOR WATERWAYS

As discussed in Section 5.7, scour is the primary problem in bridge waterways. For this reason, most mitigation strategies used in waterways involve preventing and repairing the undermining of foundations by scour. Control devices are commonly used as prevention mechanisms. Riprap, a control device shown in Figure 6-15, is a method used to prevent erosion, which can cause contractions and increase stream velocity

(Kattell and Eriksson 1998). It is important that riprap is placed properly in order to avoid reducing the width of the stream. Gabions serve a similar purpose to riprap but are used on steeper slopes, as shown in Figure 6-16 (Ryan et al. 2006). Spurs and vanes are used to direct the stream away from erosion-prone banks and prevent shifting of the stream, as shown in Figures 6-17 and 6-18 (Kattell and Eriksson 1998).

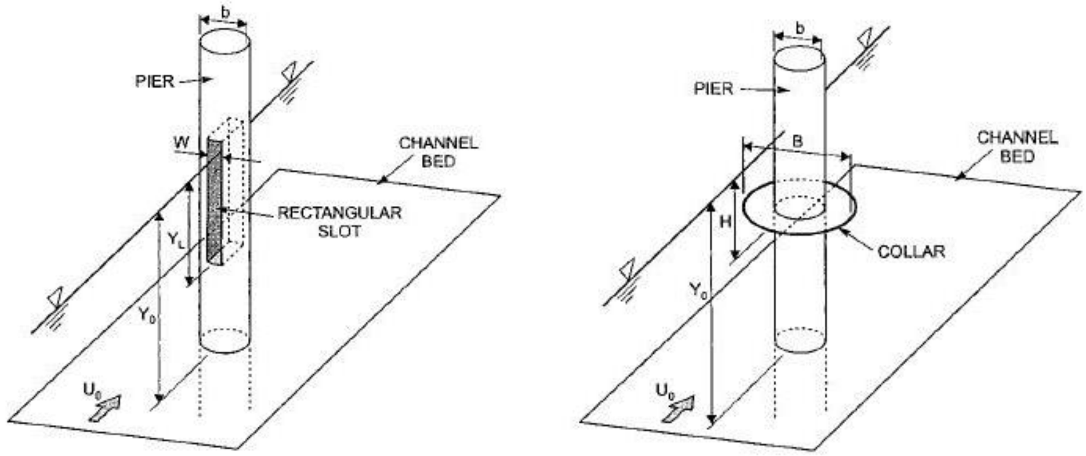
Figure 6-15. Use of Riprap to Prevent Erosion (Ryan et al. 2006).

Figure 6-16. Use of Gabion to Prevent Erosion (Ryan et al. 2006).

Figure 6-17. Use of Spurs to Redirect Stream Flow (Ryan et al. 2006).

Figure 6-18. Use of Vanes to Redirect Stream Flow (Ryan et al. 2006).

Other scour prevention mechanisms can be applied directly to substructure elements. Because scour is caused by vortices formed when water collides with the substructure of a bridge, measures have been taken to eliminate these vortices (Kumar et al. 1999). Cutting slots through piers is one method that has been proven to be relatively successful in reducing turbulence [Figure 6-19(a)]. This is achieved by allowing water to flow through a slot rather than colliding with piers and creating downward flow. Placement of collars around piers below the surface of the stream is another method that can be used to reduce turbulence [Figure 6-19(b)]. The collars redirect the vortices from the stream bed and thus reduce scour and undermining. Placing sandbags at the base of piers, bents, and abutments can also help to prevent scour, as recommended by the FHWA (Rossow 2011).



a) b)

Figure 6-19. Scour Prevention Mechanisms. a) slot, b) collar. (Kumar et al. 1999).

Methods for repairing damage caused by scour are also available. Klaiber et al. (2004) recommend placing bags of grout underneath undermined footings as underpinning and protecting them with a stone riprap. Underwater concrete has also been used successfully in the past (Clee 2005). This concrete is usually highly cohesive and resistant to washout and contains a plasticizing agent.

6.9 SUMMARY

Rehabilitation, repair, and maintenance techniques relevant to historic bridges are presented in this chapter. This overview of methods is intended to be used as a guide of available practices. In the rehabilitation of any bridge, safety and adequacy are the primary concerns, but in the case of historic bridges, preservation of historic integrity adds another constraint.

CHAPTER VII

PRESERVATION PLANS

7.1 OVERVIEW

With knowledge of both the current condition of each bridge in the inventory and available mitigation strategies, an individual preservation plan can be devised for each bridge. These plans outline the actions that would ideally be taken if adequate funding was available. Each plan consists of the following four sections:

1. Current Condition and Recommended Actions: This section of the preservation plan lists rehabilitation, repair, and maintenance actions that would be beneficial to the bridge based on the current condition. This includes all actions that would ideally be performed if funding was not an issue. A reliable condition assessment of a bridge often requires inspection that goes beyond routine visual inspection methods. This is especially true for historic bridges. Information can generally be obtained using the methods discussed in Chapter V. This section should also list significant rehabilitative actions or repairs performed on the bridge in the past.
2. Regular Interval Maintenance: This section lists maintenance actions that should be performed on regular intervals regardless of the condition of the bridge. These actions will likely be similar for all bridges. Section 6.3 discusses regular interval maintenance and suggests recommended frequencies for specific actions.

3. Condition-Based Actions: This section lists rehabilitation, repairs, and maintenance that should be performed if bridge elements reach certain condition states in the future. When rehabilitating a bridge, it is important to aim to solve the cause of the problems rather than only the symptoms. Section 7.2 contains tables and flowcharts for guidance on determining necessary actions.

As stated previously, preservations plans provide an outline of how each bridge would ideally be preserved if adequate funding was available. In nearly any case, however, correcting every problem with a bridge is not economically feasible. For this reason, it is beneficial to use a resource allocation framework to distribute funding among bridges, as described in Chapter VIII.

7.2 GUIDANCE FOR CONDITION-BASED ACTIONS

Tables 7-1 through 7-7 list condition states and corresponding actions to be considered on an individual element basis. Figure 7-1 shows a flowchart for determining corrective actions to be taken on concrete elements in the case of spalling, scaling, delamination, pop-outs, and reinforcing steel corrosion. Figure 7-2 shows a flowchart dealing with cracking, efflorescence, and discoloration in concrete elements. Information on the mitigation strategies listed in the tables and figures can be found in Chapter VI.

Table 7-1. Condition States and Corrective Actions for Deck Overlays.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• No signs of wear, smooth driving surface • Full protection of concrete deck	No action required	
FAIR	• Minor wear, adequately smooth driving surface • Some cracking • Adequate protection of concrete deck	Repair cracks with waterproof sealant to prevent moisture infiltration	6.7
POOR	• Significant wear and cracking • Spalling and delamination • Moderately rough driving surface • Moisture infiltrating concrete deck	Repair cracks with waterproof sealant, patch spalling and delamination	6.4.4, 6.4.6, 6.7
FAILED	• Significant wear, cracking, spalling, and delamination • Rough driving surface • Failure to protect concrete deck	Remove and replace overlay and waterproof membrane (if applicable)	6.7

Table 7-2. Condition States and Corrective Actions for Deck Joints.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• Expansion and contraction of superstructure uninhibited • No leakage of closed joints or clogging of open joints	No action required	
FAIR	• Expansion and contraction of superstructure uninhibited • Some debris buildup • Minor leakage of closed joints	Remove debris, reseal joints where necessary	6.7
POOR	• Expansion and contraction of superstructure restricted by debris buildup • Leakage of closed joints • Clogging of open joints • Corrosion of steel joint components • Spalling of concrete edges	Remove debris, clean corroded components, patch spalls, reseal joints where necessary	6.4.4, 6.4.6, 6.7
FAILED	• Restriction of superstructure movement threatens structural integrity • Leakage of closed joints • Clogging of open joints • Corrosion and section loss in steel joint components • Significant spalling and deterioration of concrete at edges	Patch spalls, remove and replace joint	6.4.4, 6.4.6, 6.7

Table 7-3. Condition States and Corrective Actions for Concrete Members.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• Minimal cracking in shear and tension zones • No spalling, scaling, or delamination	No action required	
FAIR	• Some cracking in shear and tension zones • No spalling • Some scaling and delamination	No action required	
POOR	• Significant cracking; discoloration and efflorescence at cracks • Spalling, exposed rebar • Some scaling and delamination • Signs of overloading • Deterioration of concrete in drainage areas	Remove efflorescence, patch as necessary, add interior or exterior reinforcement at cracks in overloaded members	6.4.4, 6.4.6, 6.4.5, 6.4.9, 6.4.10
FAILED	• Excessive cracking; discoloration and efflorescence at cracks • Major spalling, exposed rebar, section loss in rebar • Major scaling and delamination • Signs of overloading • Deterioration of concrete in drainage areas	Remove efflorescence, remove corrosion from exposed rebars, patch spalling, add interior or exterior reinforcement at cracks in overloaded members	6.4.4, 6.4.6, 6.4.5, 6.4.9, 6.4.10

Table 7-4. Condition States and Corrective Actions for Steel Members.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• No paint defects or corrosion • No section loss • All connections intact • No fatigue cracking	No action required	
FAIR	• Some paint defects, light rust • Minor section loss in some members • All connections intact • No fatigue cracking	No action required	
POOR	• Significant paint failures and corrosion • Section loss in some members • Some broken welds, bolts, or rivets • Some fatigue cracking	Clean and repaint areas of significant corrosion and paint failure, weld major cracks, replace broken connections	6.5.1, 6.5.5
FAILED	• Major paint failures and corrosion • >40% section loss in some members • Broken welds, bolts, or rivets • Fatigue cracking significantly reduces capacities of members	Replace member or strengthen structure or member	6.5.3, 6.5.4
Special Case	• Member is distorted	Replace member or repair thermally or mechanically	6.5.2, 6.5.4

Table 7-5. Condition States and Corrective Actions for Substructures.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• Minor cracking in tension zones • No spalling • No vertical, lateral, or rotational movement	No action required	
FAIR	• Minor cracking in tension zones • Some delamination, no exposed rebar • Negligible movement, no differential settlement	Patch concrete where necessary	6.4.4, 6.4.6
POOR	• Significant cracking in tension zones; discoloration and efflorescence at cracks • Some spalling and delamination • Significant earth movement, some differential settlement	Patch spalling, remove efflorescence, drill and plug cracks as necessary	6.4.4, 6.4.5, 6.4.6, 6.4.10
FAILED	• Excessive cracking in tension zones; discoloration and efflorescence at cracks • Major spalling, section loss in rebar • Earth movement and differential settlement threaten structural integrity	Patch spalling, remove efflorescence, remove corrosion from exposed rebars, drill and plug cracks as necessary, add jacketing to piers, check for structural damage caused by settlement	6.4.4, 6.4.5, 6.4.6, 6.4.7, 6.4.10

Table 7-6. Condition States and Corrective Actions for Bearings.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• Rotation and/or translation uninhibited as designed • No corrosion or section loss • No debris buildup	No action required	
FAIR	• Rotation and/or translation uninhibited as designed • Minor corrosion, no significant section loss • Some debris buildup	Remove debris to prevent corrosion	
POOR	• Intended movement restricted by corrosion or debris • Some section loss due to corrosion	Clean and repaint non-contact surfaces, remove debris, apply lubricant with corrosion inhibitor	6.6
FAILED	• Intended movement restricted by corrosion or debris • Significant section loss due to corrosion	Remove and replace bearings	6.6
Special Case 1	• Bearings out of alignment	Identify structural problem(s), jack structure and realign	6.6
Special Case 2	• Concrete seat significantly deteriorated	Jack structure and repair concrete	6.4.4, 6.6
Special Case 3	• Elastomeric material deteriorated or cracked	Replace elastomeric pad	6.6

Table 7-7. Condition States and Corrective Actions for Waterways.

Condition State	Description	Corrective Actions	Section(s) in Thesis
GOOD	• Minimal scour, no undermining of foundation • No erosion of banks • No abrasion, delamination, or spalling from flowing water • No shifting or contracting of stream	No action required	
FAIR	• Some scour and undermining, no exposed footings • Minimal erosion of banks • Minimal abrasion from flowing water, no spalling or delamination • No shifting or contracting of stream • Some debris buildup	Remove debris, consider installation of control devices	6.8
POOR	• Scour and undermining, some exposed footings • Erosion of banks • Some delamination, spalling, and loss of concrete aggregates due to flowing water • Shifting and contracting of stream resulting in increased stream velocity • Possible damage to hydraulic control structures • Some debris buildup	Remove debris, repair control devices, consider slots or collars to prevent further scour	6.8
FAILED	• Major scour and exposed footings • Erosion of banks causing contraction of stream • Significant loss of concrete cross-section due to flowing water • Excessive spalling and rebar section loss • Possible damage to hydraulic control structures • Debris buildup causing contraction of stream	Remove debris, repair control devices, consider underwater concrete or grout bags to support undermined footings, reassess structural strength	6.8

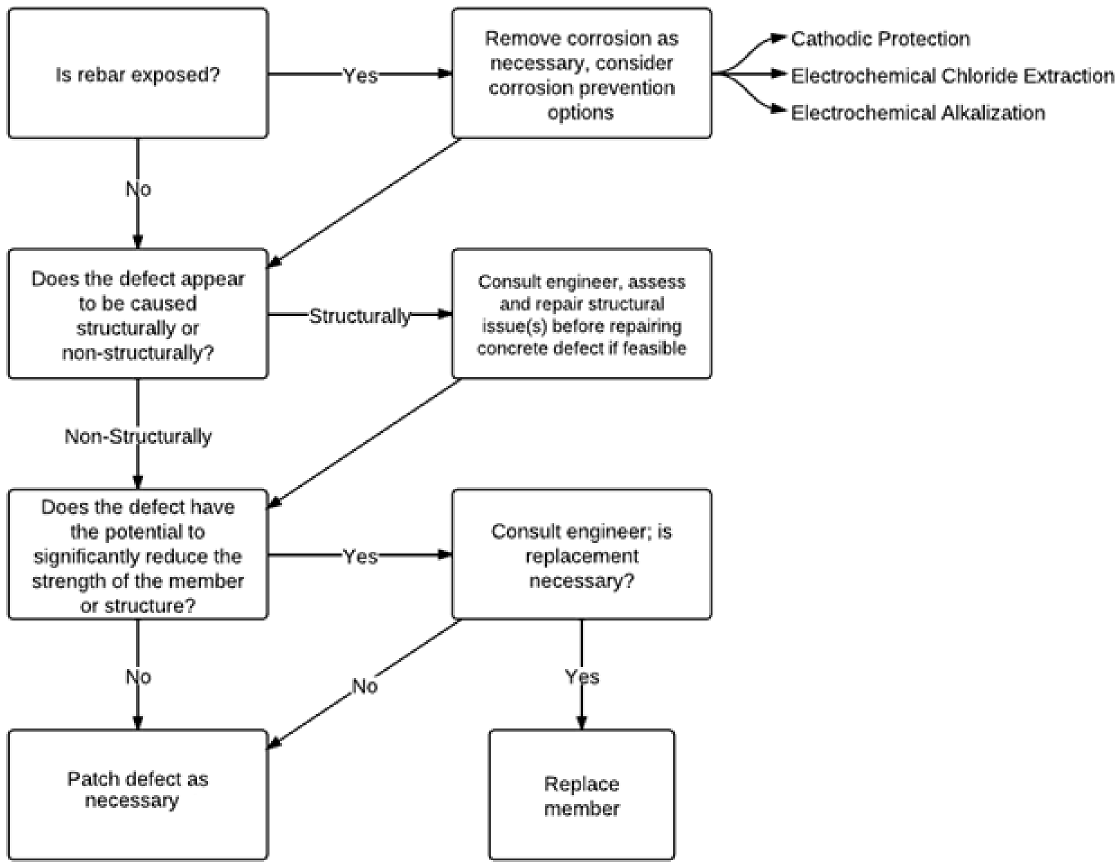


Figure 7-1. Flowchart for Spalling, Scaling, Delamination, Pop-outs, and Reinforcing Steel Corrosion in Concrete Elements.

