Performance Evaluation of Damaged Integrated Girder Bridges

Morgan State University
The Pennsylvania State University
University of Maryland
University of Virginia
Virginia Polytechnic Institute & State University
West Virginia University

The Pennsylvania State University
The Thomas D. Larson Pennsylvania Transportation Institute
Transportation Research Building ❖ University Park, PA 16802-4710
Phone: 814-865-1891 ❖ Fax: 814-863-3707
www.mautc.psu.edu

Research Report

A Performance-Based Evaluation Framework for Maintenance/Preservation of In-service Highway Bridges Based on Damage-Integrated System-Level Behavior

Submitted to

Mid-Atlantic Universities Transportation Center

and

Center for Transportation Studies
The University of Virginia, Charlottesville

Dr. Devin K. Harris
Dr. Amir Gheitasi
Mark Saliba

July 2015

ACKNOWLEDGMENT

The authors would like to thank Michael Brown of the Virginia Center for Transportation Innovation and Research (VCTIR) and Prasad Nallapaneni of the Virginia Department of Transportation (VDOT) for providing the data and details of the selected in-service structure. The work presented herein reflects the views of the authors and does not represent the views of the Virginia Department of Transportation. This research project was funded through Mid-Atlantic Universities Transportation Center (MAUTC).

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

The safety and condition of the national transportation infrastructure has been at the forefront of national debates in recent times due to catastrophic bridge failures occurred in the United States, but the issue has been a longstanding challenge for transportation agencies for many years as resources continue to diminish. The ASCE's 2013 report card for America's Infrastructure assigned in-service bridges a score of C^+, which reflects the extent of deteriorating conditions and deficiency of the national aging infrastructure network. Currently, transportation officials rely heavily on experienced-based practices to make decisions regarding maintenance and preservation of the bridge inventory. Several inspection methods and monitoring techniques have been developed and used by the bridge owners to monitor the in-service behavior and detect deteriorating conditions. Despite successful implementation of these methods, the lack of a rational understanding of the system-level behavior of in-service structures, especially in the presence of damage and deterioration, makes resolving this problem even more complicated. This constraint, coupled with limited resources and the vast network of existing structures in service, highlights the need to develop systematic strategies to help engineers better understand the system performance and estimate the remaining service life of these structures, while facilitating and supporting maintenance/preservation decision making process.

This research project aims to present a performance-based numerical modeling framework that can be used to evaluate the behavior and identify the failure characteristics of in-service bridge superstructures under the impact of common deteriorating mechanisms. Representative numerical models, ranging from basic levels of intact bridge components to more complicated levels of bridge systems with both intact and damaged configurations, were generated based on available experimental data in literature. Critical to this investigation is the strategy to leverage simulation techniques and appropriately integrate the effects of existing deteriorating conditions into the measure of system performance. Upon validation of the proposed simulation approach, the methodology was implemented to study the performance parameters, including ultimate capacity, redundancy, and operational safety, of representative in-service composite steel girder and prestressed concrete girder bridges under the of various damage conditions. It is expected that the developed framework will provide a first step for establishing a critical linkage between design, maintenance, and rehabilitation of highway bridges, which are uncoupled in current practices.

INTRODUCTION

An efficient and well maintained transportation infrastructure system not only serves as a core component to the economic health of the United States by providing a corridor for the transportation of goods and people (Cambridge Systematics Inc. 2010; Kavinoky 2007), but also provides a coast to coast and border to border passageway for the nation's military (Government Accountability Office 2008). The highway system, which includes both roads and bridges, has flown underneath the radar of the public opinion due to the recent tragic bridge collapses (NTSB 2008; NTSB 2013a; NTSB 2013b) that have brought the challenge associated with the operational safety of the national transportation infrastructure to the forefront of people scrutiny. A review of these failures found that they are often attributed to unforeseen events and manmade hazards such as impact, fires, or flooding and are not exclusively related to the existing conditions (Wardhana and Hadipriono 2003). Nevertheless, it is the condition states associated with deterioration that represents the greatest challenge for transportation agencies across the country.

Under the premise of rational structural design, the service lives of the bridge structures are governed by operating environment, load effects and history, and maintenance and preservation practices; with really only the last factor under the owner's influence. Today's aging highway system is plagued with a variety of condition defects, where 10% of over 600,000 bridges are classified as structurally deficient (FHWA 2013). This illustrates that strategies and resources for maintenance is an ongoing challenges for federal, state, and local governments, especially considering that many bridge are reaching or exceeding their design service lives, making rehabilitation or replacement inevitable. The essence of these challenges lies in the insufficiency of funds and manpower required to repair the deficient structures immediately and at the same time. A recent estimate provided by the Federal Highway Administration suggested that a \$20.5B annual investment in bridge infrastructure would be needed to eliminate the deficient blockage by the year of 2028, in light of the fact that only \$12.8B is being spent annually. What is needed for the preservation community is a fundamental understanding of the bridge in-service behavior (as opposed to design assumptions) and the potential impact of existing deteriorating conditions on their performance and operational safety. This comprehensive understanding would provide a vision for the responsible transportation agencies to facilitate the current decision-making processes, but also to prioritize their maintenance efforts for the structures with higher importance, damage severity, and repair urgency.

Within the most common types of structures in service, there are certain similarities in materials, geometry, and configuration, which make them serve common functionalities, but at the same time be vulnerable to specific sources of defect and deteriorations. The main types of damage and deterioration that girder-type bridge superstructures experience have been well documented in recent years (FHWA 2012). Much of the degradation often manifests in the main-load carrying elements, ranging from corrosion, section loss, and fatigue in steel components as well as cracking, rebar corrosion, spalling, and delamination in reinforced concrete members. Other mechanisms such as bridge settlement, bridge movement, frozen bearing and expansion joints, and vehicular lateral load impacts which address the overall system behavior are also common in different types of bridges. Figure 1 illustrates a representative set of commonly recognized damage mechanisms in in-service bridge structures.


Steel corrosion
Section Loss
Fatigue cracks
Concrete cracks


Concrete cracks
Corrosion/section Loss
Delamination
Concrete spall

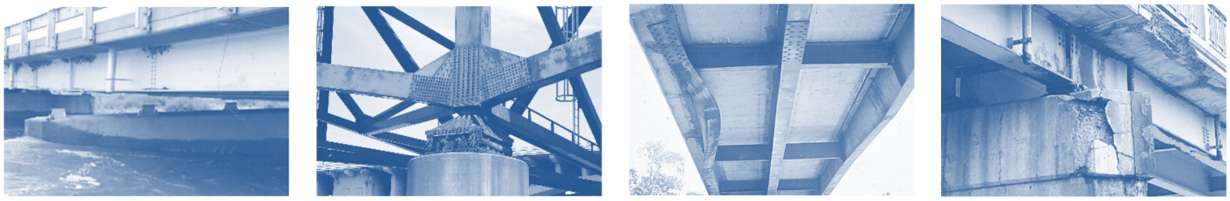

Settlement
Frozen bearing
Vehicular impact
Section loss in support

Figure 1 - Commonly recognized damage mechanisms in bridges

MONITORING AND INSPECTION OF IN-SERVICE BRIDGES

The concept of structural health monitoring (SHM), which can be described as system performance evaluation strategy for in-service structures, has come to the forefront of research community as a mean to mitigate the challenges associated with the aging highway infrastructure. Implementing this concept has the potential to provide indications of damage and even forewarning the impeding failure. Nevertheless, a comprehensive solution to the challenges described also requires integrated strategies for routine inspection, data management, result interpretation and decision support to make SHM an ongoing framework in progress. On the other hand, with the sheer volume of bridges in service in the United States, transportation officials seek a “one-size-fits-all” solution for preservation, which is a daunting task considering the wide variety of structure types, component materials, existing conditions, and operational environments under which bridges can be classified.

In general, Departments of Transportation (DOTs) attempt to maintain a constant awareness of the integrity of all in-service structures in their area of operation through biennial routine inspections. Current practices for evaluating system performance use results from the various inspection methods, which rely primarily on human evaluation, to monitor degradation over time and help provide guidance to maintenance and rehabilitation schedules. Nevertheless, as detailed and extensive as these inspection practices can be, they deliver information on the status of localized features in the structure, but they do not have the capability of determining the effects of collected features on the overall behavior and performance of the system. With the lack of a fundamental understanding of the influence of the existing damage mechanisms on the overall system performance, bridge engineers are tasked with making a subjective judgement on the implications without the science to support their decision.

