The influence of Stress Concentration Factors and SN curves in assessing the reliability of jacket marine platforms

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Abstract: The design of offshore structures, generally located in a hostile environment, with complex and repetitive loads, with low and difficult intervention possibilities in case of accidents, is a challenge for engineer teams, starting from the design phase and ending with that of decommissioning. In addition to the approximations generated by the structural calculation, the specification of the level of effort concentration and the relationship between effort and fatigue life are also sources of uncertainties in estimating fatigue degradation. Analysis of the sensitivity of fatigue degradation to stress concentration factors (SCF) and S-N curves is an important factor in obtaining realistic results. The paper seeks to establish the optimal yield theory that can be used to evaluate the structural response to cyclic loads associated with computational assumptions by comparing fatigue conditions due to fatigue at the nodes of a complex lattice-type marine drilling structure, to minimize assessment errors of structural reliability. A structural model of jacket marine platform with dimensional and material characteristics corresponding to Romanian marine platforms of "Gloria" type it is analysed, for which is evaluate and compared the fatigue life generated by hydrodynamic loads, using stress concentration factors given by Kellog and Kuang, SN curves: AWS-X, modified AWS-x and respectively BS-F. The results show that for the self-erecting platforms with lattice beam type, with small dimension elements, the stress concentration factors determined by Kellog are closer to reality while Kuang factors gives more covering results.

1. Introduction

Metal fatigue is a complex mechanism, characterized by a general reduction in the resistance capacity of structural elements to cyclic loads due, in fact, to the propagation of pre-existing cracks. A metallic element can yield at a relatively low stress if this stress is applied a large number of times, the most important parameters in the fatigue failures of welded structures being the number of loading cycles and the size of the extreme stresses $\sigma_{\min}$ and $\sigma_{\max}$.

Concentrations of stresses produced at certain points of the joints (hot spots) can be up to 20 times higher than the nominal stresses. The position of these points depends both on the geometric characteristics of the node and on the type of loads, respectively on the shape, location and dimensions of a local defect (it is of interest for analyses performed by the methods of Rupture Mechanics).
As a detailed assessment of local stresses in joints, either by approximating by FEM or experimental measurements, is expensive and time consuming, these stresses are estimated by multiplying the nominal stresses of the element by stress concentration factors (SCF) as a ratio of hot spot stress $\sigma_{\text{max}}$ and nominal stress $\sigma_N$ in joint [1].

The relationship between stress fluctuation and damage can be found using Miner's rule:

$$ D_i = \frac{n_i}{N_i} $$

where: $N_i$ - the number of failure cycles, for the same stress cycle repeated successively $n_i$ - the number of stress cycles of value corresponding to the block $i$ performed $D_i$ - grade of strength reduction

The most common model used to determine $N_i$ is the S-N approximation.

$$ N_i = \left( \frac{2\sigma B}{k} \right)^m $$

where: $\sigma$ - stress amplitude (N/mm²)

$k$ and $m$ - determined constants (modelled as random variables)

$B$ - random variable introduced in order to be able to estimate the uncertainty in the calculation of the stress amplitude.

SN curves (British Welding Institute curves - BS-F, American Welding Society curves - AWS-X and modified curves - AWS-x) are experimentally determined curves and serve as a measure of metal fatigue resistance to reversible loads, and gives the stress range applied to the number of cycles until the metal breaks.

In offshore jacket structures case, the total degradations in the yielded element $D_{\text{tot}}$, are obtained by summing the fatigue damages of a yielded element for a given state of the sea $D_i$, during the service life of the structure, speaking about a long term distribution of the sea state.

$$ D_{\text{tot}} = \int \int \int \frac{T}{T_{\text{mp}}} \frac{T}{T_{\text{mp}}} D(t, h, \theta) P_{T/\text{period}}(T, h, \theta) P_{P/\text{wave}}(h) P_{\theta}(\theta) dt dh d\theta $$

where: $P_{T/\text{period}}(T, h, \theta)$ - marginal probability density as a function of significant wave height $H_s$