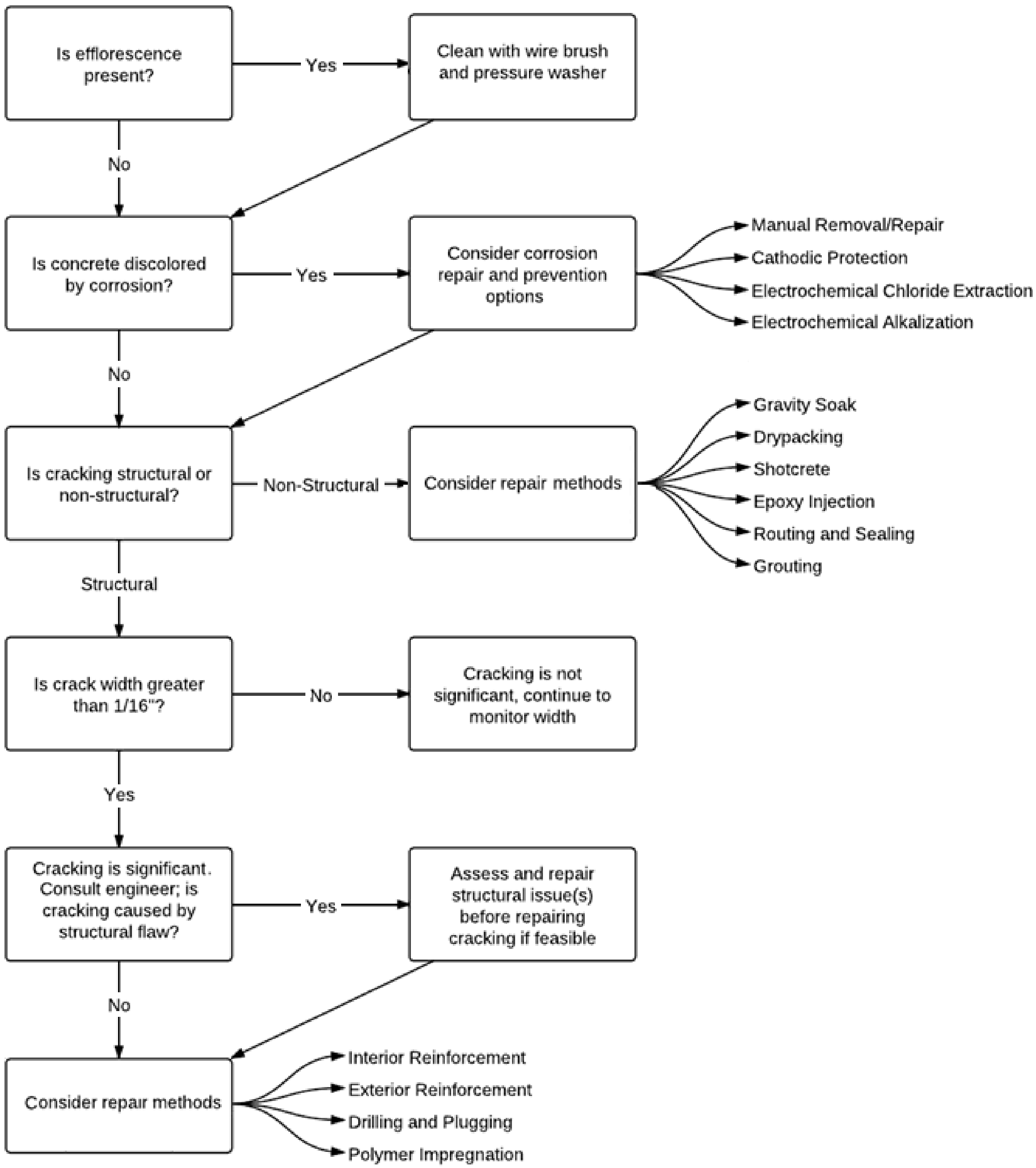


Figure 7-2. Flowchart for Cracking, Efflorescence, and Discoloration in Concrete Elements.

7.3 EXAMPLE PRESERVATION PLANS

This section contains examples of preservation plans for two bridges. The first an open-spandrel concrete arch bridge that is listed is on the NRHP. The second is a steel truss bridge that also features steel girder and concrete girder spans.

The Current Condition and Recommended Actions sections of the example preservation plans list actions that should be considered based on the inspection results. In some cases, defects may exist that are essentially beyond repair, such as misaligned arch posts in the superstructure of the concrete arch bridge. Mitigating this problem would require major rehabilitation and replacement of members, which would not be practical on a bridge its age. The Regular Interval Maintenance sections recommend actions discussed in Section 6.3 that are applicable to the bridges of concern. In the Condition-Based Actions sections, the tables and figures from this chapter are listed as references for determining actions based on element condition states.

7.3.1 Example Preservation Plan for Open-Spandrel Concrete Arch Bridge

1. <u>Current Condition and Recommended Actions</u>: This bridge possesses a concrete open-spandrel arch superstructure and a sufficiency rating of 33.5. Table 7-8 summarizes the current condition of the bridge and lists recommended actions for each element based on the current condition.

Table 7-8. Summary of Current Condition (Example Bridge 1).

Element	Notes	Recommended Actions
Deck Overlay	Replaced in 2003; random cracking on wearing surface	Seal cracks
Deck Joints	Replaced in 2003; some leaking	Reseal leaking joints
Deck	Replaced in 2011; spalling in tension zones, delamination	Patch spalling and delamination
Superstructure	Repairs to cantilevers, stringers, and spandrel column base in 2011; patches on tee beams and stringers spalling/delaminating, spalling and cracking at arch connections, shear cracking in stringers and arches, misaligned arch posts	Patch spalling and delamination, repair cracking with interior or exterior reinforcement
Substructure	Scaling, honeycombing, spalling, efflorescence on abutment caps; cracking, spalling, delamination on intermediate caps	Remove efflorescence, patch surface defects
Bearings	Corrosion and section loss	Remove corrosion and repaint
Waterway	No significant defects	None

2. Regular Interval Maintenance: It is recommended that preventive maintenance procedures be performed at regular intervals, regardless of condition state, according to Table 7-9.

Table 7-9. Recommended Regular Interval Maintenance (Example Bridge 1).

Action	Frequency
Remove debris from deck drains	6 months
Remove debris from deck joints	6 months
Pressure wash deck	1 year
Apply waterproof sealant on deck after cleaning	3 years
Clean, lubricate, and repaint bearings	2 years
Remove debris from superstructure and abutments	3 years

3. Condition-Based Actions: Table 7-10 provides references to tables and figures to be used for determining corrective actions based on element condition states in the future.

Table 7-10. References for Condition-Based Actions (Example Bridge 1).

Element	Table / Figures
Deck Overlay	Table 7-1
Deck Joints	Table 7-2
Concrete Members	Table 7-3 Figure 7-1 Figure 7-2
Substructure	Table 7-5
Bearings	Table 7-6
Waterway	Table 7-7

7.3.2 Example Preservation Plan for Steel Truss Bridge

1. Current Condition and Recommended Actions: This bridge possesses steel truss, steel girder, and concrete girder spans, and a sufficiency rating of 80.2. Table 7-11 summarizes the current condition of the bridge and lists recommended actions for each element based on the current condition.

Table 7-11. Summary of Current Condition (Example Bridge 2).

Element	Notes	Recommended Actions
Deck Overlay	Replaced in 1999	None
Deck Joints	Resealed in 2010; clogged with sand and debris	Remove sand and debris
Deck	Minor transverse cracking	None
Superstructure	Cracking in vertical steel truss members repaired in 2010; truss members are fracture critical; corrosion and section loss in gusset plates and bottom chord members, minor paint failures	Clean and repaint areas with significant corrosion, replace members with greater than 40 percent section loss
Substructure	Spalling at abutments, cracking and delamination at intermediate caps	Patch spalls and delamination, repair cracks with epoxy injection
Bearings	Some bearings and anchor bolts replaced in 2010; no significant defects	None
Waterway	No significant defects	None

2. Regular Interval Maintenance: It is recommended that preventive maintenance procedures be performed at regular intervals, regardless of condition state, according to Table 7-12.

Table 7-12. Recommended Regular Interval Maintenance (Example Bridge 2).

Action	Frequency
Remove debris from deck drains	6 months
Remove debris from deck joints	6 months
Repair loose connections in deck joints	1 year
Pressure wash deck	1 year
Apply waterproof sealant on deck after cleaning	3 years
Clean and lubricate bearings	2 years
Remove spot rust and repaint affected areas on steel members	3 years
Remove debris from superstructure and abutments	1 year
Remove debris from waterway	2 years

3. Condition-Based Actions: Table 7-13 provides references to tables and figures to be used for determining corrective actions based on element condition states in the future.

Table 7-13. References for Condition-Based Actions (Example Bridge 2).

Element	Table / Figures
Deck Overlay	Table 7-1
Deck Joints	Table 7-2
Concrete Members	Table 7-3 Figure 7-1 Figure 7-2
Steel Members	Table 7-4
Substructure	Table 7-5
Bearings	Table 7-6
Waterway	Table 7-7

7.4 SUMMARY

This chapter presents a template and two examples of individual bridge preservation plans. These plans provide an outline of measures that would preferably be taken on bridges if adequate funding were available. For most bridge-owning agencies, adequate funding is not available, but it is good practice to have a plan of the ideal preservation methods. Because of a general limitation on funding, choices must be made regarding which preservation efforts offer the most benefit and feasibility. This presents a need for a resource allocation methodology, as developed in the following chapter.

CHAPTER VIII

RESOURCE ALLOCATION

8.1 OVERVIEW

The overall goal in historic bridge preservation is to maintain the historic integrity, aesthetic value, commercial value, and functionality of bridges while limiting expenditures. In the case of historic bridges, nearly every element of every bridge would benefit from some level of service beyond routine maintenance. However, due to limited budgets, not all work that bridge owners may prefer to be performed is feasible. For this reason, a resource allocation methodology that designates funding to the most significant structures and the most feasible actions is useful to bridge-owning agencies. The system must consider costs and benefits of all options. For example, replacing a member carries benefits such as improvement of the current condition, lengthening of the expected service life, and reduction of future costs of maintenance and repair; but the costs of replacement can include a high initial cost and a potential loss of historic integrity. This chapter presents a resource allocation framework that can be used to help agencies make more efficient use of available funding. The framework is designed to be a means of helping bridge-owning agencies determine which actions are the most beneficial while taking feasibility into account.

The end result of the resource allocation framework is a list of sets of actions on every bridge in the inventory, each ranked according to the benefit obtained by the actions. Each bridge should be broken down into the following nine elements: deck, deck overlay, deck joints, rails, superstructure, abutments, piers or bents, footings, and waterway. The steps of the framework are summarized by the flowchart in Figure 8-1. The first step of the methodology is to consider each element of each bridge in the inventory on an individual basis and list sets of actions that may be beneficial, as discussed in Section 8.2. These action sets will later be evaluated under the following six criteria (discussed further in Section 8.4): reduction of life-cycle cost, impact on commercial value, impact on utility and functionality, impact on aesthetic value, preservation of historic integrity, and reduction of risk to structural integrity. The next step is to assign weights to each of the criteria based on the characteristics and surroundings of each bridge (Section 8.3). Each set of actions is then issued a rating on a 10-point scale under each of the six criteria. A benefit score is then calculated for each set of actions, and the optimal action sets on each element are chosen and ranked using one of two methods presented in Section 8.5. The first method maximizes total benefit within the inventory, while the second maximizes benefit-to-cost ratio. It is recommended that the highest ranked actions be performed first, but exceptions exist. Section 8.8 presents an example illustrating the use of the framework.

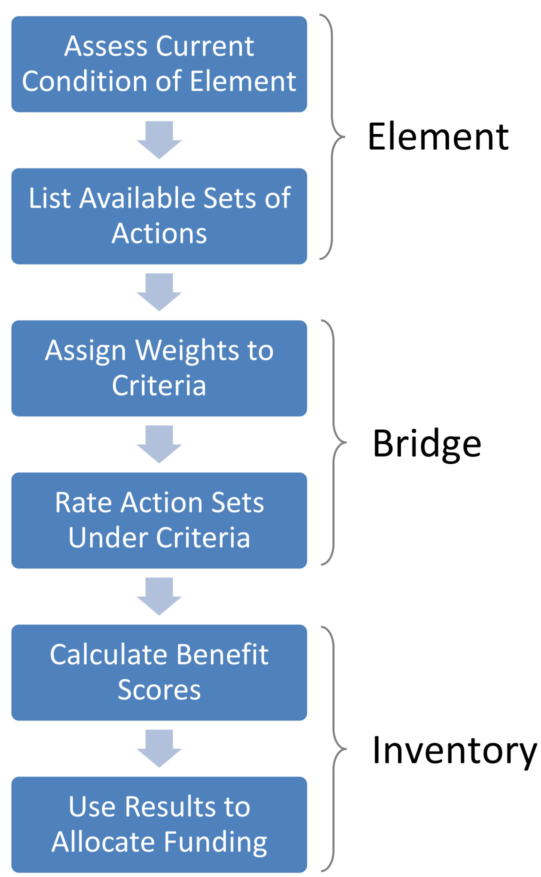


Figure 8-1. Flowchart Depicting the Resource Allocation Framework.

The following subsections discuss concepts relevant to the resource allocation framework. A modified version of the weighted sum model will be used to calculate benefit scores of actions, and the Delphi method is recommended as a way to predict the impact of actions on various qualities of bridges.

8.1.1 Weighted Sum Model

In any project, situations are bound to arise in which a decision must be made between multiple courses of action. Many methods exist for quantifying the relative desirability of several available options. The most simple and most commonly used of these methods is the weighted sum model (WSM) (Triantaphyllou et al. 1998). In the WSM, each alternative course of action ($A_1, A_2, \ldots, A_M$) is evaluated based on several chosen criteria ($C_1, C_2, \ldots, C_N$) and given a numeric rating under each criterion, for example, a_{11} represents the rating of the first alternative under the first criterion. Each criterion is assigned a weight ($W_1, W_2, \ldots, W_N$) based on importance, all of which should add up to exactly one. The desirability, D_i, of the i^{th} alternative when rated under N criteria is then calculated as follows:

$$D_i = \sum_{j=1}^{N} a_{ij} W_j \tag{8.1}$$

The alternative with the highest desirability is then considered the optimal choice. Alternatives, criteria, weights, and ratings can be visualized in a decision matrix as shown in Figure 8-2.

	Criteria				
	C_1	C_2	C_3	…	C_N
Alternatives	W_1	W_2	W_3	…	W_N
A_1	a_{11}	a_{12}	a_{13}	…	a_{1N}
A_2	a_{21}	a_{22}	a_{23}	…	a_{2N}
A_3	a_{31}	a_{32}	a_{33}	…	a_{3N}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_M	a_{M1}	a_{M2}	a_{M3}	…	a_{MN}

Figure 8-2. Decision Matrix for *M* Alternatives and *N* Criteria (adapted from Triantaphyllou et al. 1998).