PROBLEM TO ADDRESS

In recent years, the industry has attempted to integrate some of the research findings and advances in novel technologies in the areas of monitoring and inspection into practice by developing long-term bridge monitoring systems. Most of these applications have been deployed on high profile structures; however, these applications have been met with skepticism by transportation agencies mainly because of the cost of application related to the size of the inventory, the potential for large amounts of data and the man-power and skills required to interpret the results, as well as the long-term durability and power requirements of the instrumented tools and devices. For SHM to gain traction within the transportation community, a number of questions still need to be answered, including: 1) what does the data collected mean?; How can the data be used for decision making?; 3) what impact does the collected damage and deterioration mechanisms have on the performance of the monitored structure?; and 4) how can the collected data be effectively managed over the structure’s lifetime?

Successful implementation of a SHM framework to evaluate the operational safety of routine bridges with common functionalities not only requires knowledge of the current condition state of the structures, but also a comprehensive understanding of the impact of detected damage mechanisms on the overall system performance. Without this level of knowledge, engineers within the preservation community are left to make subjective judgements on the most appropriate maintenance practices, which most often are overly conservative due to undermining the system-level behavior and its capability to remain in service in the presence of damage. Recent advances in non-destructive evaluation and testing (Lynch and Loh 2006; Sukun et al. 2007; Vaghefi et al. 2013; Vaghefi et al. 2011) have furthered the science of assessment, allowing for more accurate quantification of visible deteriorations and improved confidence in locating internal deterioration mechanisms. Even within the spectrum of these assessment methods, there exists a divide between metrics for structural response at the global level and material distress at the local level. What is lacking within the current framework is an integrated approach that considers the existing system-level behavior-driven structural performance as a part of the maintenance and preservation decision making process.

This project builds on a solid foundation of research in efforts to develop a performance-based behavior-driven evaluation framework that can be used to improve current decision making process for maintenance of in-service bridge superstructures. The proposed approach relies more heavily on physical behavior derived from mechanical models in lieu of experiences-based subjective methods. Through the application of computational simulation and analysis, the main focus of this research study is to provide rational and accurate representation of bridge system performance and behavior. The established foundation and logic used to generate numerical models for bridges with intact configuration has the potential to allow for the accurate incorporation of damage mechanisms in the models of simulated structures and understanding their impacts on the system-level behavior, while having implications on condition-rating and load-rating practices. This investigation has been limited to two specific classes of bridge superstructures: composite steel girder and prestressed concrete adjacent box girder bridges, but the framework is generic and can be applied to other bridge systems. With continuous improvements in computing power for simulation and analysis, it is envisioned that proposed methodology has the potential to gain further interest and traction within the bridge industry, especially for those involved within the preservation community.

CHALLENGES FOR EVALUATING BRIDGE PERFORMANCE

With today's computational resources and capabilities, the development of an analytical model to study the performance of the bridge systems with both intact and damaged configurations can be handled numerically, using a tool such as finite element method (FEM). While FEM provides an efficient mechanism to simulate the bridge system behavior, there are certain challenges that need to be properly addressed to yield acceptable results. The level of accuracy provided by FEM is known to be significantly influenced by modeling assumptions such as mesh size, element selection, as well as assumed loading/boundary conditions. For instance, representation of the internal reinforcement in concrete members or enforcement of composite action between different structural components, are the examples of simulation techniques requiring proper treatment in numerical modeling and analysis. Implementation of reasonable and appropriate material properties to the bridge model is also essential from the modeling perspective, to accurately capture the system failure characteristics. Considering concrete and steel as the primary materials used in the construction of the selected genres of bridges, their elastic and inelastic properties including features such as cracking/crushing, plastic deformations, yielding, strain hardening may dictate the ultimate capacity and even failure modes of the system.

In addition, the complex interaction between structural components, which causes inherent structural redundancy in bridge superstructures, is critical to the understanding of bridge life-cycle performance and behavior. The concept of redundancy is easily understood from its common definition, but when applied to bridges, the quantification of its amount or degree is not well understood. For bridges in service, the existence of deteriorating conditions affects the system-level behavior and makes it more complicated to interpret the redundancy. As a result, for a true measure of system performance, there exists a need to develop a robust definition of the bridge redundancy, which would require deep understanding of the actual system response including non-linear characteristics and stages to failure. Furthermore, a significant degree of complexity is introduced into the numerical models of the bridge structures in the presence of damage scenarios. Regardless of the source, cause, and initiating mechanism, degradation usually progresses and causes additional mechanisms to form or progressive failure. As an impetus to this research project, the core focus of this investigation aimed to create a mechanism for integrating damage into a measure of system performance and correlate the impacts of damage on the redundancy, ductility, operational safety, and remaining service life of the in-service bridge superstructures.

INVESTIGATION APPROACH

With the goal of establishing a performance-based framework to evaluate the behavior of in-service bridge superstructures, the investigation approach of this study has been categorized into four distinct phases with increasing complexity, ranging from simple intact element-level models, to significantly more complicated damaged bridge models. This multi-phase approach was necessary for the developed simulation to be progressively evolved and to yield a rational final system-level model with integrated damage mechanisms. For each phase, a series of numerical models were generated based on the extensive experimental data available in the literature, along with rational assumptions on appropriate material constitutive relationships and simulation techniques. Comparison of analytical results to available experimental data allowed for evaluating the validity and consistency of the developed numerical models. Figure 2 illustrates the schematic of the proposed numerical modeling framework that can be applied to any type of bridge superstructure.

As depicted, the first phase focuses on the development of undamaged element-level numerical models representing the main structural components of the selected bridge system. This phase aims to characterize the behavior and failure modes of intact bridge components, with consideration of both material and geometric non-linearities. Following validation of the intact models within the element level domain, phase two focuses on the development of system-level numerical models representing ideal intact bridge superstructures. These system-level models can be loaded to the ultimate capacity to define their full non-linear system behavior, highlight critical behavioral stages inherent to a particular bridge system, and correlate system response to the component-based design behavior. The primary challenge associated with model validation in this phase is the limited pool of complete dataset exists in the literature. The outcome of this phase will be a mechanism to describe the behavior of bridge systems based on their inherent level of system redundancy that are expected to be unique to each bridge superstructure type and design characteristics. This phase will also be essential to the latter stages on this investigation as it provides a baseline for as-designed behavior from which actual in-service behavior can be referenced to define the influence of damage and deterioration (Phase IV).

Following the first two phases, the purpose of the third phase of the proposed framework is to establish an effective constitutive behavior of the individual bridge components that are affected by common damage and deteriorating mechanisms. Despite the variety of sources that may cause each damage scenario, from a mechanics perspective it is their influence on the structural behavior that is of primary concern. Critical to this phase is the strategy to leverage modeling techniques appropriate for each damage mechanism considered. Validation of the damage-integrated elements through available experimental data is essential to the last phase of this investigation. Upon completion of the damaged element-level validation, the damage modeling strategies will be integrated into the system-level models to investigate their influence on system behavior. Parametric investigations can then be performed to quantify the influence of damage mechanisms on the system-level behavioral stages defined in Phase II and establish a measure of remaining life and susceptibility to failure.

