Design of Coastal Bridges against Severe Storms and Sea-level Rise

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Abstract A vulnerability assessment of coastal bridges will be beneficial to policy makers prioritizing recovery efforts and allocating resources after severe storms such as a hurricane. This study identifies critical parameters necessary for the bridge vulnerability assessment, effectively correlates the input and output parameters by adopting a metamodeling approach, and produces a fragility function which describes the probability of failure of vulnerable coastal bridges in terms of wind speed and surge height. The input comprises of bridge parameters and hazard intensity measures, and the output parameters represent a binary classification of bridge failure or no-failure states. The results indicate that an evaluation of bridge girder bearing connections is essential in order to assess the force demand versus capacity and estimate the probability of bridge failures. This study also illustrates the importance of identifying practical hazard intensity measures and appropriate bridge parameters that affect the bridge performance, particularly when the proposed assessment method is applied to other coastal locations.

1 Introduction

Over the 20th century, average sea-level has risen by a total of 6.7 inches globally [1]. Rises in sea level heighten the surge risk associated with extreme storm events. Hurricanes and other severe storms have proven themselves to be one of the major threats to transportation assets throughout the world, particularly to bridges located along the coast lines. There are nearly 60,000 miles of roads located along the coastal regions of the United States susceptible to tropical storm and hurricane induced surge and waves.

The U.S. DOT's Gulf Coast Study [1] has assessed vulnerabilities of selected bridges and developed tools and resources to build resilience in future bridge designs. Current study, funded by the Georgia Department of Transportation, investigates the vulnerability of bridges along the Atlantic coast of

Georgia. It is proposed to employ an innovative meta-modeling approach to generate a fragility function which describes the performance of vulnerable bridges in terms of hurricane categories [2] which translate into five wind speed classes and surge height in this study. It is anticipated that the surge elevation will vary depending on the baseline water elevation or sea-level.

The main goal of this study is to identify potential hurricane vulnerability and compare options for improving and adapting resiliency for coastal bridges. The findings of this study will have a positive influence on future design and maintenance of bridges in the coastal communities and will be beneficial to policy makers prioritizing recovery efforts and allocating resources.

2 Methodology

A majority of bridges in the Georgia's coastal region are precast/pre-stressed concrete girders on pile bents, and thus this study focuses on evaluating the susceptibility of this bridge type. However, the methodology developed herein is intended to be applied to other coastal locations and bridge types.

Probabilistic models are frequently used but are often insufficient to quantify the vulnerability of hundreds or thousands of bridges with a wide range of hazard intensity and bridge parameters. This study engages in an analysis of natural hazards (or climate stressors) that can be generated by parameters pertained in the AASHTO Guide Specifications for Bridges Vulnerable to Coastal Storms (2008), hereafter referred as the 'AASHTO guide' [3]. This process will involve the identification of bridge modeling parameters, including hydraulic data, from available GDOT database, GIS data, National Bridge Inventory (NBI), bridge drawings, and parameters in the AASHTO guide.

One thousand and five hundred nonlinear bridge models are developed in the OpenSees software to apply a time history of wave loads as a function of associated wind speeds or hurricane categories. In the OpenSees analysis, different combinations of bridge geometric and material parameters are generated, and thus its models cover a wide range of bridge configurations and wave/surge loads. This study is particularly focused on the evaluation of bridge connections between superstructure systems and substructures such as bearing connections made by dowels and anchor bolts which are identified as vulnerable components to severe storm events.

It is noteworthy that the most significant bridge modeling parameters used in this study have been selected based on past hurricane studies [4] and a series of sensitivity analyses. Based on the OpenSees analysis results, a fragility function will be derived in which the probability of a bridge failure is predicted for a wide range of surge elevations and wave heights. Thus in this approach, the wave period is calculated using the Longuet-Higgins [5] joint probability of wave height and wave period [6]. Subsequently, these wave parameters are used to determine the applied forces.

2.1 Review of Available Hurricane Vulnerability Assessments

Fragility analysis methods are commonly used to assess the reliability of infrastructure, including bridges, subjected to natural hazards such as earthquakes. Reliability analysis methods used in a vulnerability assessment of bridges are generally intended to provide risk-based decision making considering uncertainties associated with structural response and hazard intensity measures such as peak ground acceleration or wind speed. The fragility analysis method is one of the reliability models which describe the probability of demand exceeding the capacity. Fragility analysis of bridges subjected to various hazards, including hurricanes, has been extensively studied in recent years [7-11].

