Implications for Structural Health Monitoring and Load Rating Resulting from the Performance of Damage Integrated Bridges

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Abstract

According to the ASCE’s Report Card for America’s Infrastructure, in-service bridges have received scores as low as C+, highlighting an overall poor condition state. This grade reflects the need for strategies and solutions to improve the overall performance. Various studies have been conducted in attempts to resolve or ease this concern, but few have successfully integrated structural health monitoring (SHM) as a standard practice. SHM has the capability of providing accurate, real-time structural data, which can in turn be used to model the response of a structure under loading. The basic premise of SHM provides a rational framework to characterize this performance, but most studies to date have focused primarily on the measurement of response, with fewer efforts focused on the implications of this response. What is currently lacking within the structural health monitoring community is a fundamental understanding of what the measured response means for the overall health of the structure.

This investigation presents the results of an ongoing investigation on the characterization and behaviour of damaged in-service bridges. The study includes the numerical simulation of system level behaviour and characterization of two common bridge types, composite steel girder and adjacent prestressed box girders, under the presence of common damage mechanisms. The numerical models were developed using actual in-service bridges and validated against load testing results. In addition, simulation results illustrated the influence of damage on functionality, capacity and ductility, all of which have implications for performance-based decision-making practices such as load rating, maintenance, and preservation. The described framework provides a foundation that can be coupled with traditional measurements to provide credibility and coherence with existing SHM strategies. This coupling would allow for performance-based decisions such as load rating and preservation solutions to be developed based on the scientific merit of behaviour and system response.

Keywords

Structural health monitoring; bridge deterioration; damage modeling; performance-based decision making; maintenance and rehabilitation.

1. State of Practice

The significant contribution of the national highway system to the economic health of the United States has been well recognized not only by the bridge community, but also by most citizens who are using this infrastructure on a daily basis. Recent bridge failures in North America have brought the challenges associated with the safety and functionality of these structures to the forefront of people’s scrutiny (NTSB 2008; NTSB 2013a; NTSB 2013b). Although most of these failures were attributed to the manmade hazards such as vehicular impact or construction overload, it is the condition state of the bridge structures that represents the most critical challenge for the transportation officials who are responsible for keeping these structures safe and sound in service. According to the National
Bridge Inventory (FHWA 2013), over 24% of more than 600,000 bridges in service in the United States are classified as either structurally deficient or functionally obsolete. These deficient structures suffer from a variety of in-service conditions which impose damage scenarios on different structural component. Depending the structural type and the surrounding environmental conditions, the deteriorating mechanisms can initiate and propagate throughout the structure, especially within the main-load carrying elements (e.g. girders), and degrade the capacity and operational safety of the in-service structures. Moreover, the existence of damage conditions would alter the load transferring mechanism within the system, from which the structure was designed for, resulting in local failures of the system components under the various loading scenarios during the service life of the structure (Gheitasi and Harris 2014a).

The main sources of damage conditions for different bridge systems have been recognized and well-documented in recent times (FHWA 2012). Over the past few years, several research studies have been conducted to characterize the main sources of defects associated with transportation infrastructure, especially highway bridges. The concept of structural health monitoring (SHM) is one of these developed methodologies that primarily focuses on monitoring the in-situ behavior to assess the in-service performance, detect damage scenarios, and determine the condition of the structure. Within this concept, recent advances in non-destructive evaluation along with novel achievements in non-contact measurement technologies (Ahlborn et al. 2012; Vaghefi et al. 2014; Vaghefi et al. 2012) have furthered the science of assessment. This would allow for more accurate evaluation of visible damage mechanisms and improve the confidence in locating the internal deteriorations. As a result of damage and deterioration, billions of dollars (U.S.) are required each year to repair or replace bridges that are reaching or exceeding their design lives (AASHTO 2012). While it is not feasible to repair all of these deficient structures at the same time, these ongoing deteriorations underscore the importance of quality inspection and interpretation of the collected data to prioritize the repair efforts for the bridges with more severe conditions.