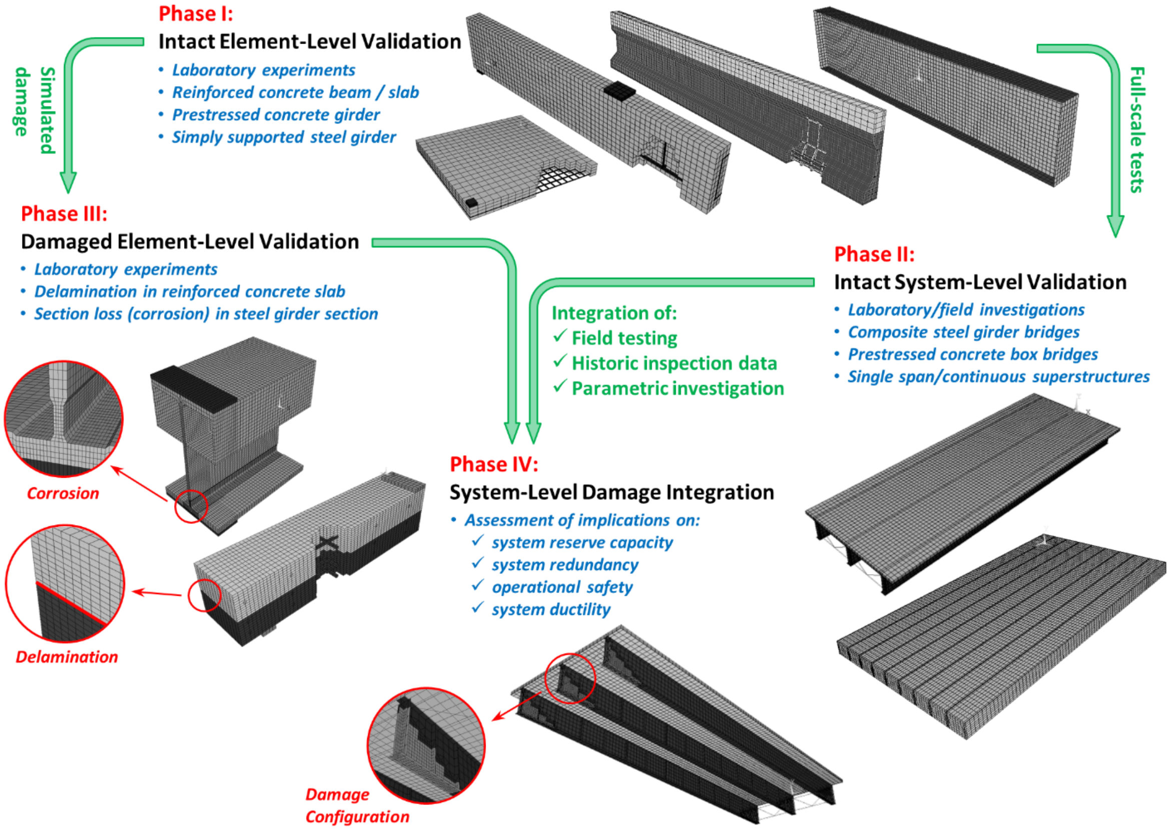


Figure 2 - Schematic representation of the proposed framework

NUMERICAL MODELING AND ANALYSIS

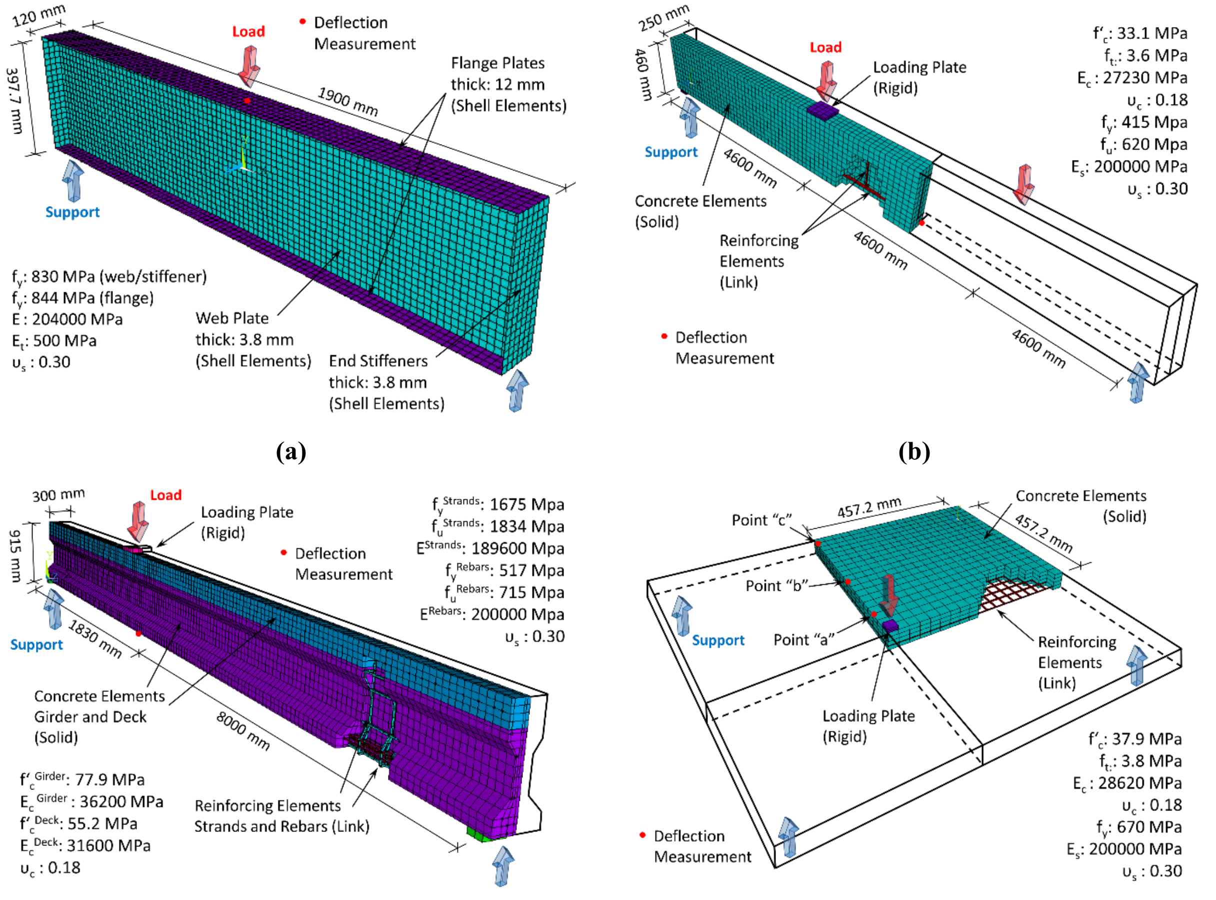
The implementation of the proposed framework requires the development and validation of numerical modeling approach for each of the described phases. Numerical models of the intact and damaged structural components within both element-level and system-level domains were generated based on the comprehensive experimental data reported in the existing literature. The commercial finite element computer package (ANSYS 2011), was used to create the numerical model within each phase of the project. The accuracy and validity of the FE simulation and analysis were investigated through comparison of the numerical results to the corresponding experimental data. The following sections describe the modeling procedure for the referenced case studies along with modeling assumptions and techniques adopted.

Phase I: Intact Element-Level Validation

The first phase served to validate the intact element-level behavior of bridge components. In the selected category of structures for study, an intact element can be translated to a single undamaged steel girder, reinforced concrete beam, prestressed girder, and reinforced concrete slab. Starting from the undamaged state of the individual bridge components allows for the transition to more complicated scenarios based on a solid comprehensive foundation. Accordingly, four cases studies were selected to accomplish the goal of this phase of the framework. The detailed information required for modeling of these components, including material characteristics, geometrical properties, loading and boundary conditions were derived from the corresponding test reports.

The first case study was based on an experimental investigation which was conducted on a series of simply-supported high-strength steel plate girders subjected to lateral patch loading (Johansson and Lagerqvist 1995; Lagerqvist 1995). Among all tested specimens, a plate girder with the geometrical configuration illustrated in Figure 3(a) was chosen in this study for numerical model development and validation. In the second case, results from an experimental study (Buckhouse 1997; Wolanski 2004) on a simply-supported reinforced concrete beam were used to achieve a fundamental understanding of the complex behavior and non-homogenous nature of the concrete material, including features such as cracking and crushing. Figure 3(b) illustrates the numerical model generated for only one-quarter of the beam, to take advantage of symmetry in geometry and loading.

In addition to the model created to simulate the behavior of reinforced concrete beam, two more case studies were selected in this project to extend the knowledge of numerical modeling of concrete components with applications in girder-type bridge superstructures. For the third case, results from an experimental study (Higgs 2013) performed on a set of four, 8-year-old prestressed concrete I-girders extracted from an in-service bridge superstructure in Orem, Utah were used to model the impact of prestressing forces on the behavior of reinforced concrete members. The extracted girders were deemed to be in excellent conditions due to their relatively short service lives. A representative numerical model for this phase, generated for half of the beam, is depicted in Figure 3(c). In addition to the models representing the one-dimensional behavior of reinforced and prestressed concrete elements, the last case study for the first phase of the framework focused on evaluating the two-dimensional behavior of reinforced concrete decks which dictate the load distribution mechanism in girder-type bridge superstructures. As a result, the element-level validation study was performed based on an experimental investigation (McNeice 1967) that evaluated the failure characteristics of a two-way corner-supported concrete slab. Due to symmetry of the structure in geometry and loading conditions, only one-quarter of the slab was modeled numerically, as illustrated in Figure 4(d).



