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DEVELOPMENT OF RISK-BASED DECISION METHODOLOGY FOR FACILITY DESIGN

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16. Abstract

This report develops a methodology for CDOT to use in the risk analysis of various types of facilities and provides illustrative examples for the use of the proposed framework. An overview of the current practices and applications to illustrate the context from which the proposed methodology has been developed is presented first. Next, the report introduces the proposed methodology for CDOT. In order to understand how the framework operates in practice, two illustrative examples are presented. The first example demonstrates the framework through the context of allocating resources for the operation and maintenance of a portfolio of signalized mast arms. Two risk assessment methods are introduced through the first example, and it is shown that mast arms could benefit from varied inspection frequencies based on current structural defects present. The second illustrative example uses the framework in the context of making design decisions with regard to seismic hazard in Colorado. A quantitative risk assessment method is introduced, and the illustration suggests that seismic hazard is not a controlling hazard in Colorado.

Implementation

Through the literature review and presented examples, CDOT is equipped with the resources and information necessary to implement a risk-based methodology in decision-making across its organization. In the near term, the report recommends the following action items for CDOT:

- Implementation of a varied mast arm inspection routine based on structural state
- Modification of the mast arm inspection records database to make information amenable to data-mining for risk assessment
- Adoption of the proposed common vocabulary and framework to discuss risk and address issues that face the organization

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EXECUTIVE SUMMARY

This report develops a framework for organizing risk-based decisions about design, maintenance, and operation for the Colorado Department of Transportation (CDOT) applying to various types of facilities. It also provides illustrative examples for the use of the proposed framework. The development and use of a risk framework is becoming increasingly important for many organizations and decision makers. CDOT has an opportunity to be a national leader in assessing risks, vulnerabilities, consequences and outcomes through the implementation of a risk-based framework for facility design, operations and maintenance.

An overview of the current practices and applications from several state DOTs is presented first (Chapter 2) to illustrate the context from which the proposed risk-based framework for facilities design and management has been developed. Next, in Chapter 3, the report introduces the proposed framework for CDOT. The framework is composed of four steps: (1) communication logistics, (2) identification of goals and standards, (3) risk analysis, and (4) continuing lessons learned. Risk analysis consists of stages of risk identification, risk assessment and risk action. The framework is adaptable to the needs of CDOT's organization and decisions at a variety of levels, and is flexible enough to incorporate the philosophy and direction of next-generation federal regulations, such as MAP-21. Three risk assessment methods are introduced to demonstrate the adaptability of the framework, ranging from qualitative to quantitative analysis. This framework integrates risk analysis procedures with avenues for continual improvement of the framework process through the feedback loops from risk monitoring back to the other stages of risk analysis. Additionally, lessons learned also loop back into communication logistics, goal identification, and risk analysis for future instances of the framework. The framework is presented through a visually represented graphic and action driven guidelines. **The result is a process that can be readily implemented in decision-making processes at CDOT at all levels of organization.**

Two illustrative examples are presented in Chapters 4 and 5 to show how the framework can be used. The first example (Chapter 4) demonstrates the framework through the context of allocating resources for the operation and maintenance of a portfolio of signalized mast arms. Inspection records of signal mast-arms are summarized, and finite element analysis was performed to investigate how each structural defect impacts structural performance. The results of the quantitative finite element analysis are then used to perform a qualitative risk analysis. Two risk assessment methods are introduced through the first example. The example also shows that most mast arms are relatively low risk and the time between inspections could be reduced. Mast arms with significant corrosion or collision damage could benefit from more frequent inspection or repair. The second illustrative example in Chapter 5 uses the framework in the context of making design decisions for bridges considering the seismic hazard in Colorado. For this example, the risk analysis is quantitative, based on structural analysis and Monte Carlo simulation to account for uncertainties. Through this technique, organizations such as CDOT can readily visualize the risk a particular hazard may impose on structural performance in order to make decisions about design standards. The second example shows that the additional requirements imposed by seismic design in zone 2 regions of Colorado have little appreciable influence on the response of pre-stressed highway bridges, as well as little effect on cost.

Through the literature review and presented examples, the report equips CDOT with the resources and information necessary to implement a risk-based decision-making methodology in across its organization. In the near term, the report recommends the following action items for CDOT:

- **Implementation of a varied mast arm inspection routine based on structural state. Low-risk mast arms could be inspected less frequently than the current inspection routine.**
- **Modification of the mast arm inspection records database to make information amenable to data-mining for risk assessment. Codes that reflect each of the structural defects need to be defined, and a new field containing the found defects with a uniform delimiter can enable CDOT to quickly identify the overall state of its**

mast arm portfolio. Similar recommendations are applicable to other CDOT databases that describe the condition of CDOT facilities.

- **Adoption of the proposed common vocabulary and framework to discuss risk and address issues that face the organization. Though mast arms and seismic design of bridges are used as examples, this framework can be extended to culvert design, organizational decision-making, and more.**

Future directions include developing guidelines for determining when to use which risk assessment approach. Three options have been presented to CDOT, as introduced in Chapter 3 and presented in Chapters 4 and 5. Caltrans and WSDOT distinguish between different levels of risk assessment based on budget; CDOT could choose to adopt a similar approach, or investigate a different metric by which to choose a risk assessment method based on the needs of the public. Additionally, refinement of a risk-tracking system, here referred to as a “risk register”, for specific applications could be made in order to develop long-term tools for the organization.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

The development and use of a risk framework is becoming increasingly important for many organizations and decision makers [1]. Every kind of organization encounters risk, but not every organization has developed procedures through which to directly identify and address those risks. Risk management is a set of practices set forth by an organization to use in order to identify, assess, address, and monitor any existing or anticipated risks to the success of the organization at all levels of operation [1]. These levels of operation range from an individual project to an organization-wide strategy.

With economic situations tightening for many organizations and public accountability increasing through the proliferation of new media, many organizations are becoming more inclined to address the existence of such risks with transparency and accountability. The increasing availability of powerful computational tools and risk models further aids this process. Across diverse industries and through various applications, “standards” of risk management have emerged in the last decade, from the International Standards Organization’s Risk Management Document 31000:2009 [1], to the Committee of Sponsoring Organizations of the Treadway Commission’s Enterprise Risk Management [2]. Specifically within transportation, modern risk-based analysis has been adopted by the National Cooperative Highway Research Program [3], and performance-based measures have been mandated at the federal level for asset-management for all states in the Moving Ahead for Progress in the 21st Century Act (MAP-21) [4]. As conceptually outlined in these documents, risk-based analysis can be used to prioritize allocation of resources among competing objectives, while maintaining and even enhancing the transportation system’s high level of safety. However, these do not specifically address the use of this approach for use the design, maintenance, or operation of built facilities. The Colorado Department of Transportation (CDOT) has an opportunity to be a national leader in assessing the risks, vulnerabilities, consequences and outcomes for the application of this approach to specific facility standards.

The State of Colorado has developed or adopted standards for design of its transportation-related facilities that ensure a high level of safety against all foreseen hazards. Although this approach has generally led to acceptable results, it can be conservative in some cases, and the demands of continued growth and limited resources dictate that more refined approaches might be used to ensure the most appropriate expenditures of state funds balancing the state’s diverse hazards and needs.

Goals

CDOT has adopted a set of standards for the design, maintenance, and operation of its structural assets. These standards provide an implied level performance in the face of both foreseen and unforeseen hazards. The level of performance may be under-conservative, over-conservative, or at the desired level of performance for a particular hazard, and may provide different levels of performance for different types of hazards. In addition to a primary performance metric of safety, these standards also have associated financial costs, construction timelines, and traffic delays, any of which could quantify a risk.

This report develops a framework for organizing risk-based decisions about design, maintenance, and operation for CDOT decision applying to various types of facilities. It also provides illustrative examples for the use of the proposed framework. The framework remains consistent with the mission and vision of CDOT. This study uses, as guiding statements, the CDOT vision of “(enhancing) the quality of life and the environment of the citizens of Colorado by creating an integrated transportation system that focuses on safely moving people and goods by offering convenient linkages among modal choices,” and the CDOT mission of “(providing) the best multi-modal transportation system for Colorado that most-effectively and safely moves people, goods, and information” [5]. Table 1 summarizes CDOT’s organizational values. The risk-based framework is intended to further the promise of safety, people, integrity, customer service, excellence, and respect by CDOT for the people of Colorado.

Additionally, using a risk-based framework promotes resiliency within an organization, and, in the case of CDOT, it builds resiliency for the whole community of Colorado, as the public relies on functional transportation systems for their livelihood and day-to-day activities. Resiliency is defined here as the “readiness for facing events which are abnormal in terms of scale, form, or timing” [6]. The concept of resilience includes the ability to respond quickly and effectively following an adverse event. A risk-based framework seeks to provide a roadmap through which an organization can take action in the midst of an extreme event, thereby increasing the resiliency of the organization.

Table 1. CDOT Values [5].

Safety	Protect human life, preserve property, put employee safety before production
People	Acknowledge and recognize the skills and abilities of CDOT employees, place a high priority on employee safety, and draw strength from diversity and commitment to equal opportunity
Integrity	Honesty and responsibility in all that CDOT does, held to the highest moral and ethical standards
Customer Service	Work together and with others to respond effectively to customer’s needs
Excellence	A commitment to quality. As leaders and problem solvers, continuously improving products and services in support of a commitment to provide the best transportation systems for Colorado
Respect	Be kind and civil with everyone, and act with courage and humility

A risk-based framework brings the concept of uncertainty and risk to the foreground of the conversation – a deliberate identification of negative uncertainties, which are often identified as risks, and positive uncertainties, which can be viewed as opportunities. Current CDOT project management practices already meet some elements of the proposed risk-based framework presented in the next chapter. Practices, however, may vary from project manager to project manager, or department to department. In CDOT’s current operational framework, risk concepts tend to be implicitly embedded in decisions with resulting consequences. This framework seeks to invert the process by identifying acceptable risk levels, and then making decisions in order to meet such levels. It also seeks to integrate a risk-based mindset throughout the organization to ensure that the discussion of risk enters every decision-making process. In the process, the framework's use builds familiarity with basic risk concepts, such as probability and consequence, such that organizations can accept the presence of risk inherent with every operation.

The ultimate goal of this research study was to develop a consequent-consistent risk approach to facility design for CDOT. The primary objectives of this study have been to:

1. Develop a Colorado-specific methodology for risk analysis of various types of facilities designed and built by CDOT, accounting for natural and intentional hazards and incorporating life-cycle assessment considerations. The facilities of interest were chosen in coordination with CDOT engineers, who provided the requisite design details, analyses and data to the investigators.

2. Conduct a full risk-based analysis of design standards for signalization mast arms, and develop draft design guidelines for a risk-based assessment based on this analysis.

3. Provide operational guidelines for further development of consequent-consistent risk-based approaches for performance design of other types of CDOT facilities.

Risk analysis is a critical tool for objective-based decision-making for modern asset management. Only by incorporating the likelihood of events and assessment of outcomes can a transportation agency such as CDOT fully optimize its decisions with respect to managing its assets, maintaining public safety, providing an efficient transportation system, and preparing for the future. Due to ever-increasing demands on our infrastructure, a reliability-based life-cycle cost approach is essential for the management of fixed assets, such as highways, bridges and associated structures to meet today's and tomorrow's needs in the most cost-efficient manner. Benefit and cost analyses for both the agency and the traveling public can only be fully utilized when they are based on a consistent, theoretical foundation incorporating a comprehensive risk- and consequence-based evaluation.

Utilization of modern risk analysis life-cycle concepts starts with a deep understanding of the engineering issues and factors, incorporating economics as well as issues of public awareness and acceptance of risk. This project has established the methodology to apply the principles of risk-based decision-making in these areas. Although these methods are gaining precedence in some engineering fields, such as structural earthquake engineering, the full benefit of these approaches for managing a complex network of structures, like that of CDOT, have not yet been realized.

Content Overview

This chapter provides an overview of the motivation and goals of a risk-based framework, in addition to a list of definitions for useful terms that will be used throughout the report. Chapter 2 provides an overview of the current practices and applications to illustrate the context from which the proposed methodology has been developed. Though the development and application of this framework to CDOT is of primary interest here, it is important to see the context out of which this methodology has grown. Chapter 3 introduces the proposed methodology for CDOT. Chapters 2 and 3 provide context for an informed comparison of the proposed framework to existing frameworks and to understand the advantages and limitations of the proposed method. Next, it is critical to understand how the framework operates in practice; this is addressed in Chapters 4 and 5. Chapter 4 illustrates the framework through the context of creating an operation and maintenance budget for a portfolio of signalized mast arms. Chapter 5 provides a second illustrative example through the context of making design decisions with regard to seismic hazard in Colorado. Chapter 6 discusses future work and concluding remarks regarding the appropriate use of the framework at CDOT.

Definition of Terms

In the general arena of risk management, there are key terms that often carry similar or interrelated connotations. For the purposes here, the words below will be used with the specific definitions provided in this list. Many of the definitions have been defined by the International Standards Organization. Definitions available from existing documents are reproduced below and denoted by [#]. These definitions are arranged by relevance.

Risk. The effect of uncertainty on objectives. It can be positive or negative, and can have various components that apply at different organizational levels. Risk is the combined effect of a risk event's probability and consequence and is characterized by uncertainty regarding its potential occurrence and impact on the outcome of interest. [1]

Risk Management. The coordination of activities meant to guide an organization with respect to risk. [1]

Risk Management Framework. The set of components that provide organizational arrangements for designing, implementing, monitoring, reviewing, and improving risk management throughout an organization. [1]

Risk Attitude or *Risk Appetite*. The organization's approach to assess and eventually pursue, retain, take or turn away from risk. [1]

Risk Owner. Person or entity with the accountability to manage a risk item. [1]

Stakeholders. Persons or organizations that can affect, be affected by, or perceive themselves to be affected by a decision or activity. [1]

Risk Source. Hazard which alone or in combination has the potential to give rise to uncertainty and therefore risk. [1]

Probability. The likelihood that a risk event could occur.

Consequence. The impact that a risk event will have on the organization if it occurs.

Risk Event. A possible action, circumstance, or condition the occurrence and consequences of which are uncertain and could have a positive or negative impact on an organization’s mission, goals, or tasks at hand. [1]

Risk Register. A transparent, consistent method of recording all risk events that could affect an organization at a project-, portfolio-, or program-level.

Organization. The entity about which projects, portfolios, and programs decisions are being made.

Project. A tightly defined task, here typically referring to a construction project, repair project, or inspection procedure.

Portfolio. A group of assets of the same type, *e.g.* a collection of bridges, mast arms, etc., which must be operated and maintained.

Program. A group of portfolios under similar operation – a group of assets that need to be built, a group of assets that require maintenance, or a group of assets that require repairs.

Resiliency. Readiness for facing events that are abnormal in terms of scale, form, or timing. Resiliency requires knowledge of the hazard, accurate perception of the risk, understanding of available alternatives, and resources and flexibility to respond successfully to the risk. [6]

CHAPTER 2. LITERATURE REVIEW

General Frameworks for Risk Management

The use of a risk management framework can be seen across multiple disciplines in management practice. All industries, organizations, and projects face risks. Specific industries, such as transportation and storage of hazardous materials, are concerned with items that have explicit healthy and safety risks, and have existing frameworks to deal with the reality of this situation [7, 8]. Other industries implicitly assume that the current practices in place provide an acceptable level of risk; the actual risk, however, may be higher or lower than the risk an organization may choose to accept if risks were considered in an explicit manner. The following is an overview of how risk frameworks have been implemented or described for various organizations, and, specifically, how risk frameworks have been implemented in the transportation context, from federal level to state level departments of transportation. The following starts with a summary of broad, cross-industry frameworks from the International Organization for Standardization and the Enterprise Risk Management to introduce the philosophy of a risk management framework. The next three sections introduce how risk management has gained momentum at the federal level through three different federal documents in, specifically, the transportation sector. Finally, the last grouping of frameworks focuses on how risk management practices have been implemented in various states' departments of transportation.

International Organization for Standardization 31000:2009

The International Organization for Standardization (ISO) published standard 31000 on guidelines and principals for risk management in 2009 [1]. This standard provides a resource for the general vocabulary, procedure, and expected scope within an organization looking to implement risk management. According to this standard, risk management processes should create and protect value within an organization and be integral in all organizational processes and decision-making. They should also provide a means to address uncertainty in an explicit, transparent, and structured manner. Additionally, the document emphasizes that risk management processes through an established framework should be tailored to the specific organization, and the management itself should be responsive to change, either within the organization or surrounding circumstances. It emphasizes that risk management should be strongly supported from the top of the organization and integrated across all levels, with the resources, training and support necessary for individuals within an organization to succeed in implementing the risk management policy.

In order to integrate such a policy, the ISO recommends a risk management framework in this standard. The framework is made up of two main processes – one for implementing risk management, and another for continuously modifying, adapting, and improving the existing risk management process. The ISO framework for risk management is illustrated in Figure 1. As shown, this framework explicitly includes the process of monitoring and modifying the risk management framework, as necessary, based on its performance within a specific organization, in addition to the risk assessment aspects of risk management. This inclusion emphasizes the need to tailor a risk management framework to the particular culture and operation within an organization. At the start (box 1), an organization must clearly state its guiding principles, and formulate a process that is consistent with their goals and purposes. An initial plan can then be formulated (box 2), then applied to the projects within the organization (box 3). Risk identification (box 3b.i) should be the collective effect of all knowledgeable parties, and should involve all potential uncertainties in the lifetime of the project. This document does not detail the mechanisms behind the actual risk analysis and evaluation, but acknowledges that there are a number of ways to assess risk qualitatively, semi-quantitatively, or quantitatively, depending on the needs of the organization. Risk treatment (box 3c) can consist of the following: avoiding a risk by not continuing the activity that may cause or lead to it; taking a risk to seize an opportunity; removing the risk; mitigating the risk; changing the outcome if the risk is certain to occur; sharing the risk with others (generally monetarily); or proceeding with the knowledge of the risk and monitoring the risk without additional action.

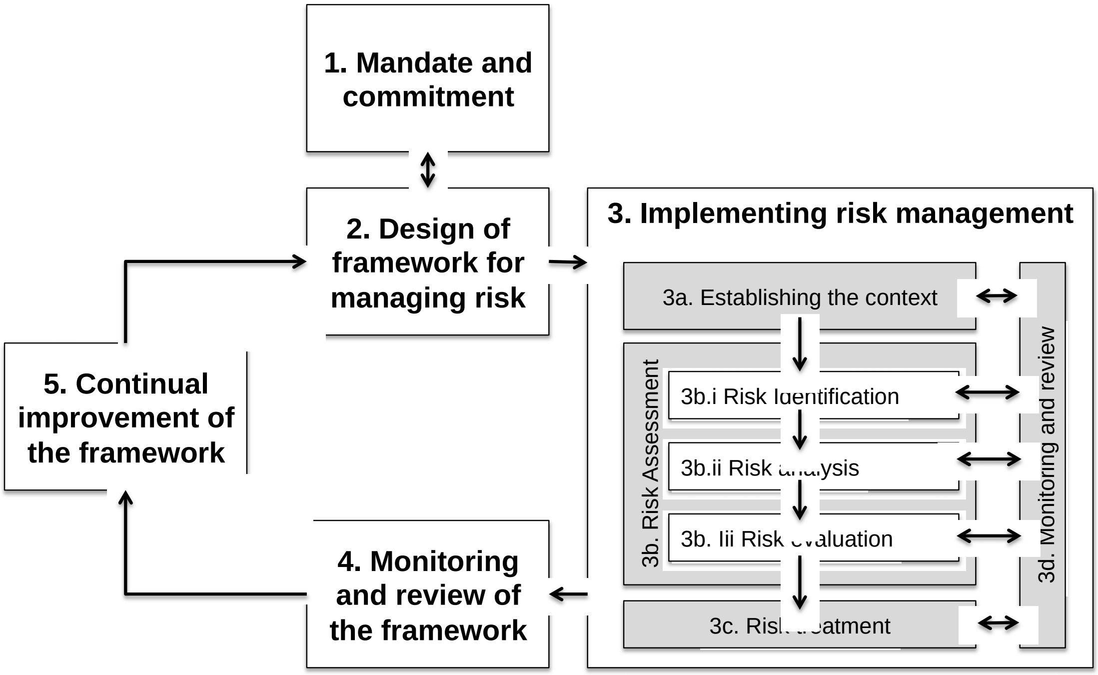


Figure 1. ISO 31000:2009 framework for risk management. Figure modified from [1].

While the ISO standard provides a common vocabulary and explicitly addresses the necessity to integrate a risk-aware mindset in every organization at every level, it is meant to be as broad as possible. This broad approach means that the document is not meant for certification or compliance, and substantial effort is needed to translate this ISO standard to practical practice for an organization [9]. This framework has been adopted by various regional government transportation agencies in Australia and New Zealand as the AS/NZS ISO 31000:2009, the Australia/New Zealand Standard [10].

Enterprise Risk Management

The Committee of Sponsoring Organizations of the Treadway Commission (COSO), a joint effort of five private sector accounting and financial organizations, created the Enterprise Risk Management (ERM) Integrated Framework in 1992, with an updated version in 2004. Like the ISO standard, the ERM framework sets out to define the essential components of the risk management plan and provides a common vocabulary for an organization to use when addressing risk, only with greater depth than provided by the ISO since it is a document meant for tangible application, *i.e.,* financial sectors [11]. The ERM framework requires an organization to address risk from a “portfolio” perspective, understanding how each individual risk is interrelated and how they can affect an organization individually and in concert [11].

As shown in Figure 2, the ERM framework emphasizes the need to integrate risk management activities (the eight items in-plane with the page) with other business operations and company culture (listed on the other dimensions of the cube). The front face of the three dimensional cube shows the actions that need to be taken. The right face shows the divisions of organization that need to implement those actions. The top face identifies the processes by which the actions and individuals are held accountable. The face on the top of the cube includes the following items: strategic, operations, reporting, and compliance. These items are critical to implementing the framework, such that the framework is used, used consistently, and used as intended. The items on the right face of the cube include: subsidiary, business unit, division, and entity-level. In the vocabulary of the ISO standard, these are the various levels across the institution or organization. The risk management activities align with the ISO principles and tasks found in box 3 of Figure 1, while the other two faces relate to the other boxes of the same figure.

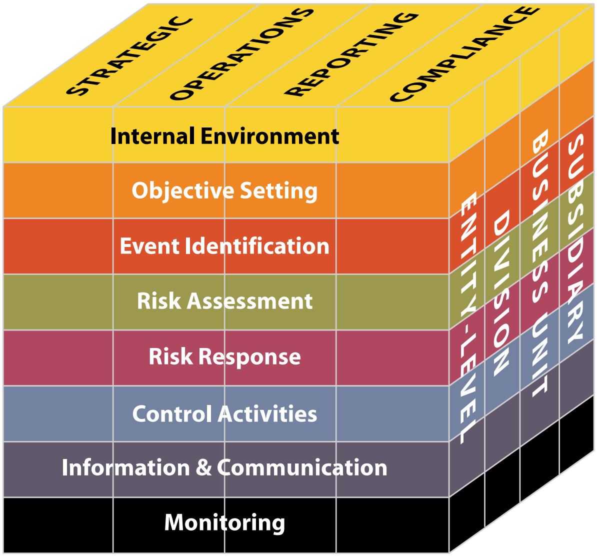


Figure 2. ERM Framework for risk management. Figure reproduced from [2].

While originally intended for accounting, financial, and insurance organizations that must manage financial risk for their customers, this framework has been adopted by several other types of organizations, including the University of California Regents [12], companies in the energy industry [13], companies involved in manufacturing [13], and state departments of transportation (DOTs) [14, 15].

Federal Mandate to Move Towards Risk Management

There have been three major federal government initiatives to move towards a risk management framework affecting the transportation sector: one addressing risk at a management level for transportation related projects, another addressing risk at a portfolio level in asset management, and a third investigating the vulnerability of the transportation sector with respect to factors related to climate change. The first is a guideline with best-practices suggestions. The second is a federal mandate imposed on state Department of Transportations, with 35% of federal funding at stake: should a state fail to implement an asset-management system, federal funding will fall to 65% of the current funding level. The third is a program in its pilot stages, implemented in only a few states thus far, and focuses exclusively on investigating the risks to the transportation sector due to factors related to climate change. Each of these major federal initiatives is discussed in the following three sections.

Federal Transit Administration: Risk Analysis Methodologies and Procedures (2004)

In June 2004, the Federal Transit Administration (FTA) released a white paper entitled "Risk Analysis Methodologies and Procedures" [16]. Building predominantly on risk work done previously for the construction and construction management industry, this paper presents a systematic approach for the evaluation of uncertainty (risk) regarding the scope, cost, and duration of a project. The scope of this paper covers the topics found in box 3 of Figure 1 of the ISO process described above, and does not cover the other aspects of risk management. The key steps include: (1) preparing to assess the risks; (2) identifying the risks; (3) quantifying the risks; (4) assessing the risks; (5) and mitigating the risks. This method results in a base cost or duration estimate for a construction project, with an itemized list of uncertain values due to potential risks that are added to the base estimates. In comparison to traditional methods of a total cost or duration estimate that implicitly include unknowns through embedded assumptions or extra allowances, this method provides far more transparency and informed decision-making.

The steps proposed by the FTA are described in greater detail here:

1. Preparing to assess the risks: At the beginning of the risk management framework, collect available information on the scope, timing, and base cost of the project. Conduct interviews with experts or relevant parties, and document the completeness or accuracy of information collected from the various sources.
2. Identifying the risks: Assess all aspects of the project to establish a comprehensive list of possible risks or uncertainties to the project. A possible list is presented in Table 2**.** The generation of this list can be completed by the participation of an expert panel or

workshop along with project members. At this stage, the framework recommends that the organization produce a list of risks as a draft for the risk register.

3. Quantifying the risks: Use an appropriate metric to quantify the likelihood that a risk will occur, as well as the impact that a risk could have if it were to occur. An impact matrix, which represents cost, time, or other performance metric, can be employed to assess the overall risk including these two components. This information is then recorded in the complete and updated risk register.
4. Assessing the risks: Evaluate the cost each risk could add to the project in dollars and/or in time, and use an analysis method (for example, Monte Carlo) to combine the risk impacts from the whole list of risks. Use of Excel$^{\text{TM}}$ with @RISK$^{\text{TM}}$ or CrystalBall$^{\text{TM}}$ is suggested for cost estimation, and MSProject$^{\text{TM}}$ with @RISK$^{\text{TM}}$ or Risk+$^{\text{TM}}$ is suggested for schedule estimation. Using this information and analysis, identify the influence each risk has on the total cost or duration of the project, and present to the team or stakeholders with the findings.
5. Mitigating the risks: At this stage, prioritize the risks that need mitigation, such as unacceptable risks or high cost and high likelihood risks. Determine which party is best equipped to manage the identified risk, and task this party with developing, implementing, and monitoring a risk mitigation strategy.

Table 2. Typical risk items identified by [4].

Project Phase	Status	Typical Risk Issues	Objectives for Risk Assessment	Expected Outcomes
Alternatives Analysis/ Conceptual Design	Focus is on general alignment and mode Project details not defined, environmental reviews incomplete Funding possibly not committed Public support uncertain; order-of-magnitude cost estimates General implementation timeline	Fatal or significant environmental, economic impacts Funding uncertainty Uncertain political and public support Competing interests and competing projects Costs relative to ridership/other benefits	Identify implementation challenges--political, public acceptance, approvals Better define a reasonable project approval and implementation schedule Quantify advantages/disadvantages of different modes, alignments Establish order-of-magnitude costs by mode, alignment Identify major design and construction risks	Better understanding of environmental, engineering, and construction issues facing each project alternative Identification of major risks associated with each mode and alignment Order-of-magnitude risk costs and possible total cost range for each mode, alignment
Preliminary Engineering	Environmental reviews approaching completion (Record of Decision) Initial approvals received but long term funding commitments still to be determined Project definition in the form of engineering design approximately 30 percent complete Cost estimates based on industry data and for aggregated activities High cost and schedule contingencies	Changes to project scope and budget Costs of environmental compliance Appropriate procurement methods Changes in design requirements Technical uncertainties Market conditions, exchange rates, inflation Funding uncertainty	Identification, quantification and likelihood of major scope, budget and schedule risks for all major project components General definition of base costs, risk costs, and total probable project costs Risks of alternative design concepts, procurement methods	List of major project risks Reasonable estimate of risk costs and probable total project costs and duration Long list of risk mitigation strategies Preliminary risk management plan, focused on design and constructability risks
Final Design	Project scope, cost and schedule well defined Minor open issues since all cost and design detail well advanced Construction approvals, including permits, agreements, not yet final	Changes to project scope and budget Errors or omissions in quantities, inaccurate unit prices Changes in design requirements Market conditions, exchange rates, inflation Permit requirements Delays in final approvals (agreements, sign-offs, grants/funding)	Identification, quantification and likelihood of all identifiable scope, budget and schedule risks for all project components Detailed definition of base costs, risk costs and total probable project costs Validation of reasonableness of contingencies and allowances in project budget and schedule	List of major critical risks; prioritization of risks based on impacts to total project cost and duration Estimate of risk costs and probable total project costs and duration Costs/benefits of risk mitigation strategies Risk management plan, focused on mitigation of unacceptable risks to project owner
Construction	Design complete; project defined Commitments (funding, policy) in place Construction in progress	Contractor performance, construction quality Final permitting, right-of-way acquisition Unanticipated site/working conditions Field design changes Construction safety Contractor coordination Cash flow	Targeted assessment of construction problems, causes and potential cost/schedule impacts Identification and systematic evaluation of possible corrective actions	Analysis of specific problem(s) Costs/benefits of possible corrective actions Corrective action plan that will allow project sponsors/owner to maintain (or recover) schedule and avoid cost overruns

Moving Ahead of Progress in the 21st Century Act (2012)

The new federal Moving Ahead of Progress in the 21st Century Act (MAP-21) was signed into law (P.L. 112-141) on July 6, 2012 [17]. This is the first new long-term transportation legislation since the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) in 2005 [18]. The main objectives listed in MAP-21 are: strengthening the United States highway system; establishing a performance-based program; creating jobs and supporting economic growth; supporting the Department of Transportation’s dedication to safety; consolidating Federal highway transportation programs; and accelerating project delivery through improved efficiency and innovation [17].

There are many important changes that were made between SAFETEA-LU and the new MAP-21. The establishment of a performance management program is described as “the cornerstone of MAP-21,” [17]. The program is meant to transition federal highway programs to performance and outcome-based measures, including infrastructure condition, safety, and system reliability, with funds allocated toward this goal. At the national level, within 18 months of enactment (originally April 2014), the Secretary, with input from states and other key stakeholders, must produce the following: minimum standards for each state to use in managing the development and operation of bridges and pavements; performance measures for pavement and bridge conditions; minimum conditions for Interstate pavements, depending on the region; and a specification of standardized data that much be collected and maintained in order to implement a performance-based approach [19].

Additionally, states are each required to develop a risk and performance-based asset management plan that accounts for, at the minimum, all national highway system (NHS) pavements and bridges, and preferably all of the infrastructure within the state’s right-of-way. Each state must produce the following within the same 18 months of the enactment of MAP-21: a summary, including conditions and other relevant parameters, of a performance-based asset management plan for at least the NHS pavements and bridges in the state; a developed list of objectives and measures for the state’s asset management plan; an identification of the performance gap between the existing conditions and the objectives of each entity (an individual bridge, for example); a financial plan and investment strategies for the asset management plan; and a lifecycle cost and risk management analysis [19]. If a state fails to comply, it can expect to lose 35% of its federal funding. It is currently slated for all anticipated coordinated performance measures to take effect midway through Quarter 2 of 2015 (approximately spring 2015) [20].

From these outlined roles, it appears that the federal government is to take the role of establishing the metrics of minimum acceptable conditions, performance levels, and data standards, while the states are responsible for producing the specific analysis tools and management procedures in order to reach the targeted specifications. Additionally, MAP-21 consolidates about 90 federal transportation programs into 30 programs, and increases eligibility for federal funding to include bridge and tunnel inspection, projects related to tolling and travel demand strategies and programs, and the development of state asset management plans as described above [4]. Funding for Colorado is projected to be fairly consistent between the two acts, at $517 million for fiscal year (FY) 2012 (under SAFETEA-LU), $517 million in FY 2013 (under MAP-21), and $522.4 in FY 2014 (under MAP-21).

Climate Change Vulnerability and Risk Assessment of Transportation Infrastructure

The Federal Highway Administration sponsored five pilot programs from 2010 to 2011 to investigate the vulnerability and risk assessment to transportation infrastructure due to climate change in each region. The regions studied included were the San Francisco Bay, coastal and central New Jersey, Virginia, Washington state, and the island of Oahu [21]. Risks were examined for 2050 and 2100 projections. New Jersey, for example, investigated impacts from rising sea levels, storm surges, extreme temperatures, and extreme precipitation levels [22]. Each region utilized the conceptual model as provided by FHWA to determine the potential climate changes and take inventory of and determine the priority of preserving existing assets (Figure 3). Using the developed inventory of assets and climate risks, the regions assessed how vulnerable each asset is to the potential climate effects – the probability of an asset being affected by any climate change – and weighs it against how much an impact that climate effect would have on the infrastructure asset if it were to occur. Together, the combined risk of probability and impact can be used to determine medium- to high-risk assets and identify, analyze, and prioritize potential adaptation options. The actual mitigation process is outside the scope of [21], but provides the groundwork to do so should the pilot study be extended. This framework provides a means to combine risk tolerance from a societal perspective with the planning and engineering that can help protect infrastructure that is deemed critical to societal function.

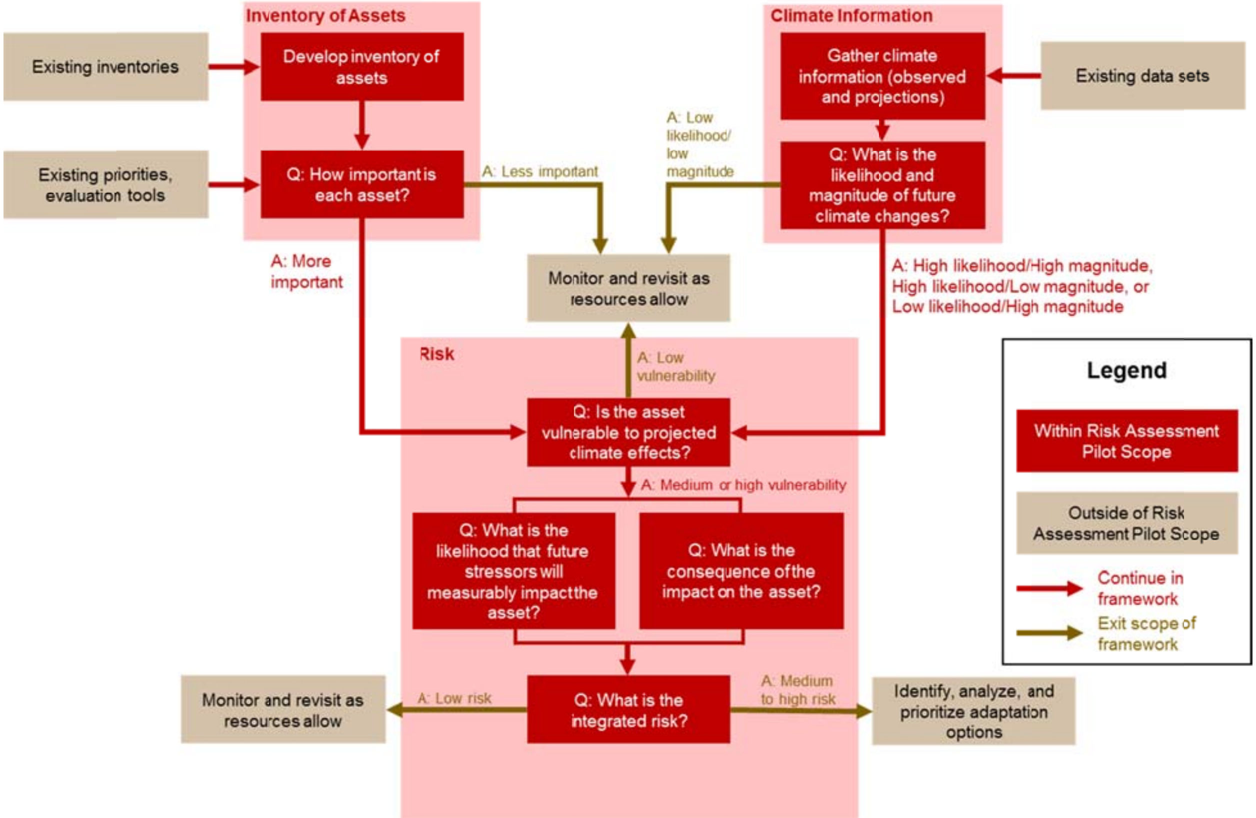


Figure 3. FHWA conceptual model. Graphic adapted from [22].

