Engineering Structures 103 (2015) 203–213

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Fragility surrogate models for coastal bridges in hurricane prone zones

Navid Ataei [a,*], Jamie E. Padgett [b,1]

[a] Freelance Researcher, USA
[b] Rice University, 6100 Main St., MS 318, Houston, TX 77005, USA

ARTICLE INFO

Article history:
Received 3 August 2013
Revised 2 July 2015
Accepted 2 July 2015
Available online 25 September 2015

Keywords:
Fragility
Coastal bridges
Hurricane
Statistical learning
Fluid–structure interaction
Random forest
Support vector machine

ABSTRACT

Simply supported multi-span bridges, that comprise the majority of bridges along the US Gulf Coast, are susceptible to the deck unseating failure mode under extreme wave and surge conditions cause by hurricanes. This paper explores central issues for accurate and efficient vulnerability assessment of such bridges under hurricane loads, including the validity of alternative surrogate models for probabilistic performance prediction as well as the modeling uncertainty introduced by adopting simplified loading profiles in the vulnerability assessment. First, a fluid–structure interaction (FSI) model that is capable of capturing the unseating mode of failure is presented to evaluate bridge deck displacements for fragility assessment. Then, different statistical learning techniques are compared to develop surrogate models of bridge fragility using the FSI model in order to reduce the computational expense of developing fragility surfaces, or statements of failure probability conditioned on hazard intensity. Additionally, due to the intricacies in developing FSI models and their significant computational burden, the use of simplified wave load profiles are explored for probabilistic performance assessment. Specifically, a modified wave load model is presented that adjusts existing estimates of wave forces on bridge decks based on insights from the FSI model. Finally, surrogate models using the modified wave loads are compared with those based on FSI analysis to quantify any additional modeling uncertainty introduced and provide further guidance for fragility assessment of coastal bridges.

1. Introduction

Observed bridge damage during past hurricanes underscores the need for methods to assess the reliability of bridges subjected to surge and wave. A primary mode of failure for coastal bridges is deck unseating [21,22,41,43], given the predominance of multi-span simply supported bridges not designed to resist surge and wave loads. Most of the current literature either focused on appraisal of wave and surge loads on bridge decks experimentally or numerically [13,20,21,31,37,51]; or reconnaissance reports describing the observed failure modes and assessment of empirical damage data for bridges [38,40,43,50]. Limited work has focused on methods to assess the vulnerability of bridges under hurricane induced loads, however. Estimation of fragility, or conditional probability of failure, is a central component of reliability and risk assessment of structures which is defined as shown in Eq. (1):

$$P_F = P[D \geqslant C|\mathbf{IM}] \tag{1}$$

where P_F is the probability of failure, D is demand, C is capacity, and **IM** is the vector of hazard intensity measures. A recent study provided a framework for rapid fragility assessment of large bridge inventories implementing static analysis in a Monte Carlo simulation targeted at bridges with limited capacity or no connections between the super- and substructure [5]. While this approach can serve to quickly screen vulnerable bridges, further investigation is required to evaluate structure-specific fragility or investigate alternative retrofits using more refined models that capture the complexity of dynamic response. Therefore, this paper introduces a fluid–structure interaction (FSI) model in Section 2, capable of capturing the unseating mode of failure and impact of alternative bridge design details on the response under surge and wave passage.

Although Monte Carlo simulation (MCS) offers a versatile approach for assessing the fragility of such complex systems, the nonlinear time-varying nature of FSI renders this a computationally infeasible solution. To reduce the computational expense, surrogate models have been employed in structural vulnerability problems to approximate the response of structures with predictive statistical models, or to estimate the limit state function using

* Corresponding author. Tel.: +1 503 729 8810.
E-mail addresses: navid.ataei@alumni.rice.edu (N. Ataei), jamie.padgett@rice.edu (J.E. Padgett).
[1] Tel.: +1 713 348 2325; fax: +1 713 348 5268.

http://dx.doi.org/10.1016/j.engstruct.2015.07.002

an approximating function [16,24,48]. For example, the structural fragility model can be presented as:

$$P_F = f(\mathbf{IM}) + e \quad (2)$$

where the surrogate model $f(\mathbf{IM})$ statistically predicts the fragility of the structure for a given set of intensity measures and e is the error due to the lack of fit of the surrogate model. While surrogate modeling techniques have found recent applications for earthquake engineering [25,52], design and optimization [26,34,53], and linear dynamic analysis [46], their ability to support bridge fragility modeling under hurricane loads has yet to be considered.