This framework uses a modified version of the WSM to calculate a benefit score for each possible set of actions to potentially be implemented on a bridge. Alternatives are available courses of action on a bridge element such as repairs or maintenance. The owning agency constructs the list of alternatives. Criteria are factors such as impact on historic integrity and reduction of life-cycle cost. Ratings under the criteria are made based on experience and must all be normalized to the same scale. This framework uses a 10-point rating scale. Weights are assigned by the owning agency and may be distributed differently depending on the bridge of concern.

Other methods for multi-criteria decision-making include the weighted product model, analytic hierarchy process, revised analytic hierarchy process, ELECTRE (Elimination and Choice for Reality, translated from French) method, and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method (Triantaphyllou et al. 1998). The WSM was chosen for this framework for its simplicity. The other available methods would likely produce similar results while bringing unnecessary complexity to the decision-making process.

8.1.2 Delphi Method

When dealing with historic bridges, decisions made by agencies affect bridges and their surrounding areas in a number of ways, most of which cannot easily be quantified. The Delphi method is a system used to predict future events that cannot be projected quantitatively (Brown 1968). The method, which has been in use since the 1940s, uses the knowledge of a panel of experts while eliminating the psychological factors that can occur in in-person discussion such as persuasion and the bandwagon effect. It also allows for anonymous criticism of reasoning while avoiding confrontation. In this framework, the Delphi method can be used to predict and quantify the effects that certain actions may have on abstract qualities of bridges such as historic integrity and commercial value.

The Delphi method involves a conducting agency and a panel of experts (Brown 1968). The first step in the process is for the conducting agency to devise a question and formulate a panel of experts on the subject. The agency then disperses questionnaires to each member of the panel. The questionnaire should ask the experts the primary question and request that they also give reasoning behind their answers. The agency then compiles the results and may take measures to exclude outlying answers, for example, Brown recommends using only the middle 50 percent of answers in the case of quantitative answers. A second round of questionnaires is then distributed, this time showing the results of the previous round while still posing the same questions as before. The second questionnaire also encourages the experts to revise their answers as desired and to critique the reasoning cited by other experts for their answers. Subsequent rounds of questionnaires may be dispersed until the results reach close enough to a consensus to satisfy the conducting agency. In the case of questions with quantitative answers, Brown recommends using the median of the middle 50 percent of answers in the final round as the final consensus.

8.2 LISTING OF AVAILABLE ACTIONS

The first step of the resource allocation process is to consider the current condition of each element of each bridge in the inventory and compile feasible sets of actions to remedy any problems that may be present. Action sets should be set up so that only one set can be chosen. For example, possible sets of actions for a steel superstructure could be 1) repaint only girders with corrosion on 40 percent of surface area, 2) repaint all girders, and 3) repaint all girders and repair fractures. Actions may include the following:

- Maintenance actions: Although it does not repair current problems, maintenance that goes beyond routine actions can prevent future issues and thus reduce life-cycle costs. Routine maintenance activities recommended in Chapter VII should be performed at regular intervals and need not be explicitly considered in the resource allocation process.
- Repairs and rehabilitative actions: Although repairs and rehabilitation often carry a relatively high initial cost, a point can be reached where it is no longer economical to delay them. Actions may include minor techniques such as patching or major procedures such as retrofitting to strengthen a structure.
- Replacement: This option should be used rarely. Replacement of a member usually carries a high initial cost and detracts from the historic integrity of a bridge but can decrease the life-cycle cost.
- Further evaluation: Problems that cannot be detected by visual inspection can arise in bridges and cause serious damage. When a bridge-owning agency has limited knowledge regarding the condition of a bridge, further evaluation such as advanced non-destructive testing can prove to be highly beneficial in relation to its low cost. Further evaluation of a bridge has no immediate impact, but can reduce risk by eliminating uncertainty surrounding the condition of bridge elements.

Engineers and other qualified personnel should be consulted when defining options. Action sets listed in this step are later evaluated based on the criteria discussed in Section 8.4.

8.3 ASSIGNMENT OF WEIGHTS TO CRITERIA

After listing possible sets of actions on each bridge element, each of the criteria should be issued a weight for each bridge. Weights should be assigned according to the characteristics and surroundings of the bridge of concern and should add up to exactly 1 for each bridge. Factors that may determine the weight distribution include the following:

- Financial situation of owning agency: If the agency is in good financial standing, monetary costs may not be as much of a concern as if funding is limited.
- Historic status of bridge: For bridges that are eligible for the NRHP and other historically significant bridges, historic integrity may be more of a concern.
- Surrounding businesses: If a bridge is considered to be important to nearby businesses either aesthetically or logistically, commercial value should be given significant weight.
- Importance of bridge to network: For bridges that are critical to road networks, utility and functionality are important criteria.
- Aesthetics: If a bridge contributes greatly to the overall aesthetics of an area, aesthetic value is more of a concern.

Table 8-1 shows suggested baseline weight distributions that could be used for peripheral bridges and downtown bridges with either high or low traffic loads. For peripheral bridges, functionality is a key characteristic because bridges located in more remote areas are usually important to the road network. Commercial value is given little weight because it is assumed that there are no businesses nearby. For downtown bridges, commercial value is given more weight because they usually are of some value to nearby businesses. For both bridge types, historic integrity is given significant weight because preservation of historic aspects is one of the primary goals in this study.

Table 8-1. Suggested Baseline Weight Distributions

Bridge Group	Life-Cycle Cost	Commercial Value	Utility/ Functionality	Aesthetic Value	Historic Integrity	Risk Reduction
Downtown, High Traffic	0.15	0.18	0.16	0.16	0.25	0.10
Downtown, Low Traffic	0.17	0.18	0.12	0.18	0.25	0.10
Peripheral, High Traffic	0.18	0.05	0.27	0.12	0.25	0.13
Peripheral, Low Traffic	0.20	0.05	0.23	0.12	0.25	0.15

8.4 CRITERIA

After assigning weights to the criteria for each bridge, each set of actions is rated based on the following six criteria: reduction of life-cycle cost, impact on commercial value, impact on utility and functional value, impact on aesthetic value, preservation of historic integrity, and reduction of risk to structural integrity. The following subsections discuss each criterion in detail.

8.4.1 Criterion 1: Reduction of Life-Cycle Cost

When comparing preservation options, life-cycle cost (also known as “cost-to-go”) must be considered in addition to initial cost. Bridge owners must consider how actions will affect the future maintenance and repair costs of a bridge. For example, an owning agency could save money in the short term by choosing to take no action, but the deterioration of the bridge while action is deferred would result in an increased cost of maintenance and repair in the future. On the other hand, performing maintenance actions on the bridge would carry some initial cost but would lessen the probability of the bridge requiring major repairs in the future, reducing the life-cycle cost. In 2012, Congress passed a bill requiring consideration of life-cycle costs in addition to initial cost when awarding federal contracts for highway bridge projects (U.S. Congress 2012). Several models exist that can assist bridge owners in formulating reasonably accurate estimates. Regardless of the methodology used, predicting the effects of actions on life-cycle costs is a highly subjective process that requires engineering judgment. No perfect model exists, but even if the owning agency uses no specific model to predict life-cycle costs, giving any amount of consideration to the matter (as opposed to considering only initial cost) greatly improves the analysis of costs and benefits.

This section presents two existing life-cycle cost analysis methodologies. Neither is a fail-proof system, but components of each can be used to analyze the impact of activities on life-cycle costs. The Delphi method could also be used, as LCCA is a subjective process that requires the opinions of experts. Using any combination of these methods, each set of actions should be rated on a scale of 0 to 10 for its impact on the life-cycle cost of a bridge (apart from the initial cost of the action). Because future costs can be highly unpredictable, it is recommended that primarily the 10-year cost-to-go be considered. Predicting costs beyond this horizon could result in inaccurate projections that would affect the decision-making process.

Table 8-2 gives a general framework for the rating scale, although ratings in between those given in the table may be assigned. It is important to rate options under this criterion in relation to the base case of taking no action. Delaying action on an element would leave a certain cost-to-go, and each set of actions is rated based on how much it would potentially reduce this future cost.

Table 8-2. Rating Scale for Reduction of Life-Cycle Cost.

Impact of Actions on Life-Cycle Cost (relative to base case)	Rating [$a_{n1}^{(ij)}$]
Neutral	0
Reduces Moderately	5
Reduces Significantly	10

8.4.1.1 Hawk LCCA Model

In National Cooperative Highway Research Program (NCHRP) Report number 483, Hawk (2003) presents an LCCA model to be used to weigh costs and benefits of different options. The model is specific to bridge LCCA and is designed to provide a comparison between any option, such as repair or maintenance activities, and a "base case" (usually no action). Component conditions after each available action are predicted, then future costs are estimated based on those conditions. The model takes into account normal repair and maintenance costs, as well as those incurred by events with high uncertainty such as earthquakes, collisions, floods, and scour (known as vulnerability costs). Probability distributions for these events are formed, then mathematical simulation is used to predict outcomes and costs. Another factor accounted for in the model is the difference between present and future value of expenditures. Depending on the discount rate used, this can be a deciding factor on when to take action.

Although Hawk's model contains some elements that could be useful in the case of this framework, there are also limitations. One of these limitations is that the model is meant to be used on a bridge as a whole, rather than a specific component. Another is that the model gives significant weight to "user costs" such as traffic congestion delays, detours, and potential damage to vehicles. These are important factors to consider, but in the resource allocation framework presented in this chapter they are covered by other criteria and need not be considered in the life-cycle cost criterion. The third limitation, acknowledged by Hawk in the report, is that parameters available in bridge inventories are not adequate input for accurately predicting life-cycle costs. For this reason, use of engineering judgment is essential. Software for the implementation of Hawk's model is available through the Transportation Research Board Business Office but should be used with caution due to the limitations mentioned above.

8.4.1.2 FHWA LCCA Recommendations

The FHWA recommends a LCCA methodology using the following five steps (FHWA 2002):

1. Establish design alternatives: In this step, the agency should compile a list of all available options. It should be noted that this method is meant to be used only to compare alternatives that achieve the same result. For example, it should be used to compare different methods of replacing a member rather than replacing versus repairing a member. Also included in this step is definition of the analysis period, the time over which costs will be analyzed. This period may or may not extend to the end of the service life of a bridge, but should include at least one major rehabilitation (after the rehabilitation currently under consideration) to the component in question.
2. Determine activity timing: After determining alternatives and defining the analysis period, the agency should establish a maintenance and rehabilitation schedule for the remainder of the analysis period for each alternative. This is a subjective process that relies heavily on engineering judgment, but past performance data can assist agencies in determining how actions affect maintenance and rehabilitation requirements in the future. Activity timing also depends on the minimum condition state that the agency considers acceptable. Aside from scheduling routine maintenance and rehabilitation, agencies should factor in costs incurred due to uncertain events such as collisions and floods. A deterministic approach to these events assigns discrete costs for events and simplifies the analysis but does not address the likelihood of events. A

probabilistic approach uses simulation software to calculate costs based on probability distributions and accounts for the uncertainty of events requiring expenditures.

3. Estimate costs: In this step, costs of the future maintenance and rehabilitation scheduled in the previous step are estimated. Because this methodology is meant to be used as a comparison tool, agencies need only consider differences in cost between alternatives. The FHWA advises agencies to consider costs incurred by both users and bridge owners, but because user costs will be considered under other criteria in this framework, only monetary costs incurred by the agency need be considered.
4. Compute life-cycle costs: After estimating the costs of future maintenance and rehabilitation activities, the life-cycle cost is calculated by adding up all activity costs. Price inflation and time value of money should be considered, and all costs should be converted to present value. If the analysis period defined in Step 1 ends prior to the end of a bridge's service life, the value of the projected remaining service life at the end of the period should be monetized and subtracted from life-cycle costs.
5. Analyze results: Once the life-cycle costs have been computed for each alternative, the agency should review and analyze the results. Alternatives may be reevaluated and possibly modified. The agency can also perform a sensitivity analysis to assess the integrity of its system. For example, adjusting the interest rate used to convert future expenditures to present value while holding all other factors constant would show how the interest rate affects the results.

As with any LCCA mechanism, a primary limitation to this methodology is that parameters currently recorded in bridge inventories are not adequate. Data such as condition ratings and sufficiency ratings do not give enough information for bridge-owning agencies to accurately project the future effects of maintenance and rehabilitation activities. For this reason, engineering judgment is important in the employment of this methodology.

8.4.2 Criterion 2: Impact on Commercial Value

Historic bridges can be of some commercial value to surrounding businesses by beautifying the area and providing traffic access to them. Improving the appearance, accessibility, or service life of a bridge located near businesses adds to the commercial value. Actions such as member replacement and widening may detract from the historic integrity of a bridge but add to the value it provides to surrounding businesses. The following factors should be considered in an analysis of the commercial value of a bridge.

- Detours and delays: If actions require lane closures, detours and delays could become severe enough that potential patrons would be discouraged from visiting businesses. This would temporarily detract from the commercial value of a bridge.
- Traffic flow: Any actions that improve the flow of traffic over a bridge make access to nearby businesses easier, increasing the commercial value.
- Aesthetic appeal: Improving the appearance of a bridge improves the surroundings associated with nearby businesses.

Taking the above factors into account, each set of actions should be rated from 0 to 10 to quantify the impact it would have on the commercial value of the bridge in relation to the base case. The Delphi method may be of use in determining this rating, as commercial value is a highly theoretical quality that is best estimated by experts. Table 8-3 gives a general framework of the rating scale.

Table 8-3. Rating Scale for Impact on Commercial Value.

Impact of Action on Commercial Value (relative to base case)	Rating [$a_{n2}^{(ij)}$]
Neutral	0
Improves Moderately	5
Improves Significantly	10

8.4.3 Criterion 3: Impact on Utility and Functionality

The overall goal of this project is to keep historic bridges in service as long as possible. Above all, bridges must serve the intended purpose of safely carrying traffic in order to be kept in service. In many cases, actions must be performed that have a detrimental effect in other areas (usually historic integrity) but are necessary to keep a bridge safely in use. Both immediate and future impact should be considered. For example, delaying action prevents detours and construction delays in the short-term but further deterioration could cause safety issues in the future. Maintenance and rehabilitation activities require traffic to be slowed or redirected during implementation but improve long-term safety and adequacy. The following factors should be considered when assigning ratings for utility and functionality.

- Delays: When actions are performed, traffic delays due to lane closures are likely to occur for some period of time. Length of required lane closures, average delay per vehicle associated with the action, and the average daily traffic of the bridge of concern should all be considered. This can be a controversial issue because the agency must put a value on bridge users' lost time.
- Detours: If an action requires a bridge to be closed entirely, a detour is necessary. Besides the considerations given to traffic delays discussed above, fuel costs incurred by users due to increased travel distance must also be considered.

- Safety: Factors such as bridge width, lane width, and rail adequacy all contribute to the overall safety of a bridge. These factors should be considered to ensure that a bridge does not pose an accident risk.
- Deck condition: Wear and tear to vehicles is a cost incurred by users if a bridge deck is in poor condition.
- Environmental concerns: Debris buildup at bridges can disrupt the flow of rivers and have adverse effects on the environment.
- Obsolescence: If a bridge deteriorates to a point where it can no longer safely serve its purpose, it must be replaced.

A general rule of thumb could be to consider how actions will affect the sufficiency rating of a bridge, which is a measure of the ability of a bridge to remain in service. The Delphi method could also be used for guidance. Considering all of the above factors, each set of actions should be assigned a rating from 0 to 10 to describe the impact that it would have on the immediate and future utility and functionality of a bridge. Table 8-4 gives a general framework of the rating scale.