State Department of Transportation Frameworks

A number of state DOTs have developed risk management frameworks. Those presented below and summarized in Table 3 were selected based on the availability of information, extent of adaptation from existing frameworks, and varying degrees of integration into the organization. For example, the California and Washington procedures address project risk management; the Georgia and Virginia documents focus on portfolio risks. Utah and Minnesota represent states that have integrated a risk management mindset across the respective organizations. It is important to note that each document is referred to primarily by state name or state DOT agency name; this is for simplicity and is not meant to imply that this is the only realm in which risk-based methodologies are considered within the entire state or organization.

Table 3. Summary of State Department of Transportation work covered in this section.

State	Year adopted	Level(s) [Scope]	Reference
California	2003	Project risk management [construction]	[23]
Washington	2010	Project risk management [construction]	[24]
Florida	2008	Project risk management [construction]	[25]
Colorado	2011	Project risk management [project delivery selection]	[26]
Georgia	2011	Portfolio risk management [transportation assets]	[27, 28]
Texas	1988-2005	Portfolio risk management [bridges]	[29]
Virginia	2009	Portfolio risk management [mast arms]	[30]
Utah	2011	Program, Portfolio, and Project risk management [many]	[15]
Minnesota	2012	Program, Portfolio, and Project risk management [many]	[14]

Caltrans: Project Risk Management: A Scalable Approach

The California Department of Transportation (Caltrans) has developed a "scaled" approach to project risk management, meaning that projects with different scales according to various metrics – typically budget – are assigned a different level or scale of risk analysis [23]. Smaller projects may be evaluated through qualitative analysis, while projects with larger budgets are required to perform more rigorous and robust methods of risk analysis. This document, first published in 2003 with the current revision released in 2012, focuses primarily on the implementation of the risk management, *i.e.,* box 3 of Figure 1. The process outlined in the Caltrans handbook consists of 6 main steps, and is visually represented by Caltrans in the graphic shown in Figure 6.

Figure 4. Caltrans risk management schematic. Reproduced from [23].

The project begins with planning and communication. The project manager determines what scale the project falls under, based on budget and political or societal sensitivity of the project. Caltrans has three predefined minimum project scale levels. The first level is for projects with an estimated budget (including capital and support) of $5 million or less. The second level is for projects with an estimated budget of $5 to $100 million. The third level is for projects with an estimated budget of greater than $100 million. If a project has additional factors, such as political sensitivity, public sensitivity to time or cost within the project, or particular concerns from the stakeholders or community of the project, a project team may choose to work at a higher level than suggested in the guidelines.

Risks are then identified and recorded in a risk register, an organized method of tracking potential risks. To identify risks, team members are suggested to brainstorm, look for any instances of uncertain technology, draw from previous experiences, consult with others with knowledge of the project, location, or environment, and consult with the stakeholders. Once an exhaustive list of risks has been created, each risk is categorized as one of the following types of risk: design, environmental, right of way, or construction. Risks are also assigned a “risk owner”, who is responsible for moving forward with the consideration of this particular item. Then, using the template for a risk register provided by Caltrans [31], risk items can be recorded. This risk register includes fields for risk identification, risk analysis, and risk action. At this step, the items under risk identification can be recorded, including the status of a risk item (active or inactive), an identification number of each item, the category of the risk item, the risk title, a risk statement, the current status or assumption associated with the risk, and the name of the risk owner.

Risk analysis is performed based on project level from (1). For level 1 risks, the risk owner assigns a “low”, “medium”, and “high” risk rating and records this rating into the risk analysis portion of the risk register along with the rationale for choosing this rating. This rating is a completely qualitative method. A “low” rating requires no risk response at the time being, a “medium” rating calls for a risk response as time or resources allow, and a “high” rating requires giving a risk item priority for determining and implementing a risk response.

The guideline for a level two project is a qualitative risk matrix. Risks are categorized as either threats (negative uncertainties) or opportunities (positive uncertainties). The risk owner and other relevant team members assess likelihood and impact of each risk through qualitative judgment. Each risk item is then given a rating for time impact, cost impact, and probability based on the chart shown in Table 4.

Table 4. Impact and probability rating guidelines for Caltrans Tier 1 Risk Assessment. Figure reproduced from [23].

Rating -->	Very Low	Low	Moderate	High	Very High
Cost Impact of Threat (CO + COS)	Insignificant cost increase	<5% cost increase	5-10% cost increase	10-20% cost increase	>20% cost increase
Cost Impact of Opportunity (CO + COS)	Insignificant cost reduction	<1% cost decrease	1-3% cost decrease	3-5% cost decrease	>5% cost decrease
Schedule Impact of Threat	Insignificant slippage	<1 month slippage	1-3 months slippage	3-6 months slippage	>6 months slippage
Schedule Impact of Opportunity	Insignificant improvement	<1 month improvement	1-2 months improvement	2-3 months improvement	>3 months improvement
Probability	1 9%	10 19%	20 39%	40 59%	60 99%

Using the ratings determined from the provided table, the risk is determined based on the Caltrans Risk Matrix, which is shown in Figure 5. Green risks are low priority, yellow risks are medium priority, and red risks are high priority. Additionally, each risk can now carry a numerical risk value, called the cost or time score for each category, which can be obtained by multiplying the "Probability Rating" number (1-5) by its "Impact Rating" (1, 2, 4, 8, or 16). For example, if a risk item has a low probability of happening, but would have a high impact if it were to occur, the overall risk value is 2 x 8 = 16.

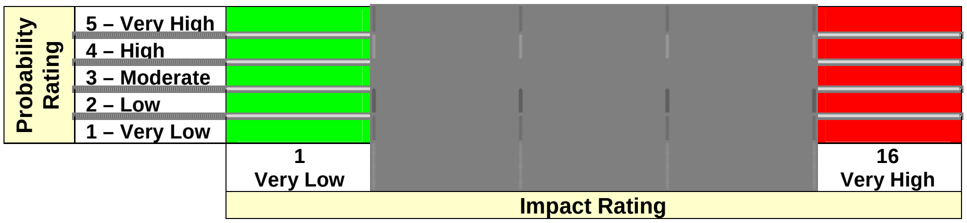


Figure 5. Caltrans Risk Matrix for Level 2 Risk Assessment [23]. Figure reproduced from source.

Once the quantitative scores are determined for each risk item, the risk owner enters the details into the risk register by completing the fields of "probability", "cost impact", "cost score", "time impact", "time score", and "rationale". The time and cost scores are obtained by multiplying the probability number by the impact number for time and cost, separately.

Level three projects require a quantitative risk analysis, where the impact of all identified and quantified risks are evaluated simultaneously. Caltrans suggests using a Monte Carlo simulation through *@Risk, Crystal Ball, or Primavera Risk Analysis* software. Each risk item is comprised of these two separate elements, time and cost, and each risk item also has an associated probability of occurrence. The risk analysis can be done for one or both the cost and schedule estimates, depending on the objective of the study. Cost estimates are to include direct costs only, and, for example, exclude costs that can be incurred due to a delay in scheduling. The degree of uncertainty in each risk element for time and cost is given a probability distribution, which can be formulated by using a “3-point estimate” comprised of the optimistic, likely, and pessimistic values for each risk item. These values can be drawn from past experience, data from previous projects, data from literature, or expert opinion. The probability of occurrence is assigned a low value and a high value. The project team or subject matter experts for each separate risk element determine these estimation points. Though this is the most quantitative of the methods, qualitative inputs are still necessary due to incomplete information or datasets in many cases of interest.

Once these metrics have been determined, the risk owner updates the risk register with the probability (“low” or “high”), cost impact (“low”, “likely”, or “high”), time impact (“low”, “likely”, or “high”), and the rationale for such the provided ratings. Assumptions are needed to determine the distribution used in the three-point fitting. The distribution could be triangular, normal, or otherwise. Using the software, it is possible to generate cumulative distribution functions for time and cost. This can give insight as to the likelihood that a project is to finish on time or within budget, as well as the extra time or money needed to satisfy a given degree of confidence. The software can also help to determine which risk items contribute most to the overall cost or schedule.

The risk owner determines risk response action and record into risk register. With the risk analysis performed on a risk item, the risk owner must also make decisions on how to best respond. There are four responses identified by Caltrans. For threats, the risk owner can choose to avoid, transfer, mitigate, or accept the risk. In avoiding the risk that poses a threat, Caltrans attempts to remove the cause of the risk or execute the project along a different path in order to avoid the item altogether. This approach, however, is not always possible. Transferring the threat involves finding others who are willing to take responsibility and liability for the risk; this option is typically associated with a financial trade-off. Mitigating the threat means to take action early in the project in order to reduce the probability or the impact of the risk. This option may bring a potential increase in resource or budget needs. The final response option for a threat is to accept the threat at the time of analysis, either because no feasible action can be taken or because the importance is low. A contingency plan can be developed for the event that the threat does occur, but otherwise this response accepts the potential impact that the threat may carry.

For risks that present opportunities, the risk responses consist of four options: exploiting, sharing, enhancing, and accepting the uncertainty. The first option is to exploit the opportunity by planning to ensure that the opportunity will occur. Exploiting the threat is an aggressive response that may require additional resources, and Caltrans recommends reserving this option for the extreme high-probability and high-impact items. The second option is to share the opportunity. Sharing requires finding other parties who may also benefit from the risk item and have them take responsibility for guiding the probability of occurrence and potential benefits in the direction of the project’s favor. This option, like transferring a threat, typically requires a third party and a budget tradeoff. Enhancing an opportunity is the opposite of mitigating a risk. The goal is to maximize the probability or impact of a risk item. Like mitigation, enhancing may require extra resources in personnel, time, or budget. The last option, accepting, is the same as for threats; a contingency plan is less necessary since the impact should be positive. After a risk response has been chosen for the risk item according to budget, other resources, and overall impact, the risk response is recorded in the risk register.

The next step is to monitor risk action by regularly assessing the status of identified risk items and updating the risk register with current statuses. Monitoring and updating are intended to span the lifetime of the project. During monitoring and updating, any new risks that appear should also be addressed. Risks should be monitored and updated at a regular time interval deemed appropriate by the risk owner and project members. Monitoring can involve reviewing the risk status, checking on compliance with risk policies and procedures, and updating the budget. Monitoring risk action may also result in producing recommendations for alternate risk responses, taking corrective action, or changing project objectives. Before updating the risk register, care must also be taken to create a backup of the current file version of the risk register for information integrity.

Finally, the last step is to return to communication and planning by recording lessons learned for future projects and learning sharing within the organization. At the end of the project, the project risk manager should meet with the team, particularly those who assumed the role of the risk owner, in order to determine what could have been done differently and why, as well as to highlight best practices that were executed or discovered along the lifetime of the project.

Washington State Department of Transportation

The Washington Department of Transportation developed a document entitled “Project Risk Management: Guidance for WSDOT Projects” in 2010 [24]. It is very similar to the process as described by Caltrans. The major difference is in determining the scope of a project and the associated required processes for qualitative or quantitative risk assessment. The discussion here focuses on these differing steps.

For projects with an estimated budget under $10 million, a qualitative risk assessment may be performed. This cutoff is higher than the $5 million prescribed by Caltrans. For projects from $10 to $25 million, an informal workshop that completes the “Self-Modeling Spreadsheet” is required. For projects from $25 to $100 million, a Cost Risk Assessment (CRA) Workshop is required, and for projects over $100 million, a Cost Estimate Validation Process (CEVP®) Workshop is required. All projects from each of these three cost categories utilize a risk register.

Qualitative risk assessment can be either on a 2x2 risk matrix (low and high) with probability and impact on the two dimensions, or a 5x5 risk matrix like the one provided by Caltrans. The risk categories for probability and impact are determined through team discussion, and the matrix is not meant to be interpreted quantitatively.

Quantitative risk assessment utilizing the “Self-Modeling Spreadsheet” is accomplished by gathering the proper data in order to create a Monte Carlo simulation that generates the probabilities of time and cost based on the uncertainty of each risk item. The CRA is a workshop of one to two days, involving internal and local experts. It is meant to produce an assessment of risks in order to evaluate and update a projected cost and schedule estimate. The CEVP is similar in concept, but convenes for three to five days and involves both internal and external subject matter experts. WSDOT specifies that the CEVP should be held as early as possible to the start of the project, but they do not specify when the CRA should be held, as it is deemed less critical by WSDOT. This difference is due to the difference in scope of projects.

Florida Department of Transportation: Project Management Handbook

The Florida Department of Transportation (FDOT) uses a risk-based methodology in project management, which is a combination of their own “Risk Based Graded Approach”, and adopting the Caltrans quantitative risk analysis described above [25]. The “Risk Based Graded Approach” developed by FDOT is used as a screening of projects to determine whether a more robust, quantitative risk analysis – the one proposed by Caltrans – is or is not necessary. The “Risk Based Graded Approach” is described below.

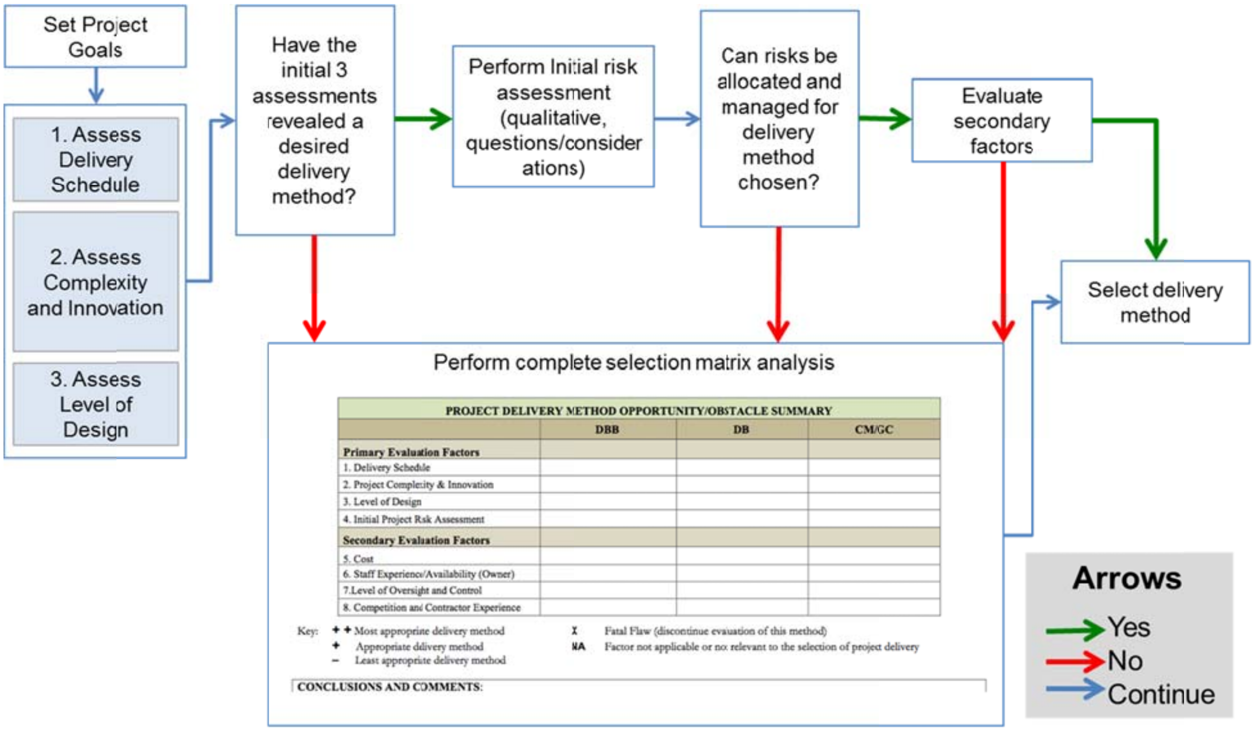
First, a list of potential risks is to be developed by the project team. Then, risk items are assigned a risk assessment, which correlates to the impact a risk item may have on the project, either for time or budget. The risk assessment is on a scale of 1, 3, or 5, with 1 being low risk and 5 being high risk. Next, the team determines which of the risk items is to be given top priority in the “risk priority” grade, also on the same 1, 3, 5 scale. The team may only assign a maximum of three items a grade of 5; the rest are given either a 3 or 1. The two scores for each risk item are then multiplied together (*i.e.*, impact x priority) to determine a final risk score for each risk. Each of these individual risk scores is added together to find the overall risk score. If a score is between 0 and 90, the project is categorized as low risk; if a score is between 90 and 150, the project is categorized as medium risk; if a score is over 150, the project is high risk. After the risks are qualitatively evaluated, high-risk projects can be quantitatively analyzed to determine the potential impact of the risk in dollar amounts or schedule time. Each risk item is then assigned a risk response plan, which consists of the threat responses from Caltrans: avoid the risk, transfer the risk, mitigate the risk, or accept the risk.

FDOT does acknowledge that risks could be either threats or opportunities, but focuses explicitly on managing the threats in the treatment of risk items in their document. Additionally, their approach does not focus on the aspects of integrating communication, feedback within the process, or lessons learned for future projects.

Colorado Department of Transportation: Project Delivery Selection

In 2011, the Colorado Department of Transportation (CDOT) developed a risk-based project delivery selection approach to determine whether projects should be 1) design-bid-build, 2) design-build, or 3) construction manager/general contractor [26]. This approach is intended to be utilized before the start of the project with the project team together at a workshop session, and can be completed within a single day.

Figure 6 illustrates the CDOT project delivery selection process. At the onset, the team is to identify the project goals, establish a delivery schedule, assess the complexity and innovation required from the project, and assess the difficulty of the design problem present. If the first assessment points to a best delivery method, the team is to move forward with that method and perform an initial risk assessment with qualitative questions and considerations. If the risks can be allocated and managed for the chosen delivery method, the team is to then consider secondary factors and confirm that this method is satisfactory. If at any point the chosen method fails any of these conditionals, or if there was no clear result for the best delivery method from the initial three assessments, the team must complete a selection matrix as provided by CDOT to determine which delivery method is correct. The worksheet contains key risk areas and requires users to rank the three options, as most appropriate (2), appropriate (1), or least appropriate (-1). The team is also allowed to mark an option as fatally flawed, at which point that particular delivery method is ruled out completely. Values for each method are then added together, and the most highly ranked option is selected.



PROJECT DELIVERY METHOD OPPORTUNITY/OBSTACLE SUMMARY			
	DBB	DB	CM/GC
Primary Evaluation Factors			
1. Delivery Schedule			
2. Project Complexity & Innovation			
3. Level of Design			
4. Initial Project Risk Assessment			
Secondary Evaluation Factors			
5. Cost			
6. Staff Experience/Availability (Owner)			
7.Level of Oversight and Control			
8. Competition and Contractor Experience			

Key: ++ Most appropriate delivery method
\+ Appropriate delivery method
\- Least appropriate delivery method
X Fatal Flaw (discontinue evauation of this method)
NA Factor not applicable or not relevant to the selection of project delivery

CONCLUSIONS AND COMMENTS:

Figure 6. CDOT project delivery selection process [26].

Georgia Department of Transportation

In 2011, Georgia Department of Transportation developed a Transportation Asset Management (TAM) strategic directive in order to prevent major problems, prolong the life cycles of critical assets, and plan for future replacements with informed decision-making [27]. The study which resulted in this directive indicates that prioritization of assets needs to be tied to the strategic goals as determined by the agency, and that the overall purpose is to reduce the risk associated with achieving those goals [28]. The basic elements of the risk framework are illustrated in Figure 7. The first step is to identify the goals of the organization, as stated above, and make sure that the agency's mission statement, objectives, and written policies are all aligned. Once the goals have been identified, the agency can identify the associated risks. With this information, risk analysis can be performed to determine which risks are acceptable, and which need mitigating action in the risk assessment stage in order to reach an acceptable risk target. The process should be under continual monitoring and review, although the use of a specific tool such as a risk register is not prescribed.

Figure 7. Georgia DOT's conceptual risk framework. Image reproduced from [28].

For the risk analysis portion of the framework, a generic risk matrix template is provided to weigh the probability and consequence of an identified risk from low, medium, to high. It is nearly identical to the risk matrix provided by Caltrans (Figure 5), though with less granularity due to having three levels rather than five levels.

The document emphasizes the importance of available data in order to make the decisions necessary in the steps above, and that the data should be collected in an ongoing, systematic fashion in order to ensure the improvement and maturity of the risk framework described above.

Texas Department of Transportation: Risk-Based Bridge Inspection

From 1990 to 2005, the Texas Department of Transportation (TxDOT) used a risk-based bridge inspection policy [29]. This policy provides an example of portfolio risk management. Depending on the condition of the bridge at the time of inspection, age of structure, traffic load, construction type, and other factors, the time for the next inspection was adjusted to minimize both risk and budget for the bridges in Texas. For each bridge, the inspection policy could be a standard 24 month inspection cycle, an extended 60 month inspection cycle for low risk bridges or an accelerated (less than 24 month) inspection cycle for higher risk bridges. This process did not extend beyond inspection policy. Figure 8 shows a schematic of this decision-making framework. Kowalik [29] found that the approximate annual inspection budget was $1,500,000 before 2005 using this risk-based inspection policy. After 2005, Texas was required to move to the federal standard 24 month cycle requirement. This change was estimated to increase the annual inspection budget to $2,860,000 [29].

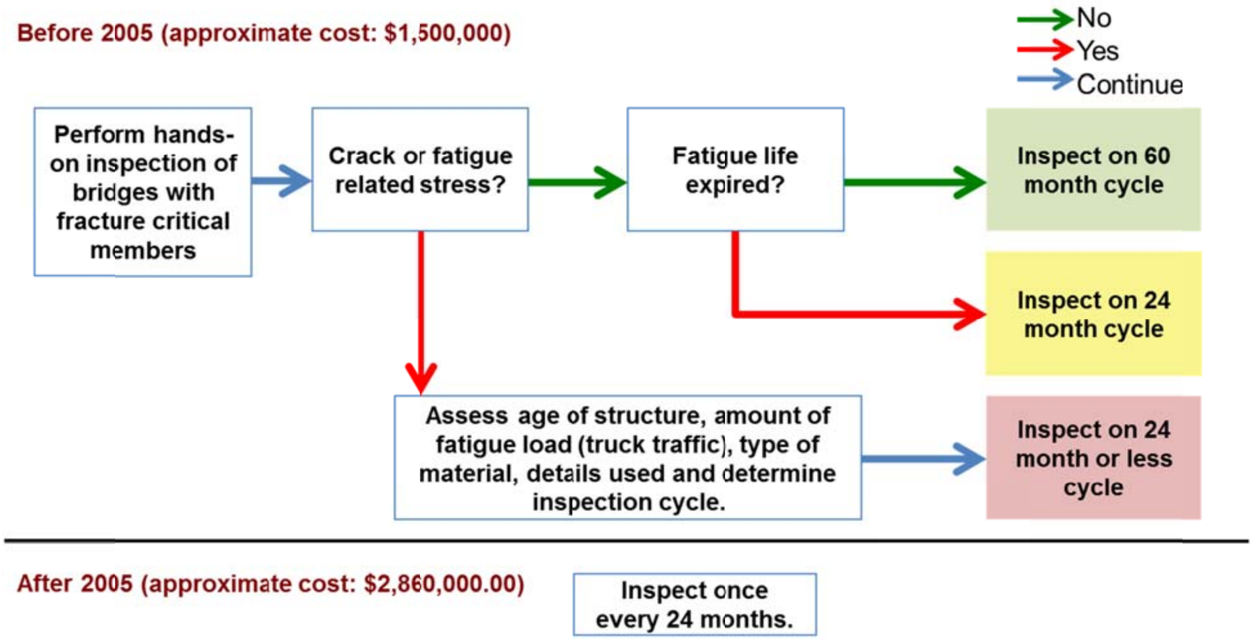


Figure 8. Texas bridge inspection policy prior to 2005 [29].

Virginia Department of Transportation

Virginia has over 3,000 signalized intersections, approximately 57,000 miles of roads, and 19,293 large structures, such as bridges, requiring maintenance [30]. On average, the Virginia Department of Transportation (VDOT) spent about $16 million on signal maintenance and operation (M&O) per year from 2005-2007; in the 2008 calendar year, this expense increased to approximately $24.6 million. To address the budget needs of M&O, VDOT began to use a needs-based budget approach in FY 2006. This approach showed the need for the M&O budget to be 10% greater than originally allocated in the state overall, and created a methodology by which funding within the state could be prioritized and ranked from a performance-based perspective. This method is driven by objective and quantifiable needs and data evidence rather than historic or routine action. Decisions are based upon field-maintained inspection inventory, life-cycle analysis, and inventory considerations.

To determine an annual budget through the lens of this framework, there are three basic input needs. First, the system assets must be characterized by type, quantity, age, life expectancy, and cost of individual physical components. Second, the scope of M&O must be defined by work categories, frequencies, and resource requirements. Finally, the infrastructure performance criteria and objectives must have clear performance targets set, such as target mean repair time, life cycle maintenance costs, or signal component mean time between failures. Performance targets are then compared to actual performance states, and work tasks are identified to bring the individual assets to target performance levels. Each task is translated into its associated cost, and the M&O budget can be determined once this analysis has been done for the entire signal system.

This framework provides flexibility for targeting certain objectives and incorporating different performance measures depending on the analysis needs, but it does not address the continuity of integrating lessons learned to future years either implicitly or explicitly. It also does not address the communication aspect of asset management, a means for record keeping, and transparency or accountability in decision-making.

Utah Department of Transportation: Implementation of ERM and WSDOT Frameworks

The Utah Department of Transportation (UDOT) has implemented the Enterprise Risk Management framework to evaluate organizational and programmatic level risks [15]. The framework names “traditional risks” to include work safety, claims, and other regulatory compliance issues. Programmatic risks involve funding levels, fostering a positive reputation, and legislative action. Project level risks include factors that may impact the scope, schedule, budget and quality of a project. Specifically for their project management needs, UDOT is using the tools developed by Washington State: the Cost Estimate Validation Process (large to very large projects) and the Cost Risk Analysis (medium to large projects). These tools both utilize a risk registry and Monte Carlo type calculations.

Minnesota Department of Transportation: Implementation of the Enterprise Risk Management Framework

The Minnesota Department of Transportation (MnDOT) also utilizes the Enterprise Risk Management (ERM) framework within their organization. MnDOT has integrated risk management into operational risk management, project risk management, program risk management, and corporate risk management [32]. For operations, the goal of risk management is to ensure a safe and reliable transportation system by preserving the existing transportation assets in the most cost effective manner. For project risk management, like project management at Caltrans and WsDOT, ERM is used in identifying, quantifying, and responding to risk items in order to achieve project objectives. Program risk management is used to assess the system risks that can help determine investment priorities in order to strengthen performance as a whole. Finally, corporate risk management can help to assess the organization’s ability to achieve its strategic goals through analysis of tasks, people, structure, and culture at MnDOT.

Lessons Learned from Literature Review for Application to Colorado Department of Transportation

Nationally and globally, ISO 31000:2009 and ERM frameworks have set precedence to identify and address risks within an organization across all levels. They have emphasized the importance of establishing the context under which an organization operates. At the federal level, risk-based management and risk analysis in the context of transportation asset management has been established, and, with the coming of MAP-21, performance-based asset management will be required of state DOTs. At the state level, the idea of risk-based project management has grown significantly since Caltrans first implemented its project risk management methodology in 2003. Some frameworks include the “soft” skills needed to run a project, such as communication amongst team members; others focus primarily on the risk analysis action items. The higher level documents, such as the ISO and ERM documents, provide guiding themes in the development and approach toward implementing a risk-based framework in an organization. The state DOT examples provide helpful insight as to how to address specific types of levels (portfolio versus project) and scopes (mast arms versus bridges). Reviewing a number of frameworks allows best practices to be gathered – items such as feedback loops between current decision-making and future decision-making are present in some frameworks but not others. Such feedback loops allow for the continued benefit of lessons learned from each project. Without them, there is no safe guard against repeated pitfalls due to the same risk item. These lessons from existing frameworks are used to guide the development of a risk-based framework for CDOT.

CHAPTER 3. PROPOSED METHODOLOGY FOR THE COLORADO DEPARTMENT OF TRANSPORTATION

This study develops and proposes a risk-based framework for use by the Colorado Department of Transportation, which is presented in Figure 9 and builds on best practices from the existing processes. The goal of this framework is to promote risk-consistent practices throughout CDOT at all levels of the organization in order to reinforce the promise of safety and performance to the Colorado public. From an asset perspective, CDOT is responsible for a variety of building, operating and maintaining structural facilities, such as mast arms, bridges, overhead signs, and more. To provide a sense of scale, this includes over 5,000 mast arms [33] and 8,591 bridges [34]. Of the bridges, 6.6% have been considered “structurally deficient”, and 10.6% named “functionally obsolete” by the American Society of Civil Engineer (ASCE), as reported in the “2013 Report Card for America’s Infrastructure” [34].

The major components of this framework include 1) communication logistics, 2) identification of goals and standards, 3) risk analysis, and 4) continuity for lessons learned. Risk analysis is broken into four subsections: 3.a) risk identification; 3.b) risk assessment; 3.c) risk action; and 3.d) risk monitoring. Central to all of these ideas is the concept of transparency, both organizationally and in technical decision-making. The framework works under the assumption that a team leader and a defined team has already been chosen to address the task at hand.

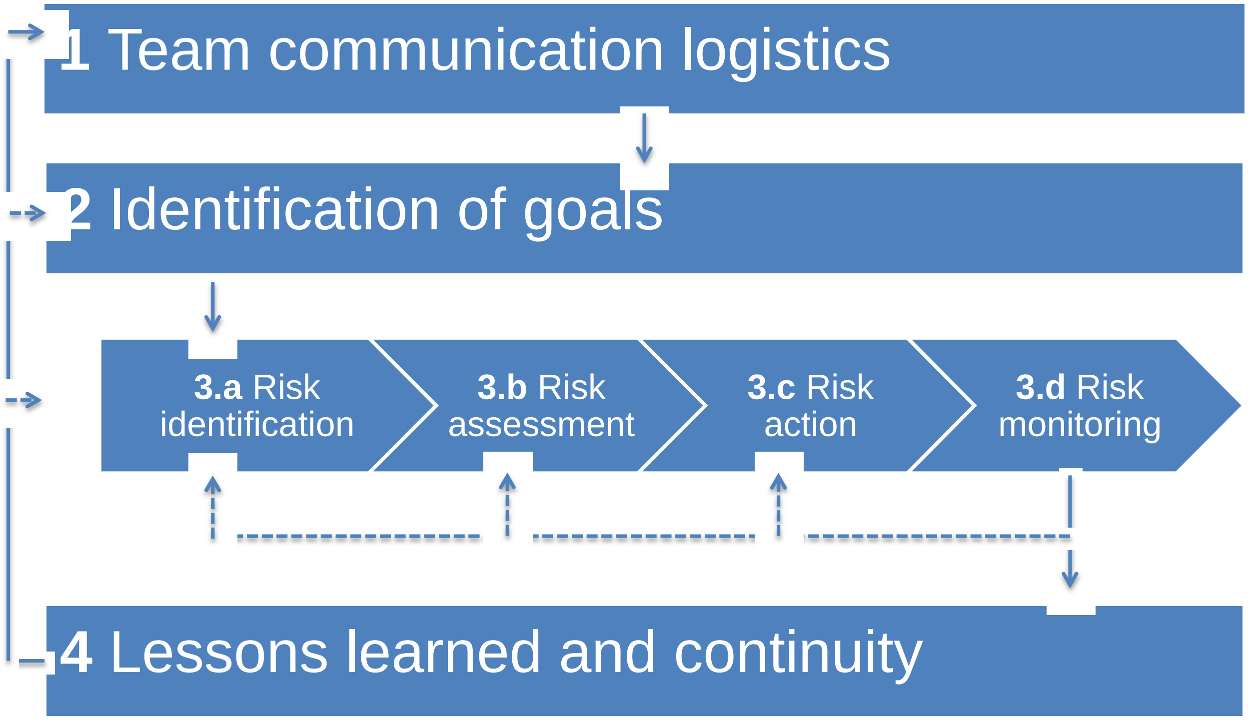


Figure 9. Proposed risk management framework for CDOT.

The framework is designed to be applicable to multiple levels of the CDOT project organization. In this study, different levels of decision-making within CDOT are referred to as the project level, portfolio level, and program level. Figure 10 highlights one example from each level. At the project level, there is “mast arm N”. Mast arm N is one of many mast arms. In this context, mast arm N has been identified as a potential risk to CDOT, for example, because inspections showed it had some structural defect. The project level is where concerns regarding individual construction or maintenance projects are addressed, such as to whom the repairs should be contracted, how to route traffic during maintenance, and other similar logistics.

At the portfolio level example, one possible portfolio of assets is the collection of mast arms in Colorado. With a given set of resources, at this level, questions such as how to allocate those resources amongst competing needs are answered. Chapter four provides an illustrative example aimed at this level of organization by investigating the challenge of allocating a budget for mast arm maintenance and operation. The example focuses on three hypothetical mast arms, named “mast arm N”, “mast arm O”, and “mast arm P”. Each of the mast arms has an identified structural state; the question of what to do with such information in terms of maintenance work or inspection frequency, and the resulting trade-offs, financially speaking, is of primary concern.

Overseeing all of the various types of assets is the program level of “maintenance and operations”. Decisions made at this level could involve a review of inspection policy, examination or modification of repair or replacement schedules, and design reviews of various assets. It could also involve decisions that prioritize the needs of one type of portfolio, or asset, over another. For example, at the program level, it could be determined that roadways should be allocated more resources than traffic signs due to the potential for roadways to cause greater delays on the traveling public. Chapter five provides an illustrative example aimed at this level of organization from a design perspective, exploring how CDOT could use this risk-based framework to evaluate seismic design procedures for bridges. At this level, there can also be communication between differing programs. The maintenance and operation program could inform design program of the design common defects seen during inspection routines in order to have the problem investigated at an earlier stage in an asset’s life-cycle.

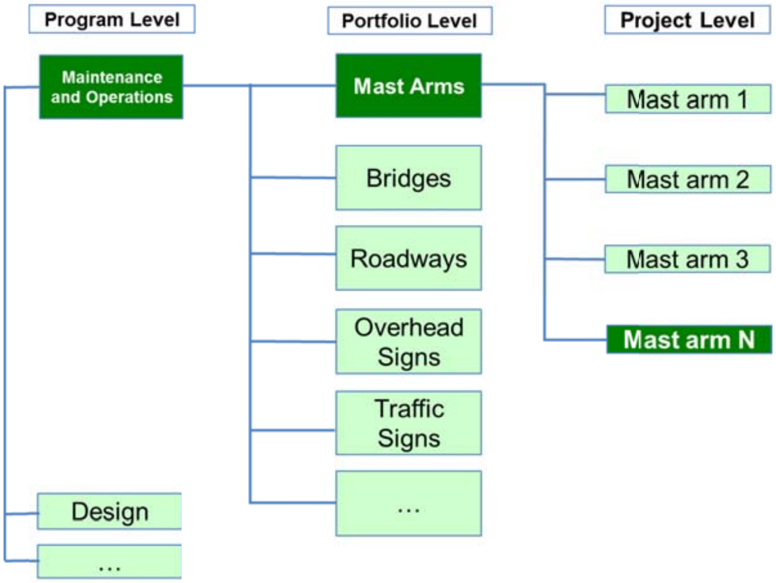


Figure 10. Schematic illustrating the meaning of "program", "portfolio", and "project" levels as used to illustrate different levels of CDOT decision-making.

Team Communication Logistics

In the proposed risk-based framework, the first step, box 1, labeled “team communication logistics,” is when the team is organized, a leader identified, and a framework for communication and work action is determined. These items are addressed before the project begins, or at the very beginning of a project. Decisions addressed at this point could be determining how often to meet, how to keep record of risk items (such as a risk registry), and by what medium to communicate. These items can be tailored to the individual team preferences, but need to be defined for clarity and managing team dynamics moving forward. Addressing communication logistics first requires the team to identify the best avenues for communication, frequency of meeting, and documentation of any communication made. This is intended specifically for risk assessment communication, but may be integrated with all team communication if this fits the group need appropriately. This step promotes organizational transparency. This can be a discussion that identifies email, phone, or in-person meetings as the preferred form of communication. Additionally, it is the appropriate time to address the expected allocation of time spent on the project or effort, and how often the team should update and be updated on progress. Finally, it is imperative to identify the way by which both operational and technical information should be recorded such that information is up to date for all team members and accountability is easily achieved.

Identification of Goals/Standards

The next step, box 2, identifies the goals of the project. In order to successfully complete a project or achieve a task, the framework includes a step early on to identify tangible goals and metrics by which success or completion can be identified and quantified. Goals should be formulated to be as clear as possible, preferably in a single, concise sentence. Each goal should be accompanied by a clearly measurable metric in order to identify whether each goal has been achieved. If a goal or metric is unclear or unmeasurable, it is difficult to assess progress. As identified in the first step of team communication, all goals and metrics should be written and saved in an agreed-upon manner such that all team members have routine access to them, such as a formatted risk register. These goals could range from a goal as straightforward as finishing a bridge construction, to meeting a certain deadline, staying within a prescribed budget, minimizing traffic delays and/or environmental impacts. The relative importance of goals needs to be identified at this time. These goals should represent the input of all team members, as well as any stakeholders available for consultation. Any existing CDOT policies for engaging stakeholders can be complemented by this risk discussion.

