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# Probabilistic fatigue damage assessment of coastal slender bridges under coupled dynamic loads

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ABSTRACT

With coupled dynamic interactions of vehicle-bridge-wind-wave (VBWW) system, fatigue damage accumulations at complicated weldments of the orthotropic steel deck (OSD) for coastal slender bridges could be critical and might affect structural safety and reliability. Due to the stochastic nature of the environmental loadings including vehicles, wind and waves, it is challenging to include uncertainties for the assessment of the fatigue damage accumulations in the bridge's life cycle. In the present study, an efficient probabilistic fatigue damage assessment framework for coastal slender bridges is proposed with a machine learning algorithm to include the coupled stochastic dynamic loads in the VBWW system. Firstly, stochastic load models are developed based on the long-term field measurements for realistic modeling of the truck load and the correlated wind and wave load, which serve as the input for the VBWW system to extract the stress time histories at critical structural details using multi-scale finite-element analysis (FEA). After calculating the equivalent stress range and the corresponding number of cycles using the rain-flow counting method, the daily equivalent fatigue damage is obtained using the linear fatigue damage rule. To reduce the calculation cost, a machine learning algorithm is utilized for probabilistic modeling of the daily equivalent fatigue damage by integrating uniform design and support vector regression to link the multiple random inputs of environmental loadings with the single output of the stress time history. The fatigue life of critical structural details, therefore, can be obtained using the established limit-state function with a target reliability index. A prototype cable-stayed bridge in a coastal region is presented to demonstrate the effectiveness of the proposed simulation framework. Finally, the impacts of the traffic growth including the traffic volume and the gross vehicle weight on the fatigue life of three welded joints are investigated and discussed, as well.

## 1. Introduction

Serving as critical links in the transportation network for coastal regions, costal slender bridges could constantly experience complex dynamic interactions with strong winds and/or high waves during extreme weather conditions, in addition to moving vehicles, such as cars, trucks, or trains. Continuously repeated stress cycles as well as corrosive coastal environments could cause significant fatigue damage accumulations through the complex interactions of vehicle-bridge-wind-wave systems during the bridge's lifetime [1]. Many approaches have been proposed for fatigue damage evaluation of existing long-span bridges, which can be mainly categorized in two groups: finite-element analysis (FEA)-based approach [2,3] and structural health monitoring (SHM)-oriented approach [4]. Recently, increasing attentions have been paid to the hybrid approach that integrates the FEA and the SHM [5], aiming to seek more reliable and effective methodologies for fatigue performance evaluation. The FEA can be used to pinpoint the critical structural details, while the SHM serves as an essential supplement for validation as well as to provide site-specific loading information.

For the FEA approach in particular, challenge still remains in modeling the large-scale coastal slender bridges. Due to the complexity of the structural details, the length scale of the local structural details in the FEA, where fatigue damages are usually initiated, are much smaller compared with that of the entire structure. A high-fidelity FEA model that includes all structural details is usually computational prohibitive due to a huge number of degrees of freedom involved if not impossible. To this end, many multi-scale/multi-level modeling schemes that include a refined FE model built with detailed geometry or substructure modeling schemes with homogenized material properties considering mesoscale or microscale material properties, are proposed [6–8,15–18]. Nevertheless, these modeling schemes usually only have deterministic parameters for the analysis to save the calculation cost. Uncertainties associated with the fatigue damage accumulation process, therefore,

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**Table 1**
Classifications of effective fatigue vehicles.

| Vehicle type | Axle spacing (m) | Total occupancy rate (%) | Occupancy rate in each lane (%) | | |
|---|---|---|---|---|---|
| | | | Slow lane | Middle lane | Fast lane |
| $V_2$ (Two-axle truck) | 5.0 | 56.29 | 19.76 | 31.18 | 5.35 |
| $V_3$ (Three-axle truck) | 4.0, 3.0 | 2.90 | 1.50 | 1.29 | 0.11 |
| $V_4$ (Four-axle truck) | 3.3, 6.6, 1.3 | 3.20 | 1.81 | 1.24 | 0.15 |
| $V_5$ (Five-axle truck) | 3.2, 6.9, 1.6, 1.3 | 15.35 | 8.80 | 6.22 | 0.34 |
| $V_6$ (Six-axle truck) | 2.9, 1.5, 6.9, 1.3, 1.3 | 22.26 | 13.18 | 8.79 | 0.28 |

could not considered. However, uncertainties from the ambient environment, such as the stochastic dynamic loads from vehicles, wind and waves as well as the other environmental parameters, such as the temperature, humidity, chloride density, etc., could affect the fatigue damage prediction significantly. As a result, there are strong needs for the reliability based approaches for fatigue damage assessment of a coastal slender bridge.