2. Structural Health Monitoring of In-Service Bridges

The concept of structural health monitoring has been around for many years with implications over different structural systems, including transportation infrastructure. In theory, SHM can be likened to human health management system, in which service/operation assessment, maintenance, and repair/replacement are analogous to well-person check-ups, preventative intervention, and surgery, respectively. The outcome of this methodology can be illustrated as a real-time performance evaluation framework with capabilities to help transportation agencies characterize the behavior of in-service bridges in the presence of deteriorating conditions and predict the possible impeding failures. To date, the SHM community has emphasized an umbrella-type strategy for bridges and adopted the “Level IV” approach, as illustrated in Figure 1.

![Figure 1: Level IV approach to structural health monitoring](image-url)
Despite successful development of various detecting and monitoring techniques, there are a number of challenges that still need to be addressed before this innovative concept can be fully implemented in actual practices. In addition, with the sheer volume of bridges 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 categorized. In recent years, industry has attempted to take some of the research findings in the area of SHM into practice by developing long-term bridge monitoring systems to provide data that can be used by the preservation community. Nevertheless, these practices have been limited to high profile bridges (Ko and Ni 2005; Liu et al. 2009), while being met with skepticism by transportation agencies who are historically slow to adopt innovation. At the core of the skepticism is the cost of the detection systems relative to the size of inventory, the potential for large amounts of data and the manpower and skills required to interpret the results, and long-term durability and power requirements of installed devices (i.e. sensors).

In recognition of advancement in technology, many of these challenges can be overcome, especially within the first three levels of SHM including detection, localization, and assessment. However, the larger issues impeding the adoption of SHM concept into practice include the challenges associated with monitoring of existing structures with no previous baseline behavior measures as well as the implementation of the collected data in safety assessment and residual life estimation of the monitored structures (Level IV). In essence, current SHM practices are not without their limitations and it is evident that there is a pressing need for strategies and solutions that take a holistic view of the bridge life-cycle behavior, especially ones that can accommodate the large population of existing in-service bridges (FHWA 2013).

3. Problem to Address

While the ultimate goal of a bridge preservation strategy is to ensure a long service life and safety of existing structures, the SHM framework does appear to provide a promising solution for this prioritization. However, the main concern that still remains is a rational use of the collected data to correlate the impact of existing damage conditions on the performance of highway bridges. In fact, what transportation officials are lacking is a fundamental understanding of the system-level behavioral characteristics of in-service structures during their varying life stages. The development of this correlation would provide transportation decision-makers with a robust mechanism to estimate the safety and a remaining service life of in-service structures, but also a tool to rationalize decisions regarding long-term preservation strategies.

In current preservation practices, there exists a lack of comprehension with respect to the performance of in-service bridges beyond the component-based behavior in design (AASHTO 2012), especially when damage is present. The focus of this paper is to provide a fundamental understanding of the complex system-level interaction inherent to bridge systems and characterize the influence of common deteriorating conditions on the system behavior of representative bridge superstructures. Using a computational analysis framework, an efficient and practical modeling approach is presented in this study to investigate the performance characteristics of two representative common bridge types, composite steel girder and adjacent prestressed box girder superstructures, with both intact and damaged configurations. The accuracy and validity of the proposed numerical simulation and analysis were evaluated via comparing the results to the corresponding load testing data of the selected structures. Although the analyses and results presented in this paper are limited to the selected bridges, the methodology is generic and the rationale can be extrapolated to other bridge types to
establish damage-integrated baseline system performance measures, from which preservation decisions can be made for in-service bridges.

4. Method of Study

The core of this investigation was established based on the numerical modeling of representative bridge superstructures to characterize their behavior and understand the impact of common damage conditions on their performance and serviceability. The investigation approach was initiated by generating the numerical models for the selected structures with intact configuration. Upon validation of the modeling approach using experimental data, the calibrated models were updated with a series of damage and deteriorating conditions. The assumed damage scenarios are the ideal representatives of actual quantities that can be collected using different SHM technologies. Further details on the modeling approach, selected structures, assumed damage mechanisms, and discussion on the obtained results are provided in the following sections.

