

Hurricane Buffeting-Induced Life-Cycle Downtime Risk Assessment of Long-Span Coastal Bridges with Performance-Based Wind Design

Ruiqing Han^{a,b}, Teng Wu^b

^a School of Civil Engineering, Central South University, Changsha 410083, China, Email address: hrq2022@csu.edu.cn

^b Department of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo, NY 14126, USA, Email address: tengwu@buffalo.edu

SUMMARY

The performance-based wind design (PBWD) of long-span bridges permits controlled inelasticity/nonlinear behaviours of selected structural components. While PBWD can potentially reduce bridge construction cost, the bridge components may suffer various damages under hurricane buffeting-induced vibrations and their inspection and repair may significantly impact daily life and economic activities. Hence, it is important to effectively evaluate the downtime of long-span bridges during their service life. Considering the stochastic nature of hurricane winds as well as the uncertainties in structural dynamics and aerodynamic properties, this study develops an efficient and reliable procedure for hurricane buffeting-induced life-cycle downtime risk assessment of coastal long-span bridges, consisting of hurricane wind hazard, bridge fragility analysis and downtime calculation modules. In addition to structural damage, the occupant discomfort and non-structural component failure are also considered in the life-cycle downtime risk assessment. An existing cable-stayed bridge is used to calibrate and validate the developed downtime risk assessment framework.

Keywords: Long-span bridge, Life-cycle downtime, Risk assessment, Hurricane buffeting, PBWD

1. INTRODUCTION

Long-span coastal bridges are vulnerable to hurricanes during operation. Since the conventional prescriptive design does not allow structural yielding, the disruption of bridges due to hurricane buffeting-induced vibration is mainly controlled by the occupant discomfort (in addition to driving safety consideration). The performance-based wind design (PBWD) of long-span bridges permits controlled inelasticity/nonlinear behaviours of selected structural components, they may suffer various damages under hurricane buffeting-induced vibrations. The inspection and repair of structural and non-structural components after major hurricanes may require full or partial closure the long-span bridges, and accordingly may significantly impact daily life and economic activities. Hence, it is important to effectively evaluate the downtime of coastal long-span bridges during their service life. Given the inherent randomness in hurricane winds, aerodynamics, and structural properties, the downtime caused by these wind-inconvenience events are probabilistic. Therefore, this study develops an efficient and reliable procedure for hurricane buffeting-induced life-cycle downtime risk assessment of coastal long-span bridges, consisting of hurricane wind hazard, bridge fragility analysis and downtime calculation modules. In addition to structural damage, the occupant discomfort and non-structural component failure are also considered in the life-cycle downtime calculation. An existing cable-stayed bridge is used to calibrate and validate the developed downtime risk assessment framework. Two case studies respectively involving prescriptive (elastic) and performance-based (inelastic) bridge designs are examined to highlight their different life-cycle downtime due to the hurricane buffeting-induced structural vibrations.

2. LIFE-CYCLE DOWNTIME RISK ASSESSMENT PROCEDURE

The downtime assessment considers three triggering events, namely occupant discomfort, electrical equipment failure, and various degrees of structural damage to bridge components (e.g.,

bridge deck and tower). Considering that these wind-induced inconvenient events tend not to occur in isolation in real situations, it is necessary to consider scenarios where multiple events occur simultaneously in life-cycle downtime assessment. With reference to the typical life-cycle cost analysis model proposed by Wen and Kang (2001), the life-cycle downtime risk assessment algorithm of long-span bridges induced by hurricane buffeting is established as:

$$E[T(t)] = E \left[t e^{-\varepsilon t} \left[(\lambda_c - \lambda_e) T_c + (\lambda_e - \lambda_1) T_e + \sum_{i=1}^{n-1} (\lambda_i - \lambda_{i+1}) (T_c, T_e, T_1, \dots, T_i)_{max} \right] + \lambda_n (T_c, T_e, T_1, \dots, T_n)_{max} \right] \quad (1)$$

where $E[\]$ represents the expectation operator; t denotes the service years of the long-span bridge; λ_c is the annual average occurrence frequency of occupant discomfort events; $\lambda_c - \lambda_e$ is the annual average occurrence frequency of events involving occupant discomfort only; T_c is the downtime corresponding to the occurrence of occupant discomfort once; λ_1 is the annual average occurrence frequency of the highest probability event among various damage levels of bridge deck and tower; $\lambda_e - \lambda_1$ is the annual average occurrence frequency of events involving only occupant discomfort and electrical equipment failure; T_e is the downtime corresponding to electrical equipment failure; n is the sum of the damage levels of the bridge deck and tower; λ_i is the annual average occurrence frequency of the i -th highest probabilistic damage events of bridge deck and tower; $(T_c, T_e, T_1, \dots, T_i)_{max}$ is the maximum downtime among i simultaneous wind-induced inconvenience events; λ_n is the annual average occurrence frequency corresponding to the event with the lowest annual average probability among those structural damage events of bridges; $(T_c, T_e, T_1, \dots, T_n)_{max}$ is the maximum downtime among those structural damage events of bridges; $e^{-\varepsilon t}$ is a time-dependent reduction factor for downtime; ε denotes a constant annual reduction rate, with a value of 0.01.

