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Service strength validation of wind-sensitive structures, including fatigue life evaluation

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ABSTRACT

In this paper the procedure for the service strength validation of stationary structures under wind loading is treated. The procedure includes static strength evaluation under maximum monotonic load and fatigue assessment under variable cyclic wind loads.

For the validation of the service strength of a mobile antenna tower placed in the Croatian coastal area, the data related to the wind speed, direction, loads and stresses were measured and analyzed.

Analyses of the specific wind load conditions (northerly and southerly winds *Bura* and *Jugo*) and resulting stresses show that the stress spectrum shape can be described by mathematical terms based on the Weibull distribution with the shape parameter value of $\beta = 1.5$. The other two spectrum parameters for the fatigue strength evaluation – maximum spectrum value and number of cycles – can be accounted for by the dynamic response of a structure under the specific wind load, obtained by a numerical procedure. Based on the derived stress spectra and corresponding fatigue data (Woehler curve related to local structural notch or structural hot-spot stress), the expected damage accumulation and the durability life are estimated according to the modified Palmgren–Miner damage accumulation hypothesis.

The fatigue strength evaluation including durability life estimation, based on structural hot-spot stress, is described for an example of the welded joint of a mobile antenna tower.

1. Introduction

Increased use of structures such as highway traffic signs, light poles, support of wind turbines and mobile antenna towers, makes it necessary to include specific wind loads to validate the durability of such structures. In this paper, the methodology to validate the service strength, which includes the fatigue life estimation, is treated.

The Croatian region of Dalmatia, where the field tests of wind load on real structures were carried out, is known to be the most unfavorable region if wind loads are taken into account.

The most powerful winds in this region are *Bura* (Bora) and *Jugo* (Scirocco). Bura is a northerly, cold and extremely volatile wind. It starts in regions where cold air, coming from the mainland, raises up the windward side of a barrier and descends down the leeward side. Similar winds exist in only a handful of locations in the world (Novorossiysk on the shores of Black Sea below Caucasus, Pacific shore of Mexico where this wind is called *Papagayos* or *Tehuantepecers*, and plains of Kanto in Japan where it is called *Oroshi* or *Karakkaze*), [1]. Jugo is a southerly wind with high occurrence and medium flow values. It has lower turbulence intensities compared to Bura.

Wind-induced forces produce variable stresses in stationary engineering structures leading to fatigue damage, which is treated in books and publications [2–6].

The difficulty in designing against fatigue arises from the adversity to describe the wind loads which change both in intensity and in direction.

According to EN 1991-1-4:2005 [7], the basic wind parameter for the calculation of wind influence on structures is the reference wind speed, defined as maximum mean value of wind speed to be expected once in 50 years, measured within a period of 10 min at the height of 10 m on a flat terrain with roughness index II (agricultural field with trees and houses). To determine the values for the design it is necessary to use statistical methods for a reliable estimation of extreme values (e.g. maximum yearly wind speed) and the spectra of wind loads, being representative for the operational usage, [6,8,9].

This paper is motivated by the forensic analyses of the fatigue fractures generated by wind loads which occurred on structures in the Croatian coastal region. Example of a structure prone to wind-induced fatigue is the traffic sign shown in Fig. 1.

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Nomenclature

A_1, A_2	Woehler curve constants
D	Damage
D_{all}	Allowable damage
E	Young's modulus of elasticity
$K_{t,hs}$	Hot-spot stress concentration factor
M	Mean stress sensitivity factor; $M = (S_{a,R=-1}/S_{a,R=0}) - 1$
N	Number of cycles
N_0	Number of cycles for specific portion of life (return period)
N_e	Number of cycles at knee point (so called 'endurance limit')
N_h	Number of cycles per hour
P_f	Probability of failure
P_o	Probability of occurrence
P_s	Probability of survival; $P_s = 1 - P_f$
R	Stress ratio
R^*	Spectrum stress ratio; $R^* = S^*_{\min}/S^*_{\max}$
$R_{p,0.2}$	Material yield point
S	Stress
S_a	Stress amplitude
S^*_a	Maximum stress amplitude of the spectrum
$S^*_{a,\mathrm{all}}$	Allowable maximum stress amplitude
$S_{a,hs}$	Hot-spot stress amplitude
$S^*_{a,\max}$	Extrapolated maximum stress amplitude of the spectrum
$S_{a,n}$	Nominal stress amplitude
S_e	The so-called 'endurance limit' usually corresponding to the knee point of the Woehler curve
S_F	Pseudo-stress corresponding to $R_{p,0.2}$
$S^*_{\max}$	Spectrum maximum stress
$S^*_{\min}$	Spectrum minimum stress
S_n	Nominal stress
S_{syp}	Structural yield point
V_e	Integration constant
k_1, k_2	Woehler curve slopes
k'	Gassner curve slope
n	Number of cycles on a given stress level
v	Wind speed
β	Spectrum shape parameter
ε	Deformation
θ	Weibull spectrum scale parameter
$Q(x)$	Cumulative distribution function
$f(x)$	Probability density function
$\Gamma(\alpha)$	Gamma function
$\Gamma(\alpha; x)$	Complementary incomplete gamma function
$\gamma(\alpha; x)$	Incomplete gamma function