5. Selected Structures

The first structure selected in this study was a four-span continuous composite steel girder bridge, which was in service in the state of Tennessee and tested to failure (Burdette and Goodpasture 1971) to evaluate its ultimate strength and failure characteristics. This structure had a total length of 97.5 m (320 ft) having two interior and exterior spans. The superstructure consisted of a uniform thickness reinforced concrete deck supported by four identical rolled-shape girders (see Figure 2a). In the experimental program, a series of concentrated loads were applied on one of the interior spans at specific longitudinal positions to produce the maximum positive moment near the midspan (see Figure 2b). The bridge system failed due to concrete crushing in the curbs at the location of maximum moment associated with the formation of plastic hinges in the steel girders.

The second bridge system was a 43 year old, three-span simply-supported prestressed concrete adjacent box beam bridge in Ohio which was subjected to a full-scale destructive testing (Huffman 2012). All of the spans had 14.6 m length with a 15° left forward skew. Each span consisted of nine prestressed box beams, which were held together with a combination of transverse tie rods and shear keys (see Figure 2a). In the load testing program, the middle span of this structure was loaded to failure under the impact of a symmetric loading scenario which transferred the applied pressures over three patch areas across the width of the bridge (see Figure 2b). As reported, the test was terminated due to crushing of the concrete in the curbs, with significant cracking propagated through the loaded span. However, steel strands were reported to behave within their elastic range of behavior with no yielding observed.

6. FE Modeling, Analysis, and Validation

A commercial finite element package (ANSYS 2011) was used in this study to develop a numerical model for the selected bridges, validate their nonlinear responses, and capture the corresponding failure modes of these structures. For the steel girder bridge, an eight-node full integration solid element, Solid65, was used to simulate the concrete material. The internal reinforcement of the deck were modeled discretely using uniaxial tension-compression spar elements, Link180. Steel girders were modeled using a four-node reduced integration shall element, Shell181, while lateral bracing was provided by cross frames using two-node linear beam elements, Beam188.
With no evidence of loss in the composite action between the girders and the reinforced concrete deck in the experimental study, full composite action was assumed in the model by simulating the fully rigid connections. Figure 3a illustrates the model generated for this structure.

Figure 2: Selected structures (a) composite steel girder bridge (b) prestressed box girder bridge

For the box beam bridge, the concrete material and prestressing strands were modeled using similar elements implemented in the concrete deck of the steel girder bridge model. However, the prestressing forces were included in this model through initial strain conditions applied on the high-strength steel strands. Given the lack of information provided on the residual prestressing forces in the strands, a number of assumptions with respect to calculation of losses and refined tensile capacity of concrete were made to provide a better correlation between the experimental and numerical outcomes. In addition, shear reinforcement was included in the model in the format of closed loops with slight modifications based on the size and spacing provided in the test report (Huffman 2012). The transverse rods were also simulated with the same approach used for discrete modeling of the rebars in the concrete media, while the shear key were assumed to provide perfect bond between the girders. Figure 3b illustrates the numerical model generated for this structure. All sources of material nonlinearities, including cracking/crushing of the concrete as well as yielding and plastic deformation of the steel components were included in the FE models of these structures.

Figure 3: Developed FE models (a) composite steel girder bridge (b) prestressed box girder bridge
For the steel girder bridge, an ideal rigid perfectly plastic nonlinear spring was used to simulate the uplift that occurred in one of the abutments during the experiment. Additional boundary conditions were also provided in the model in the format of horizontal lines of supports on the bottom flanges of girders, at the location of intermediate pier as well as other end of the bridge (see Figure 3a). In the prestressed box beam bridge, the girders were joined to the intermediate piers and the end abutments using dowel rods that were grouted in during construction. In the model, the simulated bridge system was supported along 4 lines of supports to mimic the partial fixity and the restraint which were provided by the end rods and the width of the supporting pier/abutment, respectively (see Figure 3b).

