THESIS

USING BUILDING INFORMATION MODELING TO TRACK AND ASSESS THE

STRUCTURAL CONDITION OF BRIDGES

Submitted by

Brendan Michael McGuire

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2014

Master's Committee:

     Advisor: Rebecca Atadero
     Co-Advisor: Caroline Clevenger

     Mehmet Ozbek
     Jonathan Elliott

ABSTRACT

USING BUILDING INFORMATION MODELING TO TRACK AND ASSESS THE

STRUCTURAL CONDITION OF BRIDGES

National Bridge Inspection Standards do not require documenting damage location during an inspection but bridge evaluation provisions highlight the importance of it. When determining a safe load carrying capacity of a bridge, damage location information is significant because shear and moment limit states are more critical at different locations and member capacities can vary along the length of a span. Capturing damage location information using current methods can be impractical; however, building information modeling (BIM) provides new opportunities in tracking and utilizing this information.

A method and prototype implementation to apply BIM software to the operation and maintenance stages of bridges' service lives is presented. The proposed Bridge information modeling for Inspection and Evaluation Method (BIEM) could allow transportation agencies to more efficiently manage bridge inventories using BIM capabilities while incorporating damage location information. The method, created by the author, uses BIM to document damage type, amount, severity, and location information during a bridge inspection. To leverage this information, inspection results are exported from the BIM model into a spreadsheet where a custom subroutine evaluates the structural performance and performs load ratings on selected bridge superstructure elements. In addition, based on the type, amount, and severity of damage, estimated repair quantities are given and maintenance recommendations are provided.

The proposed method was field tested on a case study bridge in Larimer County, Colorado. Official inspection reports and load ratings were obtained and a visual inspection of

the bridge utilizing supplemental location-based measurements was performed. The BIEM was implemented and numerical results were compared to the official load ratings. Results suggest that documenting the location of deterioration within a bridge element can affect the guidelines for determining a safe load carrying capacity for a bridge. In addition, the opportunity exists for BIM to play a significant role in bridge management in the future as demonstrated by its proven ability to facilitate the inspection and evaluation processes which could ultimately result in more automated practices. Overall, results from this research motivate future work in the study of deterioration modes and their effect on bridge element capacity and tailoring the principles BIM to the later stages of bridges' service lives.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AASHTO…………………American Association of State Highway and Transportation Officials

AASHTO BDS…………...American Association of State Highway and Transportation Officials
Bridge Design Specification

AASHTO MBE…………..American Association of State Highway and Transportation Officials
Manual for Bridge Evaluation

ACI…………………………………………………………………...American Concrete Institute

AEC………………………………………………………….Architecture, Engineering, and Construction

API………………………………………………………………Application Programming Interface

ASCE……………………………………………………………..American Society of Civil Engineers

BIM………………………………………...Building Information Modeling/Building Information Model

BIEM………………………….Bridge information modeling for Inspection and Evaluation Method

BMS……………………………………………………………..Bridge Management System

BrIM…………………………………………Bridge Information Modeling/Bridge Information Model

CoRe………...……………………………………….Commonly Recognized (structural elements)

DOT……………………………………………………………Department of Transportation

DET………………………………………………………………...…Damage Evaluation Tool

DLT……………………………………………………………...Damage Location Tool

FHWA……………………………………………………...Federal Highway Administration

LFR…………………………………………………………………Load Factor Rating

LRFD………………………………………………………….Load and Resistance Factor Design

LRFR………………………………………………………..Load and Resistance Factor Rating

NBI...National Bridge Inventory

NBIS…………………………………………………..National Bridge Inspection Standards

NCHRP……………………………………………..National Cooperative Highway Research Program

PC………………………………………………………………….Precast Prestressed Concrete

RC..Cast-In-Place Reinforced Concrete

RF………………………………………………………………………………..Rating Factor

VDC………………………………………………………………...Virtual Design and Construction

VBA………………………………………………………………….Visual Basic for Applications

LIST OF VARIABLES

$\beta_1 = $ factor relating depth of compressive stress block to neutral axis depth

$\gamma_{DC} = $ LRFD factor for component dead load

$\gamma_{DW} = $ LRFD factor for wearing surface dead load

$\gamma_{LL} = $ LRFD live load factor $= 1.35$ for operating and 1.75 for inventory

$\gamma_p = $ factor for type of prestressing steel

$\eta = $ modular ratio

$\rho_p = $ ratio of A_{ps} to bd_p

$\varphi_c = $ condition factor

$\varphi_s = $ system factor

$\varphi = $ LRFD shear or moment reliability factor

$\omega = $ tension reinforcement index

$\omega' = $ compression reinforcement index

$A_1 = $ LFR dead load factor $= 1.3$ for both operating and inventory

$A_2 = $ LFR live load factor $= 1.3$ for operating and 2.17 for inventory

$A = $ noncomposite area of beam (in^2)

$A_g = $ gross area (in^2)

$A_{ps} = $ area of prestressing steel in flexural tension zone (in^2)

$a = $ depth of equivalent rectangular stress block (in)

$b = $ width of compression face of member (in)

$C_1 = $ static compression force $(kips)$

$C_2 = $ static compression force $(kips)$

$c = $ distance from extreme compression fiber to neutral axis (in)

$DC = $ dead load of structural components

$DF = $ distribution factor

$DW = $ dead load of wearing surface

$d = $ distance from extreme compression fiber to centroid of mild reinforcement (in)

$d_p = $ distance from extreme compression fiber to centroid of prestressing steel (in)

$E_B = $ modulus of elasticity of beam material (ksi)

$E_{c,deck}$ = modulus of elasticity of the deck material (ksi) = $57\sqrt{f_c'}$

E_D = modulus of elasticity of the deck material (ksi)

e_g = distance between the centers of gravity of the basic beam and deck (in)

e = eccentricity between the prestressing strand and the section centroid (in)

f_{bottom} = stress at bottom of section (ksi)

f_c' = specified compressive strength of concrete (psi)

$f_c'deck$ = compressive strength of the deck material (ksi) = 3 ksi(for case study)

$f_c'beam$ = compressive strength of prestressed beam (ksi) = 6 ksi(for case study)

f_{ci}' = initial compressive stress (psi)

f_{pi} = initial stress in prestressing steel (psi)

f_{pe} = effective stress in the prestressing steel (ksi)

f_{pu} = specified tensile strength of prestressing steel (psi)

f_{ps} = stress in prestressing steel at nominal flexural strength (psi)

f_{py} = specified yield strength of prestressing steel (psi)

f_{top} = stress at top of section (ksi)

f_y = specified yield strength of mild reinforcement (psi)

I = moment of inertia of beam (in^4)

K_g = longitudnal stiffness parameter (in^4)

k = shear buckling coefficient for webs

k_b = bottom kern point (in)

k_t = top kern point (in)

L = span of beam (ft)

$(LL + IM)$ = live load plus dynamic magnification factor

M_G = moment due to gravity loads (kip $*$ in)

M_g = moment due to self weight of the girder (kip $*$ in)

M_{g+s} = moment due to self weight of girder and slab (kip $*$ in)

$M_{LL} = M_l$ = live load moment effect

M_n = nominal flexural strength of section (lb $*$ in)

M_T = moment at the time of transfer (kip $*$ in)

N_b = number of beams, stringers, or girders

$P_e = $ effective force in the prestressing steel (after losses)(kips)

$P_i = P = $ initial force in the prestressing steel (kips)

$R_n = $ required capacity

$RF = $ LRFR or LFR rating factor

$S = $ spacing of beams or webs (width of the bridge divided by N_b) (ft)

$S_b = $ bottom section modulus (in^3)

$S_t = $ top section modulus (in^3)

$S_{t,composite} = $ top section modulus for composite section (in^3)

$S_{b,composite} = $ bottom section modulus for composite section (in^3)

$SF = $ skew correction factor

$T = $ static flexural tension force (kips)

$t_s = $ depth of concrete slab (in)

1   INTRODUCTION

1.1   Motivation

As of 2012, one out of every nine bridges in the U.S. was classified as structurally deficient [1]. In addition, 30 percent of the nation's bridges have exceeded their 50-year design life [1]. With an aging inventory of bridges, transportation officials must constantly balance maintenance strategies with budget constraints. Bridge rehabilitation decisions are based on the results from periodic inspections [2] along with the experience, engineering judgment, and the memory of the bridge manager [3]. Accordingly, collecting more comprehensive and detailed information in an inspection could result in improved management decisions.

Inspections proceed by discretizing a bridge into a series of elements and recording the condition state of each element. Current bridge inspections document the type, amount, and severity of distress but lack the formal record of damage location within an element [4]. If damage location information is captured in a bridge inspection, it is documented as a text comment, rendering it unusable information in an automated evaluation. Although the National Bridge Inspection Standards (NBIS) do not require documenting damage location, the American Association of State Highway and Transportation Official's (AASHTO) bridge evaluation provisions highlight its importance. For example, if the flange of a simply supported girder contains damage near midspan where the required moment is high, it is of greater significance than if the flange is damaged near the supports. By similar logic, if the web of a simply supported girder contains damage near the supports where the required shear force is high, it is of greater concern than if the web is damaged near midspan [5]. However, current bridge inspections lack the numerical record of damage location both along the length and within the

cross-section of an element [4] [6]. Since limit states and member capacities can vary along the length of a span, and cross-section geometry can influence resistance, the location of damage is significant in determining the structural performance.

With biennial inspections of over 600,000 bridges [7], reliable and automated software methods are desired to track damage location and assess member capacity by incorporating damage location information. Modeling an instance of damage in a digital 3D environment involves the ability to reduce the cross-section of a member at a particular location and/or reduce its mechanical properties. Current built-in tools for modeling damage do not exist; however, building information modeling (BIM) software shows potential in capturing damage location information during bridge inspections. Using BIM, this can be accomplished by linking parametric geometry used to depict deterioration with an information model's database. Facilitating bridge inspections with BIM software provides a means to automate the structural evaluation process and incorporate damage location into the analysis of a selected bridge element. Currently, 29% of asset owners are receiving benefit in using BIM for facility management [8]. By incorporating the principles of BIM into the operation and maintenance of bridges, this number could be increased.

1.2   Research Objectives

The first objective of this research is to develop the Bridge information modeling for Inspection and Evaluation Method (BIEM), which will enable transportation officials to use damage location information from a bridge inspection to evaluate the structural performance of a selected superstructure element. In addition, a prototype BIEM implementation will be tested on a case study bridge. Specifics of the BIEM are presented herein. The second objective of this research is to identify the future requirements for a practical application of BIM into the bridge

management practice. This includes determining what is needed, what is available, and what is not yet available in terms of methods, software, and capabilities required to integrate BIM into the later stages of bridges' service lives.

1.3   Summary of Thesis

The method of research is detailed. A literature review of the bridge inspection and bridge evaluation practices was performed, and the principles of BIM technology were researched. The BIEM method is introduced, which includes the use of two tools developed by the author: the Damage Location Tool (DLT) for damage modeling, and the Damage Evaluation Tool (DET) for assessing the effects of damage on selected bridge members. Furthermore, the BIEM is implemented on a case study bridge by applying DLT and DET. Lastly, results and a discussion, along with conclusions and recommendations for areas of future research are given.

1.4   Definitions

Throughout this document, *damage modeling* shall be defined as the ability to depict the type, severity, amount, and location of deterioration in an information model and can include the ability to reduce the mechanical properties of an element if necessary. Depicting the amount and location can include the ability to reduce the cross-section of a member at a particular location along its length. The term *component* refers to a structural system (deck, superstructure, or substructure), while *element* refers to a structural constituent (a girder, diaphragm, or abutment). *Evaluate* means to calculate and compare the required and provided shear and moment capacities and/or to calculate inventory and operating load ratings. *Structural performance* refers to the ability to satisfy limit states and resist applied loading. *Element* and *member* are used

interchangeably throughout the document as are *damage*, *deterioration*, and *distress*. Also in this thesis, a *parallelepiped* refers to a right rectangular prism, or cuboid.

The Autodesk Revit software package uses the term *schedule* to describe the user interface that accesses the information model's database. Alone, the term *schedule* can be misleading, thus throughout this document, *schedule form* is used in reference to Revit's definition of *schedule*.

Due to their widespread use, *prestressed concrete* (PC) girder bridges are the bridge type of focus. Furthermore, for purposes of demonstration, *cracking, delamination*, and *spalling* will be damage modes of focus in this document.

2   RESEARCH METHOD

2.1   Applied Methodology

A mixed method of research was implemented throughout this study. To understand the shortcomings in the bridge inspection, bridge evaluation, and BIM practices, a qualitative research method was applied. Qualitative methodology was necessary because the aim was to generate textual resources rather than quantities as the data for further analysis [9]. A constructive method of research was implemented in developing the BIEM because the main goal was to propose a solution to the practical and relevant problems [10]. Finally, due to the objective and numerical requirements, quantitative methods are employed in the structural evaluation and validation of the BIEM.

The implemented research tasks and supporting method are outlined as follows:

- Investigate pertinent background and perform literature review (Qualitative)

- Develop the DLT for the modeling of damage on bridge elements in the Autodesk Revit BIM package (Constructive/ Quantitative)

- Develop the DET for the structural evaluation of selected superstructure elements in Microsoft Excel (Constructive/ Quantitative)

- Apply the BIEM (Constructive)

  o Create a model of an undamaged existing bridge per design specification

  o Implement the DLT

  o Export the DLT information from Revit to the DET in Excel to assess the structural performance of a selected superstructure element

5

- Perform a visual inspection and apply the BIEM to a case study bridge (Constructive/Quantitative)

- Identify areas of future research required to implement the BIEM with transportation agencies (Qualitative)

2.2 Framework for the Bridge information modeling for Inspection and Evaluation Method (BIEM)

Constitutive elements of the BIEM include a Damage Location Tool (DLT) for the modeling of deterioration in a BIM model and a Damage Evaluation Tool (DET) for evaluating the effects of deterioration on bridges' structural performance in a spreadsheet subroutine. The generic framework for the BIEM along with the proposed flow of information between the bridge inspection, BIM model, bridge evaluation, and decision making processes is depicted in Figure 2.1. Upon application of the BIEM, a BIM model generates element-level bridge inspection forms to be used in the visual inspection of a bridge using the DLT. After the inspection, the BIM model is updated with inspection results including the location-based damage information using the DLT. The bridge geometry and the damage location information is exported to a spreadsheet where a custom subroutine evaluates the structural performance of selected superstructure elements using the DET. In addition, the DET provides maintenance recommendations and estimated repair quantities which can be used by bridge managers in the decision making process.
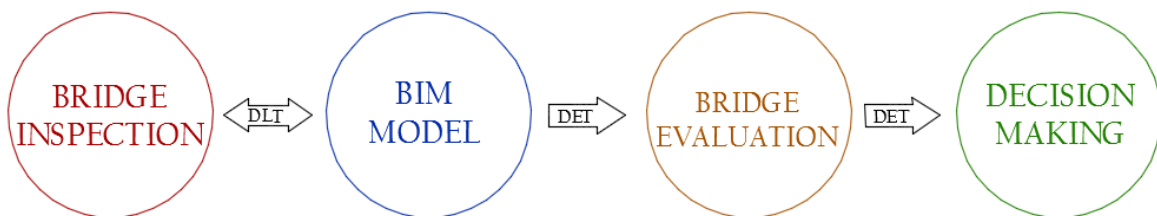
Figure 2.1 The BIEM framework

6

3   BACKGROUND AND LITERATURE REVIEW

3.1   Introduction

A search of literature was performed and pertinent material was reviewed. The subsequent chapter is outlined as follows: Section 3.2 introduces bridge management concepts including bridge inspections and bridge load evaluations, Section 3.3 summarizes limitations in the current inspection practice. Section 3.4 provides an overview of Building Information Modeling (BIM), Section 3.5 outlines limitations in the current application of BIM, and Section 3.6 describes BIM software trials and highlights the selected BIM software package.

3.2   Bridge Management

3.2.1   Bridge Management Systems

Whether a bridge is old or new, the main priorities in bridge management include safety, functionality, and longevity [11]. According to the American Society of Civil Engineers (ASCE) Report Card (2013):

> "…to eliminate the nation's bridge deficient backlog by 2028, we would need to invest $20.5 billion annually, while only $12.8 billion is being spent currently" [1].

As a result of this gap, transportation officials must constantly manage bridge assets under rigorous financial constraints. Bridge management systems (BMS) are software packages developed to help facilitate decisions about improvement strategies when considering capital and maintenance requirements for a network of bridges [2]. An effective BMS forecasts the future needs of transport based on the current condition of the bridge system [2]. Key information

stored and used in a BMS include condition ratings, maintenance cost data, and improvement strategies for each bridge in an inventory [2].

3.2.1.1 *National Bridge Inventory*

A bridge inventory is the main component of a BMS. The National Bridge Inventory (NBI) is a database containing geometric data, average daily traffic loads, and condition ratings for each bridge in the U.S. spanning more than 20 feet [12]. The NBI plays a key role in bridge funding on the federal level and is used to track the condition and functionality of bridges on the state level [13]. In December 2010, the National Bridge Inventory (NBI) consisted of records for 604,493 bridges [7].

An NBI condition rating consists of 0 through 9 ratings for the deck, superstructure, and substructure, along with an overall rating for the structure [4]. Table 3.1 provides definitions and comments for each NBI condition state [4]. As illustrated, higher NBI condition ratings correspond with better condition states.

Table 3.1 NBI component-level condition ratings [4]

Rating	Definition	Feasible Actions
9	Excellent Condition	No problems noted
8	Very Good Condition	No problems noted.
7	Good Condition	Some minor problems.
6	Satisfactory Condition	Structural elements show some minor deterioration.
5	Fair Condition	All primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
4	Poor Condition	Advanced section loss, deterioration, spalling, or scour.
3	Serious Condition	Loss of section, deterioration, spalling, or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical Condition	Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close bridge until corrective action is taken.
1	"Imminent" Failure Condition	Major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put bridge back in light service.
0	Failed Condition	Out of service; beyond corrective action.

According to the American Association of State Highway and Transportation Official's Manual for Bridge Evaluation 2011 (AASHTO MBE) the NBI ratings provide the structural condition of major components of a bridge but do not provide details on the type or severity of deficiencies [2]. Here, the NBI ratings can overlook the effect of deterioration since evaluation methods neglect element-level analysis. Although NBI bridge ratings are useful for planning and budgeting in an overall network-level assessment, for individual bridge maintenance planning, an element-based rating method is necessary; the AASHTOWare Bridge system (formerly known as Pontis) [14].

3.2.1.2 *The AASHTOWare Bridge Management System*

In 1989, the Federal Highway Administration (FHWA) collaborated with six state Departments of Transportation (DOTs) [2] to develop a BMS which later resulted in the

AASHTOWare Bridge program [14]. The AASHTOWare software application stores bridge inspection and inventory information and provides maintenance recommendations for transportation officials. The program uses a top-down approach in its optimization technique [2]. In this philosophy, optimization begins at the network-level of bridge operation to provide project-level recommendations [2]. Hence, individual maintenance programming can be determined by first understanding the condition of the entire bridge network.

Although there are several different programs available, most states have adopted the AASHTOWare Bridge system [13]. Accordingly, AASHTOWare will be the BMS of focus throughout this thesis. AASHTOWare works by discretizing a bridge into commonly recognized (CoRe) structural elements. The CoRe designation was developed to standardize the naming convention of bridge elements. As a result, the CoRe standard allows the sharing of data between transportation agencies and state DOTs [2]. In the CoRe designation, bridge components are grouped into elements based on their function, material, and expected rate of deterioration [2]. CoRe elements can be structural members such as girders, non-structural members such as railings, or protective systems such as paint. CoRe girders, for instance, are distinguished into types such as steel, prestressed concrete (PC), reinforced concrete (RC), and timber.

The AASHTOWare Bridge system involves assigning a rating to each of the CoRe elements based on their current condition state [13]. Here, the AASHTOWare element-level data is limited because it can overlook damage instances within an element. This shortcoming will be discussed in detail in Section 3.3.2. For most CoRe elements, the state of condition is represented by a one to five rating where the severity of the member deterioration increases with an increasing rating (opposite of the NBI ratings) [2]. As an example, Table 3.2 depicts the

AASHTOWare condition ratings, definitions of the rating scale, and feasible actions for the management of PC bridge elements [15]. In this case, PC elements have a one to four condition state rating.

Table 3.2 AASHTOWare element-level condition ratings **[15]**

Rating	Definition	Feasible Actions
1	Good	Little or no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability.
2	Fair	Minor cracks and spalls may be present and there may be exposed reinforcing with no evidence of corrosion. There is no exposure of the prestress system.
3	Poor	Some delamination and/or spalls may be present. There may be minor exposure but no deterioration of the prestressing system. Corrosion of non-prestressed reinforcement may be present but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge.
4	Serious	Delaminations, spalls, and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands of wire, failed anchorages, etc.). There may be sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge.

Using the AASHTOWare BMS bridge inspections are performed by discretizing the bridge into its CoRe elements and rating the overall condition state of each bridge element [13].

3.2.2 Bridge Inspections

The main goal for a bridge inspection is to provide decision makers with data that represents the current structural condition. Inspection results allow the bridge to be correctly evaluated and for improvements to be accurately scheduled and budgeted. Concerns regarding public safety and the conditions of bridges were widespread across the nation following the major collapse of the Silver Bridge spanning the Ohio River in 1967. As a result, congressional mandates led to the development of the National Bridge Inspection Standards (NBIS) [13].

3.2.2.1 *National Bridge Inspection Standards*

The NBIS is a set of federal regulations which applies to all bridges located either on or crossing public roads [7]. The NBIS sets forth inspection methods, maximum frequency of inspections, rules for qualified inspection personnel, and required content of inspection reports for use by transportation agencies and state Departments of Transportation (DOTs) [2]. In addition to outlining regulations for the inspection of structural components, the NBIS provides guidelines for rating the operational characteristics of bridges [13]. Current NBIS bridge inspections are updated in the NBI [13].

3.2.2.2 *Routine Visual Inspections*

Routine visual inspections, as outlined by NBIS, consist of measurements and observations to determine both the physical condition and the functional operation of a bridge [16]. Unless a bridge is new, or severe deficiencies are present, routine inspections are carried out every 24 months for every bridge in the NBI [12]. Inspections using the AASHTOWare Bridge BMS proceed by dividing a bridge into its constitutive CoRe elements and rating the condition state of each element. Items recorded in a routine inspection include the type, severity, and amount of damage present on each element of a bridge [4]. Element-level inspections are beneficial because transportation officials can track the effectiveness of maintenance actions over time by observing changes in the condition state of a particular member [4]. However, element-level inspections are limited because they can overlook damage instances within an element. Visual inspections are generally limited because they do not provide in-depth information about the internal condition of a member [17].

During an inspection, the most common means for record keeping is with pencil and paper [4]. In this method, a bridge inspector reports findings on inspection forms with handwritten notes and sketches. Another method for documenting an inspection is with an electronic data collection source [4]. Electronic means of record keeping could offer benefit to a bridge inspector in the following areas:

- mobile access to documentation, previous inspections, reference information and bridge plans
- potential to eliminate data reentry and the associated human error
- potential to allow inspector to compare current findings with previous inspections in real-time

Almost 2/3 of bridges in the NBI are either RC or PC [18]; accordingly, the following section outlines the inspection of concrete elements and further highlights the importance of documenting damage location.

3.2.3 Case Study: Inspection of Concrete Bridge Elements

During an inspection, RC and PC bridge elements are checked for alignment, cracking, spalling, and rust discoloration [2]. Major causes of deterioration can include: shrinkage, overstress, settlement of substructure, chemical action, poor design/construction, lack of maintenance, temperature variations, moisture absorption, abrasion, collision damage, and scour [19].

According to the AASHTO MBE, reduced member capacity can result from: loss of cross-section, delamination, loss of reinforcing steel area, insufficient development,

disintegration of the concrete matrix, or any distress that causes a change in the element's neutral axis. Further highlighting the importance of damage location, the AASHTO MBE (2011) states:

> "The actual amount of capacity reduction depends on the type of deterioration and its location" [2].

Concrete strength in tension is about 10% of its strength in compression [20]. Therefore, the location, condition, and amount of reinforcing steel is significant in determining a concrete member's flexural stiffness. Clearly this presents challenges in a visual inspection since the steel reinforcement cannot generally be directly observed. With this in mind, distresses that provide indication of corrosion in the steel reinforcement must be rigorously documented during an inspection. Rust discoloration present on concrete surfaces can indicate either prestressing or mild steel corrosion [2]. Steel is especially prone to deterioration when chloride ions from deicing agents are used on bridges [20].

Along with the detection and identification of deterioration, the diagnosis of the degradation mechanism is crucial in establishing corrective maintenance actions [21]. To plan for a repair, it is critical to determine the cause of deterioration, the extent, and whether or not the cause is still active [22]. Common distress modes in RC and PC bridges include: cracking, spalling, delamination, leaching, scaling, honeycombs, efflorescence, and potholing. For the purpose of demonstration in this thesis, cracking, delamination, and spalling are the three damage modes of focus and each are detailed in the following sections.

3.2.3.1   Cracking

Cracks and fractures provide a record of the structural history of a member along with insight into the structural condition. A crack is distinguished from a fracture in that the latter exhibits displaced portions of concrete [22]. The AASHTO MBE highlights the following

inspection observations about cracking and its structural indication. It is important to note that the location of cracking is a defining factor in each of the following statements:

- Diagonal cracks from bearings toward midspan indicate shear overstress
- Vertical cracks in the flange near midspan indicate tensile overstress
- Cracking (or spalling) near the bearings and diaphragms can be caused by creep and camber of the girders

Crack severity depends on size, location, and whether the element is a RC or a PC member. In general, a hairline crack is less than 1/16", a narrow crack is between 1/16" and 1/8", a medium crack is between 1/8" and 3/16", and a wide crack is greater than 3/16" [20]. In a RC member, hairline cracks are usually irrelevant. However, in a PC member hairline cracks may be significant since PC sections are generally designed such that the concrete carries less tension than the tensile force required to crack the section [20]. In RC or PC, low severity cracking usually does not require repair. High severity cracking in RC can generally be filled with epoxy resins or a latex mortar [22]. Although filling cracks prevents further water infiltration to avert additional deterioration, it does not address the cause. For example, filling a high severity crack in RC does nothing to alleviate overstress in the member. The cause of high severity PC cracking should be determined to develop a rehabilitation strategy.

3.2.3.2   Delaminations

Delaminations are the result of corrosion in the reinforcing steel. Corrosion is an electrochemical process that takes place in steel upon the oxidation of an anode and the reduction of a cathode [23]. The loss of electrons in the anode (the location where steel material is lost) result in the formation of ferrous ions; while the gain of electrons in the cathode (the intact steel

surfaces) result in the creation of hydroxyl ions [23]. This galvanic process is illustrated in the following oxidation/reduction process:

$$Fe \rightarrow Fe^{++} + 2e^- \qquad (Oxidation) \qquad\qquad (3.1)$$

$$2H_2O + O_2 + 4e^- \rightarrow 4(OH)^- \qquad (Reduction) \qquad\qquad (3.2)$$
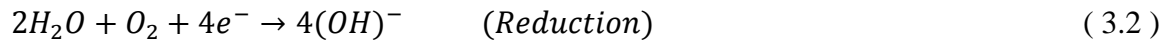
The combination of the ferrous cations with oxygen or hydroxyl anions produces corrosion which is commonly known as rust [23]. Ultimately, the formation of rust causes volumetric expansion. Therefore, delamination is the result of the debonding action between the outermost layer of steel and the surrounding concrete matrix due to this expansive process [22].

Since delaminations can indicate rebar corrosion, the location is significant since the loss of rebar cross-section has a direct and significant impact on strength. Moreover, location is significant since the loss of bond between the steel and concrete causes decreased effective stress transfer between the two materials, which ultimately results in decreased bending resistance.

Delaminations can be detected in a routine inspection by a hollow sound when tapped with a hammer or when a length of chain is pulled across. Repairing a delamination may be performed by injecting an epoxy resin into the affected concrete [22]. Alternatively, concrete beyond the delaminated interface may be removed and repaired as if it were a spall [22].

3.2.3.3   Spalling

Spalling is when concrete has been removed as a result of a fracture parallel to the concrete surface [24]. The major cause of spalling is the same as delamination where the expansion of reinforcing steel causes debonding and separation between the reinforcing steel and the concrete [22]. In addition, spalling can be caused by the alkali-silica reaction (ASR) which is a chemical reaction between the high alkali hydroxides in the cement and reactive silica minerals found in the aggregate [25] [26]. This causes swelling in the concrete which results in map-

cracking which is a widespread network of cracks [25]. Overtime, freeze-thaw cycles can lead to spalling of the concrete [25].

Since a major cause of spalling is delamination, the location of spalling can be significant for the same reasons as delamination. In addition, spalling can indicate locations where the concrete is of poor quality and also where corrosion is likely to develop (further) since the steel reinforcement can be exposed.

Spalling is considered severe if it is greater than ¾ inches in depth or 6 inches in any dimension [22]. Small spalled volumes can be repaired with fine aggregate concrete or temporarily patched with asphalt [22]. Larger spalled volumes can be filled with concrete. Substantial spalled volumes can be repaired with an overlay of Portland cement or a latex modified cement [22]. For severe spalls it is necessary to: remove the corroded steel and the corrosion enabling concrete, protect the region with a waterproof membrane, and top with an overlay [22].

Bridges with heavy or severe deterioration are evaluated for capacity, as discussed in the following section.

3.2.4   Bridge Load Evaluations

A load rating is performed when severe damage is present, the structural integrity of a superstructure element has been deemed compromised, or when the general safety of the bridge is of concern. Load ratings establish the basis for determining a safe load carrying capacity of a bridge [16]. A load rating, reported in tons, is obtained by applying a rating factor (RF) to a nominal truck weight. A generic RF equation is presented in Equation 3.3. As shown, a RF is a ratio of available live load capacity to the required live load.

$$RF = \frac{Capacity - Dead\ Load}{Live\ Load}$$ (3.3)

Stated differently, RFs are applied to adjust the allowable bridge live load depending upon the member's capacity. A legal load posting is required when the RF falls below unity. Load ratings can be used for NBI and BMS records, load posting, improvement planning, and overload permitting [2].

3.2.4.1 *Inventory and Operating Ratings*

Evaluated bridges are done so on two levels: inventory and operating. Inventory and operating ratings are generally taken to represent the lower and upper bounds of the safe load capacity respectively. The lower bound, or inventory load rating, represents a theoretical live load that the bridge could sustain indefinitely [2]. The inventory rating can be thought of as the load which produces a stress level at 55% of the yield stress of a critical bridge element [19]. The upper bound, or operating load rating, signifies the maximum live load a structure may experience [2]. The operating load rating represents the state of stress at 75% of the yield stress of a critical bridge element [19].

Two philosophies of load rating are: the Load and Resistance Factor Rating (LRFR) and the Load Factor Rating (LFR). Both LRFR and LFR are used in practice to develop guidelines for establishing a safe load carrying capacity for a bridge. According a FHWA memorandum (2006): "…it is necessary to accommodate and support LRFR, while continuing to accept LFR…" [27]. Although other methods for load ratings exist, the LRFR and LFR load ratings will be the two presented and used in this thesis due to their widespread use among both new and old bridges. Each of the two methods are evaluated at both the inventory and operating levels of reliability.

3.2.4.2 *Load and Resistance Factor Rating*

Modern bridges are designed using the Load and Resistance Factor Design (LRFD) method and load rated using the LRFR method. LRFR was developed to use consistent reliability indices between the design and the evaluation processes [2]. In the LRFR method of rating, a RF is applied to a nominal vehicle load. The LRFR RF relation is presented in Equation 3.4 as follows:

$$\mathbf{RF} = \frac{\varphi_c \varphi_s \varphi R_n - (\gamma_{DC} DC + \gamma_{DW} DW)}{\gamma_{LL}(LL + IM)} \tag{3.4}$$

Inventory and operating load ratings are distinguished by the LRFD live load factor (γ_{LL}) and are taken as 1.75 and 1.35 respectively for the AASHTO Strength I load case. Values for the remaining factors can be seen in Table 3.3.

Table 3.3 LRFR factors **[28] [2]**

LRFR Rating Method	Factor	Value
Operating	γ_DC, component dead load	1.25
	γ_DW, wearing surface dead load	1.50
	γ_LL, live load	1.35
Inventory	γ_DC, component dead load	1.25
	γ_DW, wearing surface dead load	1.25
	γ_LL, live load	1.75
Both	φ_flexural rating	1.00
	φ_shear rating	0.90
	φ_c, condition factor	varies*
	φ_s, system factor	1.00

*Condition factor varies with the severity of damage

Damage severity in the LRFR method appears in the condition factor, φ_c which is a reduction for member deterioration. Table 3.4 shows the approximate conversion between NBI ratings and condition factors. The condition factor accounts for uncertainty in the resistance of damaged members along with a future rate of deterioration [2]. Detailed inspections can

increase the condition factor because precise measurements decrease the variability in the resistance. Therefore, if cross-section losses are obtained by precise field measurements instead of approximate percentages, the condition factors can be increased by 0.05 as long as the condition factor is less than or equal to unity [2].

Table 3.4 Approximate NBI conversion in selecting ϕc **[2]**

Superstructure Condition Rating	Equivalent Member Structural Condition	φ_c
6 or higher	Good or Satisfactory	1.00
5	Fair	0.95
4 or lower	Poor	0.85

3.2.4.3 *Load Factor Rating*

Similar to LRFR, the rating of a structure using the LFR method applies a rating factor to a nominal vehicle load. However unconventional, for clarity in comparison, the LFR equation is presented in Equation 3.5 using equivalent LRFD notation. It is interesting to note that severity does not factor into the LFR relation.

$$\mathbf{RF} = \frac{\varphi R_n - A_1(DC+DW)}{A_2(LL+IM)}$$

(3.5)

Inventory and operating factors for live loads, A_2 are distinct and taken as 2.17 and 1.3 respectively [2]. Values for the LFR factors can be seen in Table 3.5.

Table 3.5 LFR factors **[2]**

LFR Rating Method	Factor	Value
Operating	A2, live load factor	1.30
Inventory	A2, live load factor	2.17
Both	A1, dead load factor	1.30

3.3 Limitations of the Current Bridge Inspection Practice

Following the collapse of the I-35W Bridge in Minnesota in 2007, an ad-hoc group of ASCE/Structural Engineering Institute and AASHTO members was formed to assess the current bridge management practice and identify areas of improvement to ensure the future safety of the nation's bridges [29]. The group identified many limitations in the current bridge inspection practice including: the lack of a standard national inspection manual, the absence of quality assurance/quality control enforcement among inspections, and not matching an inspector's qualifications with bridge types and complexities [29]. In addition, a major limitation with the current inspection practice is the lack of a detailed record of damage location within a bridge element. Although there are many areas for improvement, requiring the numerical documentation of damage location in a bridge inspection will be the primary amendment of focus in this thesis.

3.3.1 Significance of Damage Location

The location of deterioration is important from a structural evaluation standpoint for three main reasons. First, different failure modes are more critical at different locations along the length of a span. In particular, shear and moment limit states of members in flexure depend upon location [5]. Second, member strengths are determined from the deteriorated cross-section [2]. Third, the capacity of a member can vary significantly along its length. With these in mind, the significance of damage location is illustrated through an example of a simply supported girder with a distributed load. If the flange is damaged near midspan where the required moment is high, it is of greater significance than if the flange is damaged near the supports where the required moment is low. Similarly, if the web is damaged near the supports where the required

21

shear is high, it is of greater concern than if the web is damaged near midspan [5]. Since both loads and resistances can vary with position, the location of damage is significant in determining the structural performance.

3.3.2   Documenting Damage Location

Based on the author's experience, signs of deterioration provide evidence of the structural condition. To accurately evaluate a structure, an accurate depiction of deterioration is required. Since current visual inspections lack the formal record of damage location, bridge managers are presented with incomplete snapshots of the state of condition of bridges. Also, since current inspections using AASHTOWare are only performed on the element-level, damage instances within a member can be overlooked. A more refined inspection resolution is needed by not only documenting the type, severity, and amount of damage present on each element of a bridge, but also including the location of damage modes.

Interestingly, the NBIS does not require documenting damage location in a routine visual inspection while the AASHTO MBE provisions highlight the importance of it. In reference to documenting deterioration during an inspection, the AASHTO MBE (2011) states:

"Direct measurement of the surface area, depth, and location of defects and deterioration is preferred to visual estimates or percentage loss" [2].

Regardless, in an inspection report damage quantity may be expressed as an approximate percentage [4] and if damage location is documented in a bridge inspection, it is as a written comment [6]. The following Tables 3.6 and 3.7 depicts sample data from a bridge inspection report from the Oregon DOT [4]. Table 3.6 depicts AASHTOWare element-level data and contains approximate percentages of an element in a particular condition state despite the AASHTO MBE suggested numerical measurements. Table 3.7 shows example remarks for the

same CoRe elements as in Table 3.6. It is important to note here that regardless of the AASHTO MBE guidelines, the damage location information depicted in Table 3.7 is qualitative, indistinct, and incomplete.

Table 3.6 Example element level data for Oregon DOT bridge inspection **[4]**

Element ID	Description	Quantity	Units	Condition State				
				1	2	3	4	5
18	Concrete Deck	152,100	(SF)	0%	100%	0%	0%	0%
110	Reinforced Conc. Girders	3,332	(LF)	70%	20%	10%	0%	0%
144	Reinforced Conc. Arch	5,522	(LF)	78%	20%	2%	0%	0%
215	Reinforced Conc. Abutment	2	(EA)	50%	50%	0%	0%	0%

Table 3.7 Example remarks for Oregon DOT bridge inspection **[4]**

Element ID	Description	Remarks
18	Concrete Deck	Thin overlay overtops one of the joints.
110	Reinforced Conc. Girders	Girder 1 has exposed stirrups
144	Reinforced Conc. Arch	Concrete Arches have horizontal cracks near the center top. Steel exposed in spandrel column and cracks with efflorescence on arches.
215	Reinforced Conc. Abutment	None

According to the FHWA Bridge Inspector's Reference Manual (page 4.4.19), documenting the location of deficiencies in an element is only required if a load capacity analysis is to be performed. Irrespective of this, damage location information is often not present in an inspection report for a bridge that requires a load evaluation [6]. Ironically, if damage location information is recorded, the subjective content and textual format renders it unusable information from an automated load capacity analysis. For instance, the case study bridge described in Chapter 8, is a load rated and load posted bridge. The two most recent Colorado DOT bridge inspection reports neglect comprehensive numerical documentation of the location of any instance of damage. Moreover, the damage location descriptions in these reports are

either arbitrary, imprecise, or both using terms such as "various locations", "near abutments", "random cracks", and "north end of west wheel line" [6].

By requiring the numerical documentation of damage location in an inspection, in-situ conditions could be more accurately captured in a report and bridge managers could have a more comprehensive picture of the current state of condition of bridges.

3.3.3   Potential for Building Information Modeling (BIM) in Bridge Management

With an aging and deteriorating inventory of over 600,000 bridges [7], software methods are desired to store location-based damage information from inspections. In addition, with an electronic means of data collection, an inspector can have real-time access to previous inspections, documentation, and bridge plans. In utilizing damage location information from an inspection, the structural evaluation processes for a large number of bridges could be automated. Building information modeling (BIM) is a logical platform to facilitate added inspection requirements which could be used to ameliorate the bridge management practice.

3.4   Building Information Modeling (BIM)

A powerful overview of BIM according to Vanessa Quirk (2012), the managing editor of ArchDaily, is included in the following synopsis:

> "BIM software must be capable of representing both the physical and intrinsic properties of a building as an object-oriented model tied to a database" [30].

At its core, BIM is 3D modeling environment which includes three basic features according to Quirk (2012): "object based design, parametric manipulation, and a relational database" [30]. BIM is founded on the principles of centralization, collaboration, and the reuse of information

[31] [32]. The following section highlights key aspects of BIM along with a few of its current applications.

3.4.1 Overview of BIM

BIM is the evolution of computer aided design (CAD) [33]. A CAD drawing consists of nothing more than a collection of static and unintelligent objects. However, with BIM, every point, line, and plane has a level of intelligence and can report information. In addition, BIM elements have the capacity to store data and create relationships. Features of BIM are best illustrated through an example. A CAD drawing of a beam is an assembly of unassociated lines and planes that are used to visually represent a beam. Using BIM, a beam is a realistic entity with material and mechanical properties, associated placement characteristics, and can include information such as manufacturer, model, and cost. Elements in a BIM model are parametric in that changes to an object are reflected throughout all aspects of the project [34]. Information captured in a model can be presented as coordinated documents and shared across multiple disciplines [31]. Collaboration is a significant function in BIM. Industry foundation classes (IFC) define the interoperability standard and allow for the workflow transfer between different software platforms, trades, and companies.

3.4.2 Current Applications of BIM

Local transportation agencies and State DOT's are encouraged to use BIM technology by federal agencies. Under the Moving Ahead for Progress in the 21st Century Act (MAP-21), the FHWA is awarding 5% federal project funding for using the 3D technology [35]. Today, the use of BIM is widespread in the architecture, engineering, and construction (AEC) industries. Jenny

Jones (2014), a senior writer for the ASCE's Civil Engineering periodical states that "firms that aren't using it [BIM] will soon be irrelevant" [33].

The application of BIM into the bridge setting is not a new idea. Bridge information modeling (BrIM) was created as a bridge specific environment and was developed to aid in the engineering and construction simulation of bridges [32]. Similar to BIM, the fundamental concepts of BrIM consist of interoperable workflows, the reuse of information, and linking the AEC phases of bridges [32]. Also similar to BIM, the BrIM environment can be 4D by integrating time into the model and 5D by associating cost with model components [36].

3.5   Limitations in the Current Application of BIM

An attractive feature of BIM includes its potential for managing information throughout the entire life cycle of a structure. From early conceptual design to construction simulation BIM is a proven and established tool. However, little has been done to implement the use of BIM into the later stages of the project life cycle [37]. According to the 2012 Smart Market Report, almost 60% of architecture and engineering firms are receiving benefit in utilizing BIM for the design stages of a project but only 29% of asset owners are receiving benefit in utilizing BIM for the operation and maintenance stages [8]. One reason for this is the lack of as-built BIM models for structures requiring maintenance. In the bridge management field, creating individual models for each structure in an inventory would be untimely and economically unfeasible using conventional methods. With emerging technology, digitizing and modeling an entire bridge inventory could be practical for management purposes. For example, with the application of 3D laser scanning, a bridge could be modeled in a timely manner from dense point cloud data which can capture both the detailed and precise geometry required [38].

Regardless of the setting, often the goal of information modeling is to capture the real condition of a structure. Ironically, current information modeling capabilities can only depict ideal conditions and are unable to readily depict damage on an element. For example, an out-of-the-box information model of a beam is ideal, fully intact, and just that; out-of-the-box. By only modeling ideal elements, both BIM and BrIM are inherently used in the virtual design and construction (VDC) stages rather than the operation and maintenance (OM) stages of a project's life cycle.

Another reason BIM is underutilized in facility management is the ambiguity of liability for the information in a model. For example, if a contractor creates and uses a BIM model for the VDC phases of a project, and an owner wants to utilize the model for OM management, a question of who is liable for the information in the model becomes an issue. According to proceedings from the Lake Constance 5D conference (2013):

> "There needs to be a clear milestone of when the owner will assume responsibility for the data and the construction team is able [to] consider their task complete" [39].

Carefully defining the data handover process can result in a smooth transition between the as-built phases and the as-maintained phase of the project life cycle [39].

It is evident that BIM capabilities show the potential to ameliorate issues in the field of bridge management; however, BIM software has yet to have a significant role in in the bridge inspection and bridge evaluation practices. With the lack of standard means to model the in-situ conditions of bridge elements, information modeling methods to depict deterioration are desired.

3.6   Selected BIM Software Packages

Many BIM software packages are available. Six software options were researched and three of the six were tested as described in the following sections.

3.6.1 Software Researched

The three software options researched but not tested are outlined based on their modeling capabilities, intended use, and interoperability capabilities. It should be noted that observations in the following section were primarily based from researching documentation provided by the manufacturers. It is not possible to extrapolate a software's potential application by evaluating features and benefits provided by the manufacturers. Any conclusions drawn in this section are done so based on the author's observations and in no way depict the software's full capabilities.

3.6.1.1 *Graphisoft ArchiCAD*

ArchiCAD is a software package popular in Europe and it features an architecture focused BIM environment [40]. However, interoperable capabilities are robust with the program's portable document format (PDF) collaboration [41]. ArchiCAD software was not selected for use in this thesis due to its limited use in the United States when compared with other BIM packages, its seemingly limited capacity for modeling bridges, and its innate discipline specific nature provided in the software's native environment.

3.6.1.2 *Tekla Structure*

Structure is a BIM platform with diverse application in the AEC community in the United States. Collaboration is achieved through its IFC and open BIM approach. The application programming interface (API) allows users to create add-ins to tailor and enhance the program [42]. Tekla features impressive modeling capabilities especially in level of structural detail it can attain. Ultimately, Tekla Structure was not selected for use because it seemingly lacks an intuitive built-in user interface linking parametric geometry to the information model's database.

3.6.1.3 *Midas Civil*

Civil is a BrIM modeling environment for girder, suspension, cable-stayed bridges. Civil facilitates bridge design and evaluation by using the AASHTO LRFD specification, libraries of predefined sections, static and dynamic analysis, strength checks, and LRFR load ratings [43]. The predefined section libraries and bridge templates restrict the ability to model damage on a member because they limit customizable actions. Moreover, predefined elements allow for the cross-section to be changed but do not allow for the cross-section to be changed at a particular location along the length of a member. Therefore, Civil was not selected for use because damage location cannot be adequately modeled (see Section 1.4) using this platform.

3.6.2 Software Trials

After researching, three software options were tested based on their ability to model bridge geometry, potential to model damage on a bridge element, capacity for recording damage location information, and interoperability characteristics.

3.6.2.1 *Bentley LEAP Bridge*

Bentley's LEAP Bridge is a BrIM program for the design and analysis of small to medium span concrete bridges [44]. LEAP Bridge contains a parametric bridge design module, depicted in the top image of Figure 3.1, girder and abutment definitions depicted in the bottom left and right images of Figure 3.1, a prestressing module, and an analysis module.
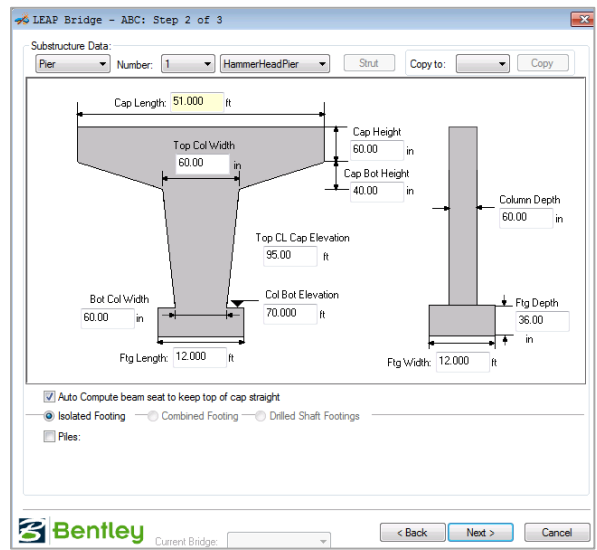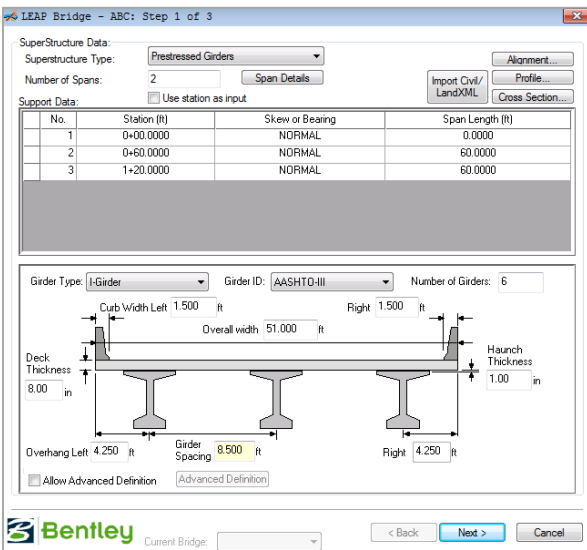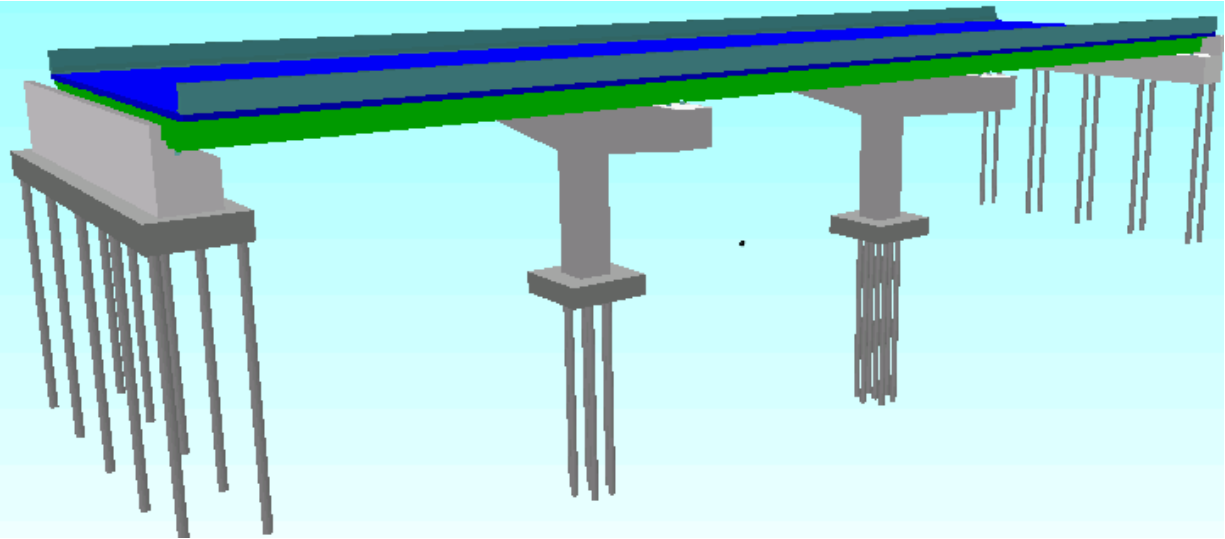
Figure 3.1 Top center: LEAP Bridge 3-D model. Bottom left: LEAP Bridge girder type definitions.
Bottom right: abutment and foundation definitions

Similar to Midas, the limitation with LEAP Bridge lies in its use of templates and its predefined structural members. LEAP's predefined elements allow for modification of the cross-section, but do not allow for the cross-section to be modified at a particular location. Accordingly, damage cannot be adequately modeled for the purposes of this thesis and LEAP Bridge was not selected for use.

3.6.2.2 *Autodesk Revit*

Demchak et al. (2009), which include a product designer, a product manager, and a licensed author for Autodesk, state: "Revit is built for managing change" [31]. With Autodesk Revit, architectural, structural, and mechanical disciplines are all supported by a parametric change engine. Custom families and user defined parameters allow for the program's widespread application. Revit can be tailored and enhanced through the API. In addition, the program offers an interoperable IFC platform which allows for the exchange of data between non-native file types [45].

In summary, Autodesk Revit 2014 was identified by the author as the most robust BIM package for the purposes of this thesis and was selected as the BIM tool for use. The following subsections highlight key aspects of the Revit platform.

3.6.2.2.1 *Revit Families, Types, and Instances*

Revit organizes model elements into three categories: families, types, and instances. Each category is best defined through example. A family, for example, is a PC single-tee beam. Revit provides templates for creating families based on desired behavior and placement characteristics. Libraries of predefined families exist and can be customized and different families can be nested into each other. As an example, a RC diaphragm family can be nested into a PC single-tee beam to form one component. Types are parametric variations of a family. A type could be a specific size or configuration of a family. An example of a type could be an 8' X 36" PC single-tee beam. An instance is a specific placement of a family type such as an 8 X 36" PC single-tee beam placed at a certain coordinate on a certain level.

3.6.2.2.2 *Revit Parameters*

The power of Revit comes from its parametric nature. A parametric object as an intelligent object that can change its size, geometry, materials, or visibility but is consistently the same object [31]. In Revit, using the human body as an analogy, parameters are the brain, dimensions are the muscle, and reference planes form the skeleton. A parametric object can be created by locking model objects to reference planes then assigning parameters to dimensions which control the position of the reference planes. Parameters could be length, compressive strength, or a user defined graphical setting. Visibility parameters act as a Boolean on/off switches controlling the appearance of an object. Shared parameters are parameters that can be reported or manipulated in a schedule form and can contain information available to export.

3.6.2.2.3 *Revit Schedule Forms*

Schedule forms act as a user interface to link parametric geometry in the model with the information model's database. Schedule forms can contain an itemized list of all instances of a family type or a selected list of shared parameters for each instance. For example, a schedule form could contain an itemized list of reinforcement bar sizes in a bridge or could be customized with parameters reporting damage location information on a bridge element.

Along with Revit, Autodesk produces a product called BIM 360 Field which could be used as a mobile BIM platform in conjunction with Revit. The following section gives a summary of BIM 360 field.

3.6.2.3 *Autodesk BIM 360 Field*

BIM 360 Field is a cloud-based information management platform that features portable use on an iPad tablet [46]. BIM 360 Field can coincide with Revit to provide field access to the

BIM model. In navigating through a model on a mobile tablet, BIM 360 Field can incorporate the use of augmented reality which provides a real-time interactive view of the physical environment in a BIM model through a tablet's video camera. Upon implementing BIM 360 Field, a Revit model could be updated with inspection results from BIM 360 Field. Benefits in using BIM 360 Field to facilitate inspections could include mobile access to the BIM model, plans, and reference information, fluid inspections with no double entry, and ease of photographic documentation throughout the inspection.