$P_{P/\text{wave}}(h)$ - conditional probability density depending on the period of the spectral peak of the wave $T_p$ and $H_s$

$P_{\theta}(\theta)$ - probabilistic density depending on the direction of wave propagation $\theta$

$T_{\text{mp}}$ - the stress cycles period in the considered sea state

The reverse of the total damage gives the fatigue life provided for welded joints. In order to compensate the errors introduced by the simplifying calculation hypotheses, subunit values are adopted for the limit damages, which values are chosen depending on the contribution of the respective node to the safety of the structure.
2. Structural modelling. Assessment of structural response and fatigue degradation

Self-erecting steel platforms are constituted as a triaxle system of beams, consisting of vertical, horizontal and diagonal tubular elements connected by K and T type connections (figure 1).

The offshore metal structure is therefore a continuous system with an infinite number of dynamic degrees of freedom and is idealized in the present study as a spatial lattice beam, using the dimensions and characteristics of the structure elements corresponding to Gloria platform.

![Figure 1. Offshore jacket in Constanța shipyard (made by authors on November 2020).](image1)

The response of the structure is determined by spectral probabilistic analysis. Local stresses are calculated by time integration (using a step of 0.02s) and using Kuang and Kellog factors for stress concentrators [2].

In order to customize the results, the study uses hydrographic and meteorological data from the Romanian exclusive economic sea zone, taking into account the specific characteristics of the Black Sea - rapid development of the water surface, with waves sometimes exceeding 10m and with a higher frequency of storms on autumn-winter period, mainly from the N and NE direction.

![Figure 2. Example of distribution of wave high on N direction on 10m izobath (processing of the data provided by Romanian Institute of Marine Research).](image2)
It is to be noted that in the area of the continental shelf, where the influence of small bottoms disappears and the fetch conditions are much better, the wave heights increase (for example, for a maximum height of 5m on the 10m isobaths, offshore waves reached 9.5m) (figure 2).

The calculation of hydrodynamic loads is performed using the Morrison relation, considering the influence of the spectral characteristics of the sea surface [3, 4].

To allow the evaluation of differentiated loads depending on the wavelength of the wave, the calculation is performed separately on each leg, the effects overlapping for each time step.

To increase the calculation accuracy, directional spectra where used, defined on cardinal and intercardinal points, each state of the sea being considered corresponding to the respective direction.

The fatigue analysis is focused on estimating the structural damages of the joints subjected to the maximum efforts in the area of breaking the waves N1 and respectively the area of the mud line N2 on the vertical elements of the legs (figure 3).

It is mainly interesting the behavior of the joints of the vertical elements with the horizontal ones, here the maximum degradation being ascertained on the occasion of the periodic inspections. The description of the modeling and structural calculation was detailed in a previous presentation [5].

![Figure 3. The structural model of the jacket, the positioning of the bars in the foot structure and the shape of $\sigma_{\min}$ and $\sigma_{\max}$ diagrams for the vertical bars 1, 2 and 3 for a wave train of average height 7m.](image)

2.1. The effects of SCF choice in assessing fatigue degradation

The determination of the number of cycles of failure and degradation from fatigue on sea states and cardinal directions was performed using the MIRA-Fatig program [6]. It is to be noted that the
structural degradations due to fatigue for the Black Sea, are generated in their great majority, by medium sea conditions, with wave heights, H, between 1-5m (figure 2).

To evaluate the effect of SCF variation on fatigue degradation on welded joints, stress concentration factors as given by Kellog and Kuang were used. Degradation is assessed using the modified AWS-X curve.

The differences between the results obtained with the help of the stress concentration factors given by Kellog and Kuang differ by about 6% for the N1 level and 17% for the N2 level, the factors proposed by Kellog being more covering.

In the following, the influence of SCF uses proposed by Kuang compared to those proposed by Kellog in assessing annual percentage fatigue damage for joints between horizontal and vertical 1, 2 and 3 bars of foot A in areas N1 and N2 is presented. The graphs show the annual percentage degradations on cardinal and intercardinal directions of wave action, as well as the cumulative degradations. The table inside the graph shows the cumulative annual percentage degradation by wave heights.

