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Fatigue testing and analysis of notched specimens with typical subsea design features

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ABSTRACT

Specimens with typical subsea design features have been fatigue tested in order to quantify the fatigue life prediction accuracy of the local stress approach as prescribed by the recommended practice DNVGL-RP-0005 (former DNV-RP-C203). A second aim has been to explore whether the use of the notch support factor method or the weakest-link method would improve the predication accuracy compared to the use of the local stress approach. Nine different notched specimen types, and a total of 139 notched specimens have been fatigue tested in air. All specimens have been subjected to an uniaxial cyclic load. Specimens have been tested at stress ratios R in the range from -1 (zero mean stress) and 0.5 (high mean stress). The specimens have stress concentration factors in the range from 1.85 and 5.45 and fatigue notch factors ranged from 1.16 to 2.03.

A statistical based procedure has been used for establishing an indicator of the degree of the prediction accuracy (test results versus estimated fatigue life). This predictability indicator showed that the local stress-life predictions according to DNVGL-RP-0005 resulted in conservative fatigue life predictions for all the tested notched specimens. The degree of conservatism was found to increase with increasing stress concentration factors. DNVGL-RP-0005 yielded fatigue life predictions closer to the observed data for the mildly notched specimen types tested with a high net-section mean stress ($R = 0.5$). The use of the notch support factor method and the weakest-link method improved the fatigue life predictions significantly compared to the use of the local stress approach for all specimen types. The highest predictability was obtained with the use of the notch support factor method. Also the weakest-link method yielded good fatigue life prediction accuracy for all specimen types.

1. Introduction

This paper is a continuation of two papers by Wormsen et al. [1,2] presenting base material fatigue data for low alloy forged steels used in the subsea industry. The S–N data in [1,2] was established by performing fatigue testing, in air and in artificial seawater with cathodic protection, of smooth specimens. The in-air fatigue testing was performed on specimens having a surface roughness R_a in the range of 0.3 μm (polished surface) and 6.3 μm (coarse production surface) in order to quantify the surface roughness effect on the fatigue life. Low alloy steel specimens having tensile strengths in the range of 600 and 800 MPa were fatigue tested to quantify the effect of tensile strength on the fatigue strength. The mean stress sensitivity was quantified for the in-air specimens by performing fatigue testing at $R = -1$ (zero mean stress), $R = 0.05$ (mean stress close to half of stress range) and $R = 0.5$ (mean stress equal to three-halves of the stress range).

This paper presents fatigue test results and analyses of low alloy steel specimens with typical subsea design features, hereafter named notched specimens. The fatigue analyses are performed using in air S–N data from [1] and from DNVGL-RP-0005 [3]. Notched specimens of varying sizes and with different notch severities have been tested. The mean stress effect of the notched specimens have been investigated by testing some of the specimen types at three different net-section stress ratios: $R = -1$, $R = 0.05$ and $R = 0.5$.

The prescribed method, in DNVGL-RP-0005 [3] for the fatigue design of offshore steel structures, is the local stress approach. This method assumes that the fatigue life of the considered component

