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PROCEDURE FOR THE SERVICE STRENGTH APPROVAL OF THE DRILLSHIP DERRICK

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Abstract

Service strength approval of a drillship derrick must include beside the static strength validation under limit loads, also the fatigue evaluation for the critical areas of the derrick structure. During the service life structural members of the derrick are exposed to giga stress cycles with variable values, caused by wave and wind action and drilling operation. These variable stresses can generate the fatigue cracks and lead to the total fracture of the structure. For the fatigue strength evaluation of a drillship derrick is important to define the loading taking into account the drillship usage. To determine the loading it is necessary to evaluate the ship motion and to calculate the corresponding loads due to waves, wind and drilling operation acting on the derrick structure. For the fatigue life validation, the resulting stresses, caused by these loads must be determined and their representative spectra (cumulative frequency distributions) derived.

In this paper the procedure to determine the operational stress spectra and to evaluate the fatigue life of a drillship derrick is described.

Keywords: Operational loading; Stress spectra; Drillship derrick; Service strength; Fatigue life estimation

1. INTRODUCTION

Due to development in energy market the number of drill ships (Fig.1) in the offshore drilling fleet has been more than doubled over the past decade, from 37 operating units in 2003 to 87 units in 2013. Further growth is expected over the next years developing drillship systems with higher efficiency and usage at higher drilling depth, polar temperatures and harsh environmental conditions.

The service strength validation of a drillship derrick must include as well the **static strength control**, based on nominal stresses in individual cross sections of the structure (failure criterion: **buckling** ;requirement: maximum monotonic stress lower than the structural yield point) and the **fatigue evaluation** for the critical areas of the derricks structure, based on local hot-spot stress (failure criterion: **fatigue cracks**; requirement: cyclic stresses under variable service loading lower than the allowable stress) for the specific service stress spectrum.

Figure 1. Drillship with derrick

Slika 1. Brod za podmorska bušenja s bušaćim tornjem.

During the service life structural members of derrick are exposed to more than 10^8 stress cycles with variable amplitudes, caused by wave and wind action and drilling operation, which can generate the fatigue cracks, as shown on an example in Fig.2, and lead to a total fracture of the derrick.

Figure 2.Cracks on derrick footing after 20 years usage.

Slika 2. Naprsline na nogama tornja nakon 20 godina upotrebe.

For the fatigue strength evaluation of a drillship derrick it is important to define the loading taking into account the drillship usage. To determine the loading it is necessary to evaluate the ship motion and to calculate the respective loads acting on the derrick structure due to waves, wind and drilling operation. Finally the resulting stresses, caused by these loads must be determined and their representative spectra (cumulative frequency distributions) derived to be used for the fatigue life validation. For the fatigue validation of a drillship derrick it is of paramount importance to determine the representative service stress spectra for possibly critical, fatigue sensitive, system-points of the structure. Due to a very complex loading at operation, caused by ship motion and wind blowing with changing direction and intensity (speed), reliable praxis related service stress spectra should be used for the fatigue validation.

Beside the stress spectra also the fatigue strength, to be used for fatigue validation, is of decisive importance. Predominantly the critical system-points are welds on which, on one side the stress concentration is present and on other side the fatigue strength is lower than in non-welded areas. Also the bolted connections could be critical and should be in such a case approved using the corresponding stress spectra.

In this paper the methodology to evaluate the fatigue life [1] of a drillship derrick is described.

Prerequisites to validation described in this paper are: (a) approval of the static strength including buckling evaluation of structural members under monotonic extreme loading and (b) check of the local hot-spot stresses in individual areas of the derrick with respect to the structural yield point. At the design process the allowable maximum local (structural or hot-spot) stress can be determined by a conservative simplified approach based on material yield point $R_{\mathrm{p},0.2}$ taking into account the required safety factor S_F (usually 1.15) : $\sigma_{max,all} \leq (0.9\, R_{\mathrm{p},0.2} + 0.002\, E) / S_\mathrm{F}$.

2. SERVICE STRESS SPECTRA

The service stress spectra valid for specific area (system point of the derrick) are defined by the **spectrum maximum value** $\Delta\sigma_0$, the **spectrum shape** $\boldsymbol{h}$ and the **number of cycles** $\boldsymbol{n_0}$ for the required fatigue life. The probability of occurrence of the specific stress spectrum must be defined additionally, to be able to carry out a reliable fatigue validation. The stress spectrum can be presented [2,3] by two-parameter Weibull cumulative frequency distribution of stress range of exceedances $Q(\Delta\sigma)$. The $Q(\Delta\sigma)$ correspond to the probability that a value exceeds $\Delta\sigma$.

$$Q(\Delta\sigma) = \frac{n(\Delta\sigma)}{n_0} = \exp\left[-\left(\Delta\sigma/q\right)^h\right] \tag{1}$$

where: h – Weibull shape parameter; n_0 *– number of cycles over the time period for which the stress range level* $\Delta\sigma_0$ *is defined;* $\Delta\sigma_0$ *– the largest stress range corresponding to* n_0 *cycles from the load spectrum and q – Weibull scale parameter defined from the stress range level* $\Delta\sigma_0$ *as* $=\Delta\sigma_0 (ln\ n_o)^{-1/h}$.

