# CONCRETE BRIDGE PRIORITIZATION SYSTEM

by

**Debbie Anne Kesselring**

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**APPROVED:**

S. Thangjitham, Chairman

D. R. Drew

P. A. Alfieri

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Committee Chairman: Surot Thangjitham
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(ABSTRACT)

An alternative method of prioritization for concrete bridge maintenance, repair, and rehabilitation activities is required due to the inability of the current system to manage the increasing number of aging concrete bridges. The Concrete Bridge Prioritization System was proposed because of its ability to address the critical technical parameters of safety and cost benefit in prioritization of funding and work allocation. The analysis includes four parts, service life assessment, service life extension, cost calculation, and prioritization. The system combines these parts to optimize consideration of the technical parameters. A systems engineering approach to the investigation and design of the Concrete Bridge Prioritization System is included.

ACKNOWLEDGMENTS

I would like to thanks all the faculty and staff at Virginia Polytechnic Institute and State University for both the Blacksburg and Telestar campuses for all their help over the years. I would especially like to thank the members of my board for their time and support throughout this process and the classes they each taught me. I will carry the lessons from my course study with for the rest of my career and life.

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# Chapter 1
# INTRODUCTION

The highway system in the United States is highly dependent upon its approximate 575,000 bridges. Many of these bridges were designed in another era and are now being forced to withstand current traffic volumes and vehicle designs. 40% of the 575,000 bridges are built from concrete [1], of this number 40% require some repair or rehabilitation. This reflects about 90,000 concrete bridges in need of support efforts. A new prioritization system is needed that will ensure bridge safety and cost benefit for the allocation of maintenance, repair, and rehabilitation funding. The Concrete Bridge Prioritization System (CBPS) proposes a new methodology that can be used as a decision tool by all levels of government (local, state and federal) in the allocation of funding and scheduling of maintenance, repair, and rehabilitation activities on our concrete bridges.

1.1 Selection of Topic: The winter of 1993/1994 was one of the most severe the Northeast United States had encountered in a long time. The extreme cold temperatures, high wind gusts, and constant exposure to various chemicals used for ice removal/prevention has had a significant impact on the bridges. While some of the damage was repaired immediately, many repairs have yet to begin. In addition, the Washington metro area is well known for the high traffic concentration and the delays that bridge maintenance repair and rehabilitation activities can cause. Also, in my travels around the country I have encountered many bridges that have been closed or weight restrictions imposed because bridge support was not provided. These conditions led me to question how the priority of maintenance, repair, and rehabilitation activities was determined and how it could be improved.

1.2 Proposed Project: This paper accomplishes the design of a new prioritization system through a study of existing procedures, a literature search, and through my experience as Structural Service Life manager of rotary wing aircraft for Naval Air Systems Command.

The new prioritization procedures will address service life assessment and extension procedures. The service life assessment phase will utilize engineering analysis, historical data (as available), physical inspection, and structural sampling testing (as available). Parameters, such as current traffic volumes, vehicle sizes, and vehicle loading, will be analyzed to determine the delta between design and actual service life. In addition, the physical condition data including maintenance, repair, and rehabilitation histories; inspection; nondestructive testing; and core samplings analysis will be considered (as available and appropriate). After service life has been assessed, life extension efforts will be examined. First, life extension efforts will be categorized into preventative maintenance, minor and major repairs, rehabilitation, and replacement activities. An individual concrete bridge may require any or all combinations of the above categories. An overview for maintenance, repair and rehabilitation activities and their service life improvement potential will be calculated. Next, costs will be associated with each of the various maintenance, repair, and rehabilitation efforts.

Finally, the prioritization phase of the new system. While the extension and costing activities are based on individual concrete bridges the prioritization activity is applied to an inventory of bridges defined by a funding jurisdiction, such as county, state or federal. Prioritization will first examine the safety issue where current usage and physical condition have exceeded designed service life. Next, the procedure will address structural benefit with respect to cost. The issue of multiple maintenance, repair and rehabilitation requirements for bridge support will be included in this part of the prioritization. The prioritization will also consider alternatives such as loading restrictions to manage concrete bridge situations until funding and work can be scheduled.

1.3 Project Contribution: The contribution of this project is the design of a comprehensive prioritization system simplifying the process of funding and work allocation by focusing on a few critical parameters. These critical parameters are safety and cost benefit. The system emphasizes bridge safety above all other factors which is not a singular concern in the current system utilized. In addition, the prioritization system provides a new methodology for both life assessment and extension calculation. The prioritization phase also simplifies cost benefit and rating of each bridge maintenance, repair, and rehabilitation requirement.

# Chapter 2
# TECHNICAL PROGRAM PLANNING, IMPLEMENTATION AND CONTROL

## 2.1 Program Requirements.

2.1.1 Description of the Problem: The United States' current prioritization procedures for maintenance, repair, and rehabilitation of its concrete bridges has failed to adequately support their usage requirements. An alternative method of prioritizing concrete bridge support is required due to the inability of the current system to manage the increasing number of aging bridges.

2.1.2 Statement of Work: The original design of most concrete bridges required routine maintenance be done. However, with the increase in traffic volume and changes in vehicle weight and size, this minimal maintenance concept is no longer valid. Unfortunately, the United States, as well as many other countries throughout the world, has failed to react, causing a critical situation to develop. Today, most concrete bridges require rehabilitation activity or replacement. Available funding to accomplish these activities is limited. A new system is required to manage both the funding and allocation of work to restore concrete bridges to a safe and maintainable level. The unique ability of this new prioritization system will be to allow any county, state, or federal government to fund and schedule work by including safety and cost effectiveness as part of the decisions. Safety is a critical issue which is often neglected because of traffic demands, and lack of understanding of an individual bridge's condition. Many bridges function for years in visibly failing condition while others fail for no apparent reason. Cost effectiveness is another area that the prioritization system will address. Often, bridges are neglected for so long that support activity is more costly than building a new bridge. The system will recognize limitations in age and cost effectiveness within the prioritization phase. The new prioritization procedures will be a viable decision tool of both the working and top management levels. The system will accommodate all designs and structural conditions of concrete bridges and be able to utilize available cost data, specific to the region in which the bridge is located.

2.2 Supplier or Subcontractor Requirements: CBPS requires some additional agreements with current state and federal agencies or the original designer of the system they are currently using. These agreements will be for the purchase and updates of the software obtained. The software will assist in the compilation of bridge data and the structural analysis required throughout the system. The application of the software will reduce the man-hours and specialized personnel required.

2.3 Technical Performance Measurements: The main task of the CBPS is to ensure that safety and cost benefit are included in the allocation of funding and work scheduling for concrete bridges. The technical performance parameters are total service life (TSL), extended service life (ESL), service life remaining (SLR), bridge condition factor (BCF), cost of combined maintenance, repair, and rehabilitation (CCMRR), and cost of bridge replacement (CBR). No limitations exist on any of these parameters because they are based on individual bridges which vary greatly in size and support requirements. However, there is one easy check that can be done to ensure that the parameters have not been calculated incorrectly. ESL should never be less than TSL. The remaining checks for stress and cost calculations are built into the system to ensure safety and cost benefit are achieved.

2.4 Program Monitoring/Maintenance: No program maintenance is required. Customization may be required within the initial usage period. The computer hardware will not require any additional maintenance because of the usage of the prioritization system. The additional software should be maintained and updated as part of the suppliers/subcontractor agreements. Program monitoring is required. Bridge maintenance, repair, and rehabilitation activity should be monitored and updated to reflect work completed. As inspection data is submitted the system will need to be updated. As housing and office building construction are ongoing the traffic loading situation will also need to be monitored and updated.

2.5 Risk Management: The ideal method for risk management would be to review the funding allocation and work scheduling from the most recent year. Comparison of the two systems should include manpower, calculated bridge service life and prioritization system results. Further risk management may be placed in raising the safety factor assumed in the assessment phase, Part I. Prior to 1940, the safety factor applied in design of the bridge was normally ten. This factor is probably not realistic in with the increase in traffic volume and weight, but a safety factor of five may be used if additional risk management is required.

# Chapter 3
# THE SYSTEMS ENGINEERING PROCESS

3.1 Identification of Need: The Concrete Bridge Prioritization System (CBPS) will be used to assess and extend the service life of any individual concrete bridge as well as prioritize funding and work scheduling for a specific region. A systems engineering approach will be utilized in the design of the prioritization system (Figure 3.1.-1) [2]. The system will be capable of utilizing any historical, inspection, and test data in the service life assessment phase, Part I. The extension phase, Part II, will list the most utilized preventative maintenance, minor and major repairs and rehabilitation efforts with a brief description of each. A more detailed description for several options will be provided. Average cost data from around the country for each maintenance repair and rehabilitation procedure will be provided, Part III. Finally, the prioritization phase will examine safety, cost, and cost benefit to optimize funding and work allocation, Part IV.

3.2 Feasibility Study: During the identification of need, several specific task areas were identified service life assessment, extension, cost benefit, and prioritization. Alternatives considered for the elements of the prioritization system are presented in Tables 3.2-1, -2, and -3.

3.2.1 Bridge Data Compilation: Table 3.2-1 considers the alternatives of compiling bridge data. Data can be obtained from the inspectors within the defined area and manually compiled, software can be developed which will compile and store the current bridge data, or existing software can be obtained from one government currently utilizing a comparable software (i.e. BRINSAP).

3.2.2 Structural Analysis: Table 3.2-2 considers the alternative of structural analysis for determining compressive, tensile and shearing stress for each bridge component. The options are manual computation of stresses, developing the software internally, or computerized analysis (i.e. BARS, BRASS).

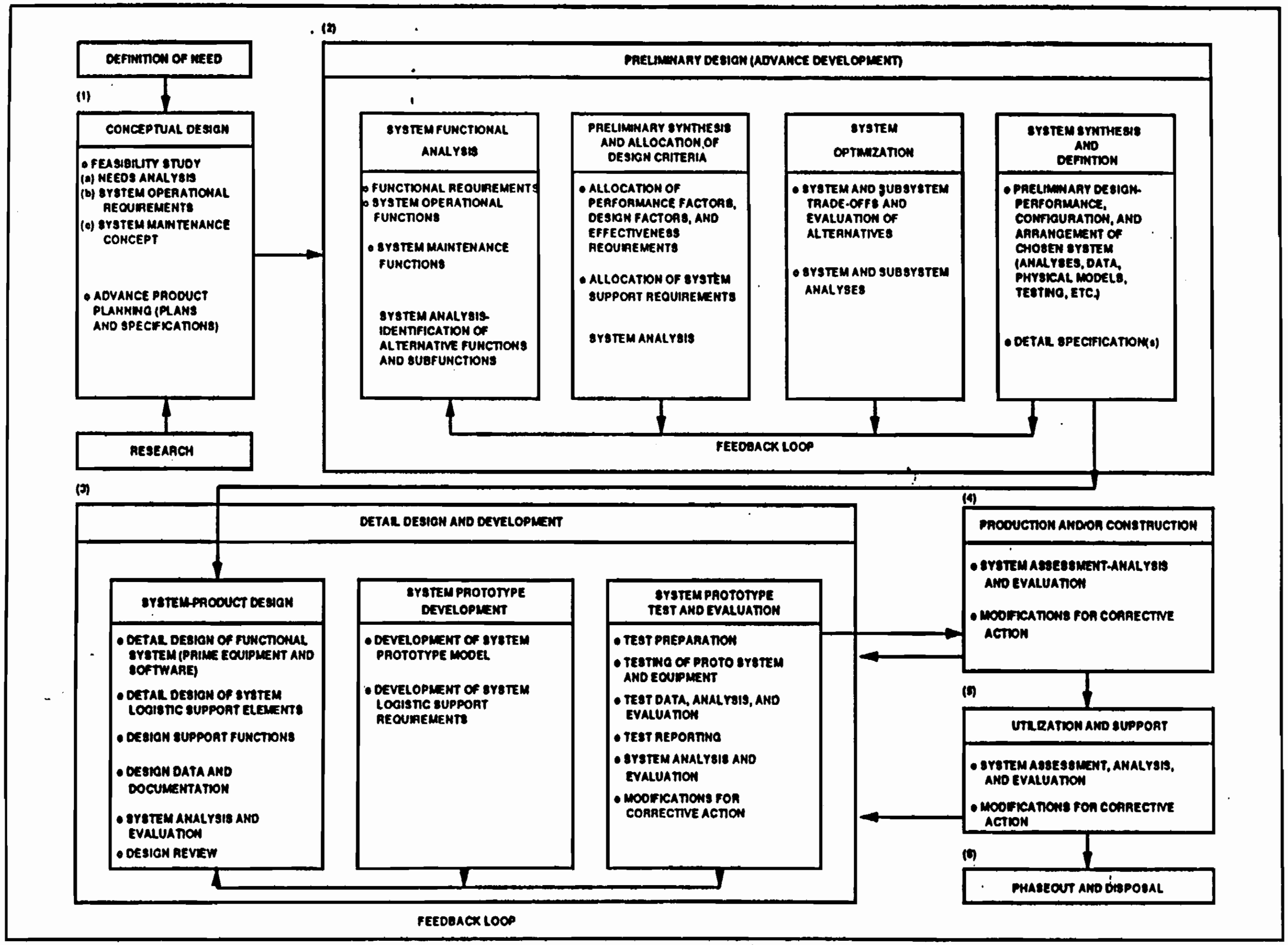



Figure 3.1-1 CBPS Life Cycle Process

3.2.3 Prioritization: Table 3.2-3 considers the alternative of rating and prioritizing the bridge work to be scheduled. These tasks may be completed by using existing software (i.e. BARS or BRASS), developing new code, or manually.

