Engineering Structures 112 (2016) 265–273

Contents lists available at ScienceDirect

Engineering Structures

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

Numerical and monitoring based Markov Chain approaches for the fatigue life prediction of concrete structures

A. Strauss

Institute of Structural Engineering, Department of Civil Engineering and Natural Hazards, University of Natural Resources and Life Sciences, 1190 Vienna, Austria

ARTICLE INFO

Article history:
Received 1 December 2014
Revised 5 January 2016
Accepted 12 January 2016
Available online 2 February 2016

Keywords:
Fatigue deterioration in concrete structures
Semi-Markov models
Finite Element modeling
Lifetime prediction

ABSTRACT

The design of special concrete structures, such as foundations for offshore wind turbines, has to be carried out against complex requirements and under challenging environmental conditions. Among these are for example dynamic and cyclic loadings caused by wind and sea waves. Concrete fatigue processes are dominant degradation processes (a) that determine the technical lifetime of such foundations, and (b) that are difficult to determine in occurrence, severity and with regard to the redistribution characteristics in the cross section or structure using classical inspection or monitoring programs. Semi-Markov Chain approaches, which are based on process sojourn time considerations, combined with smart monitoring sensor systems and advanced nonlinear Finite Element simulation methods, present very promising approaches for the realistic description of concrete fatigue processes and their redistribution characteristics and in consequence for the prediction of the remaining lifetime. The objectives of the current work are (a) to present a Semi-Markov Chain approach that is based on smart monitoring information and on advanced nonlinear Finite Element simulations for the realistic assessment and the prediction of concrete fatigue processes, and (b) to demonstrate the Semi-Markov Chain approach on an offshore wind energy tower concrete foundation in Cuxhaven. This work presents a further step toward developing a software tool that can be used to perform reliability assessments of aging concrete structures and to update their reliability with inspection and monitoring data.

1. Introduction

1.1. Motivation

Offshore wind energy (OWE) is among the emerging sustainable energy sources. Engineering design can contribute significantly to its extensive implementation. Various activities have contributed to the knowledge base that is needed for the design and technology development [28]. In Europe, offshore wind turbines are present predominantly in Denmark, Sweden, England, Holland and Norway (among others). These are close to the coast with shallow water depths of up to 10 m. New wind farms are planned in Germany at distances of up to 40–50 km [19] from the shore and with a foundation depth of 30 m. The design of the foundations for offshore wind turbines (OWEA) has to take into account the complex requirements posed by the dynamic and cyclic loading of the construction and of the subsoil caused by wind and waves [20]. In contrast to onshore wind turbines, offshore wind turbines are characterized by: (a) additional loading from waves and tides, (b) increased building dimensions due to foundation construction in deep shore areas, and (c) hydrodynamic force effects on the foundation, which can be up to ten times greater than the aerodynamic loads and hydrodynamic moments on the foundation [16]. The foundations have to fulfill their function under the demanding environmental conditions on the open sea without extensive inspection and maintenance work for 20–25 years [15]. These special conditions require an optimization of fabrication, transportation and installation of the facilities associated with a possible high level of serial prefabrication [19].

1.2. Safety of fatigue endangered concrete structures

The various design provisions are not necessarily compatible with regard to the concept of safety. API [1] follows the “working design stress” which corresponds to the global safety concept. Germanischer Lloyd (GL) [12] permits the partial safety concept as well as the global safety concept, while DIN 1054 [10] exclusively relies on the partial safety concept and its predictions based on the cross section forces. The classification of the safety level is therefore as difficult as the definition of the safety factors. Accordingly, the partial safety factors, as for instance those of DIN 1054 [10], are not readily transmissible on offshore, since the loading

---

E-mail address: Alfred.strauss@boku.ac.at

http://dx.doi.org/10.1016/j.engstruct.2016.01.020

and resistance properties of offshore systems are more uncertain than those of more general concrete structures. These uncertainties with regard to the required safety level and in keeping with the objective to keep concrete structures in operation beyond the defined technical lifetime t_L formed the basis for the development of an integrated monitoring and assessment framework (IMAF). This framework combines monitoring, modeling and prediction methods for the fatigue assessment of endangered concrete structures. A realistic assessment of the possible remaining lifetime t_R of fatigue endangered concrete structures can be assured by a balanced combination of classical and advanced monitoring systems together with numerical modeling predictions [26].

1.3. Performance related monitoring

In the IMAF of this research project, an *S*-monitoring (e.g., associated with a number of applied cyclic stress ranges) and an *R*-monitoring concept (e.g., associated with changes in the microstructure and in the strain tensor) were applied on an offshore foundation and on cylindrical laboratory concrete samples [25]. This performance related monitoring concept (see also [29]) enables a continuous and adaptive detection and assessment of not accurately known fatigue processes during and after the planned technical lifetime t_L. It also allows the review of more or less well developed predictive models that are common in the Life-Cycle Engineering (LCE). The performance-related monitoring concept also includes an accompanying numerical modeling module which enables the interpretation of the overall system performance (e.g. performance of the whole foundation tower) and which allows supervision and redundant checking of the results of the prediction models. Nevertheless, according to Gokce et al. [13], the uncertainties in the data collected, determined by means of intermittent testing or monitoring, the limitations of the models, and the non-stationary nature of structural behavior need to be considered. These uncertainties can be incorporated by using special statistical techniques [13].