Risk Analysis

The steps in box 3 constitute the risk evaluation associated with each goal. Risk analysis is made up of four parts: risk identification, risk assessment, risk action, and risk monitoring. Each of these steps is carefully recorded in order to develop a risk register for the project. In each of these steps, various levels of analysis could be applicable, depending on the available time, budget, importance of project, or any number of factors. Below, a few options are given for each one, with a brief explanation on what situations would warrant the use of which kind of analysis.

Risk Identification

The team develops a list of risks – both threats and opportunities – associated with each goal to identify which of these risk items may hinder or help achieve the identified goal, respectively (box 3.a). Depending on the scope of the project, this step may extend beyond immediate team members to include any stakeholders, other project teams, and the relevant public impacted by the project at hand.

Method 1

A method 1 risk identification would involve only the team leader and team members. Early in a project, and regularly throughout the life of a project, the team should gather in order to discuss the perceived risks, both negative and positive. Additionally, should the team have access to previous similar projects (if the framework has been in place for previous projects), pulling files from those to identify what risks were considered previously, and what issues arose during the course of the project. As discussed in the team communications meeting, the risk list should be saved in an accessible location and revisited regularly.

Method 2

A method 2 risk identification should apply all the same processes as level 1, with the addition of pulling in the expertise and knowledge from individuals outside of the team, but within the organization.

Method 3

A method 3 risk identification should apply all the same processes as levels 1 and 2, with the addition of pulling in the expertise and knowledge from individuals outside of the team and organization. This could be experts in the field, experts in related fields, input from the community, or any other relevant groups or individuals.

Risk Assessment

Next, in box 3.b, a risk assessment is performed. A number of risk assessment practices were described in the previous chapter, ranging from qualitative to quantitative methods. An illustrative example of each is developed in the following chapters.

Method 1

A method 1 risk assessment ranks each risk item with a qualitative “low”, “medium” or “high” rating. The risk rating is then recorded in a risk register or other records repository and assigned to a risk owner, who is then responsible for overseeing the status of this particular risk item. This process is then repeated for all identified risks. This method of risk assessment is illustrated in Chapter 4.

Method 2

A method 2 risk assessment ranks each risk with both a “low”, “medium”, or “high” rating for both impact and probability. Using a risk matrix that visualizes this two-dimensional problem, an overall risk rating is determined. As in level 1, the risk assessment (impact, probability, and risk rating) is recorded in the risk register and a risk owner is identified to oversee the risk item. This type of risk assessment is also illustrated in Chapter 4.

Method 3

A method 3 risk assessment uses existing data and expert opinion to quantitatively assess the risk and assign a risk rating. For example, if the team identifies the potential for rights-of-way resolution to delay the project, this would be quantified in either dollar amounts or time (in days, weeks, or months). As shown in the literature review, Monte Carlo simulation is often used for this type of assessment. As with the other two levels, the risk rating is determined and recorded, along with the name of a risk owner. This type of risk assessment is illustrated in Chapter 5.

Risk Action

In box 3.c, a risk action is determined for each risk item. A risk action should be decided upon either by the team or the individual risk owner. The actions can be categorized as choices to avoid, transfer, mitigate, or accept the risk in consideration. The category should be recorded to provide a quick overview of the risk action. In addition, the actual risk action plan should be clearly stated in a sentence, identifying how that action is to be achieved.

Risk Monitoring

In box 3.d, the risk action and impact of that action is monitored during the lifetime of the project. Risk monitoring means that the individual risk owners are diligent about regularly checking up on the risk item, recording any changes in the risk status, and identifying new risks that surface over the course of the project. At any point, the risk action, risk assessment, or risk identification may be modified due to new information or project developments. Figure 9 shows dashed lines connecting the “risk monitoring” box to the previous three boxes – these dashed lines are meant to represent the potential for this step to call for making revisions or adjustments to any one of the previous three risk analysis steps, whether to edit the list of risks, change the risk assessment, or modify the risk action based on the risk status. This feedback loop is maintained for the duration of the life of each particular risk item and for the duration of the project as a whole.

Continuation for Lessons Learned

At the end of the project, as identified by box 4, the lessons learned should be recorded and shared with other groups such that groups can identify best practices and have a better idea of which risks pose the greatest threat or opportunity.

Lessons learned and continuation are important features of the risk-based framework. They can be manifested as a debriefing meeting at the end of an effort or project to recap the risks encountered, issues encountered, and highlight successes. This encourages the constant improvement of risk analysis and goal definition, and provides data for future quantitative analysis. The information from the current project needs to be recorded in an established location in order for future projects to benefit from the lessons learned.

The framework is enveloped by the communication and continuation steps. It is important to make these deliberate and explicit, as they are tempting to forego or forget, but can improve the efficiency and knowledge base for the current project and future projects. It makes the project team risk-aware, and more attuned to situations or instances where one needs to amplify or modify a particular process or approach.

Though the word “project” is used in the descriptions above, this framework can be applied to a portfolio of assets, or even program-level planning. It is intended to be flexible enough to meet the dynamic needs of CDOT in providing safe, efficient means of travel for the Colorado public. Chapters 4 and 5 demonstrate the application of the framework through two illustrative examples.

Literature Review: Revisited

The proposed risk-based framework for Colorado consolidates and reflects many concepts already introduced in frameworks in use by other state DOTs. To frame the proposed CDOT framework in perspective, Figure 11 summarizes the aspects of each of the respective frameworks introduced in Chapter 2. The frameworks covered in Chapter 2 are divided into three categories: program level (purple), portfolio level (green), and project level (blue).

At the program level, ISO 31000:2009, Enterprise Risk Management (ERM), and Federal Highway Association represent frameworks intended to guide programs or organizations in high-level decision or strategy processes. Both ISO and ERM are broadly formulated to apply to many industries at many levels, one of which is the program or organization level. The Texas and Virginia examples from Chapter 2 describe portfolio level frameworks. Figure 11 indicates that the Texas and Virginia frameworks focus on identifying goals and standards, as well as the risk assessment portions. Neither framework, however, discusses the feedback from risk monitoring and continuation of lessons learned, or formally establishing the context of the team with communication logistics. MAP-21, positioned under “portfolio”, is shown as completely grey. This is because the law mandates the creation of an asset management system but does not specify the specifics of how that system is to be implemented. Thus, it applies to portfolios, but does not address, specifically, the boxes of this framework. Finally, frameworks applying to projects are colored blue. Many of the project frameworks represent all of the portions of the proposed risk-based CDOT framework; these project frameworks, however, apply very specifically to a certain scope of problem, and are too specific to be applied, without modification, in multiple sectors within an organization.

The proposed framework is meant to cover all three levels (program, portfolio, and project) with all boxes active in the process of management. As mentioned, many existing project management processes already implement concepts of this framework; the framework is meant to formalize many of the "softer" processes involved in a technical project and to apply them across all functions, groups, and projects in order to achieve a risk-consistent organization.

Figure 11. Literature review captured through the perspective of the proposed CDOT framework. Purple, green, and blue colors represent the portions of the framework available in each reviewed framework from literature for program, portfolio, and project level frameworks, respectively. Grey indicates no specific guidelines with respect to that particular box.

CHAPTER 4. APPLICATION TO ALLOCATING RESOURCES FOR MAST ARM MAINTENANCE

As introduced in Chapter 3, the proposed framework can be applied to a number of scopes: project, portfolio, and program. The following is an example of the risk-based framework applied to allocating resources for a maintenance and operation budget for signal mast arms in transportation. Chapter 5 discusses the framework as applied to a structural design decision. Determining how to allocate funds for a portfolio of mast arms requires having a reasonable estimate of the current state of all mast arm assets, in order to develop a realistic projection as to what maintenance operations may be required in the months and years to come. Questions about whether to repair or replace a mast arm or mast arm subcomponent based on the current state, the optimal maintenance and inspection frequency, and impacts of maintenance decisions in terms of delay or cost to the public are all possible considerations in the scope of managing a mast arm portfolio through a risk-based framework. This example is tailored to the interests of the Colorado Department of Transportation, and therefore utilizes data from CDOT mast arm inspection records. Specifically, this illustrative example seeks to answer the following questions in relation to budgeting concerns: which mast arm defects warrant immediate action; which defects can be sustained until typical maintenance; can the typical maintenance schedule by modified in order to save cost while maintaining a high level of reliability; and how can the budget reflect the findings of a detailed risk assessment?

CDOT Mast Arm Inspections

Signalization mast arms are structures that support traffic light signals in order to enhance the safety and efficiency of vehicular traffic. They are composed of a number of components [30], of which some are structural, some hardware, and some various other attachments. Each component has an expected lifetime and potential risks or issues, and is amenable to different approaches for evaluation of risk. This example will focus only on structural elements: the mast arm, pole, foundation for each signal mast arm, and connections between these structural elements, such as nuts and bolts. A schematic is shown in Figure 12.

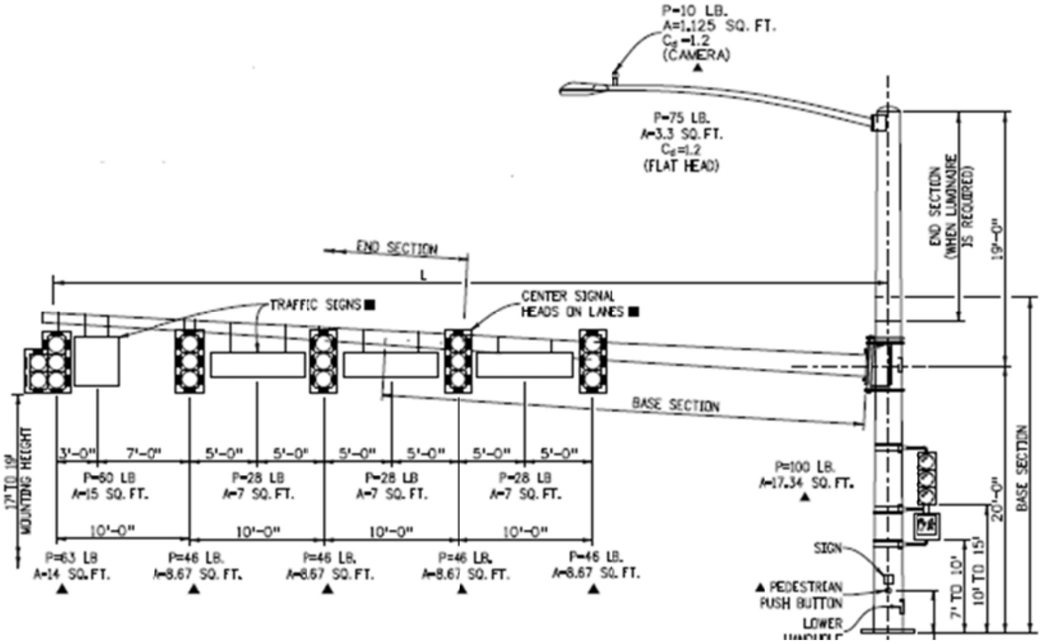


Figure 12. Mast arm schematic. Figure courtesy of CDOT and reproduced from [33].

CDOT oversees the maintenance and operation of 5,119 mast arms throughout the state [33]. The number of mast arms, by Region-Section codes as of May 2013, is presented in Figure 15. Engineering regions are shown in Figure 13; each engineering region number refers to the number in the tens digit of the Region-Section code. Maintenance sections are shown in Figure 14; these numbers refer to the ones digit used in the Region-Section code.

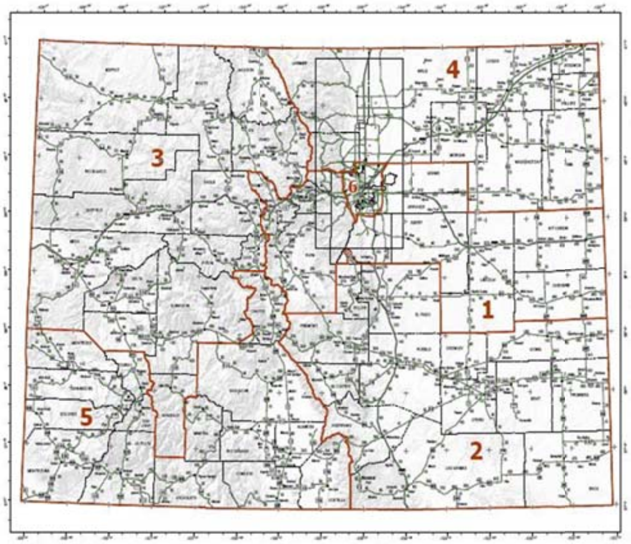


Figure 13. Engineering regions for CDOT as of May, 2013. Figure courtesy of CDOT.

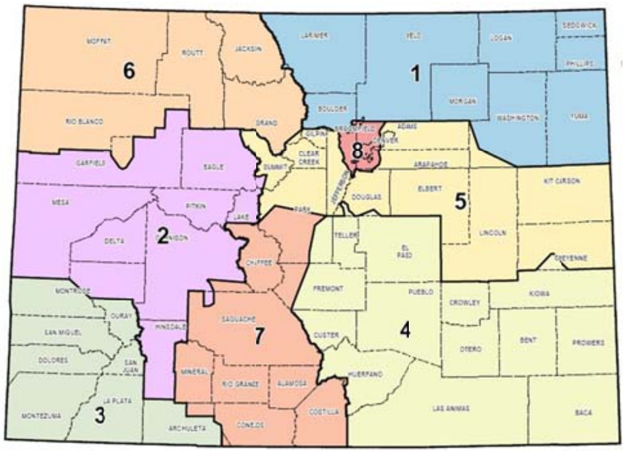


Figure 14. CDOT maintenance sections as of May, 2013. Figure courtesy of CDOT.

The dataset available consisted of over 60,000 inspection records spanning from 2004 to 2011. Inspections currently are conducted on a two-year cycle. During inspection of mast arms by CDOT, notes are recorded in the inspection records database. Deficiencies in the mast arm are denoted in a “notes” data field. Paul manually searched and sorted through these inspection records in order to categorize the key structural defects present in Colorado mast arms. He defines the main structural deficiencies as the following categories: (1) R1 corrosion, (2) R2 corrosion, (3) R3 corrosion, (4) R4 corrosion, (5) collision damage, (6) cracking, and (7) loose nuts and bolts. R1 corrosion indicates some light level of corrosion, noticeable, but not readily quantified. R2 corrosion indicates a higher degree of rusting than R1 corrosion, but less than 20% corrosion. R3 corrosion rusting levels range from 20-30% rust by material loss at the critical section. R4 corrosion rusting is the most severe, representing 30-40% rusting. Other defects noted in the maintenance records include peeling paint and chalking. These two defects are considered non-structural damage and are not classified as defects in the discussion that follows.

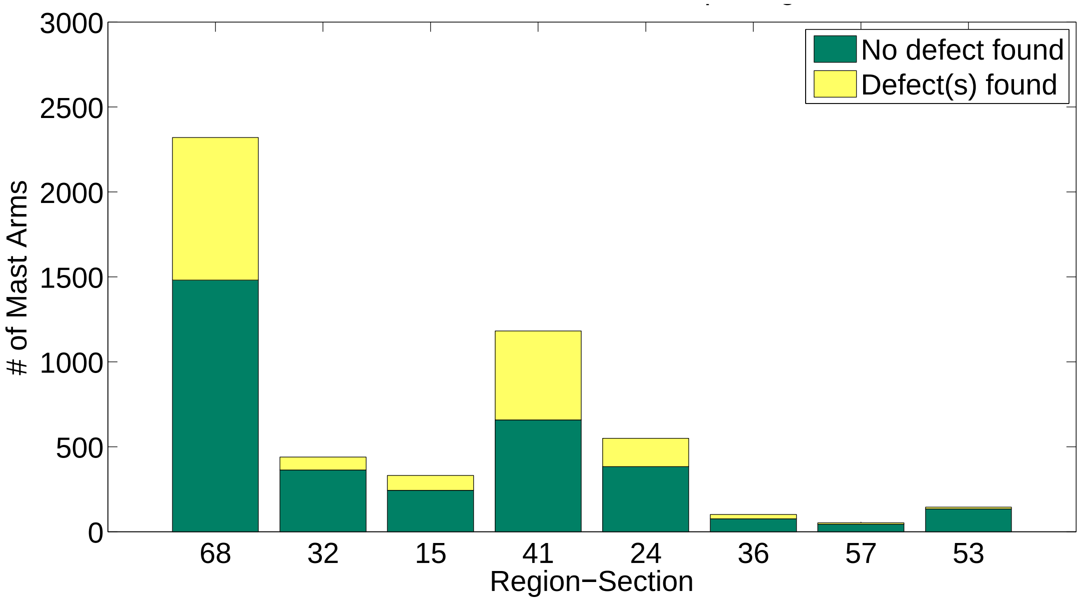


Figure 15. Total number of mast arms per region encoded by structural defect(s) found [yellow] and no defect found between 2004-2011 [green].

Figure 15 shows the fraction of mast arms in each region for which defects were observed. As shown in this figure, the largest number of mast arm defects is found in Region-Section 68, which is the Denver metropolitan area. A further breakdown of defects (the yellow proportion of mast arms from Figure 15) based on the seven structural deficiencies is presented in Figure 16. According to this analysis, 36% of this Region-Section's mast arms have at least one of the seven defects. As shown in Figure 16, of the 36%, about 60% of the defects are rust-related, and just over 10% of defects are due to collision damage. Region-Section 41, located in the north-east portion of Colorado, also had a considerable number of defects reported, with 44% of mast arms having been reported with structural damage during the 2004-2011 timeframe. Of the 44% with structural damage, 35% of the reported damages are from rust; collision damage accounts for over 20% of defects (see Figure 16).

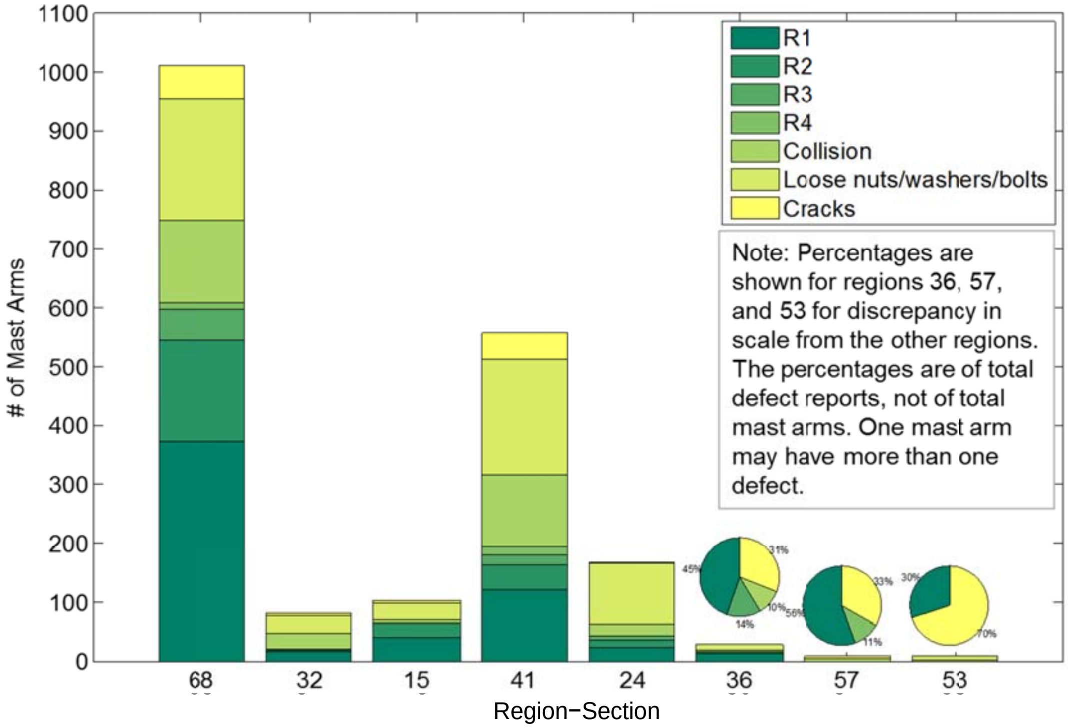
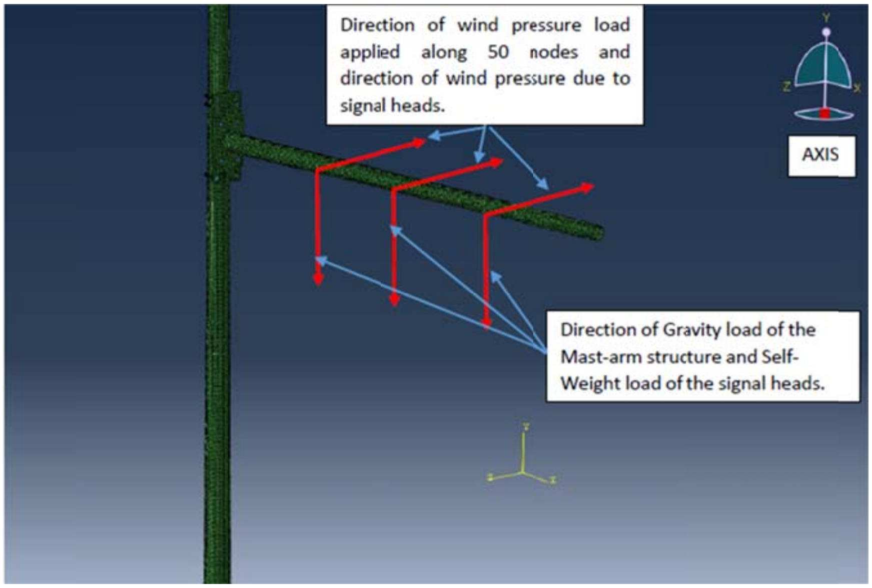


Figure 16. Breakdown of type of defects, by Region-Section.

Finite Element Analysis of Mast Arms

The relationship between these structural deficiencies and the resulting structural mast arm performance was explored through finite element analysis [33]. The mast arm was modeled using linear finite elements in the commercial software package Abaqus in a static-equivalent analysis considering wind and gravity loads. The components of the mast arm were individually modeled and assembled. Components were modeled as either a shell element or a C3D9R Hexa element, if convergence was an issue. As shown in Figure 18, components include the mast arm pole (shell element), arm, pole plate (shell element), pole base (shell element), U-channels (Hexa element), and bolts (bolts were simulated with ties). For more details on the modeling process, see Appendix A. Once the model was created, a static wind load equivalent to the design-level wind speed [35] was applied horizontally (see Figure 17) and resulting stresses compared to the maximum allowable stress of the material (65 ksi) as defined by AASHTO's Structural Specification for Structural Supports, which is the guiding document used by CDOT for the design of signal mast arms [35].



Direction of wind pressure load applied along 50 nodes and direction of wind pressure due to signal heads.

Direction of Gravity load of the Mast-arm structure and Self-Weight load of the signal heads.

Figure 17. Direction of loading in finite element modeling.

The results show that corrosion levels, as defined above, do not exceed allowable stresses when considering design level forces (see Table 5). Corrosion levels do, however, decrease the maximum wind load that the structure is capable of supporting. The study also found that collision damage greatly increases the potential for sharp edges, and sharp edges increase the likelihood for stresses to exceed maximum allowable stress values. Missing bolts can lead to increased stresses in the weld of the arm and plate, and also reduce the area through which the load can travel from the pole to the ground. Cracks were not analyzed due to modeling complexity. These findings are used in order to assign a risk rating in the semi-quantitative Risk Assessment Method 2 below. More details are provided in Appendix A and Appendix B.

Table 5. Maximum stress under two load cases.

	Load Case 1	Load Case 2
R1	23.8ksi	46.7ksi
R2	23.8ksi	48.8ksi
R3	23.8ksi	49ksi
R4	23.8ksi	49.6ksi
Collision Damage	26.9ksi	49ksi
Missing Bolts	25.2ksi	47.7ksi
Base Design	23.8ksi	39.5ksi

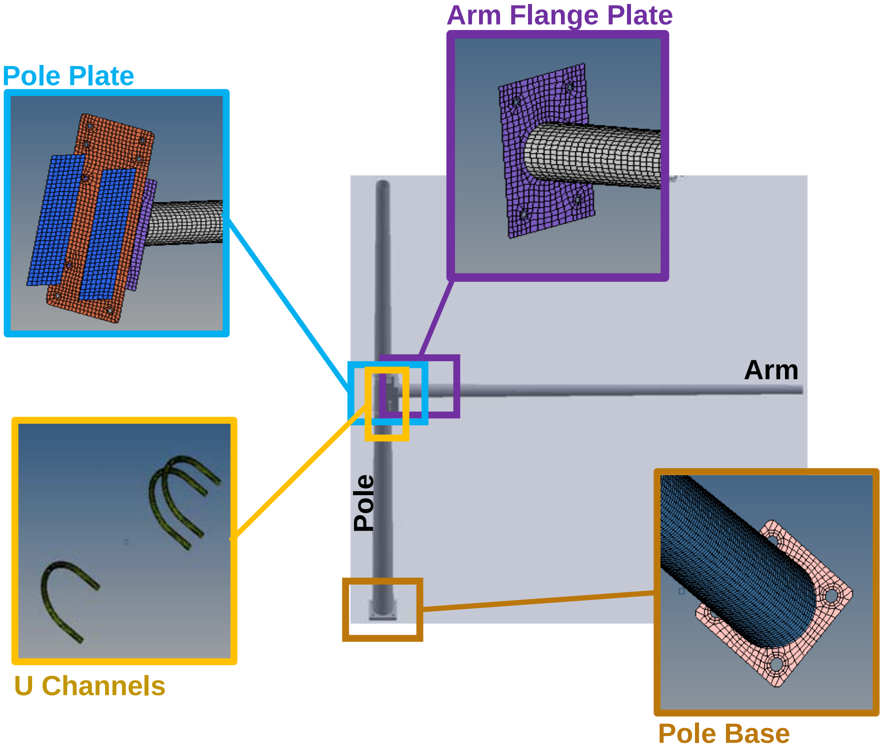


Figure 18. Mast arm components analyzed in a finite element analysis.

Framework Illustration: Resource Allocation for Signal Mast Arms

The following sections detail each of the steps of the proposed framework for CDOT to illustrate how the framework can be used in a portfolio level analysis.

Communication Logistics

The first step in the proposed CDOT framework is to establish the communication logistics. This step includes determining the frequency of the study, identifying team members, establishing the means of communication, and implementing an information management system. Assuming a team leader has already been identified, the team members will then also need to be identified, and team roles and expectations defined. Part of these roles and expectations include how often the study will occur or be updated. In this example, to determine the annual budget, the formal cycle for the study could occur once a year. In executing the study, in order to streamline the flow of information and appropriately allocate time from each member, it is important to establish the forms and frequency of communication– whether the team meets daily, weekly, or monthly and whether the team communications occur primary in-person, phone, or otherwise. Additionally, the initial steps should also identify an appropriate information management system for the project. The purpose of an information management system is to provide an established location for information access. Like establishing the frequency and means of team communication, it provides a default location for updates regarding the study and increases transparency in the progress of the assessment.

Many examples of information management systems, such as a risk register, can be found in the literature review. For the purposes of this example, the information system will be developed from a modified Caltrans risk register, tuned to the needs for a portfolio risk assessment, and applied for illustration purposes to a portfolio of three different mast arms. It should be emphasized that while the three selected mast arms are fictitious and chosen only for illustration, all of the computed quantities are based on actual statistics and finite element analysis of the Colorado mast arm portfolio. In this example, the risk register format used is displayed in

Identification of Goals/Standards

The second step is identifying the goals and standards of the portfolio assessment effort. A meeting early in the risk process can be conducted to review these standards and performance targets. The main objective of this study is to allocate limited resources (time or money, for example) for the portfolio of mast arms in order to meet maintenance and operation needs of the Colorado Department of Transportation while also satisfying the goals of safety to the public and minimizing any traffic delays to the traveling public. At this step, it is also critical to identify the tangible metrics for mast arms – standards, requirements, and performance targets. For example, for mast arms, it has been suggested that rust alone will not result in a significant decrease in structural capacity [33].

Table 6. For this example, the risk register includes the assets (including only mast arm N for example) in the first column from the left, and the components of each asset in the second column. The third column classifies each component and its expected lifetime. The following columns are items that need to be populated throughout the course of the risk-based assessment. Mast arm N's structural components have been shaded grey since the subsequent analysis will focus exclusively on these three items.

Identification of Goals/Standards

The second step is identifying the goals and standards of the portfolio assessment effort. A meeting early in the risk process can be conducted to review these standards and performance targets. The main objective of this study is to allocate limited resources (time or money, for example) for the portfolio of mast arms in order to meet maintenance and operation needs of the Colorado Department of Transportation while also satisfying the goals of safety to the public and minimizing any traffic delays to the traveling public. At this step, it is also critical to identify the tangible metrics for mast arms – standards, requirements, and performance targets. For example, for mast arms, it has been suggested that rust alone will not result in a significant decrease in structural capacity [33].

Table 6. An example risk register for a single asset, Mast Arm N. Components and expected years are taken from example values in literature [30]. Other columns are populated throughout the process of the framework as information become available.

Asset	Component	Component type	Expected years	Current Years	Operating Needs	Maintenance Cost	Maintenance man-hours	Replacement Cost	Risk Statement	Assumptions	Risk Rating	Rationale	Risk Owner
Mast Arm N	Mast arm	Structure	25										
	Pole	Structure	25										
	Mast and pole foundation	Structure	25										
	Conflict monitor	Hardware	7										
	Controller	Hardware	7										
	Master controller	Hardware	4										
	TS2 master controller	Hardware	7										
	TS2 secondary controller	Hardware	7										
	TS2 controller and cabinet	Hardware	7										
	Priority control -- 2 channel	Hardware	7										
	Priority control -- 4 channel	Hardware	7										
	Cabinet	Hardware	10										
	Modem	Hardware	10										
	Signal heads	Hardware	10										
	Flasher signal heads	Hardware	10										
	LED amber	Hardware	5										
	LED red	Hardware	5										
	LED green	Hardware	5										
	Signal section	Hardware	10										
	Loop detector Unit	Detection	4										
	Camera	Detection	4										
	Camera processor	Detection	4										

Risk Analysis

The third step, which is risk analysis, is made up of four sub-steps: risk identification, risk assessment, risk action, and risk monitoring. Three hypothetical mast arms are used to illustrate the risk analysis portion, as shown in Table 6. Mast Arm N is a new mast arm in a suburban area, only two years old. For the purposes of this illustration, the consideration of this mast arm is overseen by a fictional character with the initials, “JL”, as listed in the risk register. Mast Arm O is mast arm in a busy intersection, 15 years of age. The consideration of this mast arm is overseen by a fictional character with the initials, “CR”. Mast Arm P is a mast arm in the mountain areas, such as Region-Section 57. The consideration of this mast arm is overseen by a fictional character with the initials, “SJ”.

Table 7. Risk register with component years.

Asset	Component	Component type	Expected years	Current Years	Operating Needs	Maintenance Cost	Maintenance man-hours	Replacement Cost	Risk Statement	Assumptions	Risk Rating	Rationale	Risk Owner
Mast Arm N	mast arm	structure	25	1									JL
	pole	structure	25	1									JL
	mast and pole foundation	structure	25	1									JL
Mast Arm O	mast arm	structure	25	15									CR
	pole	structure	25	15									CR
	mast and pole foundation	structure	25	15									CR
Mast Arm P	mast arm	structure	25	24									SJ
	pole	structure	25	24									SJ
	mast and pole foundation	structure	25	24									SJ

Risk Identification

In risk identification, for the case of mast arms, the first step is to take inventory of all mast arm assets by identifying all the mast arms and mast arm subsystems. The next step is to record the age and life expectancies of each of these subsystems and determine replacement costs for each component. Other information can include maintenance and operational work categories (such as routine inspections) and associated costs with each category. Table 7 shows the risk register for the hypothetical mast arms with the current age of each subcomponent of each asset.

Risk Assessment

Once the inventory has been completed, risk assessment can be conducted. There are several methods to conduct risk assessment, ranging from qualitative to quantitative. At the project level, states such as California and Washington have a scaled or tiered method of determining what level of assessment to use in each project. For example, lower cost projects use assessments that employ less in-depth analysis, while higher cost projects use more quantitative methods. For portfolio and program assessments, the dividing line between what warrants a qualitative assessment or a quantitative assessment may require additional dimensions beyond a dollar amount.

This chapter illustrates the two more qualitative methods of risk assessment. Recall that risk is comprised of two dimensions: the probability of occurrence, and the impact of occurrence. The impact, or consequence, could include injury to vehicles or pedestrians, traffic delays, additional need for traffic direction by a traffic authority, and additional cost of replacement as opposed to cost of expected maintenance.

Risk Assessment Method 1

In a highly qualitative method, the team takes the risk identification list and brainstorms a risk rating: low, medium, or high. It is a single dimension rating that indicates the team’s perception of the line item based on current circumstances and past experiences, effectively collapsing the probability of occurrence and impact of occurrence into a single rating. Only the most qualitative method, Method 1, allows for the simultaneous consideration of these two dimensions of risk without first identifying values for the two risk dimensions separately.

Table 8 provides an example of what the risk register from Table 6 might look like for Mast Arm N, O, and P, for only the pole component of the mast arm. In this table, a risk statement is written, with assumptions, risk rating, and rationale filled out. For example, for mast arm O, the mast arm is rated with a “medium” risk rating due to its mild state of rust and urban location, while mast arm N, nearly new with no found defect, has a “low” risk rating. Risk owner initials are in the last column with the fictional initials introduced above.

Risk Assessment Method 2

In the second method, the team starts again with the inventory, and this time assigns a low, medium, or high rating to every line item in a semi-quantitative fashion. In this example, the number of defects, taking into account the type of defect, is combined with a probability score to indicate the likelihood of unacceptable stress levels in structural performance. As discussed above through the study by Paul [33], rust, combined with design wind loads, does not induce stresses above the maximum allowable stress levels, though it does reduce structural capacity overall. Quantitative results from Paul’s research are presented in Table 9. Full details of the modeling process and finite element results can be found in Appendix A and Appendix B. It should be noted that while the three mast arms discussed are for illustration only, the results in Table 8 are based on actual analysis of Colorado mast arms.

Without any defects, the maximum wind speed that the mast arm can support is 129 mph, which corresponds to an 1800 return period for Colorado or a 0.05% annual probability of occurrence. Probability scores are based on the number of years deducted from the mean recurrence interval between a mast arm with a given defect and a mast arm free of defects; they are shown in the fifth column in Table 9, and they range from 0-4.

Table 8. Method 1 example risk register.

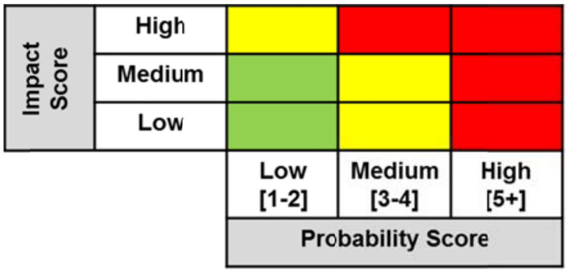
Asset	Component	Component type	Expected years	Current Years	Risk Statement	Assumptions	Risk Rating	Rationale	Risk Owner Initials
Mast Arm N	Pole	structure	25	1	The structure is relatively new and exhibits no sign of corrosion or other structural damage.	It is assumed that the most recent inspection record reflects the current state of the mast arm.	L	No visible structural damage and new construction indicates a low probability of failure	JL
Mast Arm O	Pole	structure	25	15	The structure has been regularly maintained for just over half of its expected life span and is located in a heavily trafficked area prone to vehicle accidents, increasing the risk of a vehicle collision. Additionally, R2 corrosion is present.	It is assumed that the most recent inspection record reflects the current state of the mast arm.	M	The combination of minor corrosion and collision risk, along with a mid-age structure, warrants additional attention.	CR
Mast Arm P	Pole	structure	25	24	The structure exhibits high levels of corrosion (R4) and has 2 missing nuts and bolts.	It is assumed that the structure will be replaced at the end of its design life.	H	The high level of corrosion and missing nuts and bolts may detract from Mast Arm P's performance. Existing collision damage may compound structural risks.	SJ

Table 9. Finite element analysis results by defect type, maximum allowable wind speed and corresponding mean recurrence interval taken from [33]. Probability score column added in this study for use in Risk Assessment Method 2.

Defect	**Maximum Allowable Wind Speed [mph]**	**Mean Recurrence Interval of Maximum Allowable Wind Speed [years]**	**Difference in Mean Recurrence Interval due to Defect Present [years]**	**Probability Score [1-4]**
No Defect	129	1800	0	0
R1	117	1300	500	1
R2	114	700	1100	2
R3	114	700	1100	3
R4	110	450	1350	4
Collision (all)	114	700	1100	3
Missing Bolts	117	1300	500	1
Cracks*	N/A	N/A	N/A	3

* The study by Paul did not examine cracks. Here, cracking is assigned an impact score of 3, which is the same as collision, but quantitative analysis is needed to confirm this rating.