In addressing the possible alternatives, the option of developing software for the entire new prioritization system comes into discussion. The current requirement for the system is for design only which needs only minimal repetition with limited personnel usage. This limited requirement makes internal software development, for the entire system or any part, impractical at this time.
The alternatives selected are based on the assumption that all personnel who will be using the new prioritization system will have access to a personnel computer or computer host system. The computer must have the necessary capacity and capabilities to run the recommended software. Utilizing existing software will reduce the yearly requirement for data compilation, hence reducing work load over the life cycle of the prioritization system. The structural analysis using an AASHTO supported software was selected to reduce specialized personnel requirements and the work time for structural analysis. Prioritization and rating will be completed manually since it was the remaining option which complied with the system requirements. While the BARS and BRASS system will complete both the structural analysis and prioritization task, the rating of each bridge for funding and work utilizes the current federal system which is already in question.

**Table 3.2-1 Bridge Data Compilation**

| Option | Means | Additional Requirements | Comments |
|---|---|---|---|
| 1 | Manual | None | Labor intensive and time consuming |
| 2 | Develop Software Internally | Computer Programmer and Computer Hardware Available | Expensive, time consuming, and computer programmer may not be available internally |
| 3 | Obtain Existing Software | Computer Hardware Available | Training and software procurement charges Software is tested and proven |

**Table 3.2-2 Structural Analysis**

| Option | Means | Requirements | Comments |
|---|---|---|---|
| 1 | Manual | Engineer | The personnel within a government agency who are responsible for making recommendations will not all be structural engineers |
| 2 | Develop Software Internally | Engineer, Computer Programmer, and Computer Hardware Available | Expensive, time consuming, and computer programmer, nor engineer, may not be available internally |
| 3 | Obtain Existing Software | Computer Hardware Available | Software available thru AASHTO* In-house training required Software is tested and proven |

* AASHTO - American Association of State Highway and Transportation Officials

**Table 3.2-3 Rating and Prioritization**

| Option | Means | Additional Requirements | Comments |
|---|---|---|---|
| 1 | Manual | None | Easily trained and non-labor intensive |
| 2 | Develop Software Internally | Computer Programmer and Computer Hardware Available | Expensive, time consuming, and computer programmer may not be available internally |
| 3 | Obtain Existing Software | Computer Hardware Available | Software fails to allocate work and funds to ensure safety and cost benefit |

3.3 Operational Requirements.

3.3.1 Mission Definition: To design a new prioritization system called Concrete Bridge Prioritization System (CBPS) to assess current service life, to calculate extended service life, and to prioritize funding and work scheduling according to cost benefit and safety issues.

3.3.2 Performance and Physical Parameters: The performance parameters determined throughout the system are:

a. Total Service Life (yrs) - TSL
b. Extended Service Life (yrs) - ESL
c. Combined Cost of Maintenance, Repair and Rehabilitation ($) - CCMRR
d. Cost of Bridge Replacement ($) - CBR
e. Prioritization Factor. - PF

Utilizing the previously mentioned software programs [3.2.1 Bridge Data Compilation and 3.2.2 Structural Analysis], performance parameters a - d can be established in eight man-hours. With this data, parameter e should require no more than eight additional man-hours to accomplish. The estimated man-hours to establish the Prioritization Factor is based upon the manual nature of the calculation.

3.3.3 Input data: The following parameters for each individual bridge are required for input into the system: bridge dimensions, materials, material properties, design type, weight, year built, bridge condition, recommended maintenance, repair or rehabilitation activity, and traffic loading. Should there exist any core sample or bore extraction data and/or a historical record of any maintenance, repair, or rehabilitation activity for a bridge, this data may also be included.

The parameters should be updated after the completion of any maintenance repair or rehabilitation activity to ensure that service life is calculated correctly.

3.3.4 Output data: Each part of CBPS has its own calculated output. Part I, service life assessment phase, provides current service life. Part II, service life extension data provides the extended service life. Part III, cost analysis calculates the combined cost for maintenance, repair and replacement activity and cost of replacement. Part IV will yield the prioritization factor which is to be used in determining which work should be scheduled and which should be delayed.

3.3.5 Use Requirements: CBPS is designed to be a tool used to support budget preparation. Once a data baseline has been established, Part I, II, and III may be updated at any time. This will usually occur once a year upon inspection of the bridge(s). The prioritization phase, Part IV, can be used as a budget projection tool to establish an upcoming year's budget allocations. It also can be used as a device to justify the reallocation of funds within the current budget scheme, should a bridge's condition suddenly change.

3.3.6 Operational Implementation: CBPS can be utilized by any level of government. The suggested implementation is to accomplish Parts I, II, and III at the working level and Part IV at the intermediate supervisory level. The results should then be forwarded to the decision makers or executive management for actual funding allocation and work scheduling.

The support structure needed to actually use the system is minimal. There is no requirement for additional personnel ad the procured software is designed to replace the existing system, utilizing the associated hardware. A specialized training class is recommended for each interactive level prior to the implementation of CBPS. In addition this system is intended to take advantage of the existing bridge inspection and testing practices.

If the utilization of the CBPS should become widespread and warrant the development of software which can complete the prioritization analysis, additional factors should also be included. One important factor is the retention of past analyses. This will build an individual bridge history which will assist in overall bridge support through the entire structures service life.

3.3.7 Operational Life Cycle: The prioritization system shall have a useful life of at least 10 years. After the ten year period, the use of updated maintenance, repair, and rehabilitation efforts and the new materials, mostly composites, utilized in support will have become to complex for this system. The system shall not require any maintenance except for some customization throughout that time.

The bridge data compilation and structural analysis should be updated by the original owner and updates should be included in the original agreement.

3.4 Systems Maintenance Concept: The maintenance concept for the CBPS is based on operational to depot level maintenance. The user is responsible to ensure all input data and calculations are correct. If the CBPS should require customization or update for any reason, the designer will be responsible for this activity.

3.5 Functional Analysis: Figures 3.5.1 through 3.5.8 illustrate the Functional Analysis Flow for operation and updating flow. The "First Level" layout details the initial step of defining system requirements. Once these are established, the Concrete Bridge Prioritization System design is developed. Operational flow reflects quarterly usage with an established data baseline. The design has been will be simplified and made user friendly whenever possible. Test and evaluation will be performed should the system be implemented by any county, state, or federal government. Any deficiencies or customization required will be completed at that time.

3.6 Requirements Allocation: Figure 3.6.1 shows the allocation of resources down to the part level. Since the critical technical parameters do not have limitations, this requirement allocation will be unique. For this purpose the CBPS is divided into structural and cost analyses components. Structural analysis includes the service life assessment and its extension. The cost analysis addresses the cost of any activity done to the bridge and the prioritization of these activities.

3.7 System Analysis and Trade-offs: The prioritization cost benefit analysis reviews both the extended service life versus total service life and the cost of combined maintenance, repair, and rehabilitation versus cost of bridge replacement. By maximizing the increase in service life and minimizing the cost of combined maintenance, repair and rehabilitation activity, the optimum cost benefit will be achieved. In addition, since major repairs and rehabilitation efforts will usually last for twenty years or more, none of these tasks will be considered for bridges with less than ten percent service life remaining. For maintenance, repair, and rehabilitation activities costing more than fifty percent of replacement cost (or sixty percent for widening), the cost is believe excessive and shall not be considered for bridge support [3]. Other alternatives have been listed to manage each situation.

If CBPS implementation should be required, a test-of-market is recommended prior to the final decision of which bridge data compilation and structural analysis software packages are to be used. The test-of-market should include training, maintenance, and costs for each item. Since several versions exist for each software function required, the life cycle costs and maintenance procedures will be the determinants for selection.