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Nomenclature

a_χ	constant in the notch support factor method
b_σ	exponent in the weakest-link model
DEN	double edge notched tension specimen
E	Young's modulus
f_m	mean stress reduction factor
f_χ	notch support factor
FEA	finite element analysis
HS	high strength
K_f	fatigue notch factor
K_r	surface roughness factor
K_t	elastic stress concentration factor ($= K_{t,mp}$ or $= K_{t,vM}$)
$K_{t,mp}$	elastic stress concentration factor based on the max principal stress $= \sigma_1/S_{net}$
$K_{t,vM}$	elastic stress concentration factor based on the von Mises stress $= \sigma_e/S_{net}$
LAS	low alloy steel
$\log a$	intercept constant for the mean S–N curve
$\log \bar{a}$	intercept constant for the design S–N curve
$\log a_{notch}$	intercept constant for the mean S–N curve for a notched specimen
$\log a_W^*$	intercept constant for the mean S–N curve at $R = -1$ for a smooth polished specimen
m	inverse slope of the S–N curve
M	mean stress sensitivity index $= \Delta S_W/\Delta S_A - 1$
Mean_r	mean fatigue life ratio
$\mathbf{n}$	unit eigenvector of the maximum principal stress
N	number of cycles to failure
N_{test}	fatigue life for tested specimen
NS	normal stress criterion
R	stress ratio $= S_{min}/S_{max}$
r	notch root radius
R_a	arithmetic average surface roughness height
$\hat{R}$	normalised stress ratio $= (1+R)/(1-R)$
R_m	tensile strength at room temperature
$R_{p0.2}$	yield strength at room temperature
RW	Rudolph and Weiß criterion
s	number of specimens
SD_r	standard deviation of fatigue life ratio
$s_{\log N}$	standard deviation of $\log N$
S_{net}	net-section stress
ΔS	stress range in the gauge section of a smooth specimen
ΔS_A	fatigue strength at $R = 0$
ΔS_{net}	net-section stress range
$\Delta S_{net,\ initial\ yield}$	net-section stress range causing yielding upon first application of the load
$\Delta S_{net,\ reversed\ yield}$	net-section stress range causing reversed yielding at the notch root
$\Delta \bar{S}$	fatigue stress range for a smooth specimen
ΔS_W	fully reversed ($R = 1$) fatigue strength
SN	Sines' criterion
t, $\hat{t}$	time points
TS	threaded segment specimen
V	volume
V_0	reference (gauge) volume for a smooth fatigue test specimen
x, y, z	cartesian co-ordinates
ϕ	angle between the x-axis and the plane normal in the counter clockwise direction
S_a	net-section stress amplitude
S_m	net-section mean stress
$\Delta\sigma$	stress range
$\Delta\sigma_{notch}$	local peak stress range in notch
$\Delta\sigma_{WL}$	stress range in the weakest-link method
$\Delta\bar{\sigma}$	fatigue stress range
σ_{ij}	stress tensor
σ_{max}	maximum stress in the cycle $= \Delta\sigma/(1-R)$
σ_{min}	minimum stress in the cycle $= R\ \sigma_{max}$
σ_m	mean stress
σ_e	von Mises stress
σ_1	max principal stress
$\Delta\tau$	shear stress range
χ	absolute value of the relative stress gradient $= (1/\sigma_{notch})\ \lvert\partial\sigma/\partial x\rvert_{x=0}$

is equal to the fatigue life of a standard uniaxial stressed smooth specimen subjected to the same cyclic stress and environment as the most highly stressed point in the component. A multiaxial fatigue criterion is required for converting the stress in a component into an equally damaging uniaxial stress. DNVGL-RP-0005 [3] recommends using either the normal stress criterion or the Sines' criterion [4] in fatigue analysis of notches in base material. These two multiaxial fatigue criteria are considered in this paper. In addition, the multiaxial criterion by Rudolph and Weiß [5] is also considered. The latter is a modified version of the Sines' criterion. The difference between the two criteria is related to how the mean stress is calculated.

While the local stress approach is an excellent tool for performing design screening and design optimization of fatigue exposed equipment, it is well recognised [6,7] that this method will yield a conservative fatigue life estimate especially for equipment having design features with high stress concentration factors. In order to reduce the conservatism of the local stress approach, several non-local stress approaches for fatigue assessment have been developed [6–28]. Two such methods are the notch support factor method by Siebel and Stieler [10] and the weakest-link method by Weibull [29,30]. In the notch support factor method, the peak stress in the component is adjusted with respect to the stress gradient in front of the notch. The stressed volume sensitivity on the fatigue strength is taken into account in the weakest-link method [6].

In this paper, the predictive capability of the local stress approach has been compared with both the notch support factor method and the weakest-link method, for estimating the fatigue life of specimens with typical subsea design features. The comparison also includes an investigation of the fatigue life predication accuracy as a function of the stress ratio R (notched specimens have been tested at stress ratios R in the range from -1 and 0.5).

2. Aim of this paper

Specimens with typical subsea design features have been fatigue tested with the aim to determine the following:

- Selection of an appropriate multiaxial stress criterion.
- Exploring the degree of conservatism in using DNVGL-RP-0005 [3], in fatigue analysis of the tested notched specimens, by comparing fatigue life predictions with test results.
- Exploring the capability of non-local stress methods (notch support factor method [10] and the weakest-link method [6,29,30]) in estimating the fatigue life of the tested notched specimens compared to using the local stress approach.