2.1.1 Gulf Coast Study

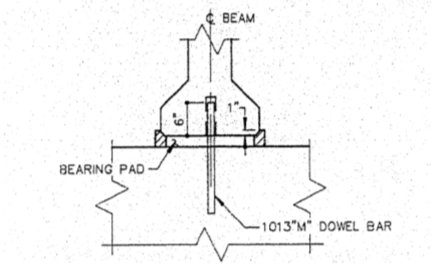
In the U.S. DOT's Gulf Coast Study, eleven storm scenarios were developed using Hurricane Georges and Hurricane Katrina as base storms and adjusting certain characteristics of the storms [1]. Storm surge was modelled for each of these storm scenarios using the ADvanced CIRculation model (ADCIRC). ADCIRC provided estimates of wind speeds, and wave characteristics were simulated using the Steady State spectral WAVE (STWAVE) model [12].

2.1.2 Susceptible Bridge Components

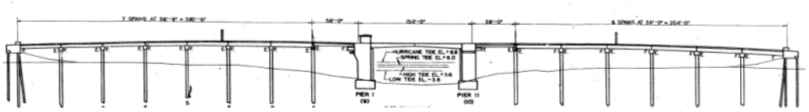
Previous studies indicate that bridge failures during hurricane events are primarily attributed to deck-unseating due to uplifting loads imposed by a storm surge and wave action [13-15]. Although the effect of wave and surge forces on offshore structures has been extensively addressed in the literature [16-18], little attention had been given to susceptibility of bridge components vulnerable to these forces.

Deck segments of low-level bridges in regions subject to coastal inundation should be restrained against uplift and provided with shear keys designed to resist all anticipated lateral loads [23]. However, limited shear keys are used in existing coastal bridges. Therefore, the tensile and shear capacity of bearing connections must exceed their anticipated loads. Figures 1 and 2 show typical bearing connection types commonly found in simply supported concrete bridges.

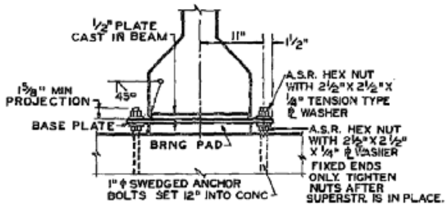
(a) Elevation View: Simply Supported Bridge (ID 029-0047-0)



(b) Elevation View: Bearing Connections by Dowels
Figure 1 – Typical Dowel Connection [22].



(a) Elevation View: Typical Simply Supported Bridge (ID 051-0146)



(b) Bearing Connection by Anchor bolts (Elevation View)
Figure 2 – Typical Anchor Bolt Connection [22].

2.2 Proposed Approach

The two hazard parameters (or climate stressors) considered in this study are ‘storm surge elevation’ and ‘wind speed.’ It is assumed that predominant failure modes result from deck shifting or unseating of simply supported concrete bridges [4], in the absence of shear keys on bent caps.

2.2.1 Vulnerability Assessment Objective and Methodology

This study focuses on storm-induced loads that can be generated by parameters pertained in the AASHTO guide. In this study, the dynamic loads resulting from actual wave action are applied to the 1,500 OpenSees models to perform a time-history analysis. Coastal bridges are subjected to significant hydraulic loads, including hydrostatic uplift due to buoyancy, which is amplified by the effect of entrapped air, and hydrodynamic uplift due to vertical wave action [23], particularly when bridge decks are submerged during a coastal inundation.

It is proposed that the vulnerability assessment employs a prediction model, often referred to as 'meta-models', to obtain a parameterized fragility function of coastal bridges subjected to hurricane induced wave and surge loads. In this approach, the vulnerability assessment procedure is mainly divided into three stages: (1) Generation of OpenSees models with a wide range of bridge and hazard intensity parameters; (2) Selection of a meta-model which best describes the observed relationship between input and output parameters; and (3) Fragility analysis to assess the vulnerability of any selected bridge. A metamodel in this study specifically refers to an approximation algorithm which predicts the bridge performance. The binary classification method (0-failure/1-no failure) is used to define the bridge performance as described in Section 2.2.2.