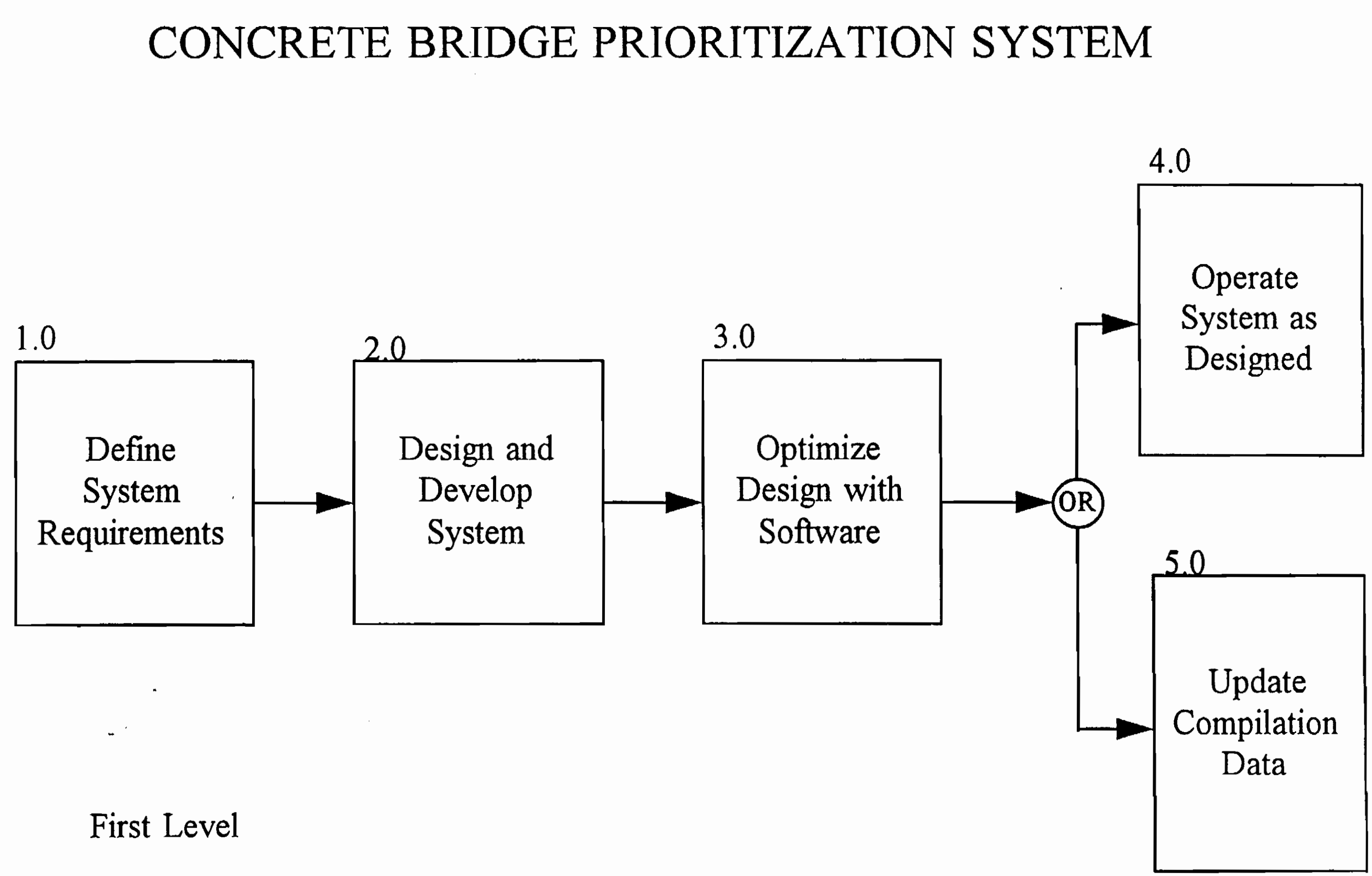



Figure 3.5-1 Operational Functional Flow

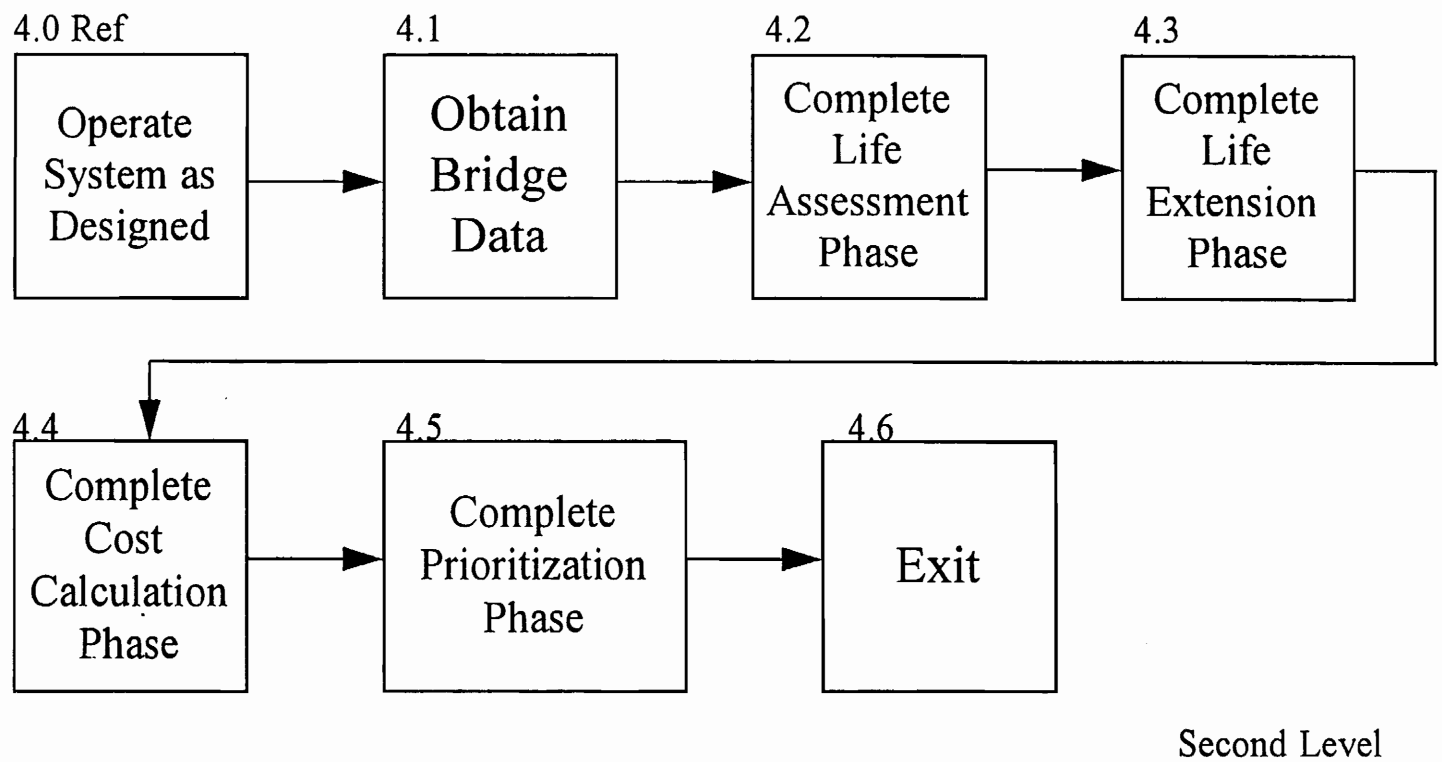



Figure 3.5-2 Operational Functional Flow

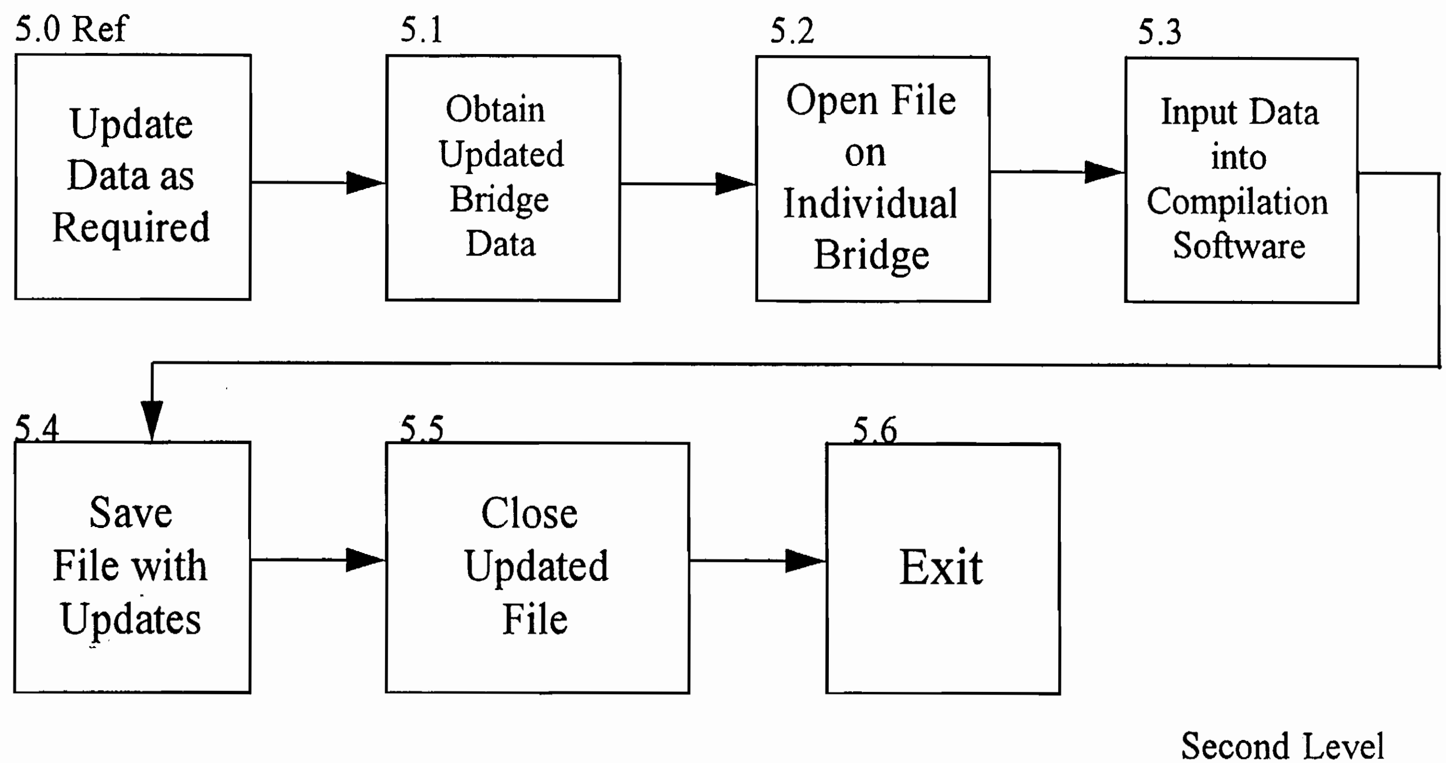



Figure 3.5-3 Update Functional Flow

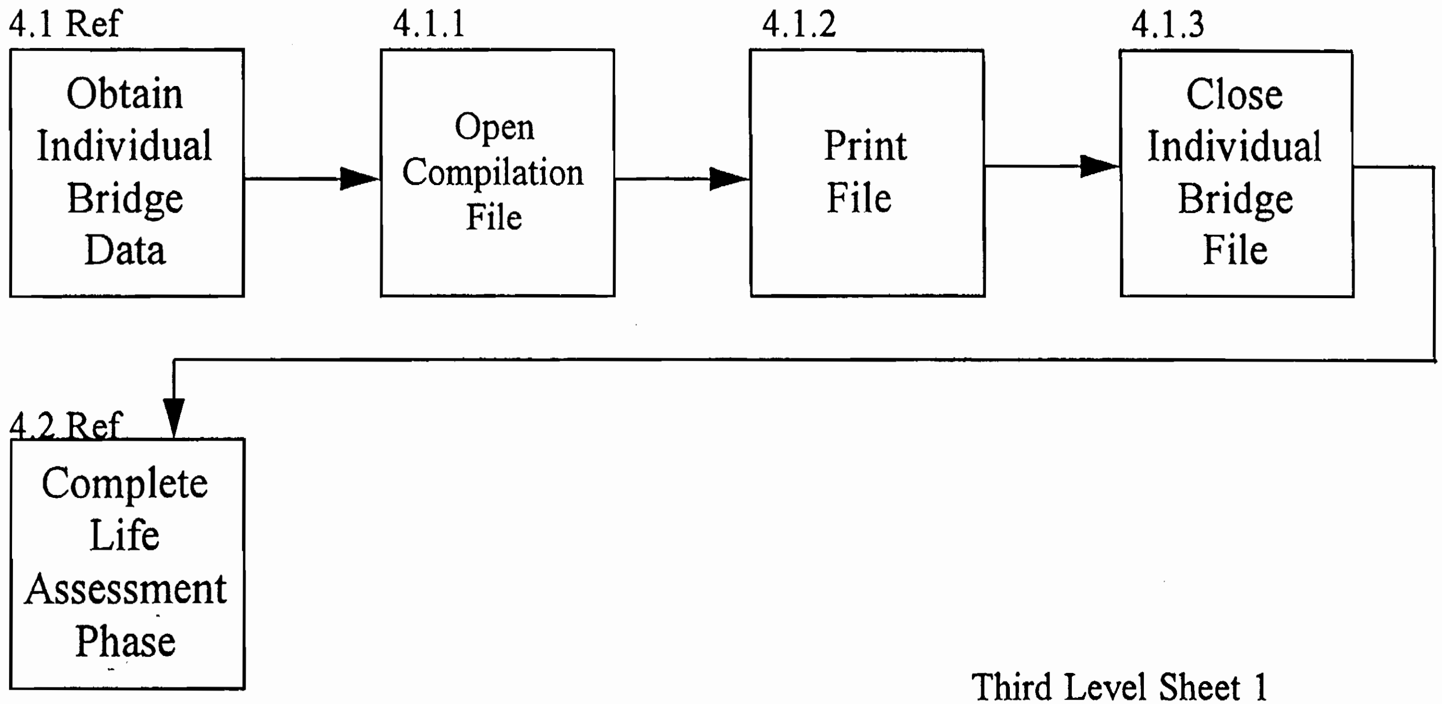



Figure 3.5-4 Operational Functional Flow

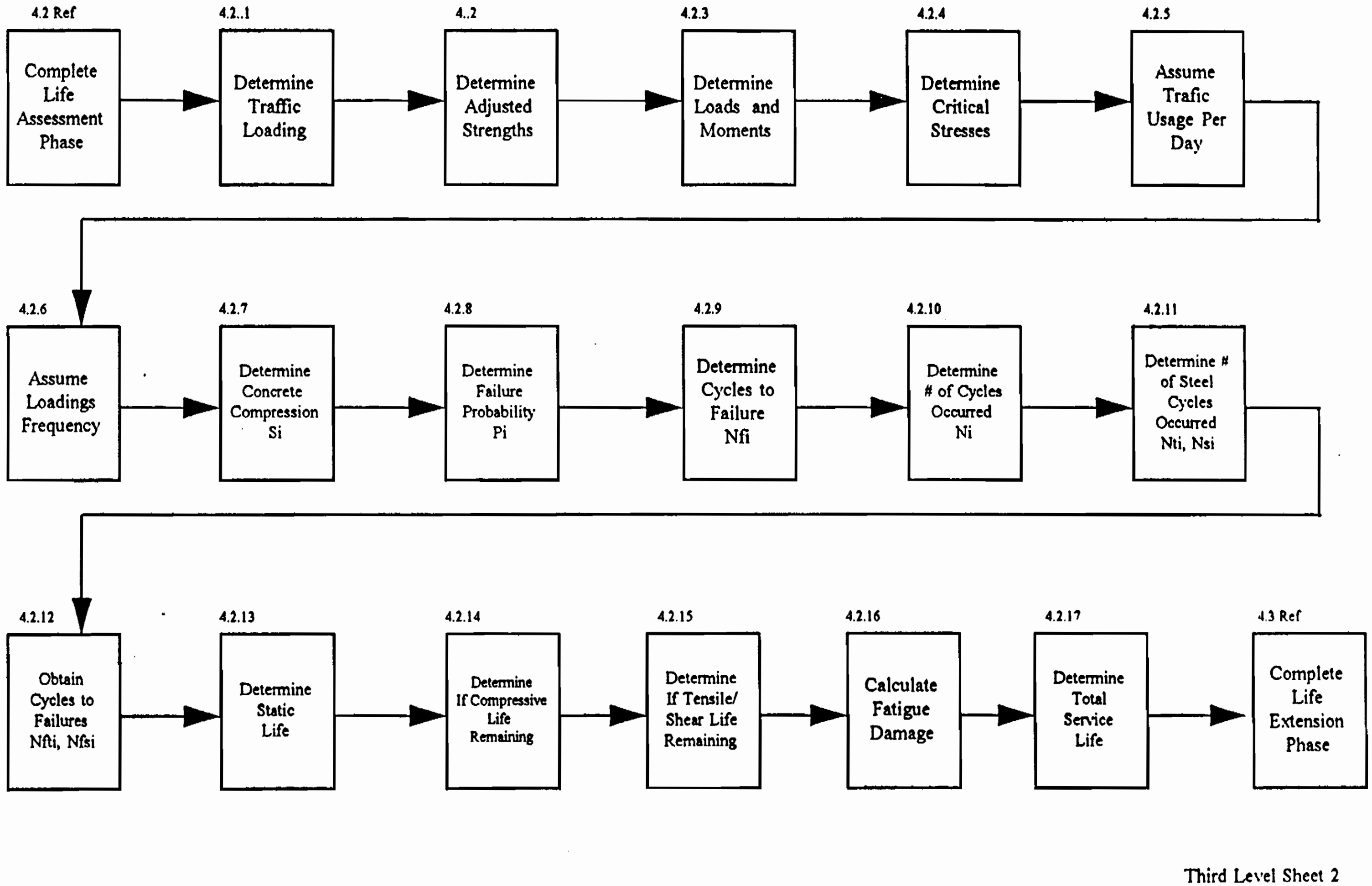



Figure 3.5-5 OperationalFunctional Flow

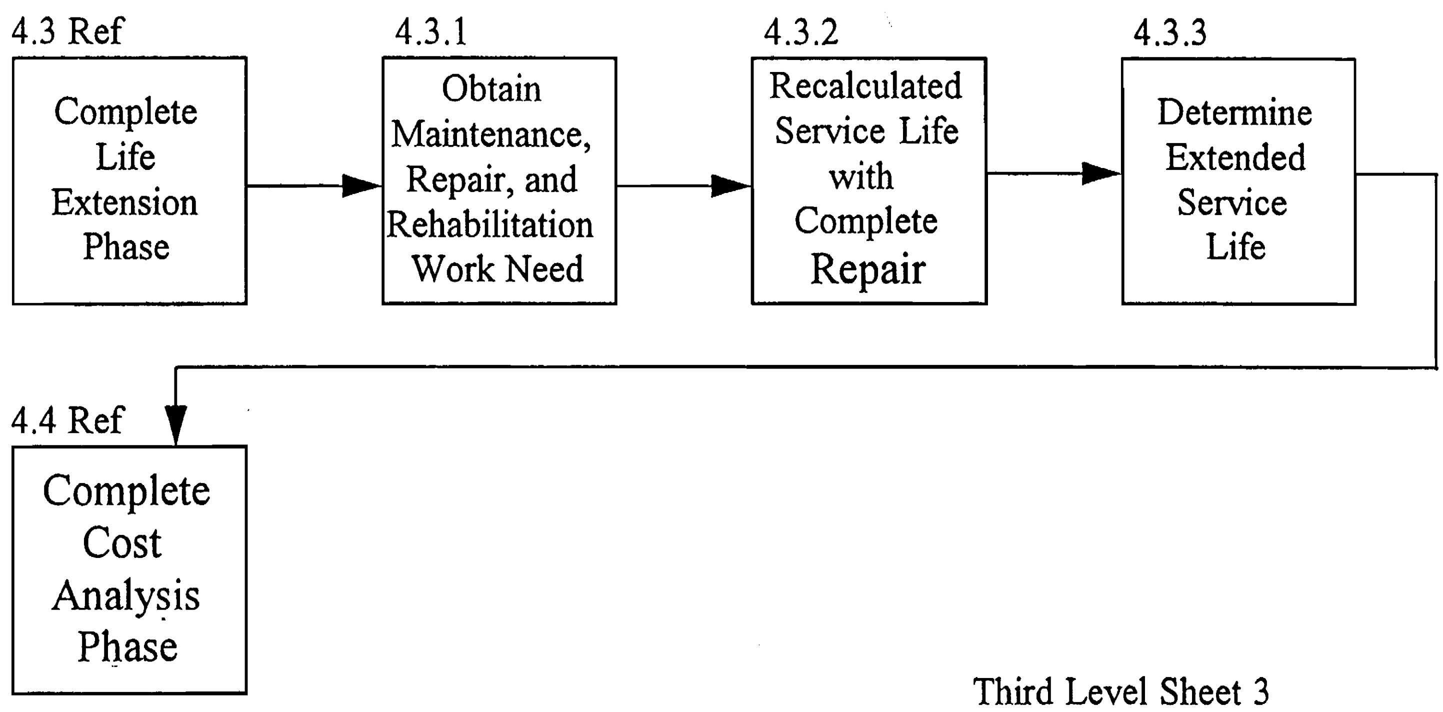



Figure 3.5-6 Operational Functional Flow

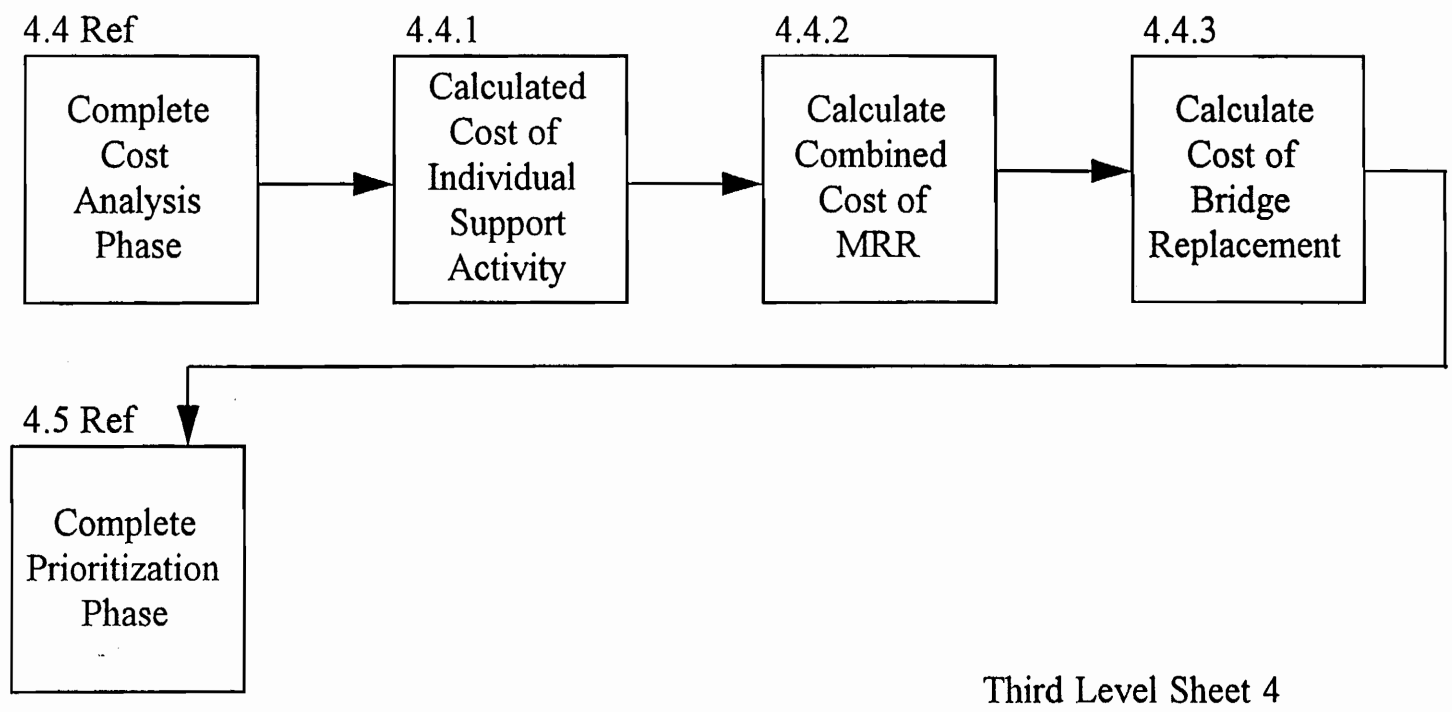



Figure 3.5-7 Operational Functional Flow

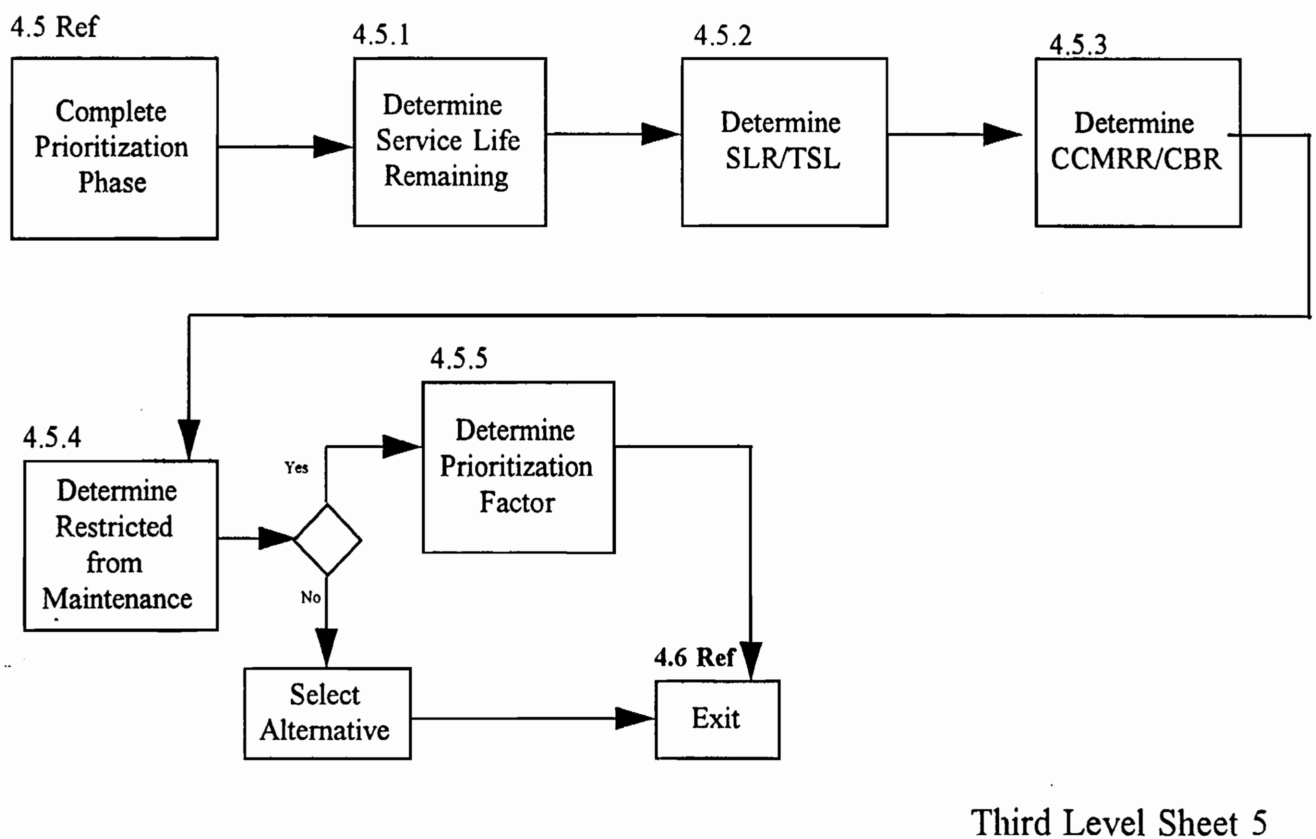



Figure 3.5-8 Operational Functional Flow

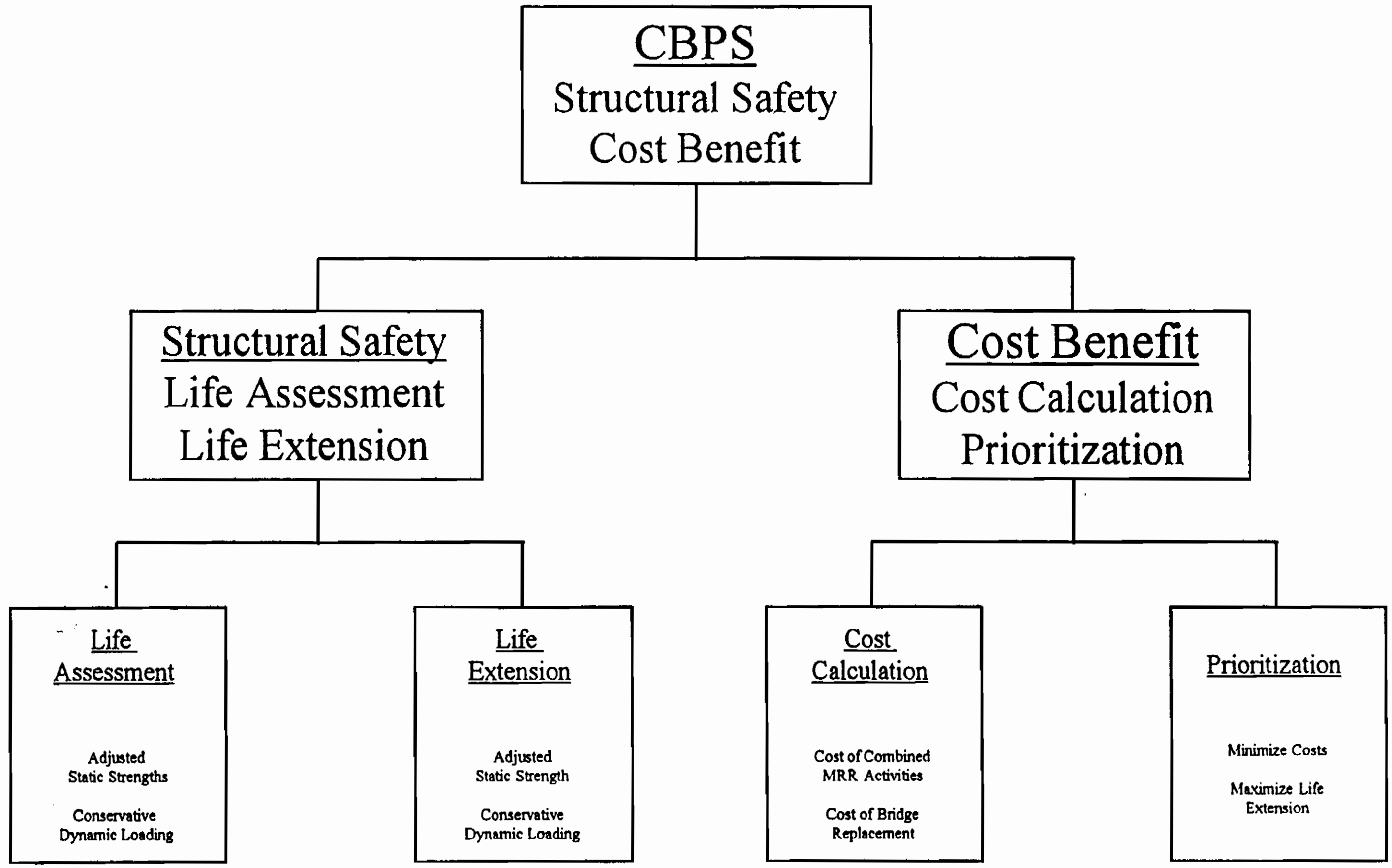



Figure 3.6-1 Requirements Allocation

## 3.8 SYSTEM DESIGN

Introduction: The research for the design of the Concrete Bridge Prioritization System was completed by literary search. The life assessment methodology is a combination of several different evaluation procedures. The comprehensive system is based on the analysis utilized by the Structures Branch of the Naval Air Systems Command for managing aircraft service life.

PART 1: Life Assessment of Individual Bridges

1. Obtain data from existing bridge. Utilize bridge compilation software.
   a. Dimensions
   b. Material and Material Properties
   c. Design Type
   d. Weight
   e. Year Built

2. Determine current representative traffic loading
   a. Based on actual usage, select equivalent pattern from Figure 3.8-1 [4]
   b. Utilize current design traffic loading from Figure 3.8-1 [5]

3. Utilize historical and inspection data; Determine adjusted strengths.