Both of the models were loaded with a series of patch loads in accordance to the experimental setup. Nonlinear static analysis with small displacements was used in this study to capture the full nonlinear response of the simulated structures and postulate the failure characteristics observed in the corresponding load testing programs. To validate the proposed numerical modeling approach, the results obtained from the analyses were compared to the measured experimental data. For the steel girder bridge model, the load-deflection behavior at the centreline of the loaded span was selected for comparison. As depicted in Figure 4a, results obtained via nonlinear FE analysis are in a good correlation with experimental outcomes. Accordingly, the bridge model behaves linearly elastic prior to formation of first flexural cracks in the concrete deck (stage A). Beyond the first crack, the structure continues to carry additional loads until plasticity initiates in steel girders (stage B) and propagates through the depth to form plastic hinges (stage C). The analysis was eventually terminated due to crushing failure of the concrete deck close to the curbs (stage D).

For the prestressed box beam bridge, the load deflection behavior at midspan of the structure underneath the middle girder was monitored in the numerical analysis and compared to the experimental data for validation purposes. As illustrated in Figure 4b, the proposed model was able to predict the nonlinear response and the path to failure for this structure. However, there exists a discrepancy between the results especially after cracks initiated and propagated throughout the structure. This can be attributed to the simplifying assumptions, especially those related to simulation of the boundary conditions and shear keys with fully bonded characteristics. Future research will focus on refinement of boundary conditions and implementation of contact algorithm to simulate the actual behavior of the shear keys. It is envisioned that these refinements would help the model to better correlate with the experimental outcome, thus providing an improved understanding of the system-level characteristics in prestressed box beam bridges.

Figure 4: Model validation (a) composite steel girder bridge (b) prestressed box girder bridge
It should be highlighted that understanding the behavior of intact systems is a fundamental step in characterizing the behavior of the system in presence of different damage scenarios, while providing a rationale for safety assessment and service-life prediction of the in-service structures. Further details on the numerical modeling approach of the selected types of structures have been previously investigated by the authors and can be found elsewhere (Gheitasi and Harris 2014b; Gheitasi and Harris 2014c; Harris and Gheitasi 2013; Saliba et al. 2015).

7. Integration of Damage Conditions

With the validated intact behavior of the selected structures, a series of representative damage scenarios were chosen in this study to be integrated into the developed numerical models and investigate their potential impacts on the behavior of these structures. Figure 4 illustrates different analysis cases representing different types of defects that can be found in actual in-service structures. For the composite steel girder bridge, the validated intact model of structure was updated with three deteriorating conditions. In Case (S1), one of the interior girders was removed while the others were reconfigured to maintain the symmetric configuration within the cross section. This case could be a representative of a complete member loss in actual practices, where a main load-carrying member fails to serve its functionality due to vehicular/ship impact. Case (S2) represents 30% reduction in the thickness of the reinforced concrete slab. This type of damage can be postulated in actual structures in the format of scaling and/or spalling of the driving surface due to defects such as chemical reaction of the concrete with de-icers and/or corrosion-induced subsurface deteriorations.

In the numerical model of the corresponding intact system, it was assumed that girders were in full composite action with the reinforced concrete deck. However, with respect to damaged state of the structure, any defect in girder-deck connection would influence the behavior and performance of the system. As a result, the third damage scenario, Case (S3), was attributed to model the potential impact of girder-deck deterioration on the load-carrying capacity of this specific structure. For this case, surface-to-surface contact elements were implemented to model the interaction between top flanges of the girders and the bottom surface of the concrete deck in the loaded span. The mechanical properties of the contact elements were set such that the compressive stresses can be transferred between the surfaces, while the shear transferring mechanism was eliminated to simulate the ideal case of debonding along the length of the loaded span. Although in reality this case is less likely to occur, the updated model can represent the worst-case scenario (lower bound) with respect to the magnitude of bond deterioration that can take place in actual practices.