Probability score assignments for R1, R2, R3, and R4 are 1, 2, 3, and 4, respectively. Though R2 and R3 have the same maximum wind speed value in Table 9, they are assigned different scores so as to reflect the progression in rust from R2 to R3 to R4. These scores imply that the mast arm, if exhibiting rust alone, will fall into a low or medium risk category, according to the risk matrix in Figure 19. Collision was found to have a significant impact on safety, as it has a higher probability of inducing stresses above the maximum allowable stress levels. Collision is assigned a probability score of 3, which will result in a medium-to-high overall risk rating. Additional defects of loose nuts and bolts and cracks are assigned to fall also in the low and medium risk range, if considered independently of the other defects. Combinations of defects were not examined in Paul's study; it is logical to assume that the effects would compound. It is assumed that the defects occur around the same region (*i.e.,* rust along the base of the pole would also be the location of a vehicle collision), and thus the effect on structural performance is likely to compound. To capture the combination of defects in a single mast arm, probability ratings for each mast arm are added up to account for all defects in order to calculate an overall probability score.



Impact Score				
	High	🟨	🟥	🟥
	Medium	🟩	🟨	🟥
	Low	🟩	🟨	🟥
		Low [1-2]	Medium [3-4]	High [5+]
		Probability Score		

Figure 19. Risk matrix to determine risk rating based on probability and impact. Probability scores are listed in brackets.

The impact of the failure of a mast arm may lack data. In this semi-quantitative method, the impact is determined by brainstorming. The impact of a failure of a mast arm can be measured by traffic delays, injuries, or damage to surrounding assets. In this semi-quantitative method, the impact is taken to be a qualitative indication of population density in an area, and, by extension, density of traffic. Rural regions correspond to a low impact score; suburban regions correspond to a medium impact score, and urban regions (such as Denver) correspond to a high impact score.

The risk matrix shown in Figure 19 is used to combine the impact score and probability impact ratings provided in Figure 18. As shown in Table 10, Mast arm N has a “low” risk rating, consistent with method 1. Mast arms O and P have “high” risk ratings due to the multiple defects found for each mast arm. The risk matrix can be tailored to each problem or organization depending on its risk appetite. This is presented as an example, not necessarily as a guideline to be reproduced in an actual risk analysis.

It is worth noting that the risk ratings using different risk analysis methods may differ, as shown here. While Mast Arm N and Mast Arm P had consistent ratings between Method 1 and Method 2, Mast Arm O was thought to be a “medium” risk item under Method 1 but a “high” risk item under Method 2. This is not alarming, as additional consideration and quantification can lead to different conclusions. It should be taken as a precaution that, depending on how the risk register, risk matrix, and/or rating weights are predetermined, many situations may fall on the borderline between different ratings and risk ratings should be considered guidelines, but not absolute indicators.

Table 10. Method 2 risk rating system.

Asset	Component	R1 [score = 1]	R2 [score = 2]	R3 [score = 3]	R4 [score = 4]	Collision [score = 3]	Crack [score = 3]	Loose Nuts/Bolts [score = 1/missing item]	Impact Score [L, M, H]	Probability Score	Risk Rating	Rationale	Risk Owner Initials
Mast Arm N	Pole								M	0	L	No visible structural damage and new construction indicates a low probability of failure	JL
Mast Arm O	Pole		2			3			H	5	H	The combination of minor corrosion and vehicle risk, along with a mid-age structure, warrants additional attention.	CR
Mast Arm P	Pole				4			2	L	6	H	The high level of corrosion and missing nuts and bolts may detract from Mast Arm P's performance if encountered by an unexpected event.	SJ

Risk Action

Depending on the risk rating determined from the Risk Assessment portion, different actions can be taken. Since this example focuses on determining how to allocate resources, such as money and time, one risk action that can be taken is to allocate additional, or decreased, time between inspections for a particular mast arm based on its components' risk ratings. If the risk ratings from Method 1 are used to move forward in this example, the Risk Action might be summarized in an additional column in the risk register as shown in Table 11. For example, since mast arm N was shown to be in a reliable structural state, CDOT could allocate fewer resources to the inspection of this mast arm than the traditional two-year period. As shown from the quantitative results, the examined defects do not have a significant change in most wind speed return periods. In combination with the relatively low consequence of a mast arm failure (for example, no loss of life was recorded in the inspection records), the quantitative results can be used to support a decrease in inspection frequency from every two years to every four or five years.

For defects that did have a greater impact on wind speed return periods, such as collision and R4 rust, a screening inspection can be implemented on the traditional two-year schedule. For this example, it could be advised for future years, mast arms like P should have more resources allocated towards them in order to maintain an acceptable level of risk. It could also be recommended that mast arms like N could be given less attention in inspection policy or frequency, thereby requiring a smaller budget. Mast arms like O could be investigated to determine what percent increase in budget would be best suited for future budget allocations.

As a further step not explored in the scope of this example, mast arms could be grouped by characteristics and location, and then further grouped by inspection results and consequence of failure. Factors such as traffic density, vehicle speeds, availability of alternate routes, and pedestrian traffic should be considered when grouping mast arms. Additional portfolio decisions could include feedback to modify the inspection policy or maintenance routine.

Table 11. Risk Action entry in risk register. Refer to Table 8 for details on entries filled below with ".".

Asset	Component	Component type	Expected years	Current Years	Risk Statement	Assumptions	Risk Rating	Rationale	Risk Action	Risk Owner Initials
Mast Arm N	Pole	.	.	.	.	.	🟩	.	Maintain current inspection frequency and investigate decreasing inspection frequencies for the future.	JL
Mast Arm O	Pole	.	.	.	.	.	🟨	.	Maintain current inspection practice at a high-level	CR
Mast Arm P	Pole	.	.	.	.	.	🟥	.	Increase inspection frequency and increase detail of inspection.	SJ

Risk Monitoring

Risk monitoring is the responsible of the risk owner, as indicated in the risk owner column. Risk monitoring activities can include such items as monitoring the incoming inspection reports with respect to each asset, comparing the historic budget allocation to the actual dollar amount spent, and adjusting risk action or risk rating as needed. The last item – adjusting the risk action or risk rating – corresponds to the dashed lines from "Risk Monitoring" to Risk Identification, Risk Assessment, and Risk Action shown in Figure 20. This feedback loop is critical to maintaining a resilient organization – an organization that is flexible in its response to changing situations, hazards, or challenges. During communication logistics, it should have been determined how frequently the risk owner should monitor his or her risk item.

In this example, the primary form of risk monitoring is keeping the inspections database up-to-date. This can be aided by a well-designed database that allows for the easy "flagging" of any changes or updates in defects found during an inspection that could then alert the respective risk owners of the potential need to repeat any of the previous three steps (risk identification, risk assessment, or risk action).

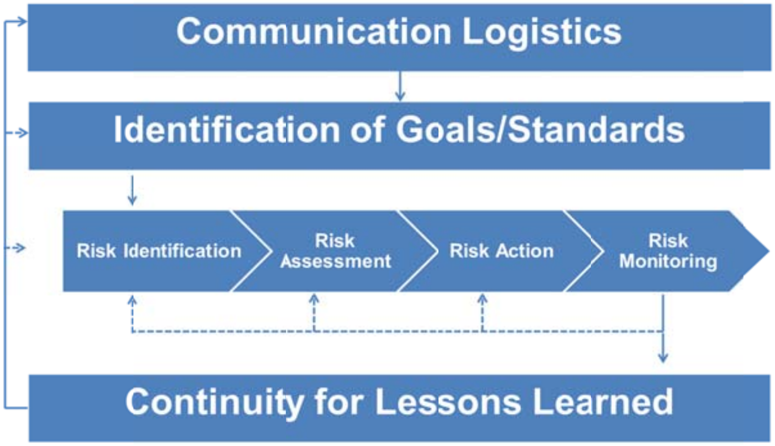


Figure 20. The risk framework, revisited.

Continuity for Lessons Learned

The last step, Continuity for Lessons Learned, is an integral part of the risk framework that is easy to overlook. At this point, the risk analysis been completed. It is important, however, to implement a debriefing session where team members gather to discuss the aspects of the project – whether management, risk register items, budget shortcomings, or otherwise – that did and did not go smoothly or as expected. Recording both successes and challenges can prove to be a useful contribution for future teams facing similar problems, or even for the same team in future years. This also helps to ensure that, as employees may change companies or work functions, knowledge is recorded and not lost with specific individuals. The arrow from Continuity for Lessons Learned therefore is a feedback loop to modify each of the various steps in the framework. This is a key feature of the framework in maintaining consistency and shared knowledge within an organization. Organizationally, a database or repository of “Lessons Learned” should be made available and shared regularly amongst engineers and managers alike.

The lessons learned from the portfolio could also be used to inform decisions at the program level. For example, the timing of maintenance efforts, such as repainting the mast arm, or replacement efforts may be influenced by this study. This approach allows CDOT to examine the tradeoffs of risk for different budget amounts. Additionally, these risks and benefits could be compared to the other risks and benefits subjected to both CDOT and the traveling public encounter in Colorado. Such risks and benefits could also be compared cross other state agencies.

Additionally, changes to the risk register could be instituted at this time. If a different type of data entry (an additional column, a number field instead of a text field, etc.) would be more useful in flagging items than high, medium, or low risk, such changes should be made to modify the risk register for future projects in order to tailor the operation to the specific application it is needed for.

Conclusion

In this chapter, the framework was applied to the investigation of budgeting for the maintenance and operation of a collection of mast arms. This is an example of a portfolio-level application to a collection of assets. The illustration uses three hypothetical mast arms to determining the appropriate inspection routine and, consequently, a budget that reflects the decisions made from an inspection, maintenance, and operational perspective. Utilizing available finite element analyses done on mast arms from a previous study, many structural defects were shown to have a minimal impact on the overall structural performance and reliability of the mast arm structure. Of the defects, including levels of corrosion, collision damage, and missing nuts and bolts, it was found that only the highest level of corrosion and the formation of sharp edges from a collision could pose an influential change in a mast arm's ability to resist forces such as wind. From this analysis, it is recommended that inspection frequency can be relaxed for certain defects, such as low levels of corrosion, and increased for the defects that have the potential to alter the structural performance of a mast arm, including collision damage and the highest category of corrosion, R4.

This illustration also demonstrated two risk assessment methods. The first method is highly qualitative, and the second method is semi-qualitative, translating quantitative results to a readily understood, qualitative setting. From these two analysis, the three hypothetical mast arms, N, O, and P, are given similarly themed risk ratings, but the fine detail between risk ratings may differ. For example, mast arm O was rated with a "medium" risk rating through method 1, but rated with a "high" risk rating with method 2.

The methods presented in this chapter can be applied to different portfolios of available assets. One such application could be investigating culvert material performance based on the current culvert stock. In order to implement the framework in this context, the team will require available inspection records from which to base risk ratings from. The team or organization must also formulate an appropriate risk register, such as the ones presented in the risk analysis section of this chapter, to use in the analysis procedure.

CHAPTER 5. APPLICATION TO ASSESSING SEISMIC BRIDGE DESIGN IN COLORADO

The second illustrative example focuses on how the framework could be used in making design decisions at the programmatic level. The purpose of including this example is twofold: to illustrate the adaptability of the framework to different decision processes and to illustrate an additional, more quantitative, risk assessment method that could be used in the context of this framework. As discussed above, the framework can be applied at any level within an organization. In the first example, the problem focuses on maintenance decisions; this second example seeks to provide evidence to the diversity of its use through the examination of a design decision. This example investigates the seismic performance of two bridges: one designed for the lowest seismic zone, the former seismic zone for all of Colorado before recent revisions in the AASHTO bridge design standard, and a second bridge designed for a moderate seismic zone, the different seismic zone that parts of Colorado have been categorized after the revisions. By considering the two bridges as representatives of the two respective seismic zones, this type of design decision is a high-level decision that could inform seismic implications for the whole stock of bridges in the state of Colorado.

Bridges are critical lifelines in communities. They are often vital for the livelihood of the traveling public, for transportation of goods in and out of a metropolitan area, and for emergency situations. For example, if a bridge were to collapse from something such as an earthquake motion, the occurrence of which is rare, but possible, in the state of Colorado, CDOT and the public will incur penalties in the form of traffic delays from repair, costs of repair, damage to surrounding features or vehicles, and possibly loss of human life. These consequences are severe, as the repair of a bridge could take months. Because of the heightened consequences from the inoperable state of a bridge as opposed to the consequences of a damaged mast arm, quantitative methods, as opposed to qualitative methods, will be showcased here during the risk analysis stage.

In 2008, the AASHTO code, 4th edition, changed the cutoffs for seismic zone definitions. In combination with the soil types present in Colorado, parts of Colorado were moved from being the lowest seismic risk level (zone 1) to the second seismic risk level (zone 2) [36]. Additionally, zone 2 increased the return period of a seismic event from a 500 year event to a 1000 year event, according to the commentary in Article 5.10.11.3 [36]. To investigate these changes, an example bridge set in zone 1, adapted from a constructed CDOT bridge, is compared with a modified version of the same bridge designed to meet the requirements of a zone 2 bridge. The two bridges are then compared using three time-history analyses to assess possible maximum displacements and maximum accelerations under earthquake motions. This analysis is meant to compare the difference in the two designs when assessing performance. Ultimately, it seeks to address the question: does designing for zone 2 make a significant difference in terms of risk for the select, newly-named zone 2 regions?

In order to investigate these concerns, this chapter will focus exclusively on certain aspects of the framework. Figure 21 highlights in purple the portions of the framework that will be discussed in this chapter. Included in the discussion is the identification of goals and standards, risk identification, risk assessment, and risk action. Communication logistics, risk monitoring, and continuity for lessons learned have been discussed in previous chapters; the focus of this chapter is meant to be the type of risk analysis performed for various types and/or levels of challenges that CDOT may encounter as an organization.

Figure 21. Portions of the framework covered in Chapter 5 are shaded purple. Grey boxes are outside the scope of this chapter.

Identification of Goals/Standards

The design standard used in this example is the AASHTO bridge design manual [36]. Changes made in the 2008 and 2009 revisions to 4th edition are of particular interest.

Risk Analysis

Risk Identification

The full design of a bridge requires taking into consideration a vast number of hazards and their associated loads. Every bridge is subjected to support its own self-weight (dead load); each bridge is also built to support a live load, consisting of passenger vehicles and larger trucks. Bridges may also face other hazards such as snowfall, flooding, high winds, and earthquakes. Each of these hazards has a corresponding load case. Snow-fall can be represented by an additional downward-acting gravity load, while a load representing the force from high winds would be applied laterally. AASHTO provides guidance as to how to calculate the design load for the expected hazards, and how to calculate load combinations to investigate the occurrence of multiple loads applied simultaneously.

While many of these hazards may pose a risk to the structural performance of a bridge, the risk examined here is a seismic load in the state of Colorado, which is considered a low-to-moderate seismic region. According to the AASHTO design manual, “regular” bridges are allowed to incur significant damage and/or disruption to service in an extreme event. Such bridges are designed with the objective of a low probability of collapse rather than continued use in extreme events. The seismic event considered in the design of bridges is defined as a 7 percent probability of exceedance in a 75 years ground motion (a return period of 1000-year earthquake) (Section 3.10.1 from [36]). Bridges are designed with a 75 year design life (Section 1.2 from [36]).

Risk Assessment Method 3

In the fourth edition revisions in 2008, the AASHTO code required treatment of seismic considerations for bridges of seismic zones 2-4, updated from only zones 3-4 before this revision. Thus, from the revisions made in the fourth edition, there are regions in Colorado that now belong to zone 2, requiring seismic provisions in bridge design, and those provisions associated with zone 2 have been changed. The classification of a location into a seismic zone is based on $S_{D1,}$ the design earthquake response spectral acceleration coefficient at a period of 1.0s, of a particular site, accounting for both seismic hazard and soil type. For zone 2, the requirements indicated in the 2008 and 2009 revisions include: p-delta effects, flexural resistance requirements for steel reinforcement, abutment seat lengths, transverse steel reinforcement spacing, and longitudinal steel reinforcement. These changes generally allow for greater ductility and higher confinement in columns.

To investigate the inclusion of zone 2 in Colorado, this study investigates two hypothetical bridges through a Monte Carlo simulation-based quantitative risk assessment. A “typical bridge” was chosen under the guidance of CDOT Bridge Inspection Engineer Lynn Croswell. This bridge is located in northeast Colorado on SH71 over I-76, a zone 1 site. It is a two-span, prestressed concrete box girder and is considered representative of current construction and design. The bridge was designed using AASHTO LFRD, 6th Edition, with current interims as of December 7, 2012. According to the bridge drawings, the bridge was not designed with seismic provisions. Specifications of this existing bridge are discussed in the following section. A second bridge is then designed based on the first bridge, but modified to meet the requirements of a zone 2 bridge. Specific changes are discussed in the "Description of the Zone 2 Modified Design" section below.

In Figure 23, the areas of Colorado which fall into AASHTO Seismic zone 2 are shown, indicating the areas of Colorado in which this study would be of relevance.

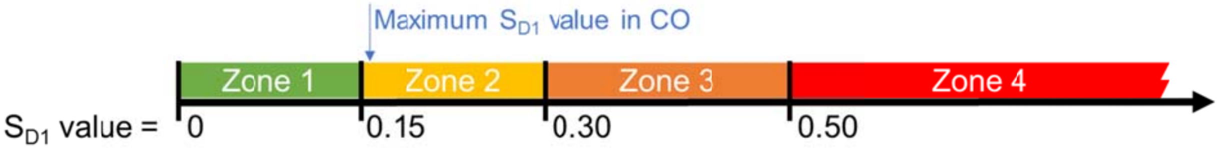


Figure 22. Seismic zones according to AASHTO 2008 revisions.

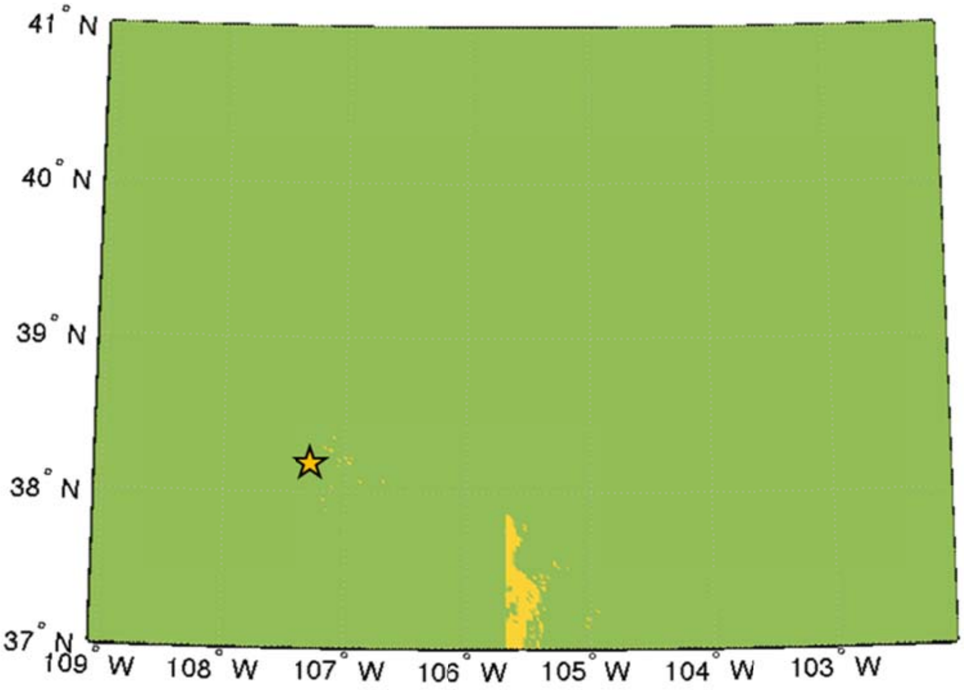


Figure 23. Seismic zone classifications in Colorado. Figure created from combining data available from [37, 38]. Colors correspond to the zone colors from Figure 22. The maximum peak ground acceleration site is marked with a yellow star.

Ground Motion Selection

Because this study is based in Colorado, it is desirable to identify ground motion recordings or simulations that are representative of the seismic hazard in Colorado for use in time history analysis. Using information available through USGS, the maximum PGA in Colorado is identified to be 14.9% g at N38.21, W107.54 for a 7% in 75 year hazard level [38]. In combination with the soil type, this results in a zone 2 classification.

Using these coordinates, the hazard de-aggregation tool [39] was used to identify the contributing seismic hazards. The contributing seismic hazards are de-aggregated by magnitude and distance from the site of interest (see Figure 24). The hazard de-aggregation at this site indicates that the primary hazard will be from magnitude 4.6-4.8 earthquakes at a distance of about 16 km.

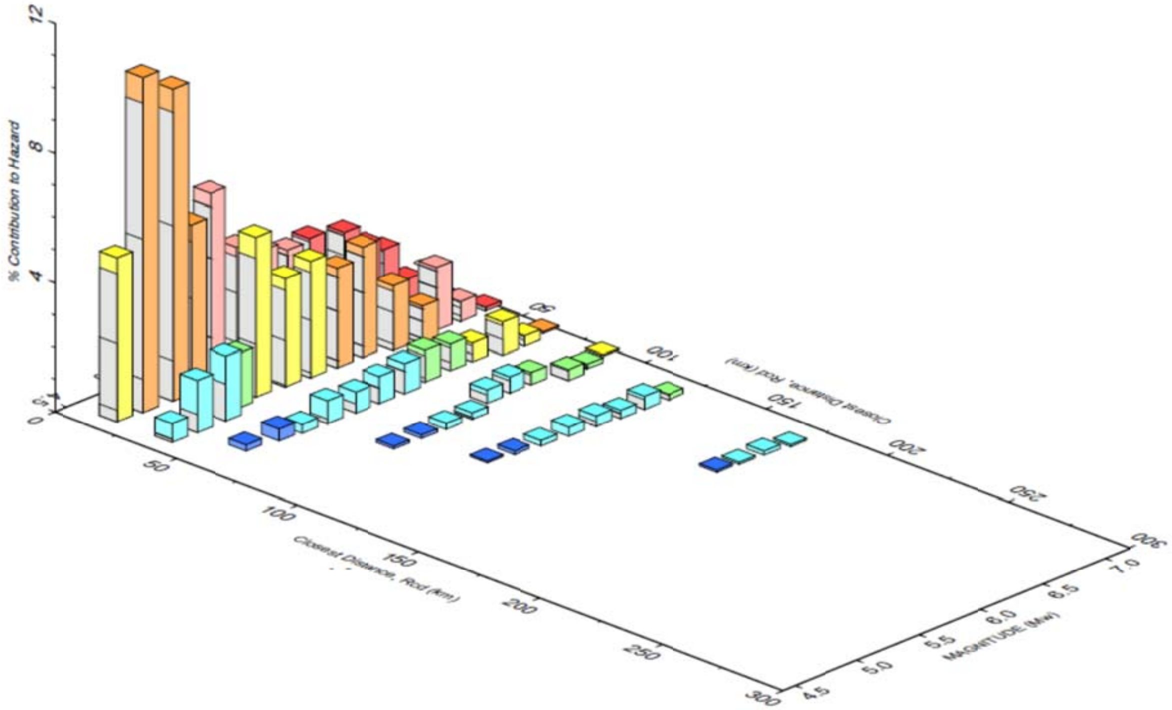


Figure 24. Hazard deaggregation for the maximum peak ground acceleration site in Colorado [39].

In investigation of the Institutions for Seismology (IRIS) database through tools such as JWEED [40] and SOD [41], Colorado does not have sufficient data for a past earthquake of the relevant magnitudes recorded at stations at distances that match or are close to that in the hazard de-aggregation information. Consequently, three different ground motions are used in place of a Colorado-specific ground motion (summarized in Table 12).

Table 12. Summary of ground motions used in study.

Ground Motion	Date	Location	Maximum PGA	Source
El Centro	May 19, 1940	Imperial Valley	0.31 g	[42]
Utah	Jan. 3, 2011	N38.25 W112.34	0.01 g	[43]
Stochastic	NA	Based on Colorado N38.212, W107.542	0.19 g	[44]

First, a historic ground motion, El Centro, is used. Second, a ground motion from the neighboring state of Utah is used, a magnitude 4.5 event with a clear signal from a nearby station (26.5 km from the epicenter) located at N38.28, W112.64. This motion is most consistent with the hazard de-aggregation. The third motion is a stochastic ground motion created by Kiousis *et al.* for a previous CDOT study at the Colorado School of Mines [44]. Each of these motions is described in greater detail below.

El Centro

The El Centro earthquake erupted in Imperial Valley, California on May 18, 1940. It was a magnitude 7.0 event with a maximum peak ground acceleration of 0.31 g, recorded at 5.2 miles away [42]. It is acknowledged that this ground motion exceeds the ground motion expected in Colorado for a 1000-year event, which is a maximum PGA of 0.19 g rather than El Centro’s maximum PGA of 0.31g. It is used as an additional example to accompany the other two ground motions, which are both “realistic” magnitudes for the state of Colorado. The El Centro acceleration time history can be seen in Figure 25, and the corresponding spectral acceleration and spectral displacement plots can be found in Figure 26.

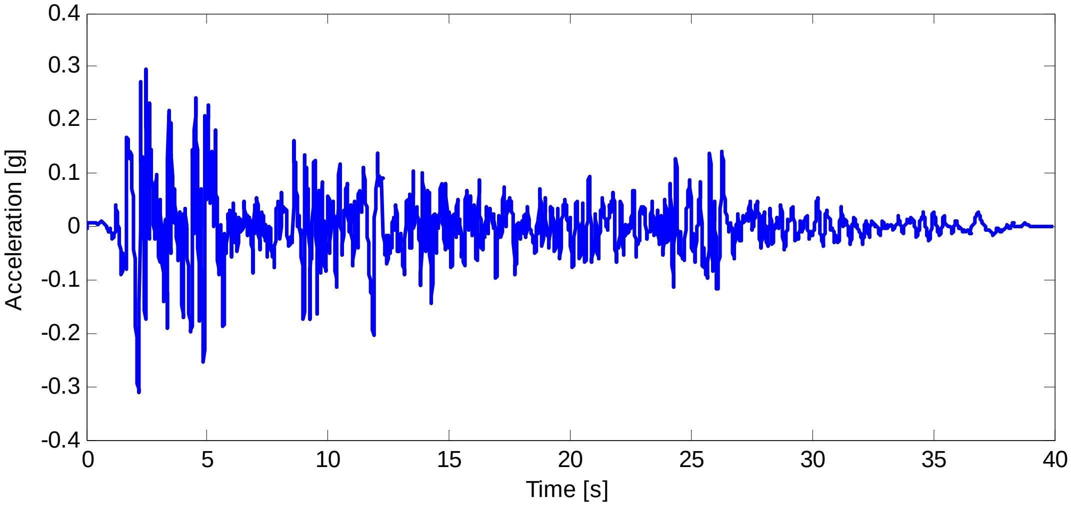


Figure 25. El Centro ground motion (East-West).

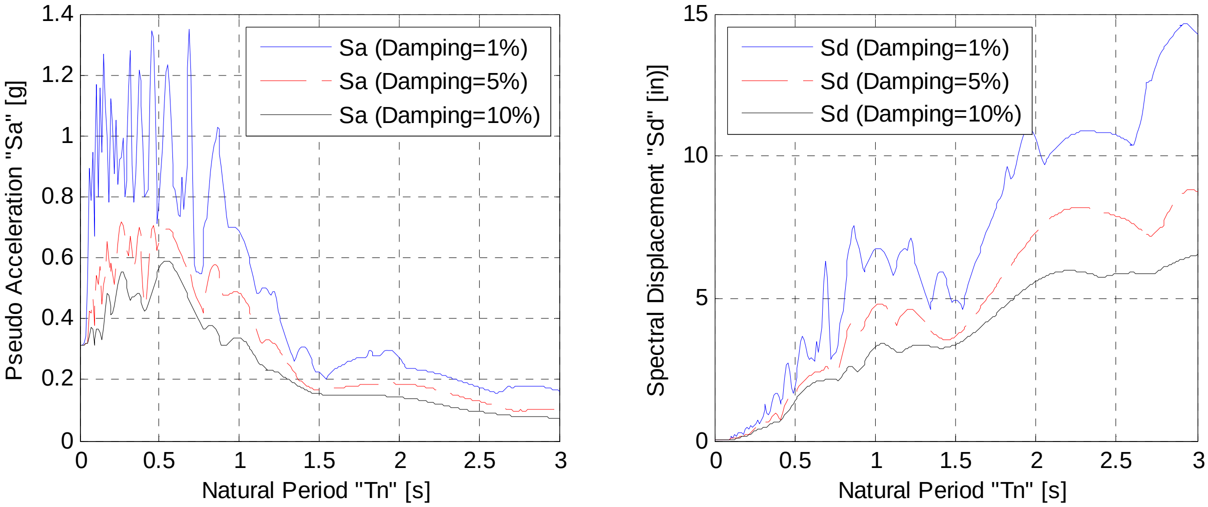


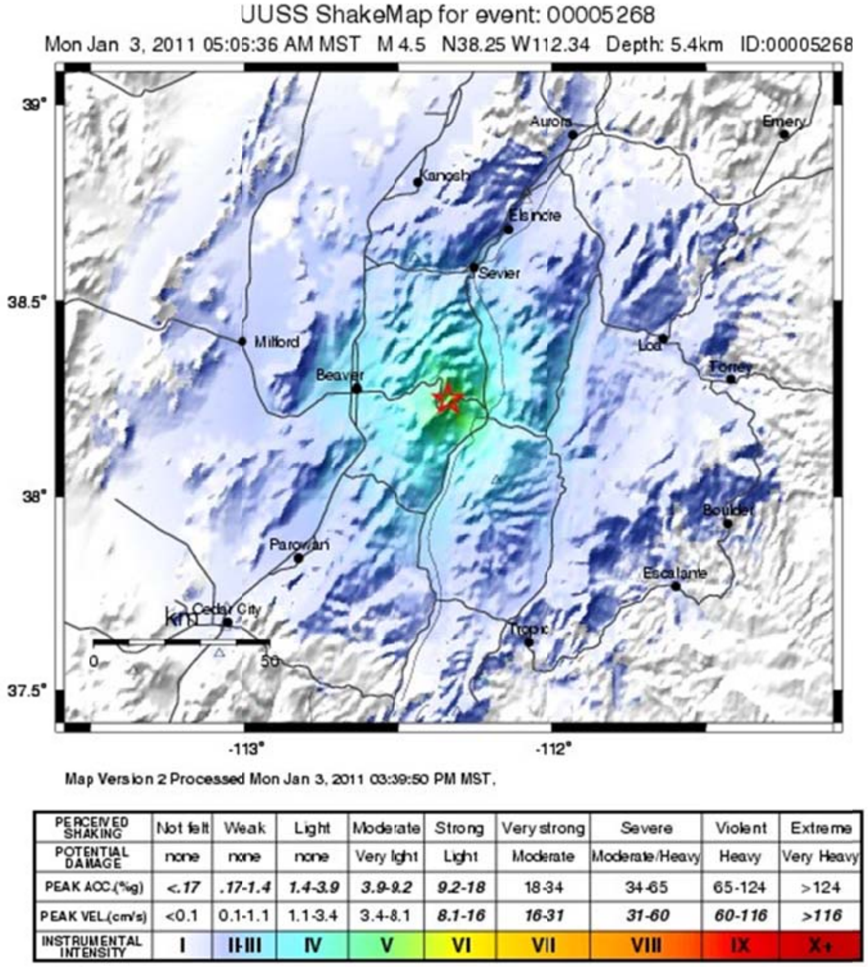
Figure 26. Left: Spectral acceleration values for the El Centro ground motion; right: spectral displacement values for the same ground motion.

Utah

California faults and attenuation relationships have been well-studied, but Colorado crustal characteristics and fault characteristics are not readily transferred from such studies. Additionally, attention to study attenuation relationships has been given to areas such as South Carolina, but again, there is not geological evidence to suggest that Colorado would benefit from the findings of these studies. Instead, Utah is chosen as a closer comparison to Colorado with the observation that it is in the mountain west but not the west coast. It is assumed to be reasonable that the attenuation of Colorado is most similar to that of Utah, given the options of regions that have been recorded by seismographs for seismic activity.

The University of Utah Seismograph Stations (UUSS) Network consists of over 200 stations transmitting continuously to the University of Utah earthquake center in Salt Lake City [45]. Peak values from events and ShakeMaps are available online [46]. Time history values, however, must be obtained through IRIS. To obtain the waveform for this event, the URL Builder available from IRIS was used [43]. After the waveform is obtained, SeismoSignal [47] is used to baseline correct and filter the motion. Baseline correction was chosen as a linear polynomial type. The filter type chosen was a Butterworth type bandpass filter configuration.

The earthquake chosen occurred on Monday, January 3, 2011 at 5:06am Mountain Standard Time. The epicenter was located at N38.25 W112.34 at a depth of 5.4 km, as shown in Figure 27. The recording station with the peak velocity and peak acceleration values was Beaver High School, located at N38.28W 112.64, 26.5 km from the epicenter. In the east-west direction on a low frequency channel, which corresponds to the frequency code ENE, it recorded peak values of 1.03%g maximum acceleration and 0.257 maximum velocity in/s [48]. Specifications on this low frequency channel is available through IRIS [49], and the frequency and phase response plot can be found in the appendix. The filtered ground motion is shown in Figure 28. This motion is representative of the major contributing seismic hazard indicated by the USGS hazard de-aggregation tool (Figure 24) in magnitude and distance from the source.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 27. Map of event in Utah on January 3, 2011 [46].

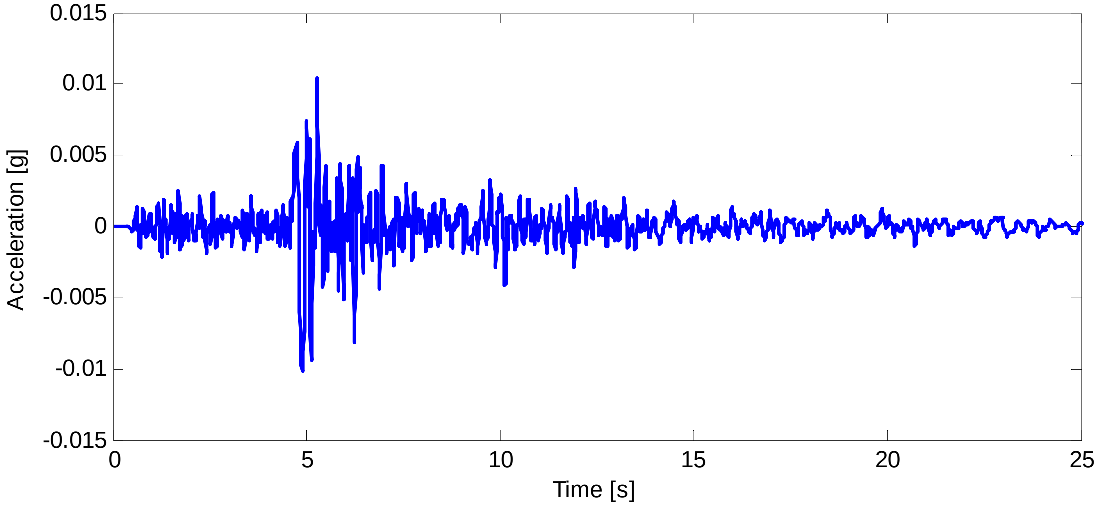


Figure 28. Utah ground motion (east-west direction at Beaver High School).

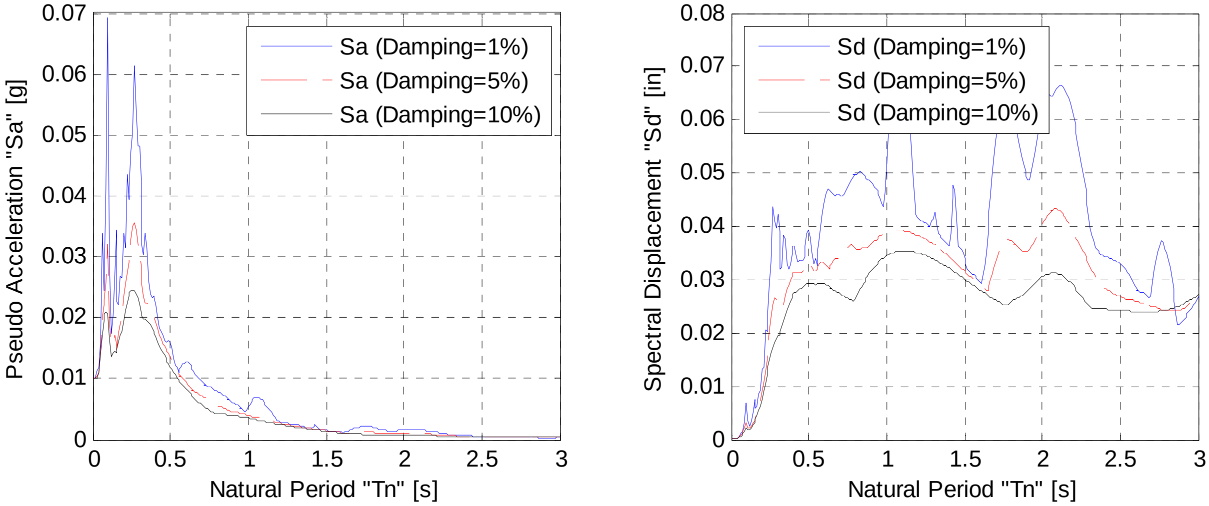


Figure 29. Left: Spectral acceleration values for the 2011 Utah ground motion; right: spectral displacement values for the same ground motion.