Historical and inspection data will influence the yield and ultimate strength a bridge is able to withstand. For each situation an increase or decrease in strength shall be determined and applied to later computations. The assumption that fatigue damage is cumulative [6] will lead to the addition or subtraction of factors where more than one situation applies. In addition, the assumption of a safety factor of two is applied to offset bridge manufacturing and construction flaws.

   a. Safety factor
      Yield Strength / 2
      Ultimate Strength / 2

| Year | Highway Class | Truck Loads | Distributed Loads |
| --- | --- | --- | --- |
| 1917-1922 | Class A | 5 — 10' — 10 ≡ 15 Tons | 100 lbs/ft$^2$ |
| 1923-1934 | Class A | 5 — 10' — 10 ≡ 15 Tons | 80 to 100 lbs/ft$^2$ |
| | B | 3.33 — 10' — 6.67 ≡ 10 Tons | 50 to 80 lbs/ft$^2$ |
| | C | 6.67 — 10' — 13.33 ≡ 20 Tons | 80 to 135 lbs/ft$^2$ |
| 1935-1952 | H20 | 4 — 14' — 16 ≡ 20 Tons | 80 to 100 lbs/ft$^2$ |
| | H15 | 3 — 14' — 12 ≡ 15 Tons | |
| | H10 | 2 — 14' — 8 ≡ 10 Tons | |
| 1953-1978 | HS20-44 | 4 — 14' — 16 — 14' — 16 ≡ 36 Tons | 640 lbs/ft/Loaded Lane Point Load of 18000 lbs. and 26000 lbs. |
| | HS15-44 | 3 — 14' — 12 — 14' — 12 ≡ 20 Tons | 3/4 x HS20-44 |
| | HS20 | 4 — 14' — 16 ≡ 20 Tons | 1 x HS20-44 |
| | HS15 | 3 — 14' — 12 ≡ 15 Tons | 3/4 x HS20-44 |
| | H10 | 2 — 14' — 8 ≡ 10 Tons | 1/2 x HS20-44 |
| 1979 (OHBDC) | A,B, & C | 60 — 3.6 — 140 — 1.2 — 140 — 6 — 200 — 7.2 — 160 kN ≡ 700 kN | 70 per cent Truck + 10 kN/m/Lane Class A, 9 kN/m/Lane Class B, 8 kN/m/Lane Class C |

Figure 3.8-1 Traffic Loads Classification

b. Historical data [7]

1) Preventative maintenance:
   - Yield Strength + [Yield Strength x .01]
   - Ultimate Strength + [Ultimate Strength x .01]

2) Patching of Minor Damage
   - Yield Strength / 2.05
   - Ultimate Strength / 2.05

3) Patching of Significant Damage
   - Yield Strength / 2.2
   - Ultimate Strength / 2.2

c. Inspection data (Visual, Sounding, Stains)

1) Good Condition (no sign of physical/environmental damage)
   - Yield Strength /2
   - Ultimate Strength /2

2) Fair Condition (minor cracking, bumps, or scaling)