(a) (b)

(c) (d)

Figure 3 - Intact element-level FE model development (a) steel girder (b) reinforced concrete beam (c) prestressed concrete girder (d) reinforced concrete slab

All of the developed models were analyzed using displacement-controlled non-linear static analysis, where the Newton-Raphson method was used as the non-linear solution algorithm. Representative sources of material non-linearities, including cracking/crushing and plastic deformations of concrete elements as well as yielding and strain-hardening of steel components were included in the analysis. In addition, the geometric non-linearity was also included in the analysis of the steel plate girder to allow for the development of local instabilities, such as buckling (Alinia et al. 2011). Initial imperfections in the form of out-of-plane flatness and twisting of the web and flange plates were introduced into the model to agitate the occurrence of the buckling phenomenon (Tryland et al. 1999).

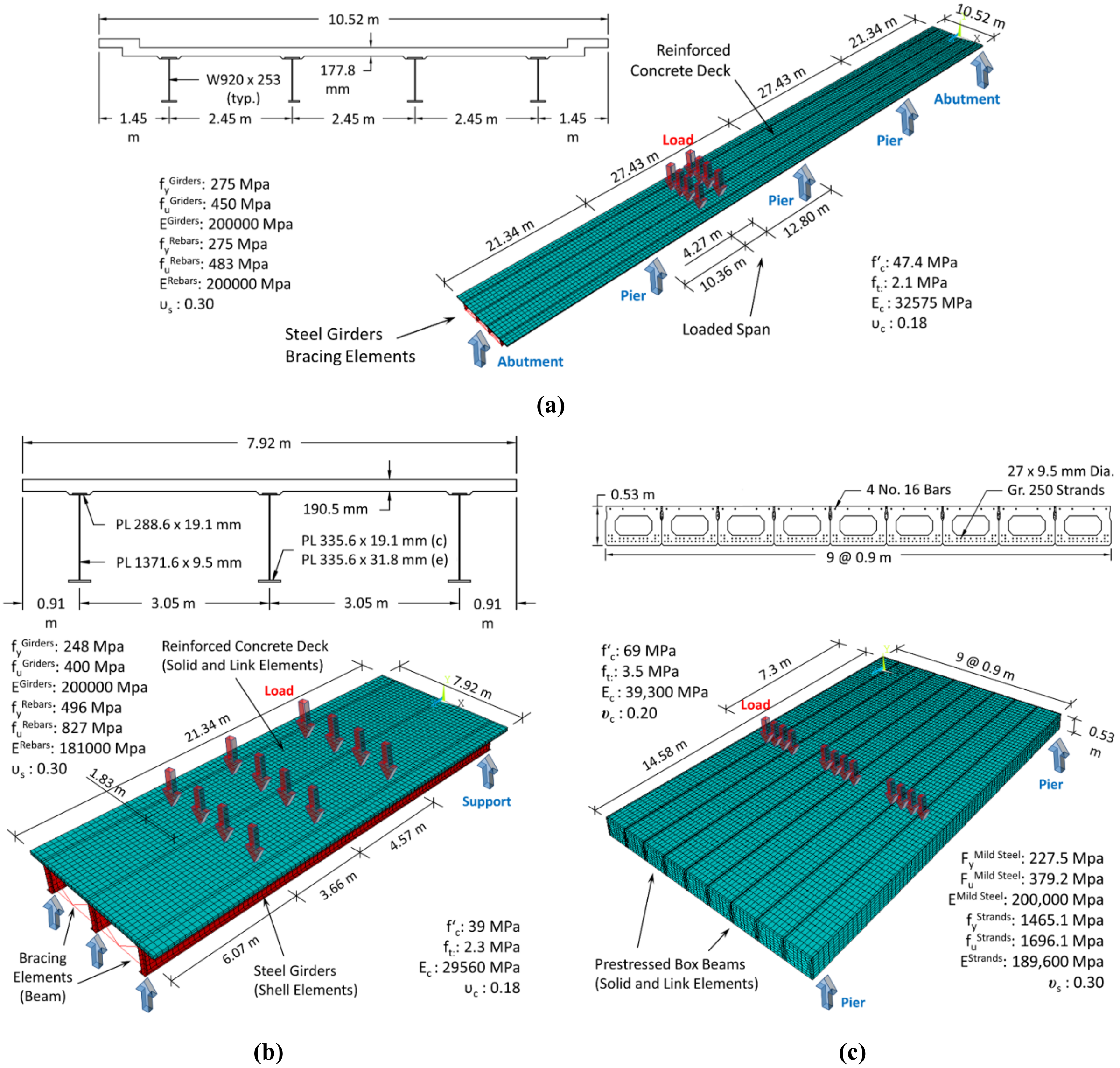
Upon completion of the analyses, load-deflection responses at predefined locations (shown in red dots in Figure 3) were derived from the numerical analysis and compared to the corresponding experimental outcomes for validation. Despite the minor discrepancies that exist between the results, the proposed numerical models in this phase were able to capture the overall behavior and highlight the failure characteristics of the simulated structural components. It should be noted that the main goal of this phase was to understand the basics of the behavior of the simulated structural members, and provide a fundamental knowledge for bridge system-level simulation and analysis. For this purpose, the selected case studies and the corresponding performed numerical analysis were deemed adequate. Additional details on the modeling approach within the element-level domain, comparison of the results, and validation of the developed numerical models can be found in recent works (Gheitasi 2014; Saliba 2015).

Phase II: Intact System-Level Validation

The second phase focuses on the development of system-level numerical models for intact bridge superstructures to provide a comprehensive understanding of their non-linear behavior, failure characteristics, and correlation with the expected element-level response. The outcome of this phase will be essential to the later stages of the investigation as it provides a baseline for as-designed behavior from which intact behavior can be referenced to define the influence of damage and deterioration. Results from literature on full-scale destructive tests of representative steel girder and prestressed box girder bridges were used in this investigation as case studies to accomplish the goal of this phase. These structures were selected due to the availability of the well-documented reports containing detailed information on the testing procedure and setup, data acquisition, and obtained results. It should be noted that the primary challenge associated with model development and validation in this phase was the limited pool of complete experimental data sets available in the literature on destructive testing of full-scale bridge systems; however, the selected cases provided numerous features that allowed for the implemented modeling approach to be extrapolated to the alternative scenarios, considering different bridge structural types.

The first case study selected in this investigation was a four-span continuous steel girder highway bridge, which was in service in Tennessee and subjected to a destructive testing program (Burdette and Goodpature 1971) to evaluate its ultimate capacity and the corresponding failure mode. Figure 4(a) illustrates the numerical model generated for this bridge superstructure according to the experimental report. In the second case, a simply-supported composite steel girder bridge model, which was constructed in the laboratory at the University of Nebraska (Kathol et al. 1995) and tested to failure, was selected in this study for model development and validation. The controlled laboratory conditions together with the available information on the construction and testing procedure allowed for detailed numerical model to be developed for this case, as depicted in Figure 4(b). The last case study selected to fulfill the scope of the second phase of the investigation was a full-scale destructive testing performed on a 43-year-old prestressed concrete box girder bridge superstructure (Huffman 2012), which was in service in Ohio. At the time, the structure had three equal simply-supported spans, which were fully inspected to detect existing damage and deteriorating conditions before testing (Steinberg et al. 2011). Structural inspection concluded that there was minimal degradation in the center span of this bridge system; thus supporting the assumption that this span can serve as a suitable candidate for numerical study. Figure 4(c) illustrates the numerical model that was developed for the mid-span of this structure, representing an intact and undamaged condition state of the system.

In the models, all of the structural components including the main load-carrying elements (i.e. girders and deck), secondary members (i.e. lateral bracings), and composite action amongst them as well as loading and boundary conditions were simulated using the material and section properties given in the corresponding test reports. However, the models incorporated several minor simplification, including modification to the geometry and idealizing boundary conditions to help reduce the modeling complexity while facilitating the computational efforts required to analyze the simulated systems. The models were loaded with a series of concentrated loads which mimic the corresponding test setups, and analyzed using load-controlled non-linear static analysis. Load vs. deflection response at specific locations on the models were extracted from the performed non-linear FE analysis and compared to the experimental values obtained in the corresponding testing programs. Upon comparison of the results, the validity and accuracy of the applied numerical modeling approach at the system-level domain was evaluated.