Stochastic Colorado Motion

A stochastic seismogram was used to represent an earthquake that could occur in Colorado. The stochastic seismogram was provided by a previous CDOT study by Kiousis *et al.* [44]. It is 8 seconds long with a time step of 0.005s. This stochastic motion was used because, as mentioned above, such an observed motion does not exist yet for the state of Colorado; additionally, it was thought to be beneficial to CDOT to use a consistent ground motion from recent seismic studies. Kiousis *et al.* describes the stochastic seismograms as a method that uses random phase spectrum modifiers in order to distribute a ground motion from a hazardous earthquake of a particular magnitude and distance from the source over a specified time duration. To do so, the method considers source, path, and site parameters to predict such ground motions. It is a commonly used method by engineers, and is regarded as a useful tool for simulating ground motions of high frequencies [44]. This site is located at N38.212, W107.542 as described previously. The waveform can be seen in Figure 30, and the corresponding spectral acceleration and spectral displacement plots can be found in Figure 31.

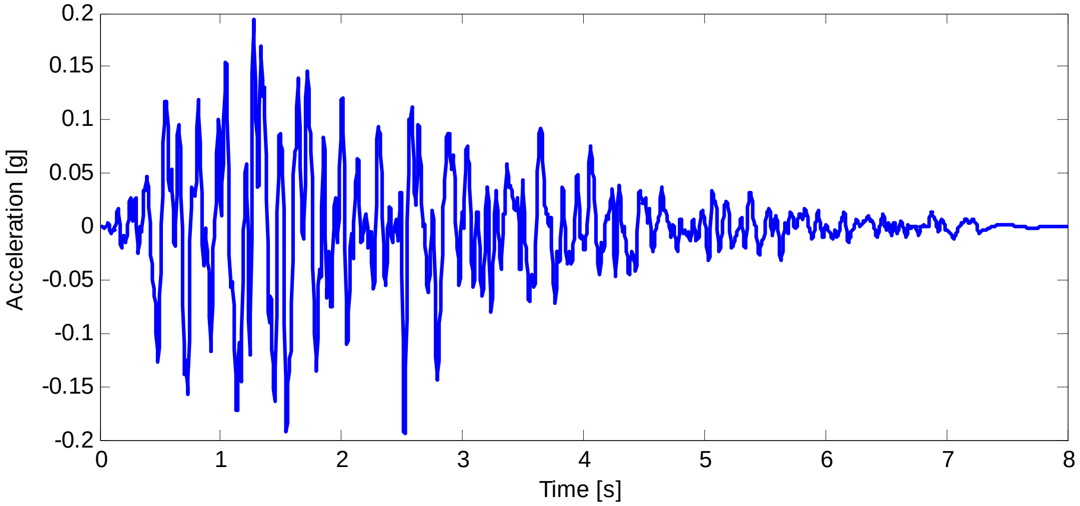


Figure 30. Stochastic Colorado ground motion based on the maximum PGA site

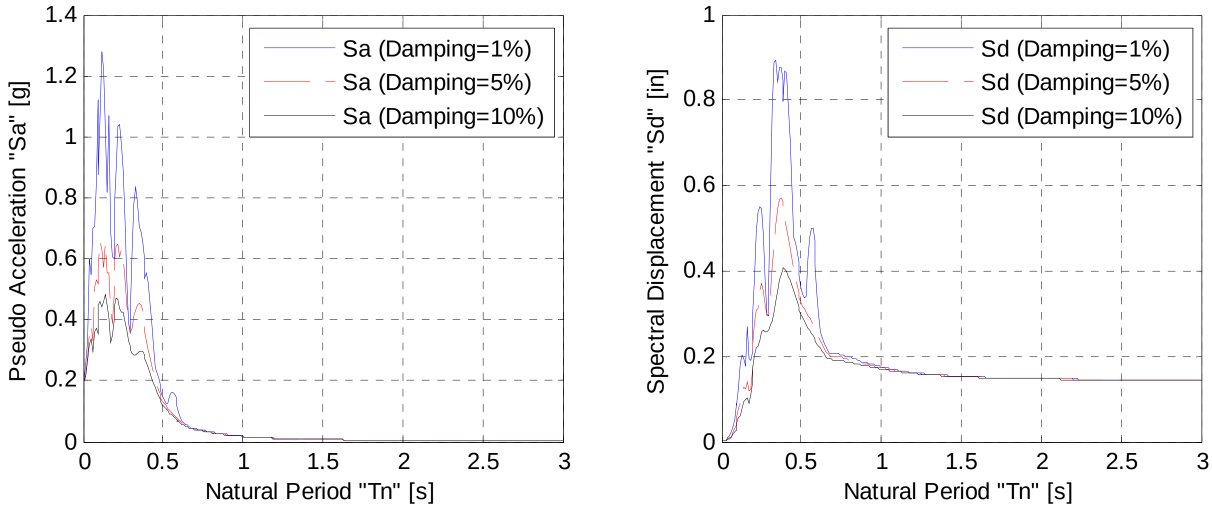


Figure 31. Left: Spectral acceleration values for the stochastic ground motion; right: spectral displacement values for the same ground motion.

Description of "Typical Bridge" Design and Model

The initial effort to identify the attributes of a "typical bridge" in Colorado included skew, main material, deck width, main design, deck width, maximum span length, and number of spans. When filtering the database of CDOT bridges, however, it became apparent that each of the most "popular" characteristics of the attributes did not exist in a single bridge.

Furthermore, upon speaking with bridge inspection engineer Lynn Croswell, bridge styles have shifted in recent years, and the recent bridges tend to be two-span pre-stressed concrete girder bridges [50]. The team was provided with as-constructed drawings of a recent bridge with such characteristics. The drawings are dated from December 7, 2012. The bridge is located on state highway 71 over I-76. It is a two-span bridge, 228'-0'' in length, with each span is 112' 9'', and the abutment on each end is 1' 3''. The bridge was built to replace a previous four-span bridge on the same length in the same location. The drawings for the current bridge are of a pre-stressed box-girder (see Figure 33), designed using the AASHTO LFRD, 6th Edition, with interims as of 12/7/2012. It was designed with Load and Resistance Factor Design, with a live load of HF-93 (Design truck or tandem, and design lane load) with vehicle collision. The dead load was assumed to be 36 pounds per square foot for the bridge deck overlay.

According to the provided as-constructed drawings, the connections to the superstructure were modeled as pinned (denoted by the "P" on sheet 433). Additionally, the pile-cap, comprised of steel pipe and reinforced concrete, can be idealized as a fixed connection to the ground, as represented in Figure 32.

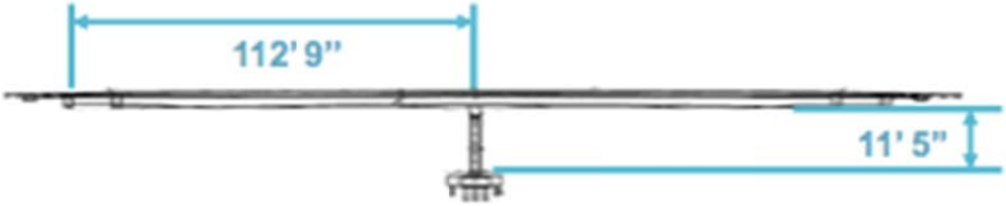


Figure 32. Idealized bridge connections used for analysis as indicated in available as-constructed drawings. Both spans are the same length. Figure courtesy of CDOT [50].

While this bridge is considered "typical" in span length, material, width, and number of spans for recent construction, the substructure is not symmetric due to reinforced concrete pipes that already existed at the site prior to construction (see Table 13 for bridge characteristics). The middle pile is not perfectly centered, as shown in Figure 33. For the purposes of this study, the substructure will be modified as symmetrical about this axis so as to not introduce irregularities in results that may be specific to the asymmetry of this particular bridge.

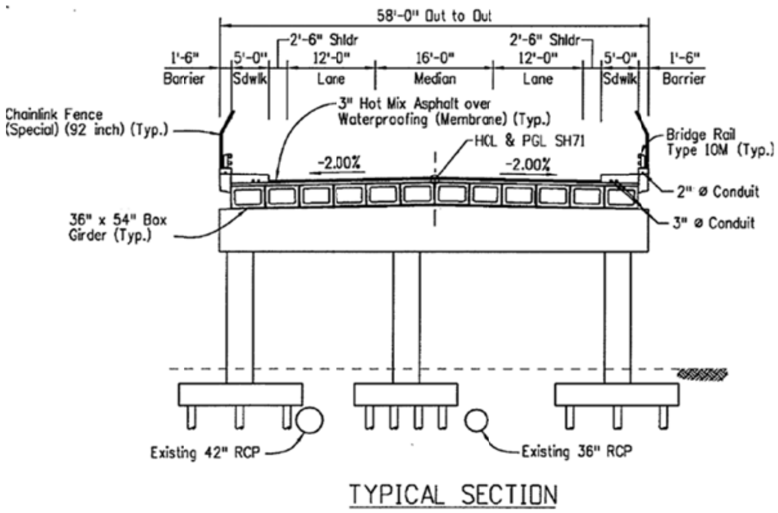


Figure 33. Substructure is asymmetric due to existing reinforced concrete pipes. Drawings courtesy of CDOT [50].

Computer and Structures, Inc.'s CSiBridge software [51] was chosen for its modeling capabilities specific to bridges, in conjunction to its ability to perform nonlinear analysis. A nonlinear hinge was included at the base and top of each pier column using built-in nonlinear material properties. A damping of 5% was used, which has been used in literature and is considered to be a reasonable value for concrete bridge construction in the central U.S. [52].

Prestressing strands were idealized as grouped strands at an equivalent location for ease of modeling. Each girder is prestressed to a final force of 1539.8 kips after all losses. Ground motions are considered only in the horizontal directions, both transverse to the bridge and longitudinally along the line of traffic, as specified in AASHTO 3.10.1. Time history analyses were conducted using Newmark's method of integration available in CSiBridge. Coefficients gamma, equal to 0.5, and beta, equal to 0.25, were specified for use in the analyses.

Table 13. Summary of the control bridge used in this study.

Attribute	"Representative" recent bridge characteristics
Skew	90 degrees
Material	Pre-stressed Concrete
Design	Box Girder
Deck width	58 meters
Max span	114'
Number of spans	2

Description of the Zone 2 Modified Design

The modified bridge features the same dimensions as the original bridge. According to AASHTO, the area of longitudinal reinforcement must not be less than 0.01 times the gross cross sectional area. The original bridge already satisfied this requirement. Transverse spacing for a zone 2 bridge is the minimum of either ¼ the member dimension or 4 inches center-to-center. For the modified bridge, the 4 inch center-to-center case controls, and this is a major change from the control bridge, which had 6 inch center to center spacing. Abutment fixities were modified based on Section 4.7.4.4 Minimum Displacement Requirements for bridge seat lengths. P-delta check was satisfied according to section 4.7.4.5; this check had not previously been included in earlier editions.

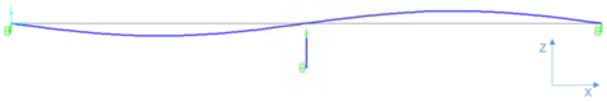
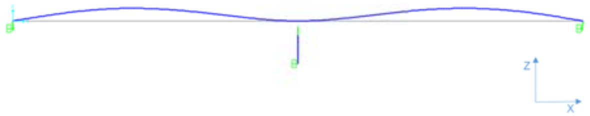
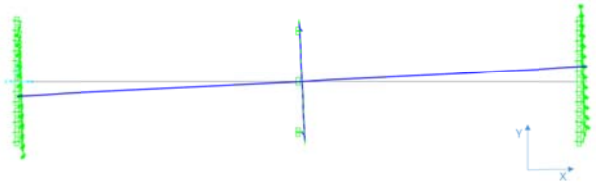
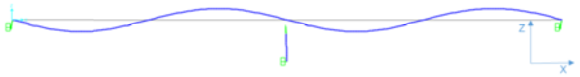
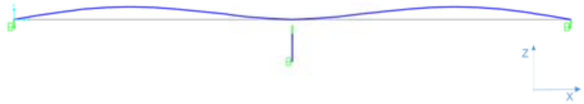
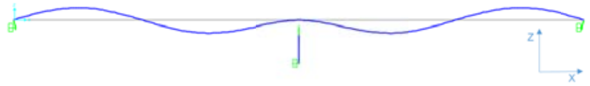
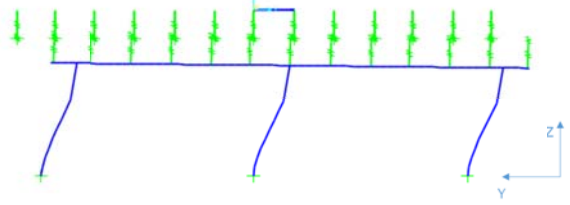
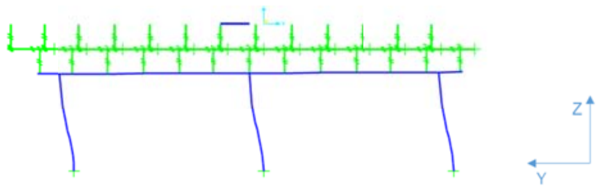
Structural Analysis Results

A modal analysis was first performed on each of the two bridges to identify the dominant mode shapes and mode periods of each bridge. The mode shapes and periods are reported in Table 15. The first mode shapes and periods are very similar, with the modified bridge reporting a slightly shorter first mode period of 0.69 seconds as opposed to 0.73 seconds. This can likely be attributed to the additional transverse reinforcement in the modified bridge. Additionally, the modified bridge has additional mode shapes not seen in the control bridge, as seen in the modified bridge mode shapes 2 and 4, due to differences in end constraints. Figure 34 provides a closer view of the fourth mode shape of the modified bridge, which captures the major difference in end constraints.

Table 14. Relevant bridge model inputs and characteristics. "---" for modified bridge indicates the same input was used from the control bridge.

Input	Control Bridge	Modified Bridge
Superstructure	Pre-stressed concrete girder	---
Pier Columns		
Height	11 ft. 5 in.	---
Diameter	42 in.	---
Clear cover	3 in.	---
Longitudinal reinforcement	18 #10 bars	---
Transverse reinforcement	#6 bars @ 6 in. spacing	#6 bars @ 4 in. spacing for 42 in. at top and bottom of columns
Pier Bent		
Depth	66 in.	---
Width	48 in.	---
Clear cover	3.5 in.	---
Longitudinal reinforcement	#9	---
Confinement bars	#4	---
Abutment constraints		
X translation	Fixed	Free
Y translation	Fixed	Free
Z translation	Fixed	---
X rotation	Free	---
Y rotation	Free	---
Z rotation	Free	---
Top of Pier Bent Connection		
X translation	Fixed	---
Y translation	Fixed	---
Z translation	Fixed	---
X rotation	Free	Fixed
Y rotation	Free	Fixed
Z rotation	Free	Fixed
Bottom of Column Fixity		
X translation	Fixed	---
Y translation	Fixed	---
Z translation	Fixed	---
X rotation	Fixed	---
Y rotation	Fixed	---
Z rotation	Fixed	---
Fundamental periods		
Longitudinal Tn	0.44 seconds	0.28 seconds
Transverse Tn	0.15 seconds	0.23 seconds

Table 15. Mode shapes for the two bridge models. Asterisks denote the dominating mode shape in the longitudinal direction for each bridge.

Control Bridge Mode Shapes	Modified Bridge Mode Shapes
 Mode 1 = 0.73 s	 Mode 1 = 0.69 s
 Mode 2 = 0.47 s	 Mode 2 = 0.64 s
 Mode 3* = 0.44 s	 Mode 3 = 0.47 s
 Mode 4 = 0.18 s	 Mode 4* = 0.28 s
 Mode 5 = 0.15 s	 Mode 5 = 0.23 s

Time-history responses were collected at the top of the pier bent for each of the three ground motions in both the longitudinal and transverse directions. This resulted in twelve runs, as detailed in Table 16. The outputs from the 2011 Utah ground motion in the longitudinal directions from the control and modified bridges are plotted against an SDOF analysis with the dominating mode shape (see asterisks in Table 15) in the longitudinal direction for comparison in Figure 35 (control bridge) and Figure 36 (modified bridge).

Figure 34. Mode 4 for the modified bridge. Note the lateral movement apparent at the right end of the bridge due to a roller fixity rather than a pinned fixity in the x direction.

The additional transverse detailing required in the seismic zone 2 bridge resulted in a slightly stiffer column, as evidenced by the smaller fundamental period in the longitudinal direction. This is further shown by the smaller displacements experienced by the modified bridge when compared to the control bridge. Results from each of the three ground motions in the fundamental period in the longitudinal direction are compared to the elastic SDOF analysis in the appendix.

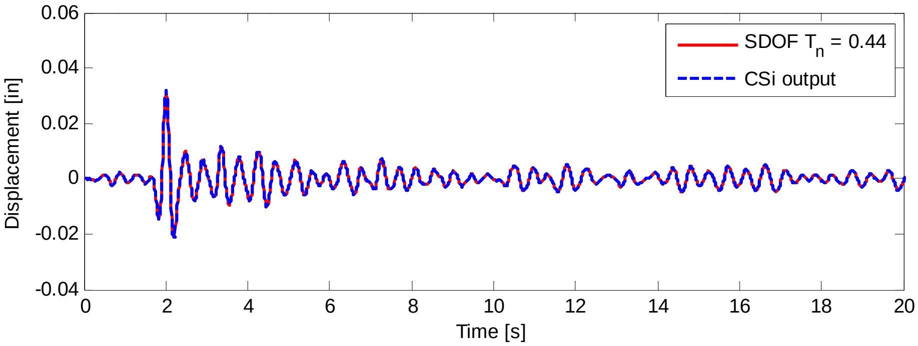


Figure 35. Control bridge displacement at top of pier bent in blue. In red, the SDOF comparison for the fundamental period in the longitudinal direction of the control bridge.

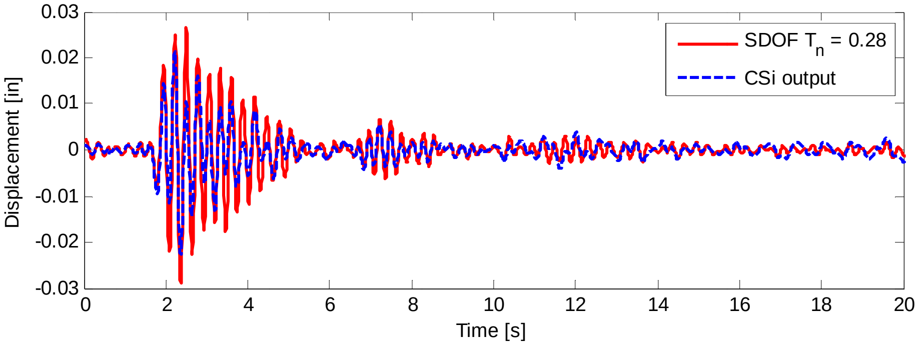


Figure 36. Modified (zone 2) bridge displacement at top of pier bent in blue. In red, the SDOF comparison for the fundamental period in the longitudinal direction of the modified bridge.

Table 16. CSiBridge run descriptions and results summary.

Run	Run Name	Model	Direction	Ground Motion	ξ [%]	Max. Disp [in]	Max. Acc [g]
1	T_EC_pre	Control	Transverse	El Centro	5	0.089	0.599
2	T_EC_pos	Zone 2	Transverse	El Centro	5	0.175	0.367
3	L_EC_pre	Control	Longitudinal	El Centro	5	1.489	0.775
4	L_EC_pos	Zone 2	Longitudinal	El Centro	5	0.758	0.547
5	T_UT_pre	Control	Transverse	Utah 2011	5	0.002	0.015
6	T_UT_pos	Zone 2	Transverse	Utah 2011	5	0.008	0.020
7	L_UT_pre	Control	Longitudinal	Utah 2011	5	0.032	0.017
8	L_UT_pos	Zone 2	Longitudinal	Utah 2011	5	0.023	0.025
9	T_MP_pre	Control	Transverse	Max PGA	5	0.067	0.457
10	T_MP_pos	Zone 2	Transverse	Max PGA	5	0.127	0.328
11	L_MP_pre	Control	Longitudinal	Max PGA	5	0.422	0.222
12	L_MP_pos	Zone 2	Longitudinal	Max PGA	5	0.199	0.270

The model outputs from the three ground motion inputs can be combined to produce a probabilistic seismic demand model [53], as shown in Figure 37. Results from each of the three ground motions (Utah, stochastic ground motion, and El Centro) are plotted on the x-axis by the maximum PGA in each ground motion and, on the y-axis, by the maximum displacement. The three points are used to create a linear extrapolation, which is used in this example as the probabilistic seismic demand model.

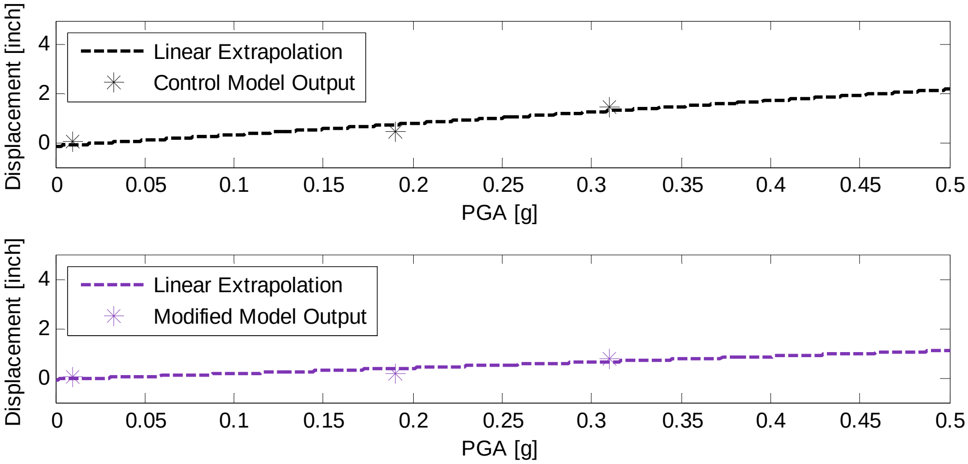


Figure 37. Peak ground acceleration versus longitudinal displacement, extrapolated from structural analysis from three ground motions.

Monte Carlo Simulation

Although many probabilistic methods exist for the quantitative assessment of risk, Monte Carlo simulation is used here for simplicity and ease of understanding. The following is an outline of the Monte Carlo simulation process as applied to assess the structural performance of the two bridge designs. The example examines the structural displacement at the top of a bridge pier through a 1,000 year sample period with respect to annual probable seismic excitations.

First, seismic hazard curves for the maximum peak ground acceleration were obtained through USGS for the maximum PGA site and Denver to represent seismic zones 2 and 1, respectively [54]. The hazard curves as obtained are in units of an annual rate of exceedance (P[PGA>X]) for a given level of ground motion, measured in peak ground acceleration. When P[PGA>X] is very small, the probability can be assumed to be equal to the rate of exceedance. The hazard curves are based on a Poisson distribution of earthquake occurrence in time. This relationship is best seen on a log-scale (Figure 38).

Thus, annual peak ground acceleration values can be generated consistently with the seismic hazard probabilities provided by the USGS, as discussed above. For a given probability of occurrence, a peak ground acceleration can be identified using the seismic hazard curve in Figure 38. By generating a uniformly distributed random number to determine the annual probability of occurrence in the seismic hazard curve on the y-axis, the process can be repeated for many trials to create a distribution of peak ground acceleration values. The corresponding PGA value from Figure 38 can then be used in the probabilistic seismic demand model (Figure 37) to find a mean value in order to generate a normal distribution of displacement values for a given PGA value. Each of the points in the dotted, extrapolated line is then used as the mean value for a given PGA value, with a normal distribution surrounding the mean value. A normal distribution has been assumed for this example for simplicity. The normal distribution is defined by the mean value and a coefficient of variation equal to 0.30, a moderate level value according to literature [53]. A random value within this normal distribution is then chosen and recorded as a simulated displacement due to seismic hazard in a year.

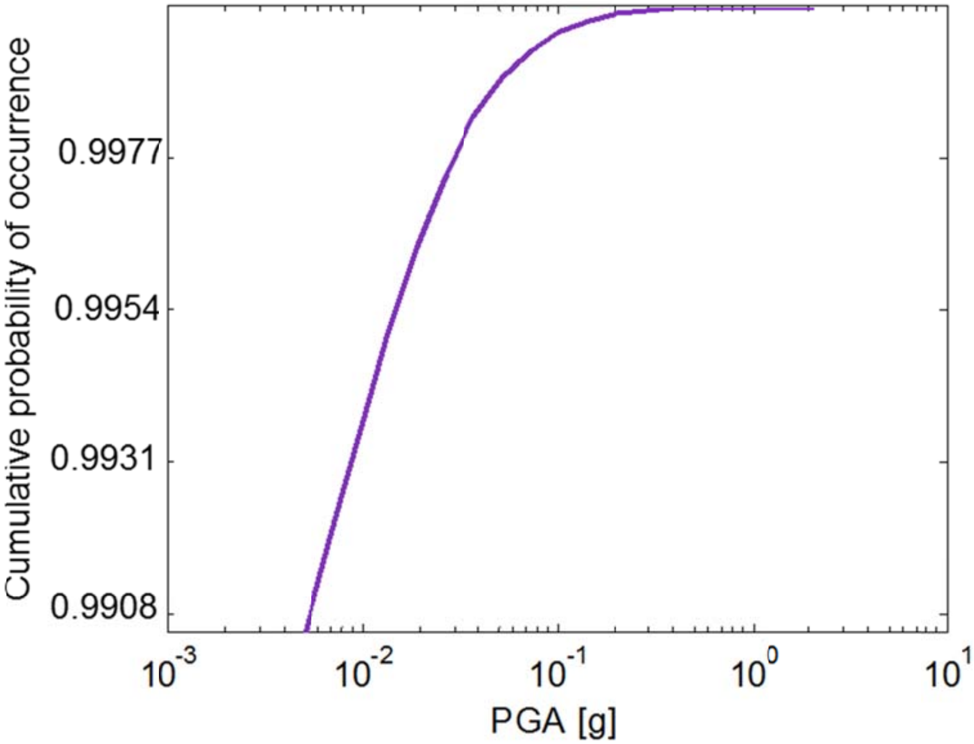


Figure 38. Cumulative distribution function for the probability of a ground motion's peak ground acceleration.

For this Monte Carlo simulation, the process described in the previous paragraph was repeated 1,000 times, representative of 1,000 years. The result for the maximum peak ground acceleration site is summarized as a probability distribution, shown in Figure 39. The mean displacement in the longitudinal direction from a longitudinal excitation for the control bridge was found to be 0.0158 in., with a standard deviation of 0.0067 in., and the mean displacement for the modified bridge was 0.0155 in., with a standard deviation of 0.0057 in. This simulation suggests that the two bridges perform very similarly in a thousand year period, when subjected to zone 2 ground motions, such as ones expected at this maximum PGA site. The process was then repeated for a zone 1 location, represented by Denver, CO (Figure 40). For this second location, the mean displacement for the control bridge was found to be 0.0155 in., with a standard deviation of 0.0057 in., and the mean displacement for the modified bridge was 0.0157 in., with a standard deviation of 0.0047 in. Again, this second simulation suggests that the two bridges perform similarly in a thousand year period at this zone 1 site. Furthermore, the results between the two zones are very similar for the two bridges, suggesting the seismic hazard in either zone, using either design, is not a controlling hazard.

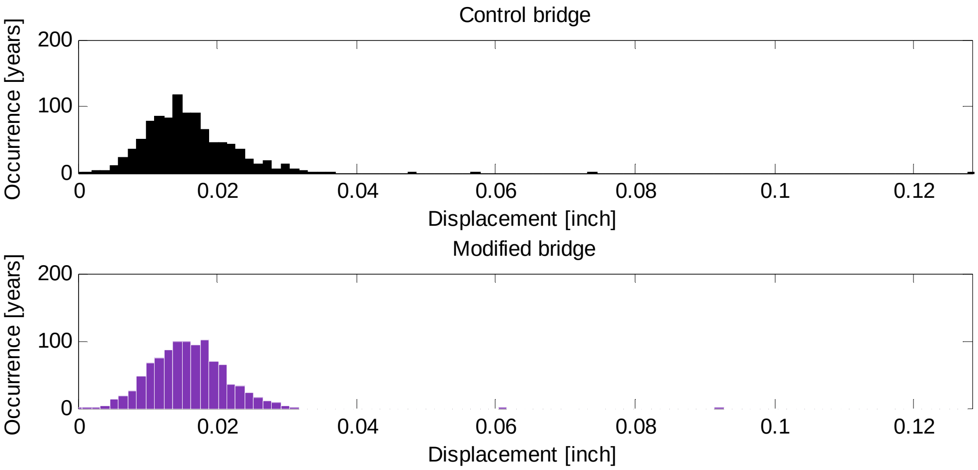


Figure 39. Probability distribution of displacement of the top of the bridge deck for the zone 2, maximum peak ground acceleration site in Colorado.

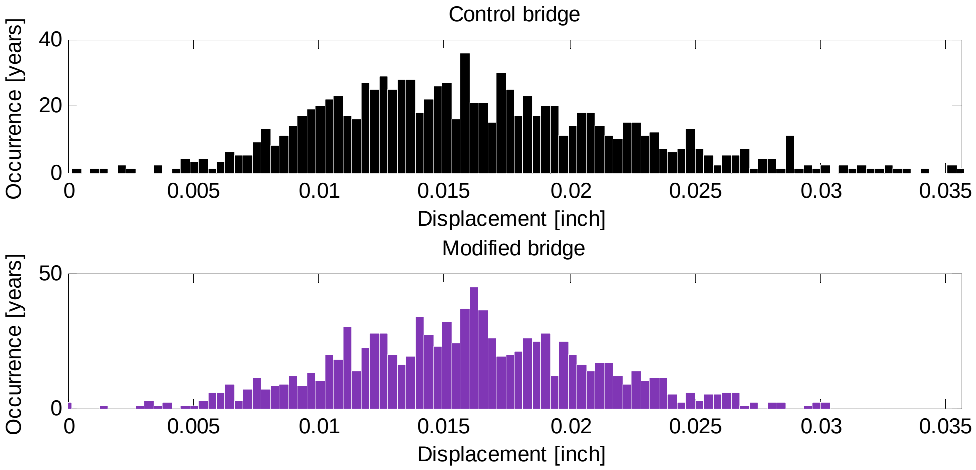


Figure 40. Probability distribution of displacement of the top of the bridge deck for a seismic zone 1 location, Denver, Colorado.

Given a particular displacement of interest, the distributions from Figure 39 and Figure 40 could be used to determine the percent of bridges that would or would not meet the acceptable displacement value.

Economic Metric

Using the costs listed in the cost estimate summary run on June 17, 2013 [55], the costs for materials in the original bridge and modified zone 2 bridge are shown in Table 17 and Table 18, respectively. The difference in material costs come from the different volume of transverse steel used between the two bridges. This difference amounts to 345 lbs of steel, which corresponds to a cost of $297 according to the unit price used by CDOT. This analysis considers strictly material costs; additional transverse reinforcement is likely to cost more in construction costs. Furthermore, the additional analysis required for designing a seismic zone 2 bridge is likely to incur additional costs in the design stage as well.

Table 17. Costs for the control bridge.

Item	**Quantity**	**Units**	**Unit price [2013 $]**	**Subtotal [2013 $]**
Concrete Class D (Bridge)	843	CY	465	391,995
Reinforcing Steel	15,794.00	LB	0.62	9,792
Reinforcing Steel (Epoxy Coated)	142,330.00	LB	0.86	122,404
Prestressed Concrete Box (Depth 32" Through 48")	12,159.00	SF	49	595,791
			Total	**$1,119,982**

Table 18. Costs for the modified bridge. Modified values bolded in table.

Item	**Quantity**	**Units**	**Unit price [2013 $]**	**Subtotal [2013 $]**
Concrete Class D (Bridge)	843	CY	465	391,995
Reinforcing Steel	15,794.00	LB	0.62	9,792
Reinforcing Steel (Epoxy Coated)	**142,675.76**	**LB**	**0.86**	**122,701**
Prestressed Concrete Box (Depth 32" Through 48")	12,159.00	SF	49	595,791
			Total	**$1,120,279**

As an extension of this example, CDOT could investigate a variety of bridge designs using a similar method to add to this plot to have a more complete understanding of how the change from zone 1 to zone 2 affects some regions of Colorado.

Risk Action

Based on the outcome of the risk analysis, and assuming that the illustrative bridge is indeed representative of bridges built in Colorado, it is recommended that CDOT Region-Sections 32 and 57 consider designing to Seismic zone 2 standards since many of requirements are met by conventional design already, aside from ductile detailing in the pier columns, and the difference in cost can be considered negligible compared to the overall cost of construction, differing by only 0.02% of the control bridge design.

Continuity for Lessons Learned

This analysis can be incorporated to decision-making processes regarding design code changes at the program level. It is also worth investigating whether the fact that this bridge met many of the Seismic zone 2 considerations already resulted from a conservative bridge design, other controlling loads during design not considered in this example, or otherwise.

Conclusion

This chapter identifies the many hazards a bridge may be designed for given its location and expected use. Of primary focus is the consideration of seismic forces in Colorado, which had been updated in the AASHTO fourth edition such that parts of Colorado are categorized as seismic zone 2. To do so, an existing bridge designed for seismic zone 1 and a modified version of the bridge, updated to meet seismic zone 2 design requirements, were modeled and analyzed. The bridges were subjected to three ground motions. Model outputs showed relatively small deflections for the maximum PGA expected in Colorado. The seismic zone 2 bridge had stiffer columns due to seismic detailing required at the top and bottom of each pier column, and, consequently, smaller deflections. The deflections seen from both the stochastic ground motion, modeled to be characteristic of the maximum peak ground acceleration expected in Colorado, and the Utah ground motion, chosen to represent the greatest contributing hazard in Colorado, do not suggest that structural collapse would be triggered by expected ground motions in Colorado.

The above example illustrates what a quantitative assessment may look like through the use of Monte Carlo simulation, using the displacement from the three ground motions in combination with available seismic hazard curves. The simulation presented shows the distribution of deflections over a 1,000 year period. The level of effort required of the team and engineer is higher than that of the qualitative methods used in the operation and management of a portfolio of mast arms. This added effort is due to the relative importance of the different assets; the failure of a bridge could devastate a region, while the failure of a mast arm would likely cause some minor delays, but could be readily replaced and poses a smaller potential to claim human lives. The example could be expanded to investigate life-cycle performance of other structures, such as culverts, in assessing the risks that they face, in an informed, quantitative fashion.

This chapter also illustrates how the framework can be applied at the program level. The example could be extended to include the investigation of additional hazards. This method requires structural analysis software, an availability of hazard data for a given location, and the computational ability to perform a quantitative risk assessment.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

CDOT has existing standards for the design, maintenance, and operation of its assets. These standards provide an implicit level of performance or risk. However, it is hard to compare risks or examine tradeoffs in actions that may affect some risks and assets. It is critical to identify an explicit, transparent framework through which risks can be addressed, including the flexibility for implementation to a number of different levels (program, portfolio, or project), and different scopes (such as maintenance and operations verses design decisions), while still providing tangible, meaningful direction for end-users of such a framework.

From the literature review in Chapter 2, a risk-based framework intends to enable an organization to perform work in a deliberately risk-aware fashion. The risk analysis process, as shown by many organizations, can be tailored to provide the amount of risk information desired by an organization, the depth of which is typically proportional to the amount of time and effort required of the team. This analysis must be accessible enough so as to not hinder its adaptation into normal management processes, yet informative and comprehensive enough as to bring additional insight to the situation in investigation.

Thus, in Chapter 3, the risk-based framework developed for CDOT in this report proposes a method that can be readily integrated with such existing practices. The framework is composed of four steps: communication logistics, identification of goals and standards, risk analysis, and continuing lessons learned. It is also flexible enough to match the philosophy and direction of next-generation federal regulations, such as MAP-21. Key features to the framework are the feedback loops from risk monitoring back to the other stages of risk analysis, including risk identification, risk assessment, and risk action. Additionally, lessons learned also loop back into communication logistics, goal identification, and risk analysis for future instances of the framework. The framework is adaptable to the needs of the operation on hand. Three risk assessment methods are introduced to demonstrate the adaptability of the framework. This framework integrates risk analysis procedures with avenues for continual improvement of the framework process through the feedback loops. The framework is presented through a visually represented graphic and action driven guidelines. The result is a process that can be readily implemented in CDOT at all levels of organization.

Chapter 4 contains an illustrative example of the framework as applied to developing a budget for mast arm maintenance and operation. This chapter demonstrates how quantitative structural analysis can be used to guide qualitative risk analysis. It seeks to further the reader's understanding of the kinds of decisions and processes that happen at the portfolio level. The results of the illustrative example suggest that, informed by inspection records, some mast arms may not need as frequent inspection as others, and the current policy for a uniform inspection schedule could be modified to reflect such findings.