   - Yield Strength / 2.1
   - Ultimate Strength / 2.1

3) Poor Condition (rust, crusts, cracking or swelling)
   - Yield Strength / 2.2
   - Ultimate Strength / 2.2

4) Critical Condition (concrete/steel separation, large cracks)
   - Yield Strength / 2.3
   - Ultimate Strength / 2.3

d. Core/Bore samples: Structural samples should be applied to determine good-critical condition based on the testing results.

4. Determine loads and moments for each bridge component (Figure 3.8-2)[8]. Utilize structural analysis software.

a. Deck
b. Abutments
c. Piers
d. Superstructure

Notes: [9]

(1) Dead loads are the weight of the bridge itself and should be represented as both a point load and distributed loads.

(2) Loads and moments should be determined utilizing both applied point and applied distributed loads to allow for the identification of maximum loads and moments within each bridge component.

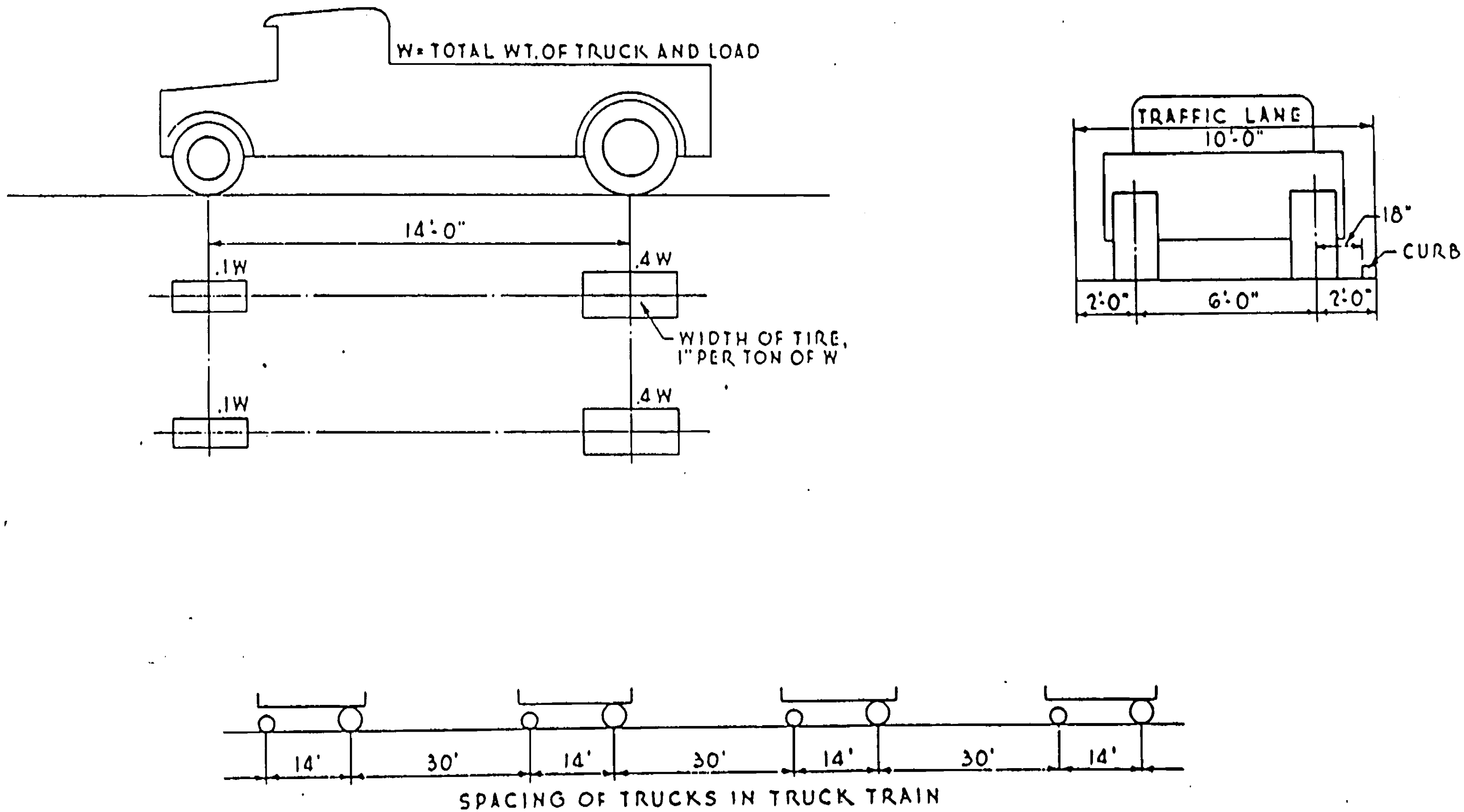



Figure 3.8-2 Load Transfer Configuration

(3) Live point loads should be applied at various locations, when determining maximum loads and moments, due to construction influence on load distribution to each bridge component.

5. Determine maximum compressive, tensile, and shear stresses. Determine critical stress areas. Utilize structural analysis software.

Note: Concrete is very poor under tensile and shear stresses. Steel should be present throughout the structure to carry these loads but especially in areas where maximum tensile and shear stresses are located [10].

6. Assume traffic usage for a 24 hour period is:
   5% at .80 maximum stress
   30% at .60 maximum stress
   45% at .50 maximum stress
   20% at .15 maximum stress

Note: Actual data may be substituted.

7. Assume loadings occur at a frequency of 5 Hz (5 cycles/sec) [11].

Steps 8 - 11 are for compressive loads for concrete[12].