(a)

(b) **(c)**

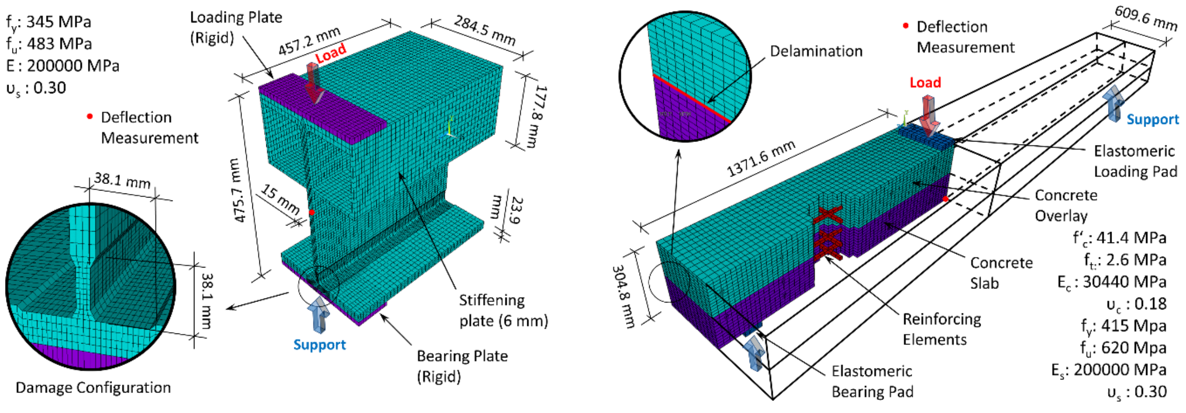
Figure 4 - Intact system-level FE model development (a) continuous steel girder bridge (b) single span steel bridge model (c) prestressed concrete box bridge

The calibrated numerical models were used to identify the failure characteristics and stages to failure in the specific genres of bridges selected in this study. In addition, results from both experimental and numerical studies highlighted significant amount of reserve capacity that exists over the component-based design capacity in the in the evaluated bridge superstructures. The identified reserve capacity can be attributed to the system interaction and concept of redundancy, which are inherent to the behavior of girder-type bridge systems. Comprehensive details on the modeling assumptions and discussions of the behavioral characteristics of the selected types of structures are presented elsewhere (Gheitasi and Harris 2014a; Gheitasi and Harris 2014b; Saliba 2015).

Phase III: Damaged Element-Level Validation

With the limited experimental data that exist on the full-scale behavior of bridge superstructures with accumulated and measured level of damage, the development of modeling strategies for integrating damage mechanisms at the element-level domain provides a suitable alternative. Despite the variety of sources that may cause each damage scenario, from a mechanics perspective it is their influence on the structural behavior that is of primary concern. As a result, the third phase of the proposed framework aims to establish a fundamental understanding of the impact of damage and deteriorating mechanisms on the individual bridge components. End deterioration in a steel girder sub-section and delamination in a reinforced concrete slab were the two damage scenarios selected in this study to achieve the goal of the third phase. Although the validation of damage modeling strategy was limited to two specific cases as they are common in practice (FHWA 2012), the simulating approach is generic and can be applied to identify the impact of other types of deteriorating mechanisms on the behavior of bridge structural members.

As the first case study, results from a comprehensive experimental investigation conducted at Michigan Technological University to characterize the influence of end deterioration on the capacity of degraded sub-sections of wide flange beams (van de Lindt and Ahlborn 2005), was used for model development and validation. Figure 5(a) illustrates the numerical model that was created for one of the tested specimens, in which the effect of damage was simulated via reducing the thickness of the elements in the degraded section. In addition to the model with damage configuration, another FE model was generated in this study to represent the behavior of the same specimen with intact configuration. For the second case, an experimental investigation performed at the University of California, San Diego to evaluate the performance of overlaid concrete slabs (Seible et al. 1988), was used in this study to develop a numerical model representing the impact of delamination in reinforced concrete members. Among all of the tested specimens with different interlayer surface conditions, the one that had been lubricated with bond breaking agents to simulate the ideal case of delamination was chosen in this study for model development. Figure 5(b) illustrates the numerical model that was generated for this specimen, in which the damage scenario (delamination) was included using surface-to-surface contact elements. Similar to the case of deterioration in steel wide-flange subsection, an intact model was also generated for the second case study, where the contact elements have been removed and replaced with perfect bond condition between the two layers of the reinforced concrete slab and its overlay.



(a) **(b)**

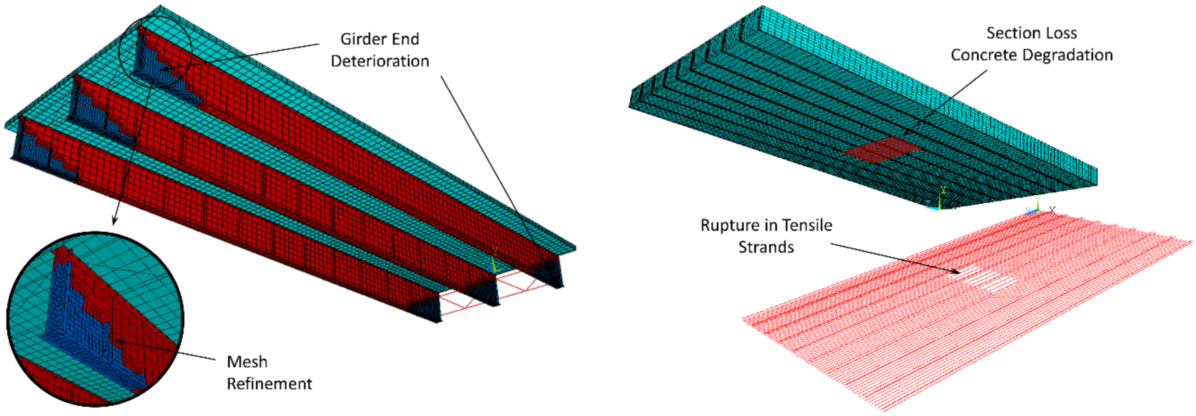
Figure 5 - Damaged element-level FE model development (a) end deterioration in steel girder (b) delamination in reinforced concrete slab

All of the developed models in this phase where supported and loaded according to the loading and boundary conditions reported in the corresponding test documents. Displacement-controlled non-linear static analyses were performed to assess the validity of the implemented damage modeling strategy. In addition to all sources of material non-linearities included in the analysis, geometric non-linearity were also included in the models to capture the large deformations in the case of deteriorated steel section, and the changing status of the contact surfaces in the concrete slab model with delamination. Upon analysis, load-deflection behavior at specific locations of the models were recorded via numerical analysis and compared to the corresponding results obtained from the experimental studies. Comparisons of the results highlighted the accuracy and validity of the proposed modeling approach in simulating the impact of selected damage mechanisms on the behavior and ultimate load-carrying capacities of selected structural members. Further details on the numerical modeling, validation study, and comparison of the results obtained in this phase can be found in the previous work of the authors (Gheitasi and Harris 2014c)

Phase IV: System-Level Damage Integration

The first three phases aimed to establish a comprehensive foundation on the model development and damage integration strategies, which were essential to the body of proposed framework. Accordingly, the main objective of the last phase is to integrate different types of damage and deteriorating mechanisms into the measure of system performance and characterize the impact of damage on the system ultimate capacity, redundancy, and operational safety. The system-level model with integrated damage would be an extrapolation of the validated damage modeling strategies along with the established understanding of the intact system-level behavior and the corresponding interaction among subcomponents. To illustrate the impact of damage on the system-level behavior, a conceptual schematic of the model updating procedure for representative bridge systems affected by common damage mechanisms is provided in this section. The same methodology can be applied to other bridges, as well as other types of damage conditions, provided the validation of numerical modeling approach via comparison to suitable experimental data.

After generating the FE model of the bridge system based on the validated simulation approach in phase II, the geometry of the model can be updated to accommodate the existence of any type of damage and deteriorating conditions. The first damage scenario considered in this study was corrosion and section loss in steel girders in the composite bridge superstructures. In order to update the bridge model with the assumed damage mechanism, the mesh of the girders at the location of damage should be refined to allow for accurate simulation of the deterioration pattern. As validated in phase III, corrosion in steel girders can then be integrated into the model of the bridge system by reducing the thickness of the deteriorated elements at the corroded regions, as depicted in Figure 6(a). Another type of damage condition considered in this study was strand rupture in the prestressed concrete bridges. This damage scenario is common in reinforced and prestressed concrete structures as a result of corrosion in steel reinforcement caused by penetrating moisture/chemicals through the concrete cracks. To model this damage, the cross-section of the deteriorated strands can be reduced, while other modifications in residual prestressing forces and bond behavior are required in the model to accommodate the existence of damage, see Figure 6(b).



