NOTES ON LOW CYCLE FATIGUE OF HIGH STRENGTH STEEL STRUCTURES

Arno Landewers (Viro, Engineering Analysis Department, Vlaardingen, Netherlands)

With current possibilities to optimize steel constructions (especially by using FEM analysis), average stress levels in constructions have the tendency to rise close to allowable stresses, especially in cases where additional requirements for weight, material properties or design volume exists. The presence of locations with stress concentrations (like welds) or with complex stress distributions (like contact surfaces) may lead to the necessary of non-linear FEM analysis. Part of these analyses is the allowance for local plastic deformations, which is subject to a criterion for the number of load cycles.

The low cycle fatigue phenomenon

In case of oscillating loads, resulting (local) strains may act in the plastic range. Repeated yielding due to subsequent loading may cause crack initiation (which, in case of contact loads will be initiated below the contact surface due to shear stress), typically occurs for a number of cycles (< 10000) below conventional fatigue load damage occurs and is called low cycle fatigue. Note that certain low duty cycles for high loading operations or even vessel movements for offshore applications may cause damage due to low cycle fatigue.

(the absence of) rules for low cycle fatigue

So for certain situations (stresses close to allowable values in combinations with the occurrence of stress concentrations and repeated oscillating loads) a damage criterion is needed. Typical class society rules do not address fatigue damage in the low cycle region, but relative recent published investigations give guidelines.

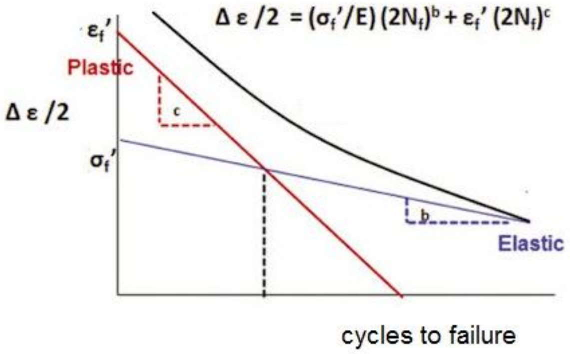
The subject of low cycle fatigue in marine structures was pioneered in a paper by Xiaozhi Wang et al. (reference [1]), which described typical material behaviour and recommended a method to calculate damage based on a combination of experimental data and literature study.

For the total stain amplitude ε_a is assumed $\varepsilon_a = \varepsilon_{ea} + \varepsilon_{pa}$, where ε_{ea} is the elastic strain amplitude and ε_{ep} the plastic strain amplitude. From the basics of fatigue analysis it follows that:

$\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\,(3N_f)^c$, where N_f is the number of cycles to failure, E is the modulus of elasticity and the other parameters ($\sigma'_f, b,\ \varepsilon'_f$ *and* c) are material constants, which can all be determined from experiments.

This practical formula can also be found in the (for now) only class society publication giving guidelines for low cycle fatigue on high strength steel constructions: the DNV/GL recommended practice "determination of structural capacity by non-linear FE analysis methods" (DNV-RP-C208, June 2013).

It follows that the practical relation of strain amplitude with number of allowable cycles for low cycle (plastic) fatigue has (on logarithmic scales) a steeper (negative) slope compared to the relation for high cycle (elastic) fatigue, as shown in the ε-N curve in below figure.

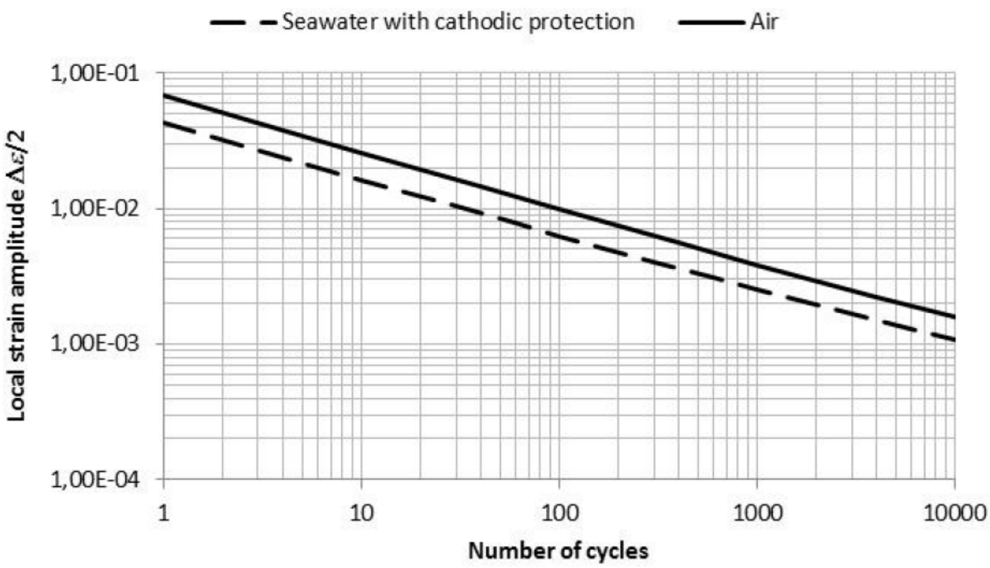


Note that for both low cycle fatigue and high cycle fatigue Miner's rule applies, i.e. $D = \sum_{i=1}^{k} \frac{n_i}{N_i}$, where D is the accumulated fatigue damage, n_i the actual number of cycles and N_i the allowable number of cycles for a block i. In case of occurrence of both high cycle fatigue and low cycle fatigue:

D(total) = D(high cycle fatigue) + D(low cycle fatigue).

Practical values for allowable strain amplitudes at low cycle loads

RP-C208 presents a ε-N curve for low cycle fatigue for both welds and base material (both for tubular joints), of which the curve for base material is repeated below. Note that for instance for a number of cycles of 100 only a plastic strain of 1 % is permitted.



A limitation of RP-C208 is that it only covers steel grades S235, S355, S420 and S460. So the extra high steel grades with yield stresses between 500-700 N/mm^2, which are increasingly used in high loaded steel structures, are not described. However, with lack of availability of further data (and an apparent soft relationship between allowable strain and yield stress), above curve can also be carefully used for extra high steel grades.

Practical peak values for allowable plastic strain

RP-C208 also provides allowable local plastic stain values, which have to be used for the evaluation of notches or contact surfaces (presented in tabular form, table 5-2 in RP-C208). Also here extra high steel grades are not covered, but the tabular data suggests a strong linear relation between allowable local plastic strain and yield stress, giving an (carefully to be used) allowable plastic strain of S690 of about 3%.

Reference

[1] Xiaozhi Wang, Joong-Kyoo Kang, Yooil Kim and Paul H. Wirsching – *low cycle fatigue analysis of marine structures*, originally published by the American Society of Mechanical Engineers (ASME) and part of the proceedings of OMAE 2006 25th International Conference of Offshore Mechanics and Arctic Engineering, 2006