Table 8-4. Rating Scale for Impact on Utility and Functionality.

Impact of Action on Utility and Functionality (relative to base case)	Rating [$a_{n3}^{(ij)}$]
Neutral	0
Improves Moderately	5
Improves Significantly	10

8.4.4 Criterion 4: Impact on Aesthetic Value

The next criterion to be considered is the impact of actions on the aesthetic value of a bridge. This criterion is similar to historic integrity and commercial value in some ways but is considered separately because actions may exist that have a positive impact in one category but negative in the other. For example, replacing a deteriorated original rail would detract from the historic integrity of the bridge but would improve the overall aesthetic appearance of the bridge. Installing external post-tensioning on girders would improve the commercial value of a bridge by increasing the adequacy and lengthening the service life but would detract from the aesthetic appeal of the bridge. When considering a set of actions under this criterion, it is important that only the overall appearance of the bridge is considered, regardless of the impact of that the action may have on the historic integrity of the bridge. Options should be rated on a scale of -5 to 5, where actions that detract from the appearance of a bridge receive a negative rating. A general framework of the rating scale is shown in Table 8-5.

Table 8-5. Rating Scale for Impact on Aesthetic Value.

Impact of Action on Aesthetic Value (relative to base case)	Rating [$a_{n4}^{(ij)}$]
Reduces Significantly	-5
Reduces Moderately	-2.5
Neutral	0
Improves Moderately	2.5
Improves Significantly	5

8.4.5 Criterion 5: Preservation of Historic Integrity

Another factor that must be weighed when considering preservation alternatives is how actions will affect the historic aspects of a bridge. This factor is especially important on highly visible components such as rails and large girders. Attention to historic integrity and character-defining features is required by law when dealing with structures on or eligible for the NRHP. The National Historic Preservation Act of 1966 requires that proposed alterations to historic structures be reviewed and approved by the SHPO and that any adverse effects be avoided unless no other feasible options exist (United States Senate 1966). Section 4(f) of the USDOT Act of 1966 states that in order for projects on historic structures to qualify for federal funding, harm to historic integrity and character-defining features must be minimized (USDOT 1966).

In general, all original workmanship and materials should be preserved whenever possible. Through the use of engineering judgment and possibly the Delphi method, each set of actions should be rated from -10 to 0 based on the immediate impact that it would have on the historic integrity of a bridge. This rating is assigned under the assumption that historic aspects can only be preserved and not gained. For example, replacement of a highly visible original member would receive a highly negative score, while a maintenance action that keeps all original materials intact would receive a 0 because it neither adds nor detracts from the historic integrity of the bridge. Table 8-6 gives a general framework of the rating scale.

Table 8-6. Rating Scale for Impact on Historic Integrity.

Impact of Action on Historic Integrity	Rating [$a_{n5}^{(ij)}$]
Detracts Significantly	-10
Detracts Moderately	-5
Fully Preserves	0

8.4.6 Criterion 6: Reduction of Risk to Structural Integrity

While delaying an action has no immediate negative impact on the condition of a bridge, it poses a risk of future deterioration. For this reason, risk to structural integrity should be considered when choosing preservation options. This criterion focuses primarily on sets of actions that ignore certain defects. For example, corrosion and fracturing may be present in the girders of a steel bridge. Repainting the girders (as opposed to the optimal action of repairing the fractures then repainting) poses a risk to the structural integrity of the bridge by failing to address the fractures. If an agency chooses not to immediately address an issue, there is no immediate impact on the structural integrity of the bridge, however, the risk of deterioration increases.

While actions such as maintenance, rehabilitation, and repair reduce the risk of future structural damage by improving or maintaining the current condition state, further evaluation of a bridge or element can reduce the risk by providing more information about the current condition. (This is the only criterion under which the action of further evaluation will receive a significant rating.) A more detailed and accurate assessment can reduce uncertainty about the condition state either by revealing defects that had previously gone undetected or by reinforcing the findings of previous inspections. This is especially beneficial in bridges of which the owning agency lacks detailed knowledge of the condition. The action of further evaluation should receive higher ratings in cases where uncertainty is high. Also to be considered is the information revealed by some rehabilitation and repair actions. For example, repainting steel girders requires removal of paint and corrosion, which exposes the girders and may reveal fatigue cracking that was previously unnoticed. Actions such as this can reduce the risk of future damage by providing more information about the condition of the bridge, in the same way that further evaluation does.

Under this criterion, sets of actions should be rated in relation to the base case of taking no action. Deferring action on an element poses a certain risk of future structural damage, and the rating is a measure of how much a set of actions would reduce this risk. Table 8-7 gives a general framework of the rating scale.

Table 8-7. Rating Scale for Reduction of Risk to Structural Integrity.

Reduction of Risk to Structural Integrity (relative to base case)	Rating [$a_{n6}^{(ij)}$]
Neutral (no reduction)	0
Moderate	5
High	10

8.5 CALCULATION OF BENEFIT SCORE

After each set of actions has been rated under each of the six criteria, the benefit score can be calculated using a modified version of the WSM. As shown in Section 8.1.1, the desirability of an option is calculated by taking the sum of the ratings under each of the specified criteria multiplied by the respective weight assigned to each criterion (the weighted sum). In this framework, the benefit score of each action is calculated by multiplying the weighted sum by a factor based on the quantitative rating assigned to the associated bridge using the rating system presented in Chapter III. This system uses several parameters to formulate a numerical representation of the historical and engineering significance of a bridge. This, in effect, uses the importance of the bridge within the inventory as a weight factor in the prioritization of actions. The benefit score of each set is calculated by the following set of equations:

$$k^{(i)} = \frac{QR^{(i)}}{\sum_{i=1}^{N} QR^{(i)}} \tag{8.2}$$

$$WS_n^{(ij)} = \sum_{m=1}^{6} a_{nm}^{(ij)} \cdot W_m^{(i)} \tag{8.3}$$

$$B_n^{(ij)} = k^{(i)} \cdot WS_n^{(ij)} \tag{8.4}$$

where:

i	=	Bridge Number
j	=	Element Number
n	=	Action Set Number
m	=	Criterion Number
$k^{(i)}$	=	Importance Factor for Bridge *i*
$QR^{(i)}$	=	Quantitative Rating of Bridge *i*
N	=	Number of bridges in inventory
$WS_n^{(ij)}$	=	Weighted Sum for Action Set *n* on Element *j* of Bridge *i*
$a_{nm}^{(ij)}$	=	Rating under Criterion *m* of Action Set *n* on Element *j* of Bridge *i*
$W_m^{(i)}$	=	Weight assigned to Criterion *m* for Bridge *i*
$B_n^{(ij)}$	=	Benefit Score of Action Set *n* on Element *j* of Bridge i

8.6 ALLOCATION OF FUNDING

The benefit score is a measure of the total benefit of a set of actions weighted according to the historical and engineering significance of the bridge within the inventory. Once each benefit score is calculated, funding may then be allocated. Agencies must decide between the following two objectives when allocating funding:

1. <u>Maximize total benefit within the inventory</u>: To maximize the total benefit, sets of actions are prioritized strictly according to benefit score. With this method, the action sets that provide the most total benefit are ranked the highest, regardless of

cost. The highest rated remaining actions in the inventory should continue to be performed as long as the budget allows.

2. Maximize benefit-to-cost ratio: Benefit-to-cost ratio is maximized within the inventory by dividing each benefit score by the initial cost of the corresponding actions and prioritizing actions accordingly:

$$R_n^{(ij)} = \frac{B_n^{(ij)}}{C_n^{(ij)}} \cdot 10^6 \tag{8.5}$$

where:

$R_n^{(ij)}$ = Benefit-to-Cost Ratio of Action Set *n* on Element *j* of Bridge *i*

$C_n^{(ij)}$ = Cost of Action Set *n* on Element *j* of Bridge *i*

The first method ensures that the most beneficial actions are performed first, while the second aims to obtain the most benefit per dollar spent. The method should be chosen based on the goals and financial situation of the agency. Depending on the method chosen, the highest rated set of actions on each element (considered to be the optimal action set for that element) is placed on an inventory-wide ranking list. Thus the final result of the framework is a list consisting of the optimal action set for each element, ranked either by benefit score or by benefit-to-cost ratio.

Regardless of which ranking method is chosen, the highest ranked actions would ideally be performed first, but due to economies of scale, exceptions exist. Benefit scores and benefit-to-cost ratios should be used be a guideline for determining which actions should be funded first, but common sense and engineering judgment should be exercised to make exceptions when necessary. For example, it can be advantageous to perform multiple actions on a single bridge before tending to a second bridge even if an action on the second bridge rates slightly higher in priority. Multiple actions on a bridge can be submitted as a single project, saving the time and effort of receiving approval on multiple projects, while also saving money by limiting mobilization of construction crews. Performing similar actions on multiple bridges under a single contract could have the same effect, as it would likely save the agency money, as well as the time and effort that would otherwise be spent on receiving approval for each individual action.

In cases where further evaluation is chosen as the optimal action on an element, the next highest rated set of actions on the element should be given consideration after the evaluation is performed. Only one action set from each element is placed in the inventory-wide rankings, but once a further evaluation is performed, other actions on the element that were not originally included should be considered. Other actions may also need to be reevaluated given new information from the further evaluation.

8.7 REVIEW OF METHODOLOGY

To implement the resource allocation framework to prioritize sets of actions within a bridge inventory, the following steps should be followed:

1. For each element (deck, deck overlay, deck joints, rails, superstructure, abutments, piers and bents, footings, waterway) of each bridge in the inventory, determine all available sets of actions including non-routine maintenance, rehabilitation, repair, replacement, and further evaluation. Action sets should be exclusive (only one set can be chosen for each element).
2. Based on the characteristics and surroundings of the bridge of concern, assign weights ($W_m^{(i)}$) to each criterion for each bridge, the sum of which should equal 1. For example, commercial value would be weighted higher for a bridge in a downtown area than a rural bridge, and historic integrity would be weighted more for a bridge on or eligible for the NRHP.
3. Using past data and trends and possibly the Delphi method, rate each set of actions ($a_{nm}^{(ij)}$) under each of the six criteria as discussed in Section 8.4.
4. Calculate the benefit score ($B_n^{(ij)}$) of each action set using the modified weighted sum model as shown in Section 8.5.
5. Prioritize actions within the inventory using one of the two methods presented in Section 8.6 and place the highest rated set of actions from each element on an inventory-wide list. Begin the proposal process for the highest rated actions as allowed by the budget. Consider making exceptions due to economies of scale;

for example, performing multiple actions on a single bridge or similar actions on multiple bridges may prove to be cheaper and more efficient.

8.8 APPLICATION EXAMPLE

This section presents a hypothetical example of how the resource allocation framework would be implemented to prioritize sets of actions within an inventory.

8.8.1 Bridge Inventory

For the sake of brevity, this example will use an inventory of three bridges. Most historic bridge inventories are larger, but an inventory of this size is sufficient to show how the framework can be used. The owning agency in this example has a budget of $4 million to spend on bridge work outside of routine maintenance.

8.8.1.1 Bridge 1: Steel Plate Girder

Bridge 1 is a steel plate girder bridge located in a downtown area and is known as a local landmark. It is listed as eligible for the NRHP and received a quantitative rating of 95. It carries a high daily traffic volume but in the case of a detour, several alternate routes would be available. Significant fatigue cracking is detected in the girders, especially in one of the exterior girders. Moderate corrosion and paint failure also exist throughout the superstructure. The deck overlay shows significant wear, and some of the deck joints have leaks. Scour is a minor issue at the bases of the piers. The bridge has undergone routine maintenance and has been repainted in the past but no significant rehabilitative actions have been performed.

8.8.1.2 Bridge 2: Concrete Girder

Bridge 2 is a concrete girder bridge crossing a river in a rural area on a farm-to-market road. It is over 60 years old but does not hold any particular historical or artistic significance, and received a quantitative rating of 67. The engineering technology used to design and construct a bridge of its span length was notable at the time it was made, giving it some engineering significance. It is not in close proximity to any businesses nor does it carry a large traffic load, but it is important to the road network as it is the only bridge crossing the river for several miles. Some cracking has developed in tension zones on the top and bottom of the deck, and the girders show cracking and spalling in tension areas. Efflorescence is present in both the superstructure and substructure, and the piers show significant wear near the water surface. The concrete rails were replaced several years ago but no other notable work has been performed.

8.8.1.3 Bridge 3: Concrete Arch

Bridge 3 is a concrete arch bridge located in a suburban area near several businesses. It is listed as eligible for the NRHP, received a quantitative rating of 80, and is generally well-liked by the community. It carries a moderate traffic load and is considered to be relatively important to the road network. It is in acceptable condition overall and has not undergone any significant repairs in the past. Erosion and debris buildup are somewhat of a problem in the waterway, and cracking has developed in the tension zones of the arch. The original concrete rails have also deteriorated. The bridge carries only two lanes, but transportation engineers have determined that it would ideally carry four due to increased traffic in recent years. The width of the bridge poses somewhat of a safety hazard, as the narrow approaches have been the cause of several accidents in the past.

The following subsections show how each step of the resource allocation framework would be carried out to prioritize actions within an inventory. It should be noted that when the framework is used on a real inventory, the research and analysis involved in assigning weights and ratings should go far beyond the level discussed in the proceeding subsections. This example is only meant to give a general idea of how the arithmetic of the methodology works.

8.8.2 Step 1: List Available Sets of Actions

After consulting bridge engineers, the list of action sets shown in Table 8-8 are compiled. It should be noted that in many situations, the number of available actions listed may be greater than in this example. Because the example is only intended to show how the framework is to be used, the quantity of actions to consider is kept at a minimum.

Table 8-8. for Application Example Available Sets of Actions.

Bridge	Element	Actions
1. Steel Plate Girder	1. Deck	1. Inspect with ground-penetrating radar (GPR)
	2. Deck Overlay	1. Replace overlay
	3. Deck Joints	1. Reseal leaking joints
		2. Replace only leaking joints
		3. Replace all joints
	4. Rails	None
	5. Superstructure	1. Remove corrosion and repaint girders
		2. Remove corrosion, repair fractures, and repaint girders
		3. Remove corrosion, repair fractures, repaint girders, and replace exterior girder
	6. Abutments	None
	7. Piers/Bents	1. Install collars to prevent further scour
	8. Footings	1. Place sandbags to prevent further scour
	9. Waterway	None
2. Concrete Girder	1. Deck	1. Repair cracks with interior reinforcement
		2. Repair cracks with exterior reinforcement
	2. Deck Overlay	None
	3. Deck Joints	None
	4. Rails	None
	5. Superstructure	1. Remove efflorescence and patch spalling
		2. Remove efflorescence, patch spalling, and repair cracks with interior reinforcement
		3. Remove efflorescence, patch spalling, and repair cracks with exterior reinforcement
	6. Abutments	1. Remove efflorescence
	7. Piers/Bents	1. Remove efflorescence
		2. Remove efflorescence and install jacketing
	8. Footings	None
	9. Waterway	None

Table 8-8. Continued.

