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Vulnerability to failure of cable-stayed bridges for beyond-design basis wind events

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ABSTRACT

This paper develops a vulnerability assessment framework for cable-stayed bridges based on critical elements identified through a failure analysis. The framework refers to a simple and effective model developed to assess the vulnerability of a bridge failure due to beyond design-basis wind loads. The proposed framework differs from the probability-based approach in that it uses a cable-stayed bridge in operation, not a prototype bridge for fragility assessment, to identify critical elements vulnerable for a bridge failure. Furthermore, this study provides a detailed procedure to calculate the wind loads that account for varying wind speeds. The vulnerability index is defined as the demand-to-capacity ratio determined at threshold wind speeds. By assessing a cable-stayed bridge located in southeastern Georgia in the U.S., it is demonstrated how the proposed framework and analysis model can be successfully used to verify the results, identify critical elements associated with bridge failures for beyond design basis wind speeds, and assess the vulnerability. It is also concluded that a sensitivity analysis of significant variables such as aerodynamic pressure coefficients and dynamic load factor identified through this study is noteworthy, in order to accurately define analytical sensitivity and establish a practical limit on wind speeds for determining if a bridge closure is necessary thorough a vulnerability assessment study.

1. Introduction and motivation

Cable-stayed bridges are increasingly becoming an appealing option in North America with many located on the Mississippi River, Ohio River, and the eastern seaboard in the United States. They are often situated along the open coastlines that are vulnerable to major hurricanes [1] due to its ability to offer longer spans and are generally designed to meet the requirements for minimum wind loads in the LRFD AASHTO bridge design specifications [2]. However, cable-stayed bridges are designed for 100-year design wind speed and thus remain vulnerable to significant environmental forces such as hurricanes and severe windstorms due to their relatively lightweight, flexibility, and low damping ratios ranging between 0.55% and 1.5% [3]. Cable supported precast/post-tensioned concrete deck and tower structures are relatively flexible than other structures and thus are easily excited by wind loading. The excitation forces acting on cables and cable-supported concrete bridge superstructures are aerodynamic by nature, and their response is highly dependent upon their underlying structural dynamics of the bridge components. Therefore, understanding the response of cable-stayed bridges to large magnitude wind forces is essential for predicting the vulnerability to failure due to beyond design-basis wind forces.

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This study develops a vulnerability assessment framework for cable-stayed bridges based on critical elements identified through a failure analysis. A simple and effective model is proposed to assess the vulnerability of a bridge failure due to beyond design-basis wind loads. The proposed framework differs from the probability-based approach in that it uses a cable-stayed bridge in operation, not a prototype bridge for fragility assessment, to identify critical elements due to a bridge failure.

The Eugene Talmadge Memorial cable-stayed bridge in Brunswick, Georgia is analyzed to illustrate the vulnerability assessment procedure. Due to the location of this bridge near the coast, it is subject to high wind loading as it is in the direct path of hurricanes. This bridge has been in service since 1991, with an estimated construction cost of $65 million at the time of construction. It has been closed to traffic several times at the imminent threat of hurricanes such as Matthew (2016) and Irma (2017).

1.1. Significance and scope of the study

By performing an assessment of failure due to beyond design basis winds on the Talmadge cable-stayed bridge, both experience and knowledge are gained on how the bridge behaves and performs to beyond design basis wind loads. In performing the proposed vulnerability assessment for failure, state transportation agents should be able to identify the point at which the load demand exceeds the load carrying capacity. The proposed framework provides a comprehensive performance evaluation procedure associated with severe wind loading and outlines the method from the initial interpretation of construction documents to identification of vulnerable bridge elements resulting from hurricane wind forces.

A failure analysis often includes an inelastic analysis utilizing nonlinear materials; however, in the proposed approach, only a geometric nonlinearity is considered. That is, a redistribution of forces, which requires an iterative solution, is not considered. The criteria for determining the capacity of reinforced concrete sections are the stresses required to yield the tension steel enabling an engineer to identify vulnerable points of a structure. It should be recognized that the intent of the proposed study is to identify the most critical bridge elements for beyond design wind loads. The design basis wind speed is 41 m/s (or Category 2). That is, the wind speed of 41 m/s was the required wind speed that the bridge needed to be designed in accordance with the LRFD AASHTO Bridge Design Specifications (1983) [2]. All wind speeds greater than 41 m/s are considered herein for beyond design-basis cases. Table 1 presents the hurricane categories and associated wind speeds. The assessment of a progressive failure is beyond the scope of this study.

1.2. Limited information on wind analysis available in literature

A review of the literature was mainly focused on understanding the underlying structural dynamics of cable-stayed bridges and their supporting structures. In studying previous work on the subject of wind analysis of cable-stayed bridges, few sources were found. Previous studies do not provide much detail on the dynamic response [4].

1.3. Representation of dynamic wind effects and vibration problems

A statistical method accounting for mean, resonant, and background forces for loading has been experimentally studied within wind tunnel tests [5]. A more recent study considers the dynamic contributions through an evolutionary random process [6]. Another approach involves the use of gust loading for dynamic load [7] although this method requires a full wind tunnel test to incorporate the structure's behavior at both low and high wind speeds. The aerodynamic wind forces result in vibrations of the bridge deck and/or cables and can cause torsional divergence, flutter, galloping, and ultimately collapse [4,8–11]. In addition, rain-wind induced cable vibrations have been reported for a relatively low wind velocity, and rehabilitation schemes such as cable ties are studied for mitigating a cable vibration problem [12].

Generally, a CFD analysis or a wind tunnel test of a scaled-bridge model is conducted to evaluate the wind-induced structural response and aerodynamic pressure coefficients needed for cable-stayed bridge analysis and design. The aerodynamic pressure coefficients are generally used to quantify wind forces needed for bridge design. Most of all, a wind tunnel test should be conducted to verify bridge design against flutter, vortex induced vibration, and buffeting.

Table 1
Hurricane wind speeds.

Categories	Minimum		Maximum	
	m/s	mph	m/s	mph
1	33.1	74	42.5	95
2	42.9	96	49.2	110
3	49.6	111	57.7	129
4	58.1	130	69.7	156
5	70.2	157	70.2	n/a