BIM 360 Field contains checklists where inspection sheets can be defined and issues where acceptable criteria can be established as shown in Figure3.2. Push-pins can be placed to mark issues. However, in BIM 360 Field, damage parameters from the Revit model are not accessible, push-pins are not intelligent in their spatial location, and checklists are unassociated with push-pins. Due to its inability to depict the level of modeling detail required, BIM 360 Field was not implemented.

Figure 3.2 Left: BIM 360 Field inspection checklists. Right: BIM 360 Field issues in an inspection checklist. Photos from (Autodesk, 2014) **[46]**

3.6.3   Software Conclusions

A summary of the software trials is available in Table 3.8. This table is divided into two segments: the software researched but not tested and the software researched and tested. Table 3.8 provides a summary of the decision criteria along with the author's observations for each package.

Table 3.8 Software trials and decision criteria

	Software Platform	Intend. Use	Modeling Capabilities	IFC	Ability to Model Bridge Geometry	Ability to Model Damage	Ability to Record Damage Location
Software Researched but Not Tested	Graphisoft ArchiCAD	Arch.	Buildings	Yes	Unknown	Unknown	Unknown
	Tekla Structure	AEC, Detail	Buildings and Infrastructure	Yes	Yes	Unknown	Unknown
	Midas Civil	Engr.	Bridges and Infrastructure	Yes	Yes	No	Unknown
Software Researched and Tested	Bentley LEAP Bridge	Engr.	Bridges	Yes	Yes	No	No
	Autodesk Revit	AEC	Buildings and Infrastructure	Yes	Yes	Yes	Yes
	Autodesk BIM360 Field	Field Inspect.	Buildings and Infrastructure	Yes	Yes*	No	No

*In conjunction with Autodesk Revit

In summary, Revit's custom families and user defined parameters provide the means for modeling the location, amount, type, and severity of damage on a bridge element. To reiterate, the author identified Autodesk Revit 2014 as the most robust BIM package for this application and was selected as a demonstration tool for use in this thesis.

4 THE BRIDGE INFORMAION MODELING FOR INSPECTION AND EVALUATION METHOD (BIEM)

4.1 The Purpose of the BIEM

The Bridge information modeling for Inspection and Evaluation Method (BIEM) was developed to serve two purposes. First, it is used to demonstrate the capacity for BIM software to capture and reuse information gathered during an inspection to automate the structural evaluation process. Second, it is used to identify what is needed, what is available, and what is not yet available for a practical application of BIM into the bridge management practice.

4.2 Overview of the BIEM

The BIEM is a method developed by the author to be used by transportation officials to aid in the management of simply supported, low-volume, PC bridges. The framework of the BIEM is depicted previously in Figure 2.1. The first main function of the BIEM is to document damage type, amount, severity, and location information from a bridge inspection using the Damage Location Tool (DLT) as discussed in Chapter 5. The second main function is to utilize damage information from an inspection to evaluate the structural performance using the Damage Evaluation Tool (DET) as outlined in Chapter 6. The DET yields capacity calculations, along with LRFR and LFR load ratings for selected superstructure elements. In addition, the DET provides estimated repair quantities and maintenance recommendations for the selected elements.

Implementing the BIEM could help transportation officials make decisions regarding maintenance and rehabilitation strategies for bridges. Specifically, the BIEM could provide

benefit because it allows for the rapid observation of consequences in inspection results and maintenance actions such as:

- the change in capacity if the severity of a certain damage instance is changed

- the change in load rating if a certain damage mode occurs at different locations

- the change in capacity if loads are added such as an asphalt overlay

The specific tasks in the BIEM development are as follows:

- utilize Revit to apply BIM principles to the bridge environment

- implement the DLT to document the type, severity, amount, and location of damage instances on bridge elements

- execute the DET to assess structural performance utilizing the damage location information stored in the BIM

- identify the future requirements for a practical application of BIM into the later stages of bridges' service lives

4.3   Legal Liability Issues

Following the collapse of the Silver Bridge spanning the Ohio River in 1967, the evolution of bridge inspections and bridge evaluations have been driven almost exclusively by issues of public safety and liability [12]. As a result, bridge inspection and load rating reports are both official, legal documents. Potential litigation can pose as an area for considerable risk for public agencies, transportation officials, consultants, and individual engineers working in the bridge practice [20]. If a method such as the BIEM were implemented in practice, agencies, managers, or individuals should rigorously investigate the profound legal implications and public safety issues that could be related. The author made no attempt in the development of the BIEM

and its constituents to address liability and legal issues that could be involved upon implementation.

5   MODELING DAMAGE USING REVIT

The following chapter contains a depiction of the requirements for modeling damage on bridge elements, a presentation of a tool to meet those requirements, and a discussion of limitations of the tool.

5.1   Requirements for Modeling Damage

Since current BIM capabilities are unable to readily depict damage on an element, a software method to document damage information from an inspection is desired. As previously mentioned, cracking, delamination, and spalling of PC bridge elements are the three damage modes of focus in this thesis; therefore, modeling damage in this thesis will include only these three damage modes. However, in a practical application of the proposed method, the capacity for modeling many types of damage would be necessary to accurately depict in-situ conditions during a bridge inspection. In addition to cracking, delamination, and spalling, the ideal tool for modeling damage on PC bridge elements would include modeling damage modes such as: leaching, scaling, honeycombs, efflorescence, and potholing.   Moreover, the modeling of damage on steel bridge elements might include: cracking, fracturing, corrosion, local buckling, local yielding, lateral torsional buckling, and crippling.

Autodesk Revit does not currently have the built in capacity for modeling damage nor was it designed to model bridges. Nevertheless, the author developed a method to use existing tools in Revit to accomplish the major objectives in modeling a bridge and documenting damage information from bridge inspections. Key requirements for modeling damage include:

- Ability to reduce the cross-section or part of the cross-section at a particular location along the length of an element

- Ability to reduce the mechanical properties of an element

- Ability to document the type, severity, amount, and location of damage on an element

The following section presents a tool developed to satisfy these requirements.

5.2   The Damage Location Tool (DLT)

By adding the location of deterioration to current NBIS inspection requirements, comprehensive information about the structural condition of bridges can be captured. Accordingly, the author developed the Damage Location Tool (DLT) to be used similar to a plug-in in Revit as required for the Bridge information modeling for Inspection and Evaluation Method (BIEM). The DLT will provide bridge inspectors with the ability to reduce the cross-section of a bridge element at a particular location along its length. In addition, the DLT will provide the ability to document the location, type, amount, and severity of deterioration during an inspection. Information from the DLT will be used further downstream by decision makers to evaluate the structural performance, discussed in Chapter 6.

The following subsections highlight the primary function of the DLT, introduce the use of the author's coined 'damage cubes' for documenting damage information, describe the user interface for the DLT, discuss means for adjusting mechanical properties, and outline software and file requirements for the user to implement the DLT.

5.2.1   Primary Function of the DLT

The primary function of the DLT is to document the type, severity, and location of up to three different distress modes on any specified bridge element.

5.2.2   Damage Cubes

The DLT works with the use of the 'damage cube' family created by the author. A damage cube is a parametric parallelepiped used to represent a volume of a certain damage type at a particular location on a bridge element. Information embodied in one damage cube include the severity and location of one instance of one damage type. Since there are three damage types of focus in this thesis: cracking, delamination, and spalling, one set of three damage cubes could represent three instances of three different types of damage. In the DLT, one cube represents one instance of cracking, one cube represents one instance of spalling, and one cube represents one instance of delamination. In an inspection, if there are more than one instance of a certain damage type on an element, additional sets of damage cubes can be placed on that particular element. For example, if in an inspection, ten instances of cracking, five instances of spalling, and eight instances of delamination exist on a member, ten sets of damage cubes should be placed on that member. This will be discussed further in Section 5.2.3.1.

Damage cubes can be placed on any element in any Revit model. As an example, the left portion of Figure 5.1 depicts a default Revit single-tee PC girder family. On the right side of Figure 5.1 are three generic damage cubes placed on the single-tee family. In the DLT, the cracking, delamination, and spalling deterioration modes are represented with red, orange, and yellow damage cubes respectively. The circle in the lower right corner of the PC single-tee depicted in Figure 5.1 defines the origin from which all location parameters for all three damage cubes reference.
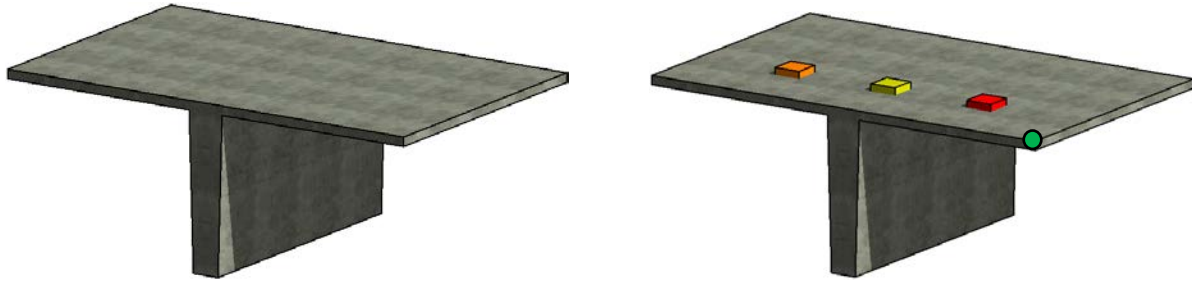
Figure 5.1 Left: the PC single-tee family. Right: damage cubes hosted on the PC single-tee family

5.2.2.1 *Options for Depicting Damage*

Damage cubes can be created as void forms, where the damaged volume is physically cut from the hosting geometry, or they can be solid forms as shown previously in Figure 5.1, where the damaged volume is illustrated by color coded cubes. Solid form damage cubes are used in the DLT due to their visible nature and graphical implications. Specifically, solid form damage cubes can be used as a visualization tool to emphasize graphically the precise locations of deterioration on a bridge in the model.

In Revit, there are many hosting options available that define different relations between the damage cubes and other families in the model. Here, the term *hosting* refers to creating or placing the damage cubes within or on another family. For example, the damage cubes can be face based or hosted on any face of another family, line based or hosted along any line of another family, hosted completely inside another family, or created as a generic model, as discussed herein. Various hosting options were explored to determine the best suited and most diverse option for the damage cubes in the DLT. Table 5.1 depicts several options that were tested and their associated pros and cons.

Table 5.1 Hosting options for damage cubes

	Pros	Cons
Face Based	Cube easily placed on any face in the model	Unable to control out of plane parameters
Line Based	Cube easily placed on any line in the model	Only have control over parameters in one dimension
Hosted Inside of an Existing Family	Able to constrain some cube dimensions to reasonable values	When value large, cube moves to constraint but unreasonable dimension remains in the properties
	Condensed schedule form since cubes and hosting family are the same entity	Many parameters required; parametric dimensions likely to conflict and cause errors
		Cubes can conflict with vertical extents of hosting family to cause unintended changes to the model geometry
Generic Model Family	Diverse application, can be placed on any girder, deck, abutment, etc.	Dimensions are not constrained; unreasonable dimensions can be entered
	All parameters function without conflict	Less compact schedule form since cubes and inspection elements are 'separate' entities
	Typos in the dimensions can be easily detected graphically	
	Fewer parameters required since geometric constraint is unavailable; less chance for errors	

Examination of the host relations in Table 5.1 reveals that the best suited option for the DLT is creating the damage cubes in a generic family since they can be placed at any point on any family and the cubes parameters cannot conflict with the hosting geometry. Creating the damage cubes inside existing families was ruled out because of its limited applicability to the specific hosting family, the likelihood for conflicting parameters, and the potential for parameters to adversely affect the vertical extents of the family[1].

---

[1] Objects are placed and exist in Revit on levels, or horizontal planes. When parameters of a damage cube such as "From Top" or "Depth" exceed the vertical extent of the hosting family, the position of the entire family adjusts vertically according to what Revit thinks is the "new height" of the family. This causes undesirable effects because it enables the user to unintentionally change the model. For example, if the damage depth is set to 4' and the depth of a beam is 3', the entire beam shifts (instead of the damage cube) downward by 6".

5.2.2.2 *Generic Model Family Damage Cubes*

The main benefit for creating the damage cubes as a generic model family is utilizing the widespread hosting options. The generic family damage cubes can be hosted on any family, whether it be a girder, slab, diaphragm, or abutment. In the generic family configuration, a single cube can represent damage on a girder or a slab or both. The ability to represent damage on more than one element is beneficial, for example, when considering girder/slab composite action. In this case, deterioration in the slab has an effect on the capacity of the composite girder.

Another benefit in creating the cubes as a generic family is the inability for conflicting parameters. When the damage cubes are created as a generic family, the damage cube dimensions cannot be geometrically constrained. For example, this means an instance of cracking can be 40' long on a beam that is only 30' long. When no geometric limits are established for the damage cubes, parameters controlling the cubes are unable to conflict with the hosting geometry. However, as another example, nesting and constraining the damage cubes inside of a beam family causes the frequent conflict of parameters between the damage cubes and the beam geometry; ultimately causing errors in the DLT.

5.2.2.3 *Unrestrained Damage Cubes*

As a result of the parametric nature and the referencing relations between the damage cube and the member geometry, an unrestrained damage cube can exist beyond the extents of a member. This can be seen on the right of Figure 5.1 shown previously, where the top of each damage cube is not flush with the top of the PC single-tee family. This visual overlap is beneficial because otherwise, the damage cubes would be concealed by the hosting family. The

drawback to this is that deterioration clearly cannot exist beyond the boundary of a member. It is important to note here that regardless of the visual overlap between a damage cube and a member, the damage cube's volume will always remain as accurate as field measurements from a bridge inspection. In addition, the magnitude of the inaccuracy is negligible in when applied to the member capacity calculations and the load ratings.

5.2.2.4   *Damage Cube Parameters*

To fully describe the spatial location of a damage cube in relation to member geometry, parameters must be defined that report the distance between a family's reference point and a reference point on each cube. Since element-level inspections discretize a bridge into a series of elements, a global coordinate system is irrelevant and local coordinate systems must be established. In a 3D environment, referencing a parallelepiped's centroid to a known point on the element is logical. Overall, six parameters are required to fully document the location and size of one instance of damage; three to describe the 'local' Cartesian position, and three to define the volume of a damage cube. In the DLT, the first Cartesian parameter is the distance from a specific load bearing support to the centroid of the damaged volume. The second is the distance from a particular edge of a member to the centroid of the damaged volume. The third Cartesian parameter is the distance from the top a member to the centroid of the damaged volume. Finally, the three volume defining parameters for one cube include length, width, and height. Also, for each cube, a visibility parameter and a parameter denoting damage severity is assigned. Therefore, for one set of three damage cubes, 24 shared parameters are defined; 18 to control dimensions, three to manage visibility, and three to report severity.

The damage cubes were created by locking the faces of cubes to reference planes then assigning parameters to dimensions which control the position of the reference planes. When a

cube's face is aligned and locked to a reference plane, geometry can be flexed by the controlling parameters. Figure 5.2 illustrates a top view of the three damage cubes, their reference planes, dimensions, and the origin. The origin from which all of the location parameters reference is depicted with a circle in the lower right corner of Figure 5.2. Parameters assigned to each cube are illustrated with the text dimensions and the reference planes are illustrated by the dashed lines in Figure 5.2.
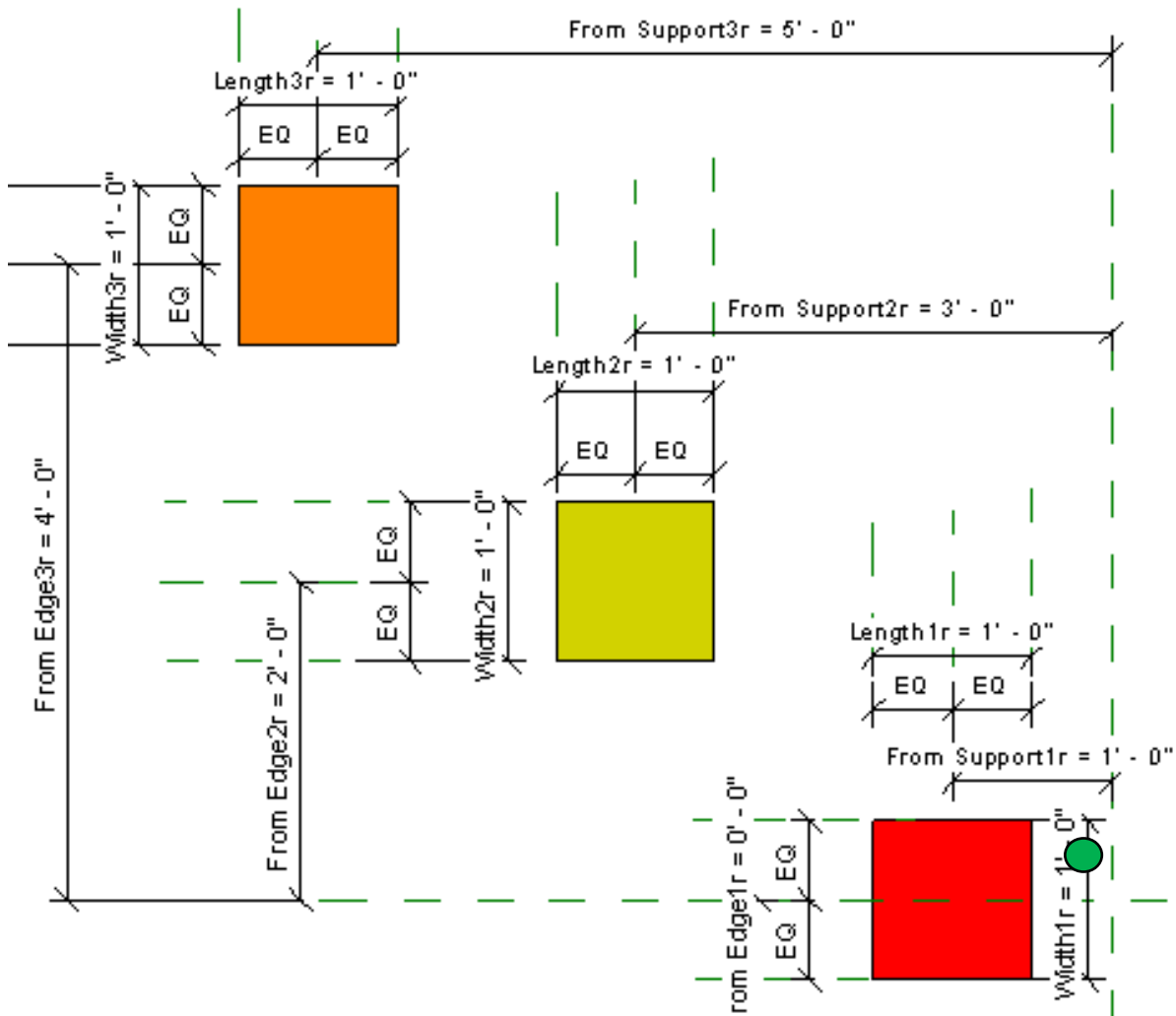
Figure 5.2 Damage cubes with dimensions controlled by shared parameters

In summary, the generic model family was chosen to be used for the damage cubes in the DLT. Overall, the purpose of a damage cube is to store and report three kinds of parameters:

damage type, severity, and location. Controlling the type, severity, and location attributes of a damage cube is done in a schedule form in Revit, described in the following section.

5.2.3   The User Interface for the DLT

The primary user interface for the DLT is a custom schedule form created in Revit. A schedule form is used to control damage cube parameters, access the model's information database, and facilitate the bridge inspection operation of the DLT. The first function of the schedule form is to provide a bridge inspector with a checklist of elements to inspect. The second function is to update the BIM model with results from an inspection.

Damage cubes can be controlled in three different ways with varying levels of accuracy and control. The first and most robust method is through the bridge inspection schedule form. Table 5.2 illustrates a portion of a sample inspection form. In this form, the cube's parameters can be specified on a bridge element simply by inputting values into the form. Note that Table 5.2 is divided into two segments; the upper is an itemized list of girders on the bridge, and the lower is an itemized list of the damage cube sets (consisting of three cubes) on each girder. Note that all length measurements in Table 5.2 are in inches.

Table 5.2 Sample bridge inspection form in Revit linked to damage cubes

Girder #	Family	Spalling_v	Spall Sev	Length2	Width2	Depth2	From Support	From Top2	From Edge2
Girder A	Precast-Single T								
Girder B	Precast-Single T								
Girder C	Precast-Single T								
Girder a	DAMAGE CUBE	✓	0	12	12	6	300	40	48
Girder b	DAMAGE CUBE	☐	0	1	1	1	0	0	0
Girder c	DAMAGE CUBE	☐	0	1	1	1	0	0	0

The second method for controlling the damage cubes is by selecting the desired damage cube instance and defining the parameters in the cube's property window. This method is

accurate but is limited to updating one damage cube at a time. The last and least accurate method involves changing the cube's position and size with the shape handles. The shape handles for a damage cube appear upon selection and can be adjusted by clicking and dragging with the mouse.

5.2.3.1   *Type of Damage*

Damage types are identified in the DLT in Revit with visibility parameters which act as Boolean on/off switches. Damage types include cracking, delamination, and spalling and are defined with check boxes in the schedule form. To illustrate, the spalling damage mode is toggled with the check boxes in Table 5.2 shown previously. Therefore, during an inspection, checking a certain damage type in the form causes the corresponding damage cube to appear on the bridge model.

It should be noted that damage types in the DLT not mutually exclusive, in other words, two or three different damage types can be depicted at the same time. Furthermore, multiple instances of the same damage type can be depicted. To review the example in Section 5.2.2, if ten instances of cracking, five instances of spalling, and eight instances of delamination exist on a member, ten sets of damage cubes should be placed on that member. Since there would be ten sets of damage cubes but only five instances of spalling and eight instances of delamination, only five spalling check boxes and eight delamination check boxes should be checked in the schedule form.

5.2.3.2   *Severity of Damage*

Damage severities can be defined in Revit in the bridge inspection schedule form by the corresponding combo boxes. Note these fields can only contain integer values. Damage

severities in the DLT are similar to but have a subtle distinction from the AASHTOWare Bridge condition states, described in the following subsection.

5.2.3.2.1 *The DLT Severities vs. the AASHTOWare Condition States*

In both the AASHTOWare Bridge and the proposed DLT, higher rating values indicate higher severities. However, there are several distinctions that will be addressed. In practice, the AASHTOWare Bridge ratings function by categorizing how much of an element is in a certain one to five condition state (for most elements) [2]. However, in the DLT, a one to five rating is proposed to indicate the volumetric severity of each instance of a damage type within an element. The main distinction here is that AASHTOWare can amalgamate different damage types and instances into a single condition rating for an element. The DET has a more detailed resolution in that the severity of damage types and instances are determined and distinguished on a case-by-case basis, instead of combining them for the entire element. Another distinction is that quantities reported using AASHTOWare Bridge can be depicted by integers, linear dimensions, or areas. Conversely, the DLT strictly reports quantities using volumetric dimensions.

The following example is provided to illustrate the differences between the existing AASHTOWare Bridge condition states and the DLT damage severities. For instance there is one instance of severe spalling that exists on a girder and measures 2" in length, 2" in width, and 3" in depth and one instance of severe cracking exists and measures 3" by 1" by 1". In the AASHTOWare Bridge convention, these damage modes would be lumped together and reported as 7 square inches (2" X 2" + 3" X 1") in condition state five. However, in the DLT, the same instances of damage would be reported separately as 12 cubic inches of spalling (2" X 2" X 3") with a severity of five and 3 cubic inches of cracking (3" X 1" X 1") with a severity of five.

5.2.3.3 *Location of Damage*

Location parameters define the damage cube's position and volume. These parameters can be accessed and adjusted most efficiently in the inspection schedule form. Location parameters for each cube are titled:

- From Top

- From Support

- From Edge

- Length

- Width

- Depth

5.2.4 Adjusting Mechanical Properties

If the modeling of damage includes the need to decrease mechanical properties of a member, the user can make the necessary adjustments in Revit independent of the DLT as shown in Table 5.3. However unconventional, units are provided in pounds per square foot as per default in Revit.

Table 5.3 Mechanical properties in the schedule form

Girder #	Family	f'c (psf)	fpu (psf)	fpy (psf)	fy (psf)	UW (pcf)	Ec (psf)
Girder A	Precast-Single Tee	432000	36000000	30600000	8640000	150	580464000
Girder B	Precast-Single Tee	432000	36000000	30600000	8640000	150	580464000
Girder C	Precast-Single Tee	432000	36000000	30600000	8640000	150	580464000
Girder a	DAMAGE CUBES						
Girder b	DAMAGE CUBES						
Girder c	DAMAGE CUBES						

5.2.5   Required Software and Files for Using the DET

To implement the DLT, a transportation agency would need a bridge model in Revit 2014 (.rvt), the Damage Cube family file (.rfa), and the Bridge Inspection 4-14 shared parameters text file (.txt). The Damage Cube family file contains the core of the DLT including the generic model damage cubes and their associated parameters. The Bridge Inspection 4-14 text file allows access to the predefined parameters that control the damage cubes.

5.3   Limitations of Current tools

Several inaccuracies and limitations of the DLT are present. In practice, multiple damage instances of several damage types are likely to exist on a single bridge. As discussed, the DLT is capable of modeling as many instances as necessary of the three damage types. However, to demonstrate the use of the damage location information, the programming of the DET only supports the modeling of the worst case scenario of each damage type. To implement the BIEM prototype, the user must model only the most severe crack, the most severe spall, and the largest delaminated region in the DLT. This will be discussed in further detail in Section 6.2.2.

In addition, the DLT approximates damage modes geometrically with parallelepipeds, when in reality, it is inaccurate. For instance, the modeling of a spiral (or curved) crack must be approximated with a right rectangular prism. The lack of geometric constraint of the generic family damage cubes also presents inaccuracies because a cube, or portions of a cube, can exist outside of the hosting geometry. This is inaccurate because clearly, deterioration cannot exist outside of a member. In addition, Revit only supports positive dimensions. Repercussions of this are illustrated in the last two rows in the previous Table 5.2. Here, spalling instances on Girders B and C 'do not exist' because their corresponding damage type check boxes are

unchecked rendering them invisible. However, in reality, the damage cubes still exist and small (one inch in this case) dimensions must be specified for the length, width, and depth parameters because Revit cannot handle a zero dimension when creating geometry. The last drawback is that the damage cube family and the hosting member are separate entities. Although this does not adversely affect the evaluation computations downstream, it ultimately results in a less compact schedule form.

Based on information captured with the DLT, a software method to evaluate the structural performance of selected bridge elements was designed and is presented in the next chapter.

6   EVALUATING DAMAGE USING EXCEL

The following chapter introduces the requirements for evaluating damage on bridge elements, presents a tool to meet those requirements, and discusses future extensions of the tool.

6.1   Requirements for Evaluating Damage

Once damage information is collected in a bridge inspection, transportation officials need a tool to utilize the data to make informed management decisions. To use information gathered in an inspection bridge for the evaluation and decision making processes managers need three main pieces of information. First, they need the in-situ capacity of the bridge including the effects of deterioration. Second, bridge managers need the safe load carrying capacity of the bridge. Third, they need to know what necessary maintenance actions are required to prevent or alleviate the effects of deterioration on the bridge.   The following section presents a tool to satisfy these requirements.

6.2   The Damage Evaluation Tool (DET)

The author developed the Damage Evaluation Tool (DET) to provide decision makers with the ability to evaluate the structural performance and establish guidelines for the safe load capacities of superstructure elements. The DET application is designed to be used in Microsoft Excel as required for the BIEM. Excel was chosen as the tool for evaluation due to its widespread use and to demonstrate interoperable usage of information between different software manufacturers. The following subsections highlight the primary function of the DET, introduce limitations in the prototype, outline the necessary preliminary calculations, describe

inputs and outputs to the DET, and outline software and file requirements for the user to implement the DET.

6.2.1 Primary Function of the DET

The DET is a software application add-in programmed by the author using the Visual Basic for Applications (VBA) programming language. The DET is developed to use location-based damage information obtained from the Damage Location Tool (DLT) in Revit to perform a structural evaluation on selected superstructure elements. Initially, a schedule form containing inspection results from the DLT is exported from Revit into Excel. Upon execution of the DET, the tool provides estimated repair quantities and maintenance recommendations, determines the required and damaged flexural and shear capacities, and calculates the LRFR and LFR operating and inventory flexural load ratings for a specified composite girder.

6.2.2 Limitations of the DET Prototype

The overarching goal of the BIEM is to capture and reuse location-based damage information from a BIM model to automate the bridge evaluation process. To reach this ultimate goal and for the purposes of demonstration, the prototype DET was tailored to a specific but commonplace circumstances of bridges. Fundamental assumptions in the programming of DET allow for its application to a wide range of bridges with further modifications. Specifically, the programming of the DET is tailored to the case study bridge as described in Chapter 8 which is a simply supported PC single-tee girder bridge with a composite deck and it evaluates one instance of damage at a time. Assumptions and default values specific to the case study bridge will be discussed in detail in Section 8.5.1.

6.2.3   Preliminary Calculations

The main goal in modeling damage is to represent the existing condition. Depicting damage can be accomplished by reducing the cross-section of a member at a particular location and/or decreasing the mechanical properties of a member. To accurately evaluate a superstructure element, knowledge of the design loads are required. The following subsections highlight each attribute.

6.2.3.1   *Undamaged Cross-Section Properties*

To reduce the cross-section of a member at a particular location, a means of generating cross-sections to subtract areas from is required. Main cross-section dimensions such as the flange thickness, web thickness, slab thickness, width of member, and height of member are reported by the DLT and are read by the DET. A VBA subroutine is developed to use this geometric information to generate and discretize a girder/slab composite cross-section. Since the AASHTO MBE specifies the measurement accuracy of concrete elements to the nearest ½ inch [2], the section generator meshes the cross-section into ½ inch square increments. Output from the VBA subroutine in the form of a virtual undamaged cross-section spreadsheet is presented in Figure 6.1. Each "pixel" is an Excel cell containing the value 0.5. The 0.5 values placed in each cell represents a 0.5 by 0.5 inch square increment of the discretized cross-section. The cross-section is color coded in Figure 6.1 according to the respective compressive strengths of the material. The values in red represent a RC slab while the values in black represent a PC single-tee cross-section. The isolated rows and column of digits shown in green in Figure 6.1 are sums of the discretized flange/slab and stem increments respectively. Using the flange, slab, and stem summations from the undamaged geometry, composite cross-section properties are generated

and calculated. Desired cross-section properties include area, centroid, moment of inertia, section moduli, radius of gyration, and kern points.
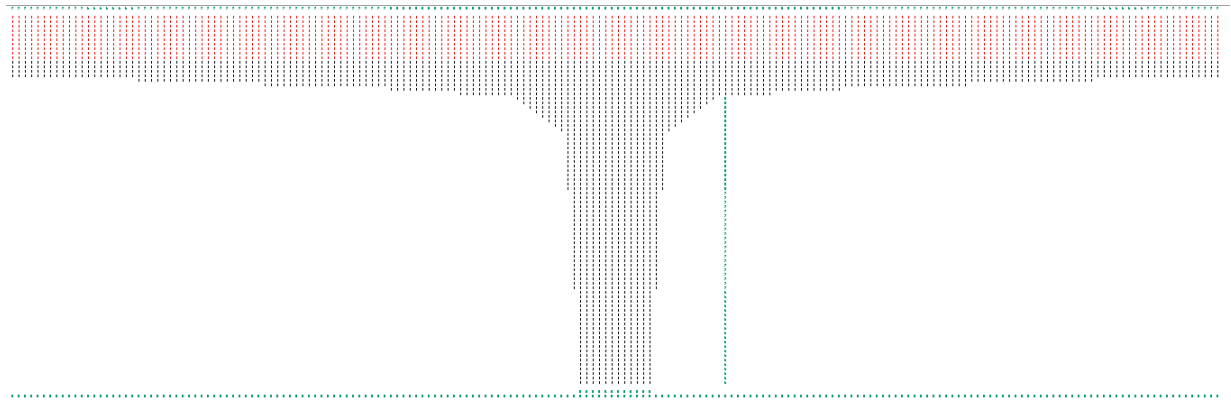
Figure 6.1 Output from the undamaged cross-section generator subroutine in Excel

6.2.3.2 *Damaged Cross-Section Properties*

Using the damage location information from the BIM model similar subroutines for cracked, spalled, and delaminated geometries are programmed to create the corresponding damaged cross-sections. As an example, an instance of spalling is created by subtracting spalled areas recorded in the DLT from an undamaged cross-section. Damaged volumes are obtained by sequencing the damaged cross-sections according to the "length of damage" parameter. With material now subtracted from the undamaged cross-section, major dimensions are re-calculated as averages with respect to the ½ inch cross-section resolution. Section properties are then calculated for each instance of damage type on a selected member.

6.2.3.3 *Mechanical Properties*

Mechanical properties of steel and concrete are necessary for determining an element's strength. If the modeling of deterioration includes the need to decrease the mechanical properties of a member, the user can make the necessary adjustments to parameters in Revit

independent of the DLT. When the mechanical properties are changed in Revit, the DET will register these changes upon execution.

6.2.3.4 *AASHTO Design Loads*

Design loads are significant in evaluating capacity and determining load ratings because they define required strengths that an element in question must resist. All design loads are pre-calculated independent of the DET according to the American Association of State and Highway Transportation Official's 2012 LRFD Bridge Design Specification (AASHTO BDS). The component dead load, DC, and the wearing surface dead load, DW are determined using the AASHTO BDS unit weights and the case study bridge geometry specified in Section 8.3.2. The live load, LL, is determined by varying the axle spacing of a moving AASHTO truck to determine the maximum moment envelope. Live loads factors into account: dynamic magnification, load distribution, and skew, and are calculated using the AASHTO BDS moving truck loadings. Sample calculations for the case study and procedures for the live load and live load factors are depicted in further detail in Appendix B.

The design loads in the DET are specific to the geometry of the case study bridge, discussed in Chapter 8. Accordingly, it is necessary for a user of the DET to analyze the bridge of interest to determine the design loads for the bridge geometry at hand.

Utilizing the design loads, required moments are determined in the DET by assuming the loads act uniformly along the length of the girder. Since the DET supports the analysis of simply supported girders, the required moment is presented in Equation 6.1 as follows:

$$M_u = \frac{\omega_u l^2}{8}$$

(6.1)

In applying this relation, an important assumption is made regarding the live load moment and shall be discussed. The AASHTO HS-20 truck generates a moment envelope from the three moving axle (point) loads. The DET uses the maximum live load moment from the envelope to calculate a distributed live load using Equation 6.1. In doing so, it is assumed that the live load moment from the envelope is equivalent to the maximum moment generated from a uniformly distributed live load. Calculations proved this assumption to be valid for a 40' span and HS-20 trucks with variable rear axle spacing, with an average of 1.4% difference.

6.2.4   Inputs to the DET

The user interface for the DET is depicted in Figure 6.2 and will be described in the following subsections. In summary, user inputs are divided into three categories: direct user inputs, indirect user inputs, and function buttons. Direct user inputs are those defined through the user interface in the DET by the list box and check boxes. These inputs include the member number and the damage type selections. Values are required in both of the direct user input boxes in the user interface; otherwise an error message will appear prompting the user for proper input. Indirect inputs include those which are automatically obtained from the DLT in Revit by the DET in Excel upon export of the inspection form. Indirect inputs include damage location and severity. Function buttons provide basic program operations for the user. Function buttons include: run evaluation, show assumptions, clear results, and exit. Figure 6.2 illustrates direct user inputs along with the function buttons in the user interface for the DET.
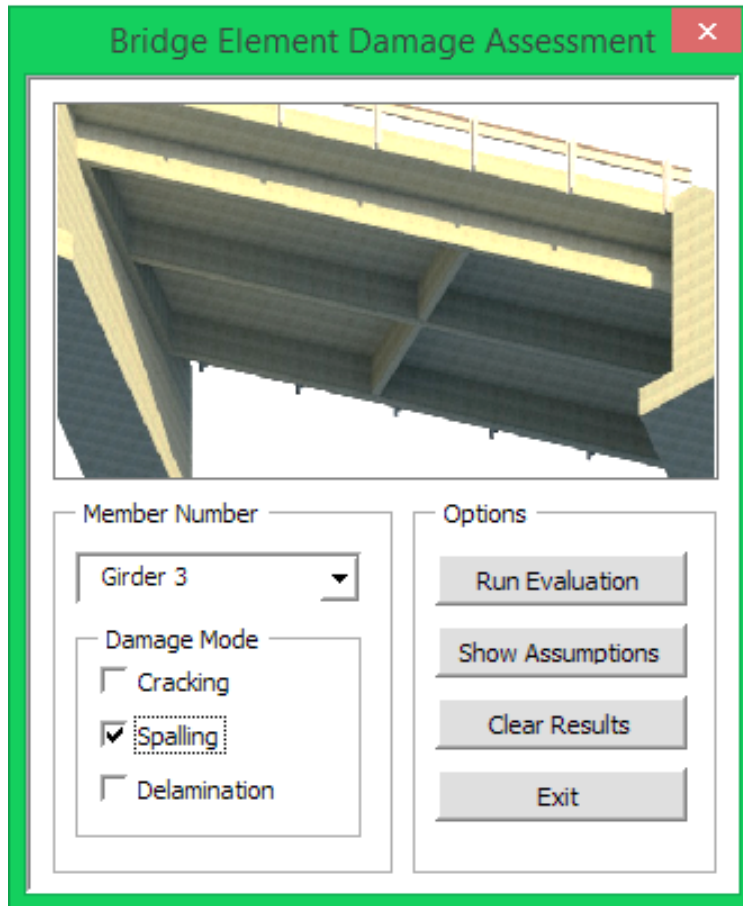
Figure 6.2 The DET user interface in Excel

6.2.4.1 *Member Number*

The member number is a direct user input, as indicated by the combo box in Figure 6.2. Selection of the member number defines which superstructure element and corresponding damage cube information are read by the DET.

6.2.4.2 *Type of Damage*

Damage type, as indicated by the check boxes in the previous Figure 6.2 is the second direct user input. The damage type selection determines which damage mode will be analyzed on the selected girder number. For the purposes of demonstration and to utilize the worst case inspection results, inputs supported by the damage mode selection are mutually exclusive.

Acceptable input includes one instance of cracking or one instance of delamination or one instance of spalling. If the user wanted to explore the effects of each case, simulations can easily be run individually for each damage type and compared to determine the most severe results.

Type of damage information is also used by the DET to provide the appropriate maintenance recommendations. For example, the damage type, in conjunction with the damage severity information, are used by the DET to offer feasible maintenance actions to a bridge manager according Table 6.1 discussed later in this chapter.

6.2.4.3 *Severity of Damage*

Damage severity is an indirect input obtained from the condition ratings from the bridge inspection and is automatically read upon export of the inspection form. Severity information determines which LRFR condition factor is used in the analyses. The conversion between element-level condition ratings from an inspection and the condition factor values to apply in the LRFR rating factor calculation are shown previously in Table 3.4. Also recall from Chapter 3, since deterioration is proposed to be measured with precise field measurements (instead of approximate percentages), according to the AASHTO MBE, the values in Table 3.4 can be increased by 0.05 [2]. Note here that in the AASHTO MBE provisions, severity does not factor directly into LFR calculations.

6.2.4.4 *Location of Damage*

The location of damage is the second indirect input and is used to determine where the damage is located along with the size. In particular, the "from support" parameter is used to determine where the centroid of the damage is located with respect to the span. As previously

mentioned, damaged cross-sections are sequenced according to the "length of damage" parameter to obtain a volumetric representation of a damage type.

Also, the location of damage information is used by the DET to provide the estimated repair quantities. Since parameters in the DLT track volumetric information of damage instances, this information is reused in the DET to provide information on the quantities of material required in a repair. For example, if a 12" X 12" X 2" spall exists, the estimated repair quantity feature would report an approximate 288 in^3 of material required for the repair.

6.2.4.5 *Run Evaluation*

The DET executes by clicking the Run Evaluation button. If there is information on any Excel sheet other than Sheet 1, this information will be overwritten and data will be lost unless it is manually saved elsewhere. Output from the DET is provided in Section 6.2.5 and demonstrated in Section 8.5.

6.2.4.6 *Show Assumptions*

Assumptions made throughout the development of the DET are readily available for the user to view by selecting the Show Assumptions button in the DET's user interface. Upon selection, a text file opens as depicted in Figure 6.3, containing all underlying assumptions made in the programming of the DET's algorithms. Specific assumptions pertaining to the case study bridge are discussed in detail in Section 8.5.1.
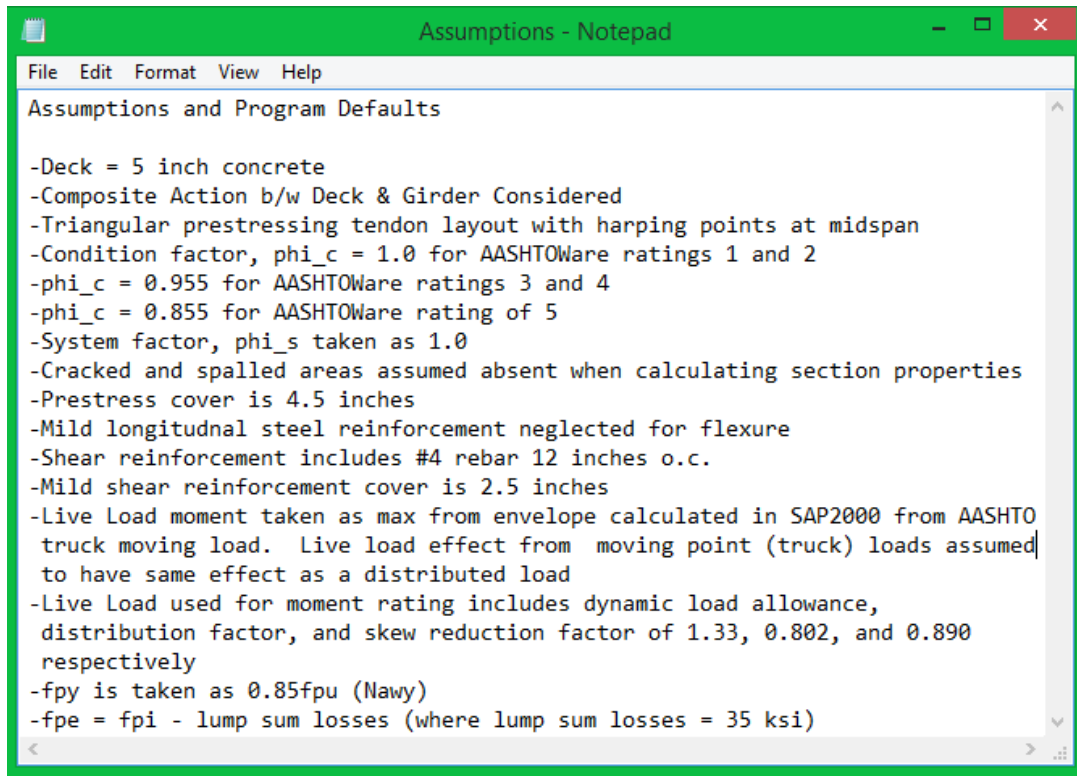
Figure 6.3 Assumptions window in the DET

6.2.4.7 Clear Results

The Clear Results option deletes all Excel sheets including charts other than Sheet 1. If multiple evaluations are desired using the same data sheet, information from the DLT is preserved on Sheet 1.

6.2.4.8 Exit

The Exit button simply terminates the DET user interface and returns to Sheet 1 in Excel.

6.2.5   Outputs of the DET

Results from the DET are divided into three categories: maintenance information, member capacity calculations, and load ratings. Outputs of DET are outlined and discussed in the following sections:

- Maintenance Information
    - Estimated repair quantities
    - Maintenance recommendations
- Member Capacity Calculations
    - Flexural capacity of an undamaged section
    - Flexural capacity of the damaged section
    - Shear capacity of an undamaged section
    - Shear capacity of the damaged section
- Load Ratings
    - LRFR flexural load rating
    - LFR flexural load rating

6.2.5.1   *Maintenance Information*

Estimated repair quantities are provided by the DET based on damage location information read from the DLT. In particular, the DLT reports the length, width, and depth of damage instances which are used to establish the estimated repair quantities on a selected member.

Maintenance recommendations are presented for a selected member based on the damage type and severity selection. For the DET to provide maintenance recommendations, the AASHTOWare Bridge one through five condition states are categorized as follows:

- ratings of one and two are classified as low severity

- ratings of three and four are classified as medium severity

- ratings of five are classified as high severity

Maintenance recommendations are based on the AASHTO MBE specification and the ACI Committee 546: Guidelines for the Repair of Concrete Bridge Superstructures. Maintenance recommendations are provided for cracking, spalling, and delamination damage modes. Table 6.1 illustrates all possible combinations of maintenance recommendations provided by the DET [2] [22].

Table 6.1 The DET maintenance recommendations **[2] [22]**

Damage Mode	Damage Severity		
	Low	**Medium**	**High**
Cracking	None	Fill and/or seal cracks	Seal and patch cracks (widen if needed), or rehab unit
Spalling	None	Patch and/or seal	Clean steel reinforcement, patch, and seal or replace unit
Delamination	None	Inject epoxy into delaminated region	Remove concrete down to steel, repair as a high severity spall

6.2.5.2 *Member Capacity Calculations*

The required shear and moment capacities are conservatively calculated based on the AASHTO BDS dead and live loads for an interior girder. Composite action between the RC slab and the PC girder is considered in calculating moment capacity. However RC/PC composite action is conservatively neglected in the evaluation for shear. Since the moment capacities are generally found to be more critical in the analysis of PC members, moment capacity will be the focus of discussion herein.

On the capacity side, other important assumptions are made. According to the AASHTO MBE, in evaluating a PC member for strength, it is permissible to neglect the flexural resistances of all non-prestressed steel [2]. In the flexural analysis the compressive strength of a composite RC slab/PC girder is conservatively taken as the compressive strength of the slab. This is logical because if the slab and entire top flange of the cross-section are in compression, the RC slab will crush before the PC girder.

From the undamaged cross-section geometry, undamaged shear and moment capacities are calculated. To determine the moment capacity, the distance from the extreme compression fiber to the neutral axis, c, is required. From the statics of a girder in flexure, the tensile and compressive forces are equivalent as shown in Equation 6.2, therefore the relation presented in Equation 6.3 can be made. Figure 6.4 illustrates a cross-section of a single-tee girder with a composite deck. The compressive stress block, show in in red on the top right, is equivalent to the tensile resultant force carried by the prestressing tendon centroid, depicted with the red arrow on the bottom right.

$$T = C_1 + C_2 \tag{6.2}$$

$$A_{ps}f_{pu} = 0.85f_c'b\beta_1c + kA_{ps}\frac{f_{pu}}{d_p}c \tag{6.3}$$
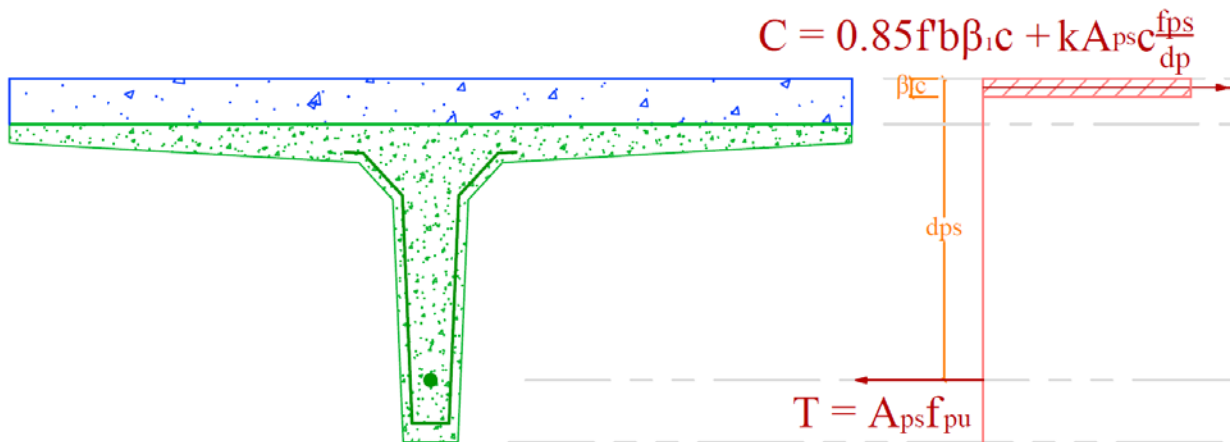
Figure 6.4 Statics of a PC single-tee girder in flexure

A sample calculation for c is illustrated in Appendix B. The provided moment capacity is calculated by summing the moment about the compressive resultant force. The resulting equation for the flexural strength of a PC girder neglecting the non-prestressed reinforcement shown in Equation 6.4 as follows [47]:

$$M_n = A_{ps} f_{ps} \left(d_p - \frac{a}{2} \right) \tag{6.4}$$

Based on the undamaged cross-section geometry less the volume of a damage type, damaged shear and moment capacities are calculated in the DET for the cracked, spalled, and delaminated scenarios. This is done in a similar manner as the undamaged case except the DET re-calculates the cross-section and mechanical properties based on damage information registered in the DLT as discussed previously in Section 6.2.3.2.

6.2.5.3 *Load Ratings*

Upon execution of the DET, the LRFR and LFR load rating methods are both calculated on the operating and inventory levels for the selected superstructure element. Both the LRFR and LFR methods are calculated by the tool for completeness, but also to compare the DET results with official LFR load ratings for the case study bridge, described in Chapter 9. The rating factors, as discussed in Section 3.2.4, are calculated according to the AASHTO BDS guidelines. The load ratings calculated by the DET are outlined as follows:

- LRFR inventory
- LRFR operating
- LFR inventory
- LFR operating

In review of Section 3.3.1, member capacities are determined from the deteriorated cross-section [2]. Therefore, conventional load ratings are performed at the most critical location. The DET load ratings are unique in that instead of only considering one location, it provides member capacity and rating factors along the entire length of the span while factoring in the effects of deterioration.

6.2.6   Required Software and Files for Using the DET

To implement the DET, a transportation agency would need the DLT and its necessary software and files as mentioned in Section 5.2.5. In addition, a transportation agency would need the Damage Evaluation Tool (.xlsm) file, an exported bridge inspection from the DLT (.xls) file, and Microsoft Excel 2013.

6.3   Future Extensions of the DET

Due to the modular structure of the VBA code, a transportation agency can adapt the DET for their specific purposes. With some effort the DET can be configured for the evaluation of any short to medium span simply supported PC girder bridge and can be appended to include the evaluation of continuous spans. To increase its applicability in the future, the tool could be programed to support: different types of bridge elements, more damage modes, and more instances of damage modes.

Although not tested in this research, an alternative to using the DET involves applying cross-section geometry and damage locations from the DLT into the structural analysis by utilizing industry software and/or techniques such as the finite element method. Data transfer through the use of standard file types, such as .DXF or .DGN, is available to all major BIM and finite element software programs [48]. As another alternative, information from the DLT can

potentially be translated and used in commercial load rating software such as AASHTOWare Bridge Rating (formerly Virtis).

In summary, with the ability to capture damage type, amount, severity, and location information in a bridge inspection using the DLT and the capability to utilize this information to automate and evaluate the structural performance using the DET, the Bridge information modeling for Inspection and Evaluation Method (BIEM) can be implemented.

7   PROCEDURE FOR USING THE BIEM

The following chapter presents a general framework for a transportation agency to implement the BIEM. This chapter describes the necessary requirements and procedures for implementing the DLT in Revit and executing the DET in Excel.

7.1   Procedure for Using the DLT

General guidelines for using the DLT in Revit assume the user has a bridge model in Revit (.rvt), the damage cube family file (.rfa), and the "Bridge Inspection 4-14" shared parameters text file (.txt). The general procedure for using the DLT is as follows:

1. Open the desired Revit bridge project (.rvt).

2. Load the shared parameters text file (.txt) into Revit by clicking the shared parameters icon under the manage tab. Next click browse and select the appropriate file location.

3. Load the damage cube family file by clicking load family under the insert tab.

4. Create the bridge inspection schedule form by clicking schedules under the view tab. Next click schedules/quantities. Create a new structural framing schedule and load the appropriate damage cube shared parameters into the schedule form.

5. An inspector has two options when it comes to recording and entering data:

    a. Prior to the inspection, the schedule forms can be printed and used as element-level forms to be filled out by hand during the bridge inspection.

    b. A laptop with the BIM model can be taken to the field and directly updated with measurements from the inspection.

6. Inspect the bridge. In addition to current NBIS methods, document the location of damage instances. The additional field measurements will include:

a. From support

b. From top

c. From edge

d. Length

e. Width

f. Depth

7. If not completed in the field during the inspection, input the inspection results into the Revit bridge inspection schedule form to update the Revit model.

7.2 Procedure for Using the DET

The guidelines for using the DET in Excel assume the user has updated the inspection schedule form in Revit with bridge inspection results. Also, it is assumed the user has the DET Excel file (.xlsm) which contains the VBA code for evaluation tool and the Assumptions (.txt) file. It is assumed the user has installed the Revit BIMCoder Schedule Sync[2] add-in [49]. The general procedure for using the DLT is as follows:

1. Ensure that the inspection schedule form in Revit is updated with the most recent or desired inspection results.

2. Export the schedule form. To do this, in Revit, under the BIMCoder suites tab click the schedule export button.

---

[2] BIMCoder Schedule Sync is a Revit add-in that synchronizes a schedule form with an Excel spreadsheet. This provides a shortcut to exporting a schedule form into a text document then importing the text document into Excel. BIMCoder Schedule Sync is available for free through the Autodesk Exchange Apps <https://apps.exchange.autodesk.com>.

3. Add all inspection parameters to the list of items to export by clicking the '>>>>' button in the export schedule window. Select a desired destination for the Excel file and click the export button.