(a) **(b)**

Figure 6 - Developed FE model with integrated damage (a) corrosion in steel girders (b) strand rupture in prestressed box girders

Another type of damage condition selected in this study was the subsurface delamination in the reinforced concrete slabs of girder-type bridge superstructures. To accurately integrate the effect of delamination into the numerical model of the bridge system, it is essential to understand the details of the corresponding damage mechanism and its effects on the material properties and geometrical characteristics within the damaged area of the deck. Figure 7 illustrates a conceptual schematic of the modeling approach that can be used to integrate the corresponding subsurface fracture planes into the numerical model of the bridge decks. As it is demonstrated, irrespective of the location, depth and relative position of the fracture plane, corrosion-induced delamination would cause alterations in the material and geometrical characteristics of the damaged elements. Several parameters have been proposed in the literature to quantify these alterations and provide more accurate measurement of the extent level of delamination and its corresponding damage mechanisms in the reinforced concrete members. The most dominant effects which were considered in this numerical study are the crack width, reduction in the cross section and yield stress of the corroded rebars, change in the compressive strength of the concrete cover due to micro cracking induced by rebar rust expansion, and concrete–rebar bond deterioration.

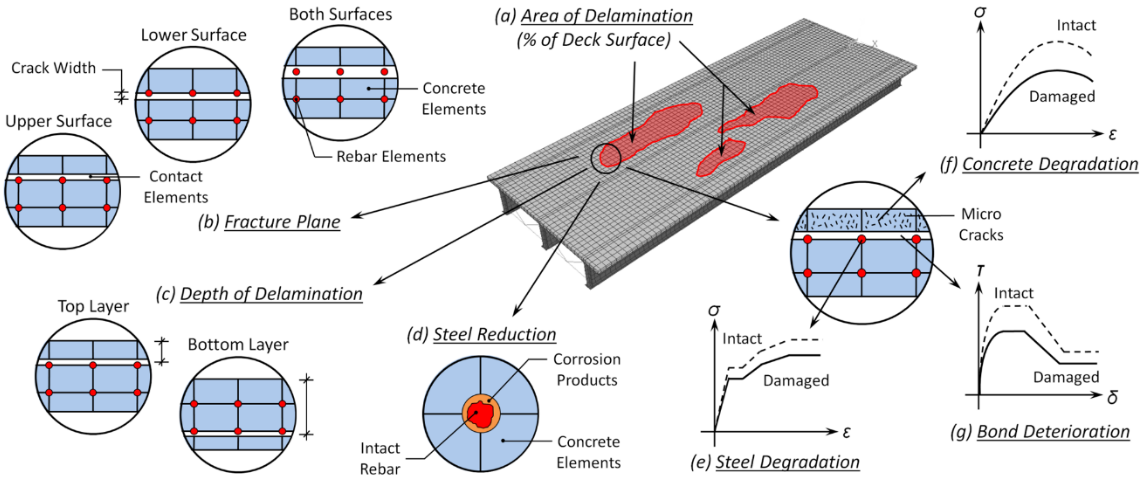


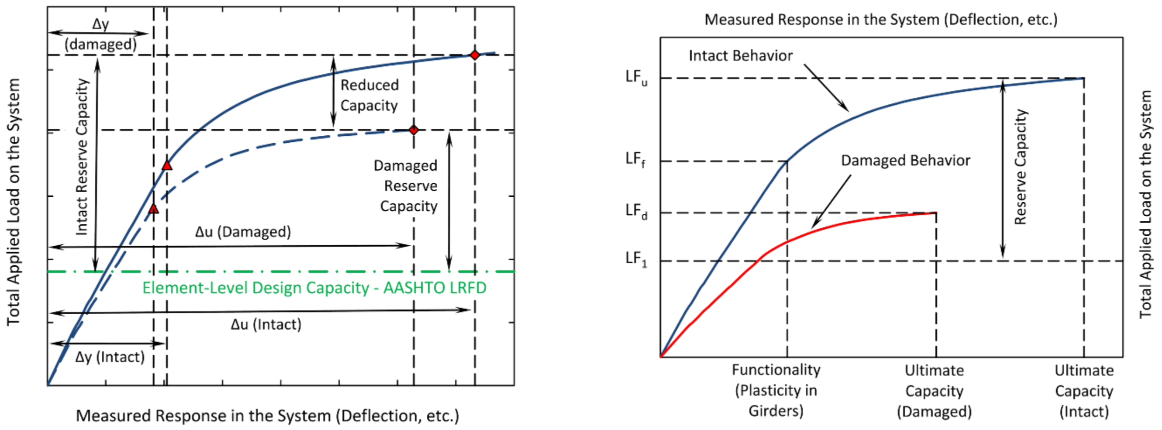
Figure 7 - FE model development to simulate delamination in reinforced concrete slabs

It should be noted that the presented damage configurations are ideal representatives of actual quantities and were selected to demonstrate the applicability of the proposed modeling framework. With improvement in non-destructive inspection techniques, more refined values regarding the damage parameters can be provided and integrated in the corresponding numerical models. The updated numerical models can then be subjected to different loading scenarios and analyzed to define the impact of integrated damage conditions on the overall behavior and performance characteristics of various types of in-service bridge superstructures. Additional information on the application of the proposed numerical modeling approach to identify the impact of common damage mechanisms on the behavior of in-service bridge superstructures are provided elsewhere (Gheitasi and Harris 2015; Gheitasi and Harris 2015; Saliba et al. 2015).

SYSTEM PERFORMANCE AND SAFETY ASSESSMENT

In a given bridge superstructure, whether it is intact or damaged, the measure of system performance can be preliminarily defined based on the capacity, system redundancy, and system ductility. As it is demonstrated in Figure 8(a), the ultimate capacity of the system in the maximum level of load that can be tolerated before any failure mechanism takes place. The difference between the ultimate and component-based design capacities, is characterized as system reserve capacity, which would represent an indication of the level of redundancy exits in the system. Thus, any reduction in the system reserve capacity due to presence of any damage mechanism can be interpreted as reduction in the system redundancy, which could be defined as a measure of system safety in terms of strength and susceptibility to failure. In addition, system serviceability and/or functionality can be defined in the context of overall system ductility. As illustrated in Figure 8(a), the system ductility can be defined as the ratio of the maximum measure response of the system at the moment of failure to the system response when the material non-linearities initiate in the main load-carrying elements (i.e. girders). It should be highlighted that the described definitions for the system redundancy and ductility are qualitative, and based on the behavioral stages characterized for each structural type studied in this investigation. However, in order to have a true measure of system performance, a comprehensive approach is required to quantitatively characterize the concept of redundancy in bridge superstructures with different structural systems.

According to the AASHTO specifications (AASHTO 2012), a structure is classified as non-redundant if failure of a single element results in the collapse of the structure. In other words, bridge redundancy can be defined as the capability of the superstructure system to carry loads and continue its functionality after damage or failure has occurred in one of its members. As a result, the level of safety in a given bridge superstructure has a direct correlation with the concept of system redundancy. The investigation approach presented in National Cooperative Highway Research Program (NCHRP) Reports (Ghosn and Moses 1997; Ghosn and Yang 2014) was used in this study to evaluate the redundancy in highway bridge superstructures. The direct analysis approach proposed in these studies has the potential to evaluate the safety of highway bridges and provide a quantitative measure of system redundancy. Based on this study, a bridge system is considered safe if it can satisfy the following criteria: (1) provide a reasonable safety level against first member failure; (2) not to reach its ultimate capacity under extreme loading conditions; (3) not to produce large deformations under expected loading scenarios; and (4) be able to carry some traffic loads after damage occurred to a component. These criteria define the limit states that are required to be checked for safety assessment of any bridge superstructure. Using incremental nonlinear analysis, the capacity of a bridge superstructure to carry live loads before these limit states are reached can be defined as proportional factors that are multiples of the weights of the trucks that can be applied on the system. These multipliers are referred herein as the load factors, LF (see Figure 8(b)). The following subsections provide a brief summary on the selected limit states and the application of the direct analysis method in evaluating the redundancy of the system.