8. Bridges undergo variable load conditions in the 24 hour period given. With the assumption of fatigue damage is cumulative, cycles can be accrued in any order, each load pattern will be applied separately. For each critical area, determine Si as percent maximum stress / adjusted yield strength.

9. Determine Pi, probability of failure, for each corresponding Si as follows:
   for Si >= .75 let Pi = .95
   for .75 > Si > .50 let Pi = .50
   for .50 >= Si >= .01 let Pi = .05

10. Determine Nfi, number of cycles until failure, for each Si as follows:
   - for plain concrete:
     for Si < .50: log Nfi = 1.978 x Si^-3.033 x (-log(1-Pi))^.0596
     for Si >= .50: log Nfi = 1.862 x Si^-4.430 x (-log(1-Pi))^.0651

- for reinforced concrete: use above equations substitute (Si/2) for Si

- for precast/prestressed concrete: use above equations substitute (Si/3) for Si

11. For each Si at 5 Hz for the current life of the bridge, determine the number of cycles accrued, Ni.

Steps 12-13 are for steel members

12. For steel under tensile and shear stresses for each critical area, determine the number of cycles accrued, Nti and Nsi.

13. Use log Nti and log Nsi or determine Nfti or Nfsi, the number of cycle until failure. These results can be obtained with appropriate S-n curve for the material. See Figure 3.8-3 for an example.

14. Determine static life. From step 6:
If max stress>adjusted yield strength, work required
If max stress>adjusted ultimate strength, replacement required
If max stress<adjusted yield strength, structure static life OK

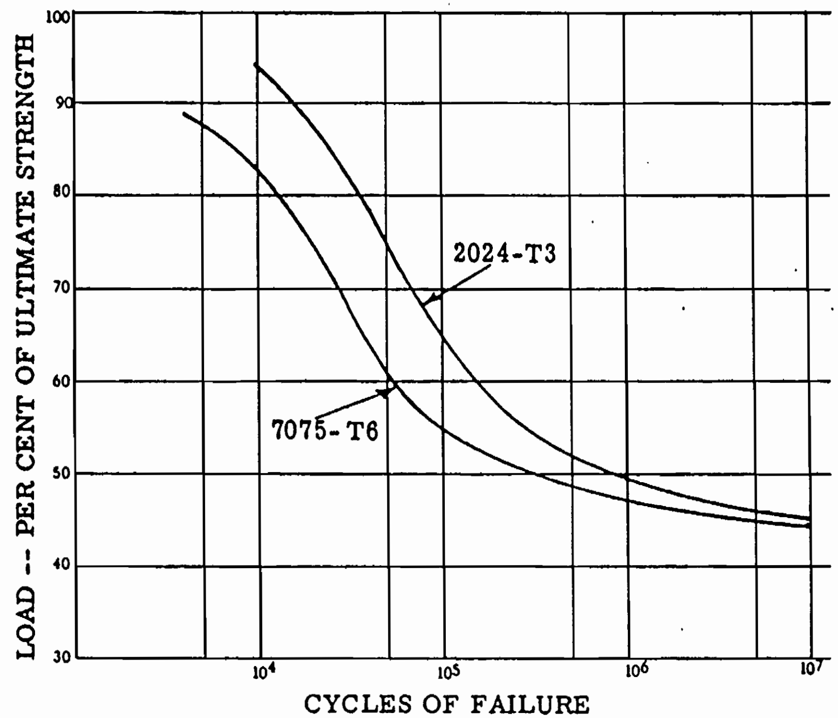
15. Determine if compressive service life remains. From steps 10 and 11:
If log Ni> log Nfi, work required- Service life is 0.
If log Ni< log Nfi, see step 17.

16. Determine if tensile or shear service life remains. From steps 12 and 13:
If log Nti or log Nsi > log Nfti or Nfsi, work required
Service life =0
If log Nti or log Nsi < log Nfti or Nfsi, see step 17

17. Accrual of fatigue damage for each critical area:
- for load stress / adjusted yield strength >= .75, determine
Nc = Summation Ni and Nfc = Summation Nfi

Nt = Summation Nti and Nft = Summation Nfti

Ns = Summation Nsi and Nfs = Summation Nfsi




For Unnotched 2024-T3 and 7075-T6 Aluminum Alloys

Figure 3.8-3 S-n Curves For Fatigue Strengths

18. Determine service life for each critical area as follows:

Solve for X:

Current life / log(Summation of Nc) = Xc / log(Summation Nfc)
Current life / log(Summation of Nt) = Xt / log(Summation Nft)
Current life / log(Summation of Ns) = Xs / log(Summation Nfs)

Total Service Life (TSL) is the lowest number from Xc, Xt, or Xs from all critical areas.

PART II: Life Extension of Individual Bridges

Based on the information determine in Part I, Life Assessment, the prioritization system continues by addressing extension activities required. While most areas for extension activities are considered, not every possibility has been included. These activities make no distinction between normal (planned) and usage/environmentally-required (unplanned) maintenance, repair and rehabilitation efforts.

1. If max stress>adjusted yield strength
   a. Increase structural load carrying capacity (discussed below)
   b. Replace Deck with light weight material (discussed below)

2. If max stress>adjusted ultimate strength
   a. Replace bridge component (discussed below)

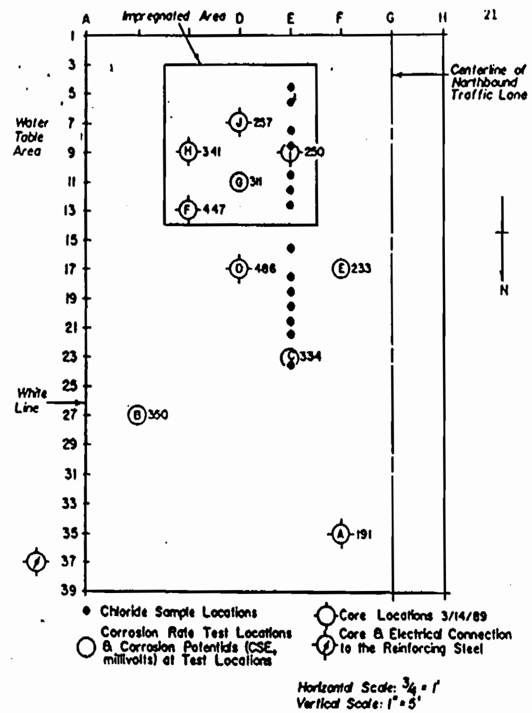
3. If max stress<adjusted yield strength
   a. Go to step 6

4. If log Ni > log Nfi
   a. Replace bridge component (discussed below)

5. If log Nti or log Nsi > log Nfti or log Nfsi
   a. Replace bridge component (discussed below)

6. For bridges with service life remaining using inspection data
   a. Bridge in Good Condition require preventative maintenance

1) Deck Overlay: The overlay (Figure 3.8-4) [13] is applied within the structure to prevent corrosion of the steel and to seal the surrounding concrete to prevent further deterioration. The process consists of drying the concrete, impregnating the concrete with a monomer at a sufficient depth to protect the top mat of steel into the structure and polymerizing the monomer. This process should immobilize any existing chloride as well as seal the concrete to protect the reinforcing steel from further exposure to chlorides, water and oxygen.




Example

| Depth, cm | Chloride Content, kg/m³ * 1989, $\bar{X}$ | 1984, $\bar{X}$ | 1989 minus 1984 |
|---|---|---|---|
| | IMPREGNATED AREA | | |
| 1.27 | 4.55 | 4.15 | 0.40 |
| 2.54 | 2.24 | 1.54 | 0.70 |
| 3.84 | 1.55 | 0.90 | 0.65 |
| 5.08 | 0.88 | 0.40 | 0.48 |
| 6.98 | 0.91 | 0.30 | 0.61 |
| | NONIMPREGNATED AREA | | |
| 1.27 | 5.54 | 4.32 | 1.22 |
| 2.54 | 3.25 | 2.95 | 0.30 |
| 3.84 | 3.21 | 1.91 | 1.30 |
| 5.08 | 2.37 | 1.27 | 1.10 |
| 6.98 | 1.97 | 0.57 | 1.40 |
| DIFFERENCE BETWEEN NONIMPREGNATED AND IMPREGNATED, 1989 AND 1984 | | | |
| 1.27 | 0.82 | | |
| 2.54 | −0.40 | | |
| 3.84 | 0.65 | | |
| 5.08 | 0.62 | | |
| 6.90 | 0.79 | | |

NOTE: $\bar{X}$ = mean.
*kg/m³ = 1.68 lb/yd³.

Testing Results

# Figure 3.8-4 Deck Overlay Engineering

2) Cathodic Protection: Cathodic protection is focused on protection of the steel that is reinforcing the concrete. The protection is achieved by the use of sacrificial zinc and anodes. The anodes are strategically place throughout the structure and charged with electrical current which enhances chloride attachment to the zinc. This protection prevents chloride from attacking the steel. Chloride is mostly available from salt water, pollution, and deicing salts which can easily permeate concrete.

3) Sealing: Sealing is conducted throughout the bridge structure to fill the top layer of voids within the concrete that are left from the manufacturing process. Concrete structures should be sealed to prevent any corrosive material from damaging the structure. Sealants can be applied by sprayer, rollers or brush, similar to paint. Many different types of sealants exist to provide protection under a variety of environments. In addition, environment plays an important role in how often sealants must be reapplied to remain effective. Sealant material and application must be carefully selected for underwater environments.

b. Bridge in Fair Condition require minor repairs

1) Expansion joint maintenance: One critical aspect of expansion joints is the bonding with the concrete. During inspection and maintenance of the joint, care should be taken to ensure the bonding is not damaged or defective.

a) Shot Peening: Shot peening (Figure 3.8-5) [14] is the process of projecting small round objects onto the surface of the joint. The increase in mass and availability of residual stresses combine to strengthen the current material. The shot material is usually of equal or greater material strength than the joint. The size of the shot and distance required for peening vary according to conditions and availability of the surface.

b) Welding: Welding can be conducted to repair existing cracks in expansion joints. Welding is performed to restore proper load transfer. Welding for small cracks is performed with the addition of a heat element to the existing structure. Larger cracks will require the addition of patching material. Prior to the application of the patching material, the surface must be properly prepared.

c) Cleaning: Cleaning is critical to remove any build up of corrosive materials and should be done frequently prior to actual damage to the joint. Cleaning is also required to ensure the ability of the joint to expand properly.

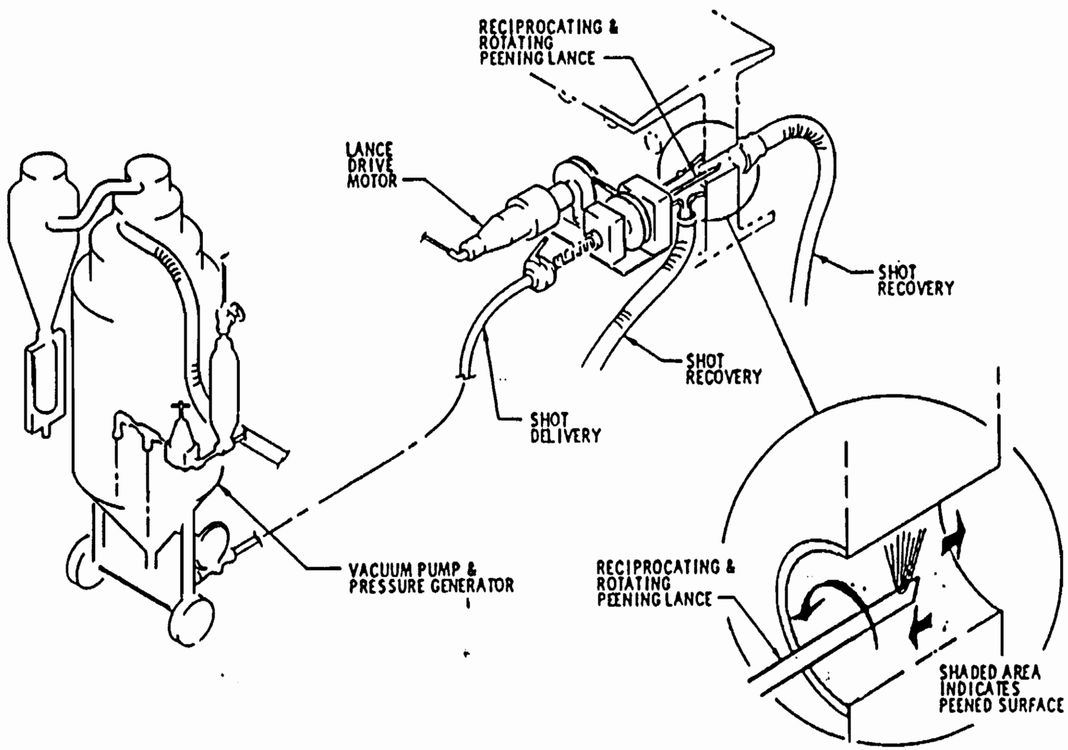



Figure 3.8-5 Portable Shot Peening Equipment

d) For more extensive damage of expansion joints, the installation of dowels and rebars may be selected. Dowels and rebars are installed by drilling the proper diameter hole, inserting the bars and sealing the connection completely. The required number and spacing of dowels and rebars is based on the extent of the damage and the dimensions of the bridge.

e) After any expansion joint activity, resealing of the entire joint should be conducted to prevent corrosion.