2.2.2 Fragility Function

The methodology to derive a fragility function is discussed herein. It provides the probability of occurrence for specified input and output variables. Vulnerability assessments generally involve training deterministic statistical techniques for creating meta-models, which are built around generating low-order polynomials using the least-square regression method [24]. Meta-modeling refers to an explicit representation of how a specific model is developed and thus generally represents a simplified mathematical function which defines the relationship between input and output parameters (the binary numerical system using '0's and '1's). This corresponds to bridge survival and failure in this study, and the binary outcomes are introduced to available meta-models [21].

$$P[Unseating \Big| X, U_{10min}, d_s] = \int_F f(\theta) d\theta \qquad \text{Eq. (1)}$$

In Eq. (1), X denotes a vector which includes bridge (structural and material) parameters; U_{10min} is the wind speed at the standard height of 10m averaged for 10mins; d_s is the storm water elevation at bridge location; f is the fragility function; θ is a function of structural and hazard intensity parameters, and F is the failure domain.

In this equation, the probability of failure is conditioned on two hazard intensity measures (e.g., U_{10min} and d_s) as well as a matrix of bridge input parameters or 'X'. In this manner, fragility estimates for each bridge sample can be obtained by introducing the input and output variables into a meta-model. For example, Eq. (1) provides the probability of deck unseating failure (or yielding a binary number of 0) for specified bridge input and hazard intensity variables.

3 Vulnerability Assessments of Coastal Bridges

One thousand and five hundred bridge models have been developed in OpenSees and run to determine the force demands at each bearing locations, resulting from a range of dynamic wave and surge loads. Figure 3 shows selected two models for illustration.

(a) 4-span model (b) 7-span model

Figure 3 – Illustration of Typical Bridge Models Developed in OpenSees.

3.1 Assessment of Vulnerable Components

Deck unseating during a hurricane event occurs either by vertical uplifting or a shear failure due to large horizontal forces resulting from hurricane or storm-induced wave and surge loads.

3.1.1 Bridge Deck Self-weight

In case of the superstructure uplifting failure, one or two bridge components are conventionally engaged in resisting uplifting forces. The self-weight of bridge deck is the primary factor for resisting the vertical forces [13] as well as resisting the horizontal forces (i.e., friction). Anchor bolts provided in the bearing connections should resist the remaining vertical force once the deck self-weight is overcome.

3.1.2 Bearing Connections

The two most common bearing connection types between substructure and superstructure include anchor bolts and dowels, and anchor bolts generally provide additional resistance beyond the point when the uplifting forces overcome the deck weight, whereas the dowels do not have the fall-back capacity [1].

3.2 Connection Capacity

Both dowels and anchor bolts provide the resistance to horizontal movement against wave-induced forces. The capacity of anchor bolts in the vertical direction is calculated as per Chapter 17 of ACI 318-14 [19]. The anchor strength for resisting uplifting forces is the smallest value of tensile strength of anchor steel material, concrete breakout strength in tension, and anchor pullout strength. The shear strength of anchor bolts and dowels are evaluated to resist the horizontal forces resulting from storm-induced wave and surge loads. The size of anchor bolts and dowels considered in this study are 2.54cm (1"), 3.18cm (1.25") and 3.81 (1.5"). The number of anchor bolts and dowels evaluated in this study is limited to 2 and 1, respectively.

4 Results

The following two sub-sections present the results of 1,500 OpenSees [20] model runs covering a wide range of bridge and hazard intensity parameters.

4.1 Horizontal Force Demand and Capacity

The horizontal force demands determined from the OpenSees analysis range between 0 kN and 500 kN as shown in Figure 4, noting that U_{10min} denotes the wind speed at the standard height of 10m averaged for 10mins and d_s is the storm water elevation at each bridge location. The force demands are compared against the shear capacity of anchor bolts and dowels. The friction developed due to the compressive load (or deck self-weight) is considered in the analysis.

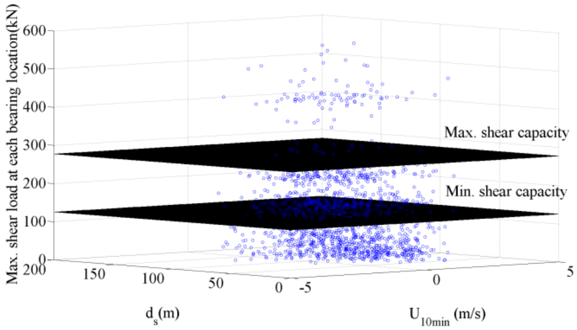


Figure 4 – Horizontal Force Demand versus Capacity.

