Computers and Structures 154 (2015) 101–115

Contents lists available at ScienceDirect

Computers and Structures

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

Long-term performance assessment and design of offshore structures

Yi Zhang [a], Michael Beer [b,*], Ser Tong Quek [a]

[a] Department of Civil & Environmental Engineering, National University of Singapore, Singapore
[b] Institute for Risk & Uncertainty, University of Liverpool, Liverpool, UK

ARTICLE INFO

Article history:
Received 24 June 2014
Accepted 24 February 2015
Available online 11 April 2015

Keywords:
Extreme value distribution
Nonlinear dependencies
Copula model
Reliability estimation
Jacket structures
Significant wave height

ABSTRACT

The design of an offshore structure is highly dependent on the operating environmental parameters, where a realistic statistical model of the latter is essential to produce a representative estimate of the performance and failure probability. Establishing an accurate model of the offshore environment can be a challenging task. The use of simple probabilistic models may lead to biased results in the stochastic structural analysis since the environmental impact to an existing offshore structure is associated with a wide range of inter-dependent factors. In this paper, the specification of long-term design loads for offshore structures considering multiple environmental factors is investigated where the dependency between several commonly used sea state parameters are instituted through a copula-based multivariate probabilistic model. Several copula functions, capable of modeling both linear and non-linear dependence structures, are considered. The developed multivariate model based on copula concept is compared with the available approaches in the literature using actual environmental data. The modeled sea state parameters are then utilized to characterize the sea load for the reliability analysis of a real jacket structure where the prediction of the long term load is derived in a discretized form. The applicability of this approach in a high dimensional multivariate problem is also discussed.

1. Introduction

Designing an offshore platform in an uncertain marine environment is a challenge which requires extensive engineering analysis and decisions. While addressing different load cases on offshore structures, designers are usually required to estimate the environmental conditions at the ocean site, and usually a multivariate analysis is performed. The safety of the structure must be ensured at least over the design life of the structure, which is associated with many years of exposure. Normally, the design code requires an operation period of 50 or 100 years for the designed structure [13]. However, the long term assessment of offshore structures considering the stochastic nature of several environmental loads such as wind and wave loads encountered by the structure can be quite complicated. The consideration of only one parameter in the load extrapolation may not lead to realistic predictions of the response of the structure. The presence of several significant parameters that characterize a complex offshore environment requires suitable multivariate models to predict the long term performance of structures.

Besides the marginal distribution of the individual parameters, such as wave heights and wave periods, the dependency structure between various ocean parameters affects the response statistics and eventually the estimation of the structural reliability. If the actual dependency is nonlinear, then the models commonly used may only offer quite coarse approximations [25,55]. To remedy this problem, a number of approaches have been developed in the context of multivariate analysis in wave climate studies and other areas [26,20,27]. However, a criterion for selecting the most appropriate model choice is still lacking data, and the numerical analysis for the long term reliability and performance assessment is demanding. The application of a direct integration method with environmental parameters simulated from the constructed multivariate model is often not feasible. Approaches to answer these two challenges include the use of efficient numerical methods and model test [1,5], reduction in simulation efforts by selecting the critical sea states [41], use of environmental contour and inverse first order reliability method (IFORM) [49,28], and use of bootstrap methods in deriving the confidence interval from the structural analysis [15]. These studies also assessed various types of structures with regards to long term performance, such as jacket structures [18], jackup rigs [39] as well as floating structures [56]. It was recognized that the long term assessment remains one of the most difficult tasks, and the statistical modeling of the ocean

* Corresponding author. Tel.: +44 1517945224.
E-mail address: mbeer@liverpool.ac.uk (M. Beer).

http://dx.doi.org/10.1016/j.compstruc.2015.02.029
0045-7949/

parameters remains challenging due to their usually complicated relationships between the parameters.

The nonlinear dependency between parameters needs to be addressed, especially in the context of efficient numerical processing when applied to large structures. This is addressed herein through the development of a copula-based multivariate model for ocean parameters, and an associated numerically efficient simulation approach to derive a long term design load for offshore structures. The paper is organized as follows. Section 2 presents the basic framework for the long term safety assessment of offshore structures. Related literature on multivariate statistical models and copula theory is discussed in Section 3. In Section 4, an example of measured data from a buoy at the southern coast of Alaska is analyzed to demonstrate the approach. Specifically, the data are preconditioned to treat the time-dependent dependencies between the environmental variables. The copula model is established in Section 5 and compared against alternative models based on the collected, preconditioned data. To facilitate efficient numerical simulation, a discretized form of the copula model is developed in Section 6. The derivation of a long-term design load is demonstrated through a jacket structure. Section 7 discusses the extension to higher dimensional problems. The concluding remarks of this paper are summarized in Section 8.