To include the aforementioned stochastic loads, the conventional reliability based approach usually involves with a large-scale FEA runs, or Monte-Carlo simulations (MCS), which could be very computationally expensive, if not inhibitive. To this end, several approaches have been proposed to avoid the exhaustive-computational MCS. Kwon et al. [9] proposed a probabilistic approach for modeling the equivalent stress range for a ship, in which the continuous domain of loading parameters are discretized into a series of representative blocks with associated probabilities of occurrence. Similar approach was also adopted for bridges by Zhang et al. [3], in which lifetime wind and traffic loads are partitioned into several representative blocks. Later on, Yan et al. [10] proposed a fatigue stress prediction strategy for OSD under cyclic truck loads, in which the random truck load parameters such as axle weight and location are considered by integrating the influence surfaces with the regression model. Recently, Lu et al. [11] proposed a machine learning algorithm to develop a regression model between the input traffic load and the output stress with limited number of FEAs, to enable efficient fatigue performance evaluation.

Although many works have been carried out for fatigue reliability analysis of steel bridges, research on the combined effects of vehicles, wind, and waves on the coastal slender bridges are still limited due to the complexity of the coupled structural dynamic system. Based on the established VBWW system [12], this study proposes a framework for probabilistic fatigue damage assessment of coastal slender bridges by combining the multi-scale FEA with SHM. Firstly, the stochastic load models are established using the site-specific SHM data: the truck load model is characterized by the vehicle type, vehicle-occupied lane, and the vehicle gross weight; the correlated wind and wave model is parameterized with the wind speed, wave height, and the wave period. Secondly, multi-scale FEA is performed using the established load models as the dynamic input to compute the stress responses at critical welded joints, which are further transformed into the daily equivalent fatigue damage accumulation based on the Miner's law. To overcome the time-consuming issue in dealing with the stochastic loads, a machine learning algorithm, i.e., support vector regression (SVR) model, is implemented to substitute large-scale FEA simulations to improve the computational efficiency. Finally, the efficiency and accuracy of the proposed framework is illustrated through a case study on a coastal cable-stayed bridge. The effects of the traffic, wind and wave loads on the fatigue damage of the OSD is discussed. The impact of an increase in the traffic volume and the vehicle weight on the fatigue reliability is investigated, as well.

## 2. Modeling of stochastic dynamic loadings

Primary structural loads on coastal slender bridges include those from the traffic, wind, and wave. Since the structural loads are stochastic in nature and can be affected by many factors, it is vital to parameterize these loads using parameters that contribute most to the structural fatigue damage. In the present study, the following fatigue-related parameters will be included: the traffic related ones, such as the vehicle types, vehicle weights, and driving lanes [11]; and wind and wave related ones, such as the wind speed, wind direction, wave height, wave period, and wave direction [13]. In addition, the traffic related parameters are assumed to be independent with the wind and wave related parameters. These parameters for modeling the coupled VBWW system based on long-term field measurements will be elaborated below.

### 2.1. Vehicle load model

For fatigue design in many codes or specifications, such as AASHTO [14] and Eurocode 1 [15], fatigue trucks are typically defined to represent the truck traffic. Several fatigue truck models with various deterministic gross vehicle weights (GVW) and configurations are defined in these design codes. However, the actual site-specific truck loads could be different. In a long term, possible increase or pattern change of local traffic, such as over-loaded heavy trucks, could also introduce different fatigue truck loadings. Therefore, a realistic fatigue truck load model is needed to account for the actual traffic condition, especially for the probabilistic bridge fatigue damage evaluation.

In the present study, the fatigue truck load model is established based on the site-specific WIM data including the vehicle types, GVW, and vehicle moving lanes. A coastal slender cable-stayed bridge with WIM system, which supports two-way six traffic lanes, is selected as a prototype. The traffic data was collected over one month, during which a total of 307,200 vehicles were passing through the bridge. Among the total monitored vehicles, 62% vehicles with GVW larger than 30 kN are considered to have contributions to the fatigue damage, which can be further classified into 5 categories, as summarized in Table 1. The reason to exclude the vehicles with GVW less than 30 kN from the fatigue analysis is due to their negligible contributions to the fatigue damage, according to the preliminary analysis. As shown in Table 1, among the effective traffic volume, the vehicle type 2 with two axles accounts for 56.29%, followed by vehicle type 6 with six axles and vehicle type 5 with five axles, occupying 22.26% and 15.35%, respectively. The remaining two types of vehicles, i.e., type 3 and type 4, in the effective traffic volume is 6.10%. This indicates that there is a large amount of heavy trucks, i.e., type 5 and type 6, among the effective traffic volume. The majority of these loads are in the slow lane and middle lane. In addition, the GVW of each type of vehicle were also recorded and modeled with an appropriate probability density function (PDF). It is worth noting that the actual vehicle weight may exhibit