2) Bearing maintenance: Bearings should be cleaned on a frequent basis to eliminate corrosive elements and to ensure proper movement.

3) Parapets/Guard Rail Maintenance: Parapets and guard rails should be maintained and repaired in the same manner as the deck structure.

4) Surface/Drainage Maintenance: Drainage systems should be cleaned frequently to ensure proper drainage. Surfaces may require washing to eliminate build up of minerals and corrosive elements.

5) Crack Sealing: Hair line cracks which can be caused by a number of factors require sealing to ensure that corrosive agents do not further erode the concrete or attack the steel. The sealant utilized for crack seals is required to seep into the depth of the crack to ensure that no area is left untreated.

6) Patching: Patching of loose or flaking concrete requires the area to cleaned of any loose material, the area should then be dried and reconcreted.

c. Bridge in Poor Condition require major repairs

1) Expansion joint replacement: Expansion joint replacement requires removal of the existing joint, treatment of attach areas with special concrete/steel resin, and reinstallation of a new joint.

2) Bearing replacement: Bearing replacement should be conducted by temporarily raising the superstructure to allow access to the bearing and its attach points. The bearing should be removed in a vertical direction to minimize damage to the remaining structure.

3) Parapets/Guard Rail Replacement: Parapets and guard rails should be replaced by removal of the existing components, cleaning and preparing the area and installation of new components. Parapets and guard rails will requirement replace when the deck is replaced. In addition, replacement may be necessary because of an accident or environmental effects.

4) Drainage Replacement: The drainage system should be replaced by removing of the existing system, inspection of the contact surface for corrosion, and reinstallation of the system. The drainage system will need to be replace concurrent with deck or superstructure replacement or when corrosion prevents proper drainage.

5) Surface Rework: For larger cracks, two primary repair methods are normally utilized to restore load capacity.

a. Routing and Sealing: Routing and sealing is conducted by enlarging the crack by cutting a groove in the material surrounding the crack and then sealing the groove with a flexible sealer which will allow the crack to function as a joint.

b. Stitching: Stitching is performed by drilling holes on both sides of the crack and grouting a U-shaped bar in place.

6) Abutment and Pier Maintenance: The majority of abutment and pier maintenance besides surface rework and fatigue damage repair, which are covered in other areas, is under water maintenance. The major cause of failure in under water arenas is caused by scour. The main prevention of scour is deflecting water away from the abutment or pier. There are several common practices of scour prevention:

a. Sheet piling: Sheet piling consists of inserting metal sheets in intervals around the water-exposed area of the abutment or pier. The piling should be inserted a specific distance from the pier or abutment as not to increase scour and should be driven into stable soil.

b. Riprap: Riprap is a flexible ground covering which serves as a protective layer and is composed of singular pieces of material that can adjust to changes in the subbase. The material used most often is a mixture of rock, broken concrete and rubble. Application of the material is usually dumped or hand placed.

c. Artificial Sea Grass: Artificial sea grass mats are anchored to the bottom of the body of water. The sea grass is placed to absorb the energy of the water current and trap sediments.

d. Hydraulic vanes: Hydraulic vanes are installed to make water and sediment move straight past the piers and abutments. In addition, the hydraulic vanes generate a secondary motion causing the formation of sand bars or reduce erosion of soil.

7) Fatigue Damage Repair: Depending on the severity of the fatigue damage, there may be extensive cracking or loss of concrete.

a. Splicing: Splicing is used to restore the capacity of the existing reinforcing steel. Several splice methods are widely used today. Splicing is basically bonding additional steel into the structure and then reconcrete.

b. Transverse Stiffening:

1) Steel plate attachment (Figure 3.8.-6) [15] will increase the flexural capacity of the concrete, which should slow cyclic fatigue damage. This procedure is to prepare the reinforced concrete beams by removing any dirt or foreign material. The surface should be marked and bolt holes drilled, after identification for stirrups and longitudinal steel. The steel is then applied and bolted.

2. Concrete sleeve or covers will increase the flexural capacity of a bridge member. Surface preparation is critical to developing a bond between the old and new concrete. After preparation, the application of a suitable epoxy-resin primer and the new concrete should provide a full continuous bond. Stirrups should be included to add additional support.

d. Bridge in Critical Condition require rehabilitation

1) Increase structural capacity

a. Composite Action: Composite action (Figure 3.8-7) [16] is intended to increase the moment of inertia of a reinforcing steel component. The addition of a welded flange to a beam will improved the shear and somewhat flexural load capacity of the beam. Access is granted with the removal of deck and superstructure. Also, access can be obtained by drilling holes through the existing material, adding the flanges, and grouting the holes.

b. Post-tensioning: Post-tensioning is the application of high strength steel cables/tendons to increase structural load carrying capacity. Depending on the shape of the cables/tendons and the manner in which they are placed, this method of strengthening is capable of supplementing all static and dynamic load areas.

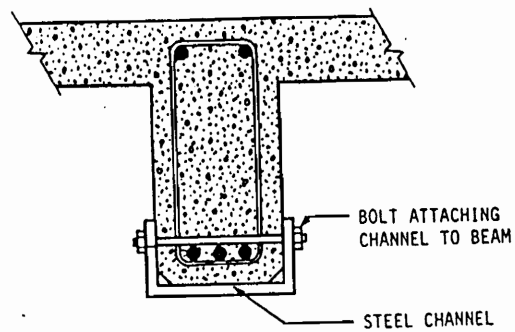
c. Adding supplementary members: The addition of supplementary members involves the removal of existing superstructure to allow attachment of new member, splicing the member in place, strengthening the connection, and reconcrete.

d. Developing Additional Bridge Continuity:

1. Changing Single-Span into continuous multi-span bridge: The incorporation of additional piers at the appropriate attach points can change live load capacity to resemble that of a multiple-span.

2. Modification of Simple Spans: Simple spans are connected together with a moment and shear to resemble the live load capacity of a continuous span bridge.

2) Replace superstructure elements: Replacement of superstructure components requires the removal of the component and any structure or part of structure required to gain access to the superstructure component, replacement and reattachment of the component.



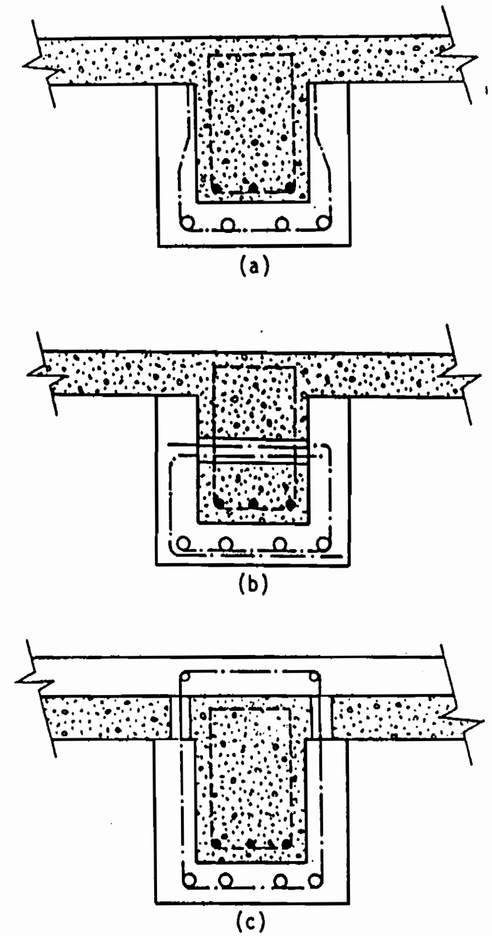




Figure 3.8-6 Addition of a Steel Channel

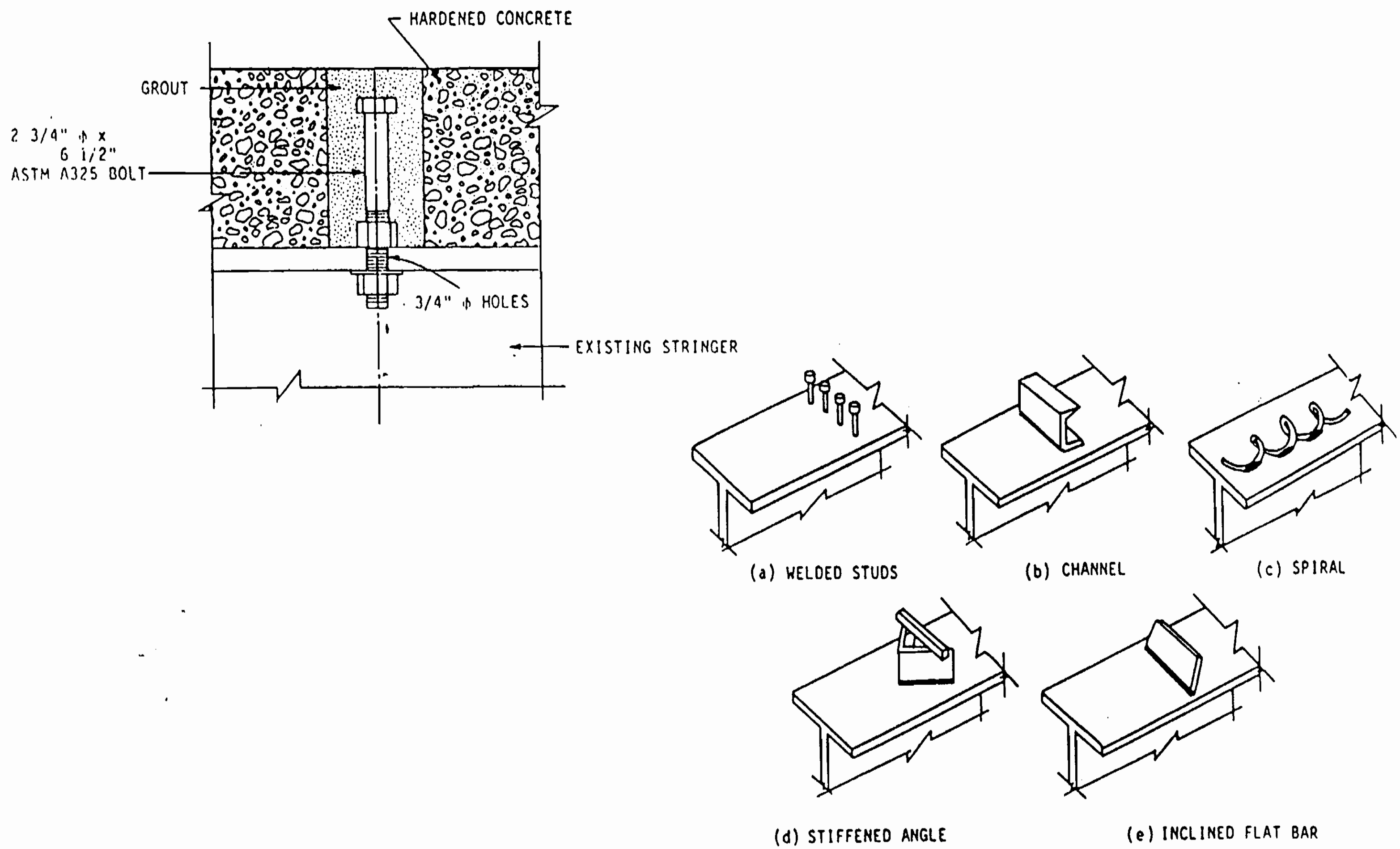



Figure 3.8-7 Composite Action Shear Connectors

3) Deck replacement: Deck replacement is complete by removing the current deck, and replacing the structure. Deck replacement is usually done by cast-in-place or precast panels of concrete which reduces the installation time. The materials chosen for deck replacement can be selected in a manner that will reduce the dead load. A wearing surface may also be included to prevent erosion.