4. Open the exported schedule form (.xls) Excel file.

5. Display the developer tab in Excel by clicking file, options, customize ribbon. On the right side of the Excel options window, click the developer checkbox.

6. Enable macros by clicking macro security under the developer tab. Then click enable all macros and click ok.

7. Under the developer tab, click the Excel analysis button.

8. When the user DET interface appears, select the desired element number, and damage modes.

9. Click the Run Evaluation button to execute the DET.

With the BIEM in place, the method was field tested on a case study bridge in Larimer County, Colorado. The case study application is described in the next chapter.

8   CASE STUDY IMPLEMENTATION OF THE BIEM

The following chapter presents a case study implementation of the BIEM. This chapter introduces the case study bridge, discusses findings from the bridge inspection, and describes the modeling of the bridge in Revit. In addition, this chapter illustrates how the DLT can update the Revit model with bridge inspection results, and demonstrates the execution of the DET on a selected superstructure element.

8.1   The Larimer County Bridge

A bridge northeast of Fort Collins in Larimer County, Colorado is selected for use as a demonstration structure for the BIM modeling, inspection, and damage assessment. Bridge LR3-0.2-50 is owned and maintained by Larimer County and was built in 1962 as a means to cross the Larimer County Canal. The structure is located in a rural agricultural region, and experiences an average daily traffic volume of 300 vehicles.

The bridge is a simply supported prestressed single-tee girder bridge. Flexural resistance is provided by the prestressed concrete (PC) girders acting compositely with the reinforced concrete (RC) deck. The exposed five inch two-way RC deck is unique in that it serves as both a structural component and a wearing surface. Lateral restraint and girder stability is provided by the cast-in-place diaphragms located between the girders at each end and at midspan. Loads flow from the girders into strip footings through abutments capped with elastomeric bearing pads. The bridge alignment with respect to the roadway is skewed such that all three girders frame into the abutments at 54 degree angles. In addition, tapered wingwalls extend from the abutments at unique angles where they separate the earth from the canal. An east elevation view

of the span is shown in Figure 8.1. Depicted in the photograph is an irrigation valve on the southwest wingwall which is unrelated to the bridge.

Figure 8.1 Bridge LR3-0.2-50 east elevation view

As of May 2013, the sufficiency rating of the bridge is a 23.6 out of 100 and the bridge is classified as structurally deficient [6]. Sufficiency ratings are a way of assigning a single numerical rating to a bridge to reflect the load carrying capacity, how critical the bridge is to the roadway system, how well it functions, and how well the bridge meets current traffic safety requirements [20]. Moreover, the bridge is load restricted and is currently load posted as shown in Figure 8.2. Maximum permissible two, three, and four axle truck loads include 21, 33, and 34 tons respectively. To review, load postings are required when the rating factor falls below unity.

Figure 8.2 Advanced warning sign and load posting

Although larger more complex bridges with multiple spans might benefit to a greater extent from the proposed method, a small, simple structure was intentionally selected for demonstration purposes. Bridge LR3-0.2-50 was selected for use as a case study due to its common PC type. Its single span and girder configuration simplifies the structural analysis significantly to allow for a more direct comparison between official load ratings and results provided by the DET. The bridge was also selected because of its poor condition with distinct, abundant, and measurable distresses. In addition, the lack of a wearing surface provides a unique opportunity to directly observe deterioration in the deck. Lastly, the documentation including plans, girder drawings, previous bridge inspection reports, and load ratings were complete and readily available.

8.2   Visual Inspection of the Bridge

Bridge LR3-0.2-50 was inspected thoroughly by the author primarily using routine visual inspection techniques on August 23, 2014. Comprehensive information about the structural condition was obtained by supplementing the current NBIS practices with the record of damage location. Items recorded during the inspection included the type (cracking, delamination, and spalling), severity, amount, and location each damage instance on each superstructure element on the bridge.

For clarity in gathering measurements during the inspection, the author created a plan view of the bridge in Revit as illustrated on the left in Figure 8.3. As shown, the girders are assigned the letters A through C from west to east, and the abutments A1 and A2 from south to north[3]. As required for the DLT, the red circles depicted in the left image of Figure 8.3 denote

---

[3] For ease of comparison, this lettering and numbering convention is used to maintain consistency between the case study inspection and the official inspection reports for Bridge LR3-0.2-50 as provided in Appendix A.

the origins, or reference points, from which all damage measurements were taken for a particular superstructure element. Inspection forms were created and used to document the damage location information along with the type and severity data. A sample location-based element-level inspection form for the spalling damage mode is depicted in Figure 8.3 on the right. Note here that the damage location measurements in the inspection form correspond to the controlling parameters for the DLT as described in Section 5.2.2.4.
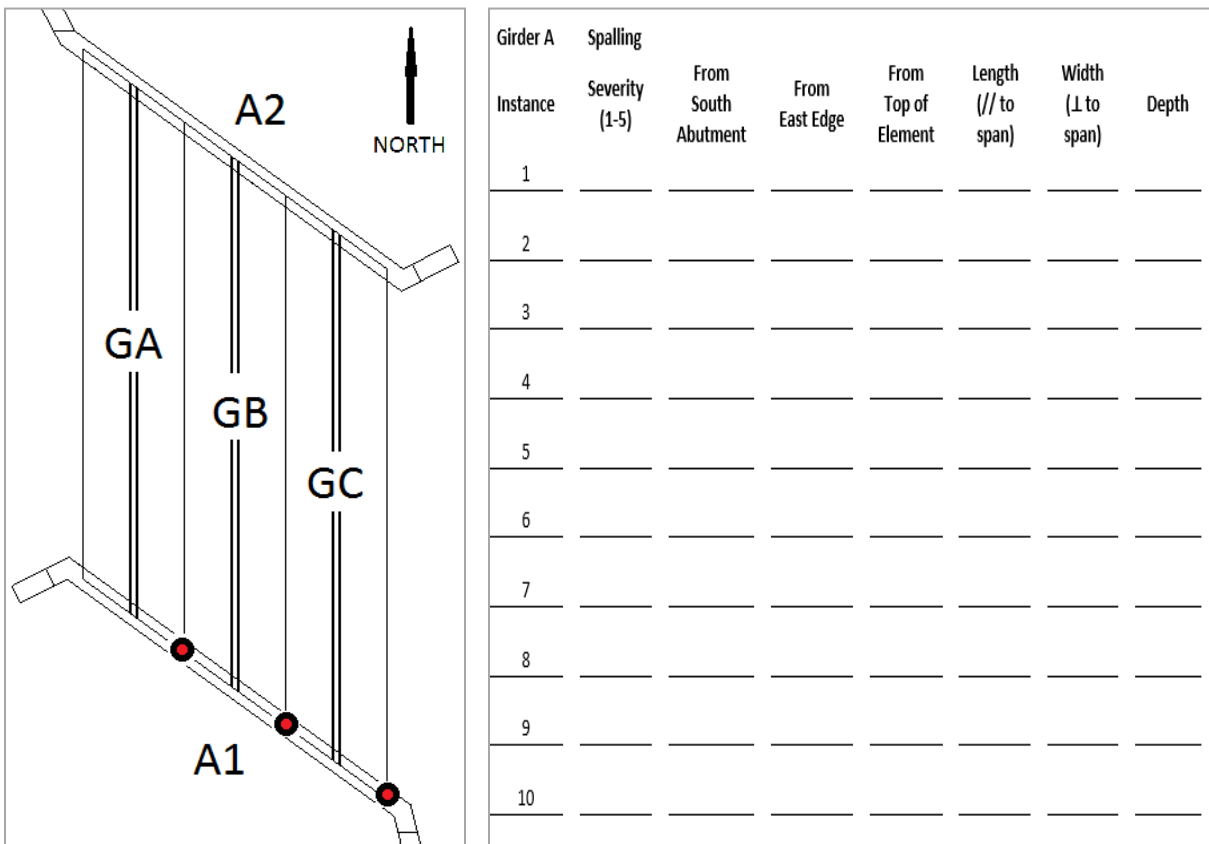
Figure 8.3 Left: plan view of Bridge LR3-0.2-50 with reference information. Right: sample inspection form for Girder A and the spalling damage mode.

Six different types of measureable distresses including cracking, spalling, delamination, potholes, honeycombs, and corroded reinforcement were observed upon inspection. However, in demonstrating the BIEM, cracking, delamination, and spalling were the damage types of focus and are discussed in the following subsections.

8.2.1 Cracking

Cracking is prevalent on all superstructure elements on Bridge LR3-0.2-50. Figure 8.4 depicts the top of the decking surface looking to the north. The transverse epoxy patch repairs are filling cracks and also covering spalls and potholes [6]. A longitudinal crack located along the seam between girders B and C spans the length of the bridge can be seen in the bottom middle of the figure. The dark line centered near the bottom of Figure 8.4 is a pencil to provide a rough scale. The vast majority of deterioration on the deck is likely attributable to the lack of a wearing surface.

Figure 8.4 RC deck with longitudinal and transverse cracking

Figure 8.5 depicts a view of the bottoms of the stems of girders B and C looking to the east down the diaphragms. Here, a longitudinal crack on the inner face near the bottom of the stem on girder C just south of midspan is present. Similar cracks are present intermittently near the bottom of the stem along the entire span of girder C. The vertical protrusions of steel on the

diaphragms are untrimmed concrete form ties leftover from construction and are not necessarily distresses.
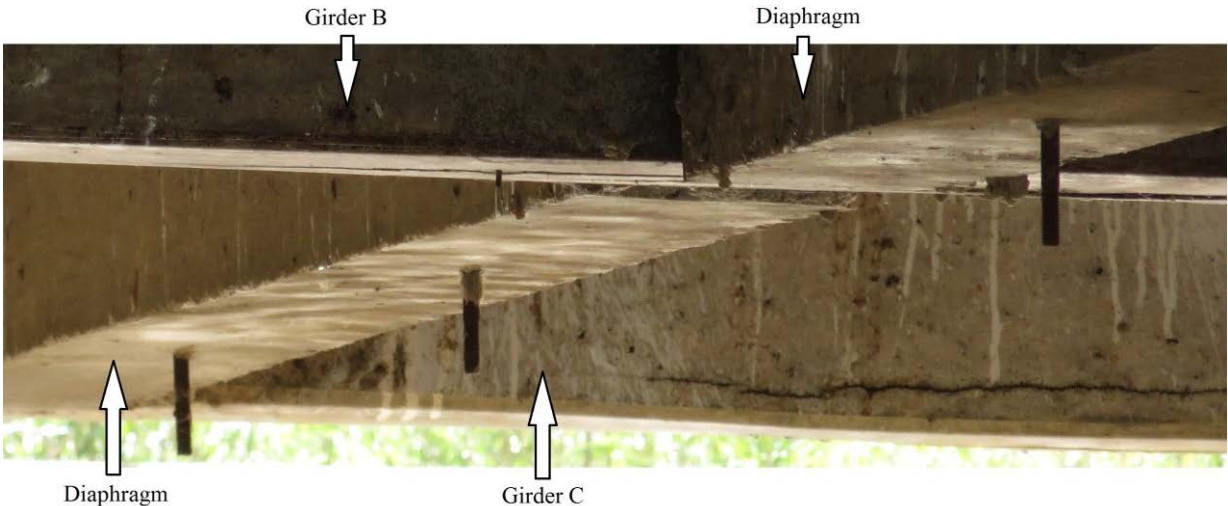
Figure 8.5 Longitudinal crack on Girder C just south of midspan

Figure 8.6 is a view taken from the underside of the bridge looking up at girder B and the two diaphragms at midspan. This figure depicts a severe longitudinal crack running north/south on the bottom face of the stem on Girder B. The crack is located at midspan in between the diaphragms. Similar severity longitudinal cracking is present intermittently on the bottom face of the stem on Girder C.

Figure 8.6 Longitudinal crack on Girder B at midspan

8.2.2   Delaminations

It is interesting to note that delamination in the RC deck was the most prevalent distress found during the inspection. This could be attributed to water infiltrating through the numerous epoxy patch repairs on the deck surface causing corrosion in the steel and debonding between the reinforcement and the concrete matrix. Overall, delaminations were detected in about 7% (of the total 1180 square feet) of the deck. As discussed in Section 3.2.3.2, delaminations can be detected by a hollow sound when a length of chain is pulled across. The chain drag test was performed during the inspection and instances of delamination present in the RC deck were marked with chalk and measured as per the DLT requirements. Figure 8.7 is a view looking north of the author performing this basic test for delaminations during the inspection.

Figure 8.7 Chain drag test to detect delamination

8.2.3 Spalling

Figure 8.8 is a view looking up at the bottom face of the stem on girder C just north of midspan. A severe spall is present with a small piece of spalled concrete still attached to the stem. For scale reference, the tee stem is 6" in width. It is surprising to note in this figure the exposed and corroded prestressing strands. The lower portion of steel depicted in Figure 8.8 is exposed around its entire circumference. For safety reasons, the author was unable to measure the diameter of the strand. Also illustrated are longitudinal cracks just north of the spalled region. The instance of damage depicted in Figure 8.8 was the most severe distress found on the bridge during the inspection.
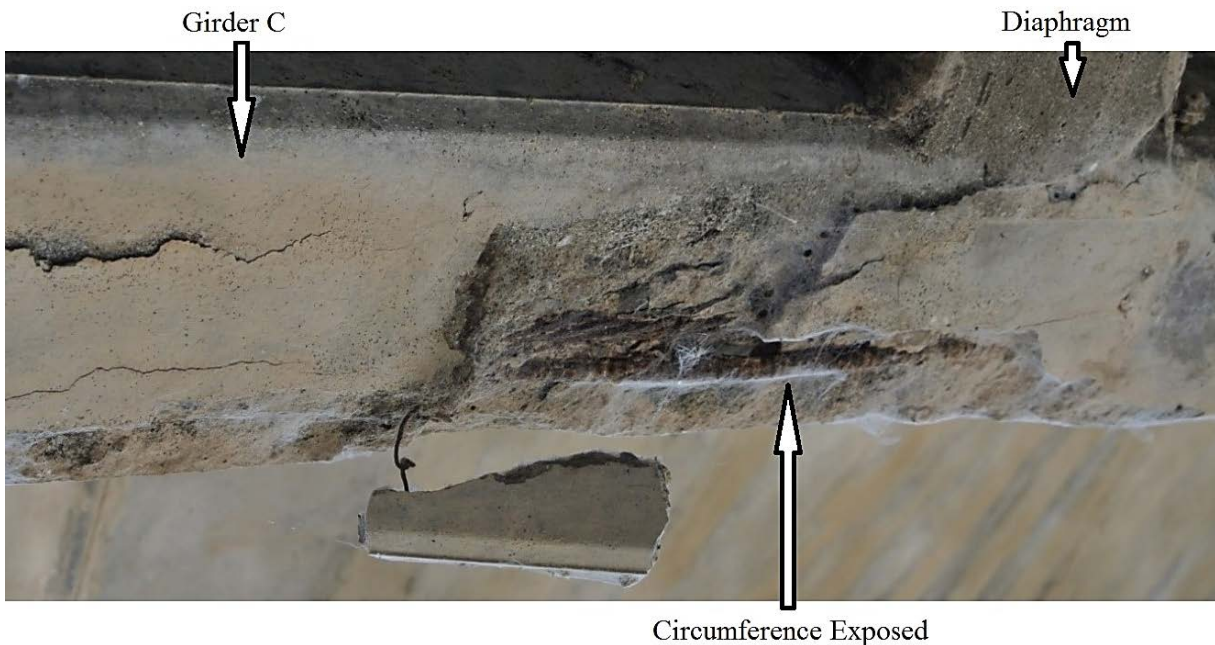
Figure 8.8 Spalling with exposed prestressing strands on Girder C just north of midspan

Figure 8.9 shows a view from the underside of the bridge looking up at the bottom face of girder C, 15' north of Abutment 1. In this view, an instance of severe spalling is evident with another segment of exposed prestressing strand. The rust discoloration on the prestressing strands should be noted in both Figures 8.8 and 8.9.

Figure 8.9 Spall on Girder C with exposed prestressing strand just south of midspan

An instance of spalling is shown on the outer east face of the stem on Girder C just south of midspan in Figure 8.10 where a portion of corroded and exposed mild steel shear reinforcement is evident.

Figure 8.10 Spalling with exposed shear reinforcement on Girder C just south of midspan.

Although not related to the bridge superstructure, Figure 8.11 depicts a large spalled region on the southwest abutment wingwall caused by an untrimmed piece of rebar. This picture

is provided to illustrate the significant extent that steel corrosion can have on the concrete matrix. Here, the spalled region measures about 9" in diameter and is 2 ½" deep.

Figure 8.11 Large spalled region on Abutment 1

8.3   Revit Modeling of the Bridge

With conventional BIM modeling techniques, it is economically unfeasible for bridge managers to create models of each bridge in an inventory. As indicated in Section 3.5, with emerging technology such as 3-D laser scanning, the modeling of bridge networks can be created from point cloud data. With the technology in place, the potential to equalize the 29% of asset owners currently receiving benefit in using BIM during the operation and maintenance stages with the 60% of contractors and engineers receiving benefit during the VDC stages [8] is evident.

The goal of the following subsections is to not only illustrate how the bridge is modeled but to show how the model can be used and offer additional insight on the benefit that decision makers might realize in utilizing BIM. This section begins with providing techniques for

80

modeling the bridge in Revit. Orthographic projections are captured from the model and will be used to highlight the orientation, geometry and dimensions of the bridge. Next, a method for storing material property information in Revit is discussed.

8.3.1   Modeling the Bridge

Constitutive elements of Bridge LR3-0.2-50 include: three PC single-tee girders, a two-way RC deck, diaphragms, railings, abutments, wingwalls, and strip footings. Revit families available in the default library can be used to depict the necessary information and geometry of these elements. In general, certain families and types necessary for the modeling of bridges may not exist in default Revit libraries. The two most direct solutions include modifying existing family parameters to suit bridge modeling needs or to simply represent the needed bridge elements with close family substitutions. For example, prestressing strand can be modeled with the rebar family with custom parameters defining its strength, RC diaphragms can be modeled as face based linear steel stiffeners with the material modified to be cast-in-place concrete, galvanized W-beam steel guardrail can be visually depicted with steel C-channel. Table 8.1 illustrates Revit families and a few modifications and substitutions that are used in the modeling of the bridge.

Table 8.1 Revit families and their structural usages

Revit Family	Revit Type	Bridge Component	Bridge Structural Usage
Wall Foundation	Bearing Footing 5' x 2'	Substructure	Foundation
Basic Wall	Foundation 18" Concrete	Substructure	Abutment
Precast-Single-tee	8' x 3'	Superstructure	Girder
Linear Stiffener - Plate	Standard 6"	Superstructure	Diaphragm
Rebar	#4	Superstructure	Mild Reinforcement
Rebar	#5	Superstructure	Mild Reinforcement
Rebar	No Prestressing Strand	Superstructure	Prestressing Strand
Concrete Rectangular Beam	9" x 12"	Deck	Curb
Foundation Slab	5" Foundation Slab	Deck	Deck
W8X10 W-Wide Flange	W8X10	Rail	Rail Support
Light Gauge-Joists	No W-Beam	Rail	Guardrail

Geometry in the bridge model is based on dimensions and details obtained from Larimer County engineering drawings and Rocky Mountain Prestress Inc. girder drawings, both dating to 1961. During a site visit, dimensions from the shop drawings were verified with field measurements taken by the author. Minor discrepancies were found between the as-planned and as-built dimensions. Specific bridge dimensions are presented in Section 8.3.2 to follow.

The modeling of the bridge in Revit begins with creating reference lines to fit the overall geometry and skew of the bridge per design specification. Next, the strip footings, abutments, and wingwalls are created as shown in the left of Figure 8.12. The taper on the wingwalls is created with a face based void form family which is used as a miter cutting tool as indicated by the prism in the top left image in Figure 8.12. Next, the single-tee girders are placed on top of the abutments. The skewed orientation of the girders are depicted by defining reference planes parallel with the abutments and trimming the unbounded girder geometry to the reference planes. At the ends of the girders and at midspan, diaphragms are placed between the girders.
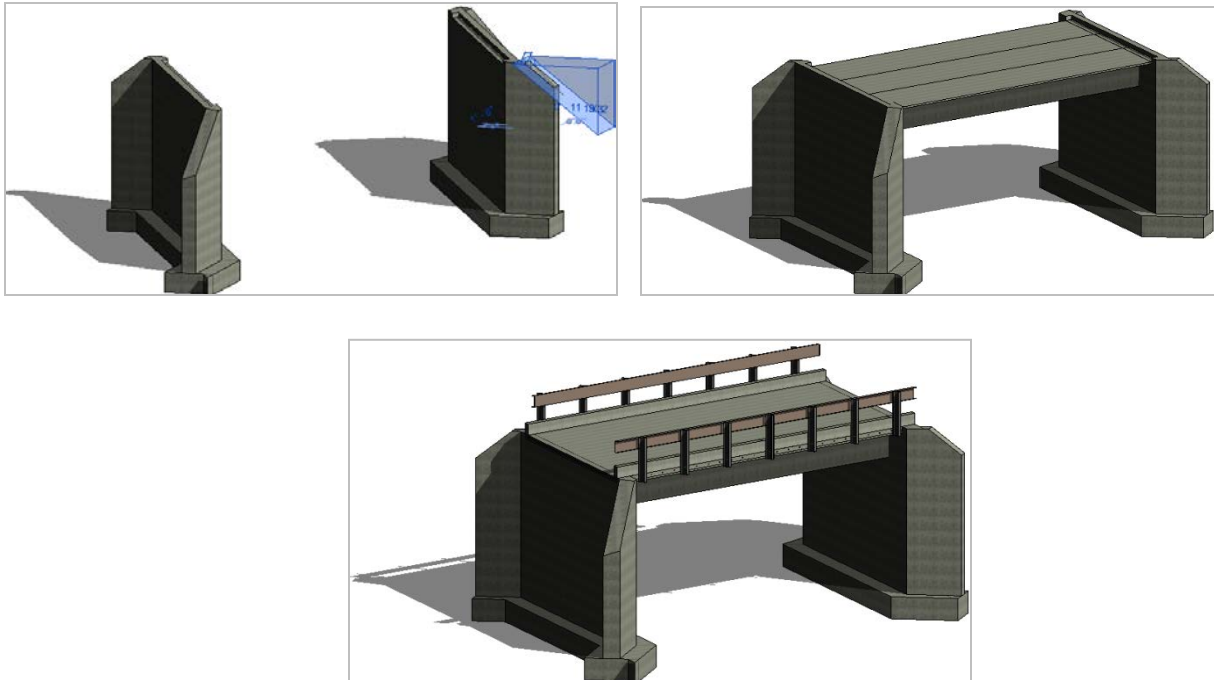
Figure 8.12 Top left: footings, abutments, and wingwalls. Top right: adding the girders and diaphragms. Bottom: deck, curbs, railing supports, and guard rail

The concrete deck slab is created on top of the three girders. Once the deck is placed, the reinforcement in the superstructure is modeled. In Revit, any element that is composed of concrete can be specified to host reinforcement. Utilizing the convenient templates for the appropriate scheme, two-way reinforcement is placed in the deck slab followed by shear reinforcement in the girders. Rebar sizes, cover, spacing, and stirrup shapes are modeled according to the design specifications. Finally, with a user-defined pattern, the prestressing strands are modeled in the girders with harping points located at midspan.

Often, steel detailing (or plans in general) are not available for a bridge especially regarding older structures [3]. Therefore, when evaluating the safe capacity of a bridge, engineers are left to make assumptions. With the ability to document and visualize in 3-D any desired level of structural detail, bridge analyses in the future can be made more reliable, and more informed decisions can be made if proper bridge documentation is kept. Accordingly,

filtered views are created to visually depict the mild steel and prestressing tendon detail. Figure 8.13 illustrates a filtered view of the bridge depicting steel reinforcement in the superstructure. Although the abutments, diaphragms, footings, and wingwalls all contain reinforcing steel in Bridge LR3-0.2-50, for clarity these substructure reinforcement schemes were omitted. This is logical because these components do not provide flexural resistance nor factor into the flexural load rating. However, bridge maintenance is an all-inclusive process; in practice, the modeling of the substructure detail may be of interest.
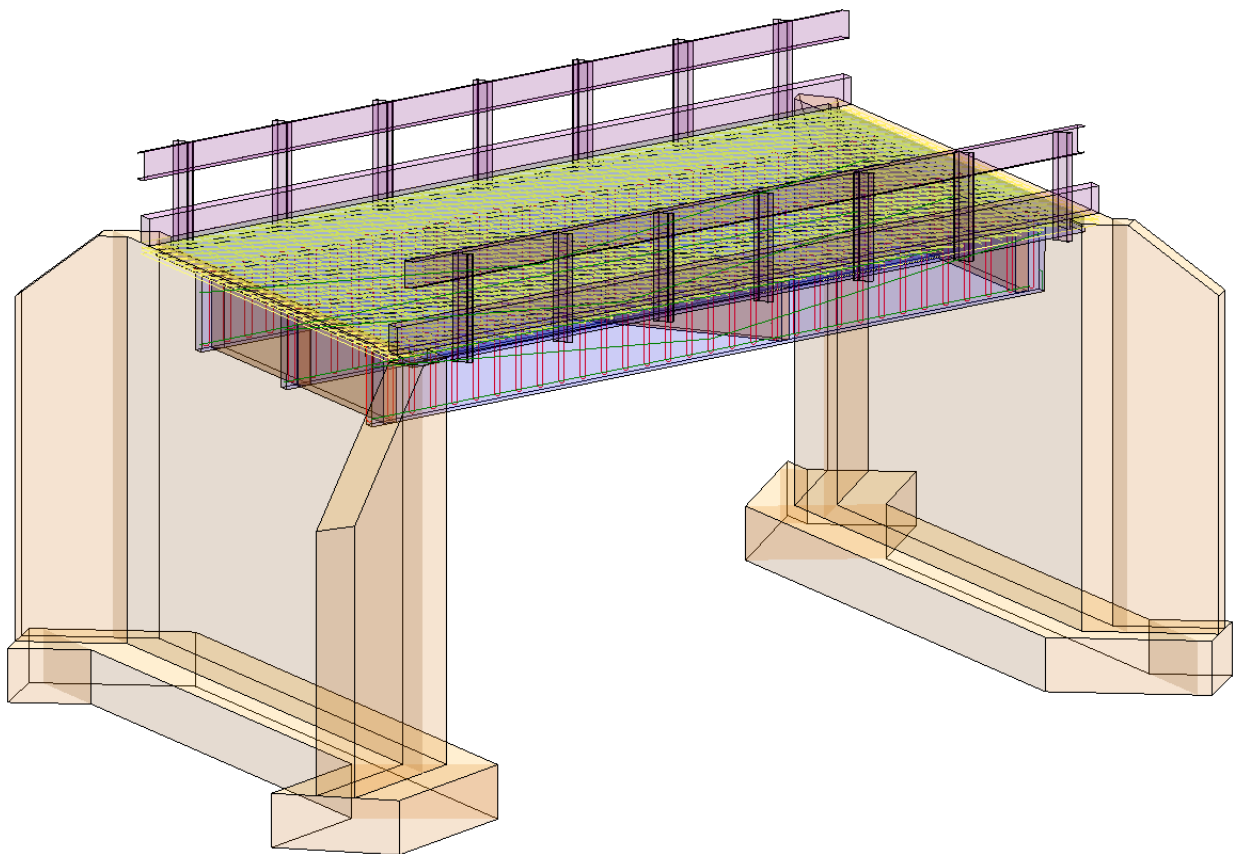
Figure 8.13 Filtered view of Bridge LR3-0.2-50 model in Revit

A filtered view isolating the bridge model's superstructure is depicted in the top of Figure 8.14. Here, the two-way mild steel reinforcement in the deck is indicated in yellow, the mild steel shear stirrups in the tee-beams are shown in red, and the prestressing tendon layout is depicted in green.
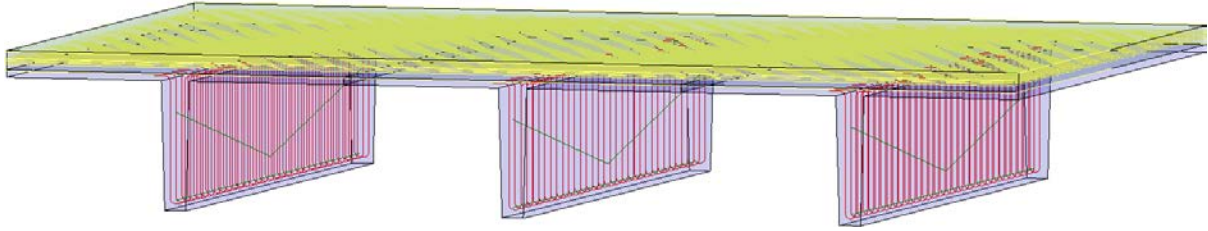
Figure 8.14 Reinforcement in the bridge model superstructure.

With access to a BIM model, transportation officials could also benefit from its graphical and photorealistic rendering capabilities. For example, if a bridge is to be remodeled, or a major retrofit is necessary, BIM could be used as a visualization tool to present proposed renovations to the public or interested stakeholders [50]. To illustrate, a rendering of the case study bridge is shown in Figure 8.15. This is a view looking up at the bridge from the west. In this view, the diaphragms at midspan along with the strip footings supporting the abutments are apparent.
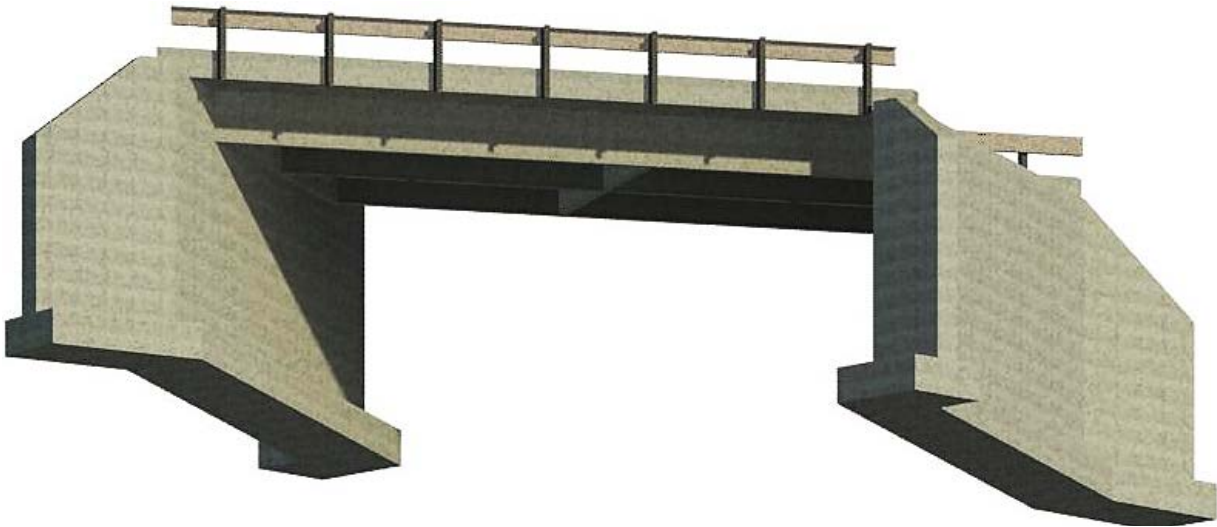
Figure 8.15 3D rendering of Bridge LR3-0.2-50 in Revit

8.3.2   The Bridge Geometry

Orthographic projections from the model are used in the following section to illustrate the overall orientation, geometry, and dimensions of the bridge. Figure 8.16 depicts a plan view of the bridge. In this view, the 36 degree skewed orientation of the bridge with respect to the

85

roadway is evident. This view also highlights the angled wingwalls retaining the earth from the canal. Bridge LR3-0.2-50 has a clear span of 40.4 feet and a width of 24 feet, measured from the outer faces of the girders.
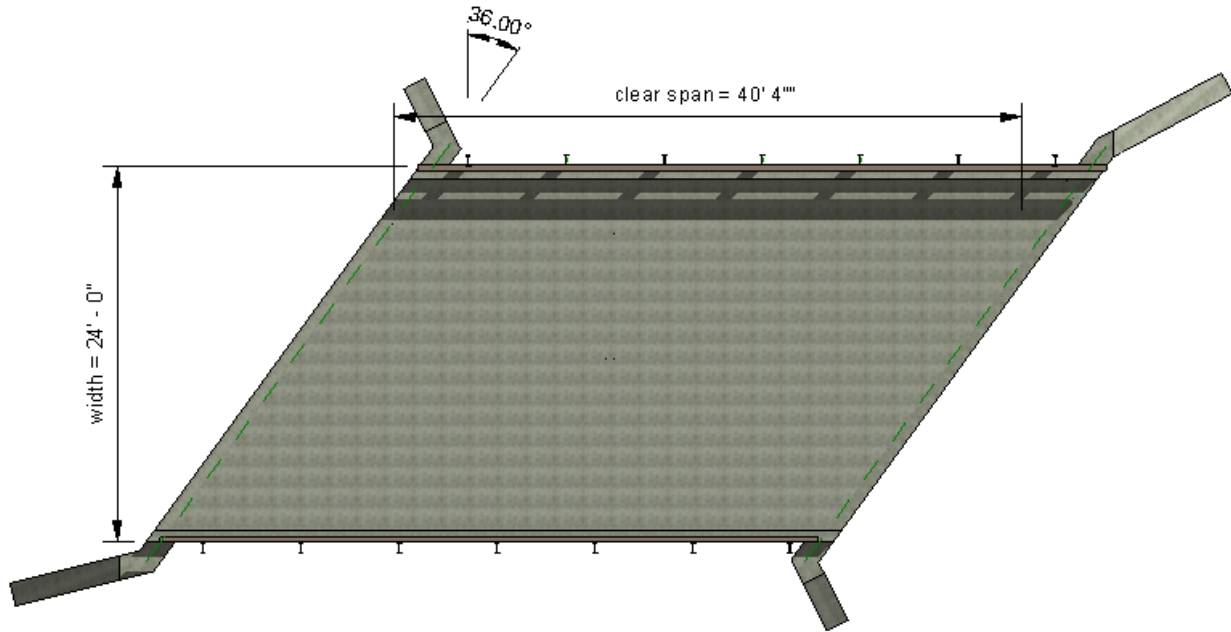
Figure 8.16 Plan view

An east elevation view of the structure is depicted in Figure 8.17. The clearance of the bridge is about 13 feet from the top of the footing and about 10 feet above the streambed. As shown in Figure 8.17, the distance from the foundation to the top of the deck is 15 feet.
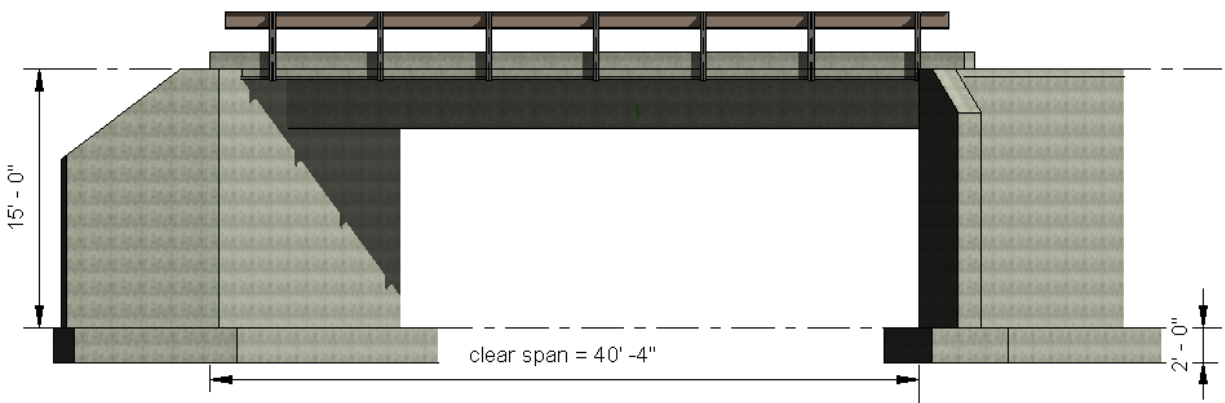
Figure 8.17 East elevation view

86

A section view looking edge-on to the girders is shown in Figure 8.18. The overall width of the bridge is 24 feet and the depth of the girder/deck composite is 3.42 feet. The S.1 indicates a callout view of Girder C.
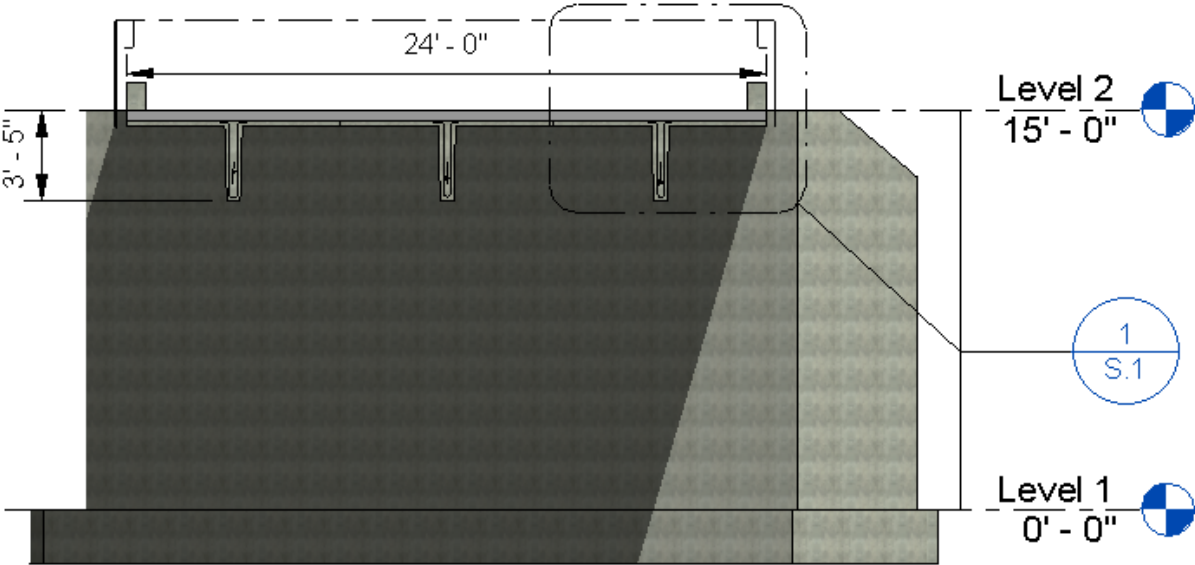
Figure 8.18 Section view

Figure 8.19 depicts the S.1 callout view. In this detail, individual components of the bridge are highlighted. Elements depicted include the PC single-tee girder, RC deck slab, mild and prestressing steel, curb, rail, and abutment.
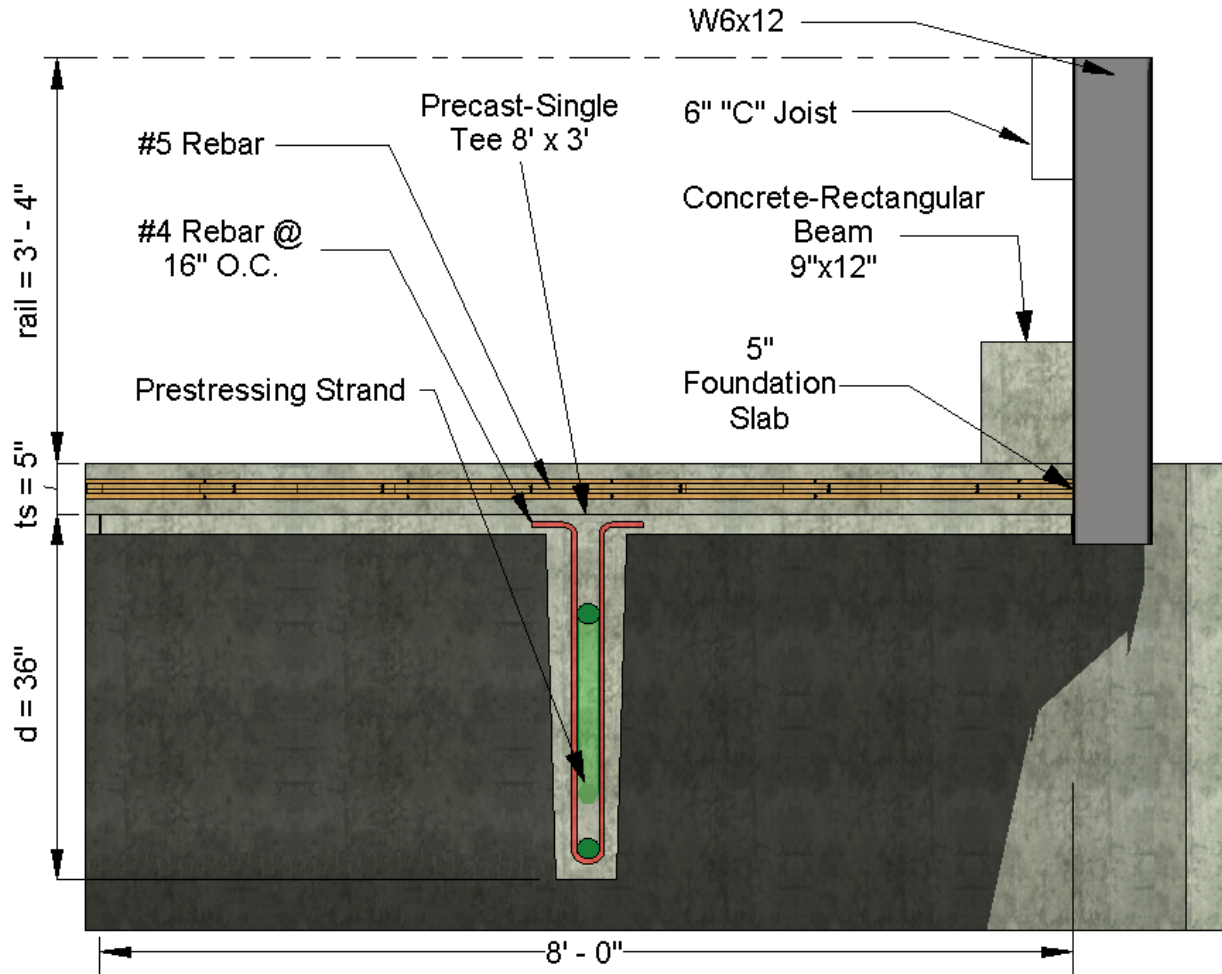
Figure 8.19 Callout of Section 1

8.3.3 Storing Mechanical Properties

The majority of the mechanical properties of steel and concrete used as the default values in the DLT were obtained from the Rocky Mountain Prestress girder drawings dated 1961 and a Colorado DOT Load Factor Rating Summary for the bridge dated 1997. Table 8.2 contains a compiled list of the mechanical properties of aging steel and concrete that is stored and used in the model. The term 'aging' is used to describe typical mechanical properties available in 1961 and it should be noted that these properties do not include the effects of deterioration. Shared parameters inside the bridge superstructure families are created to store and report this

information. Recall that shared parameters can appear and be edited in the bridge inspection schedule form, and can contain information available to export.

Table 8.2 Mechanical properties of aging steel and concrete

Factor	Value	Source
f'c slab	3 ksi	1961 Larimer County Plan Set
f'c girder	6 ksi	1961 Larimer County Plan Set
fy mild steel	60 ksi	1961 Larimer County Plan Set
f'ci	5.4 ksi	1961 Larimer County Plan Set
fpy	0.85fpu	[51] Nawy, Prestressed Concrete
fpu	250 ksi	[2] MBE 2011 for bridges < 1963
fpi	0.74fpu	[51] Nawy, Prestressed Concrete
Losses in prestress	35 ksi	[52] ACI Committee 423

As illustrated in Table 8.2, several simplifications are made including lumping all of the prestress losses according to American Concrete Institute (ACI) Committee 423 [52] and obtaining the initial stress in the prestress by taking 74 percent of the ultimate stress of the tendon according to Nawy [51].

8.4   Updating the Model using the DLT

The following section demonstrates the use of the DLT. First, to demonstrate the capacity for Revit and the DLT to store the damage location information, all results from the inspection are input into the DLT. This comprehensive inspection schedule form will not be not be used as input for the DET since the evaluation tool is capable of only evaluating one instance of each damage type on each member, as discussed in Section 6.2.2. Second, to implement the BIEM and to demonstrate the reuse of information, only the worst case instances of each damage type will be input, as per the DET requirements. During the inspection, it was found that Girder C exhibits the most severe instances of deterioration found on the bridge; as a result, Girder C will be the bridge element of focus throughout the implementation of the DLT and DET.

8.4.1   Input All Inspection Information in the DLT

To input all inspection information into the DLT, the appropriate number of damage cube sets are placed at the respective origins on each girder. For example, during the inspection, it was found that Girder B had 10 instances of cracking, 1 instance of spalling, and 11 instances of delamination; therefore, 11 damage cube sets are placed at the origin point as depicted in the image on the left in the previous Figure 8.3. The cracking portion of the completed inspection form is shown in Table 8.3. The upper portion of the table represents the three girders and the lower portion of the table captures results from the bridge inspection including each instance of the three damage types. To summarize, columns A and B provide the appropriate girder letter and define the whether the row is a damage cube or the member itself. Column C and D define if cracking exists and its severity. Columns E, F, and G are volumetric defining parameters for the cracking damage cube. Lastly, columns H, I, and J are the Cartesian parameters referencing the centroid of the cracking damage cube to the origin of the respective girder. Spalling and delamination modes exist in the same table and are laid out in the same format in the DLT but are not shown. Note from the previous example that there are 11 damage cube sets for Girder B, one row for each instance. All length measurements in Table 8.3 are in inches.

Table 8.3 The DET bridge inspection form

A	B	C	D	E	F	G	H	I	J
Girder #	Family	Cracking	Crack Sev	Length1	Width1	Depth1	From Support1	From Top1	From Edge1
Girder A	Precast-Single Tee								
Girder B	Precast-Single Tee								
Girder C	Precast-Single Tee								
Girder A	DAMAGE CUBES	☑	3	4	2	1	48	41	48
Girder A	DAMAGE CUBES	☑	2	72	1	1	36	7	24
Girder A	DAMAGE CUBES	☑	3	84	1	1	384	7	24
Girder A	DAMAGE CUBES	☑	4	132	1	1	372	0	80
Girder B	DAMAGE CUBES	☑	3	18	1	1	180	41	48
Girder B	DAMAGE CUBES	☑	3	60	1	1	30	7	72
Girder B	DAMAGE CUBES	☑	2	240	1	1	156	7	60
Girder B	DAMAGE CUBES	☑	2	1	70	1	159	0	96
Girder B	DAMAGE CUBES	☑	2	1	90	1	420	0	67
Girder B	DAMAGE CUBES	☑	3	1	45	1	425	0	48
Girder B	DAMAGE CUBES	☑	2	1	30	1	447	0	48
Girder B	DAMAGE CUBES	☑	4	1	47	1	459	0	12
Girder B	DAMAGE CUBES	☑	2	1	54	1	216	0	30
Girder B	DAMAGE CUBES	☑	1	1	60	1	468	0	12
Girder B	DAMAGE CUBES	☐	0	0	0	0	0	0	0
Girder C	DAMAGE CUBES	☑	4	24	1	1	216	41	48
Girder C	DAMAGE CUBES	☑	4	1	48	1	96	7	72
Girder C	DAMAGE CUBES	☑	3	1	47	1	100	0	47
Girder C	DAMAGE CUBES	☑	3	1	60	1	118	0	34
Girder C	DAMAGE CUBES	☑	4	1	40	1	157	0	25
Girder C	DAMAGE CUBES	☑	2	1	87	1	194	0	12
Girder C	DAMAGE CUBES	☑	4	1	76	1	265	0	2
Girder C	DAMAGE CUBES	☑	4	1	60	1	383	0	12
Girder C	DAMAGE CUBES	☑	4	240	1	1	252	0	0
Girder C	DAMAGE CUBES	☑	4	1	36	1	413	0	16

Upon entering the inspection results into the schedule form, damage instances are depicted graphically in real-time in the BIM model.

A side-by-side comparison between an inspection photograph of the deck and graphics from the DLT of the deck are shown in Figure 8.20, both views looking to the north. It is interesting to note that the epoxy patch repairs that are visible on the deck surface, shown in the left, coincide closely with delaminations detected inside the deck, highlighted with the orange damage cubes. As mentioned in Section 8.2.2, this could be a result of water infiltrating through the patches and corroding reinforcement inside the deck. It is also interesting to note that

delaminations in the deck are approximately in-line with the vehicular wheel-paths especially regarding northbound traffic.
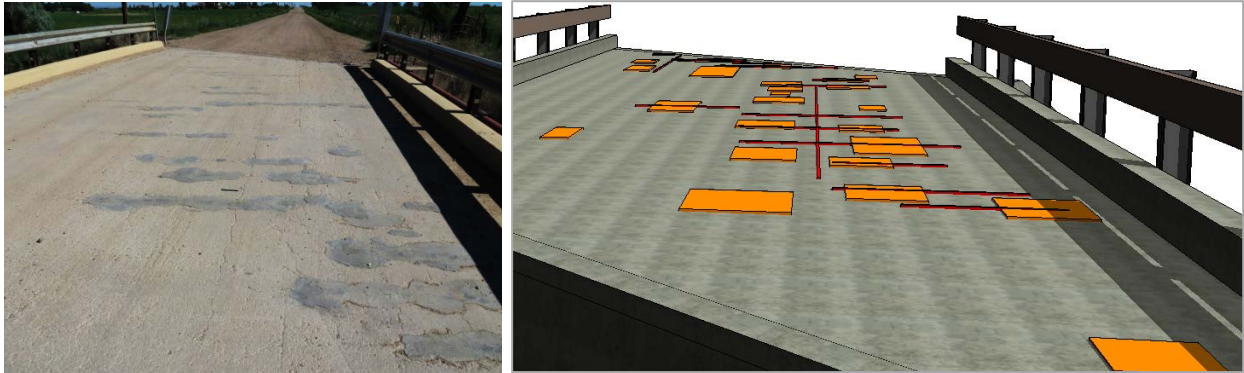
Figure 8.20 Left: inspection photo of patch repairs on the bridge deck. Right: model with delaminations and cracks

Figure 8.21 is an isolated view illustrating all damage instances detected on the underside of the superstructure. Cracking and spalling damage cubes shown in red and yellow respectively.
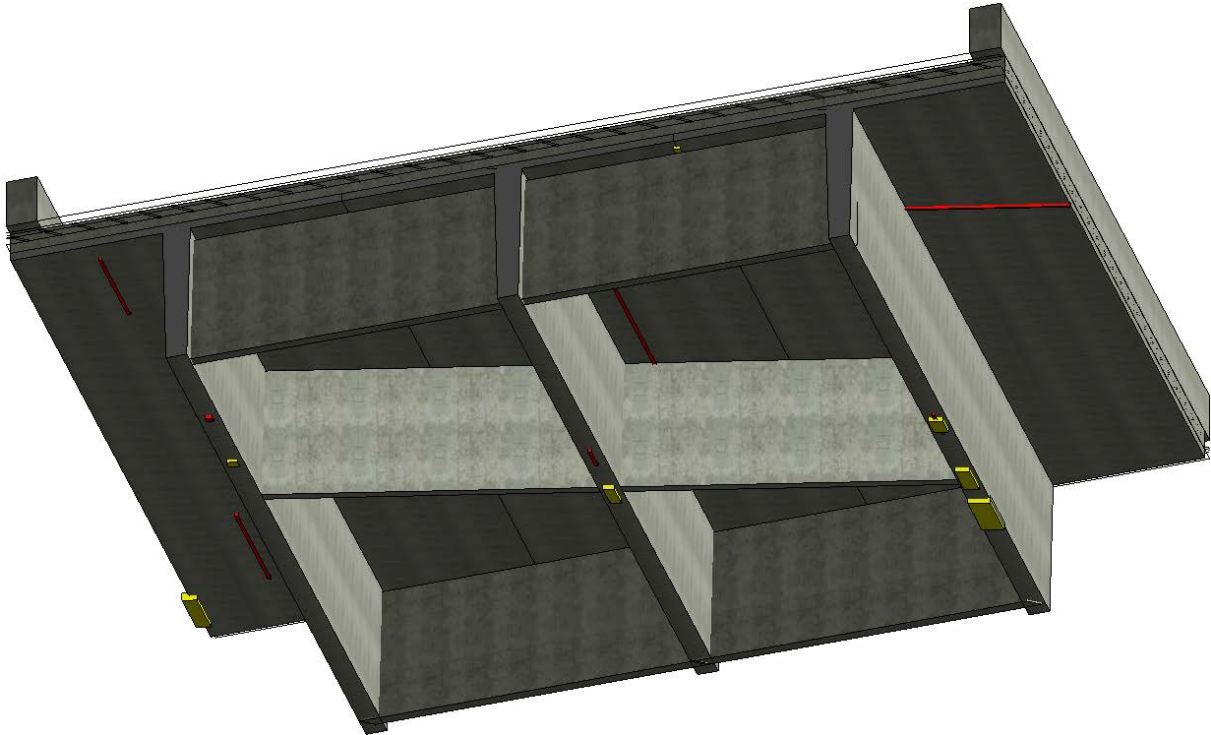
Figure 8.21 Isolated view of the bottom of the superstructure with cracking and spalling damage cubes

8.4.2 Input Most Severe Inspection Information in the DLT

To utilize the DET, only the worst case damage instance for each damage mode on each member are input into the DLT. For example, damage cubes on Girders A, B, and C, will represent the most severe crack, the most severe spall, and the most severe delamination on each girder. As mentioned, Girder C contains the most severe deterioration modes found on the bridge. An isolated top view and a bottom view of Girder C and the locations of the worst crack, spall, and delamination instance are shown in Figure 8.22 in red, orange, and yellow respectively.