Chapter 5 illustrates the framework as it would be applied to a program level design question. Particularly, the consideration of seismic hazard is investigated for the particular regions in Colorado that qualify as seismic zone 2 according to the AASHTO revisions from 2009. This example shows that with less than 1% change in material cost, seismic provisions for the highest seismic zone in Colorado (zone 2) can be readily satisfied. The quantitative analysis shows that, with a basic Monte Carlo simulation and structural analysis results, organizations such as CDOT can readily visualize the risk a particular hazard may impose on structural performance.

Recommendations

It is recommended that the presented risk-based framework be adopted for use by CDOT in their design, operations, and maintenance of built facilities. To enhance the proposed framework, future work includes developing guidelines for determining when to use which risk assessment approach. Three options have been presented to CDOT, as introduced in Chapter 3 and presented in Chapters 4 and 5. Caltrans and WSDOT distinguish between different levels of risk assessment based on budget; CDOT could choose to adopt this, or investigate a different metric by which to choose a risk assessment method based on the needs of the public. Refinement of a risk-tracking system, here referred to as a “risk register”, for specific applications could be made in order to develop long-term tools for the organization. This report does not include an example for the application of the framework to make decisions about modifying organizational strategic direction and long-term planning, although it is intended that the framework could be applied to such decisions. In the near term, the following action items are immediately applicable to CDOT:

- Implementation of a varied mast arm inspection routine based on structural state. Low-risk mast arms could be inspected less frequently than the current inspection routine.

- Modification of the mast arm inspection records database to make information amenable to data-mining for risk assessment. The mast-arm inspection record database has structural defects embedded in a “notes” column. Uniform inspection codes for defects in an independent column could greatly enhance the database, especially towards future data-mining efforts. Codes that reflect each of the structural defects need to be defined, and a new field containing the found defects with a uniform delimiter can enable CDOT to quickly identify the overall state of its mast arm portfolio. Similar recommendations are applicable to other CDOT databases that describe the condition of CDOT facilities.

- Adoption of the proposed common vocabulary and framework to discuss risk and address issues that face the organization. Though mast arms and seismic design of bridges are used as examples, this framework can be extended to culvert design, organizational decision-making, and more.

Though extra steps on top of existing management practices are necessary to implement such a framework, much of the existing practices overlap with risk-based framework concepts introduced in Chapter 3. It is a matter of formalizing such practices, as well as familiarizing the organization with the concept and developing a meaningful understanding of what risk means. Risk is the combination of probability and impact, and the impact could be measured in dollars, CDOT's time, the public's time, injury accidents, or another clearly measurable, relevant metric. Through the application of this framework, CDOT can continue to be a leader in the transportation sector by efficiently managing its assets, maintaining public safety, and preparing for the uncertain future.

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APPENDIX A – FINITE ELEMENT MODELING OF MAST ARMS

The main objective of this analysis was to determine the reduction in strength and risk of the designed mast-arm structure when affected by the various defects and damages which means to see whether the area with maximum stress concentration is of significance in relation to the stability and risk of the mast-arm structure. Only static, elastic analysis was considered and stresses were checked against the yield value. Material nonlinearity (that is plastic analysis) was not done since a data set of the nominal stress and nominal strain was not present. The approach was quite simple and was divided into two phases.

Phase 1

The designed mast-arm without any defect was analyzed under the maximum loading as per AASHTO – Standard Specification for Structural Supports 2001 [35]. The resulting stresses were checked against the yield strength of the Mast-arm material. If the material had not yielded, the load was increased in steps in order to compute the maximum allowable loading. The mean return period for the maximum load computed was estimated from AASHTO – Standard Specification for Structural Supports 2001 [35].

Phase 2

New models were created taking into consideration each type of defect individually. The same procedure as followed in Phase 1 was done. The computed stresses were compared to yield strength of the material and iterated to finally generate the maximum allowable load, which in turn gives the return period.

Finally, the results from Phase 1 and Phase 2 were compared to have an estimate of the difference in the strength between the base design and each defect individually. This gave a clear picture of the risk of the mast-arm structures inspected in the state of Colorado.

Material Definition and Boundary Conditions

The following material properties have been used for the model.

- All poles have been fabricated with ASTM A572 Grade 65 steel.
- All arms have also been fabricated with ASTM A572 Grade 65 steel.
- Elastic modulus for the above mentioned alloy was calculated to be 3.046e+7psi.
- Poisson's ratio was taken to be 0.3.
- Density of steel was calculated to be 0.2901lb/cu.in.

With regard to the boundary conditions, the bottom base plate was fixed at the bolt holes in all directions. See Figure 41 for location of the constraints.

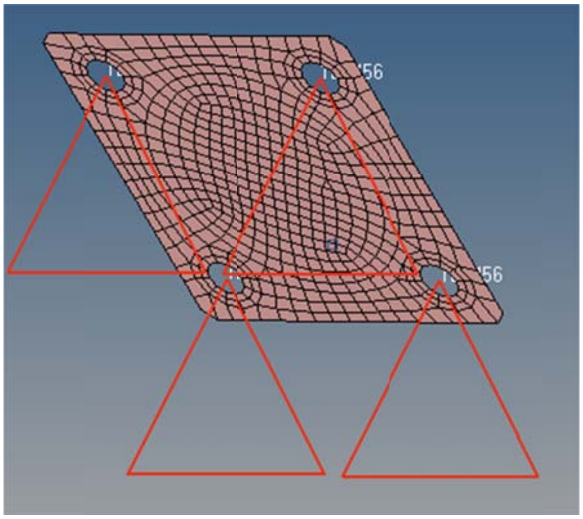

Figure 41. Boundary Conditions

As shown in the above figure the holes were constrained in both displacement and rotation in all degrees of freedom to simulate the bolts.

At first wind pressure analysis was considered in this analysis. The wind pressure was applied to the arm only and wind pressure due to presence of signal head was not considered. Also gravity load was not included in the analysis. After analyzing, and studying the structure, three more loads were added: 1. Gravity load, 2. Self-weight Load due to 3 signal heads attached to the arm, and 3. Wind load due to presence of the signal heads. This model was then again analyzed and the results were studied. The continuous forces were modeled by a series of concentrated loads acting parallel to the ground in negative z-direction on the arm. Gravity load was applied in negative y-direction. Self-weight load was applied in negative y-direction. Wind load due to presence of signal heads was applied in negative z-direction. A total of 50 nodes were selected in a line and hence the loads calculated from AASHTO – Standard Specification for Structural Supports 2001 [35] were modified to account for 50 nodes.

50 nodes were selected in equal intervals a line to create a wind pressure force acting on the arm in negative z-direction parallel to the ground. Three nodes were selected at a distance measured as per the drawing in S-614-40A guideline [56]. At these 3 nodes wind pressure load due to signal heads and self-weight load of the signal heads were applied in negative z-direction and negative y-direction respectively.

Load Calculation

Wind Pressure load was calculated as per AASHTO – Standard Specification for Structural Supports 2001 [35]. Wind Pressure equation is given by: $P_z = 0.00256K_zGV^2I_rC_{d.}$ (psf).

Table 19. Wind load factors

Kz	Height and Exposure Factor	1.05
G	Gust Effect Factor	1.14
V	Wind Velocity	38(m/s)
Ir	Wind Importance Factor	0.87
Cd	Drag Coefficient	1.2

Table 19 shows the value of various factors that were required to determine the wind pressure. Wind Pressure calculated in psf was converted to psi. From this the wind pressure for 50 nodes was equally divided over the length of the arm. This was then applied to 1 sq.in of mesh area. The load was computed to be 0.99lbs, which was approximated to 1lb.

For signal loads, the wind pressure computed was not adjusted for 50 nodes and this overall wind pressure was applied as a point load at the 3 defined points for the signals. This load computed in psi was converted to pounds by computing it over an area of 8.67 sq.ft which was referred from Traffic Signal Standards [35]. Table 20 shows the wind pressure calculated for distributed load over 50 nodes and signal loads applied at 3 nodes. It also shows the gravity load for signal heads, which was referred from Traffic Signal Standards [35]. This was hence computed to be 60lbs for 12 inch lens signal heads.

Table 20. Loads applied to mast arm

Loads	PSF	PSI	Pounds
Wind Load(50 nodes)	143psf	1psi	1lb
Wind Load(Signal Heads)	7171psf	50psi	1248lbs
Gravity Load(Signal Heads)	NA	NA	60lbs

Model

To model the Mast-arm, the whole structure was divided into 6 components. These 6 components were then modeled in Solid works as per the dimensions given in S-614-40A manual of CDOT which was accessed from CDOT in Denver [56].

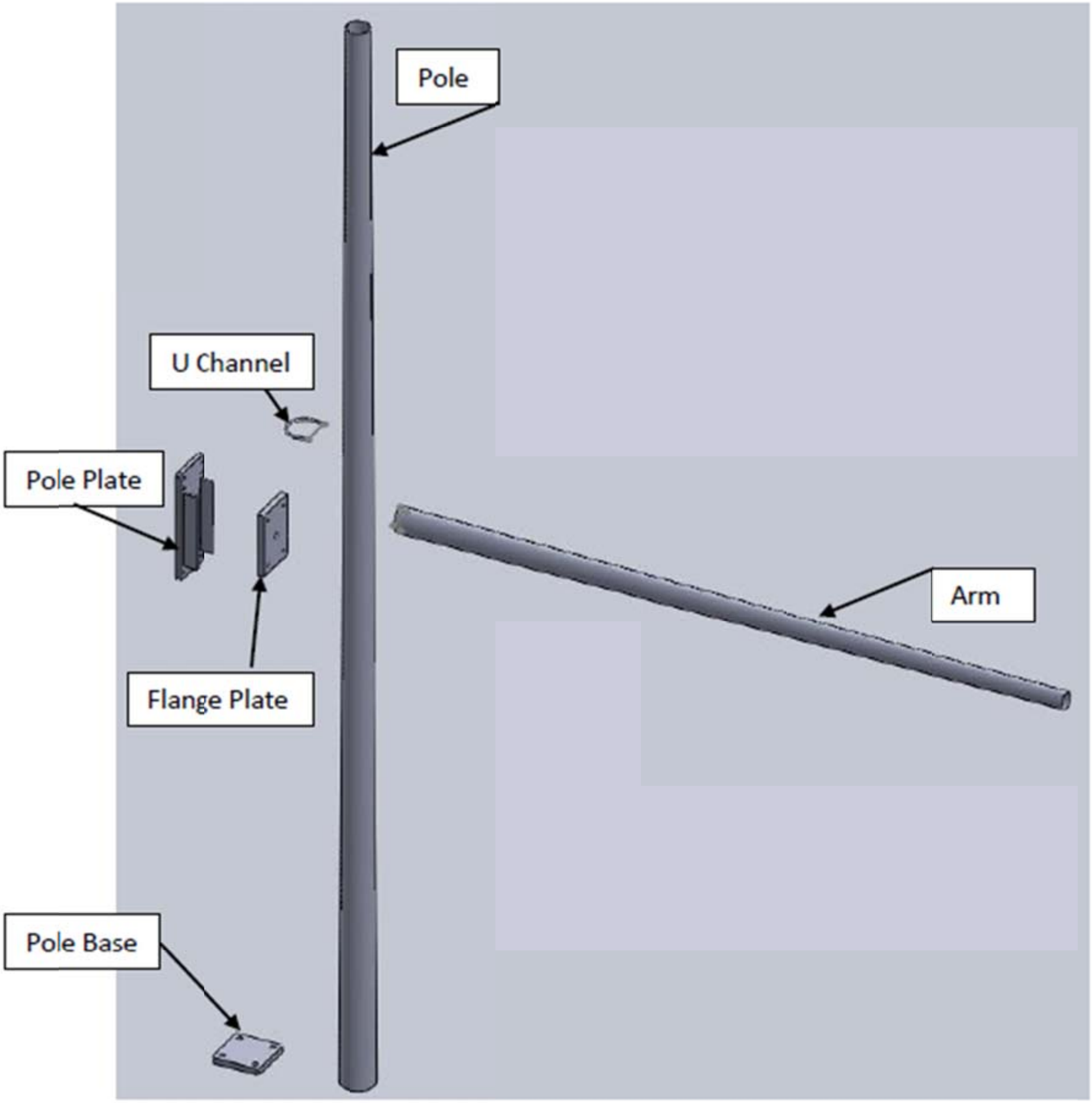

Figure 42. Mast arm components modeled in SolidWorks.

Figure 42 shows the 6 components that were designed in Solid Works as per the S-614-40A manual of CDOT [56].

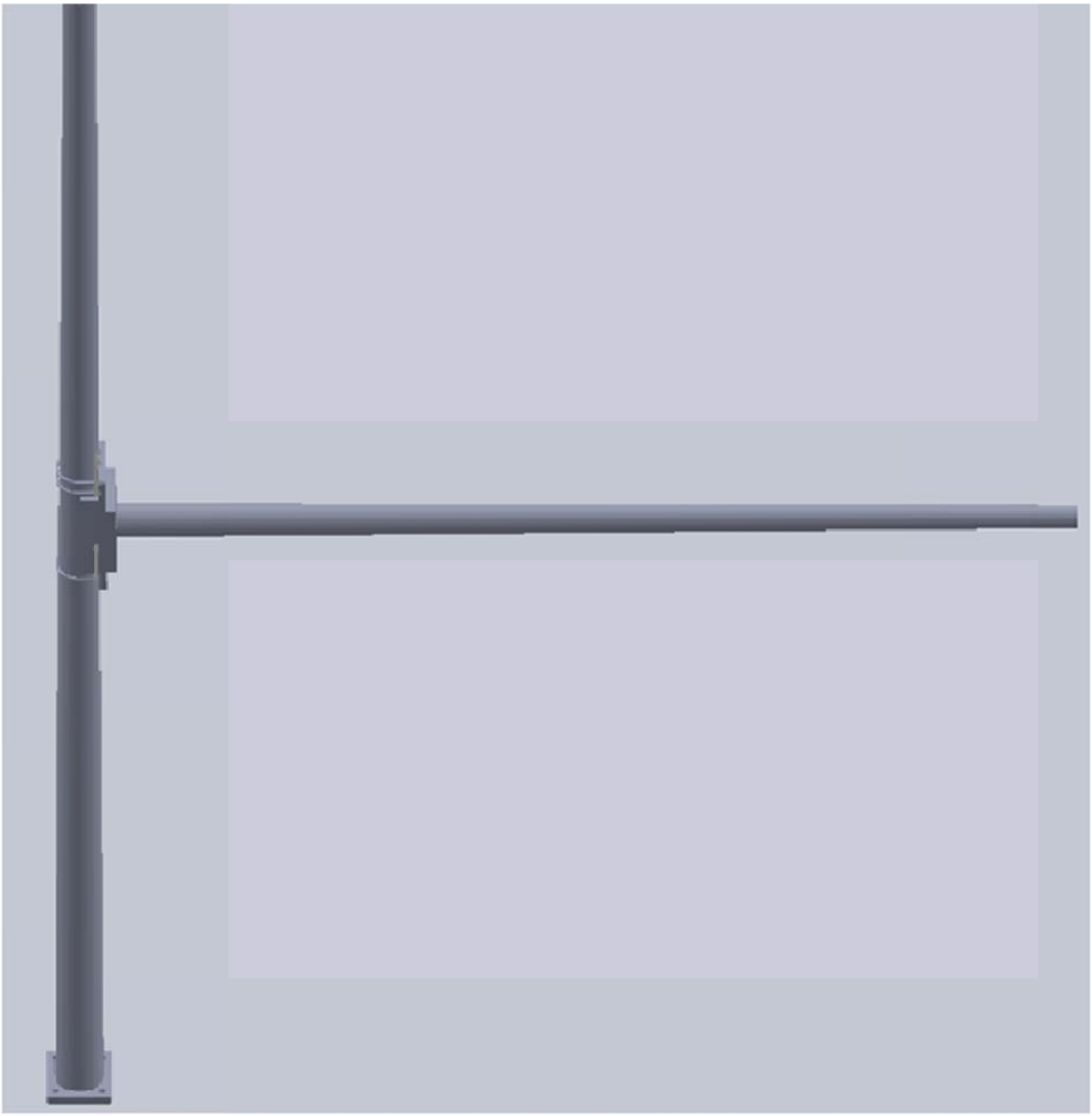

Figure 43. Assembled mast arm in SolidWorks

The parts were then assembled in Solid works as shown in Figure 43 before being imported to Hypermesh for preprocessing, where they were modeled in order to perform finite element analysis.

In Hypermesh software, this solid model was converted in order to mesh with shell elements. In order to do so, mid surface for each component except U-channels was created, and then given a thickness to account for the solid sections. They were meshed with a combination of S3 and S4R quad and mixed shell elements since this helped in reducing the Jacobian issues in the mesh. For the U-channels, they were modeled with C3D8R Hexa elements since shell elements were giving convergence issues. The quality of the mesh was then checked and found out to be good, with zero warpage and minimal jacobian issues. This took several iterations.

Ties were used to simulate the bolts. In order to do this, all the nodes at the edges of the U channels and the holes of the Pole plate were tied together at a point which acted as a rigid constraint. This approach was also used to simulate the bolts between pole plate and arm flange plate. Kinematic coupling was used to define the contacts. A clearer picture of this can be seen in Figure 44.

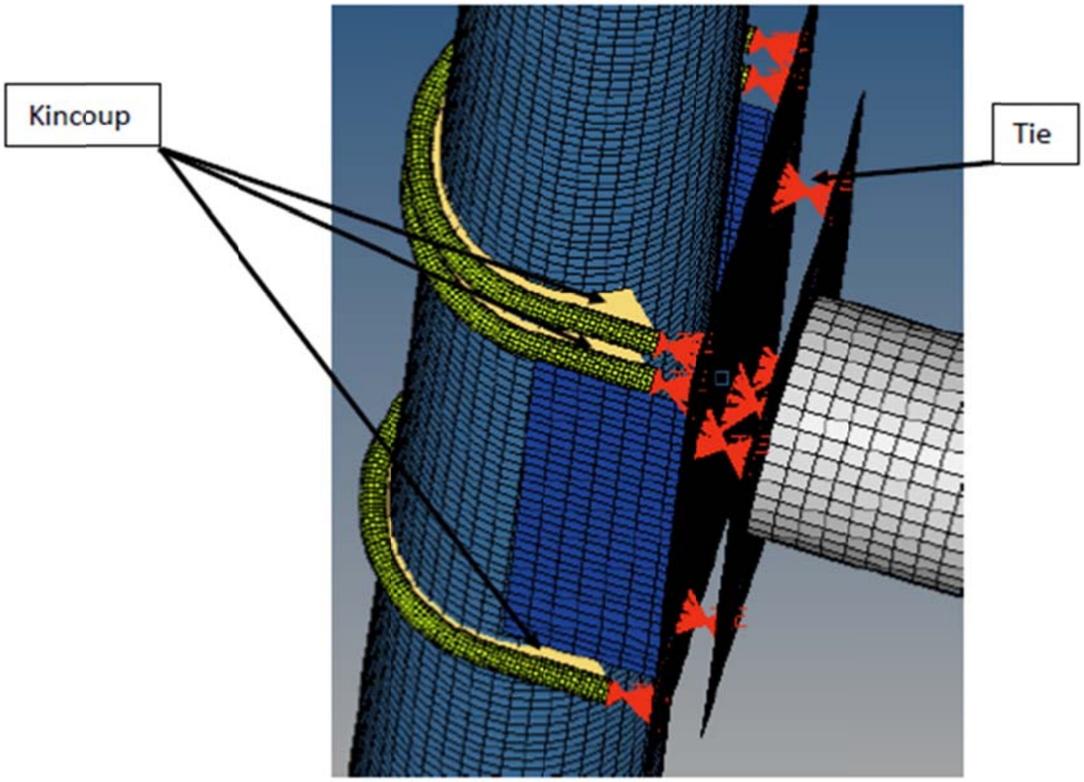

Figure 44. Contacts

The red colored strands depict the ties used to simulate the bolts and the yellow strands between the U-channels and Pole denote the contact. All the boundary conditions and material properties were defined and an input file created. This input file was then imported into Abaqus to solve the finite element problem.

APPENDIX B - RESULTS OF THE MAST-ARM STRUCTURE ANALYSIS

Base Design

The base design is the initial design as per the guidelines of AASHTO – Standard Specification for Structural Supports 2001. This did not include any defects. The material properties were defined as showed in Chapter 4. The following were the results after static, elastic analysis.

In Figure 45, the red colored area is the maximum stress concentration which is at the connection between the arm and the arm flange plate. From the legend it can be seen that the maximum value is of 23000 psi which is equivalent to 23 ksi, which is far below the yield stress of 65 ksi. Also a stress pattern can be seen on the pole just below the U channels because of that U-channel is trying to move into the pole and is resisted from the pole. In Figure 46, we can see the stresses developed around the base of the pole around 5.9 ksi. The area between point A and point B is of significance since all the defects have been defined at this area and all the variation in stress pattern can be seen here.

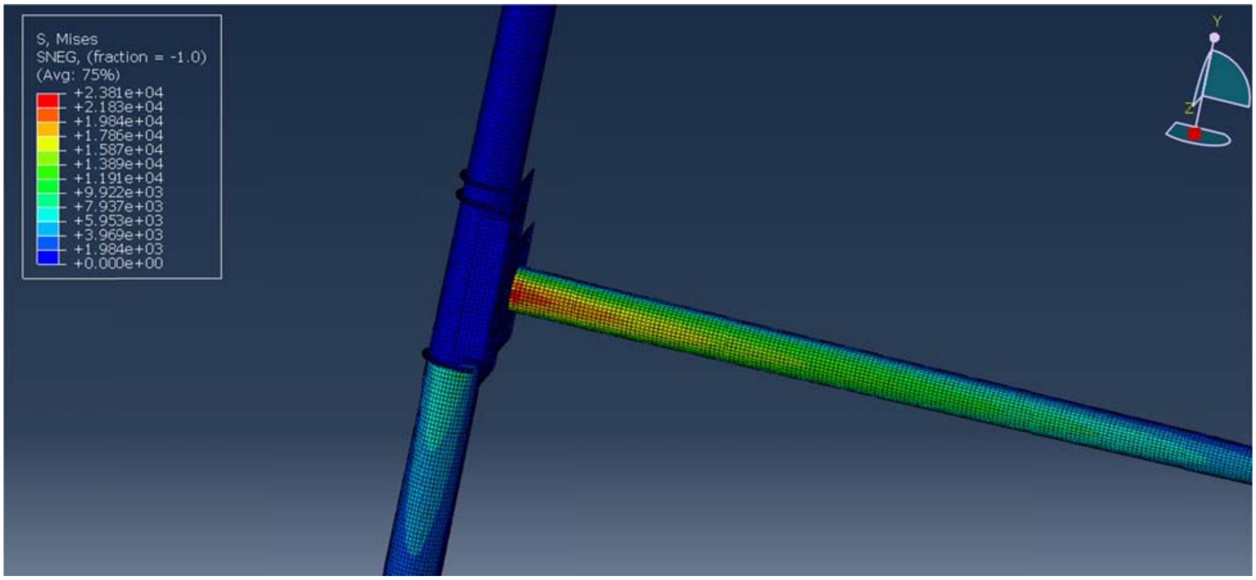

Figure 45. Base design stresses

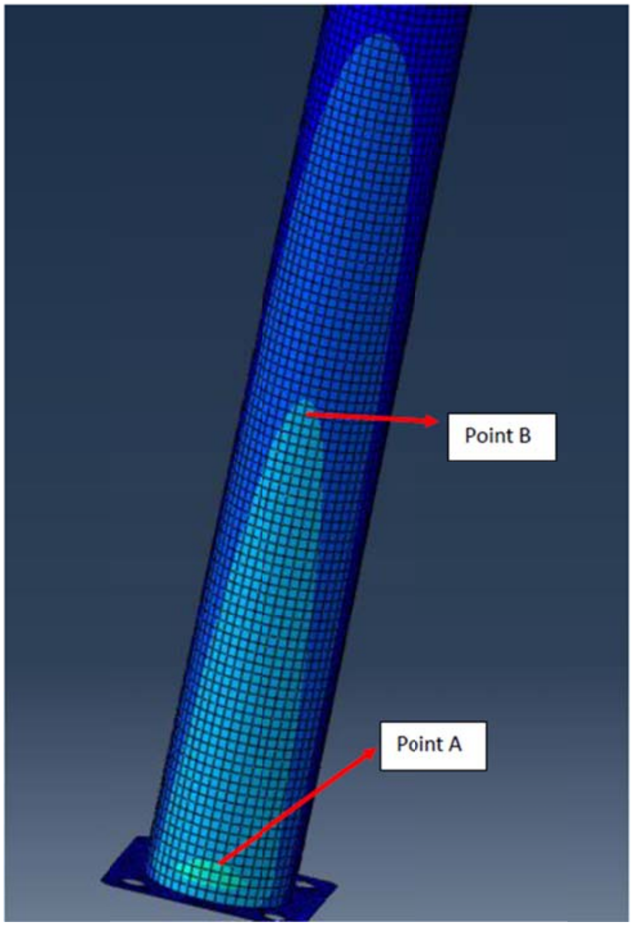

Figure 46. Detailed view of the stress patterns around the base.

R1 Corrosion

This next figure is when a small patch of corrosion was defined. One can see the small patch of corrosion in brown color. The material property and thickness of this patch was altered as discussed in Chapter 4. Therefore a total loss of 10% was taken in all the properties and thickness for these elements to account for R1 type of corrosion. Here the patch of corrosion has been defined perpendicular to the vertical plane of the arm and in line with the direction of wind loading.

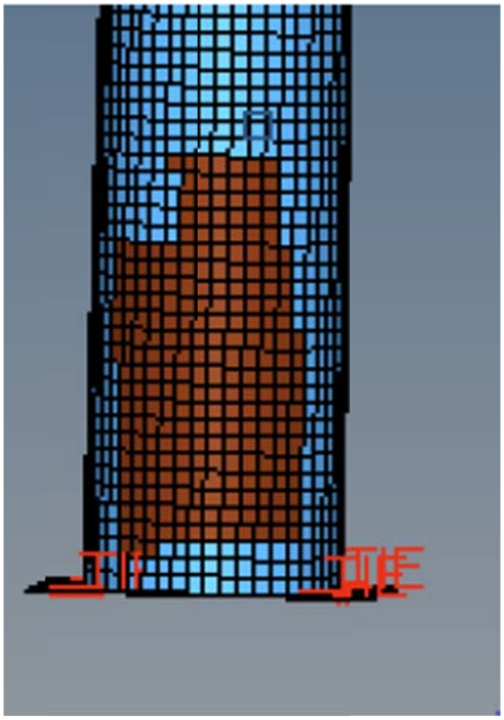

Figure 47. Corrosion patch

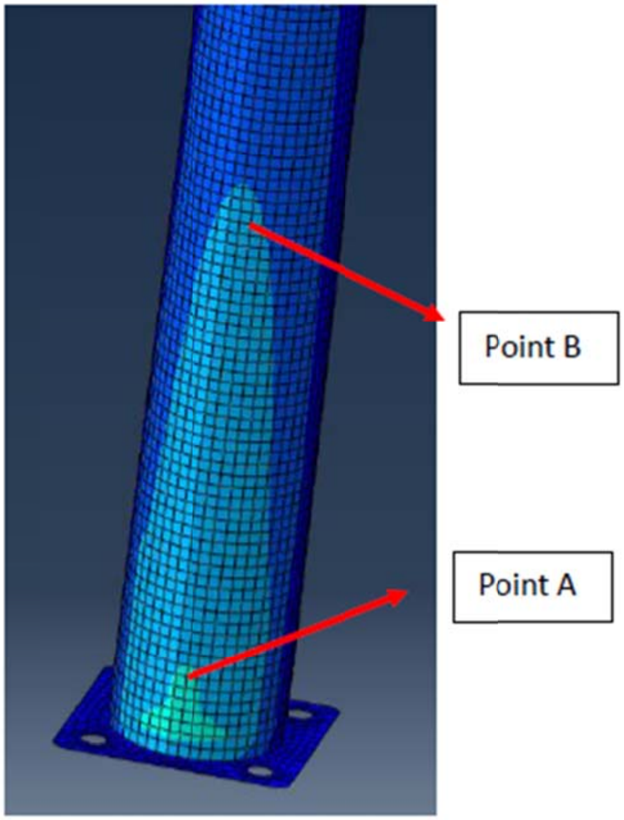

Figure 48. Stress contour due to R1 corrosion

In Figure 48 one can see an increase in stress near the bottom of the pole. This small increase in stress is due to minor weakening of the material of that particular area of the pole due to R1 corrosion.

After this the load was increased to see the maximum load possible before the material yields. This took 3 to 4 iterations. The maximum loading was computed to be 2.65 lbs. Wind pressure was computed from this load. From this wind pressure, the importance factor was calculated and from AASHTO – Standard Specification for Structural Supports 2001, the return period was calculated.

This 2.65lbs was back-calculated for 50 nodes and then converted to psf and the wind pressure was found out to be 19080 psf. Using AASHTO – Standard Specification for Structural Supports 2001, Wind Importance factor was calculated to be 2.31 > 1.15 for V = 1496.06 in/s. From this the return period was estimated to be greater than 100 years.

In Figure 48 it can be seen that a small patch of R1 corrosion has been defined again but this time it has been defined parallel to the vertical plane of the arm and perpendicular to the loading. The material property and thickness is same as defined earlier since it is still R1 type of corrosion.

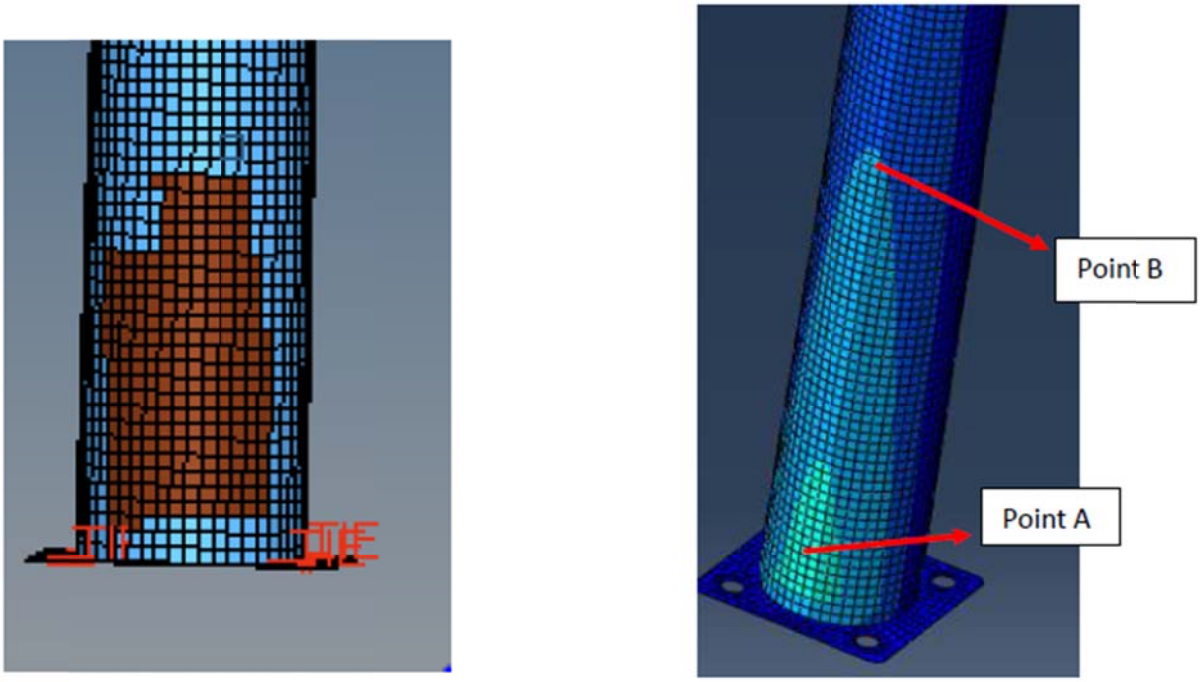

Figure 49. R1 patch perpendicular to loading (left); stress contour of R1 corrosion (right)

In Figure 49 we can see a greater increased level of stress, due to the fact that instead of spreading upward it is actually trying to spread laterally from the center point of that spike visible in the figure. This pattern become much more distinct when a higher level of corrosion is considered.

R2 Corrosion

Figure 50 shows the second type of corrosion which is R2 type of corrosion. It can be seen that the patch of the corrosion is slightly bigger than the R1 type of corrosion. Also the loss of material property and thickness is more than R1 as discussed in Chapter 4. A total loss of 15% has been defined for this level of corrosion.

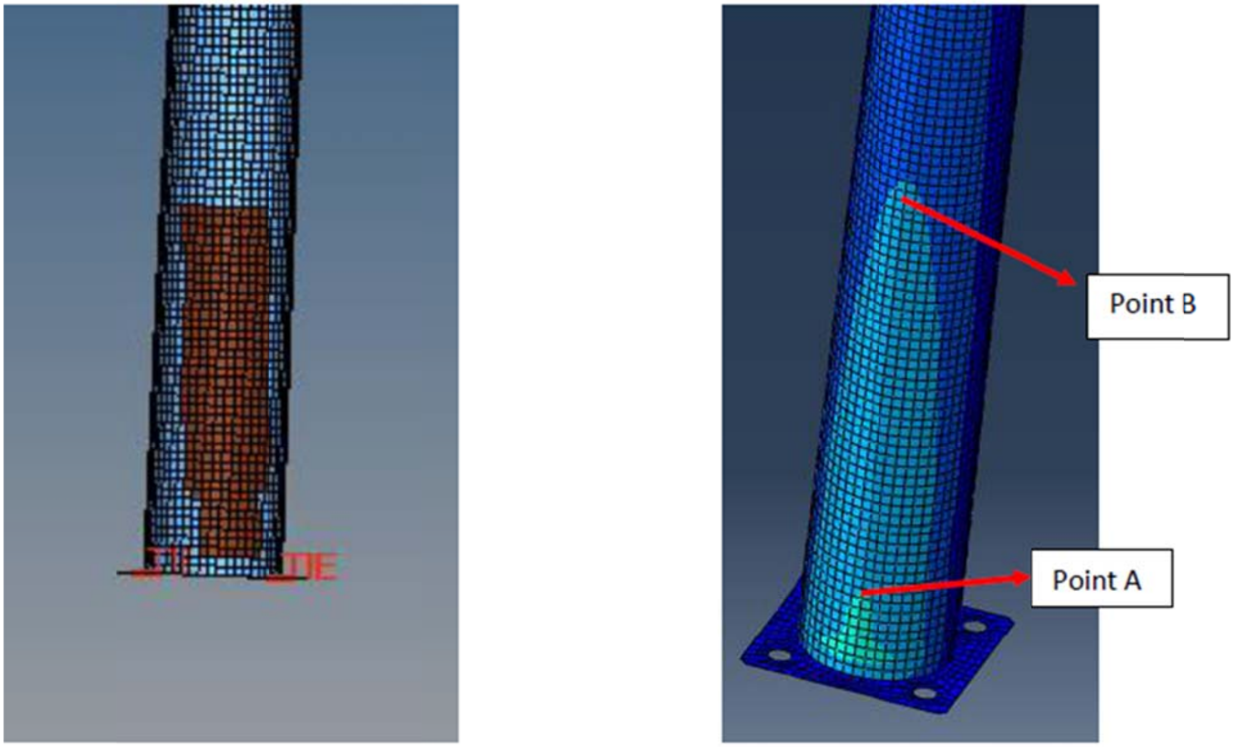

Figure 50. R2 corrosion patch (left); R2 stress contour (right).

In Figure 50, the corrosion is in line with the direction of wind loading, and one can see a stress increase similar to that in R1. The difference is very similar to that found with R1 since the difference in loss of material property is only 5%. A similar patter with a slight increase in stress levels as compared to R1 can be seen in R2 type of corrosion.

Figure 51 is when R2 type of corrosion patch is defined parallel to the vertical plane of the arm and perpendicular to the direction of loading. Due to increased weakness of the material one can see the stresses increasing and moving out laterally toward the area of defect.