A schematic presentation of the stress spectra is given in Figure 3.

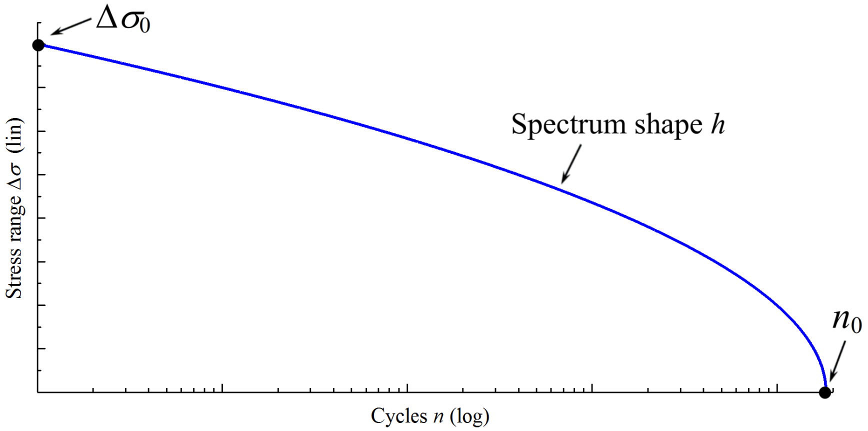

Figure 3. Schematic presentation of service stress spectrum.

Slika 3. Shematski prikaz spektra pogonskog opterećenja.

The stress range contains stress maximum and the stress minimum for specific lading defining the stress ratio between the minimum to maximum value of the stress in a cycle.

2.1 Operational stresses

The loads acting on derrick are result of ship motion (heave, roll, pitch) due to **waves**, **wind** activity and **drilling** operation. These loads generate variable stresses in individual system-points of derrick. To systemize these stresses the loading due to the ship motion in waves is divided in operational conditions at **navigation** and at **drilling**.

Navigation (NA) include different loading conditions: survival loading with 25 m wave height and wind up to 52 m/s speed, navigation at "bad weather" with waves of 15-25 m height and wind up to 52 m/s speed, navigation at "rough sea" with waves of 6m and wind of 16 m/s and navigation at calm weather condition, with specific usage time and loading resulting in different stress spectra.

Drilling (DR) operation could be divided in drilling at moderate/high sea state and wind up 17 m/s, and drilling with overpool at low ship motion with waves up to 4 m and wind up to 17 m/s.

The largest service stress range $\Delta\sigma_{0,i}$ for individual spectrum is determined based on acting loads and the stress calculation of derricks structure. The maximum values for ship motion and environmental loading at navigation are chosen to be extreme loading condition for stress spectrum which is used also for the static strength validation. The ship motion and environmental condition values for the load case NA are chosen to be extreme environmental condition according to the maximal load forces values for survival conditions which is used also for the static strength validation

2.2 Spectrum shape

Beside the stress $\Delta\sigma_{0,i}$ the shape parameter h in the Weibull distribution has a significant impact on calculated fatigue damage. Taking into account the data in literature and recommendations [4-6] a shape parameter for the service stress spectrum generated through environmental loading (wind and waves) between $h = 0.8$ and $h = 1.1$ should be used. It is proposed to use value $h = 1$ for the resulting spectrum and spectra for the environmental loading at drilling. For the spectrum of drilling operations value $h = 1.1$ to 1.2 is proposed.

2.3 Number of cycles

The number of cycles $\boldsymbol{n_0}$ for individual usage depends on the dynamic behavior of the structure under the specific loading. The dynamic response of the derrick structure to the environmental loading (wind and waves) depends on its natural frequencies ν_0.

For the spectra at drilling the maximal load up-crossing frequency is determined by the ship motion which is usually lower than the natural frequency of the derrick.

The number of cycles per year (n_0 / y) for each loading case is achieved by multiplying the time spent in seconds with specified frequency ν_0 ($n_0 / \mathrm{y} = \mathrm{days} \cdot 24 \cdot 3.6 \cdot 10^3 \cdot \nu_0$).