Figure 8.22 Left: view from top of Girder C with most severe cracking and delamination instances. Right: view from bottom of Girder C with most severe spalling instance

As a visual tool, bridge managers could benefit in utilizing the DLT because of its potential for accuracy and the level of detail it could attain in identifying problem areas. As an example, the top image of Figure 8.23 shows an isolated and filtered view of Girder C with a

spalling damage cube highlighting the worst case damage instance on the bridge. The bottom left image is a closer view depicting the spalling cube intersecting with the bottom prestressing tendons and the edge of a shear stirrup. On the bottom right of Figure 8.23 is an inspection photograph illustrating the same instance of damage and depicting the exposed rebar and tendons. Here, the distress is visually apparent, but even in less distinct cases a bridge manager would be provided with the capabilities to track damage locations in relation to critical structural constituents such as the steel reinforcement that cannot be readily observed in the field.
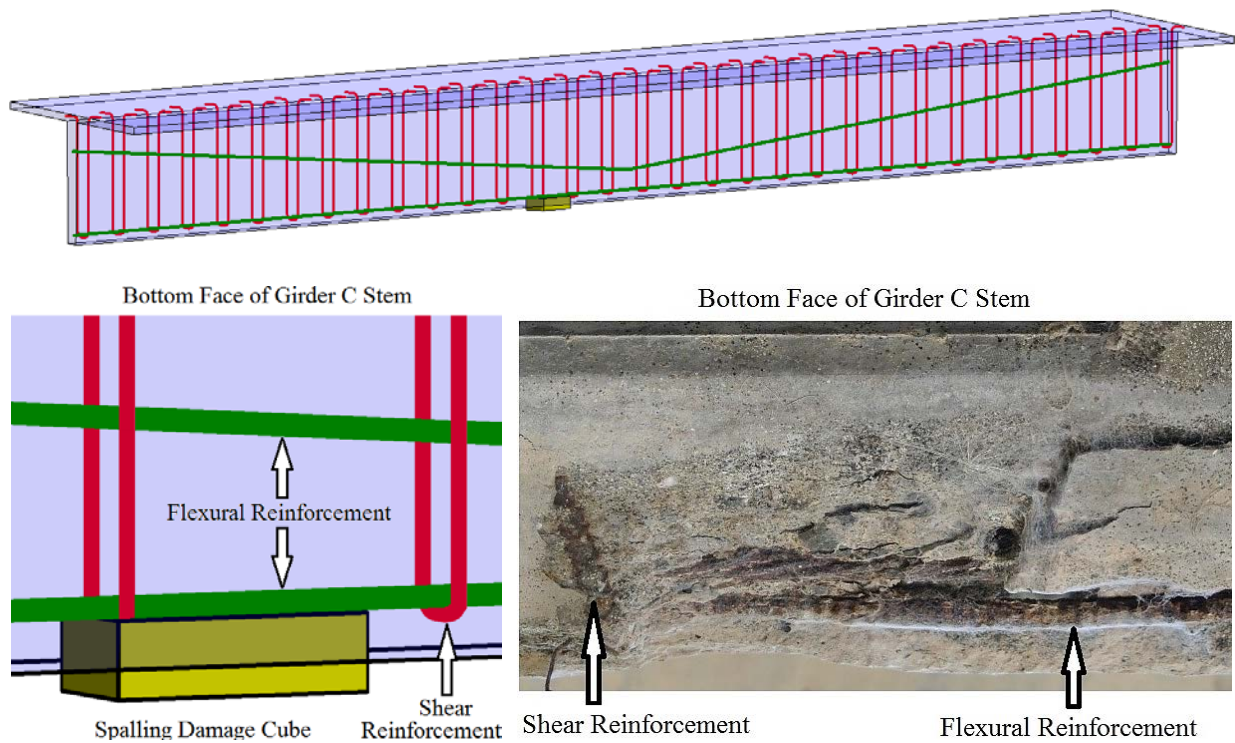
Figure 8.23 Top center: Girder C filtered and isolated with spalling damage cube. Bottom left: spalling cube intersecting with tendon and stirrup. Bottom right: spalling instance photo from inspection

With the most severe damage instances documented on each element in the DLT, information from the model is ready to be reused in the DET.

8.5   Evaluating Structural Performance using the DET

First, the following section contains assumptions and system defaults in the DET. Second, a demonstration on how to export bridge inspection information from the DLT to the DET is presented. Lastly, the DET is executed on Girder C since it has the most severe damage instances present on the bridge.

8.5.1   Assumptions and System Defaults

The DET is developed for a simply supported single span, 8'X36" PC single-tee girder with a composite 5" RC deck. Girders include a triangular prestressing tendon layout with a harping point at midspan. The DET is programmed to account for composite action between the deck and girders. Damaged volumes are assumed to be absent when calculating section properties. All non-prestressed steel is assumed negligible in the flexural capacity calculations. The live load is assumed to include: a dynamic load allowance, distribution factor, and skew reduction factor (for flexure, these values are calculated to be 1.33, 0.802, and 0.890 respectively for the case study bridge; sample calculations are provided in Appendix B). In addition, the live load moment envelope from AASHTO trucks are assumed equivalent to a moment distribution from a uniform live load. This assumption was checked by comparing the moment envelopes generated from moving AASHTO truck loads using SAP2000 with moments caused from equivalent uniform live load distributions. Calculations proved there to be a 1.4% difference between the max live load moment envelope value and the max uniformly distributed live load moment approximation.

Pre-calculated design loads specific to the case study bridge geometry are the prototype system default loads for the prototype DET. These design loads can be changed readily in the

VBA code if, for example, an asphalt overlay were added to the bridge. Upon further development of the DET, with the ability to evaluate different bridge types, the ease of changing the design loads is appealing. As mentioned previously in Section 6.2.3.4, AASHTO loads are calculated independent of the DET. Maximum moments resulting from dead loads are calculated based on the AASHTO BDS unit weights. Also, the maximum live load moment is determined by analyzing a moving AASHTO HS-20 truck in SAP2000. A summary of the DET prototype default values including maximum required moments for the case study bridge are presented in Table 8.4.

Table 8.4 Summary of moments from the AASHTO loads

Type	Moment (kip*in)
DC (Wt. of Girder)	1892.386
DW (Wt. of Slab)	1263.129
LL+IM for Moment Calculations	5496.618
LL+IM for Shear Calculations	7355.838
WS (Wind Effect)	5.132

Using the pre-defined maximum moments, the DET calculates the AASHTO BDS load combinations to determine the required moment. Table 8.5 shows each load case and depicts the controlling Strength I load combination that was determined by the DET during the case study application.

Table 8.5 AASHTO load combinations and factored moments

Type [28]	AASHTO Load Combo [28]	Factored Required Moment, Mu (kip*in)
Strength I	1.25DC + 1.25DW + 1.75LL	13563.476
Strength II	1.25DC + 1.25DW + 1.35LL	11364.828
Strength III	1.25DC + 1.25DW + 1.4WS	3951.579
Strength IV	1.5DC + 1.5DW	4733.272
Strength V	1.25DC + 1.25DW + 1.35LL + 0.4WS	11366.881
Service I	DC + DW + LL + 0.3WS	8653.673
Service III	DC + DW + 0.8LL	7552.810
Service IV	DC + DW + 0.7LL	7003.148

→Strength I Controls   Mu (kip*in) =   13563.476

8.5.2   Export Inspection Information from DLT to DET

Once the damage type, severity, amount, and location information are updated in the BIM model from the DLT as discussed in Section 8.4.2, the inspection schedule form is exported from Revit into Excel using the BIMCoder Schedule Sync add-in [49].   In the Export Schedule window, shown in Figure 8.24, all DLT parameters are selected from the Available Field column and moved to the Export Field column.   Upon export, the BIMCoder Schedule Sync add-in transfers all selected data from the Revit schedule form into a newly created Excel file.
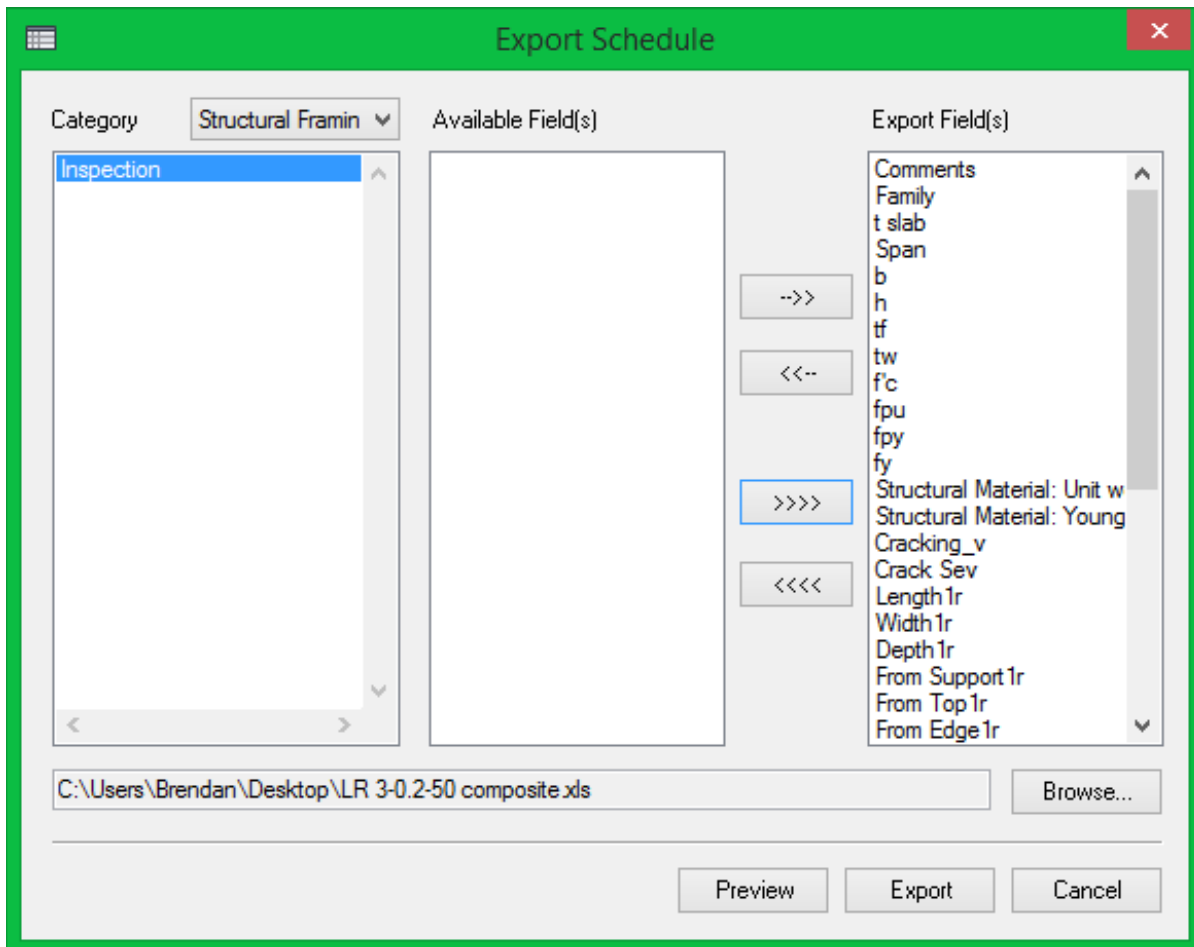
Figure 8.24 Inspection schedule form export menu using BIMCoder Schedule Sync

Table 8.6 shows the exported information from the DLT into Excel in its entirety.   This information includes: the significant bridge and cross-section geometry, mechanical properties,

and inspection results for the worst case damage instances. Parameters reporting bridge geometry are included to allow for further software development in applying the DET to variations in cross-sections and bridge geometry. Mechanical properties are included because the DET will register and apply changes as discussed. The remainder of the exported parameters contain the inspection results that the DET will read and analyze. The inspection information contains: the damage type, severity, amount, and location for the most significant cracking, spalling, and delamination instances.

Table 8.6 The DLT schedule form information upon export into Excel

Girder	Girder A	Girder B	Girder C
Family	Precast-Single-tee	Precast-Single-tee	Precast-Single-tee
t slab (in)	5	5	5
Span (in)	484	484	484
b (in)	96	96	96
h (in)	41	41	41
tf (in)	3	3	3
tw (in)	7	7	7
f'c (psf)	432000	432000	432000
fpu (psf)	36000000	36000000	36000000
fpy (psf)	30600000	30600000	30600000
fy (psf)	8640000	8640000	8640000
Unit Weight (pcf)	150	150	150
Young modulus (psf)	580464000	580464000	580464000
DAMAGE CUBES	DAMAGE CUBES A	DAMAGE CUBES B	DAMAGE CUBES C
Cracking_v	Yes	Yes	Yes
Crack Sev (1 - 5)	3	4	4
Length1r (in)	84	1	1
Width1r (in)	1	54	76
Depth1r (in)	1	1	1
From Support1r (in)	384	216	293
From Top1r (in)	7	0	0
From Edge1r (in)	24	30	51
Spalling_v	Yes	Yes	Yes
Spall Sev (1 - 5)	4	5	5
Length2r (in)	6	18	36
Width2r (in)	3	3	6

Depth2r (in)	2	2	2
From Support2r (in)	108	228	336
From Top2r (in)	41	41	41
From Edge2r (in)	48	48	48
Delam_v	Yes	Yes	Yes
Delam Sev (1 - 5)	3	3	3
Length3r (in)	30	63	34
Width3r (in)	18	29	27
Depth3r (in)	1	1	1
From Support3r (in)	329	384	192
From Top3r (in)	0	0	0
From Edge3r (in)	66	27	27

8.5.3   Execute the DET

Once the damage type, severity, amount, and location information are in Excel, the evaluation is executed using DET. Since spalling on Girder C is the controlling damage instance on the bridge, the DET will be carried out Girder C demonstrating the spalling damage mode. Accordingly, the appropriate input is entered into the DET user interface by selecting Girder C and the spalling damage mode.

8.5.3.1   *Maintenance Recommendations*

Upon execution, a maintenance recommendation window appears based on the damage type and severity information as discussed in Section 6.2.5.1. The exported inspection schedule form, the user interface for the DET, and a sample maintenance recommendation window for spalling on Girder C are all depicted in Figure 8.25.
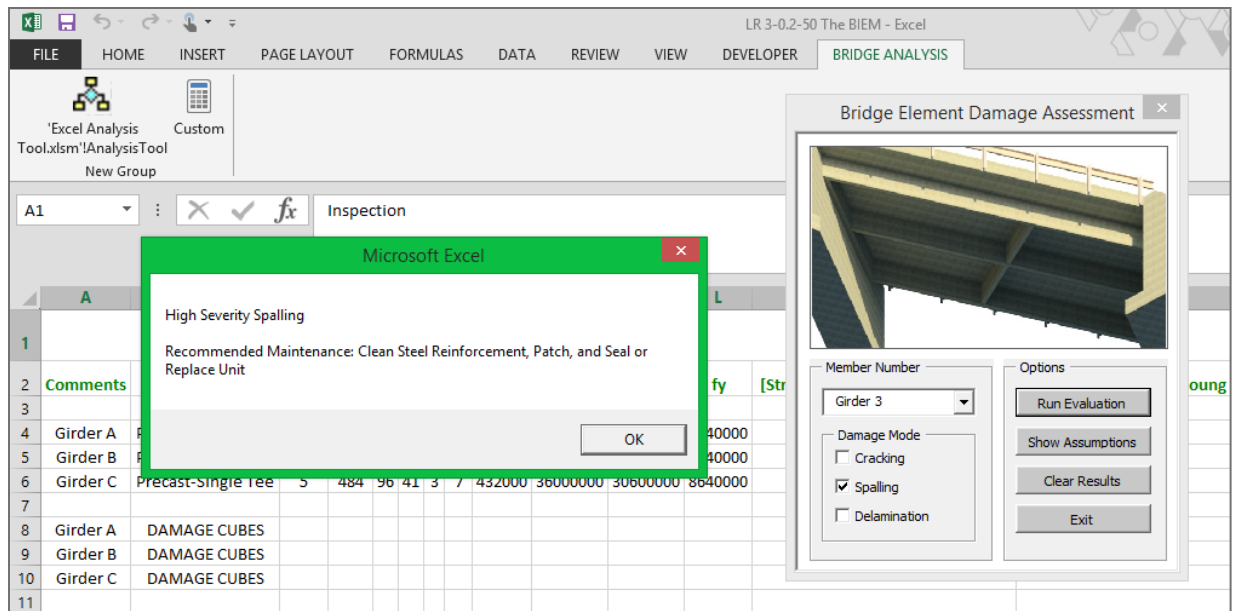
Figure 8.25 Demo of the DET execution and the maintenance recommendation window for Girder C

8.5.3.2 *Estimated Repair Quantities*

After maintenance recommendations have been presented, the estimated repair quantities are calculated in the DET. Output for the estimated repair quantities are shown in Table 8.7. Estimated repair quantities are determined by the DET in Excel by multiplying the volumetric damage parameters for an instance of damage from the DLT in Revit.

Table 8.7 Estimated repair quantities for Girder C

Damage Mode	Severity (1-5)	Volume (in^3)
Cracking	4	38
Spalling	5	432
Delamination	3	918

8.5.3.3 *Moment and Shear Capacity Evaluations*

The DET calculates and plots the required and provided shear and moment capacities as shown in Figures 8.26 and 8.27. The provided moment capacity of the girder is shown in Figure 8.26 with the triangular curve. The shape of this curve is due to the triangular prestressing

tendon layout. Also in Figure 8.26, the required moment is illustrated with the parabolic curve. Here, the consequence of damage location is illustrated by the 'notch' around the 330 inch mark. This 'notch' on the provided moment capacity curve is the effect of the spalling instance on the bottom of the stem on Girder C. When compared with the overall member capacity, the effect of this damage instance is small, about 210 kip*in. However, by observing Figure 8.26, this instance of deterioration occurs at one of the two most critical locations, where the distance between the required flexural strength curve is closest to the provided capacity curve. Although the impact of damage on strength is small in this case, the location is significant. This suggests that documenting the location of deterioration can be critical because, in a more severe case, knowledge of damage location information could be the determining factor of whether a bridge member is structurally adequate.

Shear capacities are plotted in Figure 8.27. In this figure, the provided shear capacity is indicated in blue and the required shear capacity is depicted in the green linear relation. The spalling mode on Girder C has a small impact on the shear capacity of the girder and its effect cannot be seen in Figure 8.27. In sum, the spalling mode decreases the shear capacity by about 1.5 kips. In both the moment and shear cases, the damaged capacity curves are greater than the required strength, indicating adequacy in the member from a strength standpoint.
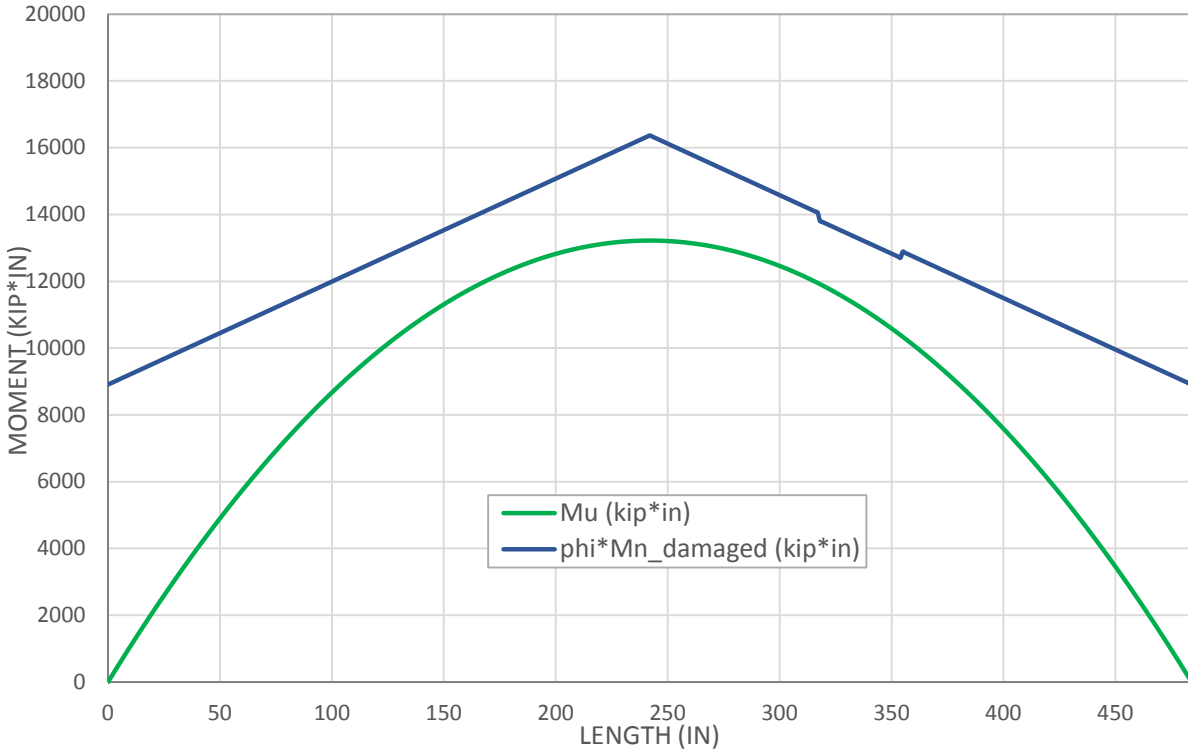
Figure 8.26 Required strength and capacity in flexure for Girder C
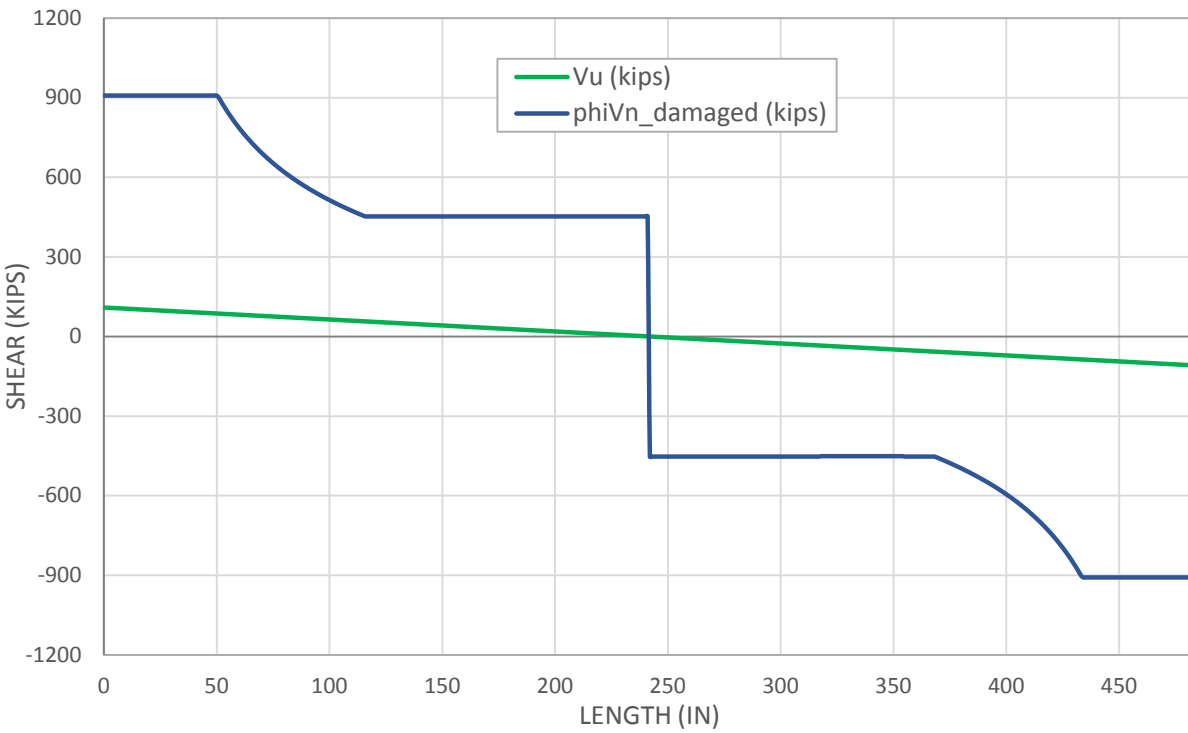
Figure 8.27 Required strength and capacity in shear for Girder C

102

8.5.3.4 *LRFR and LFR Rating Factors*

The final output of the DET includes LRFR and LFR operating and inventory load rating factors. To review, load ratings for a member are determined by multiplying the rating factors by standard truck weights. Figure 8.28 depicts the LRFR operating and inventory rating factors plotted along the length of the span for Girder C. Figure 8.29 is the same plot but using the LFR rating method. The unique shapes of the rating curves reflect the critical locations of the girder where the required capacity is closest to the provided resistance as shown in the previous Figure 8.26. In general, with a PC girder, the location will affect the rating factor because the capacity of the member often varies along the length of the span due to the prestressing tendon layout. It is clear from the rating curves shown in Figures 8.28 and 8.29 that midspan is not the critical location as it is for a conventional simply supported member in flexure. In both figures the effect of the spalling instance on Girder C can be seen with the 'notches' in the curves around the 330 inch mark. The significance of the damage location is evident because in this case it controls the load ratings for both the LRFR and LFR methods.
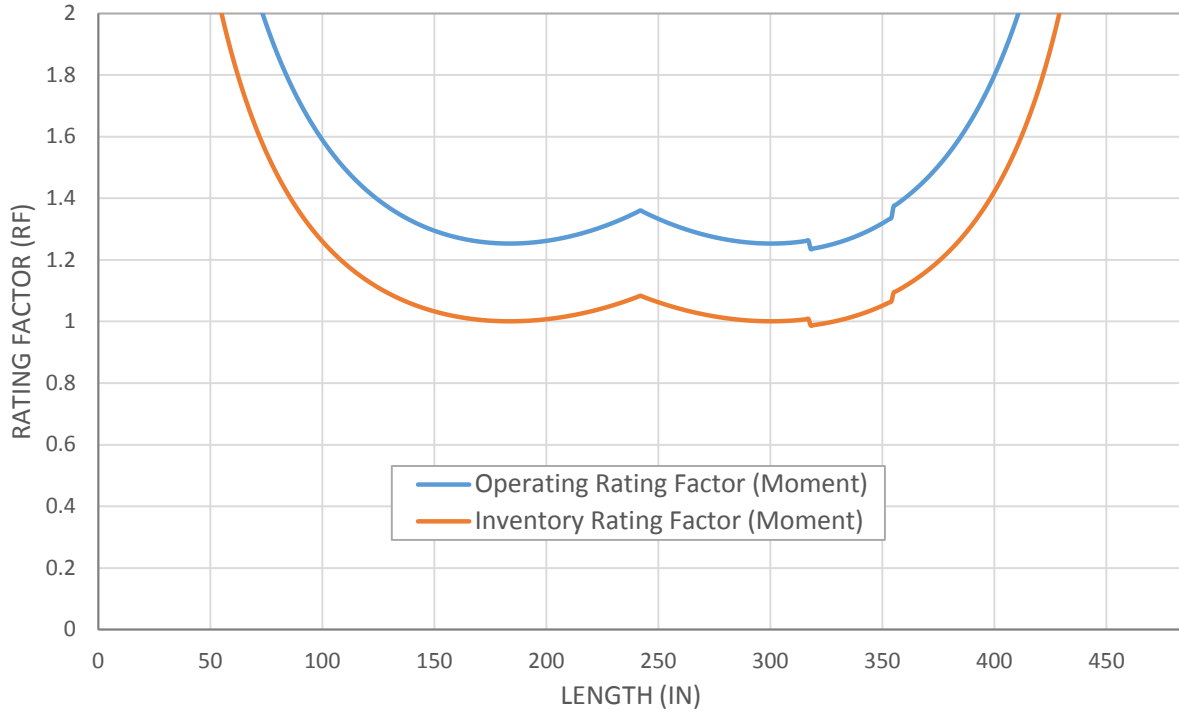
Figure 8.28 LRFR rating method for flexure for Girder C
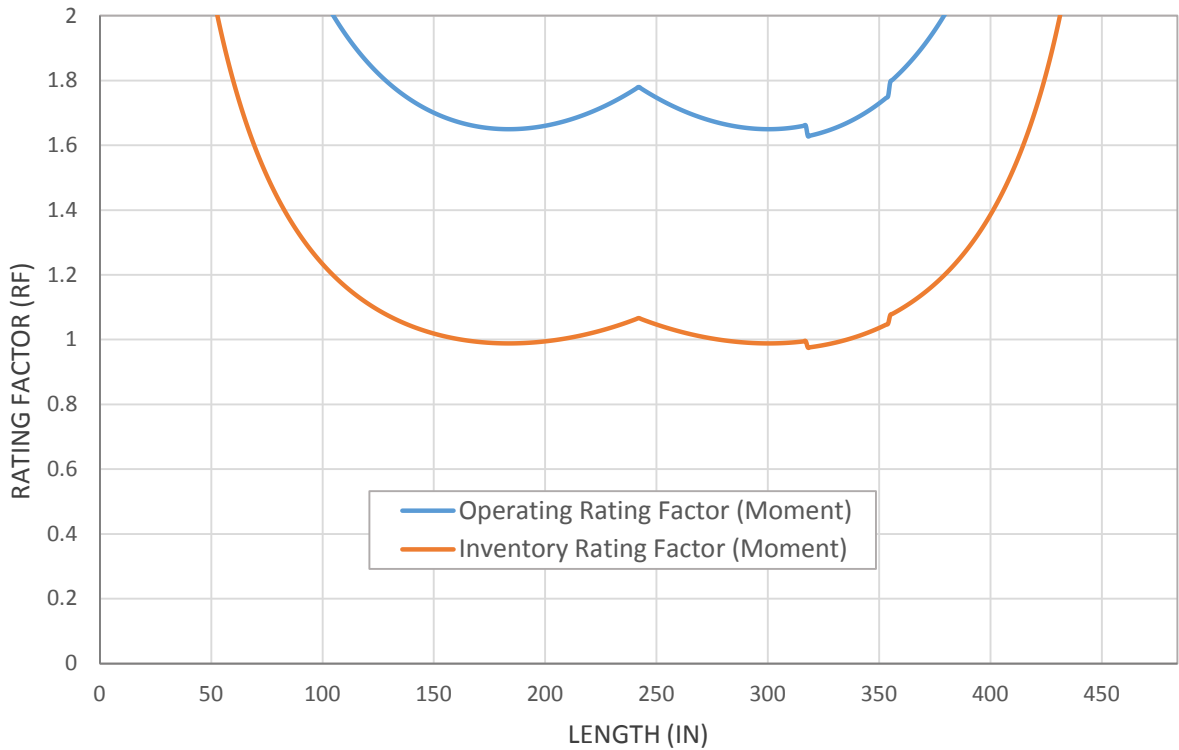
Figure 8.29 LFR rating method for flexure for Girder C

9   RESULTS AND DISCUSSION

The following chapter is divided into two sections. First, quantitative results from the case study implementation of the BIEM are presented and compared with official inspection and load rating results. Second, qualitative findings upon implementing the BIEM on the case study bridge are discussed.

9.1   Testing the Accuracy of the BIEM Components on the Case Study Bridge

In order to test the functions of the prototype BIEM for accuracy, the DLT and DET output are compared with official inspection and load rating reports for the case study bridge.

9.1.1   Comparing Results from the DLT to Current Practice

An official inspection report of the bridge utilizing current NBIS practices was obtained from the Larimer County Engineering Department and can be seen in Appendix A. Quantities based on the AASHTOWare condition states are checked with corresponding DLT quantities of damage severities utilizing inspection data for the entire superstructure. Since the element-level measurements for girders are only provided in linear feet in the official inspection report, the DLT linear foot parameter "length of damage" will be summed and used for comparison. Table 9.1 illustrates the comparison between official inspection quantities and quantities noted during the case study inspection. Although condition state and damage severity quantities differ somewhat, the total linear foot measurement between the two methods are quite close.

Table 9.1 Comparing DLT linear quantities with the official inspection report

	Condition State/ Damage Severity	Linear Feet	Totals (LF)
Larimer County Inspection Results	1	64	
	2	58	
	3	8	130
	4	0	
	5	0	
Case Study DLT Inspection Results	1	49	
	2	57	
	3	14	131
	4	9	
	5	2	

The purpose of this table is to highlight two points: First, measurements during the case study inspection were accurate when compared with the official inspection. Second, the DLT is capable of capturing all information during an inspection as required by the current regulations, while concurrently storing additional relevant information. In table 9.1, the differences between the AASHTOWare condition state ratings and the DLT damage severities can be attributed to the DLT having a more refined resolution than the AASHTOWare element-level condition states as discussed in Section 5.2.3.2.

9.1.2   Comparing Results from the DET to Official Reports

An official load rating report of the bridge utilizing the LFR method was obtained from Larimer County and can be seen in Appendix A. Section 3.3.1 reported that load ratings are to be based on the deteriorated cross-section according to AASHTO MBE provisions [2]. Therefore, the LFR operating and inventory load ratings from the official report are compared with results from the DET at the location of the worst case damage mode. As mentioned, this location is a severe instance of spalling on Girder C. Table 9.2 illustrates rating factors (RFs) from the official LFR load rating in comparison to LFR RFs from the DET. In summary,

operating RFs between the two sources are comparable, with an 8.7% difference between the two. Although on the higher end, the inventory ratings are also found comparable with a 9.6% difference.

Table 9.2 Comparing LFR girder results from the DET with the official rating factors

Rating Factors (RF)	Larimer County Load Rating Factors	DET's Rating Factors	Percent Difference
Operating	1.789	1.633	8.7%
Inventory	0.892	0.977	9.6%

To review, the inventory, or lower bound, load rating represents a theoretical live load that the bridge could sustain indefinitely [2] and it represents the load which produces a stress level at 55% of the yield stress of a member [19]. The operating, or upper bound, describes the maximum live load a structure may experience [2] and it represents the state of stress at 75% of the yield stress of a member [19].

It is not possible to determine the exact cause for the discrepancies between the DET results and the official load ratings because no detailed calculations are present in the load rating report. However, differences could be attributed to different loads used between the official ratings and the DET. For example, since the dead loads, live loads, and member capacity used in the DET's ratings are taken pointwise along the length, the critical load rating location is not necessarily the location where the load effects are at their maximum. The official load rating likely used maximum loads and capacities in the rating calculations. Differences between the DET results and official load ratings could also be accounted for by differing assumptions made throughout the capacity calculations. It is not possible to determine the assumptions made in the official rating, however, a major assumption in the DET's member capacity calculation includes neglecting the flexural resistance provided by all non-prestressed steel as per the AASHTO MBE provisions [2].

Table 9.3 depicts load ratings when the rating factors are applied to a HS-20 truck with a gross weight of 36 tons. From this table it is clear that the DET results provide narrower guidelines for a safe load carrying capacity for the bridge. In particular, the lower limit (inventory level) truck load is about 3 tons higher than the official rating, while the upper limit (operating level) truck load is about 5 tons lower than the official rating.

Table 9.3 LFR load rating comparison for a HS-20 truck

HS-20 Load Rating	Larimer County HS-20 Rating (tons)	DET HS-20 Rating (tons)	Difference (tons)
Operating	64	59	- 5
Inventory	32	35	+ 3

It is interesting to note that results from the DET are more conservative for the operating case and less conservative for the inventory case when compared with the official rating. Ultimately, this results in a narrower window for the safe load carrying capacity for the case study bridge. This could be the result of the instance of severe spalling on Girder C occurring at the critical location where the provided capacity is closest to the required moment as shown in the previous Figure 8.26, but not at the location of the critical load effect which occurs at midspan. From midspan to the instance of damage, the member capacity decreases at a higher rate than the required moment. As a result, the operating and inventory dead and live load factors could affect the load rating to a varying degree causing the operating rating to be more conservative and the inventory rating to be less conservative when compared to the official report.

9.2   Findings upon Implementing the BIEM on the Case Study Bridge

9.2.1   Bridge Management and the BIEM

At its core, the BIEM is providing a way to capture more information in a bridge inspection and to reuse that information in an automated way to help make decisions. With a method such as the BIEM to provide capacity results, load ratings, and maintenance recommendations from augmented inspection information, transportation officials can be better equipped to make informed decisions regarding rehabilitation strategies for bridges. If inspection results were to include the numerical documentation of damage location, this information can be reused in an automated way to make informed management decisions for a network of bridges. In particular, the BIEM could offer improvements to bridge management in two main fields: bridge inspections and bridge evaluations.

9.2.2   Bridge Inspections and the DLT

By supplementing the current NBIS procedures with the numerical documentation of damage location, bridge managers could have access to refined data and a more representative snapshot of the current structural condition of bridges. The DLT was developed as a demonstration tool to illustrate the capacity for BIM software to capture and depict this location-based information during an inspection. Current inspection techniques can overlook damage instances because the focus is inherently on the element-level. The DLT has a more refined resolution in that it can store location-based element-level damage information gathered in an inspection. In addition, the DLT can serve as a helpful visualization tool for decision makers by graphically depicting the location and extent of deterioration. In utilizing the DLT, transportation officials could be able to track the effectiveness of maintenance actions over time

by observing changes in the volume, location, and severity of damage instances on bridge elements.

Current bridge inspection data is limited because damage location information is documented in textual format in comment sections of an inspection report [4]. By adopting the numerical record of damage location in an inspection, this information can input into databases so that it can be queried, reused, and manipulated as needed. To document the supplementary location information, bridge inspectors would be required to take additional measurements. Bridge inspections would likely take longer but the location-based measurements could help an inspector identify and document what they see during an inspection. For a bridge manager, additional field measurements results in enhanced data but also costs more money; if supplemental NBIS measurements of a bridge are on file (paper-based or in a BIM model), it could save money in maintenance planning because it would be unnecessary to verify and collect more detailed information before making repairs if comprehensive measurements were available.

9.2.2.1 *Future Improvements to the DLT*

To accomplish the objective of capturing and reusing location-based damage information using BIM, Autodesk Revit was selected as the tool for use due to its custom families and user defined parameters. Revit does not currently have a built in capacity for modeling damage nor was it designed to model bridges. The author developed the DLT which uses existing tools in Revit to accomplish the major objectives in modeling a bridge and documenting damage information from a bridge inspection. To do so the DLT was created with limited capabilities. Areas for improvement in both software development in Revit and the capabilities of the DLT exist and are summarized as follows:

- Incorporate more damage types and different modes for different types of material[4]

- Depict deterioration with more customizable or curved shapes rather than only flexing the geometry of parallelepipeds

- Resolve the vertical extents conflict when in creating the damage modeling within the host family (instead of a generic model family) such that the parametric damage instances do not affect the vertical extent of the member[5]

- In modeling damage within the host family, offer more effective constraint between the host geometry and the parametric damage modeling to restrict the ability for damage instances to be placed outside of the extents of a member

- Improve the placement of the damage instances by establishing more intuitive control with the geometric shape handles

- Provide standard Revit families for steel prestressing tendons, concrete diaphragms, W-beam steel guardrail

9.2.2.2 *Future Extensions of the DLT*

Although not explored in this thesis, the DLT has potential future extensions with its interoperable characteristics.   For example, the DLT could potentially supply the input information for finite element software analysis or structural analysis packages.   Also not

---

[4] In an inspection, more than three damage types are likely to exist on a bridge. In addition, different distress types exist on different material types. For example, deterioration on a steel girder might include cracking, fracturing, corrosion, local buckling, local yielding, lateral torsional buckling, or crippling. Damage on a timber beam might include shakes, splits, checks, knots, or warping to name a few.

[5] See Section 5.2.2.1

explored in this thesis, includes using information from the DLT as a potential input in existing load rating software such as AASHTOWare Bridge Rating.

9.2.3 Bridge Evaluations and the DET

Ultimately, precise bridge evaluations result in accurate guidelines for establishing the safe load carrying capacities for bridges. By documenting the location of damage instances during an inspection, bridges could be more accurately evaluated because failure modes are more critical at different locations and member capacities can vary along the length. Therefore, transportation officials could benefit in utilizing the DET because it offers a unique and complete snapshot of load ratings along the length of members. The DET's maintenance recommendations and estimated repair quantities feature could offer a resource to help bridge managers develop rehabilitation strategies and budget accurately for repairs. Although not explored in this thesis, the DET could save time when compared to the traditional load rating process. Since bridge inspections would likely take longer with the additional measurements required, the potential automated load rating process could offer a cost-savings tradeoff.

9.2.3.1 *Future Improvements to the DET*

The DET was developed as a demonstration tool to illustrate how information from a BIM model can be used. For a practical application, areas for improvement exist in the DET since its capabilities are currently tailored to the case study bridge. Specific areas for a software developer to improve the DET are as follows:

- Provide the DET with the flexibility to be applied to different bridge types, girder configurations, span lengths/types, and bridge materials using information reported from the BIM model

- Code the AASHTO design loads and the preliminary structural analysis into the DET using geometry variables reported from the BIM model

- Adapt the DET cross-section generators to handle different sizes and types of cross-sections

- Provide the DET with the ability to read and analyze an increased number of damage modes including modes acting concurrently.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Summary

This thesis investigated the use of a new method to apply BIM software to the operation and maintenance stages of bridges' service lives. Research conducted throughout this study explored supplementing current bridge inspection techniques with the numerical documentation of damage location to better depict the true condition of existing bridges. To integrate these research goals, BIM was utilized to track and assess the effect of damage locations on the structural condition of a case study bridge. The BIEM was developed by the author which could allow transportation agencies to more efficiently manage bridge inventories. To accomplish this, the DLT was created to use existing capabilities in Revit to model and store deterioration information on bridge elements gathered during an inspection. The DET was developed to reuse damage information from DLT to analyze and evaluate the effects of deterioration on the structural performance of bridges in Excel.

Conclusions are based upon a review of literature on current methods, software trials, observations, along with a case study implementation of the BIEM. Applying the BIEM first involved modeling the case study bridge using existing tools in Revit. A detailed field inspection was then performed on the case study bridge using routine visual inspection techniques along with collecting supplemental information on the location of deterioration. Next, results from the bridge inspection were input into Revit utilizing the DLT. Following this, the DET was executed to evaluate the effects of damage on a selected superstructure element. The requirements for a future application of BIM in bridge management, major conclusions, and recommendations for future work are provided in the following sections.

10.2 Integrating BIM with Bridge Management

The case study described herein shows that the prospects for the application of BIM to the operation and maintenance stages of bridges' service lives is promising. In this research, the ability for BIM to facilitate the bridge inspection and evaluation processes has been demonstrated. Throughout this study it has been shown that in using BIM, transportation officials could benefit by its proven ability to collect, store, and use damage location information. BIM is able to document the type, amount, location, and severity information during an inspection in a timely and accurate manner. In addition, BIM can offer benefits to bridge managers as a graphical tool in its level of detail, photorealistic rendering capabilities, and its parametric ability to visually depict deteriorated volumes in 3-D and in real-time.

10.3 Conclusions

Observations and results from implementing the BIEM on the case study bridge suggest the following:

1. Documenting the location of deterioration in an inspection can be significant in determining the structural adequacy of a bridge member and can affect the guidelines for determining a safe load carrying capacity for a bridge

2. Evaluating the rating factors at discretized increments along the length is important to uncover the true critical location since limit states, deterioration modes, and member capacities are all location dependent

3. The future of BIM in bridge management could be favorable by its proven ability to facilitate the inspection and evaluation processes, which could ultimately result in a more automated practice

4.   For the practical future integration of BIM into the bridge management field, steps in software development need to be taken to further tailor the principles of BIM to the operation and maintenance of bridges' service lives

10.4 Requirements for the Future Application of BIM in Bridge Management

Using BIM to link key aspects of bridge management such as bridge inspections and bridge evaluations could ultimately result in more automated management practices in the future. In order to integrate the principles of BIM in the management of bridges, several areas of study exist. The following sections offer a comprehensive list of observations and requirements for the future full implementation of BIM in the operation and maintenance stages of bridges' service lives. Specifically, the following sections present: standard capabilities that do not currently exist, areas that need further research and development, and other issues that need to be addressed to implement BIM in bridge management.

10.4.1 Standard Capabilities that Do Not Exist

- Built-in standard tools for parametric damage modeling
  - Built-in tools to reduce the cross-section or part of the cross-section of a member at a particular location along its length
  - A built-in means to easily decrease any desired mechanical property of an element
  - Built-in and intuitive means to document damage information including the type, severity, amount, and location of damage instances

- Ability to store additional NBI required data including bridge type and materials, roadway classification, age and service data, current load ratings and postings, proposed improvements, etc.

10.4.2 Areas that Need Further Research and Development

- Feasibility studies on using 3D laser scanning to quantify the practicality of modeling a network of bridges using BIM and point cloud data

- Improved access to 'mobile BIM' models and all associated parameters on portable tablets[6]

  o Integrate augmented reality[7] technology on tablets with the current GPS capabilities of BIM

  o Link/attach inspection photographs to problem areas in BIM models in a timely manner

- Improve interoperability between BIM and finite element, structural analysis, and/or load rating packages to semi/fully-automate the evaluation process

---

[6] Using Autodesk as an example, the ability to access and manipulate Revit parameters in BIM 360 Field would allow for the field documentation of a bridge inspection on a tablet. With a portable electronic data collection source, an inspector could be provided with mobile access to documentation, previous inspections, bridge plans, and reference information. Documenting an inspection electronically in the field would also eliminate data reentry and the associated human error and it could allow the inspector to compare current findings with previous inspections.

[7] See Section 3.6.2.3 for a definition of augmented reality. Upon further development, for example, if an inspector were to focus on a problem area with the tablet's video camera, the location could be automatically identified in the BIM model, and appropriate information could be entered.

10.4.3 Other Issues

- For bridge models that already exist, issues need to be resolved between the model creators and the bride owners on who is liable for the information in a model

- Legal liability issues would need to be resolved since inspection reports and load ratings are both legal documents

10.5 Recommendations for Future Work

Results from this research highlight future work in updating current bridge management practices and extending BIM applications. In particular, topics for future study include:

1. The study of steel and concrete deterioration modes and their effect on the mechanics and capacity of bridge elements

2. Using 3-D laser scanning technology for the BIM modeling of bridges on a network-level using point cloud data

3. Software development in BIM to provide standard, built-in tools for modeling damage on elements and capturing information from an inspection

4. Interoperability between BIM platforms and industry standard structural analysis, finite element, and bridge load rating software programs

BIBLIOGRAPHY

[1]   ASCE, "Report Card for America's Infrastructure," 2013. [Online]. Available: http://www.infrastructurereportcard.org/a/#p/bridges/overview.

[2]   AASHTO, The Manual for Bridge Evaluation, Washington D.C.: American Association of State Highway and Transportation Officials, 2011.

[3]   R. Winnie, Interviewee, *Bridge Management in Larimer County.* [Interview]. 27 February 2014.

[4]   FHWA, Bridge Inspector's Reference Manual, Arlington, VA: Federal Highway Administration, 2012.

[5]   A. C. Estes and D. M. Frangopol, "Updating Bridge Reliability Based on Bridge Management Systems Visual Inspection Results," *Journal of Bridge Engineering Volume 8 Number 6,* pp. 374-382, 2003.

[6]   Short Elliot Henderickson Inc., "Bridge Inspection Report (English Units) LR3-0.2-50 (unpublished)," CDOT, Fort Collins, CO, 2013.

[7]   USDOT; FHWA; FTA, "2013 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance. Report to Congress," U.S. Department of Transportation, Federal Highway Administration, Federal Transit Administration, Washington D.C., 2013.

[8]   McGraw-Hill Construction, "The Business Value of BIM for Infrastructure: Smart Market Report," McGraw-Hill Construction, Bedford, MA, 2012.

[9]   M. Patton and M. Cochran, "Field Research," 2002. [Online]. Available: http://fieldresearch.msf.org/msf/bitstream/10144/84230/1/Qualitative%20research%20methodology.pdf.

[10]   C. Lassenius, J. Vanhanen and T. Soininen, "Research Methods," 26 11 2001. [Online]. Available: http://www.soberit.hut.fi/~mmantyla/work/Research_Methods/.

[11]   OECD, Bridge Management, Paris, France: Organization for Economic Cooperation and Development, 1992.

[12]   NCHRP, NCHRP Synthesis 375: Bridge Inspection Practices, Washington D.C.: National Cooperative Highway Research Program, 2007.

[13]   NCHRP, NCHRP Synthesis 397: Bridge Management Systems for Transportation Agency

Decision Making (2009), Washington D.C.: National Cooperative Highway Research Program, 2009.

[14]   AASHTO, "AASHTOWare Bridge," AASHTO, 2014. [Online]. Available: http://www.aashtoware.org/Bridge/Pages/default.aspx. [Accessed 12 August 2014].

[15]   MDOT, "Michigan.gov," MDOT, 2007. [Online]. Available: http://www.michigan.gov/documents/mdot/MDOT_PontisManual_2007_195365_7.pdf. [Accessed 12 8 2014].

[16]   AASHTO, Manual for Condition Evaluation of Bridges. Second Edition, Washington D.C.: American Association of State Highway and Transportation Officials, 1994.

[17]   ACI, Recent Advances in Maintenance and Repair of Concrete Bridges, Farmington Hills, MI: American Concrete Institute, 2010.

[18]   NBI, "Material Type of Structure by State," National Bridge Inventory, Washington D.C., 2013.

[19]   K. R. White, J. Minor and K. N. Derucher, Bridge Maintenance Inspection and Evaluation. Second Edition, New York, New York: Marcel Dekker, Inc., 1992.

[20]   J. L. Austin, Computer Assisted Bridge Rating for Small Bridges (unpublished thesis), Fort Collins: Colorado State University, 1994.

[21]   G. P. Mallett, Repair of Concrete Bridges, London: Thomas Telford Services Ltd., 1994.

[22]   ACI Committee 546, Guide for Repair of Concrete Bridge Superstructures (ACI 546.IR-3), Farmington Hills, MI: American Concrete Institute, 1980.

[23]   ACI Committee 201, Guide to Durable Concrete (ACI 201.2R-08), Farmington Hills, MI: American Concrete Institute, 2008.

[24]   H. L. Trantham-Hevelone, A Knowledge Based System for the Inspection of Sub 20' Bridges (unpublished thesis), Fort Collins: Colorado State University, 1995.

[25]   FHWA, "Alkali-Silica Reactivity Field Identification Handbook," Federal HIghway Administration, Washington D.C., 2011.

[26]   SHRP, "Alkali-Silica Reactiity: An Overview of Research," Strategic Highway Research Program, Washington D.C., 1993.

[27]   FHWA, "Bridge Load Ratings for the National Bridge Inventory," 30 October 2006.

[Online]. Available: http://www.fhwa.dot.gov/bridge/nbis/103006.cfm.

[28]   AASHTO, LRFD Bridge Design Specifications, Washington D.C.: American Association of State Highway and Transportation Officials, 2012.

[29]   ASCE/SEI-AASHTO, "White Paper on Bridge Inspection and Rating," *Journal of Bridge Engineering,* vol. 14, no. 1, pp. 1-5, 2009.

[30]   M. S. Bergin, "A Brief History of BIM," Archdaily, 7 12 2012. [Online]. Available: http://www.archdaily.com/302490/a-brief-history-of-bim/. [Accessed 9 9 2014].

[31]   G. Demchak, T. Dzambazova and E. Krygiel, Introducing Revit Architecture 2009: BIM for Beginners, Indianapolis, Indiania: Wiley Publishing, 2009.

[32]   A. Cho, "Ten Minutes with the Godfathers of Bridge Information Modeling," 22 August 2009. [Online]. Available: http://enr.construction.com/people/interviews/2009/0812-ChenShirole.asp article 8/12/2009.

[33]   J. Jones, "The Importance of BIM," *Civil Engineering,* pp. 66-69, May 2014.

[34]   E. Krygiel and B. Nies, Green BIM: Successful Sustainable Design with Building Information Modeling, Indianapolis, Indiana: Wiley Publishing, Inc., 2008.

[35]   L. Abaffy, "Law Rewards Some Tech Innovations, Requires Others," *Engineering News Record,* p. 9, 17 February 2014.

[36]   M. M. Marzouk and M. Hisham, "Bridge Information Modeling in Sustainable Bridge Management," in *The International Conference on Sustainable Design and Construction 2011*, Kansas City, MO, 2012.

[37]   P. Meadati, "BIM Extension into Later Stages of Project Life Cycle," Southern Polytechnic State University, Marietta Georgia, 2009.

[38]   P. Tang and B. Akinci, "Formalization of Workflows for Extracting Bridge Surveying Goals from Laser Scanned Data," *Automation in Construction,* vol. 2012, no. 22, pp. 306-319, 2012.

[39]   D. Gleason, "Getting to a Facility Management BIM," in *Lake Constance 5D-Conference*, Constance, 2013.

[40]   C. Eastman, P. Teicholz, R. Sacks and K. Liston, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, 2nd Edition, Hoboken, New Jersey: John Wiley & Sons, 2011.

[41]   Graphisoft, "ArchiCAD," 2014. [Online]. Available: http://www.graphisoft.com/archicad/.

[42]   Tekla, "Tekla Structures," 2014. [Online]. Available: http://www.tekla.com/products/tekla-structures.

[43]   MIDAS, "Midas User Support System," 14 3 2014. [Online]. Available: http://en.midasuser.com.

[44]   Bentley, "Bentley," 2014. [Online]. Available: http://www.bentley.com/en-US/Products/Bentley+LEAP+Bridge/.

[45]   Autodesk, "Autodesk," 2014. [Online]. Available: http://www.autodesk.com/products/revit-family/overview.

[46]   Autodesk, "BIM 360 FIeld," 2014. [Online]. Available: http://www.autodesk.com/products/bim-360-field/features.

[47]   B. J. Kim, H. K. Robert and R. E. Jonathan, Simplified LRFD Bridge Design, Boca Raton, FL: CRC Press, 2013.

[48]   S. DiBernardo, "Integrated Modeling Systems for Bridge Asset Management - Case Study," in *Structures Congress*, Chichago, Illinois, 2012.