Bridge	Element	Actions
3. Concrete Arch	1. Deck	1. Replace deck and widen bridge to four lanes
	2. Deck Overlay	None
	3. Deck Joints	None
	4. Rails	1. Patch deteriorated areas with concrete of matching color
		2. Replace rails
	5. Superstructure	1. Drill and plug cracks in arch
		2. Repair cracks with interior reinforcement
		3. Inspect with remote acoustic testing
	6. Abutments	None
	7. Piers/Bents	None
	8. Footings	None
	9. Waterway	1. Install riprap to slow erosion

8.8.3 Step 2: Assign Weights to Criteria

For the steel plate girder bridge, the baseline values for a downtown bridge with a high traffic load are slightly modified to give more weight to historic integrity because it is eligible for the NRHP. The concrete girder bridge uses the baseline weights for a low-traffic peripheral bridge. Weights for the concrete arch are distributed subjectively because it does not fit into any of the baseline categories. Because the bridge is eligible for the NRHP, extra weight is given to historic integrity. Utility, functionality, and commercial value are also considered to be important as the bridge beautifies the area and is important in carrying traffic to nearby businesses. Weights are shown in Table 8-9.

Table 8-9. Weights Assigned to Criteria for Application Example.

Bridge	Life-Cycle Cost	Commercial Value	Utility/ Functionality	Aesthetic Value	Historic Integrity	Risk Reduction
1. Steel Plate Girder	0.13	0.18	0.12	0.16	0.30	0.10
2. Concrete Girder	0.20	0.05	0.23	0.12	0.25	0.15
3. Concrete Arch	0.15	0.15	0.15	0.15	0.23	0.17

8.8.4 Step 3: Rate Action Sets Under Criteria

After assigning weights to the criteria, each of the actions are rated under the six criteria and results are shown in Tables 8-10 through 8-12.

8.8.4.1 Criterion 1: Reduction of Life-Cycle Cost

Past data and trends are first used to make estimates as to how each set of actions would impact the future costs of maintaining the bridge. This criterion is rated on a scale of 0 to 10. In general, the action sets with the broadest scopes were found to have the largest effect, but some actions such as replacing deck joints and repairing cracks also received commendable ratings. For the deck of the steel plate girder bridge, replacing the overlay is found to have a moderate effect on the life-cycle cost, and it is assigned a rating of 5. For the deck joints, Action Set 1 (reseal leaking joints) would only temporarily stop the leaks, earning a rating of 2. Action Set 2 (reseal only leaking joints) would have more of a positive effect, and Action Set 3 (replace all joints) even more, earning ratings of 3 and 5, respectively. For the superstructure, Action Set 1 (remove corrosion and repaint girders) is issued a rating of 4, while Action Sets 2 (remove corrosion, repair fractures, repaint) and 3 (same as 2 plus replace exterior girder) are predicted to have greater effects, earning ratings of 6 and 8, respectively. For the piers and footings, both action sets (add collars, place sandbags) are determined to have a small effect, earning ratings of 3. The action sets on the other two bridges are evaluated similarly, and ratings are shown in Tables 8-10 through 8-12.

8.8.4.2 Criterion 2: Impact on Commercial Value

The action sets are next rated on a scale from 0 to 10 for impact on the commercial value of the bridges. This could be done through the use of engineering judgment, past trends, and the Delphi method. For the overlay of Bridge 1, research suggests that replacing the overlay would slightly increase the commercial value of the bridge by extending its service life and improving the smoothness of the driving surface, thus it is issued a rating of 3. The actions on the deck joints are all determined to have a minimal effect, earning ratings of 1, 2, and 3, respectively. For the superstructure, Action Set 1 (remove corrosion and repaint girders) is found to have a greater effect because it improves the outward appearance of the bridge while extending the service life, earning a rating of 6. The other two action sets on the superstructure meet the same needs while further extending the service life, earning ratings of 7 and 8, respectively. The scour prevention actions are both determined to have minimal effects and are assigned ratings of 2. Action sets on Bridges 2 and 3 are rated in a manner similar to those on Bridge 1, and results are summarized in Tables 8-10 through 8-12.

8.8.4.3 Criterion 3: Impact on Utility and Functionality

After rating the actions under the commercial value criterion, the agency then evaluates the impact that each would have on the utility and functionality of the bridge. This criterion uses a scale ranging from 0 to 10. For the steel girder bridge, the actions on the deck overlay and joints (replace overlay, reseal leaking joints, replace leaking joints, replace all joints) would improve the condition of the driving surface while causing brief delays, earning ratings of 3, 2, 2, and 3, respectively. For the superstructure, Action Set 1 (remove corrosion and repaint girders) is found to slightly improve the current condition of the bridge and prevents future corrosion without requiring detours or significantly delaying traffic, earning a rating of 4. Action Sets 2 (remove corrosion, repair fractures, repaint) and 3 (same as 2 plus replace exterior girder) would have the same effect but to a further extent, and are assigned ratings of 7 and 8, respectively. Actions on the piers and footings (add collars, place sandbags) would likely help prevent future scour-related problems and are both assigned a rating of 4. Ratings for the sets of actions on the other bridges are assigned using similar reasoning. Tables 8-10 through 8-12 summarize the ratings issued for utility and functionality.

8.8.4.4 Criterion 4: Impact on Aesthetic Value

The agency next assesses the impact of each action on the aesthetic value of the bridge using a rating scale from -5 to 5. Many of the actions are determined to have no effect on the outward appearance of the bridge and are given neutral ratings of 0. Actions such as replacing the overlay of Bridge 1 and removing efflorescence from Bridge 2 are determined to slightly improve the appearance of the bridges, earning ratings of 1. Other actions such as repainting the girders of Bridge 1 and repairing or replacing the rails of Bridge 3 receive ratings of 3 or 4 for a greater aesthetic improvement. Adding riprap or exterior reinforcement would detract from the appearance of the bridges, thus these actions are assigned negative ratings. Aesthetic value ratings are summarized in Tables 8-10 through 8-12.

8.8.4.5 Criterion 5: Preservation of Historic Integrity

The next factor to be considered is preservation of historic integrity. This criterion uses a rating scale ranging from -10 to 0. Many of the actions are determined to have no adverse effect on the historical aspects of the bridges, thus earning ratings of 0 for full preservation. Actions that involve patching of concrete such as adding reinforcement and repairing spalling are deducted points. Action sets that involve replacement of members and addition of new materials are given lower ratings. Historic integrity ratings are summarized in Tables 8-10 through 8-12.

8.8.4.6 Criterion 6: Reduction of Risk to Structural Integrity

The final factor considered is the degree to which each set of actions could reduce the risk of future structural damage to the bridge. Each set of actions is rated from 0 to 10. Some action sets only temporarily fix or fail to address certain issues and pose a risk of deterioration in the future. For example, removing the corrosion and repainting the girders of the steel girder bridge address the issues of corrosion and paint failure but ignores the fatigue cracking, thus it is given a rating of 4. Other actions, such as replacing the deck of the concrete arch bridge, fully fix the problems with the element and are assigned higher ratings. Actions involving further evaluation receive moderate ratings because they reduce uncertainty regarding the condition of elements. Another consideration is the information that some actions may reveal. For example, adding interior reinforcement to concrete elements requires some removal of concrete, which may uncover interior defects that had previously gone unnoticed. Sets of actions such as this are assigned slightly higher ratings. Risk reduction ratings are summarized in Tables 8-10 through 8-12.

Table 8-10. Ratings for Bridge 1 Actions.

Element	1. Deck	2. Deck Overlay	3. Deck Joints			5. Superstructure			7. Piers/Bents	8. Footings
Criteria / Action(s)	1. Inspect with GPR	1. Replace overlay	1. Reseal leaking joints	2. Replace leaking joints	3. Replace all joints	1. Remove corrosion, repaint	2. Remove corrosion, repair fractures, repaint	3. Remove corrosion, repair fractures, repaint, replace girder	1. Install collars	1. Place sandbags
1. Life-Cycle Cost	0	5	2	3	5	4	6	8	3	3
2. Commercial Value	0	3	1	2	3	6	7	8	2	2
3. Utility/ Functionality	0	3	2	2	3	4	7	8	4	4
4. Aesthetic Value	0	1	0	0	0	3	3	4	0	0
5. Preservation of Historic Integrity	0	0	0	0	0	0	0	-6	0	0
6. Risk Reduction	5	4	3	5	6	5	7	9	3	2

Table 8-11. Ratings for Bridge 2 Actions.

Criteria \ Element / Action(s)	1. Deck: 1. Interior reinforcement	1. Deck: 2. Exterior reinforcement	5. Superstructure: 1. Remove efflorescence, patch spalling	5. Superstructure: 2. Remove efflorescence, patch spalling, add interior reinforcement	5. Superstructure: 3. Remove efflorescence, patch spalling, add exterior reinforcement	6. Abutments: 1. Remove efflorescence	7. Piers/Bents: 1. Remove efflorescence	7. Piers/Bents: 2. Remove efflorescence , install jacketing
1. Life-Cycle Cost	6	5	3	6	6	1	1	3
2. Commercial Value	5	5	2	6	5	1	1	2
3. Utility/ Functionality	5	5	3	5	6	1	1	2
4. Aesthetic Value	0	-1	1	1	1	1	1	1
5. Preservation of Historic Integrity	-2	-3	-2	-3	-4	0	0	-2
6. Risk Reduction	6	6	2	7	7	1	1	4

Table 8-12. Ratings for Bridge 3 Actions.

Criteria	Element: 1. Deck	4. Rails		5. Superstructure			9. Waterway
Action(s)	1. Widen deck	1. Patch rails	2. Replace rails	1. Drill and plug cracks	2. Interior reinforcement	3. Inspect with remote acoustic testing	1. Install riprap
1. Life-Cycle Cost	4	1	3	6	7	0	2
2. Commercial Value	8	5	6	3	3	0	1
3. Utility/ Functionality	10	1	6	6	7	0	4
4. Aesthetic Value	1	3	4	0	0	0	-2
5. Preservation of Historic Integrity	-10	-6	-10	-2	-2	0	-5
6. Risk Reduction	9	2	5	6	7	5	2

8.8.5 Step 4: Calculate Benefit Scores

After each action set is rated under the six criteria, benefit scores are calculated by multiplying the weighted sum for each set of actions by the importance factor of the corresponding bridge. For example, the benefit score of Action Set 2 on the superstructure (Element 5) of Bridge 1 is calculated as follows:

$$k^{(1)} = \frac{QR^{(1)}}{\sum_{i=1}^{3} QR^{(i)}} = \frac{95}{95+67+80} = 0.39 \tag{8.6}$$

$$WS_2^{(15)} = \sum_{m=1}^{6} a_{2m}^{(15)} \cdot W_m^{(1)} = 6(0.13)+7(0.18)+7(0.12)+3(0.16)+0(0.30)+7(0.10) = 4.06 \tag{8.7}$$

$$B_2^{(15)} = k^{(1)} \cdot WS_2^{(15)} = (0.39)(4.06) = 1.59 \tag{8.8}$$

8.8.6 Step 5: Prioritize Actions and Allocate Funding

After the benefit score is calculated for each set of actions, the optimal action set on each element is placed in the inventory-wide rankings of actions. The rankings can be made based on either benefit score (total benefit) or benefit-to-cost ratio. Table 8-13 shows benefit scores and benefit-to-cost ratios for all action sets. The rating of the optimal action set according to both parameters for each element is listed in bold and placed in the inventory-wide rankings shown in Tables 8-14 and 8-15. It should be noted that for most elements, the optimal set of actions is different depending on whether benefit score or benefit-to-cost ratio is used as the deciding parameter.

8.8.6.1 Method 1: Maximize Total Benefit

Table 8-14 shows the optimal sets of action for each element ranked according to benefit score. The first six action sets on the list would cost the agency a total of $2.65 million, leaving $1.35 million to spend. Because the action in the rankings (replace deck and widen Bridge 3) is too expensive, the next highest ranked actions should be performed as allowed by the budget. If this method of ranking was chosen, the six most beneficial action sets in the inventory could be performed (1-6), followed by other lower ranked actions (8, 11). To save time and money, the agency could consider combining multiple actions into one contract. For example, several actions involve adding interior or exterior reinforcement and could be performed as a single contract.

8.8.6.2 Method 2: Maximize Benefit-to-Cost Ratio

Table 8-15 shows the optimal sets of action for each element ranked according to benefit-to-cost ratio. This method focuses on maximizing the benefit gained per dollar spent. Using this method, the agency could afford all of the optimal action sets (1-13) except the widening of Bridge 3, the lowest ranked action in the inventory.

Table 8-13. Benefit Scores and Benefit-to-Cost Ratios.

Bridge	Bridge Importance Factor [$k^{(i)}$]	Element	Action Set	Weighted Sum [$WS_n^{(ij)}$]	Benefit Score [$B_n^{(ij)}$]	Cost [$C_n^{(ij)}$]	Benefit-to-Cost Ratio [$R_n^{(ij)}$]
1	0.39	1	1	0.50	0.20	$10,000	19.6
		2	1	5.91	2.32	$500,000	4.64
		3	1	4.68	1.84	$20,000	91.9
			2	5.09	2.00	$100,000	20.0
			3	5.75	2.26	$200,000	11.0
		5	1	6.86	2.69	$1,000,000	2.69
			2	4.06	1.59	$1,500,000	1.06
			3	6.78	2.66	$3,000,000	0.89
		7	1	5.33	2.09	$100,000	20.9
		8	1	5.23	2.05	$50,000	41.1
2	0.28	1	1	5.80	1.61	$600,000	2.68
			2	5.23	1.45	$500,000	2.90
		5	1	4.41	1.22	$100,000	12.2
			2	5.87	1.63	$700,000	2.32
			3	5.80	1.61	$800,000	2.01
		6	1	3.85	1.07	$80,000	13.3
		7	1	3.85	1.07	$100,000	10.7
			2	4.33	1.20	$500,000	2.40
3	0.33	1	1	5.56	1.84	$8,000,000	0.23
		4	1	3.51	1.16	$300,000	3.87
			2	4.28	1.41	$1,000,000	1.41
		5	1	5.52	1.82	$500,000	3.65
			2	5.99	1.98	$800,000	2.48
		9	1	2.99	0.99	$150,000	6.59

Table 8-14. Ranking of Optimal Actions According to Benefit Score.

Rank	Bridge	Element	Optimal Action Set	Cost	Benefit Score
1	1	5. Superstructure	1. Remove corrosion, repaint	$1,000,000	2.69
2	1	2. Deck Overlay	1. Replace overlay	$500,000	2.32
3	1	3. Deck Joints	3. Replace all joints	$200,000	2.26
4	1	7. Piers/Bents	1. Install collars to prevent further scour	$100,000	2.09
5	1	8. Footings	1. Place sandbags to prevent further scour	$50,000	2.05
6	3	5. Superstructure	2. Repair cracks with interior reinforcement	$800,000	1.98
7	3	1. Deck	1. Replace deck and widen bridge to four lanes	$8,000,000	1.84
8	2	5. Superstructure	2. Remove efflorescence, patch spalling, repair cracks with interior reinforcement	$800,000	1.63
9	2	1. Deck	1. Repair cracks with interior reinforcement	$600,000	1.61
10	3	4. Rails	2. Replace rails	$1,000,000	1.41
11	2	7. Piers/Bents	2. Remove efflorescence, install jacketing	$500,000	1.20
12	2	6. Abutments	1. Remove efflorescence	$80,000	1.07
13	3	9. Waterway	1. Install riprap to slow erosion	$150,000	0.99
14	3	5. Superstructure	3. Inspect with remote acoustic testing	$25,000	0.28

Table 8-15. Ranking of Optimal Action Sets According to Cost-to-Benefit Ratio.