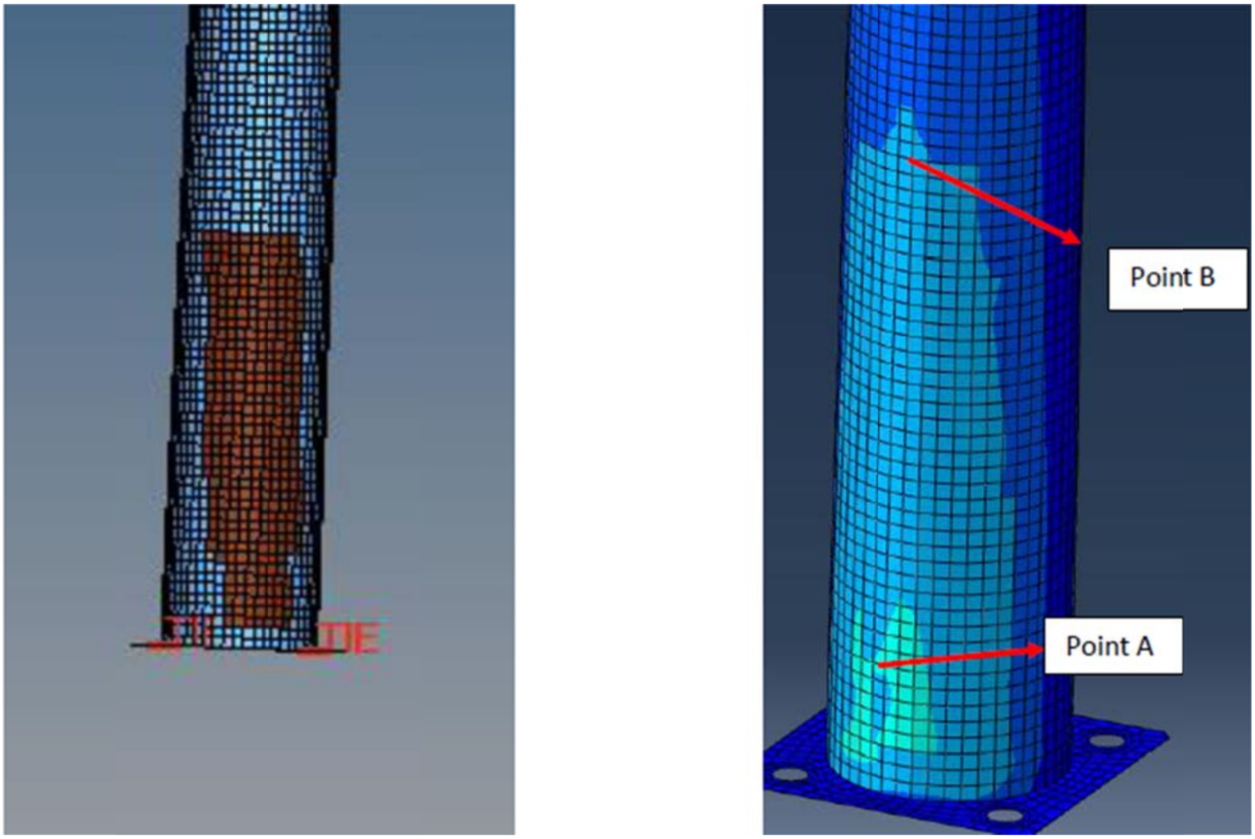

Figure 51. Perpendicular loading: R2 corrosion (left); stress contour (right).

R3 Corrosion

Figure 51 shows a major level of corrosion. The area of defect of this R3 type of corrosion is significantly more as compared to R2 type of corrosion. The total loss of material thickness is 35%, as discussed in Chapter 4.

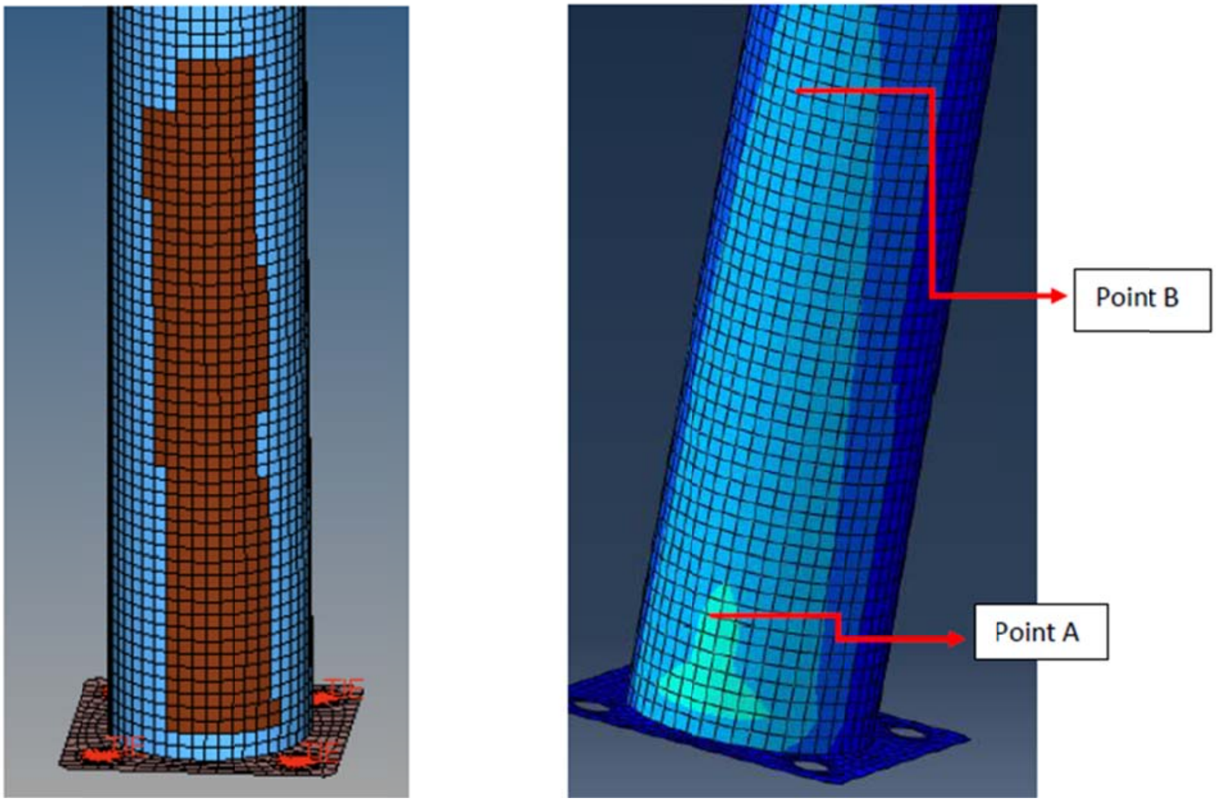

Figure 52. R3 corrosion patch (left); R3 stress contour (right).

The increase in stress is shown in Figure 52, which is for corrosion in line with the direction of wind loading. The stress levels and the area affected by higher stress concentrations are more as compared to the previous levels of corrosion.

Figure 52 is also of R3 type of corrosion but when the patch is defined parallel to the vertical plane of the arm and perpendicular to the direction of wind loading.

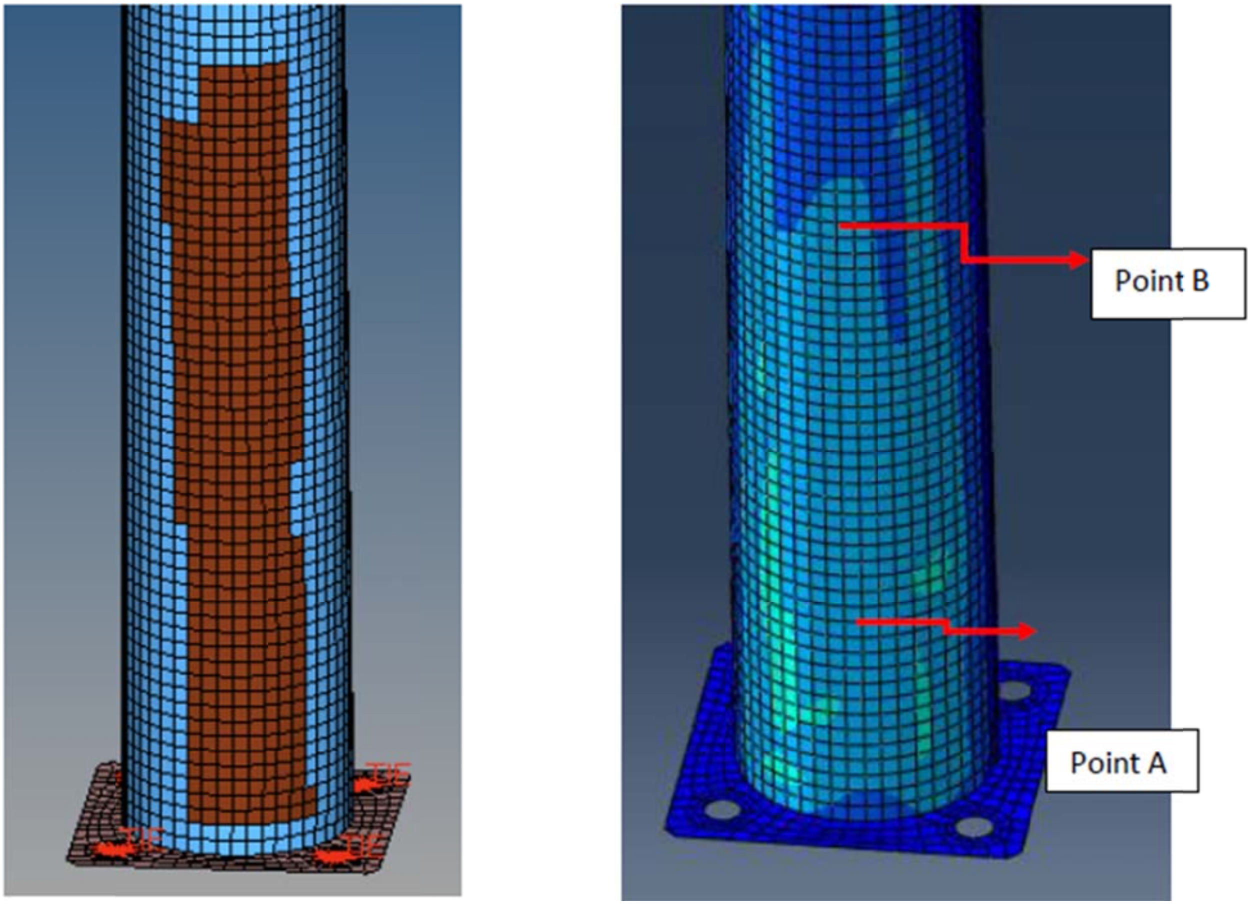

Figure 53. Perpendicularly applied R3 corrosion patch (left); R3 stress contour (right).

In this figure one can clearly see how the increased level of stresses is progressing laterally toward the area of defect. The light blue patch is distributed across the base of the pole extending towards the area where corrosion has been defined. The green patch which earlier could be seen at the center with a peak is now scattered and moving towards the defined defected area.

R4 Corrosion

This is the last level of corrosion. The area of defect is significantly high with a total loss of material and thickness to be 65% as shown in Figure 54.

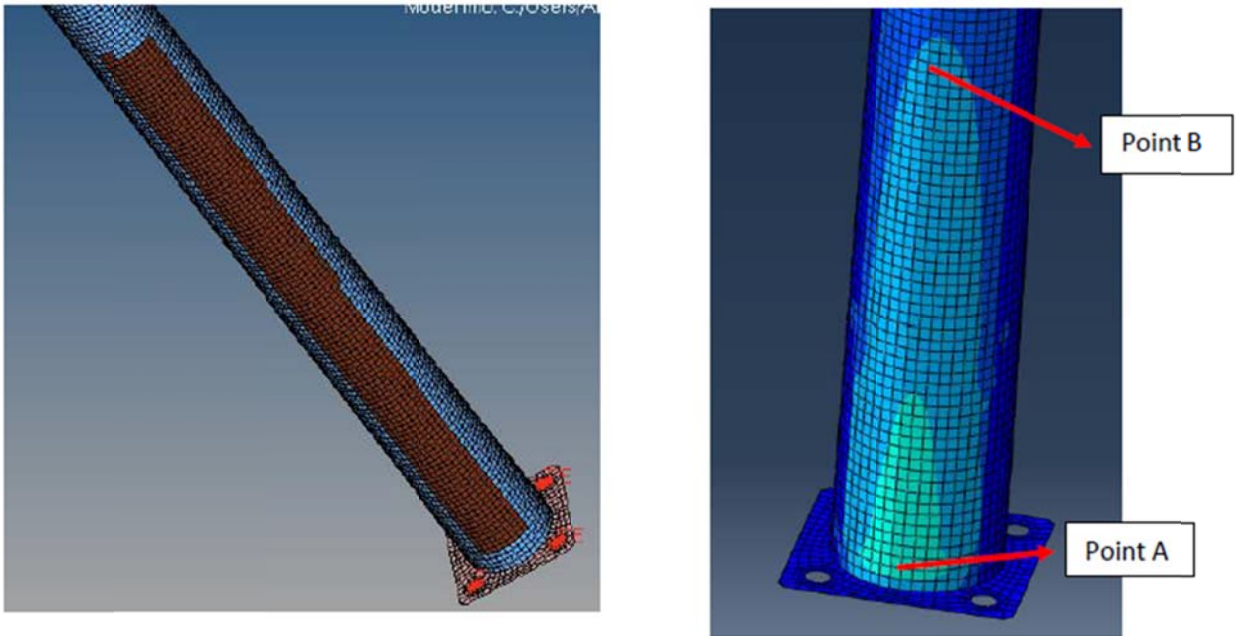

Figure 54. R4 corrosion (left); R4 stress contour (right).

Figure 54 of stress contour shows the increased level of stresses when the corrosion is parallel to the direction of wind loading. The area affected by higher stresses is now much greater as compared to that in R1 corrosion which can be seen by comparing the stress contours due to R1 and R4 (Figure 49 and Figure 54).

Collision Damage

Figure 55 shows a small impact from a vehicle. This shows small dent formations and undulations at the bottom of the pole. One should note that one of the dents modeled here has a slight edge to it, as was typical from the inspection data. In the stress analysis it could be seen that this dent showed a very high level of stress concentration. In fact the maximum stress now had been developed in this area. The figure shows highest stress to be 26960 psi which is more than the earlier computed 23810 psi, which was at the connection between arm and the pole.

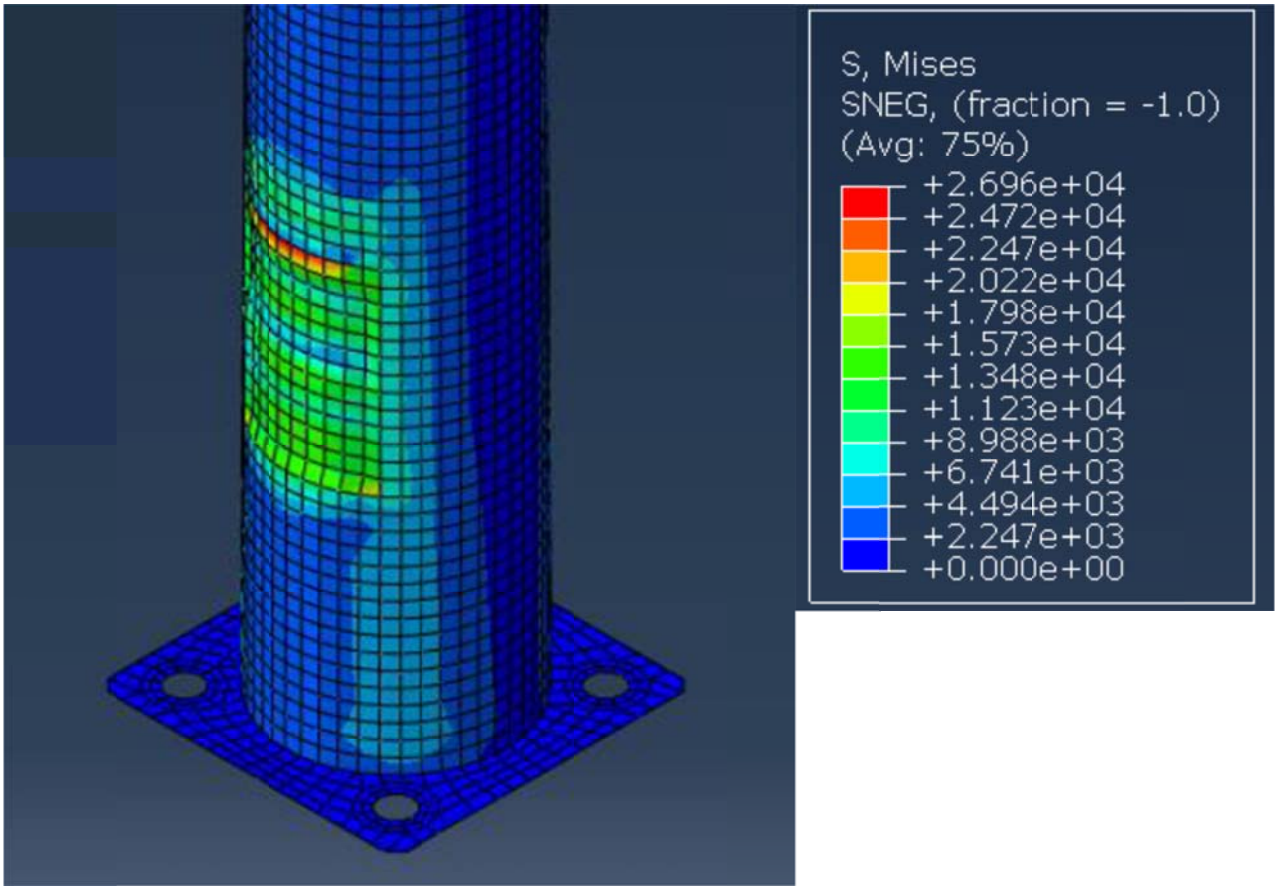

Figure 55. Collision contour by stress.

Figure 56 shows the value of stress if the earlier computed 2.65lbs of load is applied. The maximum stress at that area is computes to be 68890 psi which is 68.89 ksi > 65 ksi which is more than the yield stress, hence the structure will fail at that load. Although this is not a large difference, it is of significance because the maximum stress is now being generated at the defect unlike in corrosion. New max load is then calculated to be 2.45lbs. From this the wind pressure is calculated to be 17640 psf. Following this Wind importance factor is calculated to be 2.1 > 1.15. This gave the return period to be greater than 100 years.

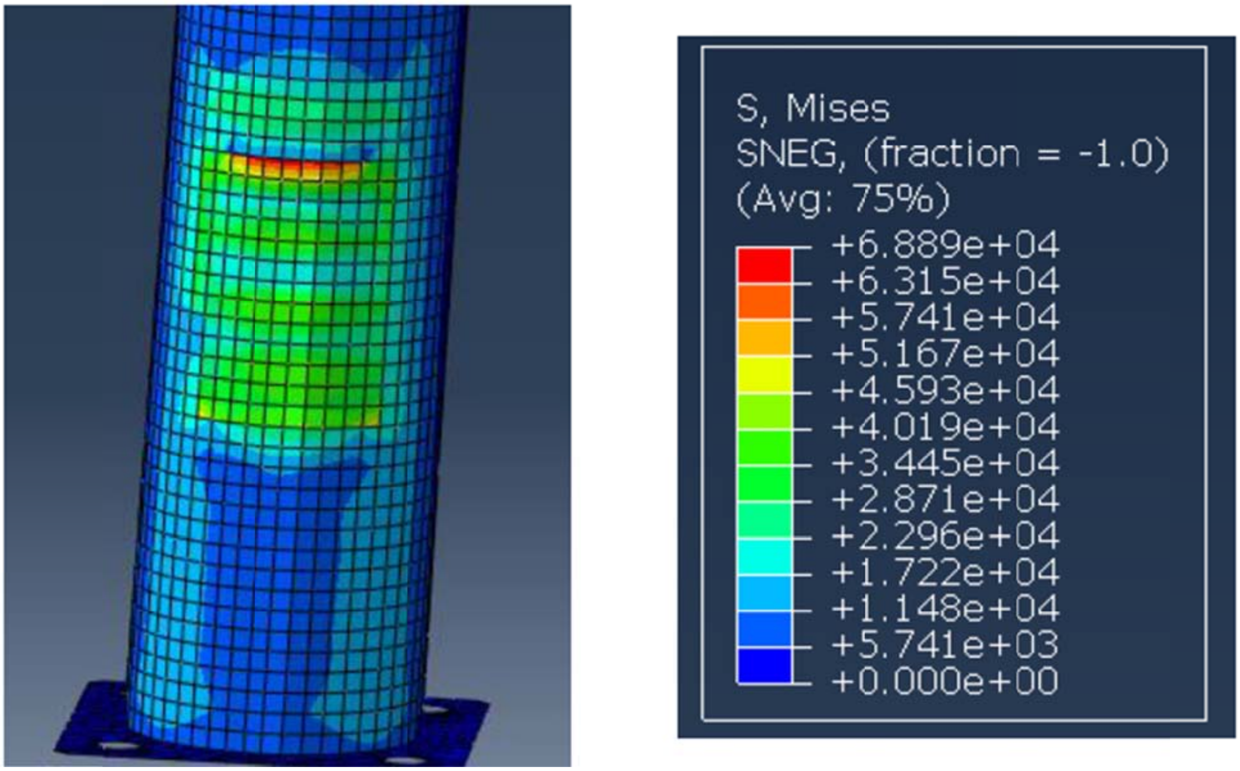

Figure 56. Low collision contour by stress.

In Figure 57, one can see a moderate level of collision damage. The penetration is more and the area of damage is more. The stress analysis shows an increased stress concentration at the edges of the affected area. Sharper edges have higher stress concentrations.

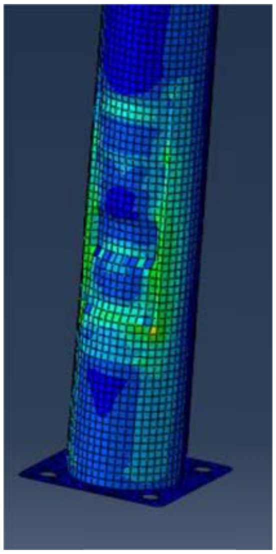

Figure 57. Moderate collision contour

Figure 58 is an image of the highest level of collision damage. The finite element analysis shows again a stress concentration development at the affected area.

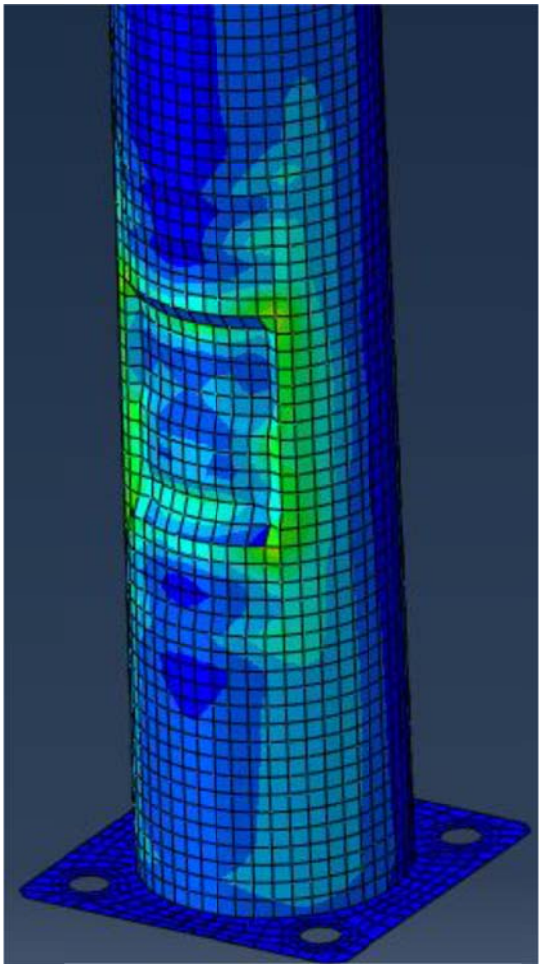

Figure 58. High collision contour

Missing Bolts

Eight iterations were run for analysis of missing bolts. The center bolt was kept and side bolts were removed one by one. There was increase in stress concentration due to absence of the bolts. Then the center bolt was also removed and then the side bolts were removed one by one. One can see increase in stress concentration due to the missing bolts. Although the stresses are low due to presence of the welding connection, which helps in load transfer, there is an increase in stress level when compared to the case of all bolts being present.

Figure 59 below shows the side bolts and the center bolts. This figure also shows the von Mises stress at the end of removing all bolts but one side bolt. 25250 psi now computed is more than earlier computed stress of 23810 psi.

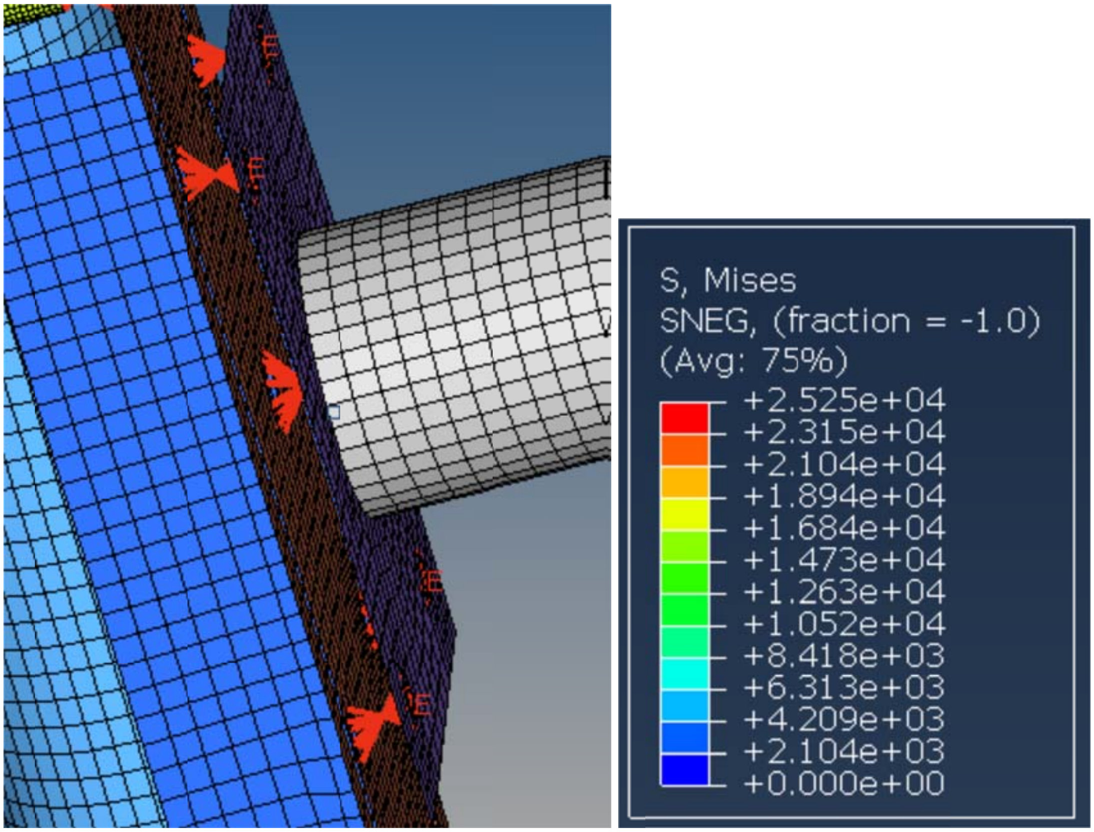

Figure 59. Simulated bolts.

Additional Load Cases

Following the above analysis, 3 more loads were added to the model. First is the gravity load, acting downwards in the negative y-direction. Second is the self-weight of 60lbs each for the signal heads acting downwards in negative y-direction. Finally, the wind load of 1248lbs acting at each point where the signal heads are attached to the arm in negative z-direction. The Following results were generated for this new model.

Base design

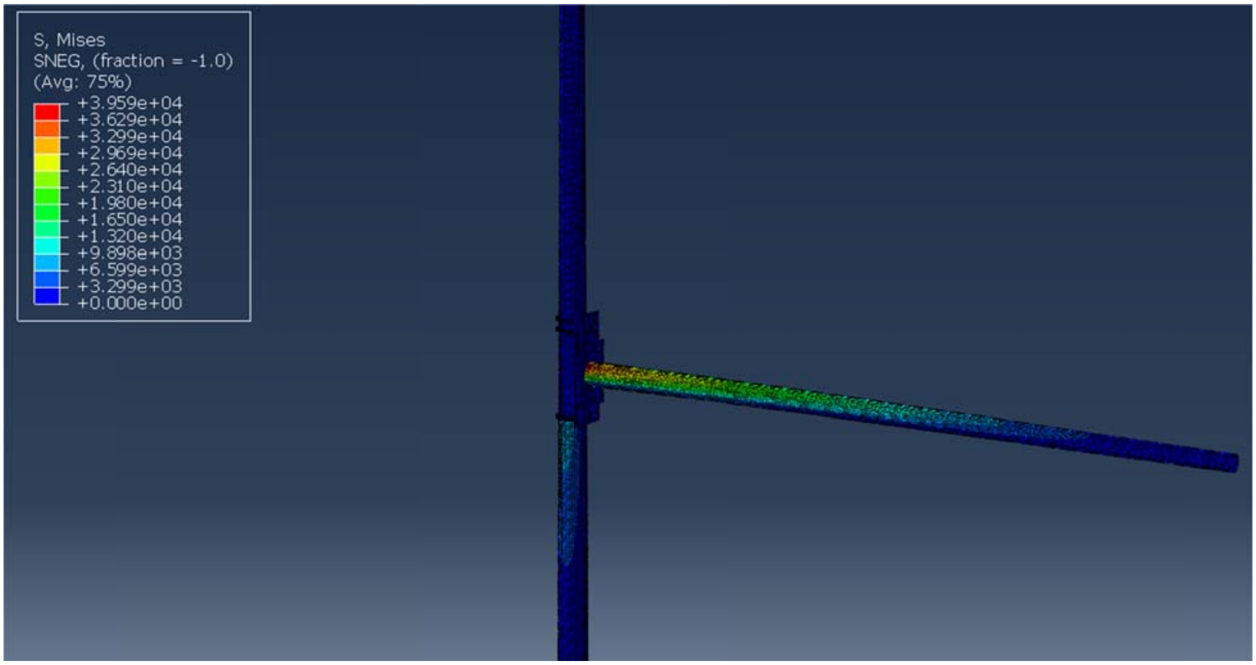

Figure 60. Base design contour stresses.

In Figure 60, the stress contour of the base design can be seen for the new model. The legend shows a maximum stress value of 39.5ksi. It can be interpreted when compared to the old analysis that addition of the 3 load cases increased the stresses developed significantly. For this base design the maximum allowable load was computed to be 2.3lbs and 2870lbs (signal head). The maximum allowable load was computed by trial and error. The load was slowly increased and the maximum stress was checked after the analysis. This was repeated until the maximum stress developed, reached close to the yield stress value of 65ksi. Figure 59 shows the value of stress after the load was slowly increased for base design to ultimately reach 2.3lbs and 2870lbs (signal head). So the maximum stress after the analysis of the increased load is 64ksi which is close to yield value of 65ksi. As a result, the wind speed was calculated to be 129mph.

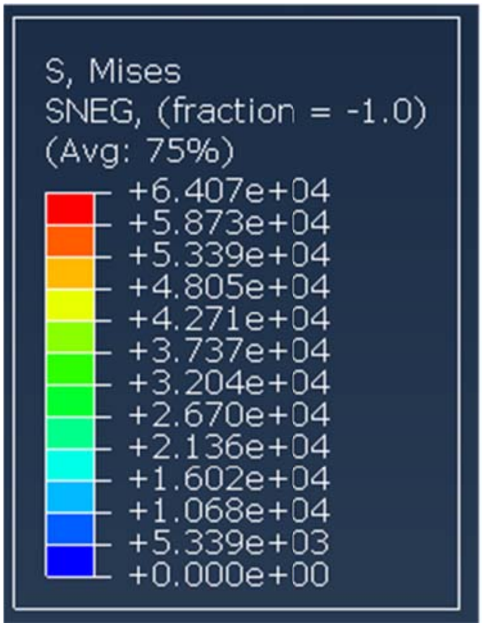

Figure 61. Maximum stress for base design.

Stress Contour plots for the following defects are same as the base design. This means that the stress pattern is similar as that of the base design with changes in maximum stress values. Therefore, the stress value legends for each case is provided with red color showing the maximum value and blue color showing the minimum value of stresses.

R1 Corrosion

Figure 62 and Figure 63 show the maximum stress values of 46.5ksi and 46.7ksi for R1 corrosion, when applied perpendicular and parallel to the vertical plane of the arm respectively. Taking the average to be 46.6ksi, the maximum allowable load was computed to be 1.9lbs and 2371lbs (signal heads). As a result, the wind speed was calculated to be 117mph.

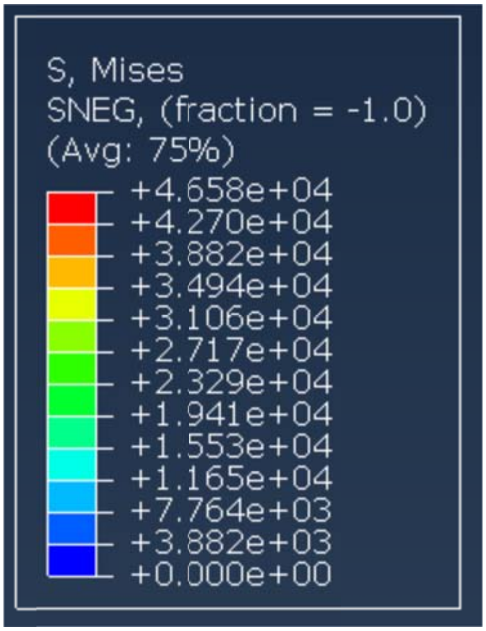

Figure 62. Maximum stress for R1 corrosion (perpendicular loading).

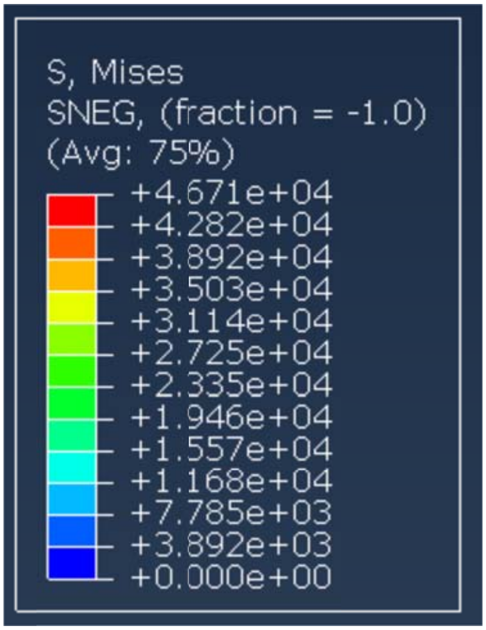

Figure 63. Maximum stress for R1 corrosion (parallel loading).

R2 Corrosion

Figure 64 and Figure 65 show the maximum stress values of 48.6ksi and 48.8ksi for R2 corrosion, when applied perpendicular and parallel to the vertical plane of the arm respectively.

Taking the average to be 48.7ksi, the maximum allowable load was computed to be 1.8lbs and 2246lbs (signal heads). As a result, the wind speed was calculated to be 114mph.

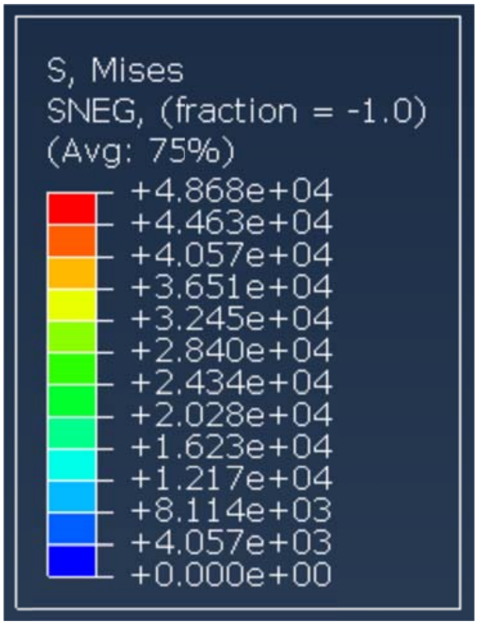

Figure 64. Maximum stress for R2 corrosion (perpendicular loading).

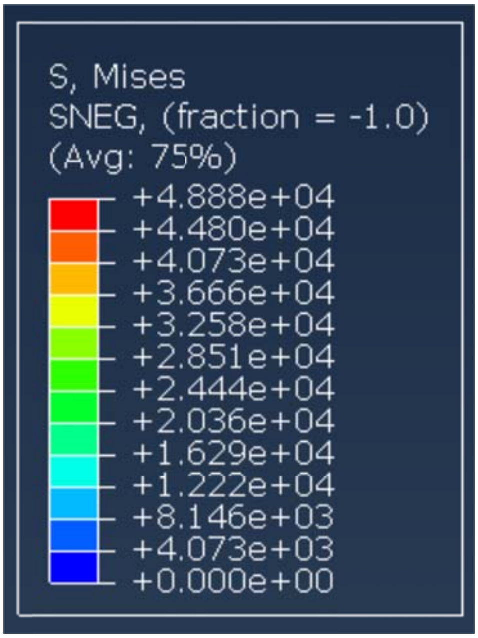

Figure 65. Maximum stress for R2 corrosion (parallel loading).

R3 Corrosion

Figure 66 and Figure 67 show the maximum stress values of 48.6ksi and 49ksi for R3 corrosion, when applied perpendicular and parallel to the vertical plane of the arm respectively. Taking the average to be 48.8ksi, the maximum allowable load was computed to be 1.8lbs and 2246lbs (signal heads). As a result, the wind speed was calculated to be 114mph.