[49]   Autodesk, "Autodesk Exchange Apps," Autodesk, 2014. [Online]. Available: https://apps.exchange.autodesk.com/RVT/en/Detail/Index?id=appstore.exchange.autodesk.com%3Aschedulesync_windows64%3Aen. [Accessed 4 9 2014].

[50]   B. Fanning, C. Clevenger and M. Hussam, "Implementing BIM on Infrastructure: Comparison of Two Bridge Construction Projects," *Practice Periodical on Structural Design and Construction,* Vols. 10.1061/(ASCE)SC.1943-5576.0000239, no. 04014044, 2014.

[51]   E. G. Nawy, Prestressed Concrete: A Fundamental Approach Third Edition, Upper Saddle River, NJ: Prentice Hall, 2000.

[52]   ACI Committee 423, Recommendations for Concrete Members Prestressed with Unbonded Tendons (ACI 423.3R-96), Farmington Hills, MI: American Concrete Institute, 1996.

[53]   ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-11), Farmington Hills, MI: American Concrete Institute, 2011.

[54] ASTM, Extending the Life of Bridges, Ann Arbor, MI: American Society for Testing and Materials, 1990.

[55] FHWA, "LRFD Comprehensive Design Example for Prestressed Concrete (PSC) Girder Superstructure Bridge," 2013 8 July. [Online]. Available: http://www.fhwa.dot.gov/bridge/lrfd/pscus051.cfm.

[56] NCHRP, NCHRP Synthesis 140: Durability of Prestressed Concrete Highway Structrues, Washington D.C.: National Cooperative Highway Research Program, 1988.

[57] Parsons Brinckerhoff, Bridge Inspection and Rehabilitation, New York, NY: John Wiley & Sons, Inc., 1993.

APPENDIX A. CASE STUDY BRIDGE: LR3-0.2-50
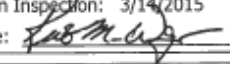
Official Bridge Inspection Report 3/14/2013

Bridge Inspection Report (English Units)

Bridge Name: LR3-0.2-50	Alias Str No. 8A:	Inspection Date : 3/14/2013

IDENTIFICATION

1. State:	08 Colo
2. District:	Reg 4 MSec 1
3. County:	LARIMER
4. City:	non-city
5A. Route On/Under:	Route On Str
5B. Route Signing Prefix:	4 County Hwy
5C. Level of Service:	1 Mainline
5D. Route Number:	003
5E. Directional Suffix:	0 N/A (NBI)
6. Feature Intersected:	Larimer & Weld Canal
7. Facility Carried On:	County Road 3
9. Location:	0.2 Mi N of Co Rd 50
11. Mile Post:	0 miles
16. Latitude:	40 d 36 ' 43.9 "
17. Longitude:	104 d 57 ' 46.9 "
18A. Survey Range:	68 W
18B. Survey Township:	8 N
18C. Survey Section:	35
98. Border Bridge Code:	(N/A)
99. Neighboring State Code:	(N/A)
% of Responsibilty:	0%

STRUCTURE TYPE AND MATERIALS

43A. Main Span Material:	5 Prestressed Concrete
43B. Main Span Design:	04 Tee Beam
44A. Approach Material:	0 Other
44B. Approach Design:	00 Other (NBI)
45. No of Main Spans:	1
46. No of App. Spans:	0
107. Deck Type:	1 Concrete-Cast-in-Place
108A. Wearing Surface:	1 Monolithic Concrete
108B. Membrane:	0 None
108C. Deck Protection:	0 None
120A. Structure Type:	CSGP
120B. Construction Type:	20

CLASSIFICATION

20. Toll Facility:	3 On free road
21. Custodian:	County Hwy Agency
22. Owner:	County Hwy Agency
26. Function Class:	09 Rural Local
37. Historical Sign.:	5 Not eligible for NRHP
100. Defense Hwy:	0 Not a STRAHNET hwy
101. Parallel Str:	No II Bridge Exists
102. Dir of Traffic:	2 2-way traffic
103. Temporary Str:	Not a Temporary Structure
104. Highway Sys:	0 Not on NHS
112. NBIS Length:	Yes

GEOMETRIC DATA

10. Max. Ver Clr :	99.99 ft.
32. Appr. Roadway Width:	20 ft.
33. Bridge Median:	0 No median
34. Skew:	37 degree(s)
35. Structure Flared:	Structure Not Flared
47. Horizontal Clr	22.6 ft.
48. Length of Max. Span:	39.1 ft.
49. Structure Length:	43.2 ft.
50A. Curb/Sdwlk Width (lt):	0 ft.
50B. Curb/Sdwlk Width (rt):	0 ft.
51. Curb to Curb Width:	22.6 ft.
52. Out to Out Width:	24.3 ft.
53. Min Vert Clr Over:	99.9 ft.
54A. Ref Min Ver Clr Und:	Not a Highway or RR
54B. Min Vert Clr Und:	0 ft.
55A. Ref Min Lat Clr Und:	Not a Highway or RR
55B. Min Lat Clr Under (rt):	0 ft.
56. Min Lat Clr Under (lt):	0 ft.
Deck Area:	1049.8 sq. ft.

INSPECTION

91. Frequency:	24	90. Inspection Date:	3/14/2013	Next Inspection:	3/14/2015
92A. FC Frequency:	N	93A. FC Inspection Date:	-	Next FC Inspection:	-
92B UW Frequency:	N	93B. UW Inspection Date:	-	Next UW Inspection:	-
92C. Sp. Frequency:	N	93C. Sp. Inspection Date:	-	Next Sp. Inspection:	-
Elem Insp Freq:	24	Elem Insp Date:	3/14/2013	Next Elem Inspection:	3/14/2015
		Inspector:	WAGNERK	Signature:	

Bridge Inspection Report (English Units)

Bridge Name: LR3-0.2-50	Alias Str No. 8A:	Inspection Date : 3/14/2013

NAVIGATION DATA

38. Navigation Control:	Permit Not Required
39. Vertical Clearance:	0 ft.
40. Horizontal Clearance:	0 ft.
111. Pier Protection:	Not Applicable (P)
116. Lift Bridge Ver. Clr:	0 ft.

AGE AND SERVICE

19. Detour Length:	2 miles.
27. Year Built:	1962
28A. Lanes On:	2
28B. Lanes Under:	0
29. Avg. Daily Traffic:	282
30. Year of ADT:	2012
42A. Service Type On:	1 Highway
42B. Service Type Under:	5 Waterway
106. Year Reconstructed:	0
109. Truck ADT:	0 %
114. Future ADT:	442
115. Year of Future ADT:	2032

PROPOSED IMPROVEMENTS

75. Type of Work:	31 Repl-Load Capacity
76. Length of Improvement:	65 ft.
94. Bridge Cost:	292500
95. Roadway Cost:	29250
96. Total Cost:	438750
97. Year of Cost Estimate:	2013

Sufficiency Rating:	23.6
SD/FO Indicator:	Structurally Deficient

APPRAISAL

36A. Bridge Rail:	0 Substandard
36B. Transition:	0 Substandard
36C. Approach Rail:	0 Substandard
36D. Appr. Rail on End :	0 Substandard
36H. Rail Height :	34 in.
66T. Asphalt Thickness :	0 in.
67. Structure Evaluation :	2 Intolerable - Replace
68. Deck Geometry :	4 Tolerable
69. Und. Clr. Ver. & Hor.:	N Not applicable (NBI)
71. Waterway Adequacy:	8 Equal Desirable
72. Approach Alignment:	8 Equal Desirable Crit
113. Scour Critical:	5 Stable w/in footing

CONDITION

58. Deck:	4 Poor
59. Superstructure:	4 Poor
60. Substructure:	6 Satisfactory
61. Channel/ Channel Prot.:	7 Minor Damage
62. Culvert:	N N/A (NBI)

LOAD RATING AND POSTING

31. Design Load:	0 Unknown
41. Posting Status:	A Open, no restriction
63. Operating Rating Mthd:	1 LF Load Factor
64. Operating Rating:	17.7 tons.
65. Inventory Rating Mthd:	1 LF Load Factor
66. Inventory Rating:	10.6 tons.
70. Posting:	5 At/Above Legal Loads
129. Truck Load:	0 0 0 tons.
130. Rating Date:	3/14/1997

Bridge Notes:
Bridge kept on 24 month cycle.

Inspection Notes:
Date 3/14/2013 -
Temp: 64 Degrees   Time: 6:00 PM   Weather: High clouds, calm

Bridge Inspection Report (English Units)

Bridge Name:	LR3-0.2-50	Alias Str No. 8A:	Inspection Date : 3/14/2013

MAINTENANCE ACTIVITY

Activity No. : 306.02   **Priority :** S-P2

Description : Railin Rep & Repl

Install Adequate Bridge & Approach Rail

Detail of Work: Install bridge and approach rails to meet current AASHTO/CDOT standards.

Bridge Rail:	88 Feet X 125 / Feet X 1	=	11000.00
Approach Rail:	300 Feet X 75 / Feet X 1	=	22500.00

(Quantity X Rate X Adjustment Factor) Total Activity Cost   =   33500.00

Activity No. : 354.02   **Priority :** P-P1

Description : Superstructure

Repair girder / Truss (non-collision)

Detail of Work: Clean and patch spalls on bottom of Girders B & C legs.

Epoxy Concrete Patch:	2 Each X 350 / Each X 1	=	700.00

(Quantity X Rate X Adjustment Factor) Total Activity Cost   =   700.00

Activity No. : 399.00   **Priority :** P-P1

Description : Mtc Requiring Eng.

Maintenance Requiring Engineering

Detail of Work: Due to low calculated capacity of the deck, large expenditures on maintenance may not be warranted. Consideration should be given to replacing the bridge.

Matl, Equip & Labor:	1 Job X 438750 / Job X 1	=	438750.00

(Quantity X Rate X Adjustment Factor) Total Activity Cost   =   438750.00

Activity No. : 353.04   **Priority :** P-P2

Description : Bridge Deck Repair

Patch delams / spalls / potholes in surface

Detail of Work: Patch spalls in deck surface.

Epoxy Concrete Patch:	15 Each X 350 / Each X 1	=	5250.00

(Quantity X Rate X Adjustment Factor) Total Activity Cost   =   5250.00

Bridge Inspection Report (English Units)

Bridge Name:	LR3-0.2-50	Alias Str No. 8A:		Inspection Date : 3/14/2013

MAINTENANCE ACTIVITY

Activity No. :	206.01		Priority :	M-P1

Description : Debri & Veg Control

Remove Debris / obstructions from channel

Detail of Work: Remove trash and debris in channel.

Labor & Equipment:	5 Hours X 75 / Hours X 1	=	375.00
	(Quantity X Rate X Adjustment Factor) Total Activity Cost	=	375.00
	Total Bridge Cost	=	$478,575.00

PRIORITY DEFINITIONS:
1 S – P1 = Safety – Priority 1
2 U = Urgent
3 S – P2 = Safety – Priority 2
4 P – P1 = Programmed – Priority 1

5 P – P2 = Programmed – Priority 2
6 M – P1 = General Maintenance – Priority 1
7 M – P2 = General Maintenance – Priority 2

NOTE: The suggested maintenance activities were noted by the inspection crew on the date of inspection and consist of those deemed most critical to preserve the integrity of the bridge. Items are listed in the order of importance, with the first Maintenance Activity considered most important. Estimated costs are based upon approximate quantities and should not be relied upon for establishing funding. It is recommended that a qualified representative of the owning entity review this report at the bridge site, and using costs based upon personal knowledge, local conditions, availability of labor and materials and entity preferences, establish a revised estimate to accomplish the suggested work.

ELEMENT DATA COLLECTION

Element Number	Element Name	Env.	Total Qty	Unit	Quantity by State				
					1	2	3	4	5

Decks/Slabs

12	(5) Bare Concrete Deck	1	1052	(SF)	0	0	0	1052	0

5 inch thick concrete topping slab on 2 inch thick top flange of tee girders - Longitudinal, transverse and random cracks. Some spalls have been patched, many spalls in deck up to 2 inches deep. Transverse reinforcement exposed at 12 inch long spall at north end in west wheel line.

338	(4) Conc Curbs/SW	1	87	(LF)	80	7	0	0	0

9 inch x 9 inch curb - There are horizontal and vertical cracks in the east curb face with delamination and exposed reinforcement near north abutment (A2)=6 ft. Hairline cracks throughout length of curb. West curb broken off at south end (1 ft) with exposed reinforcement.

Joints

304	(3) Open Expansion Joint	1	61	(LF)	0	61	0	0	0

Single armor open joint at abutments - Minor leaking. R2 and R3 rust on armor. Filled with pourable asphalt sealer. Headers have moderate spalls.

127

Bridge Inspection Report (English Units)

Bridge Name:	LR3-0.2-50	Alias Str No. 8A:	Inspection Date : 3/14/2013

ELEMENT DATA COLLECTION

Element Number	Element Name	Env.	Total Qty	Unit	Quantity by State				
					1	2	3	4	5

Superstructure

109	(4)	P/S Conc Open Girder	1	130	(LF)	64	58	8	0	0

(3) 36 inch x 8 ft 0 inch single tee girder sections with concrete diaphragms midspan and girder ends - Girders B and C cracked longitudinally at midspan on the bottom of girder leg with spalling and rust stains. A lot of bounce under heavy loads. ½ inch leveling pads at girder ends. Heavy amounts of bird nests on girders.

334	(5)	Metal Rail Coated	1	87	(lF)	73	14	0	0	0

Galvanized W beam rail on steel I-beam posts - Light R1 rust on all posts. Posts are on weak axis. Posts have been painted brown and flex beam has been painted with aluminum paint prior to 2011 inspection. Paint on W beam is peeling.

Substructure

215	(4)	R/Conc Abutment	1	61	(LF)	57	4	0	0	0

oncrete wall - South abutment (A1) has (5) vertical hairline cracks, north abutment (A2) has (4). Moderate honeycomb near southwest corner of A1 = 4 ft.

326	(3)	Bridge Wingwalls	1	4	(EA)	4	0	0	0	0

Concrete wingwalls monolithic with abutments - Random cracks.

Smart Flags

359	(5)	Soffit Smart Flag	1	1	(EA)	0	0	1	0	0

Diagonal cracks due to skew with light water stains in in all bays near abutments some with light efflorescence. Longitudinal cracks in flanges at various locations.

505	(2)	Debris Smart Flag	1	1	(EA)	1	0	0	0	0

Light debris in channel.

128

Bridge Inspection Report (English Units)

Bridge Name: LR3-0.2-50	Alias Stı No. 8A:	Inspection Date : 3/14/2013

ELEMENT DATA COLLECTION

Element Number	Element Name	Env.	Total Qty	Unit	Quantity by State 1	2	3	4	5

Other Elements

| 501 | (2) | Channel Cond | 1 | 1 | (EA) | 1 | 0 | 0 | 0 | 0 |

Manmade channel (canal) with regulated flows.

| 504 | (2) | BankCond | 1 | 1 | (EA) | 1 | 0 | 0 | 0 | 0 |

Very steep (1 ½ :1) to near vertical with heavy grass, weeds and brush above normal water level. South bank is sloughing west of bridge near headgate.

| 530 | (2) | Approach Guardrail A | 1 | 1 | (EA) | 1 | 0 | 0 | 0 | 0 |

No approach rails exist.

| 600 | (5) | Genl Remarks | 1 | 1 | (EA) | 1 | 0 | 0 | 0 | 0 |

(1) 1 inch and (1) 6 inch utility pipes on east side of bridge. Posted 21T/33T/34T at both ends of bridge. Bridge does not require posting. Posting signs are in place, but not recommended.

LR3-0.2-50
MAR. 14, 2013

NORTH

WINGWALLS:
1'-6" THK. C.I.P. CONCRETE

FLOW
LARIMER AND WELD
CANAL

37°
SKEW

B.F. ABUT. 1

₡ COUNTY RD. 3

B.F. ABUT. 2

20'-0"
APPR. RDWY.

PLAN

43'-3" B.F./B.F.

ABUTMENTS:
C.I.P. CONCRETE

10'-11"

10'-9"

7'-6"

A1

₡

A2

39'-1" CLR. SPAN

ELEVATION
LOOKING WEST

3"   24'-3¾" O/O ⊥ (30'-5" O/O SKEW)   3"

22'-7" C/C

GALV. W FLEX BEAM
RAILS ON GALV. W
STL. POST @ 6'-3" O.C.

26"

34"

9"x9" CONC. CURBS
(TYP.)

5" CONC. SLAB

6" GAS LINE

14"

1" PIPE

3'-0"

A   B   C

8'-0"

4'-0"   4'-0"

1½"

2"

4"

6" CONC. DIAPHRAGM @ MID SPAN
& ENDS (PERPENDICULAR @ MIDSPAN)

28"

36"

SECTION
LOOKING NORTH

4'-0"   (3) PRECAST PRESTRESSED TEE   4'-0"
@ 8'-0" O.C.

6"
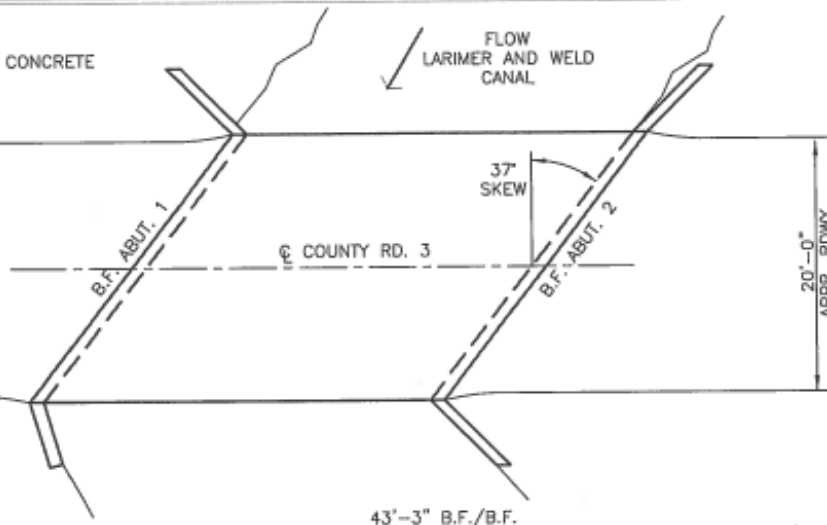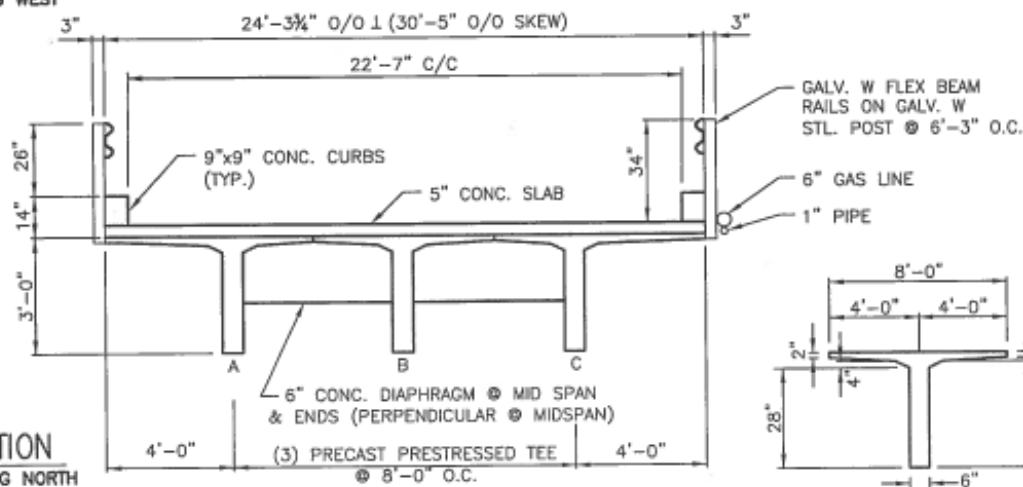
STREAMBED HISTORY

DISTANCE FROM BOTTOM OF GIRDER (FT)

Year	A1	Bridge CL	A2
2005	10.0	10.5	9.5
2007	9.5	10.5	10.0
2009	10.8	10.6	7.3
2011	10.8	10.4	7.6
2013	10.9	10.8	7.5
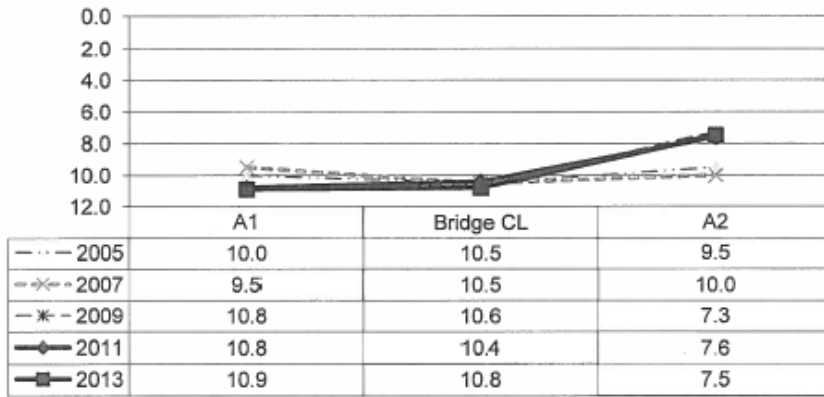
Structure Number: LR3-0.2-50   Performed By: KW
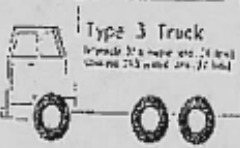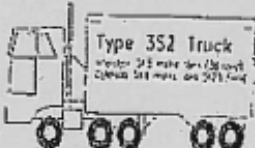
Inspection Date: 3/14/2013

COLORADO DEPARTMENT OF TRANSPORTATION
LOAD FACTOR RATING SUMMARY

Structure #	LR3-D.2-50
State highway #	County Road 3
Bridge I.D.	068019
Structure type	CSGP
Parallel structure #	N/A

Rated Using:
Asphalt thickness: 0 mm , 0 in.
[X] Colorado legal loads
[ ] Interstate legal loads
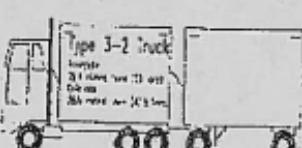
Structural Member	TYPICAL INTERIOR GIRDER		TYPICAL EXTERIOR GIRDER		DECK			
	Metric tons	(Tons)	Metric tons	(Tons)	Metric tons	(Tons)	Metric tons	(Tons)
Inventory MS 18 (HS 20)	30.9	(34.0)	29.2	(32.1)	9.6	(10.6)		
Operating MS 18 (HS 20)	62.8	(69.1)	58.5	(64.4)	16.2	(17.8)		
Type 3 truck					19.2	(21.1)		
Type 3S2 truck					30.4	(33.4)		
Type 3-2 truck					31.2	(34.3)		
Permit truck								

Type 3 Truck   Type 3S2 Truck   Type 3-2 Truck

Metric tons	Tons	Metric tons	Tons	Metric tons	Tons

Comments
NO POSTING REQUIRED

Wearing surface 5" concrete wearing surface

Bridge deck:	5" composite concrete	fc' (ksi) = 3.0	Fy (ksi) = 60
	As = 0.11si/ft	As' = 0.22si/ft	

Girders: 3-single tee prestressed girders 14 1/2" dia. strands   simply supported at ends.
fc' (ksi) = 6.00   fci (ksi) = 5.40   Pi (kips) = 352.8

Span Length: 41'-0"   c.t.c. bearing

Bridge is oriented on skew of 36 degrees.   Slab steel is placed perpendicular to roadway

The critical section is at midspan of girder.   BRIDGE REINSPECTED BUT NOT RERATED BY
HLA Infrastructure, Inc. - 1998

Comments:

Rated by	Date	Check by	Date
Thomas P. Giroux, P.E.	3/14/97		3-17-97

Previous editions are obsolete and may not be used   CDOT Form #1147 1/95

INSPECTED BUT NOT RATED
SEH, INC.
DATE: 4/30/13 BY: JASON TRIPLETT

Bridge LR3-0.2-50: Plans and Girder Drawings
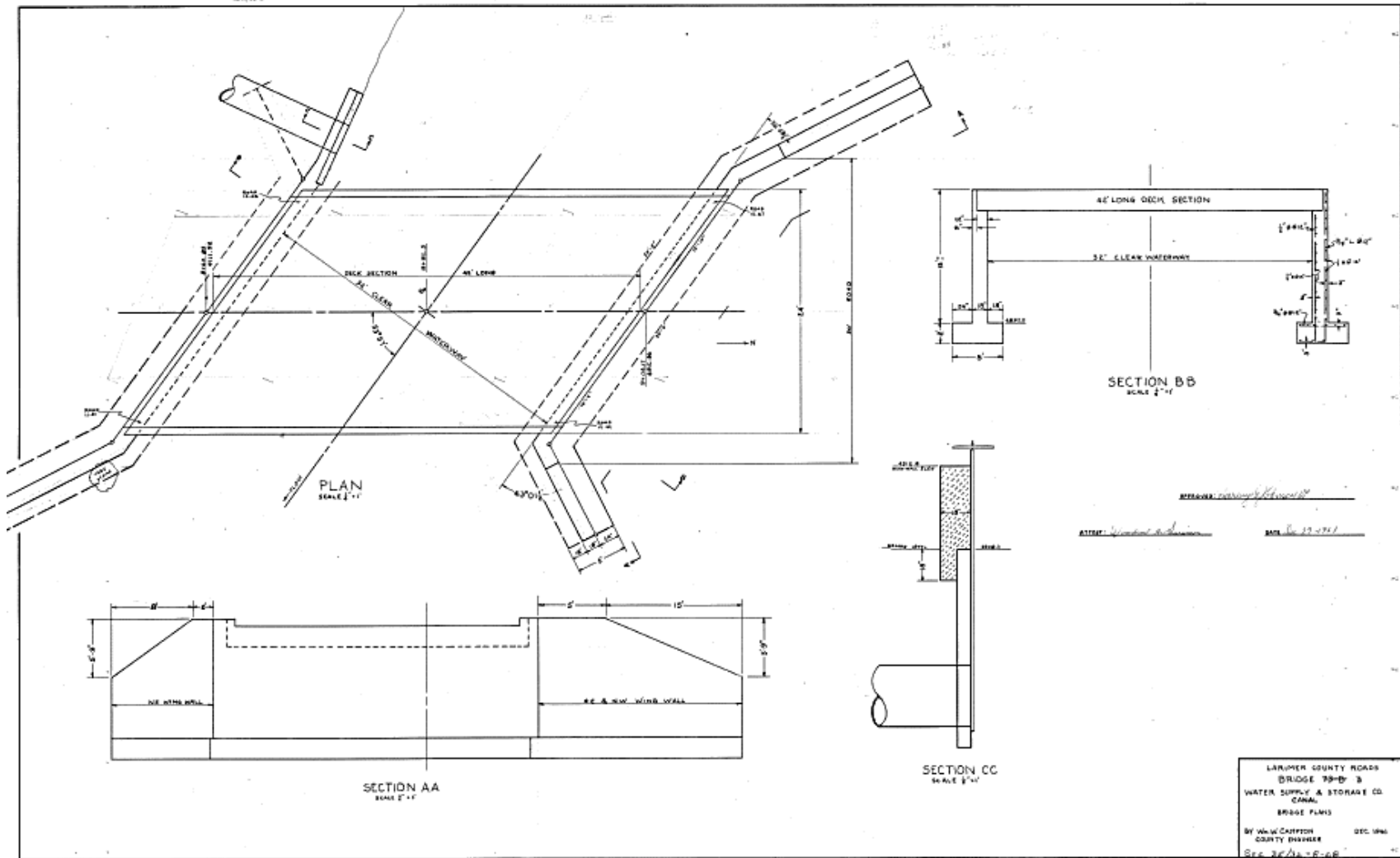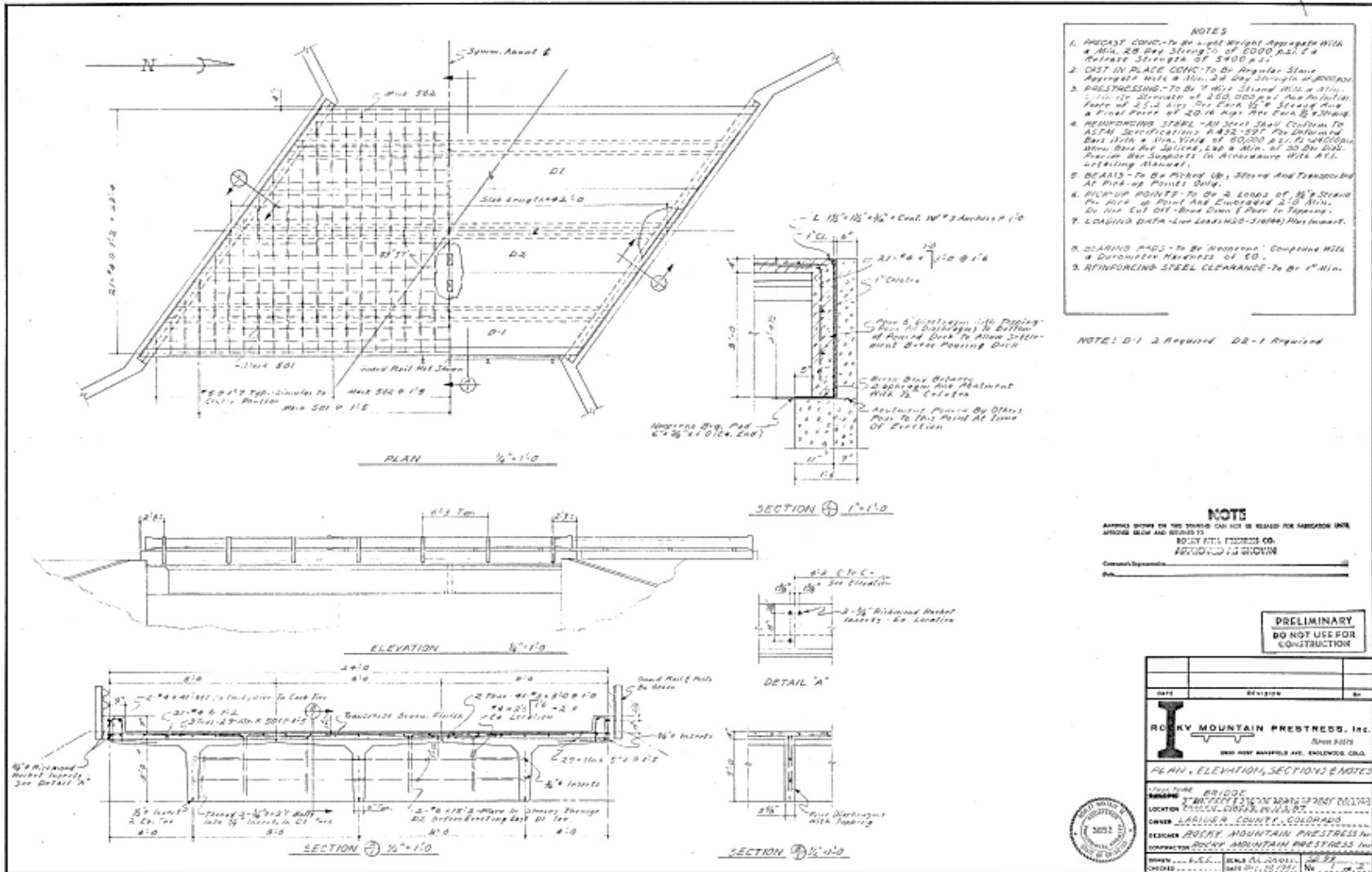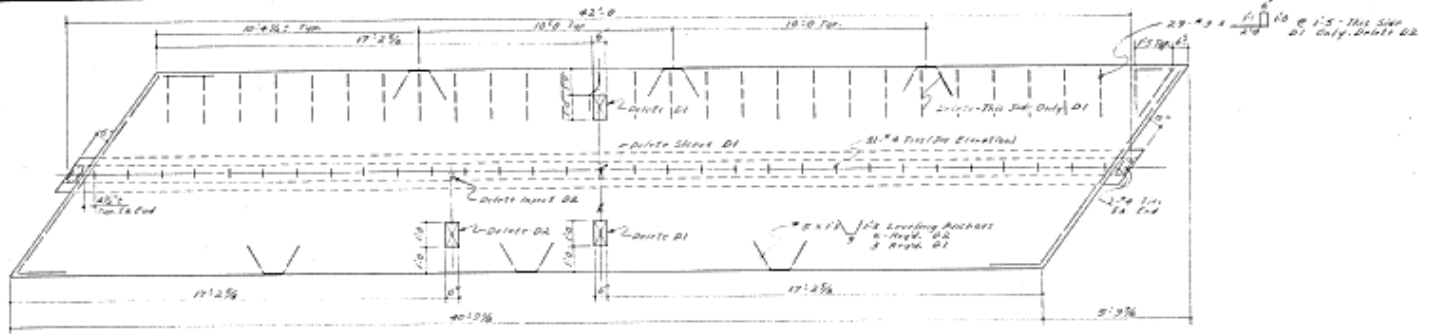
PLAN

ELEVATION

SECTION

DETAIL "A"

ROCKY MOUNTAIN PRESTRESS, Inc.

PLAN, ELEVATION, SECTIONS & NOTES

134

TYPICAL PLAN - D1 & D2
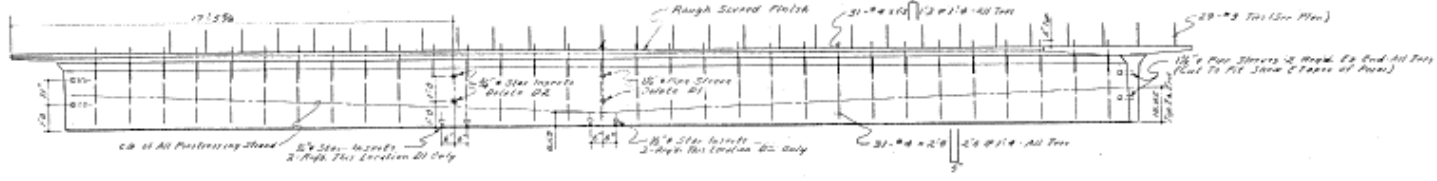
TYPICAL ELEVATION - D1 & D2

NOTE: D1 - 2 Required - D2 - 1 Required
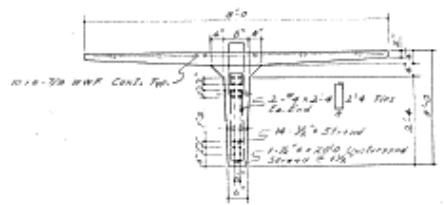
TYPICAL END SECTION
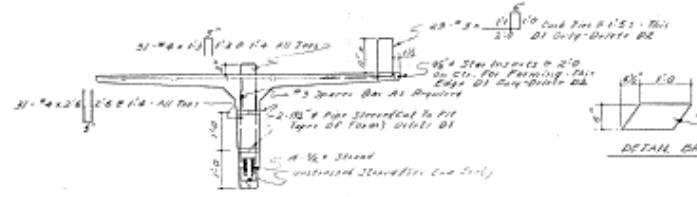
SECTION AT MIDSPAN
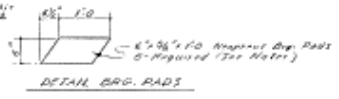
DETAIL BRG. PADS

PRELIMINARY
DO NOT USE FOR
CONSTRUCTION

ROCKY MOUNTAIN PRESTRESS, Inc.
ENGLEWOOD, COLO.

PLAN, ELEVATION & SECTION

STRUCTURE: BRIDGE
LOCATION: SKYLINE TRAFFIC CIRCLE
OWNER: LARIMER COUNTY, COLORADO
CONTRACTOR: ROCKY MOUNTAIN PRESTRESS, INC.

APPENDIX B. SAMPLE CALCULATIONS

AASHTO Live Load Calculation **[28]**

   The AASHTO design loads are calculated according to the geometry of the case study bridge LR3-0.2-50 which is an 8' x 36" PC Single-tee girder bridge. The rear axle spacing of the AASHTO design truck varied from 14' to 30' to determine the controlling truck. SAP2000 was used to iterate moving truck loads to determine the controlling moment envelope as illustrated in Figures 11.1 and 11.2. In summary, the controlling truck was found to be: HS – 20 (8 kip - 14' - 32 kip - 14' - 32 kip) as shown in Figure 11.3. The dynamic load allowance was determined from the AASHTO BDS.
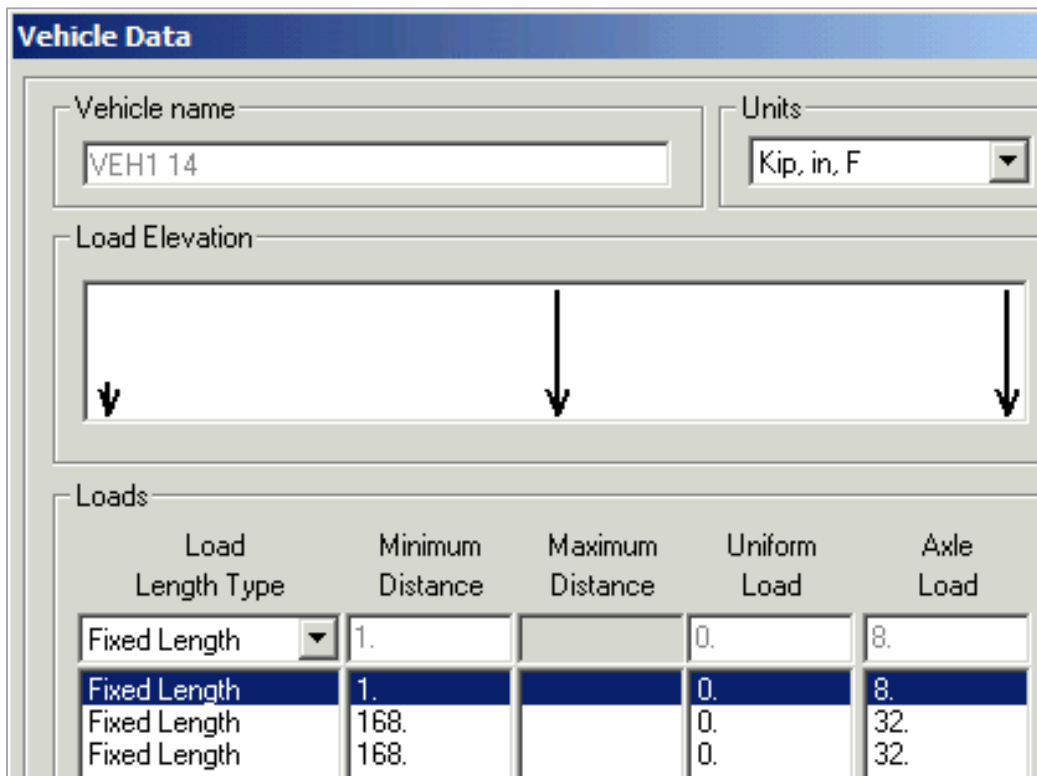
Figure 11.1 Modeling of moving load in SAP2000
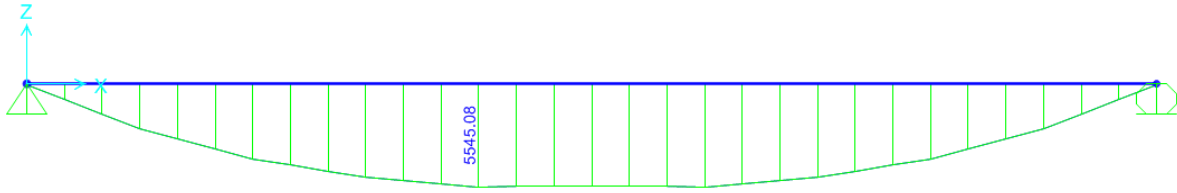
Figure 11.2 Live load moment envelope with maximum value using SAP2000
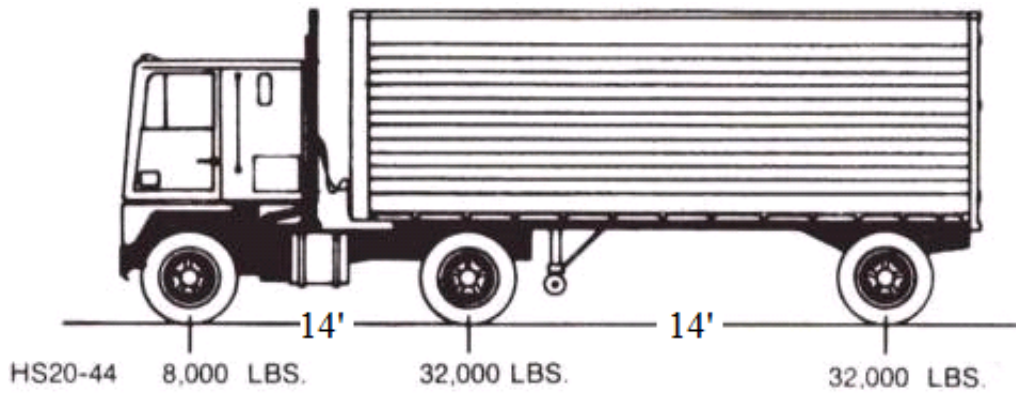
Figure 11.3 AASHTO controlling truck for live load calculation

Max Moment from Live Load envelope = 5752.45 kip*in

Dynamic Load Allowance = 1.33

AASHTO Live Load Distribution Factors

Distribution Factor for Moment [28] page 4-37

Concrete T-Beams, Cross-Section from Table 4.6.2.2.1-1 = a, e, k, and also i, j

Equations for Interior Beams (Assuming Interior controls since Nb = 3)

$$E_{c,deck} = 57\sqrt{3,000} = E_{c,deck} = 3122 \; ksi$$

$$E_{c,beam} = \left[40,000\sqrt{f_c'} + 10^6\right]\left(\frac{w_c}{145}\right)^{1.5}$$

$$E_{c,beam} = \left[40\sqrt{6000} + 1000\right]\left(\frac{150.283}{145}\right)^{1.5} = E_{c,beam} = 4324 \; ksi$$

$$\eta = \frac{E_B}{E_D}$$

$$\eta = \frac{E_B}{E_D} = \frac{4324}{3122} = \eta = 1.385$$

$$e_g = \frac{t_s}{2} + c_{t,beam} = \frac{5 \; in}{2} + 10.226 \; in = e_g = 12.726$$

$$K_g = \eta\left(I + Ae_g^2\right)$$

$$K_g = \eta\left(I + Ae_g^2\right) = 1.385 * \left(51763in^4 + 532in^2[12.726in]^2\right)$$

$$K_g = 191020.547in^4$$

Range of Applicability (for two equations, both scenarios

- $3.5 \leq S \leq 16.0$

- $4.5 \leq t_s \leq 12.0$

- $20 \leq L \leq 240$

- $N_b \geq 4$

- $10,000 \leq K_g \leq 7,000,000$

Since $N_b = 3$, use the lesser of the values obtained from the equation above with $N_b = 3$

One Design Lane Loaded (exterior beam):

$$DF = 0.06 + \left(\frac{S}{14}\right)^{0.4} \left(\frac{S}{L}\right)^{0.3} \left(\frac{K_g}{12.0Lt_s^3}\right)^{0.1} \qquad (\text{B1})$$

$$DF = 0.06 + \left(\frac{8}{14}\right)^{0.4} \left(\frac{8}{41}\right)^{0.3} \left(\frac{191020.547}{12.0(41)(5\ )^3}\right)^{0.1}$$

$$DF = 0.608$$

Two or More Design Lanes Loaded (aka interior beam):

$$DF = 0.075 + \left(\frac{S}{9.5}\right)^{0.6} \left(\frac{S}{L}\right)^{0.2} \left(\frac{K_g}{12.0Lt_s^3}\right)^{0.1} \qquad (\text{B2})$$

$$DF = 0.075 + \left(\frac{8}{9.5}\right)^{0.6} \left(\frac{8}{41}\right)^{0.2} \left(\frac{191020.547}{12.0(41)(5)^3}\right)^{0.1}$$

$$DF = 0.804 \rightarrow \text{Controls}$$

Shear Correction Factor

Reduction of Load Distribution Factors for Moment in Longitudinal Beams on Skewed Supports [28] p. 4-41

Range of Applicability

- $30° \leq \theta \leq 60°$

- $3.5 \leq S \leq 16.0$

- $20 \leq L \leq 240$

- $N_b \geq 4$

Since $N_b = 3$ for Bridge LR3-0.2-50, the AASHTO LRFD Bridge Design Specifications (2012) states:

"One or more of the parameters may be outside the listed range of applicability. In this case, the equation could still remain valid, particularly when the value(s) is (are) only slightly out of the range of applicability. However, if one or more of the parameters greatly exceed the range of applicability, engineering judgment needs to be exercised" [28].

Thus, the AASHTO shear correction factor relation is used as follows:

$$c_1 = 0.25 \left(\frac{K_g}{12.0Lt_s^3}\right)^{0.25} \left(\frac{S}{L}\right)^{0.5} \tag{B3}$$

$$c_1 = 0.25 \left(\frac{191020.547}{12.0(41)(5)^3}\right)^{0.25} \left(\frac{8}{41}\right)^{0.5} = c_1 = 0.147$$

$$SF = 1 - c_1(tan\theta)^{1.5} \tag{B4}$$

$$SF = 1 - 0.147(tan37)^{1.5} = Skew\ Reduction = 0.927$$

$$M\_LL = DynmicFactor * DF * SF * LL \tag{B5}$$

$$M_{LL} = 1.33 * 0.804 * 0.927 * 5545.084\ kip * in$$

$$M_{LL} = 5496.618\ kip * in$$

Distribution Factor for Shear

Equations for Interior Beams (assuming interior controls since Nb = 3)

DF for Concrete T-Beams

One Lane Loaded

$$DF = 0.36 + \frac{S}{25.0} \tag{B6}$$

$$DF = 0.36 + \frac{8}{25.0} = 0.68$$

Two or More Design Lanes Loaded

$$DF = 0.2 + \frac{S}{12} - \left(\frac{S}{35}\right)^{2.0} \tag{B7}$$

$$DF = 0.2 + \frac{8}{12} - \left(\frac{8}{35}\right)^{2.0} = 0.814 \rightarrow Controls$$

Range of Applicability

- $3.5 \leq S \leq 16.0$

- $4.5 \leq t_s \leq 12.0$

- $20 \leq L \leq 240$

- $N_b \geq 4$

- $10{,}000 \leq K_g \leq 7{,}000{,}000$

Skew Correction Factor for Shear

$$SC = 1.0 + 0.2 \left(\frac{12Lt_s^3}{K_g}\right)^{0.3} tan\theta \qquad (\text{B8})$$

$$SC = 1.0 + 0.2 \left(\frac{12(41)(5)^3}{191020.547}\right)^{0.3} tan37 = 1.107$$

Shear Distribution Factor

$$DF = (DF)_{controlling}(SF) \qquad (\text{B9})$$

$$DF = (0.814)(1.107) = 0.901$$

$$DF = 0.901$$

$$Shear\ LL = (0.901)(55.595\ kips) = 50.911\ kips$$

$$M_{LL} = DynamFactor * DF * SF * LL \qquad (\text{B10})$$

$$M_{LL} = 1.33 * 0.901 * 1.107 * 5545.084$$

$$M_{LL} = 7355.838\ kip * in$$

$$\omega_{LL} = \frac{8 * M_{LL}}{L^2} = \frac{8 * 7355.838\ kip * in}{(504in)^2} = 0.243\ kip/in$$

Undamaged Moment Capacity

Distance from Extreme Compression Fiber to the Neutral Axis **[2]**

Neglect all non prestressed steel [2].

$$T = C_1 + C_2 \tag{B11}$$

$$A_{ps}f_{pu} = 0.85f_c'b\beta_1 c + kA_{ps}\frac{f_{pu}}{d_p}c \tag{B12}$$

Solving for c:

$$c = \frac{A_{ps}f_{pu}}{0.85f_c'b\beta_1 + kA_{ps}\frac{f_{pu}}{d_p}} \tag{B13}$$

$$c = \frac{(2.016\ in^2)(250\ ksi)}{0.85(3\ ksi)(96\ in)(0.85) + (0.38)(2.016\ in^2)\frac{(250\ ksi)}{(34.35\ in)}}$$

$$c = 2.359\ in < t_s + t_f \Rightarrow ok$$

$$a = \beta_1 c \tag{B14}$$

$$a = 0.85(2.359\ in)$$

$$a = 2.005\ in$$

Force of Prestress

The following calculations are performed to check the approximate AASHTO MBE force of prestress approximate relation for accuracy. This was done so by comparing it to the American Concrete Institute Committee 318 2011 (ACI 318-11) force of prestress relation.

AASHTO approximate force of prestress relation [28]:

$$f_{ps} = f_{pu}\left(1 - k\frac{c}{d_p}\right) \tag{B15}$$

$$f_{ps} = 250\ ksi\left(1 - 0.38\left(\frac{2.360\ in}{34.35\ in}\right)\right)$$

$$f_{ps} = 243.47 \ ksi$$

ACI Force of Prestress [53]:

$$\frac{f_{py}}{f_{pu}} = \frac{212.5 \ ksi}{250 \ ksi} = 0.85 \ \rightarrow ACI \ 318 - 11 \Rightarrow \gamma_p = 0.4$$

$$\rho_p = \frac{A_{ps}}{bd_p} \qquad\qquad\qquad (\text{B}16)$$

$$\rho_p = \frac{2.016 \ in^2}{(96 \ in)(34.35 \ in)}$$

$$\rho_p = 0.000611$$

$$f_{ps} = f_{pu}\left[1 - \frac{\gamma_p}{\beta_1}\left(\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}(\omega - \omega')\right)\right] \qquad (\text{B}17)$$

$$f_{ps} = 250 \ ksi \left[1 - \frac{0.4}{0.85}\left(0.000611\left(\frac{250 \ ksi}{3 \ ksi}\right) + 0\right)\right]$$

$$f_{ps} = 244.01 \ ksi$$

AASHTO MBE Force of Prestress

The AASHTO MBE approximate value for the prestress force is within 0.2 percent of the ACI 318-11 value. Therefore the AASHTO MBE approximate relation is used in the moment capacity calculations herein.

Undamaged Moment Capacity

$$M_n = A_{ps}f_{ps}\left(d_p - \frac{a}{2}\right) \qquad\qquad (\text{B}18)$$

$$M_n = (2.016 \ in^2)(243.47 \ ksi)\left(34.35 \ in - \frac{2.005 \ in}{2}\right)$$

$$M_n = 16368 \ kip * in$$

States of Stress at Transfer and Service Conditions

The states of stress calculations are not used in the DET. The states of stress are calculated at both transfer and service conditions to develop insight on the internal forces involved due to prestressing and the tendon layout. At the time of transfer when the prestressing steel is released from the anchorage devices (during the manufacturing of the girders) most of the girder's cross-sections are in compression with a small amount in tension at the top of the cross-sections. This is to be expected because the prestressing steel induces compression into the members. The inverted triangular-shaped prestressing tendon layout causes resultant forces in the vertical direction causing tensile stress on the top of the sections. During service conditions (the normal operation of the bridge) the bottom of the sections experiences tensile stresses while the top of the sections are in a state of compressive stress. This is logical because the service and gravity loads should counteract the resultants from the prestressing force causing compression on the top and tension on the bottom of the sections similar to a non-prestressed simply supported member in flexure.