Rank	Bridge	Element	Optimal Action Set	Cost	Benefit-to-Cost Ratio
1	1	3. Deck Joints	1. Reseal leaking joints	$20,000	91.9
2	1	8. Footings	1. Place sandbags to prevent further scour	$50,000	41.1
3	1	7. Piers/Bents	1. Install collars to prevent further scour	$100,000	20.9
4	1	1. Deck	1. Inspect with GPR	$10,000	19.6
5	2	6. Abutments	1. Remove efflorescence	$80,000	13.3
6	2	5. Superstructure	1. Remove efflorescence and patch spalling	$100,000	12.2
7	3	5. Superstructure	3. Inspect with remote acoustic testing	$25,000	11.2
8	2	7. Piers/Bents	1. Remove efflorescence	$100,000	10.7
9	3	9. Waterway	1. Install riprap to slow erosion	$150,000	6.59
10	1	2. Deck Overlay	1. Replace overlay	$500,000	4.64
11	3	4. Rails	1. Patch deteriorated areas with concrete of matching color	$300,000	3.87
12	2	1. Deck	2. Repair cracks with exterior reinforcement	$500,000	2.90
13	1	5. Superstructure	1. Remove corrosion and repaint girders	$1,000,000	2.69
14	3	1. Deck	1. Replace deck and widen bridge to four lanes	$8,000,000	0.23

8.9 SUMMARY

In general, bridge-owning agencies do not possess the funding necessary to properly preserve every historic bridge. Choices must be made as to which preservation efforts are the most urgent and beneficial. The resource allocation methodology presented in this chapter is designed to help agencies obtain the most benefit from limited resources. By taking into account monetary costs as well as commercial value, aesthetic value, functionality, historic integrity, and risk, the methodology may be used by agencies to efficiently distribute funding among bridges in an inventory. Bridge deterioration is inevitable, but proactive planning and smart spending, as encouraged by this framework, increases the likelihood of historic bridge inventories being preserved for years to come.

CHAPTER IX

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 SUMMARY

Historic bridges provide aesthetic, artistic, and commercial value to their surroundings while also serving the purpose of carrying traffic. Ideally, they would be properly preserved for the use and enjoyment of future generations. In reality, historic bridges are often replaced because adequate funding for preservation is not available. Deterioration is an inevitable process in bridges, but proper bridge management can slow the process. This thesis provides a framework that can help bridge-owning agencies make better decisions in managing a historic bridge inventory and make the most efficient use of available funding.

The first step of the framework is the prioritization of bridges. Identifying and prioritizing the most significant structures in the inventory is necessary before taking further action. Chapter III presents a methodology for ranking bridges within an inventory based on engineering and historical significance and illustrates the use of the methodology on the inventory of Tarrant County, Texas.

The second step of the framework is the identification of funding sources. Funding may come from a variety of sources, including state and federal grant or loan programs, as well as public-private partnerships. Chapter IV provides guidance on the financial and legal procedures involved in proposing and implementing work on historic bridges.

The framework also includes a review and summary of condition assessment practices and rehabilitation, repair, and maintenance techniques. Early detection of problems is especially important in older bridges, therefore condition assessment should go beyond routine inspections and may include advanced non-destructive methods and structural health monitoring systems. Mitigation strategies should be implemented with special attention paid to preservation of historic integrity. Chapter VII provides a template for individual bridge preservation plans that include the current condition of the bridge, recommended actions based on the current condition, regular interval maintenance, and condition-based actions to be taken according to the condition of the bridge in the future.

Chapter VIII presents a resource allocation framework. In most cases, mitigation of all problems within a bridge inventory is not economically feasible. For this reason, it is helpful for agencies to have a method of prioritizing actions. The methodology presented in Chapter VIII takes several criteria into account and focuses on distributing funding to the most significant bridges and the most beneficial actions.

9.2 CONCLUSIONS

Prioritization: As previously stated, the first component of the framework developed in this thesis is the prioritization of bridges. Throughout research conducted for this step, the following conclusions were drawn:

- The NBI historical significance rating is useful as a representation of the NRHP eligibility status of a bridge, but not as a measure of engineering and historical significance. In some cases, bridges may need to be reevaluated for NRHP eligibility and the historical significance should be updated accordingly.
- Historical significance and sufficiency ratings are not adequate parameters for an accurate prioritization of bridges. In this study, several bridges possessing commendable features would have been eliminated had these been used strictly as evaluation criteria. These parameters may be used for initial guidance, but a more specific methodology such as the quantitative rating system presented in Chapter III is recommended.
- Preservation efforts made in the past are useful as models, but should be modified to fit the inventory under evaluation. The evaluation matrix and quantitative rating system used in this study employed concepts from other projects modified to fit the needs of the current study.

Guidance and Funding: The next step of the framework focuses on funding sources and guidance regarding the procedures and agreements required for the proposal and implementation of bridge projects. This led to the following conclusions:

- Consideration of various options is important when procuring funding sources. Public-private partnerships should be considered in addition to traditional grant and loan programs.
- The proposal process for repair or rehabilitation of bridges should be set in motion as quickly as possible. Completion of all of the steps in the process of gaining funding and approval may take considerable time. In the case of historic bridges, any delay of actions leads to further deterioration that may be costly.

Condition Assessment: The next component of the framework deals with the condition assessment of historic bridges. Research of condition assessment practices yielded the following conclusions:

- Routine visual inspections are generally not adequate for the condition assessment of historic bridges. Problems that exist beneath the surface cannot be detected by visual inspection, therefore advanced non-destructive evaluation methods such as those discussed in Chapter V should be employed.
- Older bridges often require more frequent inspections, thus the intervals of inspection should be decreased from the required two years. Structural health monitoring systems may also be implemented as a means of receiving continuous feedback in between scheduled inspections.
- Early detection of problems is crucial in old bridges. Repair and rehabilitation are less expensive when performed at better condition states, therefore actions should be performed as early as possible.

Mitigation Strategies: The framework also includes an overview and summary of rehabilitation, repair, and maintenance techniques for historic bridges. This led to the following conclusions:

- Preventive maintenance is essential. In addition to maintaining the condition state of a bridge and reducing the likelihood of future member failures, it also lowers the life-cycle cost. Actions are less expensive to perform if implemented early, as cost is generally inversely proportional to condition state.
- Original materials and character-defining features should be preserved whenever possible. Laws require consideration of historic integrity when work is performed on NRHP-eligible bridges.

Resource Allocation: In the final step of the framework, a resource allocation methodology is presented. In the development of this methodology, the following conclusions were drawn:

- When considering possible actions, all benefits and costs should be considered, but the weight given to each should be carefully determined. Weights should be distributed according to the most important characteristics of the bridge of concern.
- The results of the methodology (as with any quantitative system) should be used as guidance, but exceptions should be considered. This methodology can be used to give bridge-owning agencies a general idea of what actions could carry the most benefit or marginal benefit, but engineering judgment should be employed when making final decisions.

9.3 RECOMMENDATIONS FOR IMPLEMENTATION

Several areas of the framework presented in this thesis use numerical rating systems to quantify abstract qualities. These systems should be used for guidance, but not followed blindly. For example, the evaluation matrix uses historical significance and sufficiency ratings to prioritize bridges, but these parameters do not always give a full representation of the significance of a bridge. Individual review may be necessary for a more thorough prioritization. Also, the resource allocation methodology takes several criteria into account when prioritizing actions within an inventory, but does not consider economies of scale. When using these systems, engineering judgment should always be factored into any decisions.

It is also recommended that bridge-owning agencies focus strongly on maintenance and early detection of problems, both of which are important because nearly all work is less expensive to perform at better condition states. Properly implemented maintenance plans can reduce both the life-cycle cost of bridges and the probability of serious problems in the future. Early detection of problems is crucial in historic bridges because it allows the issues to be mitigated before members reach a failed condition state.

A third recommendation for bridge-owning agencies is to focus on the inventory as a whole when allocating funding rather than on individual bridges. The goal should be to maximize benefit within the inventory, rather than on each bridge individually. Full preservation of all bridges may not always be feasible, but a "big picture" approach is the best way to ensure overall preservation of the inventory. Some bridges, however, may carry enough significance that they should be preserved at all costs. In these cases, exceptions may be necessary.

9.4 RECOMMENDATIONS FOR FUTURE WORK

Because this framework covers many different aspects of historic bridge preservation, there are several areas where future studies could provide more depth and detail. A methodology for determining the level of inspection necessary for individual bridges may be useful. Routine visual inspections may be adequate for some bridges, while others would benefit from some level of advanced testing. Installation of structural health monitoring systems may also be necessary. While this study only gives information on available methods, future studies could provide guidance on determining when and how to implement them.

Information on condition assessment and mitigation of prestressed concrete bridges may also be useful in the future. This study focused only on steel and reinforced concrete bridges because prestressed concrete bridges do not generally hold a great deal of historical or engineering significance. As they age, however, some may be worthy of historic preservation.

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APPENDIX A: CALCULATION OF FHWA SUFFICIENCY RATING

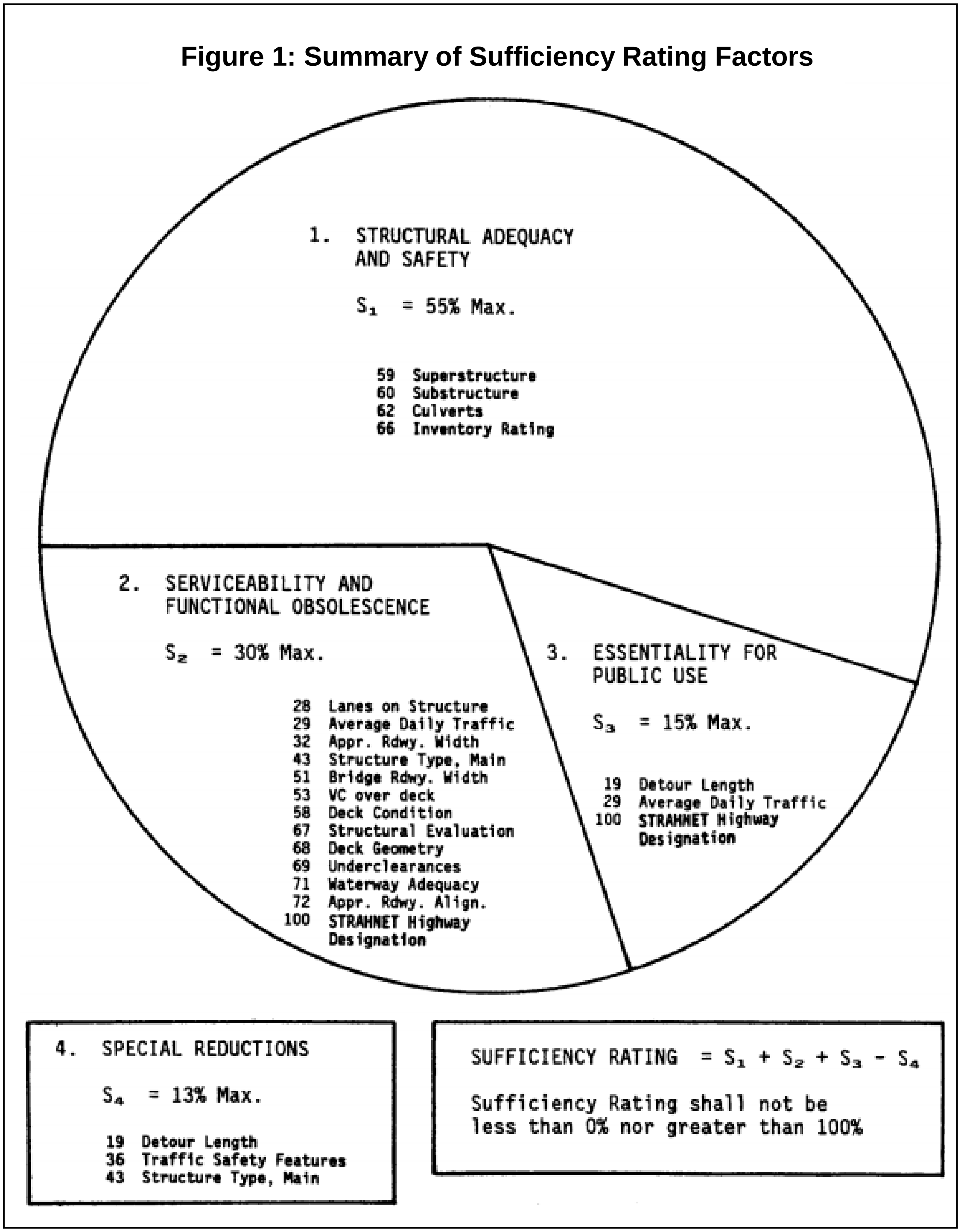


Figure A-1. Calculation of FHWA Sufficiency Rating (FHWA 1995).

1. Structural Adequacy and Safety (55% maximum)

a. Only the lowest rating code of Item 59, 60, or 62 applies.

If Item 59 (Superstructure Rating) or Item 60 (Substructure Rating) is

≤ 2	then	A = 55%
= 3		A = 40%
= 4		A = 25%
= 5		A = 10%

If Item 59 and Item 60 = N and Item 62 (Culvert Rating) is

≤ 2	then	A = 55%
= 3		A = 40%
= 4		A = 25%
= 5		A = 10%

b. Reduction for Load Capacity:

Calculate using the following formulas where IR is the Inventory Rating (MS Loading) in tons or use Figure 2:

$$B = (32.4 - IR)^{1.5} \times 0.3254$$

or

If $(32.4 - IR) \leq 0$, then $B = 0$

"B" shall not be less than 0% nor greater than 55%.

$$S_1 = 55 - (A + B)$$

S_1 shall not be less than 0% nor greater than 55%.

Figure A-2. Calculation of FHWA Sufficiency Rating (FHWA 1995).

Figure 2: Reduction for Load Capacity

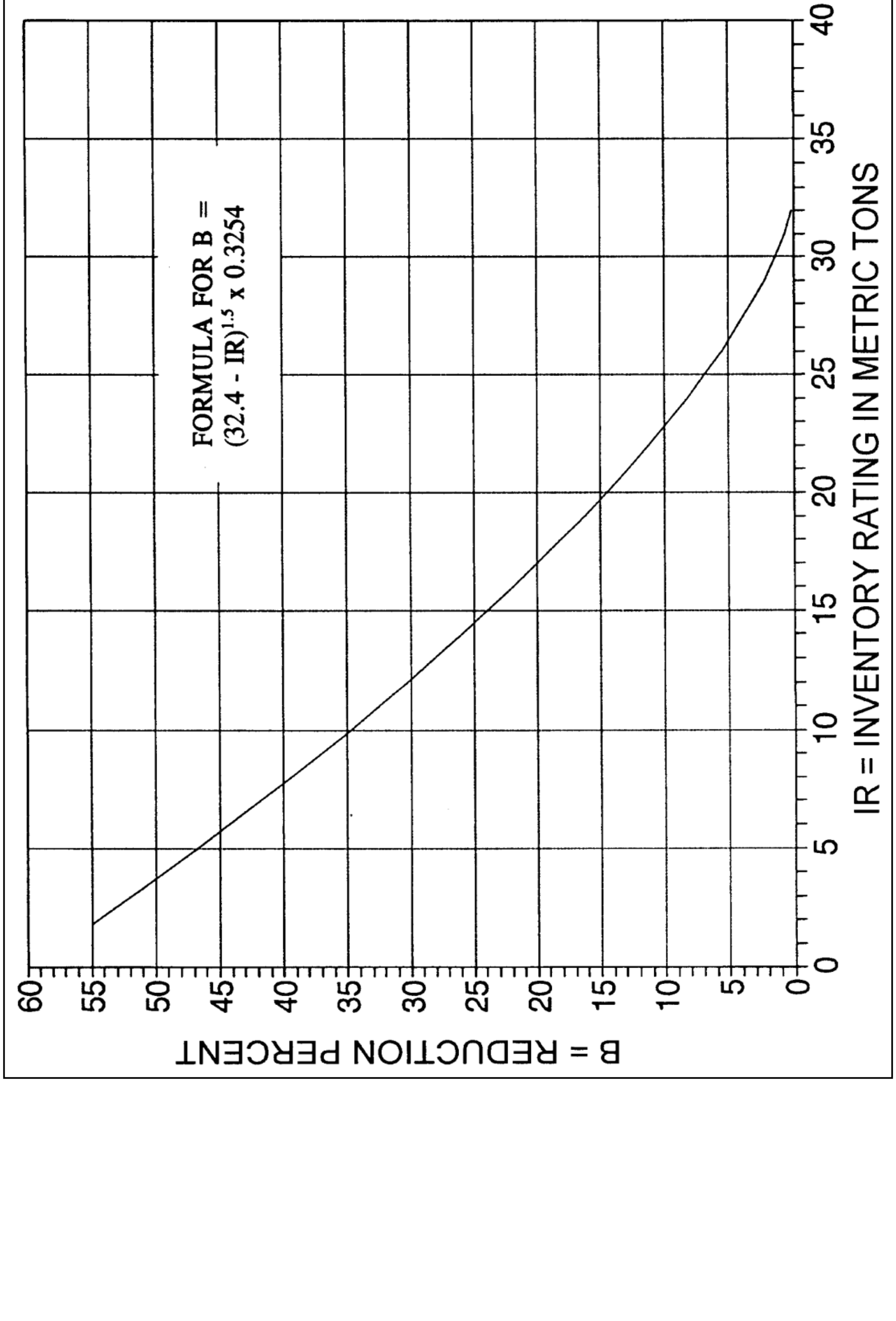


Figure A-3. Calculation of FHWA Sufficiency Rating (FHWA 1995).