2. Estimation of long term design value

The long term safety of an offshore structure is characterized by the probability that the load level exceeds the capacity of the structure. This requires the long term probability distribution of the load, which can be obtained numerically using direct integration. This yields the exceedance probability P_E corresponding to a load level l accounting for the variability of the load related parameters θ,

$$P_E = \Pr[L > l] = \int_\theta \Pr[L > l|\theta] f(\theta) d\theta \tag{1}$$

where $f(\theta)$ represents the joint distribution of the random variables associated with the load L. In offshore engineering, the set of load related parameters are mostly related to environmental factors, such as the wave height and wind speed.

However, the change in the ocean characteristics is generally slow and thus the concept of sea state, which represents a short term sea condition, can be applied [24]. The sea surface is normally considered to be stationary for a period of time from 20 min to 3 h, represented by the significant wave height H_s and the peak period T_p. The response caused by these sea loads within this short term can be described by a random process $X(t)$. Thus, Eq. (1) can be expressed in terms of how likely the short term processes will exceed a load level. The overall exceedance probability may thus be alternatively expressed as

$$P_E = \int_\theta Q(X(t) > l|\theta) f(\theta) d\theta \tag{2}$$

where $X(t)$ is the short term response conditioned on the ocean state parameters θ, $Q(\cdot)$ is the short term exceedance probability with respect to load level l. To obtain the long term solution, assuming stationary and independent and identical distributions (iid), an extreme value model can be used for $Q(\cdot)$. The long term design value corresponding to a prescribed exceedance probability, for example, 0.01 as normally used for a return level of 100 years, can be postulated.

3. Approaches for multivariate model

3.1. Conditional joint distribution

Prior to structural analysis, the collected environmental data need to be studied so as to identify a robust statistical model $f(\theta)$ to be used in Eq. (2). The challenge in some situations is that the recorded environmental data are limited and time-variant, exhibiting strong non-stationarity in time [58]. An added complication in multivariate analysis is when there are nonlinear dependencies between the ocean parameters [19,33,32].

Among the probabilistic models available in the literature, the conditional joint distribution model is the most popular and adopted in the design code [8,31,17]. A common example, is the joint distribution of significant wave height (H_S) and peak period (T_P), which characterizes the occurrences of sea states. According to the design code [13], the conditional bivariate distribution model generally assumes that H_S follows a Weibull distribution while T_P follows a lognormal distribution whose model parameters are conditional on H_S. The latter is written as

$$f_{T_P|H_S}(t|h) = \frac{1}{\sqrt{2\pi}\sigma t} \exp\left\{-\frac{(\ln t - \mu)^2}{2\sigma^2}\right\} \tag{3}$$

where t and h are variables representing the peak period and significant wave height. The parameters μ and σ are functions of h,

$$\mu = E[\ln T_P] = a_1 + a_2 h^{a_3} \tag{4}$$

$$\sigma^2 = Var[\ln T_P] = b_1 + b_2 e^{b_3 h} \tag{5}$$

and $a_1, a_2, a_3, b_1, b_2, b_3$ are coefficients, which can be determined from fitting the parametric model to the data. Although the application of the conditional joint distribution model is quite straightforward, its drawback is that the marginal distributions and the dependence structure as defined in the bivariate model reduces the degree of freedom of the model. This has been highlighted by several studies which also suggested further development of the conditional bivariate models [45,7,14].

3.2. Nataf transformation

The popular Nataf transform to describe an approximate joint probability model in offshore engineering applications and specifically, to model the ocean parameters have been reported in Wist et al. [57], Sagrilo et al. [46] and Silva-González et al. [50]. The basic idea is to transform original dependent random variables into mutually independent standard normal variates. The joint density probability distribution for the original variables can be expressed as a function of the marginal distributions and the correlation coefficients amongst all pairs of variables [34] as

$$f_{x_1,\ldots,x_n}(x) = f_1(x_1) f_2(x_2) \cdots f_n(x_n) \frac{\phi_n(\boldsymbol{y}, \boldsymbol{\rho}_\theta)}{\phi(y_1)\phi(y_2)\cdots\phi(y_n)} \tag{6}$$

$$\begin{cases} \Phi(y_i) = F_i(x_i) \\ y_i = \Phi^{-1}(F_i(x_i)) \qquad i = 1, 2, \ldots, n \end{cases} \tag{7}$$

where $F_i(\cdot)$ is the marginal distribution of the ith variable, $\Phi(\cdot)$ and $\varphi(\cdot)$ are the cumulative and density functions of standard normal variables. Each coefficient ρ_θ^{ij} in the correlation matrix ρ_θ can be determined by evaluating the integral

$$\rho_{ij} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left(\frac{F_i^{-1}(\Phi(y_i)) - \mu_i}{\sigma_i}\right)\left(\frac{F_j^{-1}(\Phi(y_j)) - \mu_j}{\sigma_j}\right) \phi\left(y_i, y_j, \rho_\theta^{ij}\right) dy_i dy_j \tag{8}$$