Transfer Conditions

$$P = f_{pi}A_{ps} = (175\ ksi - 0.38 * 35ksi)(2.016\ in^2)$$

$$P = 325.987\ kips$$

Stress at Top of Section

$$f_{top} = -\frac{P}{A} + \frac{Pe}{S_t} - \frac{M_g}{S_t}$$

$$f_{top} = \frac{-325.987\ kips}{530.5\ in^2} + \frac{325.987\ kips*(26.778" - 6.65")}{6819.96\ in^3} - \frac{1892.386\ kip*in}{6819.96\ in^3}$$

$$f_{top} = -0.614\ ksi + 0.962\ ksi - 0.277\ ksi$$

$$f_{top} = 0.071 \ ksi \ (tension) < 3\sqrt{f_{ci}'} = 0.220 \ ksi \rightarrow ok$$

Stress at Bottom of Section

$$f_{bottom} = -\frac{P}{A} - \frac{Pe}{S_b} + \frac{M_g}{S_b}$$

$$f_{bottom} = \frac{-325.987 \ kips}{530.5 \ in^2} - \frac{325.987 \ kips*(26.778"-6.65")}{2348.647 \ in^3} + \frac{1892.386 \ kip*in}{2348.647 \ in^3}$$

$$f_{bottom} = -0.614 \ ksi - 4.508 \ ksi + 0.806 \ ksi$$

$$f_{bottom} = -4.316 \ ksi \ (compression) < 0.6f_{ci}' = 3.24 \ ksi \rightarrow ok$$
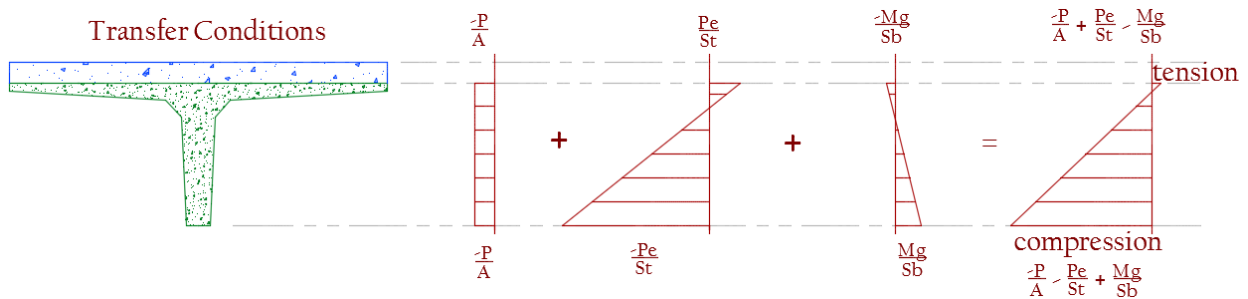
Figure 11.4 States of stress during transfer conditions

Service Conditions

$$P_e = f_{pe}A_{ps} = (175 \ ksi - 35ksi)(2.016 \ in^2)$$

$$P_e = 282.24 \ kips$$

Basic Girder

$$f_{top} = -\frac{P_e}{A} + \frac{P_e e}{S_t} - \frac{M_{g+s}}{S_t}$$

$$f_{top} = \frac{-282.24 \ kips}{530.5 \ in^2} + \frac{282.24 \ kips*(26.778"-6.65")}{6819.96 \ in^3} - \frac{3155.515 \ kip*in}{6819.96 \ in^3}$$

$$f_{top} = -0.162 \ ksi \ (compression)$$

$$f_{bottom} = -\frac{P_e}{A} - \frac{P_e e}{S_b} + \frac{M_{g+s}}{S_b}$$

$$f_{bottom} = \frac{-282.24 \ kips}{530.5 \ in^2} + \frac{282.24 \ kips*(26.778"-6.65")}{2348.647 \ in^3} - \frac{3155.515 \ kip*in}{2348.647 \ in^3}$$

$$f_{bottom} = -1.608 \, ksi \, (compression)$$

Composite Action

$$\frac{M_l}{S_{t,composite}} = -\frac{5496.618 \, kip*in}{9807 \, in^3} = -0.560 \, ksi$$

$$\frac{M_l}{S_{b,composite}} = -\frac{5496.618 \, kip*in}{2973 \, in^3} = 1.849 \, ksi$$

Total Stress at Top of Beam

$$f_{top} = -0.162 \, ksi - 0.560 \, ksi$$

$$f_{top} = -0.722 \, ksi \, (compression) < 0.5f_c' = 3 \, ksi \to ok$$

Total Stress at Bottom of Beam

$$f_{bottom} = -1.608 \, ksi + 1.849 \, ksi$$

$$f_{bottom} = 0.241 \, ksi \, (tension) < 7.5\sqrt{f_c'} = 0.581 \, ksi \to ok$$
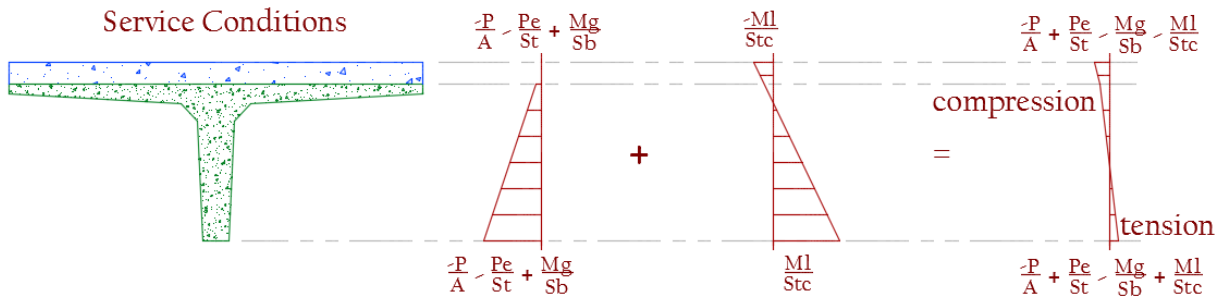
Figure 11.5 States of stress during service conditions

Magnel Diagram

The Magnel diagram is not used in the DET. A Magnel diagram was created out of curiosity of the author to check the bridge geometry designed in 1961 with current stress limit states. A Magnel diagram is used to graphically check bridge geometry at critical levels of stress to determine adequacy under allowable stress limit states. A Magnel diagram defines an acceptable range of initial prestressing force given the eccentricity between the centroid of the prestressing strand and the section's centroid. Similar to the states of stress described previously, allowable limits states at certain timeframes are calculated: tension at the top of the section at the time of prestressing force transfer, compression at the bottom of the section at transfer, compression at the top of the section during service loading conditions, and tension at the bottom of the section during service. These relations are presented as equations B11 through B14 respectively.

$$\frac{1}{P_i} \geq \frac{\left({e}/{k_b}-1\right)}{\left({M_G}/{S_t}+3\sqrt{f'_{ci}}\right)A_g} \qquad tension\ at\ top, transfer \qquad (\text{ B19 })$$

$$\frac{1}{P_i} \geq \frac{\left({e}/{k_t}+1\right)}{\left({M_G}/{S_b}+0.6f'_{ci}\right)A_g} \qquad compression\ at\ bottom, transfer \qquad (\text{ B20 })$$

$$\frac{1}{P_i} \leq \frac{\left({e}/{k_b}-1\right)\eta}{\left({M_T}/{S_t}+0.45f'_c\right)A_g} \qquad compression\ at\ top, service \qquad (\text{ B21 })$$

$$\frac{1}{P_i} \leq \frac{\left({e}/{k_t}+1\right)\eta}{\left({M_T}/{S_b}+6\sqrt{f'_c}\right)A_g} \qquad tension\ at\ bottom, service \qquad (\text{ B22 })$$

Applying the section properties and the AASHTO BDS loads to the 4 equations and plotting, produces the Magnel diagram depicted in Figure 11.6.
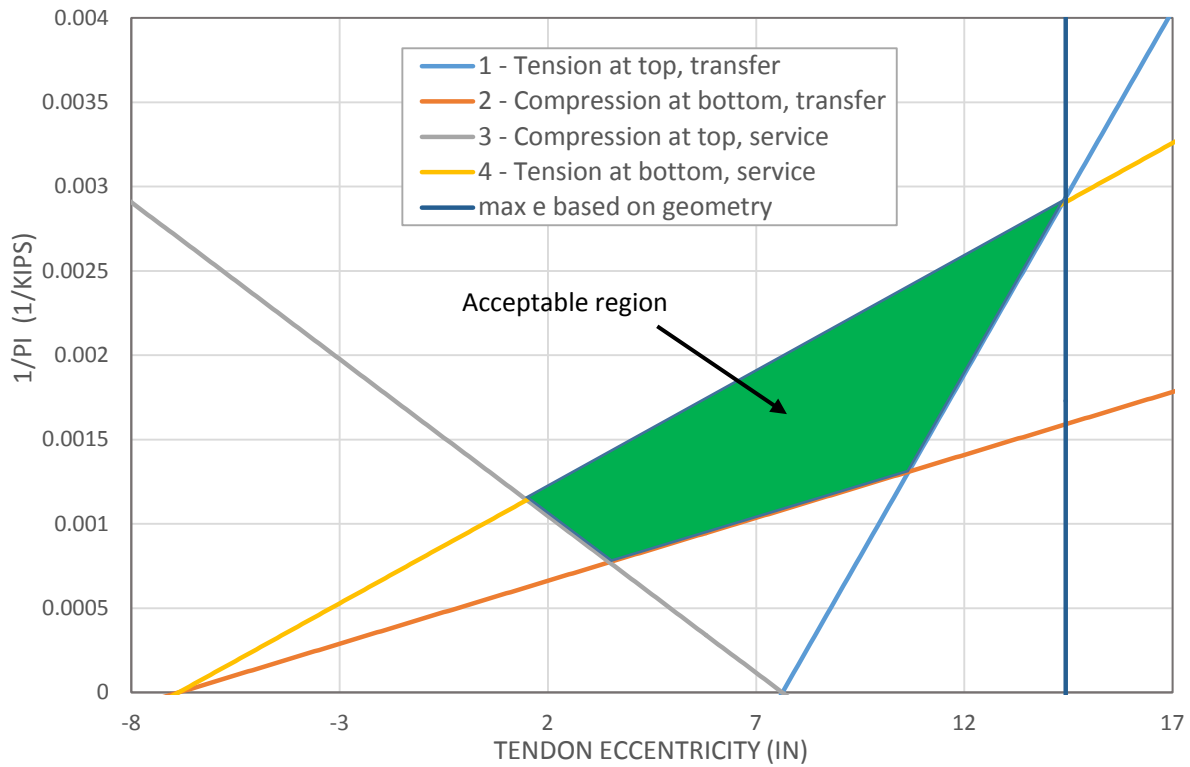
Figure 11.6 Magnel diagram for undamaged PC single-tee

The green shaded region indicates acceptable levels of initial prestressing force and tendon eccentricity. In summary, the tendon eccentricity and the initial prestressing force for Bridge LR3-0.2-50 PC girders' falls within this acceptable region.

Userform: Programming of the DET Interface

```
Private Sub ClearButton_Click()
      'deletes sheet2 and selected data from Sheet1
      Application.ScreenUpdating = False
      Call CheckAddSheet2Keep
      Call CheckAddSheet3Keep
      Call CheckAddSheet4Keep
      Call CheckAddSheet5Keep
      Call CheckAddSheet6Keep
      Call CheckAddSheet7Keep
      Call CheckAddSheet8Keep

      Application.DisplayAlerts = False
      ' deletes sheet2
          Sheets("UndamagedGeom").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes sheet3
          Sheets("CrackedGeom").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes sheet4
          Sheets("SpallGeom").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes sheet5
          Sheets("DelamGeom").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes sheet6
          Sheets("AASHTO Loads").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes sheet7
          Sheets("DataTable").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes sheet8
          Sheets("RepairQuantities").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes chart1 (MomentCapacity)
          Sheets("MomentCapacity").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes chart2 (ShearCapacity)
          Sheets("ShearCapacity").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes chart3 (MomentRatingFactor)
          Sheets("LRFRMomentRatingFactor").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes chart4 (ShearRatingFactor)
          Sheets("LRFRShearRatingFactor").Select
          ActiveWindow.SelectedSheets.Delete
      'deletes chart5 (LFRRatingFactor)
          Sheets("LFRMomentRatingFactor").Select
          ActiveWindow.SelectedSheets.Delete
```

```
        Sheets("BIMInspection").Select
        Range("A1:AZ1").Select

    Application.DisplayAlerts = True
    Application.ScreenUpdating = True
End Sub

Private Sub ExitButton_Click()
    'exits userform
        End
End Sub

Private Sub RunButton_Click()
    'error message for improper input values NEED TO IMPLEMENT WHEN > 1
    INSTANCE OF DAMAGE CAN BE MODELED
    If GirComboBox.Value = "" Or CrackCheckBox.Value = False And
        SpallCheckBox.Value = False And DelamCheckBox.Value = False Then
            MsgBox ("Please Enter: Member Number and Damage Type")
            End
        End If
    'calls macro to copy girder data to sheet2
    Call CopyGirdertoSheet2
    Application.ScreenUpdating = False
    'calls appropriate cracking macro- code is in module2
    'ALL Possibilities(7): c, s, d, c&s, c&s&d, s&d, c&d

    If CrackCheckBox.Value = True Then
        Call Cracked
    End If

    If SpallCheckBox.Value = True Then
        Call Spalled
    End If

    If DelamCheckBox.Value = True Then
        Call Delaminated
    End If

    If CrackCheckBox.Value = True And SpallCheckBox.Value = True And
        DelamCheckBox.Value = False Then
        Call CrackedandSpalled
    End If

    If CrackCheckBox.Value = True And SpallCheckBox.Value = True And
        DelamCheckBox.Value = True Then
        Call CrackedandSpalledandDelaminated
    End If

    If CrackCheckBox.Value = False And SpallCheckBox.Value = True And
        DelamCheckBox.Value = True Then
        Call SpalledandDelaminated
    End If

    If CrackCheckBox.Value = True And SpallCheckBox.Value = False And
        DelamCheckBox.Value = True Then
        Call CrackedandDelaminated
    End If
```

```vba
        Worksheets("UndamagedGeom").Activate
        Worksheets("UndamagedGeom").Select

        'Reorders Sheets and Ends on RF Chart
            ActiveWindow.ScrollWorkbookTabs Sheets:=1
            ActiveWindow.ScrollWorkbookTabs Sheets:=1
            ActiveWindow.ScrollWorkbookTabs Sheets:=1
            ActiveWindow.ScrollWorkbookTabs Sheets:=1
            Sheets("MomentCapacity").Select
            Sheets("MomentCapacity").Move Before:=Sheets(7)
            Sheets("ShearCapacity").Select
            Sheets("ShearCapacity").Move Before:=Sheets(8)
            ActiveWindow.ScrollWorkbookTabs Sheets:=1
            ActiveWindow.ScrollWorkbookTabs Sheets:=1
            Sheets("RepairQuantities").Select
            Sheets("RepairQuantities").Move Before:=Sheets(7)
            Sheets("MomentCapacity").Select
            ActiveChart.Legend.Select
            ActiveChart.FullSeriesCollection(8).Delete
            ActiveChart.FullSeriesCollection(7).Delete
            ActiveChart.FullSeriesCollection(6).Delete
            ActiveChart.FullSeriesCollection(5).Delete
            ActiveChart.FullSeriesCollection(4).Delete
            ActiveChart.FullSeriesCollection(3).Delete
            ActiveChart.ChartArea.Select
            ActiveChart.ChartColor = 10

            'closes the userform
            Unload Me
            Application.ScreenUpdating = True
End Sub

Private Sub ShowAssumptions_Click()
        'Opens Assumptions .txt file (From Desktop)

        Dim AssumptionsFile
            AssumptionsFile = Shell("C:\WINDOWS\notepad.exe
    C:\Users\Brendan\Desktop\Assumptions.txt", 1)
End Sub

Private Sub UserForm_Initialize()
        'initilizes combo boxes with default values
            With GirComboBox
                .AddItem "Girder A"
                .AddItem "Girder B"
                .AddItem "Girder C"
            End With
End Sub


Private Sub GirComboBox_Change()
        'copies selected girder properties and damage cube information to
        sheet2 (creates/deletes sheet2 as needed)
        Application.ScreenUpdating = False
        'creates sheet2 if necessary
        Call CheckAddSheet2Keep
```

```
'assumes cube data: from A4 to Y11 & property data from A17:N24
    If GirComboBox.Value = "Girder A" Then
        'copies cube info
        Sheets("BIMInspection").Range("A4:AL4").Copy
         Sheets("UndamagedGeom").Range("B1").PasteSpecial
         Transpose:=True
         Sheets("BIMInspection").Range("O8:AL8").Copy
         Sheets("UndamagedGeom").Range("B15").PasteSpecial
         Transpose:=True
         Application.CutCopyMode = False
    End If
    If GirComboBox.Value = "Girder B" Then
        'copies cube info
        Sheets("BIMInspection").Range("A5:AL5").Copy
        Sheets("UndamagedGeom").Range("B1").PasteSpecial
         Transpose:=True
        Sheets("BIMInspection").Range("O9:AL9").Copy
        Sheets("UndamagedGeom").Range("B15").PasteSpecial
         Transpose:=True
        Application.CutCopyMode = False
    End If
    If GirComboBox.Value = "Girder C" Then
        'copies cube info
        Sheets("BIMInspection").Range("A6:AL6").Copy
        Sheets("UndamagedGeom").Range("B1").PasteSpecial
         Transpose:=True
        Sheets("BIMInspection").Range("O10:AL10").Copy
        Sheets("UndamagedGeom").Range("B15").PasteSpecial
         Transpose:=True
        Application.CutCopyMode = False
    End If

   Application.ScreenUpdating = True
End Sub
```

Module 1: Create the Proper Excel Sheets


```
Sub AnalysisTool()
        'renames sheet1
        Sheets(1).Name = "BIMInspection"
      'shows userform
        AnalysisToolUserForm.Show
        Application.ScreenUpdating = False
End Sub

Sub CheckAddSheet2Keep()
      'checks for, adds, and renames sheet2 if necessary
        For Each WS In Worksheets
            If WS.Name = "UndamagedGeom" Then Exit Sub
        Next
        Set NewSheet = Worksheets.Add(After:=Sheet1)
        NewSheet.Name = "UndamagedGeom"
        Sheets(1).Select
End Sub

Sub CheckAddSheet3Keep()
      'checks for, adds, and renames sheet3 if necessary
        For Each WS In Worksheets
            If WS.Name = "CrackedGeom" Then Exit Sub
        Next
        Set NewSheet = Worksheets.Add(After:=Sheet2)
        NewSheet.Name = "CrackedGeom"
        Sheets(1).Select
End Sub

Sub CheckAddSheet4Keep()
      'checks for, adds, and renames sheet4 if necessary
        For Each WS In Worksheets
            If WS.Name = "SpallGeom" Then Exit Sub
        Next
        Set NewSheet = Worksheets.Add(After:=Sheet3)
        NewSheet.Name = "SpallGeom"
        Sheets(1).Select
End Sub

Sub CheckAddSheet5Keep()
      'checks for, adds, and renames sheet5 if necessary
        For Each WS In Worksheets
            If WS.Name = "DelamGeom" Then Exit Sub
        Next
        Set NewSheet = Worksheets.Add(After:=Worksheets(Worksheets.Count))
        NewSheet.Name = "DelamGeom"
        Sheets(1).Select
End Sub

Sub CheckAddSheet6Keep()
      'checks for, adds, and renames sheet6 if necessary
        For Each WS In Worksheets
            If WS.Name = "AASHTO Loads" Then Exit Sub
        Next
```

```vba
        Set NewSheet = Worksheets.Add(After:=Worksheets(Worksheets.Count))
        NewSheet.Name = "AASHTO Loads"
        Sheets(1).Select
End Sub

Sub CheckAddSheet7Keep()
    'checks for, adds, and renames sheet7 if necessary
        For Each WS In Worksheets
            If WS.Name = "DataTable" Then Exit Sub
        Next
        Set NewSheet = Worksheets.Add(After:=Worksheets(Worksheets.Count))
        NewSheet.Name = "DataTable"
        Sheets(1).Select
End Sub

Sub CheckAddSheet8Keep()
    'checks for, adds, and renames sheet7 if necessary
        For Each WS In Worksheets
            If WS.Name = "RepairQuantities" Then Exit Sub
        Next
        Set NewSheet = Worksheets.Add(After:=Worksheets(Worksheets.Count))
        NewSheet.Name = "RepairQuantities"
        Sheets(1).Select
End Sub

Sub CopyGirdertoSheet2()
    Call CheckAddSheet2Keep
        Application.ScreenUpdating = False
    'copies headings to sheet 2, transposes, & formats columns
        Sheets("BIMInspection").Range("A2:AL2").Copy
        Sheets("UndamagedGeom").Range("A1").PasteSpecial Transpose:=True
        Application.CutCopyMode = False
        Sheets("UndamagedGeom").Columns("A:A").HorizontalAlignment = xlLeft

    'semi-formats transposed values in sheet2
        Sheets("UndamagedGeom").Select
        Range("A1").Select
        Range(Selection, Selection.End(xlToRight)).Select
        Range(Selection, Selection.End(xlDown)).Select
    With Selection
        .HorizontalAlignment = xlLeft
        .VerticalAlignment = xlBottom
    End With
        ActiveWindow.SmallScroll Down:=-18
        Columns("A:A").EntireColumn.AutoFit
        Columns("B:B").EntireColumn.AutoFit
        Range("A1").Select
        Application.ScreenUpdating = True
End Sub
```

Module 2: Undamaged Cross-Section Generator

```
Sub UndamagedGeometry()

'declare variables
Dim L As Single: Dim b As Single: Dim h As Single: Dim tf As Single: Dim tw
As Single: Dim UW As Single: Dim fc As Single: Dim fpu As Single: Dim fpy As
Single: Dim fy As Single: Dim area As Single: Dim c_b As Single: Dim c_t As
Single: Dim Inertia As Single: Dim r As Single: Dim Sb As Single: Dim St As
Single: Dim kt As Single: Dim kb As Single: Dim coverp As Single: Dim cover
As Single: Dim t_d As Single: Dim A_ps As Single: Dim A_s As Single: Dim Pi
As Single: Dim fpi As Single: Dim fpe As Single: Dim fci As Single: Dim n As
Single: Dim dps_max As Single: Dim d_max As Single: Dim beta1 As Single: Dim
rho As Single: Dim rhop As Single: Dim w As Single: Dim wprime As Single:
Dim fpyoverfpu As Single: Dim gammap As Single: Dim fps As Single: Dim Ec As
Single: Dim a As Single: Dim harp As Single: Dim phiMn As Single

'Replaces Revits Labels with Proper Units
Sheets("UndamagedGeom").Range("A1").Value = "Undamaged Geometry"

        'Defines all variables to use throughout tool
            Sheets("UndamagedGeom").Select
            L = Range("B4").Value
            b = Range("B5").Value
            h = Range("B6").Value
            tf = Range("B7").Value
            tw = Range("B8").Value
            UW = Range("B13").Value
            'converts Revit's psf to ksi
            fc = Range("B9").Value / 1000 / 144
            Range("B9").Value = fc
            Range("A9").Value = "f'c (ksi)"
            'converts Revit's psf to ksi
            fpu = Range("B10").Value / 1000 / 144
            Range("B10").Value = fpu
            Range("A10").Value = "fpu (ksi)"
            'converts Revit's psf to ksi
            fpy = Range("B11").Value / 1000 / 144
            Range("B11").Value = fpy
            Range("A11").Value = "fpy (ksi)"
            'converts Revit's psf to ksi
            fy = Range("B12").Value / 1000 / 144
            Range("B12").Value = fy
            Range("A12").Value = "fy (ksi)"

        'Flange
            For j = 1 To 192
            For i = 1 To 14
                Cells(i + 2, j + 4).Value = 0.5
            Next
            Next
        'Flange Taper
            For j = 1 To 152
                Cells(17, j + 24).Value = 0.5
            Next
```

```
    For j = 1 To 112
        Cells(18, j + 44).Value = 0.5
    Next
    For j = 1 To 72
        Cells(19, j + 64).Value = 0.5
    Next
    For j = 1 To 50
        Cells(20, j + 75).Value = 0.5
    Next
'Web
   For i = 1 To 64
   For j = 1 To 12
        Cells(20 + i, 94 + j).Value = 0.5
   Next j
   Next i
'Web Taper
   For i = 1 To 43
        Cells(20 + i, 94).Value = 0.5
        Cells(20 + i, 107).Value = 0.5
   Next
   For i = 1 To 21
        Cells(20 + i, 93).Value = 0.5
        Cells(20 + i, 108).Value = 0.5
   Next
'Triangles
   For i = 1 To 8
        Cells(21, 84 + i).Value = 0.5
        Cells(21, 108 + i).Value = 0.5
   Next
   For i = 1 To 7
        Cells(22, 85 + i).Value = 0.5
        Cells(22, 108 + i).Value = 0.5
   Next
   For i = 1 To 6
        Cells(23, 86 + i).Value = 0.5
        Cells(23, 108 + i).Value = 0.5
   Next
   For i = 1 To 5
        Cells(24, 87 + i).Value = 0.5
        Cells(24, 108 + i).Value = 0.5
   Next
   For i = 1 To 4
        Cells(25, 88 + i).Value = 0.5
        Cells(25, 108 + i).Value = 0.5
   Next
   For i = 1 To 3
        Cells(26, 89 + i).Value = 0.5
        Cells(26, 108 + i).Value = 0.5
   Next
   For i = 1 To 2
        Cells(27, 90 + i).Value = 0.5
        Cells(27, 108 + i).Value = 0.5
   Next
   For i = 1 To 1
        Cells(28, 91 + i).Value = 0.5
        Cells(28, 108 + i).Value = 0.5
   Next
```

```
'Loop to sum flange
For i = 1 To 14
For j = 1 To 192
'Sums tf increments and places the values above section
            Cells(1, 4 + j).Value = Application.Sum(Range(Cells(3, 4 +
            j), Cells(20, 4 + j)))
            'b increment sum and place to left of section
            Cells(2 + i, 3).Value = Application.Sum(Range(Cells(2 + i,
            5), Cells(2 + i, 5 + 192)))
Next j
Next i

'Loop to sum web
For i = 1 To 64
For j = 1 To 12
            'Sums tw increments and places the values to right of
            section
            Cells(20 + i, 118).Value = Application.Sum(Range(Cells(20 +
            i, 93), Cells(20 + i, 108)))
            'Depth of web increment, sum and place below section
            Cells(86, 94 + j).Value = Application.Sum(Range(Cells(21,
            94 + j), Cells(84, 94 + j)))
Next j
Next i

'Loop to figure out hc
For i = 1 To 192
If Cells(3, 4 + i).Value = "" Then
            Cells(87, 4 + i).Value = h - DepthCrack
        Else
            Cells(87, 4 + i).Value = h
      End If
Next

'AutoSize Columns
      Cells.Select
Cells.EntireColumn.AutoFit
      Range("A1").Select

'Undamaged Geometry Calculations
'Calculates Cracked Section Properties
      b = Application.Sum(Range("C3:C16")) / 14
      h = Application.Sum(Range("E87:GN87")) / (192)
      tf = Application.Sum(Range("E1:GN1")) / (192)
      tw = Application.Sum(Range("DN21:DN84")) / 64
      Af = Application.Sum(Range("E3:GN20")) / 2
      Aw = Application.Sum(Range("CO21:DD84")) / 2
      Atri = Application.Sum(Range("CG21:CN28,DE21:DL28")) / 2
      area = Af + Aw + Atri
      hw = Application.Sum(Range("CQ86:DB86")) / 12

'c_b, distance from extreme bottom fiber of section to neutral axis
      c_b = (hw / 2 * Aw + (hw + tf / 2) * Af + (hw - 2) * Atri) / area
'c_t, distance from extreme top fiber of section to neutral axis
      c_t = h - c_b
'Inertia, Moment of Inertia of section about centroidal axis
```

157

```
         Inertia = tw * hw ^ 3 / 12 + Aw * (c_b - hw / 2) ^ 2 + b * tf ^ 3
/ 12 + Af * ((hw + tf / 2) - c_b) ^ 2 + 4 * 4 ^ 3 / 12 + 4 * 4 * (c_t -
2) ^ 2
'r, Radius of Gyration
      r = (Inertia / area) ^ (1 / 2)
'Sb, Elastic Section (bottom) Modulus
      Sb = Inertia / c_b
'St, Elastic Section (top) Modulus
      St = Inertia / c_t
'kt, Top Kern
      kt = r ^ 2 / c_b
'kb, Bottom Kern
      kb = r ^ 2 / c_t
'Cover of Prestress
      coverp = 6.65
'Cover of Mild Steel
      cover = 2.5
'Deck Thickness
      'Value Obtained in Load Rating Report for CR 3 - 0.2 - 50 on
      3/17/1997
      t_d = 5
'Aps, Area of prestressing strand in flexural tension zone
      'Value Obtained in Load Rating Report for CR 3 - 0.2 - 50 on
      3/17/1997
      A_ps = 14 * 0.144
'As, Area of Mild longitudinal tension reinforcement
      'Assuming no mild longitudnal Steel
      A_s = 0
'ASSUMING 0.4 in^2 of shear reinforcement (1 #4 stirrup, d = 0.2 in ^2)
'Av, Area of Mild shear reinforcement
      A_v = 0.4
'ASSUMING stirrups are spaced 1' o.c.
's, longitudnal spacing of shear reinforcement
      S = 12
'Pi, Initial Prestressing Force
      'Value Obtained in Load Rating Report for CR 3 - 0.2 - 50 on
      3/17/1997
      Pi = 352.8
'fpi, Initial Prestressing Stress
      fpi = Pi / A_ps
'fpe, Compressive stress in concrete (after allowance for all prestress
losses) at centroid of cross section resisting externally applied loads
or at junction of web and flange when the centroid lies within the
flange
'ACI Code Commentary (1963, 1971, 1977) 1963 Committee 423 lump sum
losses ~35 ksi. => fpe = fpi - losses
      fpe = fpi - 35
'fci, Specified compressive strength of concrete at time of initial
prestress
      'Value Obtained in Load Rating Report for CR 3 - 0.2 - 50 on
      3/17/1997
      fci = 5.4
'n, Modular Ratio
      n = fpe / fpi
'dps_max, Maximum distance from extreme top compression fiber of
section to centroidal area of prestressing strand
      dps_max = h - coverp
```

```vbnet
'd_max, Maximum distance from extreme top compression fiber of section
to centroidal area of mild steel
      d_max = h - cover
'Beta 1, Factor relating depth of equivalent rectangular compressive
stress block (Whitney) to neutral axis depth
      'beta1 = (fc - 8) * ((0.85 - 0.65) / (4 - 8)) + 0.65
      beta1 = 0.85
'rho, Reinforcement ratio for mild steel
      rho = A_s / (b * d_max)
'rho_p, Reinforcement ratio for prestressing strand
      rhop = A_ps / (b * dps_max)
'w, tension reinforcement index
      w = rho * fy / fc
'Assuming no compression reinforcement
'w prime, compression reinforcement index
      wprime = rho * fy / fc
'fpy/fpu ratio to determine gamma_p
      fpyoverfpu = fpy / fpu
'gamma_p, Factor for type of prestressing steel
'ACI 318: gammap reflects influence of different types of prestressing
reinforcement on the falue of fps
'(high strength, stress relieved, low relax, etc.)
      ' if fpy/fpu is not less than 0.8, gammap = 0.55
      ' if fpy/fpu is not less than 0.85, gammap = 0.4
      ' if fpy/fpu is not less than 0.9, gammap = 0.28
      gammap = 0.4
'a, depth of equivalent rectangular (Whitney) stress block
      'a = (A_s * fy + A_ps * fps) / (0.85 * fc * b)
      a = 0.85 * (A_ps * fpu / (0.85 * fc * beta1 * b + 0.38 * A_ps *
fpu / dps_max))

'fps, stress in prestressing steel at nominal flexural strength
      'fps = fpu * (1 - gammap / beta1 * (rhop * fpu / fc + d_max /
dps_max * (w - wprime)))
      fps = fpu * (1 - 0.38 * (a / beta1) / dps_max)
'Ec, Elastic Modulus for Prestressed Concrete >= 6 ksi (Nawy)
      'Replaces Revit's E with a computed ACI value for prestressed
      concrete
      Ec = (40 * (fc * 1000) ^ (1 / 2) + 1000) * (UW / 145) ^ 1.5
'Harp, Harping Point in Tendon Layout
      harp = L / 2
'phiMn, factored nominal flexural strength in section
      'phiMn = 1.0 * (A_s * fy * (d_max - (a / 2)) + A_ps * fps *
(dps_max - (a / 2)))
phiMn = 1# * (A_ps * fps * (dps_max - a / 2))


'Array for Labels (five on each line)
Dim Labels As String
Lables = Array("Member Number", "Type", "Deck Thickness", "Span (ft)",
"b (in)", "h (in)", "tf (in)", "tw (in)", "Unit Weight (pcf)", "Ec
(ksi)",   "f'c (ksi)", "fpu (ksi)", "fpy (ksi)", "fy (ksi)", "Cracking
Present", "Cracking Severity (1 - 5)", "Crack Length (in)", "Crack
Width", "Crack Depth (in)", "Crack Dist. From Support (in)",
"Crack Dist. From Top (in)", "Crack Dist. From Edge (in)", "Spalling
Present", "Spall Severity (1 - 5)", "Spall Length (in)", "Spall Width",
"Spall Depth (in)", "Spall Dist. From Support (in)", "Spall Dist. From
Top (in)", "Spall Dist. From Edge (in)", "Delamination Present",
```

```
          "Delamination Severity (1 - 5)", "Delamination Length (in)",
      Delamination Width", "Delamination Depth (in)", "Delam. Dist. From
      Support (in)", "Delam. Dist. From Top (in)", "Delam Dist. From Edge
      (in)", "A (in^2)", "c_b (in)", "c_t (in)", "I (in^4)", "r (in)", "S_b
      (in^3)", "S_t (in^3)", "k_t (in)", "k_b (in)", "Cover of Prestress
      (in)", "Cover of Mild Steel (in)", "Deck Thickness (in)", "Aps (in^2)",
      "As (in^2)", "Av (in^2)", "s (in)", "Pi (kips)", "fpi (ksi)", "fpe
      (ksi)", "fci (ksi)", "n ratio (n = fpe/fpi)", "dps (in)", "d (in)",
      "beta 1", "rho", "rho_p", "w Ratio", "w_prime Ratio", "fpy/fpu",
      "gamma_p", "fps (ksi)", "a (in)", "Harping Point (in)", "phi*Mn
      (kip*in)")
      'Places Labels
            Range("A1:A72").Value =
Application.WorksheetFunction.Transpose(Lables)

      'Array for Values1 (upper section of table)
      Dim Values1 As Variant
            Values1 = Array(L, b, h, tf, tw, UW, Ec, fc, fpu, fpy, fy)
      'Place Values1
            Range("B4:B14").Value =
Application.WorksheetFunction.Transpose(Values1)

      'Array for Values2 (lower section of table)
      Dim Values2 As Variant
            Values2 = Array(area, c_b, c_t, Inertia, r, Sb, St, kt, kb,
      coverp, cover, t_d, A_ps, A_s, A_v, S, Pi, fpi, fpe, fci, _
            n, dps_max, d_max, beta1, rho, rhop, w, wprime, fpyoverfpu,
      gammap, fps, a, harp, phiMn)
      'Places Values2
            Range("B39:B72").Value =
Application.WorksheetFunction.Transpose(Values2)

      'formatting
            Range("B4:B72").Select
            Selection.NumberFormat = "0.000"
            Range("A1").Select
            Range(Selection, Selection.End(xlDown)).Select
            Selection.Font.Bold = True
            With Selection.Font
               .Color = -16738048
            End With
            Range("A35").Select
            Columns("B:B").Select
            With Selection
               .HorizontalAlignment = xlLeft
            End With
      'greek letter 'phi' and place in proper label
            Range("A72").Select: ActiveCell.FormulaR1C1 = "FMn (kip*in)":
            With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
      "GreekC": .FontStyle = "Regular": .Size = 11:
            End With
            Range("A1").Select
End Sub
```

Module 3: Cracked Cross-Section Generator

```vba
Sub CrackedGeometry()

Dim L As Single: Dim b As Single: Dim h As Single: Dim tf As Single: Dim tw
As Single: Dim UW As Single: Dim Ec As Single: Dim fc As Single: Dim fpu As
Single: Dim fpy As Single: Dim fy As Single: Dim Crack As String: Dim
CrackSev As Integer: Dim LengthCrack As Single: Dim WidthCrack As Single: Dim
DepthCrack As Single: Dim FromSupportCrack As Single: Dim FromEdgeCrack As
Single: Dim coverp As Single: Dim cover As Single: Dim t_d As Single: Dim
A_ps As Single: Dim A_s As Single: Dim A_v As Single: Dim S As Single: Dim Pi
As Single: Dim fpi As Single: Dim fpe As Single: Dim fci As Single: Dim n As
Single: Dim dps_max_undam As Single: Dim d_max_undam As Single: Dim beta1 As
Single: Dim bc As Single: Dim hc As Single: Dim tfc As Single: Dim twc As
Single: Dim Afc As Single: Dim Awc As Single: Dim Areac As Single: Dim hwc As
Single: Dim c_bc As Single: Dim c_tc As Single: Dim Ic As Single: Dim rc As
Single: Dim Sbc As Single: Dim Stc As Single: Dim ktc As Single: Dim kbc As
Single: Dim dpsc As Single: Dim DC As Single: Dim rhoc As Single: Dim rhopc
As Single: Dim wc As Single: Dim w_primec As Single: Dim fpyoverfpu As
Single: Dim gammap As Single: Dim fpsc As Single: Dim ac As Single: Dim
phiMnc As Single:

        'Defines Undamaged variables to use throughout Sub
        Sheets("UndamagedGeom").Select
            L = Range("B4").Value
            b = Range("B5").Value
            h = Range("B6").Value
            tf = Range("B7").Value
            tw = Range("B8").Value
            UW = Range("B9").Value
            Ec = Range("B10").Value
            fc = Range("B11").Value
            fpu = Range("B12").Value
            fpy = Range("B13").Value
            fy = Range("B14").Value
            Crack = Range("B15").Value
            CrackSev = Range("B16").Value
            LengthCrack = Range("B17").Value
            WidthCrack = Range("B18").Value
            DepthCrack = Range("B19").Value
            FromSupportCrack = Range("B20").Value
            FromTopCrack = Range("B21").Value
            FromEdgeCrack = Range("B22").Value
            coverp = Range("B48").Value
            cover = Range("B49").Value
            t_d = Range("B50").Value
            A_ps = Range("B51").Value
            'undamaged As
            A_s = Range("B52").Value
            'undamaged Av
            A_v = Range("B53").Value
            S = Range("B54").Value
            Pi = Range("B55").Value
            fpi = Range("B56").Value
            fpe = Range("B57").Value
```

161

```vba
    fci = Range("B58").Value
    n = Range("B59").Value
    dps_max_undam = Range("B60").Value
    d_max_undam = Range("B61").Value
    beta1 = Range("B62").Value

'Loop to populate 1's for the flange
Sheets("CrackedGeom").Select
'Flange
For j = 1 To 192
For i = 1 To 14
Cells(i + 2, j + 4).Value = 0.5
Next
Next
'Flange Taper
For j = 1 To 152
Cells(17, j + 24).Value = 0.5
Next
For j = 1 To 112
Cells(18, j + 44).Value = 0.5
Next
For j = 1 To 72
Cells(19, j + 64).Value = 0.5
Next
For j = 1 To 50
Cells(20, j + 75).Value = 0.5
Next
'Web
 For i = 1 To 64
 For j = 1 To 12
      Cells(20 + i, 94 + j).Value = 0.5
Next j
Next i
'Web Taper
For i = 1 To 43
Cells(20 + i, 94).Value = 0.5
Cells(20 + i, 107).Value = 0.5
Next
For i = 1 To 21
Cells(20 + i, 93).Value = 0.5
Cells(20 + i, 108).Value = 0.5
Next
'Triangles
For i = 1 To 8
     Cells(21, 84 + i).Value = 0.5
     Cells(21, 108 + i).Value = 0.5
Next
For i = 1 To 7
     Cells(22, 85 + i).Value = 0.5
     Cells(22, 108 + i).Value = 0.5
Next
For i = 1 To 6
     Cells(23, 86 + i).Value = 0.5
     Cells(23, 108 + i).Value = 0.5
Next
For i = 1 To 5
     Cells(24, 87 + i).Value = 0.5
```

```
Cells(24, 108 + i).Value = 0.5
Next
For i = 1 To 4
Cells(25, 88 + i).Value = 0.5
Cells(25, 108 + i).Value = 0.5
Next
For i = 1 To 3
Cells(26, 89 + i).Value = 0.5
Cells(26, 108 + i).Value = 0.5
Next
For i = 1 To 2
Cells(27, 90 + i).Value = 0.5
Cells(27, 108 + i).Value = 0.5
Next
For i = 1 To 1
Cells(28, 91 + i).Value = 0.5
Cells(28, 108 + i).Value = 0.5
Next

'Loop for Crack Damage to place "" where section is cracked
For i = 1 To 2 * DepthCrack
For j = 1 To 2 * WidthCrack
      Cells(4 + 2 * FromTopCrack - 2 * DepthCrack + i, 4 + 2 *
      FromEdgeCrack - 2 * WidthCrack / 2 + j).Value = ""
Next j
Next i
'Loop to sum flange
For i = 1 To 14
For j = 1 To 192
'Sums tf increments and places the values above section
      Cells(1, 4 + j).Value = Application.Sum(Range(Cells(3, 4 + j),
      Cells(20, 4 + j)))
      'b increment sum and place to left of section
      Cells(2 + i, 3).Value = Application.Sum(Range(Cells(2 + i, 5),
      Cells(2 + i, 5 + 192)))
Next j
Next i
'Loop to sum web
For i = 1 To 64
For j = 1 To 12
'Sums tw increments and places the values to right of section
      Cells(20 + i, 118).Value = Application.Sum(Range(Cells(20 + i,
      93), Cells(20 + i, 108)))
      'Depth of web increment, sum and place below section
      Cells(86, 94 + j).Value = Application.Sum(Range(Cells(21, 94 +
      j), Cells(84, 94 + j)))
Next j
Next i
'Loop to figure out hc
For i = 1 To 192
If Cells(3, 4 + i).Value = "" Then
      Cells(87, 4 + i).Value = h - DepthCrack
Else
      Cells(87, 4 + i).Value = h
End If
Next
```

```
'Calculates Cracked Section Properties
bc = Application.Sum(Range("C3:C16")) / 14
hc = Application.Sum(Range("E87:GN87")) / (192)
tfc = Application.Sum(Range("E1:GN1")) / (192)
twc = Application.Sum(Range("DN21:DN84")) / 64
Afc = Application.Sum(Range("E3:GN20")) / 2
Awc = Application.Sum(Range("CO21:DD84")) / 2
Atri = Application.Sum(Range("CG21:CN28,DE21:DL28")) / 2
Areac = Afc + Awc + Atri
hwc = Application.Sum(Range("CQ86:DB86")) / 12
c_bc = (hwc / 2 * Awc + (hwc + tfc / 2) * Afc + (hwc - 2) * Atri) /
Areac
c_tc = hc - c_bc
Ic = twc * hwc ^ 3 / 12 + Awc * (c_bc - hwc / 2) ^ 2 + bc * tfc ^ 3 /
12 + Afc * ((hwc + tfc / 2) - c_bc) ^ 2 + 4 * 4 ^ 3 / 12 + 4 * 4 *
(c_tc - 2) ^ 2
rc = (Ic / Areac) ^ (1 / 2)
Sbc = Ic / c_bc
Stc = Ic / c_tc
ktc = rc ^ 2 / c_bc
kbc = rc ^ 2 / c_tc
dpsc = hc - coverp
DC = hc - cover
rhoc = A_s / (bc * DC)
rhopc = A_ps / (bc * dpsc)
wc = rho * fy / fc
w_primec = rho * fy / fc
fpyoverfpu = fpy / fpu
'since fpy/fpu = 0.85 ACI ==> gammap = 0.40
gammap = 0.4
'fpsc = fpu * (1 - gammap / beta1 * (rhop * fpu / fc + DC / dpsc * (w -
w_prime)))
'ac = (A_s * fy + A_ps * fpu) / (0.85 * fc * bc)
 ac = A_ps * fpu / (0.85 * fc * beta1 * bc + 0.38 * A_ps * fpu / dpsc)
 fpsc = fpu * (1 - 0.38 * (ac / beta1) / dpsc)
 phiMnc = 1# * A_ps * fpsc * (dpsc - ac / 2)

'Array for Labels (five on each line)
Dim Labels As String

Lables = Array("Span (ft)", "b_cracked (in)", "h_cracked (in)",
"tf_cracked (in)", "tw_cracked (in)", "Unit Weight (pcf)", "Ec (ksi)",
"f'c (ksi)", "fpu (ksi)", "fpy (ksi)", "fy (ksi)", "Cracking Present",
"Cracking Severity (1 - 5)", "Crack Length (in)", "Crack Width", "Crack
Depth (in)", "Crack Dist. From Support (in)", "Crack Dist. From Top
(in)", "Crack Dist. From Edge (in)", "A_cracked (in^2)", "c_b_cracked
(in)", "c_t_cracked (in)", "I_cracked (in^4)", "r_cracked (in)",
"S_b_cracked (in^3)", "S_t_cracked (in^3)", "k_t_cracked (in)",
"k_b_cracked (in)", "Cover of Prestress (in)", "Cover of Mild Steel
(in)", "Deck Thickness (in)", "Aps (in^2)", "As (in^2)", "Av (in^2)",
"s (in)", "Pi (kips)", "fpi (ksi)", "fpe (ksi)", "fci (ksi)", "n ratio
(n = fpe/fpi)", "dps_cracked (in)", "dsubcracked (in)", "beta 1",
"rho_cracked", "rho_p_cracked", "w Ratio_cracked", "w_prime
Ratio_cracked", "fpy/fpu", "gamma_p", "fps_cracked (ksi)", "a_cracked
(in)", "phi*Mn_cracked (kip*in)")

'Places Labels
```

```
            Range("A4:A55").Value =
Application.WorksheetFunction.Transpose(Lables)

        'Array for Values
        Dim Values As Variant
Values = Array(L, bc, hc, tfc, twc, UW, Ec, fc, fpu, fpy, fy, Crack,
        CrackSev, LengthCrack, WidthCrack, DepthCrack, FromSupportCrack,
        FromTopCrack, FromEdgeCrack, Areac, c_bc, c_tc, Ic, rc, Sbc, Stc, ktc,
        kbc, coverp, cover, t_d, A_ps, A_s, A_v, S, Pi, fpi, fpe, fci, n, dpsc,
        DC, beta1, rhoc, rhopc, wc, w_primec, fpyoverfpu, gammap, fpsc, ac,
        phiMnc)
        'Places Values
            Range("B4:B55").Value =
Application.WorksheetFunction.Transpose(Values)

        'Formating
        'greek letter 'phi' and place in proper label
            Range("B55").Value = phiMnc
            Range("A55").Select: ActiveCell.FormulaR1C1 = "FMn (kip*in)"
            With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
        "GreekC": .FontStyle = "Regular": .Size = 11
            End With
            Range("A1").Select
        'Formatting Header and Significant Digits
        'AutoSize Columns
            Cells.Select
            Cells.EntireColumn.AutoFit
            Range("A1").Select
        'Create boldface green titles, and round
            Range("B4:B72").Select
            Selection.NumberFormat = "0.000"
            Range("A1:A72").Select
            Selection.Font.Bold = True
            With Selection.Font
               .Color = -16738048
            End With
            Range("A1").Select
End Sub
```

Module 4: Spalled Cross-Section Generator

```
Sub SpallGeometry()

Dim L As Single: Dim b As Single: Dim h As Single: Dim tf As Single: Dim tw
As Single: Dim UW As Single: Dim Ec As Single: Dim fc As Single: Dim fpu As
Single: Dim fpy As Single: Dim fy As Single: Dim Spall As String: Dim
SpallSev As Integer: Dim LengthSpall As Single: Dim WidthSpall As Single: Dim
DepthSpall As Single: Dim FromSupportSpall As Single: Dim FromEdgeSpall As
Single: Dim coverp As Single: Dim cover As Single: Dim t_d As Single: Dim
A_ps As Single: Dim A_s As Single: Dim A_v As Single: Dim S As Single: Dim Pi
As Single: Dim fpi As Single: Dim fpe As Single: Dim fci As Single: Dim n As
Single: Dim dps_max_undam As Single: Dim d_max_undam As Single: Dim beta1 As
Single: Dim bc As Single: Dim hc As Single: Dim tfc As Single: Dim twc As
Single: Dim Afc As Single: Dim Awc As Single: Dim Areac As Single: Dim hwc As
Single: Dim c_bc As Single: Dim c_tc As Single: Dim Ic As Single: Dim rc As
Single: Dim Sbc As Single: Dim Stc As Single: Dim ktc As Single: Dim kbc As
Single: Dim dpsc As Single: Dim DC As Single: Dim rhoc As Single: Dim rhopc
As Single: Dim wc As Single: Dim w_primec As Single: Dim fpyoverfpu As
Single: Dim gammap As Single: Dim fpsc As Single: Dim ac As Single: Dim
phiMnc As Single:

        'Defines Undamaged variables to use throughout Sub
        Sheets("UndamagedGeom").Select
            L = Range("B4").Value
            b = Range("B5").Value
            h = Range("B6").Value
            tf = Range("B7").Value
            tw = Range("B8").Value
            UW = Range("B9").Value
            Ec = Range("B10").Value
            fc = Range("B11").Value
            fpu = Range("B12").Value
            fpy = Range("B13").Value
            fy = Range("B14").Value
            Spall = Range("B23").Value
            SpallSev = Range("B24").Value
            LengthSpall = Range("B25").Value
            WidthSpall = Range("B26").Value
            DepthSpall = Range("B27").Value
            FromSupportSpall = Range("B28").Value
            FromTopSpall = Range("B29").Value
            FromEdgeSpall = Range("B30").Value
            coverp = Range("B48").Value
            cover = Range("B49").Value
            t_d = Range("B50").Value
            A_ps = Range("B51").Value
            'undamaged As
            A_s = Range("B52").Value
            'undamaged Av
            A_v = Range("B53").Value
            S = Range("B54").Value
            Pi = Range("B55").Value
            fpi = Range("B56").Value
            fpe = Range("B57").Value
```

```
    fci = Range("B58").Value
    n = Range("B59").Value
    dps_max_undam = Range("B60").Value
    d_max_undam = Range("B61").Value
    beta1 = Range("B62").Value

'Loop to populate 1's for the flange
Sheets("SpallGeom").Select
'Flange
For j = 1 To 192
For i = 1 To 14
    Cells(i + 2, j + 4).Value = 0.5
Next
Next
'Flange Taper
For j = 1 To 152
    Cells(17, j + 24).Value = 0.5
Next
For j = 1 To 112
    Cells(18, j + 44).Value = 0.5
Next
For j = 1 To 72
    Cells(19, j + 64).Value = 0.5
Next
For j = 1 To 50
    Cells(20, j + 75).Value = 0.5
Next
'Web
For i = 1 To 64
For j = 1 To 12
    Cells(20 + i, 94 + j).Value = 0.5
Next j
Next i
'Web Taper
For i = 1 To 43
    Cells(20 + i, 94).Value = 0.5
    Cells(20 + i, 107).Value = 0.5
Next
For i = 1 To 21
    Cells(20 + i, 93).Value = 0.5
    Cells(20 + i, 108).Value = 0.5
Next
'Triangles
For i = 1 To 8
    Cells(21, 84 + i).Value = 0.5
    Cells(21, 108 + i).Value = 0.5
Next
For i = 1 To 7
    Cells(22, 85 + i).Value = 0.5
    Cells(22, 108 + i).Value = 0.5
Next
For i = 1 To 6
    Cells(23, 86 + i).Value = 0.5
    Cells(23, 108 + i).Value = 0.5
Next
For i = 1 To 5
    Cells(24, 87 + i).Value = 0.5
```

```
        Cells(24, 108 + i).Value = 0.5
Next
For i = 1 To 4
        Cells(25, 88 + i).Value = 0.5
        Cells(25, 108 + i).Value = 0.5
Next
For i = 1 To 3
        Cells(26, 89 + i).Value = 0.5
        Cells(26, 108 + i).Value = 0.5
Next
For i = 1 To 2
        Cells(27, 90 + i).Value = 0.5
        Cells(27, 108 + i).Value = 0.5
Next
For i = 1 To 1
        Cells(28, 91 + i).Value = 0.5
        Cells(28, 108 + i).Value = 0.5
Next
'Loop for Spall Damage to place "" where section is spalled
For i = 1 To 2 * DepthSpall
For j = 1 To 2 * WidthSpall
        Cells(2 + 2 * FromTopSpall - 2 * DepthSpall + i, 4 + 2 *
        FromEdgeSpall - 2 * WidthSpall / 2 + j).Value = ""
Next j
Next i
'Loop to sum flange
For i = 1 To 14
For j = 1 To 192
        'Sums tf increments and places the values above section
        Cells(1, 4 + j).Value = Application.Sum(Range(Cells(3, 4 + j),
        Cells(20, 4 + j)))
        'b increment sum and place to left of section
        Cells(2 + i, 3).Value = Application.Sum(Range(Cells(2 + i, 5),
        Cells(2 + i, 5 + 192)))
Next j
Next i
'Loop to sum web
For i = 1 To 64
For j = 1 To 12
        'Sums tw increments and places the values to right of section
        Cells(20 + i, 118).Value = Application.Sum(Range(Cells(20 + i,
        93), Cells(20 + i, 108)))
        'Depth of web increment, sum and place below section
        Cells(86, 94 + j).Value = Application.Sum(Range(Cells(21, 94 +
        j), Cells(84, 94 + j)))
Next j
Next i

'Calculates Spalled Section Properties
        bc = Application.Sum(Range("C3:C16")) / 14
        hc = (41 * 180 + (h - DepthSpall) * 2 * WidthSpall) / 192
        tfc = Application.Sum(Range("E1:GN1")) / (192)
        twc = Application.Sum(Range("DN21:DN84")) / 64
        Afc = Application.Sum(Range("E3:GN20")) / 2
        Awc = Application.Sum(Range("CO21:DD84")) / 2
        Atri = Application.Sum(Range("CG21:CN28,DE21:DL28")) / 2
        Areac = Afc + Awc + Atri
```

```
          hwc = Application.Sum(Range("CQ86:DB86")) / 12
          c_bc = (hwc / 2 * Awc + (hwc + tfc / 2) * Afc + (hwc - 2) * Atri)
          / Areac
          c_tc = hc - c_bc
          Ic = twc * hwc ^ 3 / 12 + Awc * (c_bc - hwc / 2) ^ 2 + bc * tfc ^
          3 / 12 + Afc * ((hwc + tfc / 2) - c_bc) ^ 2 + 4 * 4 ^ 3 / 12 + 4
          * 4 * (c_tc - 2) ^ 2
          rc = (Ic / Areac) ^ (1 / 2)
          Sbc = Ic / c_bc
          Stc = Ic / c_tc
          ktc = rc ^ 2 / c_bc
          kbc = rc ^ 2 / c_tc
          dpsc = hc - coverp
          DC = hc - cover
          rhoc = A_s / (bc * DC)
          rhopc = A_ps / (bc * dpsc)
          wc = rho * fy / fc
          w_primec = rho * fy / fc
          fpyoverfpu = fpy / fpu
          'since fpy/fpu = 0.85 ACI ==> gammap = 0.40
          gammap = 0.4
          'fpsc = fpu * (1 - gammap / beta1 * (rhop * fpu / fc + DC / dpsc
          * (w - w_prime)))
          'ac = (A_s * fy + A_ps * fpu) / (0.85 * fc * bc)
          ac = A_ps * fpu / (0.85 * fc * beta1 * bc + 0.38 * A_ps * fpu /
          dpsc)
          fpsc = fpu * (1 - 0.38 * (ac / beta1) / dpsc)
          phiMnc = 1# * A_ps * fpsc * (dpsc - ac / 2)

  'Array for Labels (five on each line)
  Dim Labels As String
  Lables = Array("Span (ft)", "b_spalled (in)", "h_spalled (in)", "tf_spalled
       (in)", "tw_spalled (in)", "Unit Weight (pcf)", "Ec (ksi)", "f'c (ksi)",
       "fpu (ksi)", "fpy (ksi)", "fy (ksi)", "spalling Present", "Spalling
       Severity (1 - 5)", "Spall Length (in)", "Spalled Width", "Spall Depth
       (in)", "Spall Dist. From Support (in)", "Spall Dist. From Top (in)",
       "Spall Dist. From Edge (in)", "A_spalled (in^2)", "c_b_spalled (in)",
       "c_t_spalled (in)", "I_spalled (in^4)", "r_spalled (in)", "S_b_spalled
       (in^3)", "S_t_spalled (in^3)", "k_t_spalled (in)", "k_b_spalled (in)",
       "Cover of Prestress (in)", "Cover of Mild Steel (in)", "Deck Thickness
       (in)", "Aps (in^2)", "As (in^2)", "Av (in^2)", "s (in)", "Pi (kips)",
       "fpi (ksi)", "fpe (ksi)", "fci (ksi)", "n ratio (n = fpe/fpi)",
       "dps_spalled (in)", "dsubspalled (in)", "beta 1", "rho_spalled",
       "rho_p_spalled", "w Ratio_spalled", "w_prime Ratio_spalled", "fpy/fpu",
       "gamma_p", "fps_spalled (ksi)", "a_spalled (in)", "phi*Mn_spalled
       (kip*in)")

       'Places Labels
       Range("A4:A55").Value = Application.WorksheetFunction.Transpose(Lables)

       'Array for Values
       Dim Values As Variant
       Values = Array(L, bc, hc, tfc, twc, UW, Ec, fc, fpu, fpy, fy, Spall,
       SpallSev, LengthSpall, WidthSpall, DepthSpall, FromSupportSpall,
       FromTopSpall, FromEdgeSpall, Areac, c_bc, c_tc, Ic, rc, Sbc, Stc, ktc,
       kbc, coverp, cover, t_d, A_ps, A_s, A_v, S, Pi, fpi, fpe, fci, n, dpsc,
```

```
        DC, beta1, rhoc, rhopc, wc, w_primec, fpyoverfpu, gammap, fpsc, ac,
    phiMnc)
    'Places Values
    Range("B4:B55").Value = Application.WorksheetFunction.Transpose(Values)

    'Formating
    'greek letter 'phi' and place in proper label
        Range("B55").Value = phiMnc
        Range("A55").Select: ActiveCell.FormulaR1C1 = "FMn (kip*in)"
          With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
          "GreekC": .FontStyle = "Regular": .Size = 11
          End With
        Range("A1").Select
    'Formatting Header and Significant Digits
    'AutoSize Columns
        Cells.Select
        Cells.EntireColumn.AutoFit
        Range("A1").Select
    'Create boldface green titles, and round
        Range("B4:B72").Select
        Selection.NumberFormat = "0.000"
        Range("A1:A72").Select
        Selection.Font.Bold = True
        With Selection.Font
            .Color = -16738048
        End With
        Range("A1").Select
End Sub
```