Fractures as shown in Fig. 2 occurred on several such structures shortly after deployment.

The structures have been designed in accordance with civil engineering rules. The resulting maximum stresses from static calculation based on the extreme wind loads were considered to be significantly lower than allowable. Nevertheless, fatigue failures as shown in Fig. 2 occurred.

Forensic analyses of these fractures including numerical calculations of stresses have shown that these fractures were the result of fatigue generated by stresses due to the variable wind loads.

Faced with the importance of the problem and evident lack of a reliable procedure for the service strength validation of such structures, different aspects to validate these structures are treated in this paper.

The validation is based on in-field measurements of the wind loading on a 39 m tall freestanding lattice antenna tower in the hinterland of the city of Split.

2. Procedure for the service strength validation

In order to carry out reliable service strength validation of engineering structures under wind loading, it is necessary to evaluate the stresses at the maximum expected service load (decisive for static strength) and the spectrum of all stresses (decisive for fatigue strength) acting during the given time period as well. The procedure that includes these requirements is shown in Fig. 3.

After the global design is made, the stresses due to the expected service loading must be determined. Based on the expected service load data the stresses in the structure are determined using FEM analysis. These analyses include global stresses (nominal) at individual cross sections of the structures and refined local structural stresses in critical areas. The validation of ultimate strength, also defined as the static strength, is based on nominal stresses. In the case where the nominal stresses in individual sections of the structure are higher than allowable, *global modification* of the design is necessary. Based on practical experience, fatigue strength validation is of paramount importance for engineering structures under wind loading. A detailed analysis for highly stressed areas of the structure are to be carried out and local hot-spot stresses should be lower than allowable; otherwise *local modifications or improvement* (e.g. of weld joint) must be carried out.

Two different concepts are used to estimate the fatigue life, namely the concept of nominal stress, and the concept of local stress. The concept of nominal stress is valid for specific structural details as shown in the rules for welded structures [10,11]. Correspondingly, the local stress concept utilizes the fatigue data based on local stress. For the design of welded joints, the engineering approach usually applied is based on the structural notch or structural hot-spot stress [12–16].

3. Service loading

The service loading is the result of the wind acting with changing intensity and direction. For the service strength validation, this loading must be transformed into operational stresses in specific areas of the structure and presented as service stress spectra. The operational stresses correspond to a stochastic process. The typical stress–time history is presented in Fig. 4. From this figure the stress amplitude is determined as $S^*_a = (S^*_{\min} + S^*_{\max})/2$ and the stress ratio as $R^* = S^*_{\min}/S^*_{\max}$.

Analyzing these stress–time histories with the intention to present them in a form applicable for damage calculation, the corresponding service stress spectra must be determined. These analyses are made by simple, one-parameter Level-Crossing (LCC) and Range-Pair counting (RPC) methods [17]. The necessary data for the extrapolation of the measurements as the derivation of the design stress spectra for the required durability life of about 30 years can be carried out. In the case where the analysis of service stresses is made by a two-parameter counting method, like the Rainflow counting, it is proposed to use its one parameter output for the extrapolation.

The service stress spectra valid for specific areas (system points) of the structure are defined by the spectrum maximum value S^*_a, the spectrum shape β and the number of cycles N_0 for the given life portion. It can be described by the following equation

$$S_a(N) = S^*_a \left(1 - \frac{\log N}{\log N_0}\right)^{1/\beta} \quad (1)$$

where N is the number of stress cycles S_a. A schematic presentation of the stress spectra is given in Fig. 5.