2. Serviceability and Functional Obsolescence (30% maximum)

a. Rating Reductions (13% maximum)

If #58 (Deck Condition) is	≤ 3	then	A = 5%
	= 4		A = 3%
	= 5		A = 1%
If #67 (Structural Evaluation) is	≤ 3	then	B = 4%
	= 4		B = 2%
	= 5		B = 1%
If #68 (Deck Geometry) is	≤ 3	then	C = 4%
	= 4		C = 2%
	= 5		C = 1%
If #69 (Underclearances) is	≤ 3	then	D = 4%
	= 4		D = 2%
	= 5		D = 1%
If #71 (Waterway Adequacy) is	≤ 3	then	E = 4%
	= 4		E = 2%
	= 5		E = 1%
If #72 (Approach Road Alignment) is	≤ 3	then	F = 4%
	= 4		F = 2%
	= 5		F = 1%

J = (A + B + C + D + E + F)

J shall not be less than 0% nor greater than 13%.

b. Width of Roadway Insufficiency (15% maximum)

Use the sections that apply:

(1) applies to all bridges;
(2) applies to 1-lane bridges only;
(3) applies to 2 or more lane bridges;
(4) applies to all <u>except</u> 1-lane bridges.

Also determine X and Y:

$$X \text{ (ADT/Lane)} = \frac{\text{Item 29 (ADT)}}{\text{first 2 digits of \#28 (Lanes)}}$$

$$Y \text{ (Width/Lane)}^{*} = \frac{\text{Item 51 (Bridge Rdwy. Width)}}{\text{first 2 digits of \#28 (Lanes)}}$$

*A value of 10.9 Meters will be substituted when item 51 is coded 0000 or not numeric.

Figure A-4. Calculation of FHWA Sufficiency Rating (FHWA 1995).

(1) Use when the last 2 digits of #43 (Structure Type) are not equal to 19 (Culvert):

If(#51 + 0.6 meters) < #32 (Approach Roadway Width) G = 5%

(2) For 1-lane bridges only, use Figure 3 or the following:

If the first 2 digits of #28 (Lanes) are equal to 01 and

$Y < 4.3$ then $H = 15\%$

$Y \geq 4.3 < 5.5$ $H = 15\left[\frac{5.5-Y}{1.2}\right]\%$

$Y \geq 5.5$ $H = 0\%$

(3) For 2 or more lane bridges. If these limits apply, do not continue on to (4) as no lane width reductions are allowed.

If the first 2 digits of #28 = 02 and $Y \geq 4.9$, $H = 0\%$

If the first 2 digits of #28 = 03 and $Y \geq 4.6$, $H = 0\%$

If the first 2 digits of #28 = 04 and $Y \geq 4.3$, $H = 0\%$

If the first 2 digits of #28 $\geq$ 05 and $Y \geq 3.7$ $H = 0\%$

(4) For all <u>except</u> 1-lane bridges, use Figure 3 or the following:

If $Y < 2.7$ and $X > 50$ then $H = 15\%$

$Y < 2.7$ and $X \leq 50$ $H = 7.5\%$

$Y \geq 2.7$ and $X \leq 50$ $H = 0\%$

If $X > 50$ but ≤ 125 and

$Y < 3.0$ then $H = 15\%$

$Y \geq 3.0 < 4.0$ $H = 15(4-Y)\%$

$Y \geq 4.0$ $H = 0\%$

If $X > 125$ but ≤ 375 and

$Y < 3.4$ then $H = 15\%$

$Y \geq 3.4 < 4.3$ $H = 15(4.3-Y)\%$

$Y \geq 4.3$ $H = 0\%$

Figure A-5. Calculation of FHWA Sufficiency Rating (FHWA 1995).

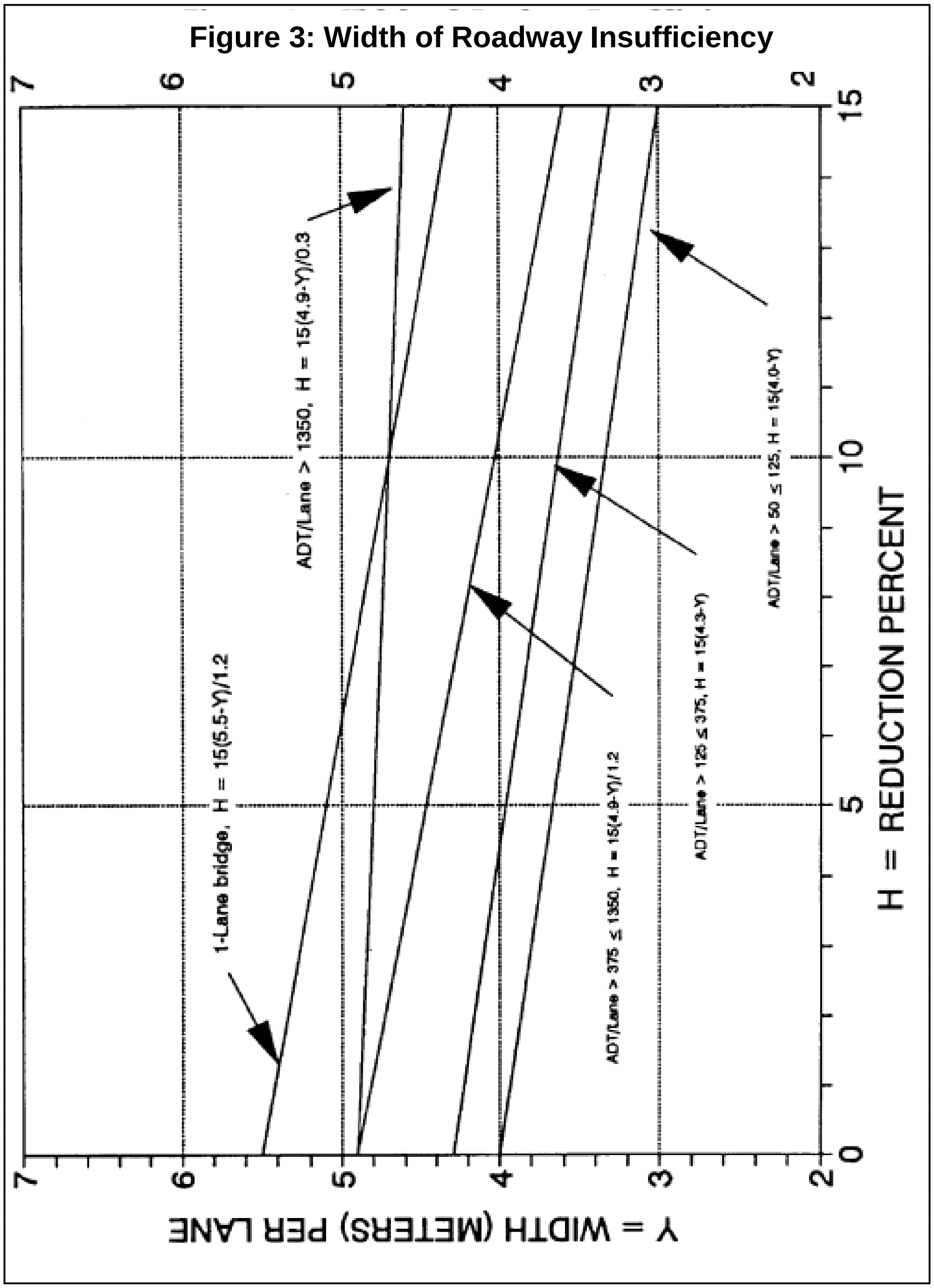


Figure A-6. Calculation of FHWA Sufficiency Rating (FHWA 1995).

If X > 375 but ≤ 1350 and

Y < 3.7	then	H =	15%
Y ≥ 3.7 < 4.9		H =	$15\left[\frac{4.9-Y}{1.2}\right]\%$
Y ≥ 4.9		H =	0%

If X > 1350 and

Y < 4.6	then	H =	15%
Y ≥ 4.6 < 4.9		H =	$15\left[\frac{4.9-Y}{1.2}\right]\%$
Y ≥ 4.9		H =	0%

G + H shall not be less than 0% nor greater than 15%.

c. Vertical Clearance Insufficiency - (2% maximum)

If #100 (STRAHNET Highway Designation) > 0 and

#53 (VC over Deck) ≥ 4.87	then	I = 0%
#53 < 4.87		I = 2%

If #100 = 0 and

#53 ≥ 4.26	then	I = 0%
#53 < 4.26		I = 2%

$S_2 = 30 - [\ J + (G + H) + I\ ]$

S_2 shall not be less than 0% nor greater than 30%.

3. Essentiality for Public Use (15% maximum)

a. Determine:

$$K = \frac{S_1 + S_2}{85}$$

Figure A-7. Calculation of FHWA Sufficiency Rating (FHWA 1995).

b. Calculate:

$$A = 15\left[\frac{\#29(ADT) x \#19(DetourLength)}{320{,}000 x K}\right]$$

"A" shall not be less than 0% nor greater than 15%.

c. STRAHNET Highway Designation:

If #100 is > 0 then B = 2%

If #100 = 0 then B = 0%

S_3 = 15 - (A + B)

S_3 shall not be less than 0% nor greater than 15%.

4. Special Reductions (Use only when $S_1 + S_2 + S_3 \geq 50$)

a. Detour Length Reduction, use Figure 4 or the following:

$A = (\#19)^4 \times (7.9 \times 10^{-9})$

"A" shall not be less than 0% nor greater than 5%.

b. If the 2nd and 3rd digits of #43 (Structure Type, Main) are equal to 10, 12, 13, 14, 15, 16, or 17; then

B = 5%

c. If 2 digits of #36 (Traffic Safety Features) = 0 C = 1%
If 3 digits of #36 = 0 C = 2%
If 4 digits of #36 = 0 C = 3%

S_4 = A + B + C

S_4 shall not be less than 0% nor greater than 13%.

Sufficiency Rating = $S_1 + S_2 + S_3 - S_4$

The Rating shall not be less than 0% nor greater than 100%.

Figure A-8. Calculation of FHWA Sufficiency Rating (FHWA 1995).

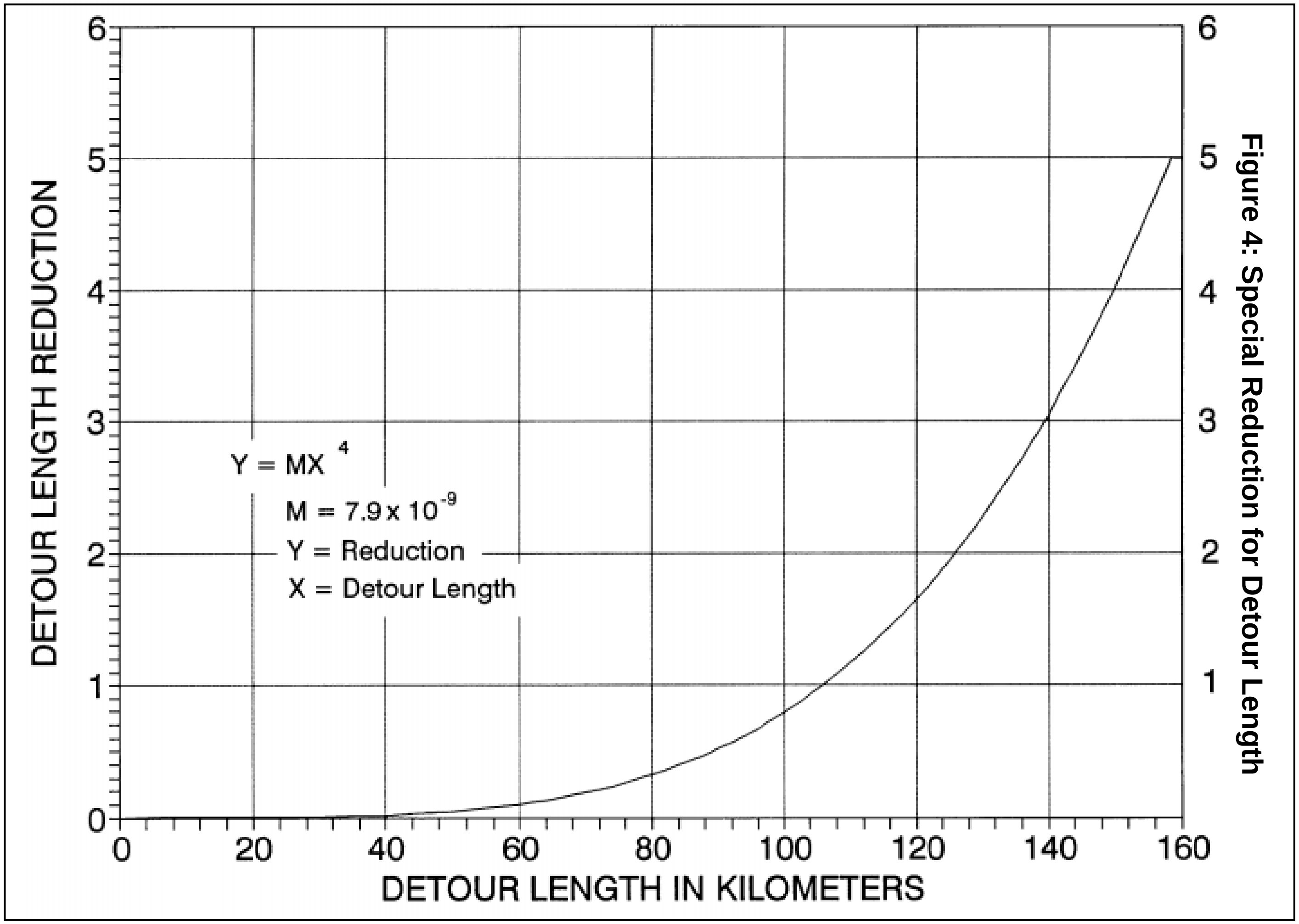


Figure A-9. Calculation of FHWA Sufficiency Rating (FHWA 1995).