Module 5: Delaminated Cross-Section Generator


```
Sub DelamGeometry()

Dim L As Single: Dim b As Single: Dim h As Single: Dim tf As Single: Dim tw
As Single: Dim UW As Single: Dim Ec As Single: Dim fc As Single: Dim fpu As
Single: Dim fpy As Single: Dim fy As Single: Dim Spall As String: Dim
SpallSev As Integer: Dim LengthSpall As Single: Dim WidthSpall As Single: Dim
DepthSpall As Single: Dim FromSupportSpall As Single: Dim FromEdgeSpall As
Single: Dim coverp As Single: Dim cover As Single: Dim t_d As Single: Dim
A_ps As Single: Dim A_s As Single: Dim A_v As Single: Dim S As Single: Dim Pi
As Single: Dim fpi As Single: Dim fpe As Single: Dim fci As Single: Dim n As
Single: Dim dps_max_undam As Single: Dim d_max_undam As Single: Dim beta1 As
Single: Dim bc As Single: Dim hc As Single: Dim tfc As Single: Dim twc As
Single: Dim Afc As Single: Dim Awc As Single: Dim Areac As Single: Dim hwc As
Single: Dim c_bc As Single: Dim c_tc As Single: Dim Ic As Single: Dim rc As
Single: Dim Sbc As Single: Dim Stc As Single: Dim ktc As Single: Dim kbc As
Single: Dim dpsc As Single: Dim DC As Single: Dim rhoc As Single: Dim rhopc
As Single: Dim wc As Single: Dim w_primec As Single: Dim fpyoverfpu As
Single: Dim gammap As Single: Dim fpsc As Single: Dim ac As Single: Dim
phiMnc As Single:

        'Defines Undamaged variables to use throughout Sub
        Sheets("UndamagedGeom").Select
            L = Range("B4").Value
            b = Range("B5").Value
            h = Range("B6").Value
            tf = Range("B7").Value
            tw = Range("B8").Value
            UW = Range("B9").Value
            Ec = Range("B10").Value
            fc = Range("B11").Value
            fpu = Range("B12").Value
            fpy = Range("B13").Value
            fy = Range("B14").Value
            Delam = Range("B31").Value
            DelamSev = Range("B32").Value
            LengthDelam = Range("B33").Value
            WidthDelam = Range("B34").Value
            DepthDelam = Range("B35").Value
            FromSupportDelam = Range("B36").Value
            FromTopDelam = Range("B37").Value
            FromEdgeDelam = Range("B38").Value
            coverp = Range("B48").Value
            cover = Range("B49").Value
            t_d = Range("B50").Value
            A_ps = Range("B51").Value
            'undamaged As
            A_s = Range("B52").Value
            'undamaged Av
            A_v = Range("B53").Value
            S = Range("B54").Value
            Pi = Range("B55").Value
            fpi = Range("B56").Value
            fpe = Range("B57").Value
```

```vba
    fci = Range("B58").Value
    n = Range("B59").Value
      dps_max_undam = Range("B60").Value
      d_max_undam = Range("B61").Value
      beta1 = Range("B62").Value

'Loop to populate 1's for the flange
Sheets("DelamGeom").Select

'Flange
For j = 1 To 192
For i = 1 To 14
      Cells(i + 2, j + 4).Value = 0.5
Next
Next

'Flange Taper
For j = 1 To 152
      Cells(17, j + 24).Value = 0.5
Next
For j = 1 To 112
      Cells(18, j + 44).Value = 0.5
Next
For j = 1 To 72
      Cells(19, j + 64).Value = 0.5
Next
For j = 1 To 50
      Cells(20, j + 75).Value = 0.5
Next

'Web
For i = 1 To 64
For j = 1 To 12
      Cells(20 + i, 94 + j).Value = 0.5
Next j
Next i

'Web Taper
For i = 1 To 43
      Cells(20 + i, 94).Value = 0.5
      Cells(20 + i, 107).Value = 0.5
Next
For i = 1 To 21
      Cells(20 + i, 93).Value = 0.5
      Cells(20 + i, 108).Value = 0.5
Next

'Triangles
For i = 1 To 8
      Cells(21, 84 + i).Value = 0.5
      Cells(21, 108 + i).Value = 0.5
Next
For i = 1 To 7
      Cells(22, 85 + i).Value = 0.5
      Cells(22, 108 + i).Value = 0.5
Next
For i = 1 To 6
```

```
      Cells(23, 86 + i).Value = 0.5
      Cells(23, 108 + i).Value = 0.5
Next
For i = 1 To 5
      Cells(24, 87 + i).Value = 0.5
      Cells(24, 108 + i).Value = 0.5
Next
For i = 1 To 4
      Cells(25, 88 + i).Value = 0.5
      Cells(25, 108 + i).Value = 0.5
Next
For i = 1 To 3
      Cells(26, 89 + i).Value = 0.5
      Cells(26, 108 + i).Value = 0.5
Next
For i = 1 To 2
      Cells(27, 90 + i).Value = 0.5
      Cells(27, 108 + i).Value = 0.5
Next
For i = 1 To 1
      Cells(28, 91 + i).Value = 0.5
      Cells(28, 108 + i).Value = 0.5
Next

'Loop for Delam Damage to place "" where section is cracked
For i = 1 To 2 * DepthDelam
For j = 1 To 2 * WidthDelam
      Cells(7 + 2 * FromTopDelam - 2 * DepthDelam + i, 4 + 2 *
      FromEdgeDelam - 2 * WidthDelam / 2 + j).Value = ""
Next j
Next i

'Loop to sum flange
For i = 1 To 14
For j = 1 To 192
      'Sums tf increments and places the values above section
      Cells(1, 4 + j).Value = Application.Sum(Range(Cells(3, 4 + j),
      Cells(20, 4 + j)))
      'b increment sum and place to left of section
      Cells(2 + i, 3).Value = Application.Sum(Range(Cells(2 + i, 5),
      Cells(2 + i, 5 + 192)))
Next j
Next i

'Loop to sum web
For i = 1 To 64
For j = 1 To 12
      'Sums tw increments and places the values to right of section
      Cells(20 + i, 118).Value = Application.Sum(Range(Cells(20 + i,
      93), Cells(20 + i, 108)))
      'Depth of web increment, sum and place below section
      Cells(86, 94 + j).Value = Application.Sum(Range(Cells(21, 94 +
      j), Cells(84, 94 + j)))
Next j
Next i

'Loop to figure out hc
```

```
For i = 1 To 192
If Cells(3, 4 + i).Value = "" Then
        Cells(87, 4 + i).Value = h - DepthDelam
Else
        Cells(87, 4 + i).Value = h
End If
Next

'Calculates Delaminated Section Properties
        bc = Application.Sum(Range("C3:C16")) / 14
        hc = Application.Sum(Range("E87:GN87")) / (192)
        tfc = Application.Sum(Range("E1:GN1")) / (192)
        twc = Application.Sum(Range("DN21:DN84")) / 64
        Afc = Application.Sum(Range("E3:GN20")) / 2
        Awc = Application.Sum(Range("CO21:DD84")) / 2
        Atri = Application.Sum(Range("CG21:CN28,DE21:DL28")) / 2
        Areac = Afc + Awc + Atri
        hwc = Application.Sum(Range("CQ86:DB86")) / 12
        c_bc = (hwc / 2 * Awc + (hwc + tfc / 2) * Afc + (hwc - 2) * Atri)
        / Areac
        c_tc = hc - c_bc
        Ic = twc * hwc ^ 3 / 12 + Awc * (c_bc - hwc / 2) ^ 2 + bc * tfc ^
        3 / 12 + Afc * ((hwc + tfc / 2) - c_bc) ^ 2 + 4 * 4 ^ 3 / 12 + 4
        * 4 * (c_tc - 2) ^ 2
        rc = (Ic / Areac) ^ (1 / 2)
        Sbc = Ic / c_bc
        Stc = Ic / c_tc
        ktc = rc ^ 2 / c_bc
        kbc = rc ^ 2 / c_tc
        dpsc = hc - coverp
        DC = hc - cover
        rhoc = A_s / (bc * DC)
        rhopc = A_ps / (bc * dpsc)
        wc = rho * fy / fc
        w_primec = rho * fy / fc
        fpyoverfpu = fpy / fpu
        'since fpy/fpu = 0.85 ACI ==> gammap = 0.40
        gammap = 0.4
        'fpsc = fpu * (1 - gammap / beta1 * (rhop * fpu / fc + DC / dpsc
        * (w - w_prime)))
        'ac = (A_s * fy + A_ps * fpu) / (0.85 * fc * bc)
        ac = A_ps * fpu / (0.85 * fc * beta1 * bc + 0.38 * A_ps * fpu /
        dpsc)
        fpsc = fpu * (1 - 0.38 * (ac / beta1) / dpsc)
        phiMnc = 1# * A_ps * fpsc * (dpsc - ac / 2)

'Array for Labels (five on each line)
Dim Labels As String
Lables = Array("Span (ft)", "b_delaminated (in)", "h_delaminated (in)",
        "tf_delaminated (in)", "tw_delaminated (in)", "Unit Weight (pcf)", "Ec
        (ksi)", "f'c (ksi)", "fpu (ksi)", "fpy (ksi)", "fy (ksi)",
        "Delamination Present", "Delamination Severity (1 - 5)", "Delamination
        Length (in)", "Delamination Width", "Delamination Depth (in)",
        "Delamination Dist. From Support (in)", "Delamination Dist. From Top
        (in)", "Delamination Dist. From Edge (in)", "A_delam (in^2)",
        "c_b_delam (in)", "c_t_delam (in)", "I_delam (in^4)", "r_delam (in)",
        "S_b_delam (in^3)", "S_t_delam (in^3)", "k_t_delam (in)", "k_b_delam
```

174

```
        (in)", "Cover of Prestress (in)", "Cover of Mild Steel (in)", "Deck
        Thickness (in)", "Aps (in^2)", "As (in^2)", "Av (in^2)", "s (in)", "Pi
        (kips)", "fpi (ksi)", "fpe (ksi)", "fci (ksi)", "n ratio (n =
        fpe/fpi)", "dps_delam (in)", "dsubdelam (in)", "beta 1", "rho_delam",
        "rho_p_delam", "w Ratio_delam", "w_prime Ratio_delam", "fpy/fpu",
        "gamma_p", "fps_delam (ksi)", "a_delam (in)", "phi*Mn_delam (kip*in)")

    'Places Labels
    Range("A4:A55").Value = Application.WorksheetFunction.Transpose(Lables)

    'Array for Values
    Dim Values As Variant
    Values = Array(L, bc, hc, tfc, twc, UW, Ec, fc, fpu, fpy, fy, Delam,
        DelamSev, LengthDelam, WidthDelam, DepthDelam, FromSupportDelam,
        FromTopDelam, FromEdgeDelam, Areac, c_bc, c_tc, Ic, rc, Sbc, Stc, ktc,
        kbc, coverp, cover, t_d, A_ps, A_s, A_v, S, Pi, fpi, fpe, fci, n, dpsc,
        DC, beta1, rhoc, rhopc, wc, w_primec, fpyoverfpu, gammap, fpsc, ac,
        phiMnc)

        'Places Values
            Range("B4:B55").Value =
    Application.WorksheetFunction.Transpose(Values)

        'Formating
        'greek letter 'phi' and place in proper label
            Range("B55").Value = phiMnc
            Range("A55").Select: ActiveCell.FormulaR1C1 = "FMn (kip*in)"
            With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
        "GreekC": .FontStyle = "Regular": .Size = 11
            End With
            Range("A1").Select
        'Formatting Header and Significant Digits
        'AutoSize Columns
            Cells.Select
            Cells.EntireColumn.AutoFit
            Range("A1").Select
        'Create boldface green titles, and round
            Range("B4:B72").Select
            Selection.NumberFormat = "0.000"
            Range("A1:A72").Select
            Selection.Font.Bold = True
            With Selection.Font
               .Color = -16738048
            End With
            Range("A1").Select
    End Sub
```

Module 6: Cracking, Spalling, and Delamination Evaluation

```
Sub Cracked()

    Dim C_sev As Integer: Dim Crack As String: Dim phic As Single: Dim S_sev
    As Integer: Dim Spall As String: Dim D_sev As Integer: Dim Delam As
    String: Dim Length As Single: Dim harp As Single: Dim h As Single:
    Dim cover As Single: Dim c_t As Single: Dim A_s As Single: Dim fy As
    Single: Dim D As Single: Dim a As Single: Dim A_ps As Single: Dim fps As
    Single: Dim fc As Single: Dim b As Single: Dim Av As Single: Dim S As
    Single: Dim A_sc As Single: Dim dsubc As  Single: Dim ac As Single: Dim
    Apsc As Single: Dim fpsc As Single: Dim hc As Single: Dim LengthCrack As
    Single: Dim FromSupportCrack As Single: Dim bc As Single: Dim gDCo As
    Single: Dim gDWo As Single: Dim gLLo As Single: Dim gDCi As Single: Dim
    gDWi As Single: Dim gLLi As Single: Dim DC As Single: Dim DW As Single:
    Dim LL As Single: Dim w_DC As Single: Dim w_DW As Single: Dim w_LLm As
    Single: Dim phif As Single: Dim phiv As Single: Dim phis As Single:

            Crack = Sheets("UndamagedGeom").Range("B15").Value
            C_sev = Sheets("UndamagedGeom").Range("B16").Value

    'msgbox for improper values
    If Crack = "No" Or C_sev = 0 Then
        MsgBox ("This section is not cracked, please re-enter damage
        type")
        End
    End If

    Call CheckAddSheet3Keep
    Call CheckAddSheet4Keep
    Call CheckAddSheet5Keep
    Call CheckAddSheet6Keep
    Call CheckAddSheet7Keep
    Call CheckAddSheet8Keep

    'msgbox and phi_c definition for low severity
        If C_sev = 1 Or C_sev = 2 Then
          MsgBox ("Low Severity Cracking" & vbNewLine & vbNewLine &
    "Recommended Maintenance: None")
          phic = 1
        End If
    'msgbox and phi_c definition for medium severity
        If C_sev = 2 Or C_sev = 3 Then
          MsgBox ("Medium Severity Cracking" & vbNewLine & vbNewLine &
    "Recommended Maintenance: Seal Cracks")
          phic = 0.955
        End If
    'msgbox and phi_c definition for high severity
        If C_sev = 4 Or C_sev = 5 Then
          MsgBox ("High Severity Cracking" & vbNewLine & vbNewLine &
    "Recommended Maintenance: Seal and Patch Cracks, or Rehab Unit")
          phic = 0.855
        End If

    'places phi_c value on BIMInspection Page
```

```vba
Sheets("UndamagedGeom").Select
Range("A100").Value = phic

Call UndamagedGeometry
Call CrackedGeometry
Call SpallGeometry
Call DelamGeometry
Call Loads
Call DataTableUndamagedInfo
Call Maintain

'Grabs Variables from UndamagedGeom
Dim L As Integer
Sheets("UndamagedGeom").Select
    L = Range("B4").Value
    Length = Range("B4").Value
    harp = Range("B71").Value
    h = Range("B6").Value
    cover = Range("B48").Value
    c_t = Range("B41").Value
    A_s = Range("B52").Value
    fy = Range("B14").Value
    D = Range("B61").Value
    a = Range("B70").Value
    A_ps = Range("B51").Value
    fps = Range("B69").Value
    fc = Range("B11").Value * 1000
    b = Range("B5").Value
    Av = Range("B53").Value
    S = Range("B54").Value
'Grabs more variables from Cracked Geom
Sheets("CrackedGeom").Select
    A_sc = Range("B36").Value
    fy = Range("B14").Value
    dsubc = Range("B45").Value
    ac = Range("B54").Value
    Apsc = Range("B35").Value
    fpsc = Range("B53").Value
    hc = Range("B6").Value
    LengthCrack = Range("B17").Value
    FromSupportCrack = Range("B20").Value
    bc = Range("B5").Value
Sheets("AASHTO Loads").Select
    gDCo = Range("B29").Value
    gDWo = Range("B30").Value
    gLLo = Range("B31").Value
    gDCi = Range("D29").Value
    gDWi = Range("D30").Value
    gLLi = Range("D31").Value
    'Moments (kip*in)
    DC = Range("B2").Value
    DW = Range("B3").Value
    LL = Range("B4").Value
    LLv = Range("D4").Value
    'Distributed Loads (kip/in)
    w_DC = 8 * DC / L ^ 2
    w_DW = 8 * DW / L ^ 2
```

```vba
    w_LLm = 8 * LL / L ^ 2
    w_LLv = 8 * LLv / L ^ 2
    phif = Range("B23").Value
    phiv = Range("B24").Value
    phic = Range("B25").Value
    phis = Range("B26").Value
    A1 = Range("B36").Value
    A2o = Range("B37").Value
    A2i = Range("D37").Value

Sheets("DataTable").Select
'Loop to Generate Values for Damaged Portion of Table
For i = 0 To L
     'Calculates dpsc STRICTLY BASED ON h - hc
         Cells(i + 3, 3).Value = Cells(i + 3, 2).Value - (h - hc)
          'Calculates phi*Mncracked
         Cells(i + 3, 6).Value = 1# * (Apsc * fpsc * (Cells(i + 3,
    3) - ac / 2))
          'Calculates Vu*dpd/Mu
If i = 0 Then
         Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i +
    3, 3) / (Cells(i + 4, 4))
        ElseIf i = L Then
         Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i +
    3, 3) / (Cells(i + 2, 4))
        Else
         Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i +
    3, 3) / (Cells(i + 3, 4))
      End If
'Tests Vu*dpd/Mu <=1
      If Cells(i + 3, 15).Value > 1 Then
          Cells(i + 3, 16).Value = 1
        Else
          Cells(i + 3, 16).Value = Cells(i + 3, 15)
      End If
'Tests U.L. & L.L.
      If (Cells(i + 3, 16).Value * 0.7) > (5 * (fc) ^ (1 / 2) / 1000)
      Then
          Cells(i + 3, 17).Value = 5 * (fc) ^ (1 / 2) / 1000
      ElseIf (Cells(i + 3, 16).Value * 0.7) < (2 * (fc) ^ (1 / 2) /
          1000)
      Then
          Cells(i + 3, 17).Value = 2 * (fc) ^ (1 / 2) / 1000
      Else
          Cells(i + 3, 17).Value = 0.7 * Cells(i + 3, 16)
      End If
      'Vcd
      Cells(i + 3, 18).Value = (0.6 * (fc) ^ (1 / 2) / 1000 + Cells(i +
      3, 17).Value) * bc * dsubc
      'Vsd
      Cells(i + 3, 19).Value = Av * fy * dsubc / S
      'phi*Vnd
      If i < L / 2 Then
          Cells(i + 3, 20).Value = 0.75 * (Cells(i + 3, 18) + Cells(i
          + 3, 19))
        Else
```

```
        Cells(i + 3, 20).Value = -0.75 * (Cells(i + 3, 18) +
        Cells(i + 3, 19))
End If
If i = 0 Or i = L Then
        'Load Rating Cracked
        'LRFR RF_moment_operating_cracked
        Cells(3, 29).Value = (phic * phis * phif * Cells(4, 6) -
        gDCo * Cells(4, 22) - gDWo * Cells(4, 23)) / (gLLo *
        Cells(4, 24))
        'LFR RF_moment_operating_cracked
        Cells(3, 41).Value = (phif * Cells(4, 6) - A1 * Cells(4,
        22) - A1 * Cells(4, 23)) / (A2o * Cells(4, 24))
        'LRFR RF_moment_inventory_cracked
        Cells(3, 32).Value = ((phic * phis * phif * Cells(4, 6)) -
        (gDCi * Cells(4, 22)) - (gDWi * Cells(4, 23))) / (gLLi *
        Cells(4, 24))
        Cells(472, 29).Value = Cells(3, 29).Value
        Cells(472, 32).Value = Cells(3, 32).Value
        'LFR RF_moment_inventory_cracked
        Cells(3, 44).Value = (phif * Cells(4, 6) - A1 * Cells(4,
        22) - A1 * Cells(4, 23)) / (A2i * Cells(4, 24))
    Else
        'LRFR RF_moment_operating_cracked
        Cells(i + 3, 29).Value = (phic * phis * phif * Cells(i + 3,
        6) - gDCo * Cells(i + 3, 22) - gDWo * Cells(i + 3, 23)) /
        (gLLo * Cells(i + 3, 24))
        'LFR RF_moment_operating_cracked
        Cells(i + 3, 41).Value = (phif * Cells(i + 3, 6) - A1 *
        Cells(i + 3, 22) - A1 * Cells(i + 3, 23)) / (A2o * Cells(i
        + 3, 24))
        'LRFR RF_moment_inventory_cracked
        Cells(i + 3, 32).Value = ((phic * phis * phif * Cells(i +
        3, 6)) - (gDCi * Cells(i + 3, 22)) - (gDWi * Cells(i + 3,
        23))) / (gLLi * Cells(i + 3, 24))
        'LFR RF_moment_inventory_cracked
        Cells(i + 3, 44).Value = (phif * Cells(i + 3, 6) - A1 *
        Cells(i + 3, 22) - A1 * Cells(i + 3, 23)) / (A2i * Cells(i
        + 3, 24))
End If
If Cells(i + 3, 27).Value = 0 Then
        'LRFR RF_shear_operating_cracked
        Cells(i + 3, 35).Value = Cells(i + 2, 35).Value
    Else
        'LRFR RF_shear_operating_cracked
        Cells(i + 3, 35).Value = (phic * phis * phif * Cells(i + 3,
        20) - gDCo * Cells(i + 3, 25) - gDWo * Cells(i + 3, 26)) /
        (gLLo * Cells(i + 3, 27))
        'LRFR RF_shear_inventory_cracked
        Cells(i + 3, 38).Value = (phic * phis * phif * Cells(i + 3,
        20) - gDCi * Cells(i + 3, 25) - gDWi * Cells(i + 3, 26)) /
        (gLLi * Cells(i + 3, 27))
End If
'Loop to Create a Mn, Vn, and LRFR RFmo, LRFR RFmi, LRFR RFvo,
LRFR RFvi for Plotting
If i < (FromSupportCrack - LengthCrack / 2) Then
        'Mn Plot Data
        Cells(i + 3, 7).Value = Cells(i + 3, 5)
```

```
            'Vn Plot Data
            Cells(i + 3, 21).Value = Cells(i + 3, 14)
                    'LRFR RFmo cracked Plot Data
                    Cells(i + 3, 30).Value = Cells(i + 3, 28)
                    'LRFR RFmi cracked Plot Data
                    Cells(i + 3, 33).Value = Cells(i + 3, 31)
                    'LRFR RFvo cracked Plot Data
                    Cells(i + 3, 36).Value = Cells(i + 3, 34)
                    'LRFR RFvi cracked Plot Data
                    Cells(i + 3, 39).Value = Cells(i + 3, 37)
                    'LFR RFmo Plot Data
                    Cells(i + 3, 42).Value = Cells(i + 3, 40)
                    'LFR RFmi Plot Data
                    Cells(i + 3, 45).Value = Cells(i + 3, 43)
                ElseIf i > FromSupportCrack + LengthCrack / 2 Then
                    'Mn Plot Data
                    Cells(i + 3, 7).Value = Cells(i + 3, 5)
                    'Vn Plot Data
                    Cells(i + 3, 21).Value = Cells(i + 3, 14)
                    'LRFR RFmo Plot Data
                    Cells(i + 3, 30).Value = Cells(i + 3, 28)
                    'LRFR RFmi cracked Plot Data
                    Cells(i + 3, 33).Value = Cells(i + 3, 31)
                    'LRFR RFvo cracked Plot Data
                    Cells(i + 3, 36).Value = Cells(i + 3, 34)
                    'LRFR RFvi cracked Plot Data
                    Cells(i + 3, 39).Value = Cells(i + 3, 37)
                    'LFR RFmo Plot Data
                    Cells(i + 3, 42).Value = Cells(i + 3, 40)
                    'LFR RFmi Plot Data
                    Cells(i + 3, 45).Value = Cells(i + 3, 43)
                Else
                    'Calculates phi*Mncracked plot data
                    Cells(i + 3, 7).Value = 1# * (Apsc * fpsc *
                    (Cells(i + 3, 3) - ac / 2))
                    'Vncracked Plot Data
                    Cells(i + 3, 21).Value = Cells(i + 3, 20)
                    'LRFR RFmo cracked Plot Data
                    Cells(i + 3, 30).Value = Cells(i + 3, 29)
                    'LRFR RFmi cracked Plot Data
                    Cells(i + 3, 33).Value = Cells(i + 3, 32)
                    'LRFR RFvo cracked Plot Data
                    Cells(i + 3, 36).Value = Cells(i + 3, 35)
                    'LRFR RFvi cracked Plot Data
                    Cells(i + 3, 39).Value = Cells(i + 3, 38)

                    'LFR RFmo Plot Data
                    Cells(i + 3, 42).Value = Cells(i + 3, 41)
                    'LFR RFmi Plot Data
                    Cells(i + 3, 45).Value = Cells(i + 3, 44)
                End If
    Next

    Call MuMnChart
    Call VuVnChart
    Call RFMChart
    Call RFVChart
```

```vba
      Call LFRRFMChart

'Finds Minimum Moment RF's
Sheets("DataTable").Select
Dim RForng As Range: Dim RFirng As Range: Dim RFvorng As Range: Dim RFvirng
As Range: Dim minimumo As Double: Dim minimumi As Double: Dim minimumvo As
Double: Dim minimumvi As Double:

        'minimum LRFR RF moment operating
        Set RForng = Range("AD3:AD472")
        minimumo = Application.WorksheetFunction.Min(RForng)
        Range("AD1").Value = minimumo
        Range("AC1").Value = "LRFR RF Moment Operating"
        'minimum LRFR RF moment inventory
        Set RFirng = Range("AG3:AG472")
        minimumi = Application.WorksheetFunction.Min(RFirng)
        Range("AG1").Value = minimumi
        Range("AE1").Value = "LRFR RF Moment Inventory"
        'minimum LRFR RF shear operating
        Set RFvorng = Range("AJ3:AJ472")
        minimumvo = Application.WorksheetFunction.Min(RFvorng)
        Range("AJ1").Value = minimumvo
        Range("AI1").Value = "RF Shear Operating"
        'minimum LRFR RF shear inventory
        Set RFvirng = Range("AM3:AM472")
        minimumvi = Application.WorksheetFunction.Min(RFvirng)
        Range("AM1").Value = minimumvi
        Range("AL1").Value = "RF Shear Inventory"
        'formats
        Range("AC1:AM1").Select
        Selection.Font.Bold = True
        Range("A1").Select

    'Reorders Sheets and Ends on RF Chart
        Sheets("LRFRShearRatingFactor").Select
        Sheets("LRFRShearRatingFactor").Move After:=Sheets(10)
        Sheets("LRFRMomentRatingFactor").Select
        Sheets("LRFRMomentRatingFactor").Move Before:=Sheets(10)
        Sheets("ShearCapacity").Select
        Sheets("ShearCapacity").Move Before:=Sheets(9)
        Sheets("MomentCapacity").Select
        ActiveChart.ChartArea.Select
End Sub




Sub Spalled()

Dim C_sev As Integer: Dim Crack As String: Dim phic As Single: Dim S_sev As
Integer: Dim Spall As String: Dim D_sev As Integer: Dim Delam As String: Dim
Length As Single: Dim harp As Single: Dim h As Single: Dim cover As Single:
Dim c_t As Single: Dim A_s As Single: Dim fy As Single: Dim D As Single: Dim
a As Single: Dim A_ps As Single: Dim fps As Single: Dim fc As Single: Dim b
As Single: Dim Av As Single: Dim S As Single: Dim A_sc As Single: Dim dsubc
As Single: Dim ac As Single: Dim Apsc As Single: Dim fpsc As Single: Dim hc
As Single: Dim LengthCrack As Single: Dim FromSupportCrack As Single: Dim bc
```

```
As Single: Dim gDCo As Single: Dim gDWo As Single: Dim gLLo As Single: Dim
gDCi As Single: Dim gDWi As Single: Dim gLLi As Single: Dim DC As Single: Dim
DW As Single: Dim LL As Single: Dim w_DC As Single: Dim w_DW As Single: Dim
w_LLm As Single: Dim phif As Single: Dim phiv As Single: Dim phis As Single:

        Call CheckAddSheet3Keep
        Call CheckAddSheet4Keep
        Call CheckAddSheet5Keep
        Call CheckAddSheet6Keep
        Call CheckAddSheet7Keep
        Call CheckAddSheet8Keep


                Spall = Sheets("UndamagedGeom").Range("B23").Value
                S_sev = Sheets("UndamagedGeom").Range("B24").Value


    'msgbox for improper values
        If Spall = "No" Or S_sev = 0 Then
          MsgBox ("This section has no spalling, please re-enter damage
          type")
          End
        End If
    'msgbox and phi_c definition for low severity
        If S_sev = 1 Or S_sev = 2 Then
          MsgBox ("Low Severity Spalling" & vbNewLine & vbNewLine &
          "Recommended Maintenance:  None")
          phic = 1
        End If
    'msgbox and phi_c definition for medium severity
        If S_sev = S Or S_sev = 3 Then
           MsgBox ("Medium Severity Spalling" & vbNewLine & vbNewLine &
          "Recommended Maintenance: Patch and/or Seal")
          phic = 0.955
        End If
    'msgbox and phi_c definition for high severity
        If S_sev = 4 Or S_sev = 5 Then
          MsgBox ("High Severity Spalling" & vbNewLine & vbNewLine &
          "Recommended Maintenance: Clean Steel Reinforcement, Patch, and
          Seal or Replace Unit")
          phic = 0.855
        End If

    'places phi_c value on BIMInspection Page
    Sheets("UndamagedGeom").Select
    Range("A100").Value = phic

    Call UndamagedGeometry
    Call CrackedGeometry
    Call SpallGeometry
    Call DelamGeometry
    Call Loads
    Call DataTableUndamagedInfo
    Call Maintain

    'Grabs Variables from UndamagedGeom
    Dim L As Integer
    Sheets("UndamagedGeom").Select
        L = Range("B4").Value
```

182

```vba
    Length = Range("B4").Value
    harp = Range("B71").Value
    h = Range("B6").Value
    cover = Range("B48").Value
    c_t = Range("B41").Value
    A_s = Range("B52").Value
    fy = Range("B14").Value
    D = Range("B61").Value
    a = Range("B70").Value
    A_ps = Range("B51").Value
    fps = Range("B69").Value
    fc = Range("B11").Value * 1000
    b = Range("B5").Value
    Av = Range("B53").Value
    S = Range("B54").Value
'Grabs more variables from Cracked Geom
Sheets("SpallGeom").Select
    A_sc = Range("B36").Value
    fy = Range("B14").Value
    dsubc = Range("B45").Value
    ac = Range("B54").Value
    Apsc = Range("B35").Value
    fpsc = Range("B53").Value
    hc = Range("B6").Value
    LengthSpall = Range("B17").Value
    FromSupportSpall = Range("B20").Value
    bc = Range("B5").Value
Sheets("AASHTO Loads").Select
    gDCo = Range("B29").Value
    gDWo = Range("B30").Value
    gLLo = Range("B31").Value
    gDCi = Range("D29").Value
    gDWi = Range("D30").Value
    gLLi = Range("D31").Value
    'Moments (kip*in)
    DC = Range("B2").Value
    DW = Range("B3").Value
    LL = Range("B4").Value
    LLv = Range("D4").Value
    'Distributed Loads (kip/in)
    w_DC = 8 * DC / L ^ 2
    w_DW = 8 * DW / L ^ 2
    w_LLm = 8 * LL / L ^ 2
    w_LLv = 8 * LLv / L ^ 2
    phif = Range("B23").Value
    phiv = Range("B24").Value
    phic = Range("B25").Value
    phis = Range("B26").Value
    A1 = Range("B36").Value
    A2o = Range("B37").Value
    A2i = Range("D37").Value

Sheets("DataTable").Select
'Loop to Generate Values for Damaged Portion of Table
For i = 0 To L
            'Calculates dpsc STRICTLY BASED ON h - hc
            Cells(i + 3, 3).Value = Cells(i + 3, 2).Value - (h - hc)
```

```
            'Calculates phi*Mncracked
            Cells(i + 3, 6).Value = 1# * (Apsc * fpsc * (Cells(i + 3,
            3) - ac / 2))
            'Calculates Vu*dpd/Mu
If i = 0 Then
            Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i +
            3, 3) / (Cells(i + 4, 4))
        ElseIf i = L Then
            Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i +
            3, 3) / (Cells(i + 2, 4))
        Else
            Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i +
            3, 3) / (Cells(i + 3, 4))
End If
            'Tests Vu*dpd/Mu <=1
If Cells(i + 3, 15).Value > 1 Then
            Cells(i + 3, 16).Value = 1
        Else
            Cells(i + 3, 16).Value = Cells(i + 3, 15)
End If
            'Tests U.L. & L.L.
If (Cells(i + 3, 16).Value * 0.7) > (5 * (fc) ^ (1 / 2) / 1000)
    Then
            Cells(i + 3, 17).Value = 5 * (fc) ^ (1 / 2) / 1000
            ElseIf (Cells(i + 3, 16).Value * 0.7) < (2 * (fc) ^ (1 / 2)
            / 1000)
    Then
            Cells(i + 3, 17).Value = 2 * (fc) ^ (1 / 2) / 1000
    Else
            Cells(i + 3, 17).Value = 0.7 * Cells(i + 3, 16)
End If
            'Vcd
            Cells(i + 3, 18).Value = (0.6 * (fc) ^ (1 / 2) / 1000 +
            Cells(i + 3, 17).Value) * bc * dsubc
            'Vsd
            Cells(i + 3, 19).Value = Av * fy * dsubc / S

            'phi*Vnd
If i < L / 2 Then
            Cells(i + 3, 20).Value = 0.75 * (Cells(i + 3, 18) + Cells(i
            + 3, 19))
        Else
            Cells(i + 3, 20).Value = -0.75 * (Cells(i + 3, 18) +
            Cells(i + 3, 19))
End If
If i = 0 Or i = L Then
        'Load Rating Cracked
        'LRFR RF_moment_operating_cracked
        Cells(3, 29).Value = (phic * phis * phif * Cells(4, 6) -
        gDCo * Cells(4, 22) - gDWo * Cells(4, 23)) / (gLLo *
        Cells(4, 24))
        'LFR RF_moment_operating_cracked
        Cells(3, 41).Value = (phif * Cells(4, 6) - A1 * Cells(4,
        22) - A1 * Cells(4, 23)) / (A2o * Cells(4, 24))
        'LRFR RF_moment_inventory_cracked
```

```
            Cells(3, 32).Value = ((phic * phis * phif * Cells(4, 6)) -
            (gDCi * Cells(4, 22)) - (gDWi * Cells(4, 23))) / (gLLi *
            Cells(4, 24))
            Cells(472, 29).Value = Cells(3, 29).Value
            Cells(472, 32).Value = Cells(3, 32).Value
            'LFR RF_moment_inventory_cracked
            Cells(3, 44).Value = (phif * Cells(4, 6) - A1 * Cells(4,
            22) - A1 * Cells(4, 23)) / (A2i * Cells(4, 24))
        Else
            'LRFR RF_moment_operating_cracked
            Cells(i + 3, 29).Value = (phic * phis * phif * Cells(i + 3,
            6) - gDCo * Cells(i + 3, 22) - gDWo * Cells(i + 3, 23)) /
            (gLLo * Cells(i + 3, 24))
            'LFR RF_moment_operating_cracked
            Cells(i + 3, 41).Value = (phif * Cells(i + 3, 6) - A1 *
            Cells(i + 3, 22) - A1 * Cells(i + 3, 23)) / (A2o * Cells(i
            + 3, 24))
            'LRFR RF_moment_inventory_cracked
            Cells(i + 3, 32).Value = ((phic * phis * phif * Cells(i +
            3, 6)) - (gDCi * Cells(i + 3, 22)) - (gDWi * Cells(i + 3,
            23))) / (gLLi * Cells(i + 3, 24))
            'LFR RF_moment_inventory_cracked
            Cells(i + 3, 44).Value = (phif * Cells(i + 3, 6) - A1 *
            Cells(i + 3, 22) - A1 * Cells(i + 3, 23)) / (A2i * Cells(i
            + 3, 24))
    End If

    If Cells(i + 3, 27).Value = 0 Then
            'LRFR RF_shear_operating_cracked
            Cells(i + 3, 35).Value = Cells(i + 2, 35).Value
            Else
            'LRFR RF_shear_operating_cracked
            Cells(i + 3, 35).Value = (phic * phis * phif * Cells(i + 3,
            20) - gDCo * Cells(i + 3, 25) - gDWo * Cells(i + 3, 26)) /
            (gLLo * Cells(i + 3, 27))
            'LRFR RF_shear_inventory_cracked
            Cells(i + 3, 38).Value = (phic * phis * phif * Cells(i + 3,
            20) - gDCi * Cells(i + 3, 25) - gDWi * Cells(i + 3, 26)) /
            (gLLi * Cells(i + 3, 27))
        End If

        'Loop to Create a Mn, Vn, and LRFR RFmo, LRFR RFmi, LRFR RFvo,
        LRFR RFvi for Plotting
        If i < (FromSupportSpall - LengthSpall / 2) Then
            'Mn Plot Data
            Cells(i + 3, 7).Value = Cells(i + 3, 5)
            'Vn Plot Data
            Cells(i + 3, 21).Value = Cells(i + 3, 14)
            'LRFR RFmo cracked Plot Data
            Cells(i + 3, 30).Value = Cells(i + 3, 28)
            'LRFR RFmi cracked Plot Data
            Cells(i + 3, 33).Value = Cells(i + 3, 31)
            'LRFR RFvo cracked Plot Data
            Cells(i + 3, 36).Value = Cells(i + 3, 34)
            'LRFR RFvi cracked Plot Data
            Cells(i + 3, 39).Value = Cells(i + 3, 37)
            'LFR RFmo Plot Data
```

185

```vba
                Cells(i + 3, 42).Value = Cells(i + 3, 40)
                'LFR RFmi Plot Data
                Cells(i + 3, 45).Value = Cells(i + 3, 43)
            ElseIf i > FromSupportSpall + LengthSpall / 2 Then
                'Mn Plot Data
                Cells(i + 3, 7).Value = Cells(i + 3, 5)
                'Vn Plot Data
                Cells(i + 3, 21).Value = Cells(i + 3, 14)
                'LRFR RFmo Plot Data
                Cells(i + 3, 30).Value = Cells(i + 3, 28)
                'LRFR RFmi cracked Plot Data
                Cells(i + 3, 33).Value = Cells(i + 3, 31)
                'LRFR RFvo cracked Plot Data
                Cells(i + 3, 36).Value = Cells(i + 3, 34)
                'LRFR RFvi cracked Plot Data
                Cells(i + 3, 39).Value = Cells(i + 3, 37)
                'LFR RFmo Plot Data
                Cells(i + 3, 42).Value = Cells(i + 3, 40)
                'LFR RFmi Plot Data
                Cells(i + 3, 45).Value = Cells(i + 3, 43)
            Else
                'Calculates phi*Mncracked plot data
                Cells(i + 3, 7).Value = 1# * (Apsc * fpsc * (Cells(i + 3,
                3) - ac / 2))
                'Vncracked Plot Data
                Cells(i + 3, 21).Value = Cells(i + 3, 20)
                'LRFR RFmo cracked Plot Data
                Cells(i + 3, 30).Value = Cells(i + 3, 29)
                'LRFR RFmi cracked Plot Data
                Cells(i + 3, 33).Value = Cells(i + 3, 32)
                'LRFR RFvo cracked Plot Data
                Cells(i + 3, 36).Value = Cells(i + 3, 35)
                'LRFR RFvi cracked Plot Data
                Cells(i + 3, 39).Value = Cells(i + 3, 38)
                'LFR RFmo Plot Data
                Cells(i + 3, 42).Value = Cells(i + 3, 41)
                'LFR RFmi Plot Data
                Cells(i + 3, 45).Value = Cells(i + 3, 44)
            End If
        Next

        Call MuMnChart
        Call VuVnChart
        Call RFMChart
        Call RFVChart
        Call LFRRFMChart

'Finds Minimum Moment RF's
Sheets("DataTable").Select
Dim RForng As Range: Dim RFirng As Range: Dim RFvorng As Range: Dim RFvirng
As Range: Dim minimumo As Double: Dim minimumi As Double: Dim minimumvo As
Double: Dim minimumvi As Double:

        'minimum LRFR RF moment operating
        Set RForng = Range("AD3:AD472")
        minimumo = Application.WorksheetFunction.Min(RForng)
        Range("AD1").Value = minimumo
```

```vba
        Range("AC1").Value = "LRFR RF Moment Operating"
        'minimum LRFR RF moment inventory
        Set RFirng = Range("AG3:AG472")
        minimumi = Application.WorksheetFunction.Min(RFirng)
        Range("AG1").Value = minimumi
        Range("AE1").Value = "LRFR RF Moment Inventory"
        'minimum LRFR RF shear operating
        Set RFvorng = Range("AJ3:AJ472")
        minimumvo = Application.WorksheetFunction.Min(RFvorng)
        Range("AJ1").Value = minimumvo
        Range("AI1").Value = "RF Shear Operating"
        'minimum LRFR RF shear inventory
        Set RFvirng = Range("AM3:AM472")
        minimumvi = Application.WorksheetFunction.Min(RFvirng)
        Range("AM1").Value = minimumvi
        Range("AL1").Value = "RF Shear Inventory"
        'formats
        Range("AC1:AM1").Select
        Selection.Font.Bold = True
        Range("A1").Select

    'Reorders Sheets and Ends on RF Chart
        Sheets("LRFRShearRatingFactor").Select
        Sheets("LRFRShearRatingFactor").Move After:=Sheets(10)
        Sheets("LRFRMomentRatingFactor").Select
        Sheets("LRFRMomentRatingFactor").Move Before:=Sheets(10)
        Sheets("ShearCapacity").Select
        Sheets("ShearCapacity").Move Before:=Sheets(9)
        Sheets("MomentCapacity").Select
        ActiveChart.ChartArea.Select
End Sub




Sub Delaminated()

    Dim C_sev As Integer: Dim Crack As String: Dim phic As Single: Dim S_sev
    As Integer: Dim Spall As String: Dim D_sev As Integer: Dim Delam As
    String: Dim Length As Single: Dim harp As Single: Dim h As Single: Dim
    cover As Single: Dim c_t As Single: Dim A_s As Single: Dim fy As Single:
    Dim D As Single: Dim a As Single: Dim A_ps As Single: Dim fps As Single:
    Dim fc As Single: Dim b As Single: Dim Av As Single: Dim S As Single: Dim
    A_sc As Single: Dim dsubc As Single: Dim ac As Single: Dim Apsc As Single:
    Dim fpsc As Single: Dim hc As Single: Dim LengthCrack As Single: Dim
    FromSupportCrack As Single: Dim bc As Single: Dim gDCo As Single: Dim gDWo
    As Single: Dim gLLo As Single: Dim gDCi As Single: Dim gDWi As Single: Dim
    gLLi As Single: Dim DC As Single: Dim DW As Single: Dim LL As Single: Dim
    w_DC As Single: Dim w_DW As Single: Dim w_LLm As Single: Dim phif As
    Single: Dim phiv As Single: Dim phis As Single:

    Call CheckAddSheet3Keep
    Call CheckAddSheet4Keep
    Call CheckAddSheet5Keep
    Call CheckAddSheet6Keep
```

```
Call CheckAddSheet7Keep
Call CheckAddSheet8Keep

        Delam = Sheets("UndamagedGeom").Range("B31").Value
        D_sev = Sheets("UndamagedGeom").Range("B32").Value

'msgbox for improper values
    If Delam = "No" Or D_sev = 0 Then
      MsgBox ("This section has no delamination, please re-enter damage
      type")
      End
    End If
      'msgbox and phi_c definition for low severity
    If D_sev = 1 Or D_sev = 2 Then
      MsgBox ("Low Severity Delamination" & vbNewLine & vbNewLine &
      "Recommended Maintenance:  None")
      phi_c = 1
    End If
      'msgbox and phi_c definition for medium severity
    If D_sev = 3 Or D_sev = 4 Then
      'edit message box
      MsgBox ("Inject epoxy fill or remove affected area and patch
      similar to a spall")
      phi_c = 0.955
    End If
      'msgbox and phi_c definition for high severity
    If D_sev = 5 Then
      'edit message box
      MsgBox ("High Severity Delamination" & vbNewLine & vbNewLine &
      "Replace Unit")
      phi_c = 0.855
    End If

'places phi_c value on UndamagedGeom Page
Sheets("UndamagedGeom").Select
Range("A100").Value = phi_c

Call UndamagedGeometry
Call CrackedGeometry
Call SpallGeometry
Call DelamGeometry
Call Loads
Call DataTableUndamagedInfo
Call Maintain

'Grabs Variables from UndamagedGeom
Dim L As Integer
Sheets("UndamagedGeom").Select
    L = Range("B4").Value
    Length = Range("B4").Value
    harp = Range("B71").Value
    h = Range("B6").Value
    cover = Range("B48").Value
    c_t = Range("B41").Value
    A_s = Range("B52").Value
    fy = Range("B14").Value
    D = Range("B61").Value
```

```
    a = Range("B70").Value
    A_ps = Range("B51").Value
    fps = Range("B69").Value
    fc = Range("B11").Value * 1000
    b = Range("B5").Value
    Av = Range("B53").Value
    S = Range("B54").Value
'Grabs more variables from Delam Geom
Sheets("DelamGeom").Select
    A_sc = Range("B36").Value
    fy = Range("B14").Value
    dsubc = Range("B45").Value
    ac = Range("B54").Value
    Apsc = Range("B35").Value
    fpsc = Range("B53").Value
    hc = Range("B6").Value
    LengthDelam = Range("B17").Value
    FromSupportDelam = Range("B20").Value
    bc = Range("B5").Value
Sheets("AASHTO Loads").Select
    gDCo = Range("B29").Value
    gDWo = Range("B30").Value
    gLLo = Range("B31").Value
    gDCi = Range("D29").Value
    gDWi = Range("D30").Value
    gLLi = Range("D31").Value
    'Moments (kip*in)
    DC = Range("B2").Value
    DW = Range("B3").Value
    LL = Range("B4").Value
    LLv = Range("D4").Value
    'Distributed Loads (kip/in)
    w_DC = 8 * DC / L ^ 2
    w_DW = 8 * DW / L ^ 2
    w_LLm = 8 * LL / L ^ 2
    w_LLv = 8 * LLv / L ^ 2
    phif = Range("B23").Value
    phiv = Range("B24").Value
    phic = Range("B25").Value
    phis = Range("B26").Value
    A1 = Range("B36").Value
    A2o = Range("B37").Value
    A2i = Range("D37").Value

Sheets("DataTable").Select
'Loop to Generate Values for Damaged Portion of Table
For i = 0 To L
     'Calculates dpsc STRICTLY BASED ON h - hc
     Cells(i + 3, 3).Value = Cells(i + 3, 2).Value - (h - hc)
     'Calculates phi*Mncracked
     Cells(i + 3, 6).Value = 1# * (Apsc * fpsc * (Cells(i + 3, 3) - ac
     / 2))
     'Calculates Vu*dpd/Mu

If i = 0 Then
     Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i + 3, 3) /
     (Cells(i + 4, 4))
```