For the prestressed adjacent box girder bridge, on the other hand, two cases of damage were assumed and integrated into the calibrated model of the intact system. Case (P1) aims to demonstrate the impact of corrosion in prestressing strands on the overall behavior of this bridge system. In this case, the cross section areas of almost 70% of the strands within all girders of the structure were reduced by 25% (compared to the intact cross-section areas), to simulate the state of uniform corrosion in the girder. It should be noted that other damage scenarios may be associated with steel corrosion, such as bond deterioration, steel material degradation, and micro cracking in the concrete cover. However, integration of these coupled damage scenarios are beyond the scope of this investigation, but can be found in the previous studies of the authors (Gheitasi and Harris 2014d; Gheitasi and Harris 2014e). Moreover, extension of corrosion may eventually result in the rupture of prestressing strands. Case (P2) aimed at integrating this type of damage by rupturing 14 strands within the 3 middle girders of this structure. These strands were cut off at the midspan of the structure, with transfer lengths that were updates and included in the model at the corresponding location of rupture.
8. Discussion of Results

Under the same loading and boundary conditions that were assumed in the analyses of the intact systems, the revised models with integrated damage scenarios were analyzed. Results of the nonlinear analyses are presented in Figure 5 for both of the selected structures. As depicted in Figure 5a, the integrated damage conditions have major impacts on the ultimate capacity and overall system ductility of the composite steel girder bridge. Removing the middle girder in Case (S1) has the most severe influence on the system capacity, while increasing the ductility of the system. Reduction in the deck thickness has moderate impact on the ultimate bearing capacity of the structure, with almost no change in the ductility of the system. Nevertheless, changing the bond characteristics between the girders and reinforced concrete deck in Case (S3), imposes considerable impacts on both the ultimate capacity and system ductility. In this case, the simulated bond deterioration causes the girders in the loaded span to experience lateral instability on their top flanges. Moreover, loss in the composite action increases the amount of compressive stresses on the top surface of the concrete deck, which results in premature crushing of the concrete and thus major reduction in overall system ductility.

For the prestressed box beam bridge, on other hand, the simulated damage conditions have major influences on the ultimate capacity of the system, with more detrimental effects caused by the rupture in the prestressing stands. As it was previously mentioned, there were a number of uncertainties associated with the model of this structure, which are mainly related to the stiffness of the shear keys in the actual structure, as well as the residual prestressing forces in the strands at the time of testing. As a result of these uncertainties, predicting the actual failure modes of the structure with integrated damage conditions seemed to be a challenge. Therefore in the analyses, the developed models with both intact and damaged configurations were loaded to a certain level that caused the structure to reach the maximum deflection recorded in the corresponding testing program. As a result, no major impact was measured on the ductility of this bridge system under the impact of the assumed damage scenarios. Capturing the exact failure modes of the system requires refinement of the model, which is under consideration in this ongoing investigation.
9. Conclusions

Bridge superstructures play a key role in the national transportation network. Recent bridge failures in the North America highlight the need to understand the actual response of in-service bridges and estimate their remaining service lives under the effect of different deteriorating conditions. The overall objective of this study was to establish a modeling strategy to evaluate the in-service condition of two representative bridge superstructures by characterizing the impact of common deteriorations on the capacity and ductility of these systems. The damage scenarios assumed in this study were ideal representations of actual conditions and were selected to demonstrate the applicability of the proposed modeling approach. With improvements in the structural health monitoring practices and the corresponding non-destructive inspection techniques, more realistic damage data can be provided and integrated in the corresponding numerical analysis of any given bridge structure. The incorporation of condition state data obtained from periodic inspection coupled with damage-integrated system-level behavior characterization has the potential to provide a real-time estimate of system performance. By evaluating the system performance parameters with updated inspection data and extrapolating the degradation trend over through the design life of the structure, bridge owners can effectively estimate the remaining service life of the bridge systems and make appropriate maintenance decisions regarding the long-term preservation strategies and load rating practices. In addition, the numerical modeling approach proposed and implemented in this study has the potential to explore the implication over advances in materials, design methodologies and construction practices on the long-term performance of bridge superstructures.

10. References


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