(a) **(b)**

Figure 8 - System performance assessment (a) impact of damage on the system-level behavior (b) measure of system redundancy and operational safety

Member Failure

The member failure criterion is defined as the maximum possible truck load that a bridge superstructure can tolerate before first member failure occurs. Bridges that are not redundant may still provide a high level of system safety if their main structural members are overdesigned. The member safety check can be performed by comparing the actual capacity of the bridge component, $R_{provided}$ (nominal capacity), to the capacity required by the design specification, $R_{required}$. The member failure load factors can be defined using Eqns. 1 and 2:

$$LF_1 = \frac{R_{provided} - D}{L} \tag{1}$$

$$LF_{1\,required} = \frac{R_{required} - D}{L} \tag{2}$$

where D and L are the dead load and live load effects on the most critically loaded member and can be defined using linear elastic analysis of the bridge system. For the live load calculation, the lateral distribution factors shall be derived for different load effects (flexure or shear) using any numerical model that can simulate the system behavior of the bridge superstructure (Barr and Amin 2006; Harris 2010; Harris and Gheitasi 2013; Huo et al. 2005). The member reserve ratio, r_1, can then be calculated using Eqn.3. Values for r_1 greater than one indicate that the selected member is overdesigned.

$$r_1 = \frac{LF_1}{LF_{1\,required}} = \frac{R_{provided} - D}{R_{required} - D} \tag{3}$$

Ultimate Limit State

The ultimate capacity of the intact system is defined as the maximum possible truck load that a bridge superstructure can tolerate before it collapses. In composite steel girder bridges, plastic hinging in the girders and crushing in the concrete deck can be identified as the primary failure mechanism (Ghosn and Moses 1997). The load factor that corresponds to this limit state is referred to LF_u, which can be defined using nonlinear static analysis of the intact bridge superstructure considering all sources of material nonlinearities (see Figure 8(b)).

Functionality Limit State

Under the effect of excessive live loading, the bridge superstructure may undergo permanent deformations that does not necessarily cause the structure to collapse, but may significantly reduce the serviceability of the system for regular traffic. Controlling the permanent deformations in a bridge superstructure can be achieved by applying specific criteria over the maximum deflection or hinge rotation that occurs in the system. In this study, load factor that corresponds to functionality limit state, LF_f, is defined as the maximum possible truck load that initiates material nonlinearity and permanent deformation in the steel girders (see Figure 8(b)). Performing nonlinear structural analysis, this approach has the potential to control the functionality of the intact system irrespective of the applied loading scenarios and assumed boundary conditions.

Damaged Condition Limit State

The existence of damage mechanisms could significantly reduce the load-carrying capacity of a bridge superstructure and as a result, decrease the level of operational safety. The damaged condition limit state is defined as the maximum possible truck load that a deteriorated bridge superstructure can tolerate before it collapses. Possible damage scenarios in composite steel girder bridges can range from localized conditions such as corrosion and section loss in steel girders or delamination in concrete deck, to complete removal of a main load-carrying element due to a truck/ship collision. The load factor that corresponds to this limit state is referred to LF_d, which can be defined using nonlinear static analysis on the damaged bridge superstructure considering both material and geometric nonlinearities, as applicable (see Figure 8(b)).

Redundancy Factors

As the concept of redundancy relates to the capability of the structure to serve its function after damage occurs to one of its main components, a comparison of LF_1, LF_u, LF_f, and LF_d would provide a measure of the level of redundancy. The system reserve ratios are defined for ultimate, functionality, and damaged condition limit states as summarized in Eqns. 4-6:

$$R_u = \frac{LF_u}{LF_1} \tag{4}$$

$$R_f = \frac{LF_f}{LF_1} \tag{5}$$

$$R_d = \frac{LF_d}{LF_1} \tag{6}$$

These ratios provide deterministic measures of bridge system redundancy. To check the adequacy of the level of redundancy in a given bridge superstructure, it is required to compare the calculated system reserve ratios to a series of minimum acceptable values (target values). These values were previously defined based on examining the results of a series of in-service bridges that are clearly redundant according to the current engineering practices (Ghosn and Moses 1997). Moreover, the reliability analysis approach that was implemented to derive these minimum acceptable values would account for the uncertainties associated with determining the loads and the resistance of the bridge superstructures. Based on the performed reliability-based analysis, the bridge system is considered adequately redundant if:

$$R_u \geq 1.3 \tag{7}$$

$$R_f \geq 1.1 \tag{8}$$

$$R_d \geq 0.5 \tag{9}$$

It is expected that the level of system redundancy for each bridge superstructure highly depends on the bridge type (material, design, geometry), but also on the existing condition states. Using the proposed approach, the redundancy factor, ϕ_{red}, for any given bridge can be defined as:

$$\phi_{red} = \min\left\{ r_1 \times r_u , r_1 \times r_f , r_1 \times r_d \right\} \tag{10}$$

in which r_1 is the member reserve ratio defined in Eqn. 3, while r_u, r_f, and r_d are the redundancy ratios for ultimate, functionality, and damaged condition limit states, respectively and can be defined as:

$$r_u = \frac{R_u}{1.3} \tag{11}$$

$$r_f = \frac{R_f}{1.1} \tag{12}$$

$$r_d = \frac{R_d}{0.5} \tag{13}$$

A ϕ_{red} greater than one indicates adequate level of system redundancy for the bridge superstructure under consideration, while ϕ_{red} less than one is the indication of an insufficient level of redundancy for the system. The bridge superstructures that fail to satisfy this criterion are no longer safe to operate. As a result, appropriate repair strategies could be applied to strengthen the main structural components of the deteriorated bridge system until an overall satisfaction of the system reliability target is achieved (Ghosn and Moses 1997).

APPLICATION TO IN-SERVICE STRUCTURES

Using the described methodology together with the validation numerical modeling framework, a sensitivity analysis was performed in this study on representative in-service bridge superstructures within the Commonwealth of Virginia to evaluate their level of redundancy and operational safety. These structures were selected as they represent the common geometrical features of in-service bridges in Virginia. A series of damage scenarios were also selected based on a questionnaire submitted to the Virginia Department of Transportation (VDOT) engineers in different districts across the Commonwealth. Based on the synthesis of the responses, the models were updated with representative damage configurations which were believed to provide a range of deteriorating conditions observed in Virginia. The models were then analyzed, while their operational safety and vulnerability to the assumed damage mechanisms were evaluated used the described methodology (Ghosn and Moses 1997). A detailed summary of the modeling assumptions with regards to the geometrical characteristics of the selected structures, assumed damage scenarios, and applied loading and boundary conditions is provided in recent publications of the authors (Gheitasi and Harris 2015; Gheitasi and Harris 2015).

CONCLUSIONS

The overall objective of this study was to establish a framework to evaluate the in-service condition of bridge superstructures in the presence of common deteriorating mechanisms and provide a measure of system performance by characterizing the impact of damage on the ultimate capacity, redundancy, and operational safety. The damage scenarios included in this study were selected as a representation of deteriorating conditions that may influence the performance and serviceability of highway steel bridges. However, for more comprehensive evaluation of an in-service bridge superstructure, the last phase of the proposed framework would need to be interconnected with a comprehensive non-destructive field inspection for each individual structure selected for evaluation, to accurately model the existing damage condition and its details. The incorporation of condition state data obtained from periodic inspection coupled with the damage-integrated system-level behavior characterization has the potential to provide a real-time estimate of system performance. By updating the developed numerical model of the in-service highway bridges based on biennial inspection data, degradations in the structural performance parameters can be monitored and evaluated over time. Extrapolating the degradation trend through the design life of the structure would help the bridge owners to estimate remaining service life of the bridge system and make appropriate maintenance decisions regarding the long-term preservation strategies.

This investigation focused exclusively on the composite steel girder and prestressed box bridge superstructures and was aimed at representing a conceptual schematic of a computational modeling strategy for describing an in-service baseline performance measure; however, this same methodology could be extended to other superstructure types. The proposed framework could be beneficial to the preservation community as a mechanism to make decisions based on in-service condition, but also has implications in the design where a system-level design strategy would have a major impact on design economy as compared to current element-level design strategies. Moreover, results obtained from this investigation highlight the ability of the proposed framework to provide a critical linkage between the design and preservation communities by correlating the element-level behavior to the system-level response under the effect of different damage scenarios. The numerical modeling approach implemented in the proposed framework also has the potential to explore the implication of advances in material, design methodologies and construction practices on the long-term performance of bridge superstructures.