189

```
    ElseIf i = L Then
        Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i + 3, 3) /
        (Cells(i + 2, 4))
    Else
        Cells(i + 3, 15).Value = Abs(Cells(i + 3, 8)) * Cells(i + 3, 3) /
        (Cells(i + 3, 4))
End If

'Tests Vu*dpd/Mu <=1
If Cells(i + 3, 15).Value > 1 Then
        Cells(i + 3, 16).Value = 1
    Else
        Cells(i + 3, 16).Value = Cells(i + 3, 15)
End If

'Tests U.L. & L.L.
If (Cells(i + 3, 16).Value * 0.7) > (5 * (fc) ^ (1 / 2) / 1000) Then
        Cells(i + 3, 17).Value = 5 * (fc) ^ (1 / 2) / 1000
        ElseIf (Cells(i + 3, 16).Value * 0.7) < (2 * (fc) ^ (1 / 2) /
        1000) Then
        Cells(i + 3, 17).Value = 2 * (fc) ^ (1 / 2) / 1000
        Else
        Cells(i + 3, 17).Value = 0.7 * Cells(i + 3, 16)
End If
        'Vcd
        Cells(i + 3, 18).Value = (0.6 * (fc) ^ (1 / 2) / 1000 + Cells(i +
        3, 17).Value) * bc * dsubc
        'Vsd
        Cells(i + 3, 19).Value = Av * fy * dsubc / S
        'phi*Vnd
If i < L / 2 Then
        Cells(i + 3, 20).Value = 0.75 * (Cells(i + 3, 18) + Cells(i + 3,
        19))
    Else
        Cells(i + 3, 20).Value = -0.75 * (Cells(i + 3, 18) + Cells(i + 3,
        19))
End If

If i = 0 Or i = L Then
'Load Rating Delaminated
'LRFR RF_moment_operating_delaminated
        Cells(3, 29).Value = (phic * phis * phif * Cells(4, 6) - gDCo *
        Cells(4, 22) - gDWo * Cells(4, 23)) / (gLLo * Cells(4, 24))
        'LFR RF_moment_operating_delaminated
        Cells(3, 41).Value = (phif * Cells(4, 6) - A1 * Cells(4, 22) - A1
        * Cells(4, 23)) / (A2o * Cells(4, 24))
        'LRFR RF_moment_inventory_delaminated
        Cells(3, 32).Value = ((phic * phis * phif * Cells(4, 6)) - (gDCi
        * Cells(4, 22)) - (gDWi * Cells(4, 23))) / (gLLi * Cells(4, 24))
        Cells(472, 29).Value = Cells(3, 29).Value
        Cells(472, 32).Value = Cells(3, 32).Value
        'LFR RF_moment_inventory_delaminated
        Cells(3, 44).Value = (phif * Cells(4, 6) - A1 * Cells(4, 22) - A1
        * Cells(4, 23)) / (A2i * Cells(4, 24))
    Else
        'LRFR RF_moment_operating_delaminated
```

```
      Cells(i + 3, 29).Value = (phic * phis * phif * Cells(i + 3, 6) -
      gDCo * Cells(i + 3, 22) - gDWo * Cells(i + 3, 23)) / (gLLo *
      Cells(i + 3, 24))
      'LFR RF_moment_operating_delaminated
      Cells(i + 3, 41).Value = (phif * Cells(i + 3, 6) - A1 * Cells(i +
      3, 22) - A1 * Cells(i + 3, 23)) / (A2o * Cells(i + 3, 24))
      'LRFR RF_moment_inventory_delaminated
      Cells(i + 3, 32).Value = ((phic * phis * phif * Cells(i + 3, 6))
      - (gDCi * Cells(i + 3, 22)) - (gDWi * Cells(i + 3, 23))) / (gLLi
      * Cells(i + 3, 24))
      'LFR RF_moment_inventory_delaminated
      Cells(i + 3, 44).Value = (phif * Cells(i + 3, 6) - A1 * Cells(i +
      3, 22) - A1 * Cells(i + 3, 23)) / (A2i * Cells(i + 3, 24))
End If

If Cells(i + 3, 27).Value = 0 Then
      'LRFR RF_shear_operating_delaminated
      Cells(i + 3, 35).Value = Cells(i + 2, 35).Value
  Else
      'LRFR RF_shear_operating_delaminated
      Cells(i + 3, 35).Value = (phic * phis * phif * Cells(i + 3, 20) -
      gDCo * Cells(i + 3, 25) - gDWo * Cells(i + 3, 26)) / (gLLo *
      Cells(i + 3, 27))
      'LRFR RF_shear_inventory_delaminated
      Cells(i + 3, 38).Value = (phic * phis * phif * Cells(i + 3, 20) -
      gDCi * Cells(i + 3, 25) - gDWi * Cells(i + 3, 26)) / (gLLi *
      Cells(i + 3, 27))
End If

'Loop to Create a Mn, Vn, and LRFR RFmo, LRFR RFmi, LRFR RFvo, LRFR
RFvi for Plotting
      If i < (FromSupportDelam - LengthDelam / 2) Then
                  'Mn Plot Data
                  Cells(i + 3, 7).Value = Cells(i + 3, 5)
                  'Vn Plot Data
                  Cells(i + 3, 21).Value = Cells(i + 3, 14)
                  'LRFR RFmo cracked Plot Data
                  Cells(i + 3, 30).Value = Cells(i + 3, 28)
                  'LRFR RFmi cracked Plot Data
                  Cells(i + 3, 33).Value = Cells(i + 3, 31)
                    'LRFR RFvo cracked Plot Data
                    Cells(i + 3, 36).Value = Cells(i + 3, 34)
                    'LRFR RFvi cracked Plot Data
                    Cells(i + 3, 39).Value = Cells(i + 3, 37)
                    'LFR RFmo Plot Data
                    Cells(i + 3, 42).Value = Cells(i + 3, 40)
                    'LFR RFmi Plot Data
                    Cells(i + 3, 45).Value = Cells(i + 3, 43)
                ElseIf i > FromSupportDelam + LengthDelam / 2 Then
                    'Mn Plot Data
                    Cells(i + 3, 7).Value = Cells(i + 3, 5)
                    'Vn Plot Data
                    Cells(i + 3, 21).Value = Cells(i + 3, 14)
                    'LRFR RFmo Plot Data
                    Cells(i + 3, 30).Value = Cells(i + 3, 28)
                    'LRFR RFmi cracked Plot Data
                    Cells(i + 3, 33).Value = Cells(i + 3, 31)
```

```
                              'LRFR RFvo cracked Plot Data
                              Cells(i + 3, 36).Value = Cells(i + 3, 34)
                              'LRFR RFvi cracked Plot Data
                              Cells(i + 3, 39).Value = Cells(i + 3, 37)
                              'LFR RFmo Plot Data
                              Cells(i + 3, 42).Value = Cells(i + 3, 40)
                              'LFR RFmi Plot Data
                              Cells(i + 3, 45).Value = Cells(i + 3, 43)
                       Else
                              'Calculates phi*Mncracked plot data
                              Cells(i + 3, 7).Value = 1# * (Apsc *   fpsc *
                              (Cells(i + 3, 3) - ac / 2))
                              'Vncracked Plot Data
                              Cells(i + 3, 21).Value = Cells(i + 3, 20)
                              'LRFR RFmo cracked Plot Data
                              Cells(i + 3, 30).Value = Cells(i + 3, 29)
                              'LRFR RFmi cracked Plot Data
                              Cells(i + 3, 33).Value = Cells(i + 3, 32)
                              'LRFR RFvo cracked Plot Data
                              Cells(i + 3, 36).Value = Cells(i + 3, 35)
                              'LRFR RFvi cracked Plot Data
                              Cells(i + 3, 39).Value = Cells(i + 3, 38)
                              'LFR RFmo Plot Data
                              Cells(i + 3, 42).Value = Cells(i + 3, 41)
                              'LFR RFmi Plot Data
                              Cells(i + 3, 45).Value = Cells(i + 3, 44)
                End If
        Next

        Call MuMnChart
        Call VuVnChart
        Call RFMChart
        Call RFVChart
        Call LFRRFMChart


'Finds Minimum Moment RF's
Sheets("DataTable").Select
Dim RForng As Range: Dim RFirng As Range: Dim RFvorng As Range: Dim RFvirng
As Range: Dim minimumo As Double: Dim minimumi As Double: Dim minimumvo As
Double: Dim minimumvi As Double:

        'minimum LRFR RF moment operating
        Set RForng = Range("AD3:AD472")
        minimumo = Application.WorksheetFunction.Min(RForng)
        Range("AD1").Value = minimumo
        Range("AC1").Value = "LRFR RF Moment Operating"
        'minimum LRFR RF moment inventory
        Set RFirng = Range("AG3:AG472")
        minimumi = Application.WorksheetFunction.Min(RFirng)
        Range("AG1").Value = minimumi
        Range("AE1").Value = "LRFR RF Moment Inventory"
        'minimum LRFR RF shear operating
        Set RFvorng = Range("AJ3:AJ472")
        minimumvo = Application.WorksheetFunction.Min(RFvorng)
        Range("AJ1").Value = minimumvo
        Range("AI1").Value = "RF Shear Operating"
        'minimum LRFR RF shear inventory
```

```
        Set RFvirng = Range("AM3:AM472")
        minimumvi = Application.WorksheetFunction.Min(RFvirng)
        Range("AM1").Value = minimumvi
        Range("AL1").Value = "RF Shear Inventory"
        'formats
        Range("AC1:AM1").Select
        Selection.Font.Bold = True
        Range("A1").Select

    'Reorders Sheets and Ends on RF Chart
        Sheets("LRFRShearRatingFactor").Select
        Sheets("LRFRShearRatingFactor").Move After:=Sheets(10)
        Sheets("LRFRMomentRatingFactor").Select
        Sheets("LRFRMomentRatingFactor").Move Before:=Sheets(10)
        Sheets("ShearCapacity").Select
        Sheets("ShearCapacity").Move Before:=Sheets(9)
        Sheets("MomentCapacity").Select
        ActiveChart.ChartArea.Select
End Sub
```

Module 7: AASHTO Loads along with LRFR and LFR Factors

```
Sub Loads()

    Dim M_DC As Single: Dim M_DW As Single: Dim M_LLm As Single: Dim M_WS
    As Single: Dim SI As Single: Dim SII As Single: Dim SIII As Single: Dim
    SIV As Single: Dim SV As Single: Dim SerI As Single: Dim SerII As
    Single: Dim SerIII As Single: Dim SerIV As Single: Dim gDCo As Single:
    Dim gDWo As Single: Dim gLLo As Single: Dim gDCi As Single: Dim gDWi As
    Single: Dim gLLi As Single: Dim phif As Single: Dim phiv As Single: Dim
    phis As Single: Dim phic As Single:

    'Defines UNFACTORED Moments (kip*in) based on applied AASHTO Unit
    Weights, Loads, etc.
        'DC without railings & curb
        'M_DC = 1415.757

        'DC with railings & curb
        M_DC = 1892.386
        M_DW = 1263.129

        'M_LL = Dynam*DF*SF*Load = 1.33*0.804*0.927*M_LL
        'M_LLm = 5546.618

        'M_LL = Dynam*DF*SF*Load = 1.33*0.901*1.107*M_LL
        M_LLv = 7355.838

        M_WS = 5.132

    'Load Combo Calcs
        SI = 1.25 * M_DC + 1.25 * M_DW + 1.75 * M_LLm
        SII = 1.25 * M_DC + 1.25 * M_DW + 1.35 * M_LLm
        SIII = 1.25 * M_DC + 1.25 * M_DW + 1.4 * M_WS
        SIV = 1.5 * M_DC + 1.5 * M_DW
        SV = 1.25 * M_DC + 1.25 * M_DW + 1.35 * M_LLm + 0.4 * M_WS
        SerI = M_DC + M_DW + M_LLm + 0.3 * M_WS
        SerII = M_DC + M_DW + 1.3 * M_LLm
        SerIII = M_DC + M_DW + 0.8 * M_LLm
        SerIV = M_DC + M_DW + 0.7 * M_LLm

    'Builds Loads Table
    Sheets("AASHTO Loads").Select
        Range("A1").Value = "Type"
        Range("B1").Value = "Moment (kip*in)"
        Range("A2").Value = "DC (Wt. of Girder)"
        Range("B2").Value = M_DC
        Range("A3").Value = "DW (Wt. of Slab)"
        Range("B3").Value = M_DW
        Range("A4").Value = "LL+IM for Moment Calculations"
        Range("B4").Value = M_LLm
        Range("C4").Value = "LL+IM for Shear Calculations"
        Range("D4").Value = M_LLv
        Range("A5").Value = "WS (Wind Effect)"
        Range("B5").Value = M_WS
```

```vb
'Builds Load Combo Table
'Headings
    Range("A8").Value = "Type"
    Range("B8").Value = "AASHTO Load Combo"
    Range("C8").Value = "Factored Required Moment, Mu (kip*in)"
'Strength I
    Range("A9").Value = "Strength I"
    Range("B9").Value = "1.25DC + 1.25DW + 1.75LL"
    Range("C9").Value = SI
'Strength II
    Range("A10").Value = "Strength II"
    Range("B10").Value = "1.25DC + 1.25DW + 1.35LL"
    Range("C10").Value = SII
'Strength III
    Range("A11").Value = "Strength III"
    Range("B11").Value = "1.25DC + 1.25DW + 1.4WS"
    Range("C11").Value = SIII
'Strength IV
    Range("A12").Value = "Strength IV"
    Range("B12").Value = "1.5DC + 1.5DW"
    Range("C12").Value = SIV
'Strength V
    Range("A13").Value = "Strength V"
    Range("B13").Value = "1.25DC + 1.25DW + 1.35LL + 0.4WS"
    Range("C13").Value = SV
'Service I
    Range("A14").Value = "Service I"
    Range("B14").Value = "DC + DW + LL + 0.3WS"
    Range("C14").Value = SerI
'Service II
    Range("A15").Value = "Service II"
    Range("B15").Value = "DC + DW + 1.3LL"
    Range("C15").Value = SerII
'Service III
    Range("A15").Value = "Service III"
    Range("B15").Value = "DC + DW + 0.8LL"
    Range("C15").Value = SerIII
'Service IV
    Range("A16").Value = "Service IV"
    Range("B16").Value = "DC + DW + 0.7LL"
    Range("C16").Value = SerIV

'Finds Maximum Load Combo
    Dim rng As Range
    Dim maximum As Double
    Set rng = Range("C8:C16")
    maximum = Application.WorksheetFunction.Max(rng)
    Range("C18").Value = maximum
    Range("B18").Value = "Mu (kip*in)"
    Range("D18").Value = "--> Strength I Controls"
    Range("B18:D18").Select
    Selection.Font.Bold = True

'Ratings Table
'Define Factors
    gDCo = 1.25
    gDWo = 1.5
```

```vba
    gLLo = 1.35
    gDCi = 1.25
      gDWi = 1.25
      gLLi = 1.75
      phif = 1
      phiv = 0.9
'phi_s taken as 1
      phis = 1
      phic = Sheets("UndamagedGeom").Range("A100").Value
      A1 = 1.3
      A2i = 2.17
      A2o = 1.3


'Create Headings
      Range("A21").Value = "LRFR Load Ratings"
      Range("A33").Value = "LFR Load Ratings"
'phi's
      'phif
      Range("A23").Select
      ActiveCell.FormulaR1C1 = "F_flexural rating"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .Size = 11
      End With
      Range("B23").Value = phif
      'phiv
      Range("A24").Select
      ActiveCell.FormulaR1C1 = "F_shear rating"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .Size = 11
      End With
      Range("B24").Value = phiv
      'phic
      Range("A25").Select
      ActiveCell.FormulaR1C1 = "F_c, condition factor"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .Size = 11
      End With
      Range("B25").Value = phic
      'phis
      Range("A26").Select
      ActiveCell.FormulaR1C1 = "F_s, system factor"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .Size = 11
      End With
      Range("B26").Value = phis

'Gamma Table
      Range("A28").Value = "Operating": Range("B28").Value = "Factor"
      Range("C28").Value = "Inventory": Range("D28").Value = "Factor"
'LRFR Operating Portion
      Range("A29").Select
      ActiveCell.FormulaR1C1 = "f_DC Operating"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC":    .FontStyle = "Bold": .Size = 11
      End With
      Range("B29").Value = gDCo
      Range("A30").Select
```

```
      ActiveCell.FormulaR1C1 = "f_DW Operating"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .FontStyle = "Bold": .Size = 11
      End With
      Range("B30").Value = gDWo
      Range("A31").Select
      ActiveCell.FormulaR1C1 = "f_LL Operating"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .FontStyle = "Bold": .Size = 11
      End With
      Range("B31").Value = gLLo
'LRFR Inventory Portion
      Range("C29").Select
      ActiveCell.FormulaR1C1 = "f_DC Inventory"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .FontStyle = "Bold": .Size = 11
      End With
      Range("D29").Value = gDCi
      Range("C30").Select
      ActiveCell.FormulaR1C1 = "f_DW Inventory"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .FontStyle = "Bold": .Size = 11
      End With
      Range("D30").Value = gDWi
Range("C31").Select
      ActiveCell.FormulaR1C1 = "f_LL Inventory"
      With ActiveCell.Characters(Start:=1, Length:=1).Font: .Name =
"GreekC": .FontStyle = "Bold": .Size = 11
      End With
      Range("D31").Value = gLLi
'LFR Table
      'headings
      Range("A35").Value = "Operating"
      Range("B35").Value = "Factor"
      Range("C35").Value = "Inventory"
      Range("D35").Value = "Factor"
      Range("A36").Value = "A1"
      Range("A37").Value = "A2"
      Range("C36").Value = "A1"
      Range("C37").Value = "A2"
      'values
      Range("B36").Value = A1
      Range("B37").Value = A2o
      Range("D36").Value = A1
      Range("D37").Value = A2i

'Format
      Cells.Select
      Cells.EntireColumn.AutoFit
      Range("A1,A1:B1,A8:C8,A21:D22,A28:D28,A33,A35:D35").Select
      Range("A8").Activate
      With Selection
        .HorizontalAlignment = xlCenter
        .Font.Bold = True
      End With
      With Selection.Font
        .Color = -16738048
```

```
          .TintAndShade = 0
     End With
     Range("B2:B5,C9:C18,B23:B40,D23:D25,D29:D31,D36:D27").Select
     Range("C9").Activate
     Selection.NumberFormat = "0.000"
     Range("A1").Select
End Sub
```

Module 8: Create and Compile Data Table with Results

```
Sub DataTableUndamagedInfo()

    Dim L As Integer: Dim harp As Integer: Dim Length As Single: Dim h As
    Single: Dim cover As Single: Dim c_t As Single: Dim A_s As Single: Dim
    fy As Single: Dim D As Single: Dim a As Single: Dim A_ps As Single: Dim
    fps As Single: Dim fc As Single: Dim b As Single: Dim Av As Single: Dim
    S As Single: Dim M_u_max As Single: Dim w_u As Single: Dim gDCo As
    Single: Dim gDWo As Single: Dim gLLo As Single: Dim gDCi As Single: Dim
    gDWi As Single: Dim gLLi As Single: Dim DC As Single: Dim DW As Single:
    Dim LL As Single: Dim w_DC As Single: Dim w_DW As Single: Dim w_LLm As
    Single: Dim phif As Single: Dim phiv As Single: Dim phic As Single: Dim
    phis As Single: Dim hmc As Single: Dim bint As Single: Dim w_LLv As
    Single

    'Grabs needed values for calculation from undamaged geom sheet
    Sheets("UndamagedGeom").Select
        'Converts L to inches
        L = Range("B4").Value
        Length = Range("B4").Value
        harp = Range("B71").Value
        h = Range("B6").Value
        cover = Range("B48").Value
        c_t = Range("B41").Value
        A_s = Range("B52").Value
        fy = Range("B14").Value
        D = Range("B61").Value
        a = Range("B70").Value
        A_ps = Range("B51").Value
        fps = Range("B69").Value
        fc = Range("B11").Value * 1000
        b = Range("B5").Value
        Av = Range("B53").Value
        S = Range("B54").Value

    'Grabs needed Loads for calculation from AASHTO Loads Sheet
        'Assumption:  Moving live load (three moving point loads)
        generates a moment envelope.
        'By including max LL moment in Mu and calculating a wu, this
        assumes that the moving
        'live load acts as a distributed load instead of creating a point
        load moment envelope
        'SAP:   M_LLm unfactored (static) = 428 kip*ft (5130 kip*in)
        'Excel: M_LLm unfactored (dynamic) = 422 kip*ft (5064 kip*in)
        '~1.4% difference.  Good Assumption
    Sheets("AASHTO Loads").Select
        M_u_max = Range("C18").Value
        w_u = (8 * M_u_max / (L ^ 2))
        'LRFR Gamma's for Rating
        gDCo = Range("B29").Value
        gDWo = Range("B30").Value
        gLLo = Range("B31").Value
        gDCi = Range("D29").Value
        gDWi = Range("D30").Value
```

```vba
    gLLi = Range("D31").Value
    'LFR Factors for Rating
    A1 = Range("B36").Value
    A2o = Range("B37").Value
    A2i = Range("D37").Value
    'Moments (kip*in)
    DC = Range("B2").Value
    DW = Range("B3").Value
    LL = Range("B4").Value
    LLv = Range("D4").Value

    'Distributed Loads (kip/in)
    w_DC = 8 * DC / L ^ 2
    w_DW = 8 * DW / L ^ 2
    w_LLm = 8 * LL / L ^ 2
    w_LLv = 8 * LLv / L ^ 2
    'Phi's for Rating
    phif = Range("B23").Value
    phiv = Range("B24").Value
    phic = Range("B25").Value
    phis = Range("B26").Value

'PLACES THIS SUB ON DataTable PAGE
Sheets("DataTable").Select
'Calculations for dps undamaged
    hmc = h - cover
    c_harp = 19.15
    'bint = hmc
    bint = hmc + (hmc - c_harp) / harp * (Length - harp)
    '
    Range("D1").Value = bint
    'all data
    Cells(1, 1).Value = "Undamaged and Damaged Capacity"
    Cells(2, 1).Value = "x (ft)"
    Cells(2, 2).Value = "dps (in)"
    Cells(2, 3).Value = "dps_damaged (in)"
    Cells(2, 4).Value = "Mu (kip*in)"
    Cells(2, 5).Value = "phiMn_undamaged (kip*in)"
    Cells(2, 6).Value = "phiMn_damaged (kip*in)"
    Cells(2, 7).Value = "phiMn_Plot (kip*in)"
    Cells(2, 8).Value = "Vu (kips)"
    Cells(2, 9).Value = "Vu*dp/Mu"
    Cells(2, 10).Value = "abs(Vu*dp/Mu) <=1"
    Cells(2, 11).Value = "U.L. (<5rootf'c)& L.L. (>2rootf'c) Applied"
    Cells(2, 12).Value = "Vc_undamaged (kip)"
    Cells(2, 13).Value = "Vs_undamaged (kip)"
    Cells(2, 14).Value = "phiVn_undamaged (kip)"
    Cells(2, 15).Value = "Vu*dpd/Mu"
    Cells(2, 16).Value = "abs(Vu*dpd/Mu) <=1"
    Cells(2, 17).Value = "U.L. & L.L. damaged applied"
    Cells(2, 18).Value = "Vc_damaged (kip)"
    Cells(2, 19).Value = "Vs_damaged (kip)"
    Cells(2, 20).Value = "phiVn_damaged (kip)"
    Cells(2, 21).Value = "phiVn_Plot (kips)"
    Cells(2, 22).Value = "M_DC (kip*in)"
    Cells(2, 23).Value = "M_DW (kip*in)"
    Cells(2, 24).Value = "M_LLm (kip*in)"
```

```vba
    'shear
    Cells(2, 25).Value = "V_DC (kips)"
    Cells(2, 26).Value = "V_DW (kips)"
    Cells(2, 27).Value = "V_LL (kips)"
    'LRFR moment
    Cells(2, 28).Value = "LRFR RF Moment Undamaged Operating"
    Cells(2, 29).Value = "LRFR RF Moment Damaged Operating"
    Cells(2, 30).Value = "LRFR RF Moment Plot Operating "
    Cells(2, 31).Value = "LRFR RF Moment Undamaged Inventory"
    Cells(2, 32).Value = "LRFR RF Moment Damaged Inventory"
    Cells(2, 33).Value = "LRFR RF Moment Plot Inventory"
    'LRFR shear
    Cells(2, 34).Value = "LRFR RF Shear Undamaged Operating"
    Cells(2, 35).Value = "LRFR RF Shear Damaged Operating"
    Cells(2, 36).Value = "LRFR RF Shear Plot Operating "
    Cells(2, 37).Value = "LRFR RF Shear Undamaged Inventory"
    Cells(2, 38).Value = "LRFR RF Shear Damaged Inventory"
    Cells(2, 39).Value = "LRFR RF Shear Plot Inventory"
    'LFR moment
    Cells(2, 40).Value = "LFR RF Moment Undamaged Operating"
    Cells(2, 41).Value = "LFR RF Moment Damaged Operating"
    Cells(2, 42).Value = "LFR RF Moment Plot Operating"
    Cells(2, 43).Value = "LFR RF Moment Undamaged Inventory"
    Cells(2, 44).Value = "LFR RF Moment Damaged Inventory"
    Cells(2, 45).Value = "LFR RF Moment Plot Inventory"
'Loop to Generate Values for dps, Mu, Vu, phiMn Undamaged
For i = 0 To L
    'Defines and Increments x (ft)
    Cells(i + 3, 1).Value = i
    'Calculates dps
    If i < harp Then
            Cells(i + 3, 2).Value = c_harp + ((hmc - c_harp) / (harp)) _
            * i
        ElseIf i > L - harp Then
            Cells(i + 3, 2).Value = bint - ((hmc - c_harp) / (harp)) * _
            i
        Else
            Cells(i + 3, 2).Value = hmc
    End If
    'Mu (FACTORED)
    Cells(i + 3, 4).Value = w_u / 2 * (L * i - i ^ 2)
    'MDC (Unfactored)
    Cells(i + 3, 22).Value = w_DC / 2 * (L * i - i ^ 2)
    'MDW (Unfactored)
    Cells(i + 3, 23).Value = w_DW / 2 * (L * i - i ^ 2)
    'MLL (Unfactored)
    Cells(i + 3, 24).Value = w_LLm / 2 * (L * i - i ^ 2)
    'VDC
    Cells(i + 3, 25).Value = w_DC * L / 2 - w_DC * i
    'VDW
    Cells(i + 3, 26).Value = w_DW * L / 2 - w_DW * i
    'VLL
    Cells(i + 3, 27).Value = w_LLv * L / 2 - w_LLv * i
    'Calculates Vu
    Cells(i + 3, 8).Value = w_u * L / 2 - w_u * i
    'Calculates phiMn_undamaged
```

```vb
        Cells(i + 3, 5).Value = 1# * (A_ps * fps * (Cells(i + 3, 2) - a /
        2))
Next
'Loop for Vu*dp/Mu, <=1, U.L. & L.L, Vc, Vs, phi*Vn, RF_moment_u
For i = 0 To L
    'Calculates Vu*dp/Mu
    If i = 0 Then
            Cells(i + 3, 9).Value = Abs(Cells(i + 3, 8)) * Cells(i + 3,
            2) / (Cells(i + 4, 4))
        ElseIf i = L Then
            Cells(i + 3, 9).Value = Abs(Cells(i + 3, 8)) * Cells(i + 3,
            2) / (Cells(i + 2, 4))
        Else
            Cells(i + 3, 9).Value = Abs(Cells(i + 3, 8)) * Cells(i + 3,
            2) / (Cells(i + 3, 4))
    End If
    'Tests Vu*dp/Mu <=1
    If Cells(i + 3, 9).Value > 1 Then
            Cells(i + 3, 10).Value = 1
        Else
            Cells(i + 3, 10).Value = Cells(i + 3, 9)
      End If
    'Tests U.L. & L.L.
      If (Cells(i + 3, 10).Value * 0.7) > (5 * (fc) ^ (1 / 2) / 1000)
      Then
            Cells(i + 3, 11).Value = 5 * (fc) ^ (1 / 2) / 1000
      ElseIf (Cells(i + 3, 10).Value * 0.7) < (2 * (fc) ^ (1 / 2) /
      1000)
      Then
            Cells(i + 3, 11).Value = 2 * (fc) ^ (1 / 2) / 1000
      Else
            Cells(i + 3, 11).Value = 0.7 * Cells(i + 3, 10)
      End If
    'Vc
      Cells(i + 3, 12).Value = (0.6 * (fc) ^ (1 / 2) / 1000 + Cells(i +
      3, 11).Value) * b * D
    'Vs
      Cells(i + 3, 13).Value = Av * fy * D / S
    'phi*Vn
    If i < L / 2 Then
            Cells(i + 3, 14).Value = 0.75 * (Cells(i + 3, 12) + Cells(i
            + 3, 13))
        Else
            Cells(i + 3, 14).Value = -0.75 * (Cells(i + 3, 12) +
            Cells(i + 3, 13))
    End If
    'RF moment undamaged calculations
    If i = 0 Then
            'LRFR RF_moment_operating_undamaged
      Cells(3, 28).Value = ((phic * phis * phif * Cells(4, 5)) - (gDCo
      * Cells(4, 22)) - (gDWo * Cells(4, 23))) / (gLLo * Cells(4, 24))
       'LRFR RF_moment_inventory_undamaged
      Cells(3, 31).Value = ((phic * phis * phif * Cells(4, 5)) - (gDCi
      * Cells(4, 22)) - (gDWi * Cells(4, 23))) / (gLLi * Cells(4, 24))
       'LFR RF_moment_operating_undamaged
      Cells(3, 40).Value = (phif * Cells(4, 5) - A1 * Cells(4, 22) - A1
      * Cells(4, 23)) / (A2o * Cells(4, 24))
```

```vba
            'LFR RF_moment_inventory_undamaged
            Cells(3, 43).Value = (phif * Cells(4, 5) - A1 * Cells(4, 22) - A1
            * Cells(4, 23)) / (A2i * Cells(4, 24))
        ElseIf i = L Then
            'LRFR RF_moment_operating_undamaged
            Cells(472, 28).Value = ((phic * phis * phif * Cells(4, 5)) -
            (gDCo * Cells(4, 22)) - (gDWo * Cells(4, 23))) / (gLLo * Cells(4,
            24))
            'LRFR RF_moment_inventory_undamaged
            Cells(472, 31).Value = ((phic * phis * phif * Cells(471, 5)) -
            (gDCi * Cells(471, 22)) - (gDWi * Cells(471, 23))) / (gLLi *
            Cells(471, 24))
            'LFR RF_moment_operating_undamaged
            Cells(472, 40).Value = (phif * Cells(4, 5) - A1 * Cells(4, 22) -
            A1 * Cells(4, 23)) / (A2o * Cells(4, 24))
            'LFR RF_moment_inventory_undamaged
            Cells(472, 43).Value = (phif * Cells(471, 5) - A1 * Cells(471,
            22) - A1 * Cells(471, 23)) / (A2i * Cells(471, 24))
        Else
            'LRFR RF_moment_operating_undamaged
            Cells(i + 3, 28).Value = ((phic * phis * phif * Cells(i + 3, 5))
            - (gDCo * Cells(i + 3, 22)) - (gDWo * Cells(i + 3, 23))) / (gLLo
            * Cells(i + 3, 24))
            'LRFR RF_moment_inventory_undamaged
            Cells(i + 3, 31).Value = ((phic * phis * phif * Cells(i + 3, 5))
            - (gDCi * Cells(i + 3, 22)) - (gDWi * Cells(i + 3, 23))) / (gLLi
            * Cells(i + 3, 24))
            'LFR RF_moment_operating_undamaged
            Cells(i + 3, 40).Value = (phif * Cells(i + 3, 5) - A1 * Cells(i +
            3, 22) - A1 * Cells(i + 3, 23)) / (A2o * Cells(i + 3, 24))
            'LFR RF_moment_inventory_undamaged
            Cells(i + 3, 43).Value = (phif * Cells(i + 3, 5) - A1 * Cells(i +
            3, 22) - A1 * Cells(i + 3, 23)) / (A2i * Cells(i + 3, 24))
        End If
        If Cells(i + 3, 27).Value = 0 Then
        'LRFR RF_shear_operating_undamaged
            Cells(i + 3, 34).Value = Cells(i + 2, 34).Value
        Else
            'LRFR RF_shear_operating_undamaged
            Cells(i + 3, 34).Value = (phic * phis * phif * Cells(i + 3, 14) -
            gDCo * Cells(i + 3, 25) - gDWo * Cells(i + 3, 26)) / (gLLo *
            Cells(i + 3, 27))
            'LRFR RF_shear_inventory_undamaged
            Cells(i + 3, 37).Value = (phic * phis * phif * Cells(i + 3, 14) -
            gDCi * Cells(i + 3, 25) - gDWi * Cells(i + 3, 26)) / (gLLi *
            Cells(i + 3, 27))
        End If
    Next
End Sub
```

Module 9: Moment and Shear Capacity along with LFR and LRFR Plots

```vb
Sub MuMnChart()
    Dim MuMn As Chart
'Creates Chart
    Set MuMn = Charts.Add
    With ActiveWorkbook.ActiveChart
    'Names Chart Worksheet
        .Name = "MomentCapacity"
        .ChartArea.Select
    'Defines Chart Type and Auto-Format Number
        .ChartType = xlXYScatterSmoothNoMarkers
        .ApplyLayout (1)
    'Defines Window
        .Axes(xlValue).Select
        .Axes(xlValue).MaximumScale = 20000
        .Axes(xlValue).MinimumScale = 0
        .Axes(xlCategory).MinimumScale = 0
        .Axes(xlCategory).Select
        .Axes(xlCategory).MaximumScale = 504
    'Labels Title on Chart
        .ChartTitle.Select
        .ChartTitle.Text = "Required Strength and Capacity in Flexure"
    'x-axis label
        .Axes(xlValue).AxisTitle.Select
        .Axes(xlCategory).AxisTitle.Select
        .Axes(xlValue, xlPrimary).AxisTitle.Text = "Length(in)"
                Selection.Format.TextFrame2.TextRange.Characters.Text = "Length
                (in)"
                Selection.Format.TextFrame2.TextRange.Characters(1,
                6).Font.Size = 10
    'y-axis label
        .Axes(xlValue).AxisTitle.Select
        .Axes(xlValue, xlPrimary).AxisTitle.Text = "Moment (kip*in)"
                        Selection.Format.TextFrame2.TextRange.Characters.Text
                = "Moment     (kip*in)"
                 Selection.Format.TextFrame2.TextRange.Characters(1,
                 15).Font.Size = 10
        .ChartArea.Select
    End With
  'Creates Boarder
    ActiveChart.PlotArea.Select
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.349999994
    End With
    Sheets("MomentCapacity").Select
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(1).Name = "=""Mu (kip*in)"""
    ActiveChart.SeriesCollection(1).XValues = "=DataTable!$A$3:$A$507"
    ActiveChart.SeriesCollection(1).Values = "=DataTable!$D$3:$D$507"
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(2).Name = "=""Mn_damaged (kip*in)"""
```

```
ActiveChart.SeriesCollection(2).XValues = "=DataTable!$A$3:$A$507"
ActiveChart.SeriesCollection(2).Values = "=DataTable!$G$3:$G$507"
ActiveChart.SeriesCollection(2).Name = "=""phi*Mn_damaged (kip*in)"""
ActiveChart.Legend.Select
Selection.Left = 213.724
Selection.Top = 294.904
ActiveChart.PlotArea.Select
Selection.Width = 578.788
ActiveChart.Legend.Select
ActiveChart.PlotArea.Select
ActiveChart.Legend.Select
Selection.Left = 288.724
Selection.Top = 296.904
ActiveChart.ChartArea.Select
ActiveChart.SeriesCollection(2).Select
With Selection.Format.Shadow
    .Type = msoShadow25
    .Visible = msoTrue
    .Style = msoShadowStyleOuterShadow
    .Blur = 4
    .OffsetX = 2.4492935983E-16
    .OffsetY = 4
    .RotateWithShape = msoFalse
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.150000006
    .Transparency = 0
End With
With Selection.Format.Shadow
    .Type = msoShadow25
    .Visible = msoTrue
    .Style = msoShadowStyleOuterShadow
    .Blur = 4
    .OffsetX = 2.4492935983E-16
    .OffsetY = 4
    .RotateWithShape = msoFalse
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.150000006
    .Transparency = 0
    .Size = 100
End With
ActiveChart.ChartArea.Select
ActiveChart.SeriesCollection(2).Select
ActiveChart.SeriesCollection(1).Select
With Selection.Format.Shadow
    .Type = msoShadow25
    .Visible = msoTrue
    .Style = msoShadowStyleOuterShadow
    .Blur = 4
    .OffsetX = 2.4492935983E-16
    .OffsetY = 4
    .RotateWithShape = msoFalse
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.150000006
    .Transparency = 0
```

```
            .Size = 100
        End With
        ActiveChart.PlotArea.Select
        ActiveChart.Axes(xlCategory).Select
        ActiveChart.Axes(xlValue).HasMajorGridlines = True
        ActiveChart.Legend.Select
        With Selection.Format.Fill
            .Visible = msoTrue
            .ForeColor.ObjectThemeColor = msoThemeColorAccent1
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = 0
            .Solid
        End With
        With Selection.Format.Fill
            .Visible = msoTrue
            .ForeColor.ObjectThemeColor = msoThemeColorBackground1
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = 0
            .Transparency = 0
            .Solid
        End With
        With Selection.Format.Line
            .Visible = msoTrue
            .ForeColor.ObjectThemeColor = msoThemeColorAccent1
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = 0
        End With
        With Selection.Format.Line
            .Visible = msoTrue
            .ForeColor.ObjectThemeColor = msoThemeColorBackground1
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = -0.349999994
            .Transparency = 0
        End With
        ActiveChart.PlotArea.Select
        ActiveChart.Legend.Select
        Selection.Left = 282.724
        Selection.Top = 296.904
        ActiveChart.ChartArea.Select
    End Sub

    Sub VuVnChart()
        Dim VuVn As Chart
    'Creates Chart
        Set VuVn = Charts.Add
        With ActiveWorkbook.ActiveChart
        'Names Chart Worksheet
            .Name = "ShearCapacity"
            .ChartArea.Select
        'Defomes Chart Type and Auto-Format Number
            .ChartType = xlXYScatterSmoothNoMarkers
            .ApplyLayout (1)
        'Defines Window
            .Axes(xlValue).Select
            .Axes(xlValue).MaximumScale = 1200
            .Axes(xlValue).MinimumScale = -1200
            .Axes(xlCategory).MinimumScale = 0
```

206

```
        .Axes(xlCategory).Select
        .Axes(xlCategory).MaximumScale = 504
    'Defines Ranges for Vu and labels
        .SeriesCollection.NewSeries
        .SeriesCollection(1).Name = "=""Vu (kips)"""
        .SeriesCollection(1).XValues = "='DataTable'!$A$3:$A$507"
        .SeriesCollection(1).Values = "='DataTable'!$H$3:$H$507"
     'Defines Ranges for phiMn_undamaged and labels
        .SeriesCollection.NewSeries
        .SeriesCollection(2).Name = "=""phiVn_damaged (kips)"""
        .SeriesCollection(2).XValues = "='DataTable'!$A$3:$A$507"
        .SeriesCollection(2).Values = "='DataTable'!$U$3:$U$507"
    'Labels Title on Chart
        .ChartTitle.Select
        .ChartTitle.Text = "Required Strength and Capacity in Shear"
    'x-axis label
        .Axes(xlValue).AxisTitle.Select
        .Axes(xlCategory).AxisTitle.Select
        .Axes(xlValue, xlPrimary).AxisTitle.Text = "Length(in)"
        Selection.Format.TextFrame2.TextRange.Characters.Text = "Length (in)"
        Selection.Format.TextFrame2.TextRange.Characters(1, 6).Font.Size = 10
    'y-axis label
        .Axes(xlValue).AxisTitle.Select
        .Axes(xlValue, xlPrimary).AxisTitle.Text = "Shear (kips)"
        Selection.Format.TextFrame2.TextRange.Characters.Text = "Shear
(kips)"
        'Selection.Format.TextFrame2.TextRange.Characters(1, 15).Font.Size =
10
        .ChartArea.Select
    End With
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.349999994
        .Transparency = 0
    End With
    ActiveChart.ChartArea.Select
    Sheets("ShearCapacity").Select
    ActiveChart.PlotArea.Select
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.349999994
    End With
    ActiveChart.Legend.Select
    With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = 0
        .Solid
    End With
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
```

```vba
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = -0.349999994
        End With
        ActiveChart.PlotArea.Select
        ActiveChart.Legend.Select
        Selection.Left = 153.449
        Selection.Top = 314.904
        ActiveChart.Axes(xlCategory).Select
        Selection.TickLabelPosition = xlLow
        ActiveChart.SeriesCollection(2).Select
        With Selection.Format.Shadow
            .Type = msoShadow25
            .Visible = msoTrue
            .Style = msoShadowStyleOuterShadow
            .Blur = 4
            .OffsetX = 2.4492935983E-16
            .OffsetY = 4
            .RotateWithShape = msoFalse
            .ForeColor.ObjectThemeColor = msoThemeColorBackground1
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = -0.25
            .Transparency = 0
        End With
        ActiveChart.SeriesCollection(1).Select
        With Selection.Format.Shadow
            .Type = msoShadow25
            .Visible = msoTrue
            .Style = msoShadowStyleOuterShadow
            .Blur = 4
            .OffsetX = 2.4492935983E-16
            .OffsetY = 4
            .RotateWithShape = msoFalse
            .ForeColor.ObjectThemeColor = msoThemeColorBackground1
            .ForeColor.TintAndShade = 0
            .ForeColor.Brightness = -0.25
            .Transparency = 0
        End With
        ActiveChart.ChartArea.Select
    End Sub

Sub RFMChart()
    Dim RFMCht As Chart
'Creates Chart
    Set RFMCht = Charts.Add
    With ActiveWorkbook.ActiveChart
    'Names Chart Worksheet
        .Name = "LRFRMomentRatingFactor"
        .ChartArea.Select
    'Defomes Chart Type and Auto-Format Number
        .ChartType = xlXYScatterSmoothNoMarkers
        .ApplyLayout (1)
    'Defines Window
        .Axes(xlValue).Select
        .Axes(xlValue).MaximumScale = 2
        .Axes(xlValue).MinimumScale = 0
        .Axes(xlValue).MinimumScale = 0
        .Axes(xlCategory).MinimumScale = 0
```

```
    .Axes(xlCategory).Select
    .Axes(xlCategory).MaximumScale = 504
'Defines Ranges for Vu and labels
    .SeriesCollection.NewSeries
    .SeriesCollection(1).Name = "=""Operating Rating Factor (Moment)"""
    .SeriesCollection(1).XValues = "='DataTable'!$A$3:$A$507"
    .SeriesCollection(1).Values = "='DataTable'!$AA$3:$AA$507"
 'Defines Ranges for phiMn_undamaged and labels
    .SeriesCollection.NewSeries
    .SeriesCollection(2).Name = "=""Inventory Rating Factor (Moment)"""
    .SeriesCollection(2).XValues = "='DataTable'!$A$3:$A$507"
    .SeriesCollection(2).Values = "='DataTable'!$AD$3:$AD$507"
'Labels Title on Chart
    .ChartTitle.Select
    .ChartTitle.Text = "LRFR Rating Method for Flexure"
'x-axis label
    .Axes(xlValue).AxisTitle.Select
    .Axes(xlCategory).AxisTitle.Select
    .Axes(xlValue, xlPrimary).AxisTitle.Text = "Length(in)"
    Selection.Format.TextFrame2.TextRange.Characters.Text = "Length (in)"
    Selection.Format.TextFrame2.TextRange.Characters(1, 6).Font.Size = 10
'y-axis label
    .Axes(xlValue).AxisTitle.Select
    .Axes(xlValue, xlPrimary).AxisTitle.Text = "Rating Factor (RF)"
    Selection.Format.TextFrame2.TextRange.Characters.Text = "Rating
    Factor (RF)"
            Selection.Format.TextFrame2.TextRange.Characters(1,
    15).Font.Size = 10
    .ChartArea.Select
End With
'Creates Boarder
ActiveChart.PlotArea.Select
With Selection.Format.Line
    .Visible = msoTrue
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.349999994
End With
Sheets("LRFRMomentRatingFactor").Select
ActiveChart.SeriesCollection(5).Delete
ActiveChart.SeriesCollection(4).Delete
ActiveChart.SeriesCollection(3).Delete
ActiveChart.SeriesCollection(1).Values = "=DataTable!$AD$3:$AD$507"
ActiveChart.SeriesCollection(2).Values = "=DataTable!$AG$3:$AG$507"
ActiveChart.Legend.Select
With Selection.Format.Line
    .Visible = msoTrue
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.349999994
End With
With Selection.Format.Fill
    .Visible = msoTrue
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = 0
    .Solid
```

```vba
    End With
    ActiveChart.ChartArea.Select
    ActiveChart.Legend.Select
    ActiveChart.PlotArea.Select
    Selection.Width = 599.233
    ActiveChart.Legend.Select
    Selection.Left = 250.484
    Selection.Top = 327.904
    ActiveChart.SeriesCollection(1).Select
    With Selection.Format.Shadow
        .Type = msoShadow25
        .Visible = msoTrue
        .Style = msoShadowStyleOuterShadow
        .Blur = 4
        .OffsetX = 2.4492935983E-16
        .OffsetY = 4
        .RotateWithShape = msoFalse
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.25
        .Transparency = 0
    End With
    ActiveChart.SeriesCollection(2).Select
    With Selection.Format.Shadow
        .Type = msoShadow25
        .Visible = msoTrue
        .Style = msoShadowStyleOuterShadow
        .Blur = 4
        .OffsetX = 2.4492935983E-16
        .OffsetY = 4
        .RotateWithShape = msoFalse
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.25
        .Transparency = 0
    End With
    ActiveChart.PlotArea.Select
    ActiveChart.Legend.Select
    Selection.Left = 271.484
    Selection.Top = 331.904
    ActiveChart.PlotArea.Select
    ActiveChart.ChartArea.Select
End Sub

Sub RFVChart()
    Dim RFVCht As Chart
'Creates Chart
    Set RFVCht = Charts.Add
    With ActiveWorkbook.ActiveChart
    'Names Chart Worksheet
        .Name = "LRFRShearRatingFactor"
        .ChartArea.Select
    'Defomes Chart Type and Auto-Format Number
        .ChartType = xlXYScatterSmoothNoMarkers
        .ApplyLayout (1)
    'Defines Window
        .Axes(xlValue).Select
```

```
    .Axes(xlValue).MaximumScale = 20
    .Axes(xlValue).MinimumScale = 0
    .Axes(xlCategory).MinimumScale = 0
    .Axes(xlCategory).Select
    .Axes(xlCategory).MaximumScale = 504
'Defines Ranges for Vu and labels
    .SeriesCollection.NewSeries
    .SeriesCollection(1).Name = "=""Operating Rating Factor (Shear)"""
    .SeriesCollection(1).XValues = "='DataTable'!$A$3:$A$507"
    .SeriesCollection(1).Values = "='DataTable'!$AJ$3:$AJ$507"
 'Defines Ranges for phiMn_undamaged and labels
    .SeriesCollection.NewSeries
    .SeriesCollection(2).Name = "=""Inventory Rating Factor (Shear)"""
    .SeriesCollection(2).XValues = "='DataTable'!$A$3:$A$507"
    .SeriesCollection(2).Values = "='DataTable'!$AM$3:$AM$507"
'Labels Title on Chart
    .ChartTitle.Select
    .ChartTitle.Text = "LRFR Rating Method for Shear"
'x-axis label
    .Axes(xlValue).AxisTitle.Select
    .Axes(xlCategory).AxisTitle.Select
    .Axes(xlValue, xlPrimary).AxisTitle.Text = "Length(in)"
    Selection.Format.TextFrame2.TextRange.Characters.Text = "Length (in)"
    Selection.Format.TextFrame2.TextRange.Characters(1, 6).Font.Size = 10
'y-axis label
    .Axes(xlValue).AxisTitle.Select
    .Axes(xlValue, xlPrimary).AxisTitle.Text = "Rating Factor (RF)"
            Selection.Format.TextFrame2.TextRange.Characters.Text =
    "Rating Factor (RF)"
    Selection.Format.TextFrame2.TextRange.Characters(1, 15).Font.Size =
    10
    .ChartArea.Select
End With
'Creates Boarder
ActiveChart.PlotArea.Select
With Selection.Format.Line
    .Visible = msoTrue
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.349999994
End With
Sheets("LRFRShearRatingFactor").Select
ActiveChart.SeriesCollection(5).Delete
ActiveChart.SeriesCollection(4).Delete
ActiveChart.SeriesCollection(3).Delete
ActiveChart.SeriesCollection(1).Select
With Selection.Format.Shadow
    .Type = msoShadow25
    .Visible = msoTrue
    .Style = msoShadowStyleOuterShadow
    .Blur = 4
    .OffsetX = 2.4492935983E-16
    .OffsetY = 4
    .RotateWithShape = msoFalse
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.25
```

```
        .Transparency = 0
        .Size = 100
    End With
    ActiveChart.SeriesCollection(2).Select
    With Selection.Format.Shadow
        .Type = msoShadow25
        .Visible = msoTrue
        .Style = msoShadowStyleOuterShadow
        .Blur = 4
        .OffsetX = 2.4492935983E-16
        .OffsetY = 4
        .RotateWithShape = msoFalse
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.25
        .Transparency = 0
    End With
    ActiveChart.Legend.Select
    With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = 0
        .Solid
    End With
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.349999994
    End With
    ActiveChart.PlotArea.Select
    Selection.Width = 606.053
    ActiveChart.Legend.Select
    Selection.Left = 282.779
    Selection.Top = 328.904
    ActiveChart.ChartArea.Select
    Sheets("MomentCapacity").Select
End Sub

Sub LFRRFMChart()
    Dim LFRRFMCht As Chart
'Creates Chart
    Set LFRRFMCht = Charts.Add
    With ActiveWorkbook.ActiveChart
    'Names Chart Worksheet
        .Name = "LFRMomentRatingFactor"
        .ChartArea.Select
    'Defomes Chart Type and Auto-Format Number
        .ChartType = xlXYScatterSmoothNoMarkers
        .ApplyLayout (1)
    'Defines Window
        .Axes(xlValue).Select
        .Axes(xlValue).MaximumScale = 20
        .Axes(xlValue).MinimumScale = 0
        .Axes(xlCategory).MinimumScale = 0
        .Axes(xlCategory).Select
```

```
    .Axes(xlCategory).MaximumScale = 504
'Defines Ranges for Vu and labels
    .SeriesCollection.NewSeries
    .SeriesCollection(1).Name = "=""Operating Rating Factor (Moment)"""
    .SeriesCollection(1).XValues = "='DataTable'!$A$3:$A$507"
    .SeriesCollection(1).Values = "='DataTable'!$AP$3:$AP$507"
 'Defines Ranges for phiMn_undamaged and labels
    .SeriesCollection.NewSeries
    .SeriesCollection(2).Name = "=""Inventory Rating Factor (Moment)"""
    .SeriesCollection(2).XValues = "='DataTable'!$A$3:$A$507"
    .SeriesCollection(2).Values = "='DataTable'!$AS$3:$AS$507"
'Labels Title on Chart
    .ChartTitle.Select
    .ChartTitle.Text = "LFR Rating Method for Moment"
'x-axis label
    .Axes(xlValue).AxisTitle.Select
    .Axes(xlCategory).AxisTitle.Select
    .Axes(xlValue, xlPrimary).AxisTitle.Text = "Length(in)"
    Selection.Format.TextFrame2.TextRange.Characters.Text = "Length (in)"
    Selection.Format.TextFrame2.TextRange.Characters(1, 6).Font.Size = 10
'y-axis label
    .Axes(xlValue).AxisTitle.Select
    .Axes(xlValue, xlPrimary).AxisTitle.Text = "Rating Factor (RF)"
            Selection.Format.TextFrame2.TextRange.Characters.Text =
    "Rating Factor (RF)"
            Selection.Format.TextFrame2.TextRange.Characters(1,
    15).Font.Size = 10
    .ChartArea.Select
End With

'Creates Boarder
ActiveChart.PlotArea.Select
With Selection.Format.Line
    .Visible = msoTrue
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.349999994
End With
Sheets("LRFRShearRatingFactor").Select
With Selection.Format.Shadow
    .Type = msoShadow25
    .Visible = msoTrue
    .Style = msoShadowStyleOuterShadow
    .Blur = 4
    .OffsetX = 2.4492935983E-16
    .OffsetY = 4
    .RotateWithShape = msoFalse
    .ForeColor.ObjectThemeColor = msoThemeColorBackground1
    .ForeColor.TintAndShade = 0
    .ForeColor.Brightness = -0.25
    .Transparency = 0
    .Size = 100
End With
ActiveChart.SeriesCollection(2).Select
With Selection.Format.Shadow
    .Type = msoShadow25
    .Visible = msoTrue
```

```
        .Style = msoShadowStyleOuterShadow
        .Blur = 4
        .OffsetX = 2.4492935983E-16
        .OffsetY = 4
        .RotateWithShape = msoFalse
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.25
        .Transparency = 0
End With
ActiveChart.Legend.Select
With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = 0
        .Solid
End With
With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.349999994
End With
ActiveChart.PlotArea.Select
Selection.Width = 606.053
ActiveChart.Legend.Select
Selection.Left = 282.779
Selection.Top = 328.904
ActiveChart.ChartArea.Select
Sheets("MomentCapacity").Select
Sheets("LFRMomentRatingFactor").Select
ActiveChart.Axes(xlValue).Select
ActiveChart.Axes(xlValue).MaximumScale = 2
Sheets("LFRMomentRatingFactor").Select
ActiveChart.Legend.Select
Selection.Left = 170.32
Selection.Top = 326.352
With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorAccent1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = 0
        .Solid
End With
With Selection.Format.Fill
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground1
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = 0
        .Transparency = 0
        .Solid
End With
With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorAccent1
        .ForeColor.TintAndShade = 0
```

```
        .ForeColor.Brightness = 0
    End With
    ActiveChart.ChartArea.Select
    With Selection.Format.Line
        .Visible = msoTrue
        .ForeColor.ObjectThemeColor = msoThemeColorBackground2
        .ForeColor.TintAndShade = 0
        .ForeColor.Brightness = -0.25
        .Transparency = 0
    End With
    ActiveChart.PlotArea.Select
    Selection.Width = 581.069
    ActiveChart.Legend.Select
    Selection.Left = 230.32
    Selection.Top = 328.352
    ActiveChart.ChartArea.Select
End Sub
```

Module 10: Estimated Repair Quantities

```
Sub Maintain()

Dim Crack As String: Dim CrackSev As Single: Dim LengthCrack As Single: Dim
WidthCrack As Single: Dim DepthCrack As Single: Dim FromSupportCrack As
Single: Dim FromTopCrack As Single: Dim FromEdgeCrack As Single: Dim Spall As
String: Dim SpallSev As Single: Dim LengthSpall As Single: Dim WidthSpall As
Single: Dim DepthSpall As Single: Dim FromSupportSpall As Single: Dim
FromTopSpall As Single: Dim FromEdgeSpall As Single: Dim Delam As String: Dim
DelamSev As Single: Dim LengthDelam As Single: Dim WidthDelam As Single:
Dim DepthDelam As Single: Dim FromSupportDelam As Single: Dim FromTopDelam As
Single: Dim FromEdgeDelam As Single: Dim CrackVol As Single: Dim SpallVol As
Single: Dim DelamVol As Single:

'grabs needed damage dimensions
Sheets("UndamagedGeom").Select
    Crack = Range("B15").Value
    CrackSev = Range("B16").Value
    LengthCrack = Range("B17").Value
    WidthCrack = Range("B18").Value
    DepthCrack = Range("B19").Value
    FromSupportCrack = Range("B20").Value
    FromTopCrack = Range("B21").Value
    FromEdgeCrack = Range("B22").Value
    Spall = Range("B23").Value
    SpallSev = Range("B24").Value
    LengthSpall = Range("B25").Value
    WidthSpall = Range("B26").Value
    DepthSpall = Range("B27").Value
    FromSupportSpall = Range("B28").Value
    FromTopSpall = Range("B29").Value
    FromEdgeSpall = Range("B30").Value
    Delam = Range("B31").Value
    DelamSev = Range("B32").Value
    LengthDelam = Range("B33").Value
    WidthDelam = Range("B34").Value
    DepthDelam = Range("B35").Value
    FromSupportDelam = Range("B36").Value
    FromTopDelam = Range("B37").Value
    FromEdgeDelam = Range("B38").Value

'calculates estimated repair quantities
    CrackVol = LengthCrack * WidthCrack * DepthCrack
    SpallVol = LengthSpall * WidthSpall * DepthSpall
    DelamVol = LengthDelam * WidthDelam * DepthDelam

'creates table in repair quantities sheet
Sheets("RepairQuantities").Select
    Range("A1").Value = "Estimated Repair Quantities"
    Range("A3").Value = "Damage Mode"
    Range("A4").Value = "Cracking"
    Range("A5").Value = "Spalling"
    Range("A6").Value = "Delamination"
    Range("B3").Value = "Severity 1-5)"
```

```
    Range("B4").Value = CrackSev
    Range("B5").Value = SpallSev
    Range("B6").Value = DelamSev
    Range("C3").Value = "Volume (in^3)"
    Range("C4").Value = CrackVol
    Range("C5").Value = SpallVol
    Range("C6").Value = DelamVol

'format
    Cells.Select
    Cells.EntireColumn.AutoFit
    Range("A1,A3:C3").Select
    Range("A3").Activate
    Selection.Font.Bold = True
    With Selection.Font
        .Color = -11489280
        .TintAndShade = 0
    End With
    Range("B4:C6").Select
    With Selection
        .HorizontalAlignment = xlCenter
    End With
    Range("A1").Select
End Sub
```