4) Repair/Replacement of Abutments or Piers: The methods employed are mostly to repair underwater piers or abutments. Damage to piers and abutments are normally managed through increase in structural capacity or other methods discussed herein.

a. Bagged Concrete: Bags are filled with dry concrete ingredients and placed in position on the pier or abutment. The bags are anchored together and to the component. The concrete hydrates and hardens when exposed to the water. The method of controlling the hydration rate is normally regulated by the bag itself. The bag is woven of a material that allows saturation at a predicted rate.

b. Concrete-Filled Tubes: Flexible nylon tubes are fabricated to the required dimensions. The tube is placed in position and injected with concrete or cement grout. Before the concrete hardens the tubes are anchored together by steel dowels that are punched through the tube. The tubes are filled and regulated using a valve on the tube.

c. Prepacked Aggregated Concrete: Aggregated concrete is constrain by forms and injected into the concrete through pipes. This method is required to start at the bottom of the pier or abutment. The pressure from the injection pipe should keep water from entering the process. The forms need to be held down by grouted dowels.

d. Replacement: Replacement of abutment and piers is done by aligning the replacement close to the existing component. The damaged element is normally left in place. The new pier or abutment is then attached to the bridge. Portions of the deck may need to be removed to place the new component.

7. Functionally obsolete concrete bridges are normally classified as such because they are unable to manage the volume of traffic even though they are structurally sound. An alternative chosen to correct this situation is widening. Widening can be accomplished by replacement of superstructure, decks, or the other replacement procedures mentioned above. Additional substructures and strengthening activities may be required to complete the widening task.

8. The inspection data which include the bridge condition will also include recommended maintenance, repair and rehabilitation activities. These activities should be assumed completed and Part I, Life Assessment, be recalculated.

9. The recalculated service life will be the Extended Service Life (ESL).

PART III: MAINTENANCE, REPAIR, REHABILITATE, AND REPLACE COSTS

All costs are averages based the data available throughout the country. The costs include removal of existing structure, if applicable, design, engineering, installation and traffic delays/rerouting, if possible. The cost data was modified to reflect current year costs utilizing a six percent interest rate.

| ACTIVITY | YEAR | COST |
|---|---|---|
| 1. Preventative Maintenance | | |
| a. Deck Overlay | 1985 | $ 16.80/sq ft |
| b. Cathodic Protection | 1985 | $ 14.00/sq ft |
| c. Sealing | 1985 | $ .35/sq ft |
| 2. Minor Repairs | | |
| a. Expansion Joint Maintenance | 1985 | $ 4.80/ln ft |
| b. Bearing Maintenance | 1985 | $ .70/ln ft |
| c. Parapets/Guard Rail Maintenance | 1988 | $ 2.10/ln ft |
| d. Surface/Drainage Maintenance | 1985 | $ 1.50/sq ft |
| e. Crack Sealing | 1985 | $ 5.00/ln ft |
| f. Patching | 1985 | $ 20.00/ln ft |
| 3. Major Repairs | | |
| a. Expansion Joint Replacement | 1994 | $ 9.70/ln ft |
| b. Bearing Replacement | 1994 | $ 38.80/sq ft |
| c. Parapets/Guard Rails | 1985 | $ 40.00/ln ft |
| d. Drainage Replacement | 1985 | $ 9.50/sq ft |
| e. Surface Rework | 1988 | $ 3.20/sq ft |
| f. Abutment and Pier Maintenance | 1988 | $ 18.30/sq ft |
| g. Fatigue Damage Repair | | |
| 1) Splicing | 1985 | $ 13.25/sq ft |
| 2) Transverse Stiffening | 1985 | $ 20.00/sq ft |
| 4. Rehabilitation | | |
| a. Increase Structural Capacity | | |
| 1) Composite Action | 1985 | $ 52.00/core |
| 2) Post-tensioning | 1985 | $ 21.00/sq ft |
| 3) Adding Supplementary Members | 1985 | $ 31.50/sq ft |
| 4) Additional Bridge Continuity | 1985 | $ 13.00/sq ft |
| b. Replace Superstructure | 1989 | $ 35.00/sq ft |
| c. Deck Replacement | 1985 | $ 27.50/sq ft |
| d. Repair Abutments or Piers | 1985 | $ 25.00/sq ft |
| e. Replacement of Abutments or Piers | 1985 | $ 32.00/sq ft |
| 5. Replacement | 1985 | $ 41.00/sq ft |

In current year dollars:

| ACTIVITY | YEAR | COST |
|---|---|---|
| 1. Preventative Maintenance | | |
| a. Deck Overlay | 1995 | $ 30.01/sq ft |
| b. Cathodic Protection | 1995 | $ 25.07/sq ft |
| c. Sealing | 1995 | $ .63/sq ft |
| 2. Minor Repairs | | |
| a. Expansion Joint Maintenance | 1995 | $ 8.60/ln ft |
| b. Bearing Maintenance | 1995 | $ 1.25/ln ft |
| c. Parapets/Guard Rail Maintenance | 1995 | $ 3.16/ln ft |
| d. Surface/Drainage Maintenance | 1995 | $ 2.69/sq ft |
| e. Crack Sealing | 1995 | $ 8.96/ln ft |
| f. Patching | 1995 | $ 35.82/ln ft |
| 3. Major Repairs | | |
| a. Expansion Joint Replacement | 1995 | $ 10.28/ln ft |
| b. Bearing Replacement | 1995 | $ 41.13/sq ft |
| c. Parapets/Guard Rails | 1995 | $ 71.64/ln ft |
| d. Drainage Replacement | 1995 | $ 17.01/sq ft |
| e. Surface Rework | 1995 | $ 4.81/sq ft |
| f. Abutment and Pier Maintenance | 1995 | $ 27.52/sq ft |
| g. Fatigue Damage Repair | | |
| 1) Splicing | 1995 | $ 23.73/sq ft |
| 2) Transverse Stiffening | 1995 | $ 35.82/sq ft |
| 4. Rehabilitation | | |
| a. Increase Structural Capacity | | |
| 1) Composite Action | 1995 | $ 93.13/core |
| 2) Post-tensioning | 1995 | $ 37.61/sq ft |
| 3) Adding Supplementary Members | 1995 | $ 56.42/sq ft |
| 4) Additional Bridge Continuity | 1995 | $ 23.28/sq ft |
| b. Replace Superstructure | 1995 | $ 49.67/sq ft |
| c. Deck Replacement | 1995 | $ 49.25/sq ft |
| d. Repair Abutments or Piers | 1995 | $ 44.78/sq ft |
| e. Replacement of Abutments or Piers | 1995 | $ 57.31/sq ft |
| 5. Replacement | 1995 | $ 73.43/sq ft |

Note: Costs specific to the region where the work is to be completed should replace the averages listed above.

A. Calculate the cost of each individual maintenance, repair, and rehabilitation activity recommended for an individual concrete bridge.

B. Calculate the cost of the combined maintenance, repair and rehabilitation (CCMRR) work required. The activities required can be identified from Part I, Part II, and the recommendations of inspection reports.

C. Calculate the cost of the bridge replacement (CBR) utilizing the current dimensions of the bridge or the dimensions of the bridge required to adequately replace the bridge (the recommendations can be approximated by inspection report that classified the bridge as functionally obsolete).

PART IV PRIORITIZATION OF MAINTENANCE, REPAIR AND REHABILITATION WORK

1. Six parameters will be required for the prioritization of work: total service life, service life remaining, extended service life, bridge condition, cost of bridge replacement, and cost of combined maintenance, repair and rehabilitation activities.

2. Calculate the service life remaining by taking the calculated total service life (from Part I) and subtract the current age of the bridge.

3. If (Service Life Remaining(SLR)/Total Service Life(TSL))<.10 and bridge condition is good, fair or poor, then the alternative is to run the loads determination with a safety factor of 1.5. A new total service life and service life remaining should be calculated and run through the remainder of the prioritization system.

Note: Within ten percent of total service life, with a bridge in above average or easily repairable condition, implies that the normal safety factor may be excessively high. Rerunning the assessment part of the system may provide a more realistic service life.

4. If (SLR/TSL) < .10 and bridge condition is critical, then replacement is in order. Until a replacement can be built load restrictions and some maintenance, repair, and rehabilitation work may be needed. Restrictions on loads and velocity should be rerun through the assessment part of the system to determine if and how much relief can be obtained. If restrictions are not practical, then the necessary maintenance, repair or rehabilitation work must be completed while the replacement is built. This is will double the expected costs but will ensure safety.

5. If (Combined Costs of Maintenance, Repair, and Rehabilitation (CCMRR)/Cost of Bridge Replacement(CBR))>.50 and bridge conditions is good, fair or poor, then the option of delaying some of the work may be examined. The delay of preventative or minor repairs may present a more cost effective solution.

6. If (CCMRR/CBR)>.50 and bridge condition is critical or if (Cost of Widening/CBR)>.6 [17] for any bridge condition, then replacement is in order. Until replacement can be built, restrictions and critical maintenance (as recommended in Part II Step 6) must be put in place.

7. For all other cases, the following equation should be used:

PF = (Extended Service Life (ESL)/TSL) x (CBR/CCMRR) x BCF

BCF is the Bridge Condition Factor which are as follows:

Critical = 4
Poor = 3
Fair = 2
Good = 1

Maintenance, Repair and Rehabilitation work should be scheduled as PF goes from highest to lowest number.

3.9 System Test and Evaluation: CBPS will be evaluated in three phases: 1) engineering test and evaluation, 2) development test and evaluation, and 3) operational test and evaluation.

3.9.1 Engineering Test and Evaluation: During engineering test and evaluation, the performance of each part of the engineering model will be verified and validated to ensure proper safety and cost benefit practices have been utilized. Preliminary analysis of the system performance will be compared to program requirements. The engineering model need not be reflective of operational CBPS.

3.9.2 Development Test and Evaluation: Development test and evaluation will include connection of all four parts of a developmental CBPS model and the associated software packages. The final aspect should be a demonstration of the functional capability of the entire system in accordance with program requirements. This developmental model should be equivalent to the final operational system.

3.9.3 Operational Test and Evaluation: Operational test and evaluation will be conducted at the subscribing government's facility. A limited test will be conducted involving a two or three employees, after special training is completed, to prove system utility as well as compliance with program requirements. In addition, any improvements based on user inputs will be identified and incorporated at that time.

# Chapter 4
# ENGINEERING SPECIALTY INTEGRATION

4.1 Manageability: The Concrete Bridge Prioritization System has been designed with consideration of the user throughout each phase. The procedures were designed to minimized the man-hours required to complete each part of the system. In addition, manageability was designed into the system by minimizing the personnel skill level needed to operate any part of the system. Each part has been simplified by the addition of software or the elimination of higher mathematics to ensure optimum human interface.

4.2 Producibility: The prioritization system has been designed and planned for easy utilization for multiple users. The system in its current form is easily reproducible with a copy of the design and the two software packages any personnel computer, with appropriate capabilities. If operational implementation is required or the two software packages are resident on a network, the prioritization system can be available to network users.

4.3 Economic Feasibility: Economic feasibility was part of system design by ensuring that multiple versions of each of the software packages was available. The software recommended has already been tested and reviewed by several experts including Federal Highway Administration (FHWA) and AASHTO. In addition, AASHTO supports the BARS and BRASS software and is easily available upon request. Finally, the system can be completed manually should the expertise be available and not the computer hardware.

# Chapter 5
# CONCLUSIONS

5.1 Results: The CBPS provides a new system for the prioritization of funding and work allocation for all levels of government. The incorporation of two existing software packages has significantly reduced the skill level necessary to operate the system, making this a viable tool. The service life assessment methodology provides a baseline that can be utilized for future planning. While the CBPS provides prioritization based on cost benefit, the main focus is on structural safety. The design complies with all specified requirements.

5.2 Recommendations for Further Research: In the literary research completed for the design of the CBPS, little variable amplitude fatigue data on concrete was found. This reflects a lack of understanding of how concrete reacts to fatigue cycles. Without a complete understanding of this material's properties, design predictions is a risk to all concrete bridge passengers. Further variable amplitude fatigue research is recommended on plain, prestressed, precast, and reinforced concrete.

## VITA

I am currently employed by the Department of Defense as an acquisition professional for the Ballistic Missile Defense Organization. Other responsibilities have included configuration manager for Air-to-Air Missiles Program Management Office, rotary-wing Aircraft Structural Life Surveillance manager for Naval Air Systems Command, and engineering consultant for the F/A-18 Systems Engineering Division. I have received an undergraduate degree in aerospace engineering from the University of Maryland.

Debbie Kesselring

Debbie Kesselring

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