One strategy for utilizing surrogate models for fragility analysis includes constructing a surrogate model for failed/safe classification of the structure for a given set of input parameters, e.g. the failure outcome is predicted based on **IM**. In this approach, the response output from each simulation is compared to a threshold limit to generate the training data for the metamodel. This resulting information of predicted failure outcome is used to present fragility models in this paper for assessment of water-crossing bridge deck performance after a strong hurricane event. Such a metamodeling strategy improves efficiency of the fragility modeling by offering a predictive model of deck performance (e.g. failed or safe condition) as a function of **IM**, without requiring costly FSI modeling required by MCS. An acknowledged alternative perspective for using metamodeling in fragility analysis would be to construct metamodels for a continuous response parameter of the structure, where the response metamodels are themselves compared to capacity estimates for reliability computation. Typically when this strategy has been employed in the past, polynomial approximation has been employed to find the predictive models of structural response used in structural vulnerability studies; these models are known as response surfaces [48,49]. However, response surface models are generally not appropriate for capturing abrupt failure modes since they provide a relationship between continuous hazard intensity measures and a continuous outcome, and past studies have advised against the use of traditional surrogate models such as response surface models for highly nonlinear and non-smooth behavior [18]. Bridge deck unseating caused by surge and wave loading is generally characterized as such an abrupt failure mode [5] where the deck displacement behavior is highly nonlinear. Thus to avoid the undue introduction of significant uncertainty posed by a continuous response prediction metamodel for this case, and directly pursue the desired outcome of characterizing likely failed or safe performance given **IM**, this paper focuses evaluating classification based metamodeling strategies for use in efficient fragility modeling of coastal bridges.

Logistic regression is a commonly used tool for classification of binary data [39] and has been employed in various fields for predicting the probability of failure of a system [44,54]. Additionally, emerging statistical learning techniques, such as support vector machines (SVMs) [19] and random forests [47] are well suited for classification of categorical data. However, these tools have not been considered for the fragility assessment of structures under hurricane hazard and have been minimally explored for structural fragility problems in general. Given the computational complexity of bridge response assessment under surge and wave action, the above surrogate modeling techniques are compared in Section 3 for estimation of deck unseating fragility under hurricane events. Recommendations on the best surrogate modeling technique for this problem are presented on the basis of goodness-of-fit estimates.

Furthermore, while the identification of viable surrogate models can render fragility analysis of coastal bridges feasible requiring fewer simulations, the use of FSI for dynamic analysis of bridges under surge and wave load is itself computationally intense [11,33]. Particularly if the notion of bridge fragility modeling is to be extended to practice or to the practical assessment of many coastal bridges across a region, simplified methods of structural analysis may be preferred. Section 4 presents a modification of existing wave load models, as an alternative to FSI. Such wave load models can significantly reduce the computational time by reducing the multi-physics problem to a single-physics one (structure only). Fragility surfaces are also constructed using the identified superior surrogate model based on the dynamic response data generated from applying the modified wave load profile. The resultant fragility surfaces from the FSI model and the bridge with modified wave load are compared to uncover any additional uncertainty introduced in the fragility analysis attributed to simplified numerical modeling. Such outcomes offer guidance on viable surrogate model and numerical model, along with uncertainty quantification, for accurate and efficient fragility analysis of coastal bridges.

2. Fluid–structure interaction model and modeling parameters

A case study bridge is used in this paper to test the application of different surrogate models to predict the deck unseating failure mode, given hurricane hazard parameters. The numerical model is developed in the ADINA software package [2]. The following subsections describe the FSI numerical modeling technique, the case study bridge structure, and the variables used to define the model that are considered random in the probabilistic analysis.

2.1. Model definition

For this study, the waves' incident angle is considered to be zero; i.e., the wave direction is perpendicular to the bridge longitudinal axis. Subsequently, the response of the bridge is mainly in the transverse direction and the bridge is modeled in the transverse plane only (2-dimensional), which significantly reduces the computational time. The fluid flow is modeled as an incompressible turbulent flow. To accommodate turbulence, the fluid domain is solved by Reynolds-averaged Navier–Stokes equations accompanied by the $k-\varepsilon$ turbulence flow model in an arbitrary Lagrangian–Eulerian coordinate system. The volume of fluid method is adopted for the fluid domain to avoid the need for re-meshing; and thus, to reduce the simulation time. The volume of fluid method was first introduced by Hirt and Nichols [28] for finite difference simulations, and later adopted in other numerical methods such as finite element method.

Relative surge elevation (Z_c) denotes the distance between the bottom line of the bridge deck and the water level. Water depth during the storm surge (d_s), maximum wave height ($H_{\max}$), and wave period (T_p) are the input parameters for the fluid boundary conditions. These parameters are employed to calculate the wavemaker velocity profile. Waves are generated by applying a moving wall boundary condition to the inlet of the model to simulate the wavemaker. The time history of the wavemaker is developed based on the approach presented in Huang and Dong [30].

A case study bridge is selected from the Houston/Galveston bridge inventory [3] to demonstrate response under hurricane induced surge and wave, and later test the application of surrogate models in the coastal bridge fragility analysis. Fig. 1 depicts the bridge geometry as well as wave and surge parameters. The bridge deck width is 11 m, and the slab thickness is 0.2 m supported by six AASHTO type III girders. The bent beam is supported by three square columns of 0.8 m dimension. The case study bridge, similar to most bridges in the area, does not have any connection between super- and substructure. This configuration is typical for the bridge inventory in the greater Houston area [7].

The structure domain is modeled by 2-dimensional solid elements representing the concrete, and truss elements representing