1.4. Structural identification

Performance-related monitoring increases in significance, as previously mentioned, when supplemented by a numerical model. This numerical model in a first step needs to be adapted to the mechanical properties of the existing structure by means of Structural Identification methods (St-Id). Even at this stage, well designed monitoring systems provide valuable information on input variables for the St-Id and for the associated model calibration variables. Structural Identification (St-Id) can be described according to Catbas et al. [8] and Strauss et al. [23] simply as estimating the properties of a structural system based on a correlation of inputs and outputs for decision-making, or according to a more detailed formulation of Catbas et al. [8]: *A complete* St-Id *process, establishing the decision making needs, developing analytical and numerical models, and conducting field measurements, along with parameter identification using the experimental data for model calibration. The associated results are expected to provide a set of solutions for the performance of a structure for optimal decision making.*

The preparatory or input phase of Structural Identification (St-Id) processes can be structured as: (a) the definition of the relevant performance characteristics, (b) the preparation of a numerical Finite Element Model (FEM) on the basis of existing information on the material and on the structure which has for example been gathered during the planning phase, execution phases and/or inspection phases, (c) the definition of significant loads or load combinations, and (d) the definition of theoretically and experimentally derived degradation processes of the considered performance characteristics. These steps are important for updating concrete fatigue degradation process models such as required for the considered wind energy offshore foundations, as shown in Fig. 1(a) and (b). As mentioned already, the used innovative monitoring systems (see Fig. 1(d)) in combination with Semi-Markov Chain approaches, which will be discussed in the following, have turned out to be essential elements for the St-Id, the condition assessment, and the lifetime t_L prediction (see Urban et al. [25]). The final results of a successful St-Id should include: (a) a representative linear or nonlinear FEM, (b) interesting performance indicators that enable a comparison of monitored with modeled performance indicators for a first verification of model uncertainties, (c) identification of deterioration mechanisms and their level and rate through the lifetime t_L based on temporal comparisons of modeled with monitored performance indicators, (d) robustness quantities, taking into account the system performance or system redistribution processes using information from FEMs.

Please note that the fatigue specific upper stress σ_o and lower stress σ_u, as well as the degradation degrees D, are associated with the Young's modulus according to [21]. Therefore, the Young's modulus has been treated as most important updating parameter.

For example, for the case study discussed in Section 3 and shown in Fig. 1(a) and (b), the following St-Id steps were carried out:

In a first step, a Nonlinear Finite Element (NLF) model and a cyclic load model of the offshore test foundation in Cuxhaven were developed. The Young's modulus distribution of the reinforced concrete E_C along the circular cross section, divided into 36 Young's modulus fields $\mathbf{E}$, was defined as an indicator for the St-Id process. The consecutive step analyses of the cyclic loading on the NLF element model and the associated stepwise adjustment of the *Young's modulus* fields $\mathbf{E_{c,NLF}}$, using the findings of Petkovic [21], enabled the *NLF model based* definition of the *Young's modulus fields* $\mathbf{E_c}$ along the circumference of the cross section for the St-Id at predefined time horizons. The Young's modulus adjustment processes essentially depend on the upper and lower concrete stress levels $S_{c,o}$ and $S_{c,u}$, wherein changes in the Young's modulus E_c cause effects on fatigue characteristics in the cross section fields as defined in fib Model Code 2010 (2013b) and in consequence on their related remaining life time t_R. The concrete stresses in the cross section fields are redistributed during transformation processes to those regions with a higher E_c, where an increase in stress is possible.

In a second step, the fatigue-associated *R*-monitoring and *S*-monitoring information from fibre optical sensor (FOS), ultra sound sensor (US), and acoustic emission (AE) sensor systems were analyzed with respect to the concrete fatigue characteristics. The comparison of the *R*-monitoring and *S*-monitoring information with the monitoring results of the laboratory small scale tests and the load depending fatigue findings of Petkovic [21] enabled the *monitoring based* characterized *Young's modulus fields* $\mathbf{E_{c,Mo}}$ distribution *along* the circumference of the cross section.

In a third step, a Bayesian updating approach was used to incorporate the *monitoring based* characterized *Young's modulus fields* $\mathbf{E_{c,Mo}}$ as short term information in the NLF based $\mathbf{E_{c,NLF}}$ so as to allow an adaptation of the NLF model to the existing structural fatigue conditions. Fig. 1(e) shows the Bayesian updated *Young's modulus fields* $E_{cm}/E_{cm,initial}$ up to applied load cycles $4.2 \cdot 10^6$ in blue.[1]

In a fourth step, the NLF models obtained by means of previously described St-Id processes for selected times of loading served as a basis (a) for a deterministic or probabilistic performance assessment, and (b) the prediction of the lifetime t_L or remaining lifetime t_R. Two strategies were considered for the performance

---

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.