APPENDIX B: QUANTITATIVE RATING SYSTEM FOR TxDOT HISTORIC BRIDGE INVENTORY SURVEY OF NON-TRUSS STRUCTURES

Table B-1. TxDOT Quantitative Rating System for Non-Truss Structures (TxDOT 1999).

Rating Category	Bridge Characteristic	Points
Year Built	1900-1920	40
	1920-1930	30
	1930-1940	20
	1940-1950	10
Length of Main Span	Steel I-Beam, >65 feet	20
	Steel I-Beam, >50 feet	10
	Concrete Girder, >45 feet	20
	Concrete Girder, >40 feet	10
	Concrete Slab, >30 feet	20
	Concrete Slab, >25 feet	10
Overall Bridge Length	Steel I-Beam, >520 feet	4
	Steel I-Beam, >340 feet	2
	Concrete Girder, >420 feet	4
	Concrete Girder, >100 feet	2
	Concrete Slab, >300 feet	4
	Concrete Slab, >200 feet	2
Rail Type	Types A-J	14
	Special Design	12
	Types K and L	10
	Type M	8
	Types P and Q	6
	Types R-8 and R-10	4
	Other post-1940 standard rail	2

Table B-1. Continued.

Rating Category	Bridge Characteristic	Points
Special Design	Decorative Elements	10
	Engineering Response	8
	Superstructure and Substructure	6
	Superstructure	4
	Substructure	2
Structural Integrity	Excellent (original design, materials, and workmanship unaltered)	8
	Good (minor damage of original design, materials, and workmanship)	6
	Fair (some replacement of original design, materials, and workmanship	4
Site Integrity	Excellent (original setting, feeling, and association unaltered)	8
	Good (minor alteration of original setting, feeling, and association)	6
	Fair (much change to original setting, feeling, and association)	4
Sufficiency Rating	Excellent to good	8
	Satisfactory to poor	6
	Serious to failed	4

APPENDIX C: DEDUCTIONS FOR HISTORIC INTEGRITY IN TxDOT 1945-1965 EVALUATION METHODOLOGY

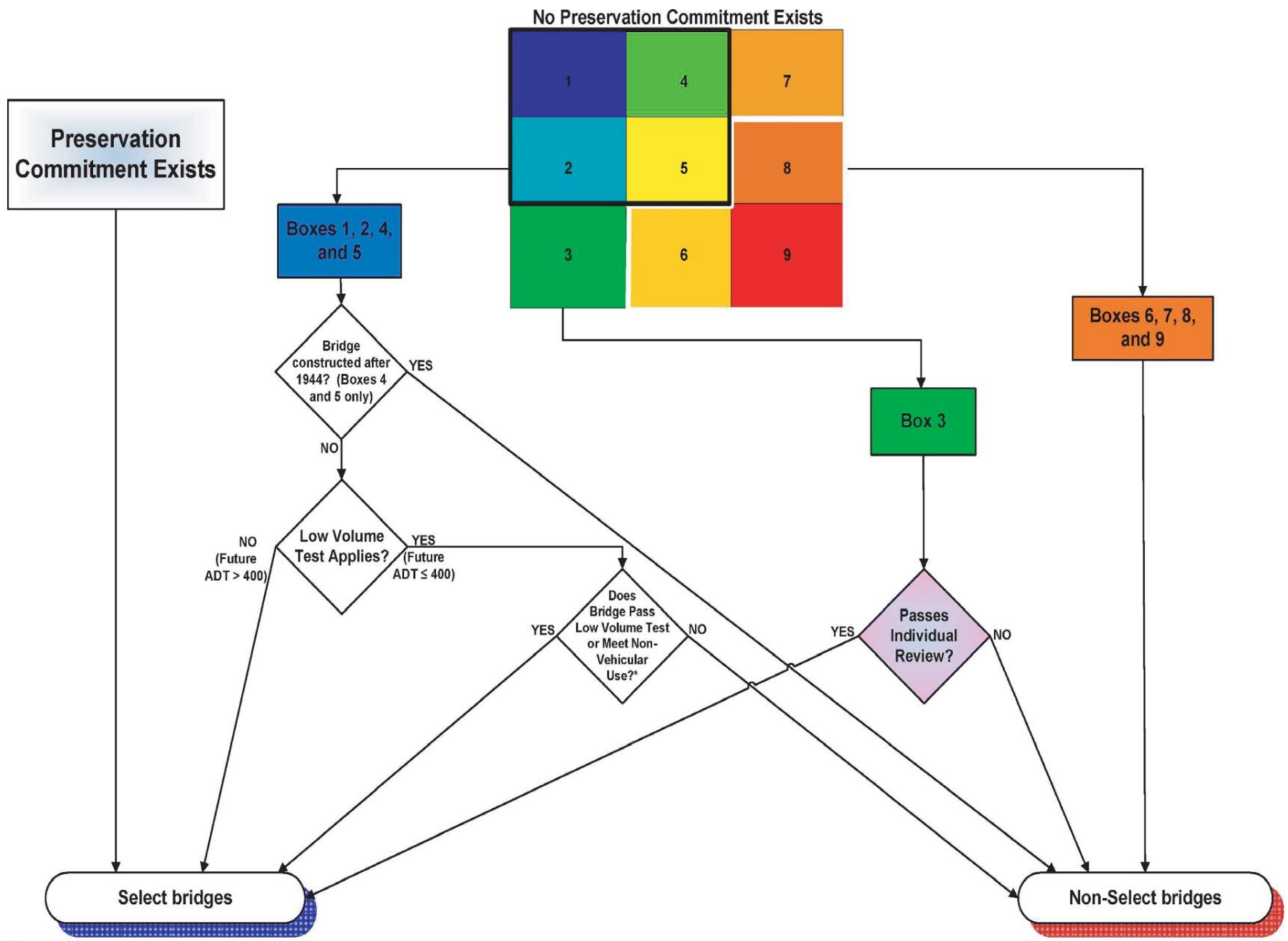
Table C-1. Deductions Under Criterion A (adapted from Mead & Hunt 2010).

Criterion A			
Aspects of Integrity	Degree of Alteration	Alterations	Points Deducted
Feeling, Association, and Setting	Major	Rural area that has been converted to an urban or developed area (does not apply to bridges on U.S. Highways or State Highways)	4
	Minor	Parallel bridge to accommodate widening	2
Location	-	Bridge relocated from original location	4
Materials, Workmanship, and Design	Severe	Widened bridge	4
	Major	- Lengthened bridge with new approach spans - Addition of new members - Replacement of original main members - Removal of main members that were integral to the superstructure - Repairs of structural connections not consistent with original connections - Removal of original architectural treatments, not including rails or parapets - Alterations to character-defining features of a bridge type	2
	Minor	- Historic railing removed and replaced with modern railing - Guardrail installed over historic railing - New rail installed on bridge that did not historically have railing - Installation of sidewalk extension	1

Table C-2. Deductions Under Criterion C (adapted from Mead & Hunt 2010).

Criterion C			
Aspects of Integrity	Degree of Alteration	Alterations	Points Deducted
Location	-	Bridge relocated from original location and does not retain character-defining features	4
	-	Bridge relocated from original location and retains character-defining features	2
Materials, Workmanship, and Design	Severe	Widened bridge	8
	Major	- Lengthened bridge with new approach spans - Addition of new members - Replacement of original main members - Removal of main members that were integral to the superstructure - Repairs of structural connections not consistent with original connections - Removal of original architectural treatments, not including rails or parapets - Alterations to character-defining features of a bridge type	4
	Minor	- Historic railing removed and replaced with modern railing - Guardrail installed over historic railing - New rail installed on bridge that did not historically have railing - Installation of sidewalk extension	2

APPENDIX D: FLOWCHART FOR INDIANA DOT PRIORITIZATION



* Bridges may pass Low Volume Test with or without exception. If the bridge type is suitable for relocation, then non-vehicular use will be considered.

Figure D-1. Flowchart for Indiana Prioritization (Rathke et al. 2010).

APPENDIX E: OHIO DOT NUMERICAL RATING SYSTEM FOR BRIDGES BUILT FROM 1941 TO 1950

Table E-1. Ohio DOT Numerical Rating System for Technological Significance (adapted from TranSystems 2010).

Rating Category	Bridge Characteristic	Points Assigned
Length of Individual Span	Pony Truss – 3 points for each span over 80 feet	12
	Pony Truss – 1 point for each span 50-80 feet	4
	Through Truss – 3 points for each span over 150 feet	12
	Through Truss – 1 point for each span 100-150 feet	4
	Concrete – 1 point for each span over 100 feet	6
Special Features	Decorative elements or railing (non-structural)	2
	Artistic treatment of structural elements	2
	Builder's distinctive structural elements	2
	Patented features (technology)	2
	Welded structural members – partial, bridges built 1941-1945	3
	Welded structural members – partial, bridges built 1946-1950	2
	Welded structural members – complete, bridges built 1941-1945	4
	Welded structural members – complete, bridges built 1946-1950	3

Table E-2. Ohio DOT Numerical Rating System for General Significance (adapted from TranSystems 2010).

Rating Category	Bridge Characteristic	Points Assigned
History	Association with Works Progress Administration	4
	Recipient of award for excellence in design or technology or use of material	4
	Built during 1941-1950 by Champion Bridge Co. master bridge builder	4
	Documentation of methods of construction or technology	4
	Older structure reused in 1941-1950	4
	Unknown	0
Integrity	Excellent	4
	Good	3
	Fair	2
Aesthetics	Excellent	4
	Good	3
	Fair	2

APPENDIX F: PROCEDURES FOR PROJECTS INVOLVING HISTORICALLY SIGNIFICANT BRIDGES

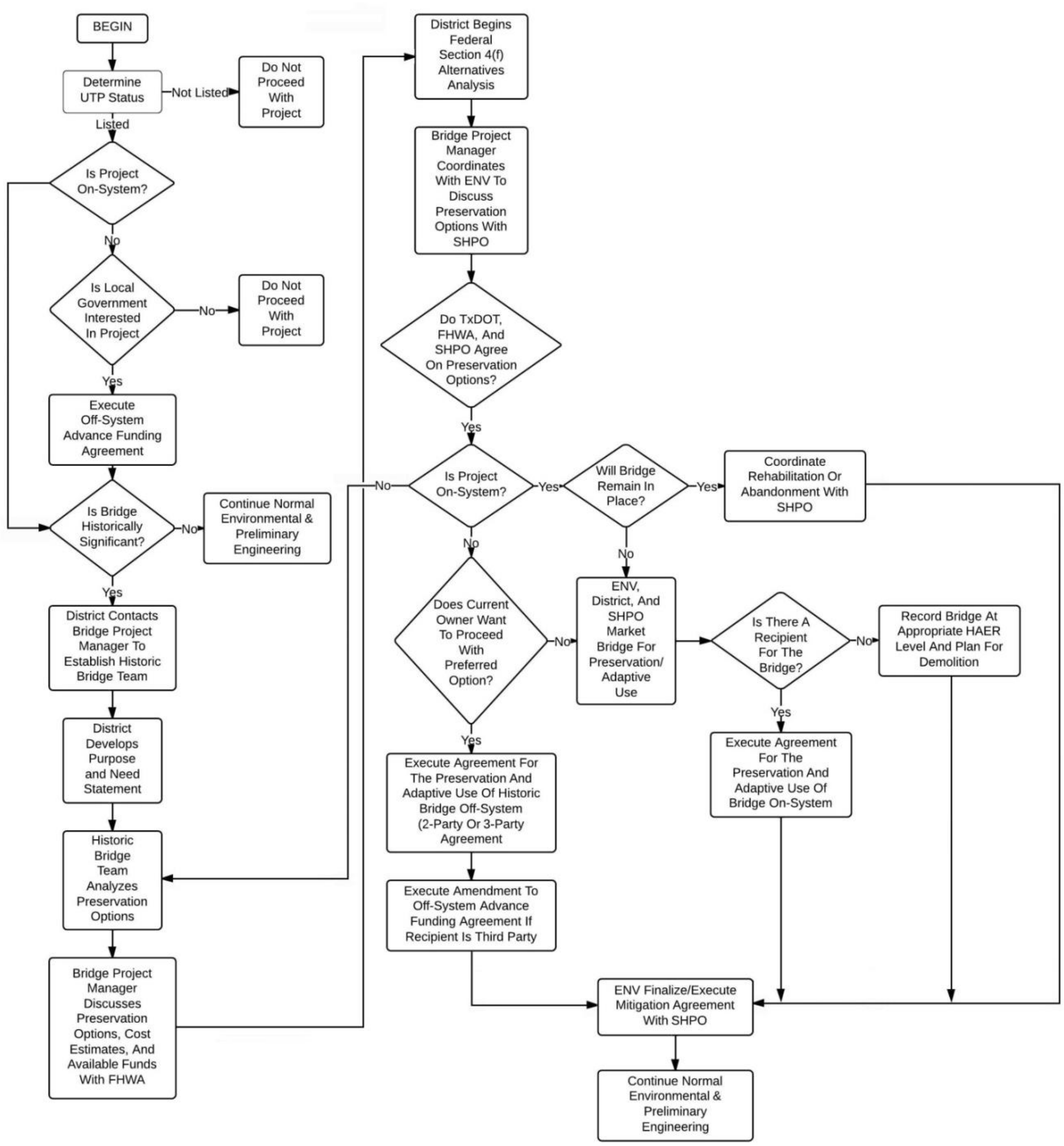


Figure F-1. Flowchart for Projects Involving Historically Significant Bridges (adapted from TxDOT 2010).

APPENDIX G: MINIMUM CRITERIA FOR CONTINUED VEHICULAR USE FOR OFF-SYSTEM HISTORICALLY SIGNIFICANT BRIDGES

Table G-1. Minimum Criteria for Continued Vehicular Use for Off-System Historically Significant Bridges (adapted from TxDOT 2010).

Current Average Daily Traffic (ADT)	Minimum Clear Roadway Width[1]		Minimum Load-Carrying Capacity (Operating Rating)	
	One-Lane, Two-Way Operations[2]	Two-Lane, Two-Way Operations	Alternate Route Available[5]	Alternate Route Not Available
ADT 100 or less	10 feet (3.0 m)	18 feet (5.4 m)	HS 5	HS 12[6]
ADT 101 to 250	10 feet (3.0 m)	18 feet (5.4 m)	HS 8	HS 12
ADT 251 to 400	Not Applicable[3]	18 feet (5.4 m)	HS 15	HS 15
ADT greater than 400	Not Applicable[3]	Not Applicable[4]	HS 15	HS 15

[1] For a minimum roadway length of 50 feet (15 meters) adjacent to the bridge end, roadway crown should match clear width across the structure plus additional width to accommodate guard fence if necessary.

[2] One-Land, Two-Way operations are assumed to allow for sight distance across the entire length of the structure. In cases where sight distance across the length of the structure is not available, the allowable minimum clear roadway width shall be the allowable minimum for Two-Lane, Two-Way operations.

[3] For ADT greater than 250, One-Lane, Two-Way operations on a structure are not permissible.

[4] For ADT greater than 400, use design standards as appropriate for the class of highway as shown within appropriate sections of the Roadway Design Manual.

[5] To allow these values, the identified alternate route must add no more than 5 miles (8 kilometers) to a trip for essential services such as school buses, and emergency fire and medical access. All bridges on the identified alternate route must have a minimum load rating of HS 12. Historic bridges which do not meet the state legal load limit shall be posted.

[6] HS 12 load rating was selected because it represents a typical minimum value for vehicles essential for educational, medical, and fire suppression services.