4.2 Vertical Force Demand and Capacity

The vertical force demand at each bearing connection determined from the OpenSees analysis ranges between -100 kN and 200 kN, as illustrated in Fig. 5. The vertical forces are compared against the vertical capacity of anchor bolts (indicated as A. B. in Fig. 5) typically used in bridge bearing connections.

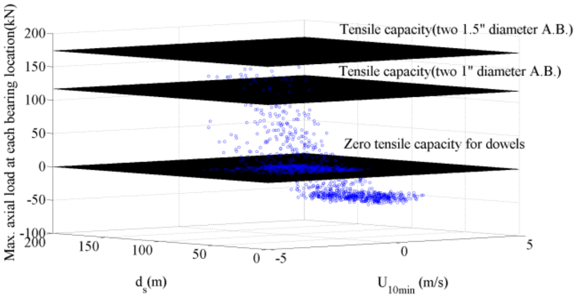
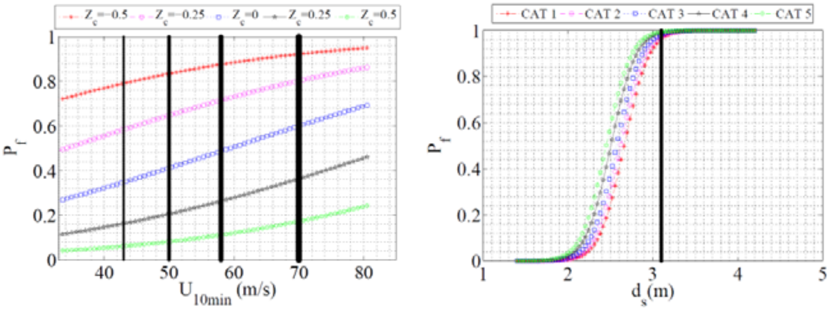


Figure 5 – Vertical Force Demand vs. Capacity (dowels provide no resistance).

4.3 Probability of Failure

Figure 6 presents the fragility curves for typical 7-span bridge shown in Fig. 3(b), where Zc denotes the distance from the storm water level to the bottom of girders. Therefore, negative Zc values indicate that the water level has reached the bridge girders. The bridge is more likely to fail when the storm water elevation increases. For instance, the probability of failure for this bridge is determined to be 90 % at a wind speed of 70 m/s. In Fig. 6(a), U_{10min} denotes the wind speed at the height of 10m averaged for 10 minutes, and the vertical solid lines represent the threshold wind speeds. Figure 6(b) presents the probability for varying water elevations, d_s. For d_s = 3.1m, the probability of failure ranges between 95 and 99%.



(a) IM: wind speed, U_{10min} (b) IM: storm water elevation, d_s.

Figure 6 – Probability of Failure (P_f) Given Hazard Intensity Measures (IM).

5 Discussions and Future Work

This study is part of an ongoing effort to evaluate the vulnerability of coastal bridges in the state of Georgia. In due course, the fragility curve will be extended to describe the probability of failures in terms of multiple hazard parameters. Thus, a fragility surface must be developed to visualize the results by means of a meta-model which yields an acceptable margin of error. While re-building new bridge structures above the highest storm surge level is the most desirable solution, coastal bridges are vulnerable to storm events may need to be designed differently. Furthermore, the following retrofit measures have been recommended for existing coastal bridges: (1) Implementation of high strength connections to prevent vertical displacement of bridge decks; (2) Addition of shear keys to prevent transverse displacement of bridge decks; and (3) Installation of restrainer cables to prevent the longitudinal motion [6]. It is important to note that large size dowels and anchor bolts do not necessarily decrease the probability of failure, due to unexpected load transfers between superstructure and substructure systems.

6 Conclusions

The primary objective of this study is to perform a vulnerability assessment of coastal bridges susceptible to hurricane-induced wave and surge loads. In the vulnerability assessment of Georgia's coastal bridges, the location of bridges in the water body (or sea-level) is considered as well as dynamic nature of wave loading. One of the main conclusions of this study is that it is important to critically review a set of climate stressors and bridge parameters that affect the performance of coastal bridges. The results indicate that bearing connection details between superstructure and substructures play a key role to a certain extent and that developing a parameterized fragility function will provide practical means to examine the vulnerability of coastal bridges for a wide range of hazard intensity parameters such as wind speed and storm water elevation. Therefore, it is concluded that an effort should made to understand regional hazard intensity limits and design details when a similar vulnerability assessment method is applied to other coastal locations.

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