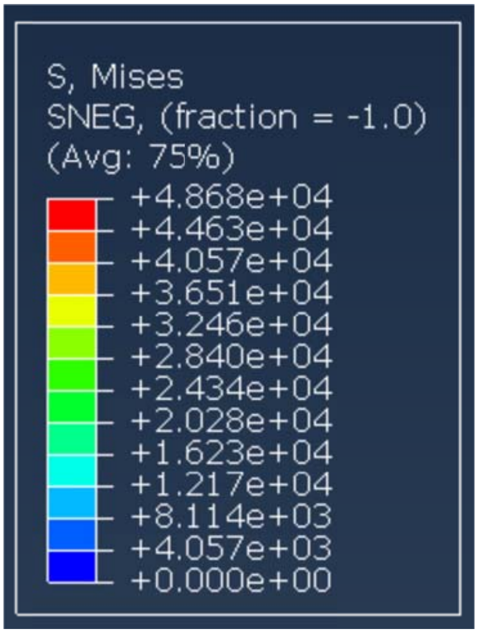

Figure 66. Maximum stress for R3 corrosion (perpendicular loading).

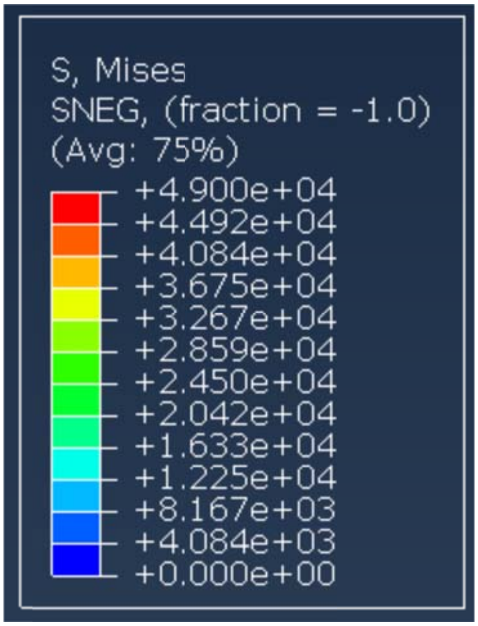

Figure 67. Maximum stress for R3 corrosion (parallel loading).

R4 Corrosion

Figure 68 and Figure 69 show the maximum stress values of 49.4ksi and 49.6ksi for R4 corrosion, when applied perpendicular and parallel to the vertical plane of the arm respectively. Taking the average to be 49.5ksi, the maximum allowable load was computed to be 1.7lbs and 2121lbs (signal heads). As a result, the wind speed was calculated to be 110mph.

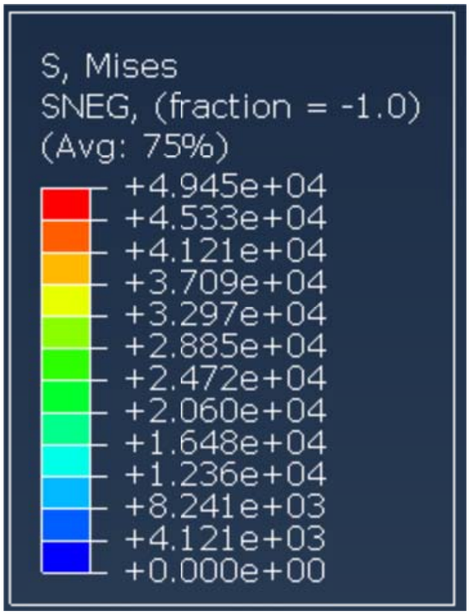

Figure 68. Maximum stress for R4 corrosion (perpendicular loading).

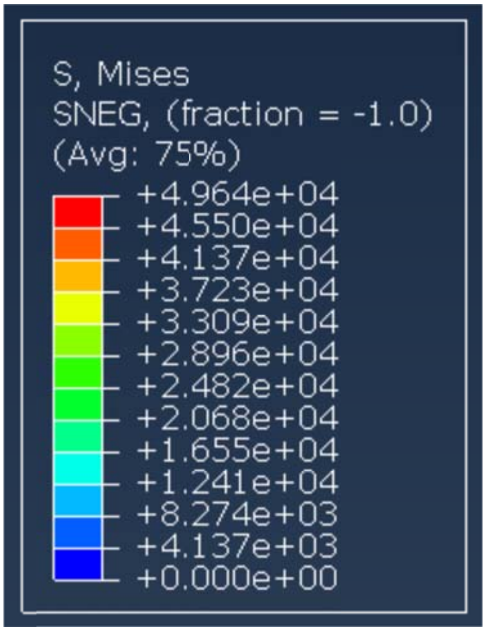

Figure 69. Maximum stress for R4 corrosion (parallel loading).

As the model with additional load cases was analyzed for corrosion, the maximum stresses were still seen at the connection joint between the pole and the arm. Unlike the previous model without the additional load cases, there is an increase in maximum stresses as the corrosion level increases when compared to the base design. To quantify this, the analysis results for the previous model show the maximum stress value to be 23ksi at the connection joint. This remained constant even after the 4 levels of corrosions were defined. Whereas, after adding the additional load cases, the maximum stress at base design was computed to be 39.5ksi. This increased to 49.6ksi for R4 corrosion which is the worst cases scenario. Hence it can be concluded, that after adding the additional load cases, which is more close to the realistic situation, corrosion plays a role in development of high stress concentrations. Although the maximum stress value is not seen at the defected area, the loss of section due to the presence of corrosion results in increase of stress at the connection joint. This implies an increase in fatigue at the joint.

Collision Damage

Figure 70 shows the maximum stress values of 49ksi, 46.6ksi and 47.1ksi for low, moderate, and high level of collision damages respectively. Considering the worst case scenario, that is 49ksi, the maximum allowable load was computed to be 1.8lbs and 2246lbs (signal heads). As a result, the wind speed was calculated to be 114mph.

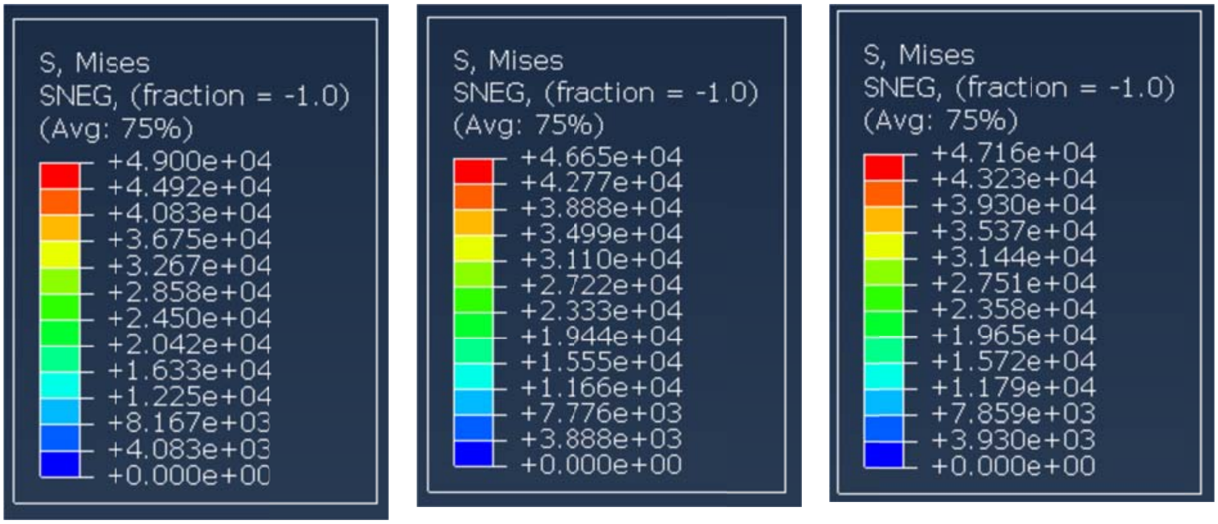

Figure 70. Maximum stress contours for low, moderate, and high collision damages from left to right, respectively.

After the analysis of the current model for collision damages, it was concluded that in the case of low collision unlike in the previous model, the location of maximum stress changed from the dent at the area of defect to the connection between the arm and the pole. Also, it can be seen that the maximum stress for low collision is still greater when compared to the moderate and high collision damage. This helps to prove that the edge formation or dents still plays a role in weakening the structure more, as compared to a smooth curve formation on impact.

Missing Bolts

Figure 71 shows the maximum stress values of 47.7ksi for missing all bolts but one at the connection between arm flange plate and arm pole plate. This is the worst case scenario for missing bolts. The maximum allowable load was computed to be 1.9lbs and 2371lbs (signal heads). As a result, the wind speed was calculated to be 117mph.

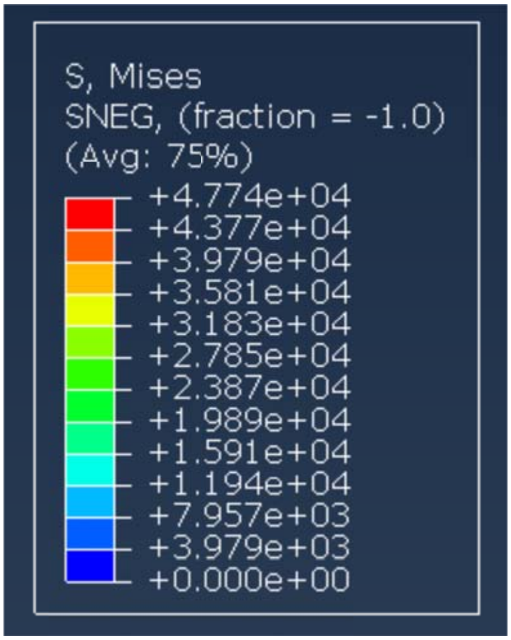

Figure 71. Maximum stress values for missing all bolts but one.

Missing bolts leads to increase in the maximum stress concentration at the connection. When compared to the base design, the stress value changed from 39.5ksi to 47.7 ksi.

Conclusions

Corrosion

Out of 1738 defective Mast-arms and a total of 5119 Mast-arms that were inspected in Colorado, 949 Mast-arms showed presence of corrosion ranging from R1 to R4 level of damage. Regarding Corrosion one can conclude from the finite element analysis of the Mast-arm structures that although the stresses developed due to these defects do not go over the yield stress, still the loss of material makes the Mast-arm prone to a higher chance of failure compared to the base design. The reason for this being fatigue. From iterations the maximum load and hence the wind pressure was computed. From this the new wind speed was estimated. The wind speed at which the structure will fail ranges between 110mph and 117mph. According to AASHTO guidelines the signal structures are designed for 25 years recurrence loading, which concludes that the risk is moderately high [35]. This needs to be studied further under fatigue.

Also as we increase the rate of corrosion from R1 to R4, the level and area of stress concentration also increases. Mast-arms with R4 level of corrosion are concluded to be most risky among all the 4 level of corrosions and should be repaired.

Collision

From Chapter 4, it was reported that out that 325 Mast-arms out of 1738 defective Mast-arms suffer from collision damage which gave around 18.7% of the total defective Mast-arms. Also it can be deduced that 325 out of total 5119 Mast-arms inspected in the state of Colorado suffer from this type of defect. This will help in estimating the number of Mast-arm with risk of failure in the state of Colorado. From the analysis, it is very clear that even low rate of damage or denting can lead to development of higher stress concentration. If the collision is smooth, which means that the dent due to collision is a smooth curve, then the stresses would be low and safety of the structure would not be affected by much and the risk factor will be very low. This changed when the new model was analyzed which further considered three more load cases as described in Appendix A. From the inspection data, however, it has been observed that in general the collision damage is not smooth and can lead to formation of edges that can very quickly develop high stress concentrations. The important fact to be noticed is that the presence of dents and edges lead to increase in maximum stress, which is visible when low collision is compared to moderate and high collision damages. Edge formation was defined for low collision damage. This implies that in the case of collision, the failure of the structure is driven by the damage to the structure. The presence of multiple sharp edges leads to higher stresses and hence reducing the allowable maximum stress. Therefore if the number of sharp edges increases, whether it be in low level of collision, moderate level or high level of collision, the stresses can certainly go beyond the yield point of the material and lead to structural failure. Hence this type of defect that is collision damage increases the risk of Mast-arm structure, and when discovered during inspection warrants immediate measures to repair these damages.

Cracks

Finite Element analysis on this type of defect was not performed since it would have required research into fatigue and crack analysis and a forensic analysis of the crack in order to come up with significant results. Such a study was out of the scope and time of this research.

Missing Bolts

There are two particular regions where the nuts and bolts come into play, one is the base of the structure and other is the connection between the arm and the pole. From the S-614-40A [56] drawings, one could see that apart from the anchor bolts, the base of the plate also has another foundation going into the ground that holds the base plate, which is welded to the pole. From structural analysis, it was found that missing nuts also pose threat to the stability of the structure.

Missing bolts on the arm lead to increase in stresses in the weld of the arm and the plate and reduce the area from where the load can travel to the pole and then into the ground. This leads to increase in the stress concentration at the weld. There was a total increase of around 5900 psi stress from the situation of all bolts to the point of single bolt.

Risk of Failure

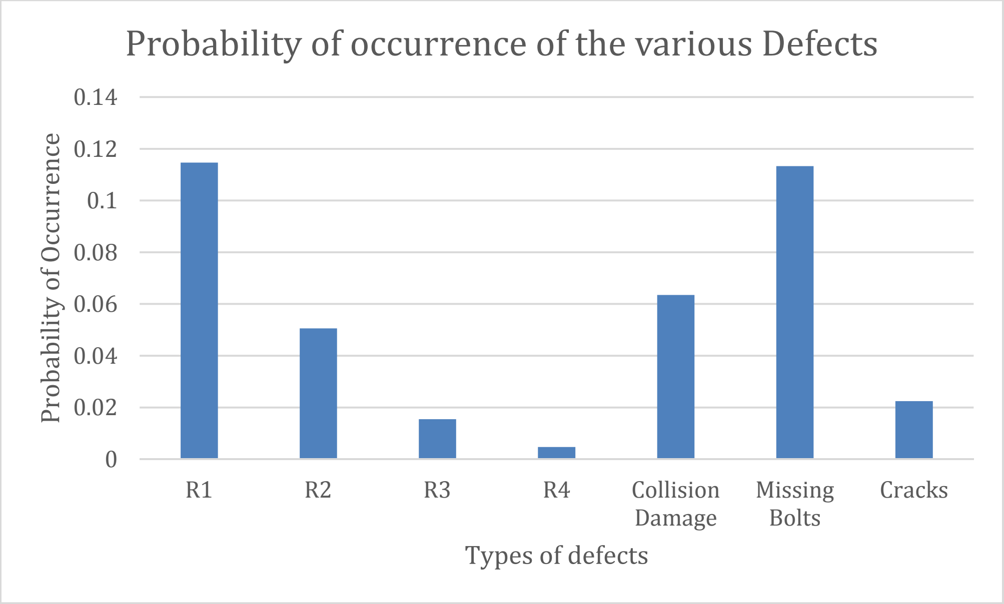

Figure 72. Probability of occurrence of various kinds of defects

Figure 72 shows the probability of occurrence of the various kinds of defects. Probability of R1 corrosion and Missing bolts is the highest followed by collision damages and probability of occurrence of R4 corrosion is the least. For example if 100 Mast-arms were inspected in state of Colorado then there is probability of presence of R1 corrosion in 11 out of those 100 Mast-arms.

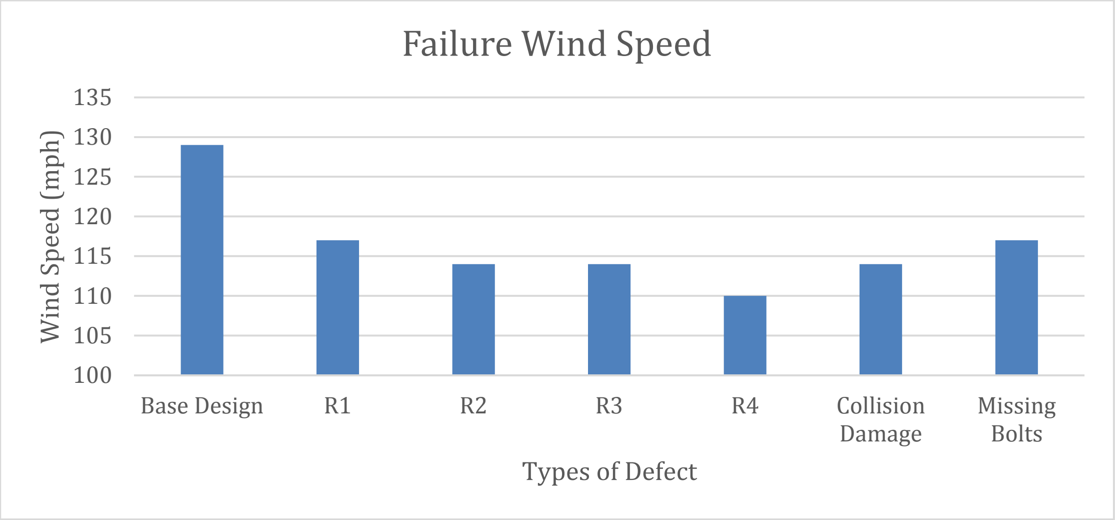

Figure 73. Wind speed of failure for various defects.

Figure 73 shows the failure wind speed in mph for base design and all types of defects except damage due to cracks, since they were not analyzed. This means that at their respective failure wind speeds, the defects and base design will reach the yield stress of the material and will fail.

Table 21. Maximum stress under two load cases.

	Load Case 1	Load Case 2
R1	23.8ksi	46.7ksi
R2	23.8ksi	48.8ksi
R3	23.8ksi	49ksi
R4	23.8ksi	49.6ksi
Collision Damage	26.9ksi	49ksi
Missing Bolts	25.2ksi	47.7ksi
Base Design	23.8ksi	39.5ksi

The difference in maximum stresses for the structure were analyzed under two load cases, Load Case 1 is the distributed wind load alone and Load Case 2 is distributed wind load, wind load due to signal heads, gravity load of the whole structure and self-weight load due to the signal heads is given in Table 21.

Table 22 includes the maximum allowable load (distributed wind load) for all the types of defects under both the load cases as defined above.

Table 22. Maximum allowable load under two load cases

	Load Case 1	Load Case 2
R1	2.65lbs	1.9lbs
R2	2.65lbs	1.8lbs
R3	2.65lbs	1.8lbs
R4	2.65lbs	1.7lbs
Collision Damage	2.45lbs	1.8lbs
Missing Bolts	2.49lbs	1.9lbs
Base Design	2.65lbs	2.3lbs

Annual Probability and MRI

Taking the risk category as 1 [57] since there is no risk to life, and exposure category to be C, the design wind speed for 3-second gust can be determined to be 105mph. For 105mph, probability of exceedance for 50 years is computed to be 15%. Thus the annual probability of exceedance is computed to be 0.0033. This gives a Mean Recurrence Interval (MRI) of 300 years. From Vickery et al., 2009 [57], a relation between the failure wind speed to the mean return period can be formulated. Figure 73 shows a relation between the wind speed and MRI.

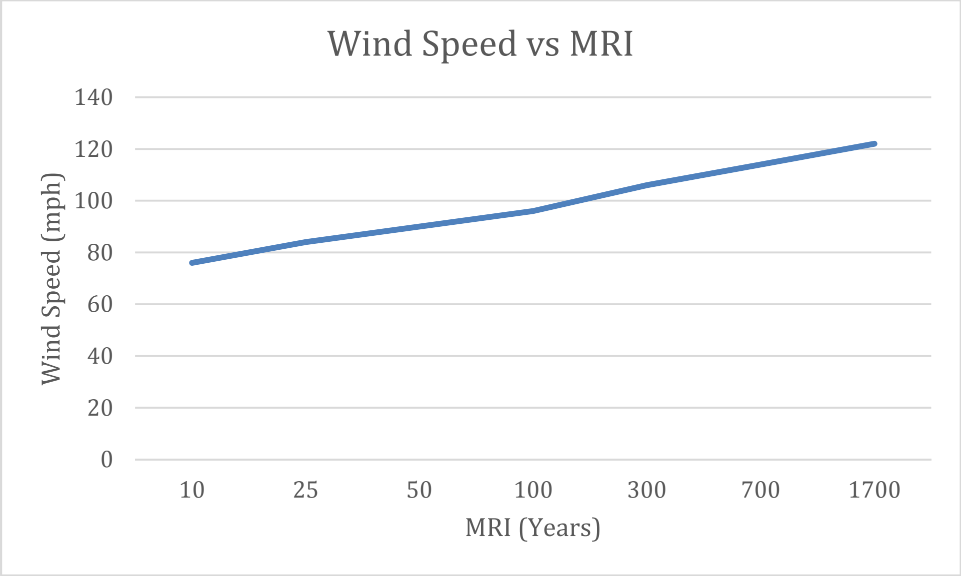

Figure 74. Wind speed vs. mean.

Based on Figure 74, the return period for the failure wind speed can be interpolated. Table 23 shows the return period for the failure wind speed.

Table 23. Return period for failure wind speed and annual probability of exceedance.

	Speed (Mph)	MRI (Years)	Annual Exceedance Probability
Base Design	129	1800	0.000588
R1	117	1300	0.0012
R2	114	700	0.00143
R3	114	700	0.00143
R4	110	450	0.00235
Collision Damage	114	700	0.00143
Missing Bolts	117	1300	0.0012
Colorado Design	105	300	0.0033

Limitations

The finite element analysis did not consider combinations of various defects, such as combination of R4 type of corrosion with loose bolts, and of corrosion with collision. That may lead to new findings of increased stress concentrations, which could indicate failure under lower loads than when the two loadings are considered separately. Secondly, the corrosion studies would benefit from fatigue analysis. Fatigue analysis would reduce the allowable maximum stress and hence reduce the return period giving corrosion damage a high risk factor. Finally the analysis of cracks as discussed above should be investigated and analyzed further.

APPENDIX C - IRIS DATABASE INFORMATION

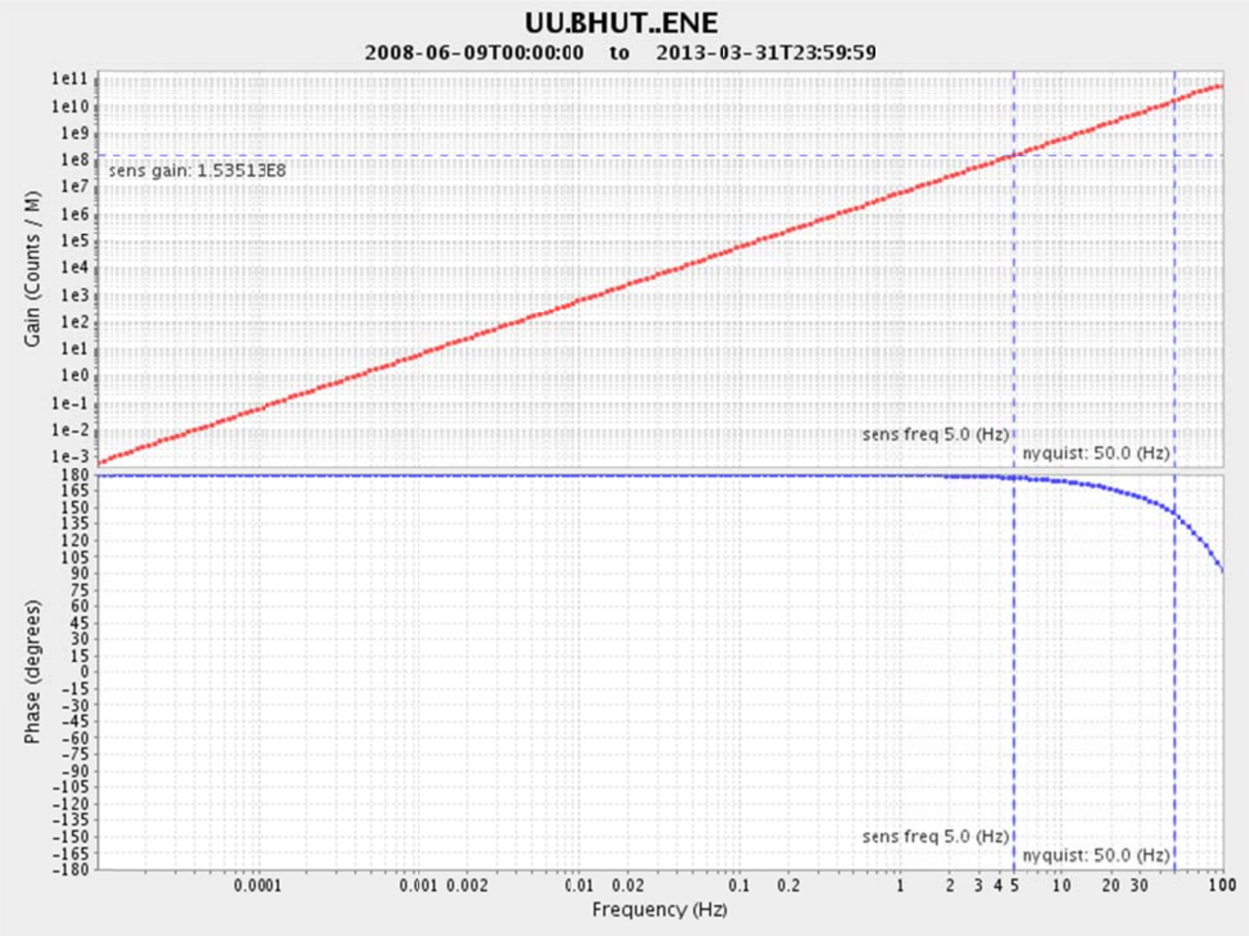

Figure 75. Frequency and phase response plot for Beaver High Channel ENE. Figure reproduced from IRIS [53].

AASHTO Specifications

Article 4.7.4.4 Minimum Support Length Requirements [36]

Support lengths must be

$N = (8 + 0.02L + 0.08H)(1+0.000125S^2)$

Where:

N = Minimum support length measured normal to the centerline of the bearing (in.)

L = Length of the bridge deck to the adjacent expansion joint, or to the end of the bridge deck (ft.)

H = For abutments, average height of columns supporting the bridge deck from the abutment to the next expansion joint (ft.)

S = Skew of support measured from line normal to span (º)

4.7.4.5 P-Δ Requirements [36]

The displacement of any column or pier in the longitudinal or transverse direction is calculated by the following equations:

$$\Delta P_u < 0.25\Phi M_n$$

In which:

$$\Delta = R_d \Delta_e$$

If T < 1.25Ts, then:

$$R_d = (1-R^{-1})1.25\mathrm{T_s}/\mathrm{T} + R^{-1}$$

If T ≥ 1.25Ts, then:

$$R_d = 1$$

Where:

Δ = Displacement of the point of contraflecture in the column or pier relative to the point of fixity for the foundation (in.)

Δ_e = Displacement calculated from elastic seismic analysis (in.)

T = Period of fundamental mode of vibration (sec.)

T_s = Reference period specified in Article 3.10.4.2

R = R-factor specified in Article 3.10.7

P_u = Axial load on column or pier (kip)

Φ = Flexural resistance factor for column specified in Article 5.10.11.4.1b

M_n = Nominal flexural strength of column or pier calculated at the axial load on the column or pier (kip-ft)

APPENDIX D - BRIDGE MODEL VALIDATION

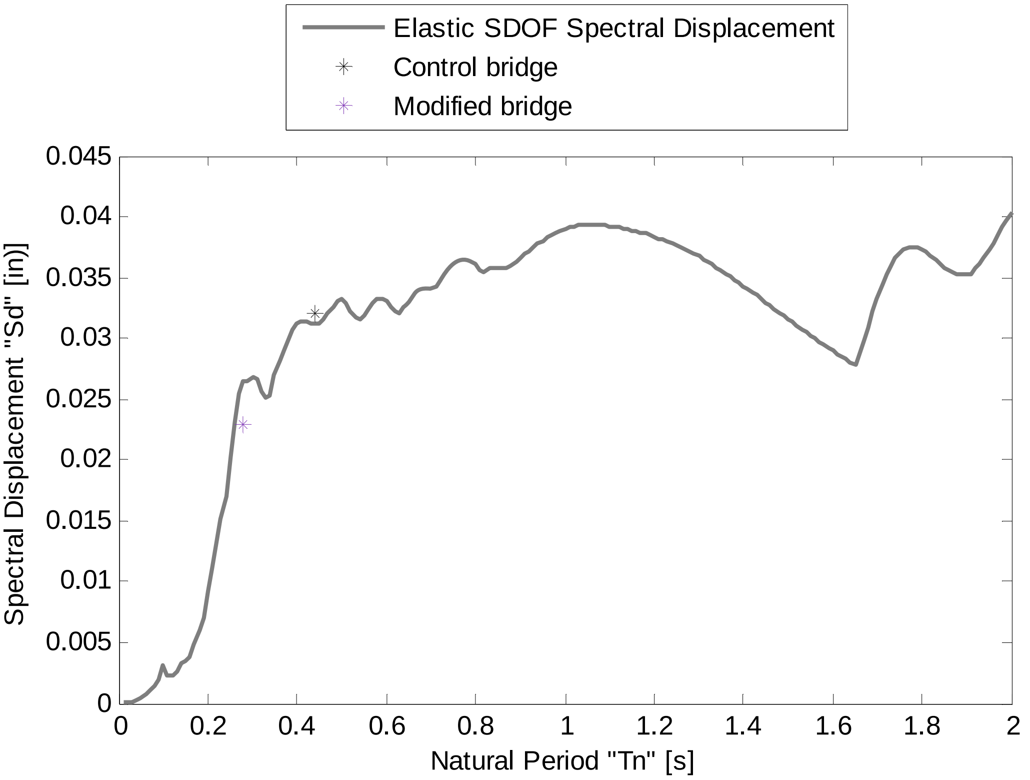

Figure 76. Longitudinal displacements due to excitation by the Utah ground motion compared to the elastic spectral displacement results from a single degree of freedom analysis.

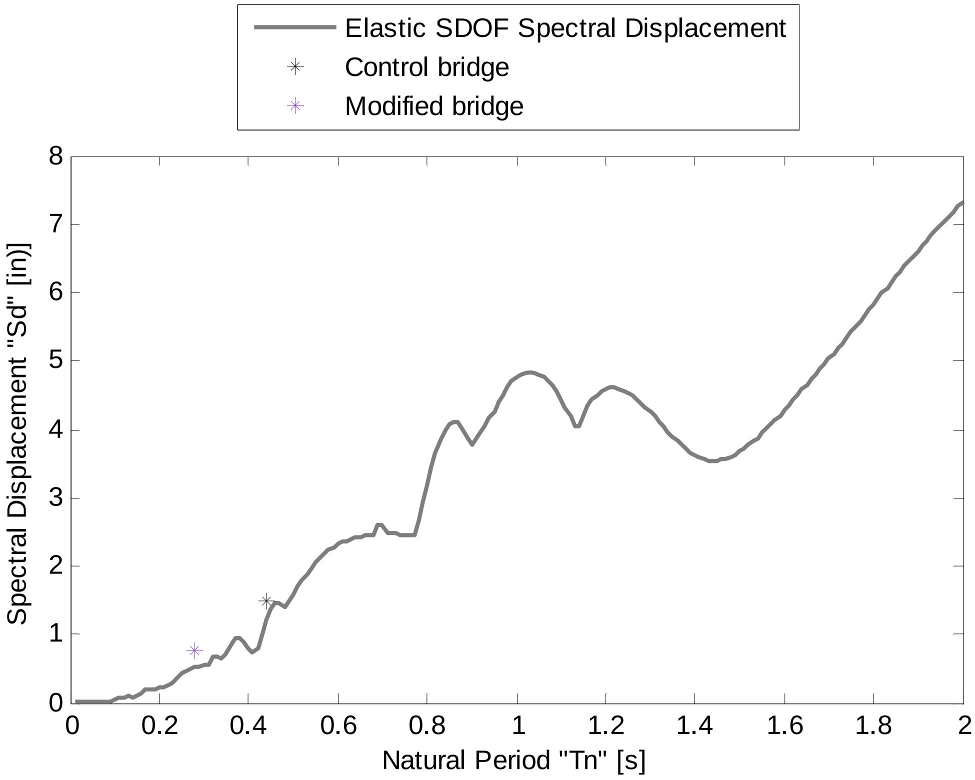

Figure 77. Longitudinal displacements due to excitation by the El Centro ground motion compared to the elastic spectral displacement results from a single degree of freedom analysis.

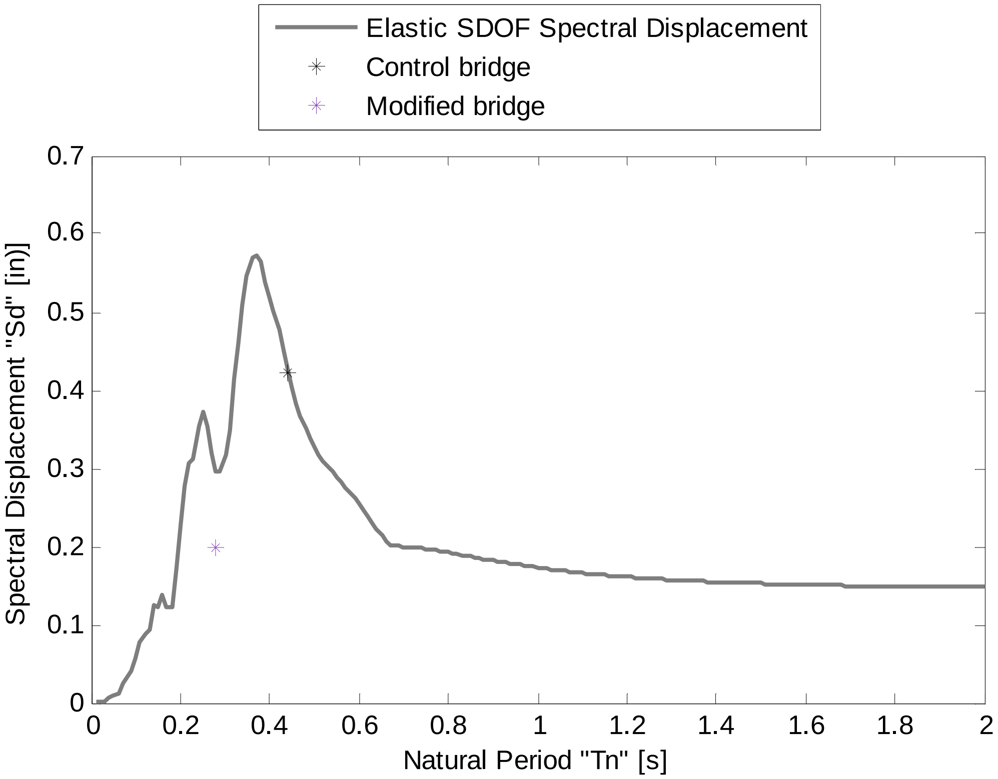

Figure 78. Longitudinal displacements due to excitation by the stochastic ground motion compared to the elastic spectral displacement results from a single degree of freedom analysis.

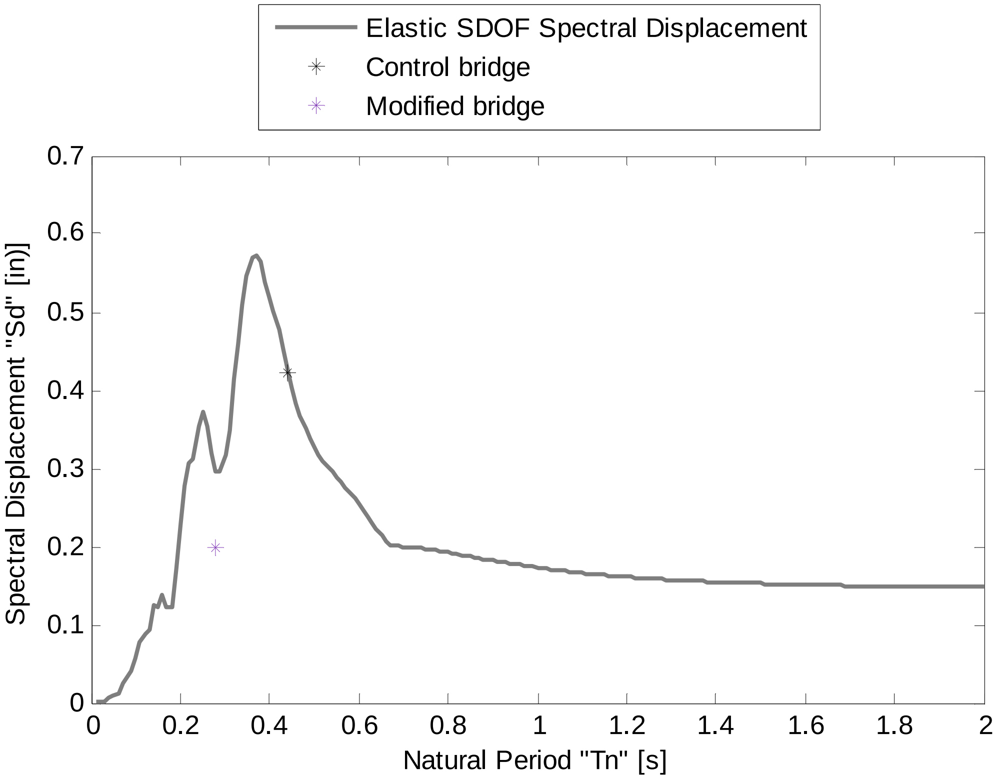

Figure 78. Longitudinal displacements due to excitation by the stochastic ground motion compared to the elastic spectral displacement results from a single degree of freedom analysis.