Considering that wind-induced inconvenient events occur independently throughout the life cycle, this study assumes they follow a Poisson distribution ($P\{X = k\} = \frac{\lambda^k e^{-\lambda}}{k!}$, $k = 1, 2, 3, \dots$ where X is the random variable and k is the specific number of event occurrences). Thus, the annual occurrence probability (P_{risk}) (probability of occurring at least once per year) can be calculated as: $P_{risk} = P(X \geq 1) = 1 - P(X = 0) = 1 - e^{-\lambda}$. Accordingly, the annual average occurrence frequency for various wind-inconvenient events can be calculated as:

$$\lambda = -\ln(1 - P_{risk}) \quad (2)$$

where λ is the annual average occurrence frequency. The annual occurrence probability (P_{risk}) can be obtained by the convolution of hurricane hazard curves and structural fragility curves:

$$P_{risk} = \int P_f(U) d\lambda_{hur}(U) \quad (3)$$

where $\lambda_{hur}(U)$ is the hurricane hazard function; $P_f(U)$ is the probability density function (PDF) of the fragility function. For hurricane wind hazard, simulated tracks (10,000 years) are used to fit a Weibull distribution for wind speed. For bridge fragility, incremental dynamic analysis (IDA) is performed using a subset of hurricane records selected via k -means clustering. Uncertainties in wind direction, aerodynamic coefficients, material properties, and damping are incorporated via Latin hypercube sampling. The performance threshold for the occupant discomfort is defined as 3.6 m/s^2 for vertical acceleration (JTG/T 3360-01 2018); the performance threshold for electrical equipment failure is defined as 0.5 g of acceleration (Li et al. 2024); the performance threshold for

various degrees of structural damage to the deck and tower is discussed by Li et al. (2018) as shown in Table 1. For downtime calculation, it is modeled using a normal distribution considering uncertainties in repair progress. Specific downtime values are drawn from the Chinese standard RISN-TG041 (2022). For long-span bridge components, slight damage corresponds to 0.6 ± 0.6 days, moderate to 2.5 ± 2.7 days, severe to 75 ± 42 days, and complete damage to 230 ± 110 days. Electrical equipment repair is defined as 3 ± 1.5 days. Since the standard does not address pre-operation inspection time, this study conservatively assigns an additional 0.5 ± 0.5 days for inspecting all components and equipment before resuming normal service. To rationally evaluate hurricane-induced downtime for coastal long-span bridges, this study incorporates the mean hurricane duration into the risk assessment framework. Considering the bridge closures typically occur at wind speeds of 25 m/s in current operational practices, this threshold is adopted to define hurricane duration.

Table 1: Performance levels and thresholds of the bridge deck and tower.

Components	Engineering demand parameters (EDP)	Slight damage	Moderate damage	Severe damage	Complete damage
Deck	Displacement (m)	/	$L/1200 \sim L/600$	$L/600 \sim L/400$	$> L/400$
Tower	Drift Ratio (%)	$0.7 \sim 1.5$	$1.5 \sim 2.5$	$2.5 \sim 5.0$	> 5.0

3. CASE STUDY

3.1. Hurricane-Bridge model and validation

The Sutong Bridge, a 1088-m main-span coastal cable-stayed bridge, serves as the case study for both elastic and inelastic design. The elastic design retains the original structural form, while the inelastic design reduces certain design parameters to introduce controlled inelastic behavior. Both bridge models are developed in ANSYS, and their accuracy is verified by comparing the first 20 modal frequencies and shapes with the literature. Extreme wind speeds of simulated hurricanes are fitted to a Weibull distribution, yielding a 100-year return period speed of 46.51 m/s, slightly lower than the code value of 49.7 m/s. Statistical analysis of 28,889 simulated hurricane records at the bridge site, assuming a Gamma distribution, yields a mean hurricane duration of 9.5 hours. Ten representative records are selected using a k -means clustering algorithm for IDA. For fluctuating wind simulation, the along-wind and vertical spectra follow the Kaimal and Panofsky spectra, respectively. Due to the rareness of the structural damage allowed in the existing (elastic) bridges, the repair activities (mainly involving non-structural damage) are typically scheduled in subsequently planned maintenance (inspections and repairs) rather than immediately after hurricane events, partially explaining the lack of emergency repair reports.