REFERENCES

AASHTO (2012). "LRFD Bridge desing specifications, 6th ed."Washington, DC.

Alinia, M. M., Gheitasi, A., and Shakiba, M. (2011). "Postbuckling and ultimate state of stresses in steel plate girders." *Thin-Walled Structures*, 49(4), 455-464.

ANSYS. 2011. User's manual revision 14.0, Canonburg, PA.

Barr, P., and Amin, M. (2006). "Shear Live-Load Distribution Factors for I-Girder Bridges." *Journal of Bridge Engineering*, 11(2), 197-204.

Buckhouse, E. R. (1997). "External flexural reinforcement of existing reinforced concrete beams using bolted steel channels." Master's thesis, Marquette University Milwaulkee, WI.

Burdette, E. G., and Goodpature, D. W. (1971). "Full scale bridge testing - an avalution of bridge design criteria." University of Tennessee, Knoxville, TN.

Cambridge Systematics Inc. (2010). "The transportation challenge: moving the U.S. economy.", National Chamber Foundation, U.S. Chamber of Commerce, Washington, D.C.

FHWA (2012). "Bridge inspector's reference manual." *Publication No. FHWA-NHI-03-001/002*, Federal Highway Administration, Washington, D.C.

FHWA (2013). "National Bridge Inventory Database." *Publication No. FHWA-NHI-03-001/002*, Federal Highway Administration, Washington, D.C.

Gheitasi, A. (2014). "Performance evaluation of damage-integrated composite steel girder highway bridges." Ph.D. dissertation, University of Virginia, Charlottesville, VA.

Gheitasi, A., and Harris, D. (2014a). "Failure Characteristics and Ultimate Load-Carrying Capacity of Redundant Composite Steel Girder Bridges: Case Study." *Journal of Bridge Engineering*, 20(3), 05014012.

Gheitasi, A., and Harris, D. (2014b). "Overload Flexural Distribution Behavior of Composite Steel Girder Bridges." *Journal of Bridge Engineering*, 20(5), 04014076.

Gheitasi, A., and Harris, D. (2014c). "A performace-based framework for bridge preservation based on damage-itergarted system-level behavior." *Transportation Research Board 93rd annual meeting,* Washington, DC.

Gheitasi, A., and Harris, D. (2015). "Redundancy and Operational Safety of Composite Stringer Bridges with Deteriorated Girders." *Journal of Performance of Constructed Facilities*, 04015022.

Gheitasi, A., and Harris, D. K. (2015). "Performance assessment of steel–concrete composite bridges with subsurface deck deterioration." *Structures*, 2(0), 8-20.

Ghosn, M., and Moses, F. (1997). "Redundancy in Highway Bridge Superstructures." National Coorporative Highway Research Program (NCHRP) Report 406, Transportation Research Board, Washington, DC.

Ghosn, M., and Yang, J. (2014). "Bridge System Safety and Redundancy." National Coorporative Highway Research Program (NCHRP) Report 776, Transportation Research Board, Washington, DC.

Government Accountability Office (2008). "Defense critical infrastructure: adherence to guidance would improve DOD's approach to identifying and assuring the availability of critical transportation assets.", Defense Capabities and Management, Washington, D.C.

Harris, D. K. (2010). "Assessment of flexural lateral load distribution methodologies for stringer bridges." *Engineering Structures*, 32(11), 3443-3451.

Harris, D. K., and Gheitasi, A. (2013). "Implementation of an energy-based stiffened plate formulation for lateral load distribution characteristics of girder-type bridges." *Engineering Structures*, 54(0), 168-179.

Higgs, A. T. (2013). "Shear and Flexural Capacity of High Strength Prestressed Concrete Bridge Girders." Master's Thesis, Utah State University, Logan, UT.

Huffman, J. (2012). "Destructuve testing of a full-scale 43 year old adjacent prestressed concrete box beam bridge: middle and west span." Master's Thesis, Ohio University, Athens, OH.

Huo, X., Wasserman, E., and Iqbal, R. (2005). "Simplified Method for Calculating Lateral Distribution Factors for Live Load Shear." *Journal of Bridge Engineering*, 10(5), 544-554.

Johansson, B., and Lagerqvist, O. (1995). "Resistance of plate edges to concentrated forces." *Journal of Constructional Steel Research*, 32(1), 69-105.

Kathol, S., Azizinamini, A., and Luedke, J. (1995). "Final report: strength capacity of steel girder bridges." Nebraska Department of Roads (NDOR), RES1(0099), 469, Lincoln, NE.

Kavinoky, J. F. (2007). "The importance of transportation infrastructure to the american business community.", U.S. House of Representatives Commitee on Transportation and Infrastructure, U.S. Chamber of Commerce, Washington, D.C.

Lagerqvist, O. (1995). "Patch-loading resistance of steel girders subjected to concentrated forces." Ph.D. thesis, Luleå University of Technology, Luleå, Sweden.

Lynch, J. P., and Loh, K. J. (2006). "A summary review of wireless sensors and sensor networks for structural health monitoring." *Shock and Vibration Digest*, 38(2), 91-130.

McNeice, G. M. (1967). "Elastic-plastic bending of plates and slabs by finite element method." Ph.D. thesis, University of London, London, UK.

NTSB (2008). "Collapse of I-35 highway bridge, Minneapolis, Minnesota." *Accident report, NTSB/HAR-08/03, PB2008-916203*, National Transportation Safety Board, Washington, D.C.

NTSB (2013a). "Washington State I-5 collapse investigation." *Preliminary report, HWY13MH012*, National Transportation Safety Board, Washington, D.C.

NTSB (2013b). "Railroad train collision, resulting in highway bridge collapse." *Preliminary report, DCA13MR004*, National Transportation Safety Board, Washington, D.C.

Saliba, M. (2015). "Influence of internal deterioration mechanisms on the system-level behavior of composite prestressed concrete girder bridges." Master's thesis, University of Virginia, Charlottesville, VA.

Saliba, M., Harris, D., and Gheitasi, A. (2015). "Influence of Internal Deterioration Mechanisms on the System Level Behavior of Composite Prestressed Concrete Girder Bridges." *Structures Congress 2015*, American Society of Civil Engineers, 2131-2142.

Seible, F., Latham, C., and Krishnan, K. (1988). "Structural concrete overlays in bridge deck rehabilitations - experimental program." Department of Applied Mechanics and Engineering Sciences, University of California, San Diego, La Jolla, CA.

Steinberg, E., Miller, R., Nims, D., and Sargand, S. (2011). "Structural evaluation of LIC-310-0396 and FAY-35-17-6.82 box beams with advanced strand deterioration." Ohio Department of Transportation, Office of Research and Development.

Sukun, K., Pakzad, S., Culler, D., Demmel, J., Fenves, G., Glaser, S., and Turon, M. "Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks." *Proc., Information Processing in Sensor Networks, 2007. IPSN 2007. 6th International Symposium on*, 254-263.

Tryland, T., Hopperstad, O. S., and Langseth, M. (1999). "Steel girders subjected to concentrated loading—Validation of numerical simulations." *Journal of Constructional Steel Research*, 50(2), 199-216.

Vaghefi, K., Ahlborn, T., Harris, D., and Brooks, C. (2013). "Combined Imaging Technologies for Concrete Bridge Deck Condition Assessment." *Journal of Performance of Constructed Facilities*, 04014102.

Vaghefi, K., Oats, R., Harris, D., Ahlborn, T., Brooks, C., Endsley, K., Roussi, C., Shuchman, R., Burns, J., and Dobson, R. (2011). "Evaluation of Commercially Available Remote Sensors for Highway Bridge Condition Assessment." *Journal of Bridge Engineering*, 17(6), 886-895.

van de Lindt, J. W., and Ahlborn, T. M. (2005). "Development of steel beam end deterioration guidelines." *MDOT Research Report, RC-1454*, Michigan Tech. Transportation Institute , Center for Structural Stability, Houghton, MI.

Wardhana, K., and Hadipriono, F. (2003). "Analysis of Recent Bridge Failures in the United States." *Journal of Performance of Constructed Facilities*, 17(3), 144-150.

Wolanski, A. J. (2004). "Flexural behavior of reinforced and prestressed concrete beams using finite element analysis." Master's thesis, Marquette University, Milwaukee, WI.