The use of SCFs proposed by Kuang for A1N1 joints determines a difference in the assessment of cumulative fatigue degradations from 0.5056094 to 0.47699, representing 5.66% (figure 4).

The annual degradation on cardinal directions is 0.0125814 for N-S, 0.214663 for E-W and 0.0188137 NE-SW (representing 5.1% N-S, 87.2% E-W and 7.7% NE-SW of the total annual degradation value (using a average wave histogram of years 2008 - 2018).

For the A1N2 joints (figure 5), a difference in the assessment of the cumulative fatigue degradation for Kellog stress concentrators from 0.297732842 to 0.2460602 representing 17.35%, is determined for those proposed by Kuang.

The annual degradation by cardinal directions is 0.0125814 for N-S, 0.214663 for E-W and 0.0188137 NE-SW (representing 5.1% N-S, 87.2% E-W and 7.7% NE-SW of the total annual degradation value).

For the A3N2 joint the values are slightly similar.
For the A3N1 joints the difference between the cumulative fatigue degradations compared to the SCF given by Kellog is from 1.9307082 to 1.8162824 or 5.92% (figure 6).

The annual degradation by cardinal directions is 0.167866e-2 for N-S, 0.998039 for E-W and 0.816564 NE-SW (representing 0.4% N-S, 55% E-W and 44.6% NE-SW of the total annual degradation value). The estimated lifespan for the A1N1 joint is 55 years.
2.2. The effects of S-N curve types in assessing fatigue degradation

Fatigue degradation analysis is performed using 3 types of S-N curves (figure 7): AWS-X, modified AWS-x and BS-F. Local efforts are assessed using SCF given by Kellog. The degradation in the A1N1 joints obtained by using the modified AWS-x curve is 1.17 times the degradation associated with the AWS-X curve; the corresponding values for A1N2, A3N1 and A3N2 joints are approximately 1.43; 1.08 and 1.25 higher. The magnitude of the stresses caused by different sea conditions are generally of greater value for the A3N1 and A3N2 joints (internal vertical element) compared to those on the A1 and A2 external vertical elements. As the AWS-X and modified AWS-x curves are identical for high magnitude stresses, the differences appearing and accentuating as the stress amplitudes decrease; the variation in the degradation percentage using these curves for A1N1 and A3N1 joints is smaller. In the other cases the differences in fatigue degradation are brought about by efforts with low amplitude values, with fatigue cycles greater than $2 \times 10^6$ where the difference between the two S-N curves is noticeable.

Figure 7. S-N curves as for DNV regulations [7].

The difference in fatigue degradation using the modified AWS-x and BS-F curves is significant. The BS-F curve is more conservative, giving lower fatigue cycles and therefore greater degradation. Fatigue degradation at the A1N1 joints using the BS-F curve is 5.17 times the degradation associated with the modified AWS-x curve. The corresponding values at A1N2, A3N1 and A3N2 joints are around 6.36; 1.98 and 3.73. The results differ because for a high amplitude of efforts the difference in the number of cycles at failure using these two curves is smaller than that for the value of low amplitude efforts.

3. Conclusions

The results show that for Gloria type self-erecting platforms of lattice beam, with small dimensions of the elements, the stress concentration factors determined by Kuang is recommended to be used when the knowledge of the hydrometeorological conditions at the site are detailed and an approximation of the loads can be made as close as possible to their real evolution over time. It also involves the designer's experience regarding the respective jacket model. On the other hand, given that the long-term assessment of loads is less reliable, the SCF proposed by Kellog offers better coverage.

As the life of the structure is governed by the maximum accepted degradation of the joint, both the AWS-X curves and the modified version can be used in estimating fatigue degradations but the choice between modified AWS-X or BS-F curves can lead to significantly different results.
The use of Kellog’s SCF factors together with BS-F curves, significantly increase the reliability coefficient of the structure, but in the same time with the costs related to the construction. So the owner of the jacket should balance between the working life time of the structure and the economic challenge.

4. References
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