3.2. Results and discussion

The life-cycle downtime of the long-span bridge (with elastic design) caused by hurricane buffeting is shown in Fig. 1(a). Hurricanes significantly impact the operational status of the long-span bridge throughout its life cycle. For a 100-year service life, the corresponding cumulative downtime (mean value) amounts to 289 days. Figure 1(b) and 1(c) present the proportional distribution of downtime attributable to various events. The proportions for occupant discomfort, electrical equipment failure, and bridge deck damage are 5.1%, 43.2%, and 47.7%, respectively, and the bridge towers account for only 4%. The non-structural damage events (along with occupant discomfort) account for nearly 50% of the total downtime.

For the inelastic design case, selected parameters of the Sutong Bridge are modified to introduce inelastic behavior. Specifically, the plate thicknesses are optimized for the deck with the top and bottom plates (t_1 , t_2) reduced by 2 mm each, the upper and lower inclined plates (t_3 , t_4) by 4 mm

each, and the heights of the upper and lower stiffeners (h_1 , h_2) by 20 mm and 50 mm, respectively. For the tower, cross-sectional dimensions are reduced at the base and the cross-beam level, including decreases in length, width, and wall thickness. It is noted that a more rational approach for inelastic design could involve applying a response modification factor (R_w) to reduce design wind loads. The life-cycle downtime for the inelastic design is shown in Fig. 2(a), yielding a cumulative downtime of 330 days over a 100-year service life. Figure 2(b) and 2(c) show the contribution of different events to the total downtime. Compared to the elastic design (289 days), the inelastic design incurs more cumulative downtime. The proportional contributions are 5.5% (occupant discomfort), 44% (electrical equipment failure), 46.6% (deck damage), and 3.9% (tower damage). The proportion of downtime due to structural damage is slightly lower than that in the elastic design.

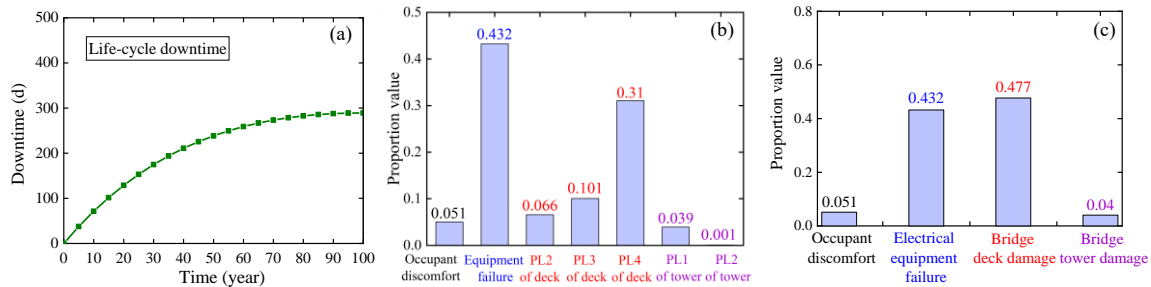


Figure 1: Total life-cycle downtime and proportional distribution of various events for an elastic design bridge.

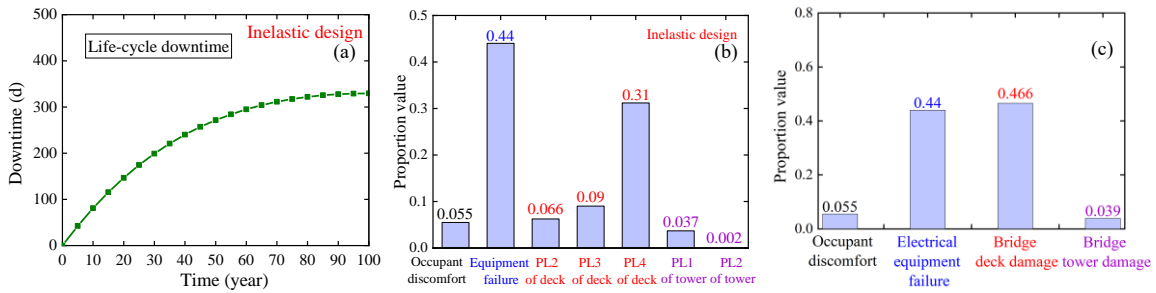


Figure 2: Total life-cycle downtime and proportional distribution of various events for an inelastic design bridge.

CONCLUDING REMARKS

This study developed an efficient and reliable procedure for hurricane buffeting-induced life-cycle downtime risk assessment of coastal long-span bridges, consisting of hurricane wind hazard, bridge fragility analysis and downtime calculation modules. The case study of Sutong bridge involving a comparison between elastic and inelastic designs showed that bridges with inelastic behavior experience more life-cycle downtime under hurricane buffeting.

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