Based on a natural frequency ν_0 of derrick and a ship usage of 25 days per year at **navigation** the number of cycle per year due to the navigation NA will result in a value of about $2.16 \cdot 10^6$ cycles.

Due to the requirements for the fatigue validation the spectrum at **drilling** is divided in two partial spectra, one for the drilling including the environmental loading (DR+E) with the frequency of ship motion $\nu_0 = 0.1$ Hz and the second for the environmental loading at drilling alone (E) with natural frequency $\nu_0 = 1.0$ Hz. The number of cycles at drilling DR+E results from cycles at drilling per each well and number of wells per year. Assuming a value for $4.\ 6\cdot10^{3}$ cycles per each well and four wells per year it results in $1.84\cdot10^{4}$ cycles for this load case. Based on a time of 310 days at drilling operation the number of cycles for the superimposed environmental loading alone will result in a value of roughly $2.68\cdot10^{6}$ cycles per year. The resulting total number of· $3.6\cdot10^{3}$ cycles per year will be then about $n_0 / \mathrm{y} = 4.86\cdot10^{3}$ and in the case of 30 years usage about $1.46\cdot10^{8}$ cycles

3. FATIGUE VALIDATION

The fatigue validation must be carried out for individual, highly stressed, possibly critical, system points of the derrick. As an example the system points of a derrick are shown in Fig.4, which must be controlled concerning fatigue under expected service loading.

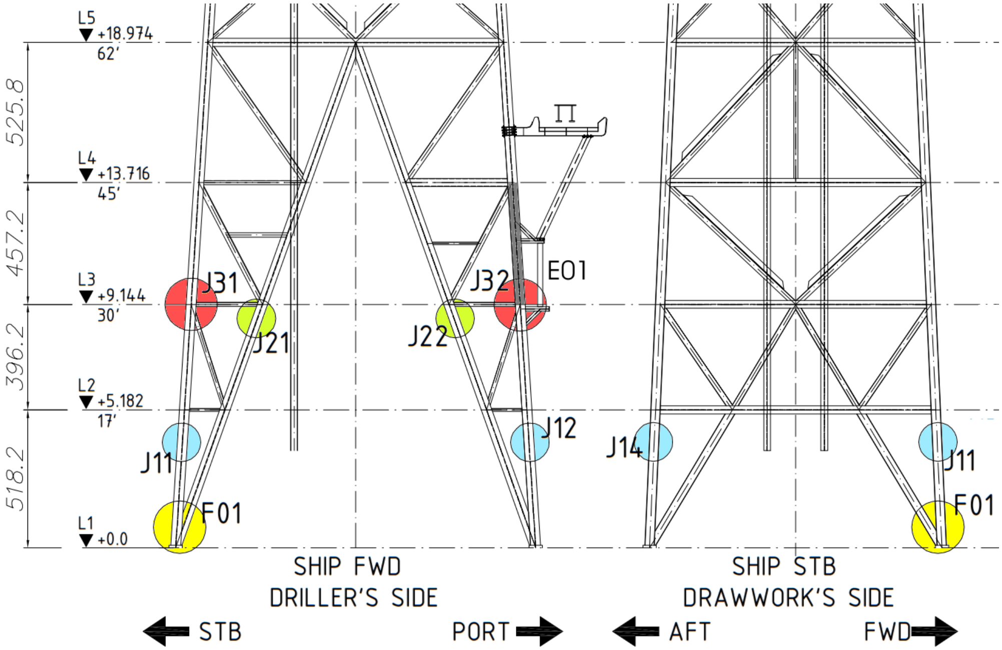

Figure 4. Possibly critical system points of a derrick to be validated respective fatigue.

Slika 4. Moguća kritična mjesta na bušaćem tornju na kojima treba provesti provjeru čvrstoće na zamor.

The fatigue validation must include the representative stress spectrum for each possibly critical system point of the derrick and the corresponding fatigue strength. For the fatigue validation following stresses, based on calculation, are used:

- prestress due to the weight σ_{DW},
- maximum calculated stress σ_{max}, which contains as well the prestress as the stress generated by the drilling and the environmental loading, as used for the static validation of the structure,
- maximum value for the superimposed environmental loading σ_E due to the ship motion and wind action,
- extrapolated stress for fatigue validation at navigation $\Delta\sigma_E$ ($\Delta\sigma_E = \sigma_{max} - \sigma_{DW}$) and
- extrapolated stress for fatigue validation at drilling $\Delta\sigma_E = 1.5 \cdot \sigma_E$ for environmental loading at drilling alone and $\Delta\sigma_{DR+E}$ ($\Delta\sigma_{DR+E} = \sigma_{max} - \sigma_{DW} = \Delta\sigma_{DR} + \sigma_E$) for drilling including superimposed environmental loading σ_E

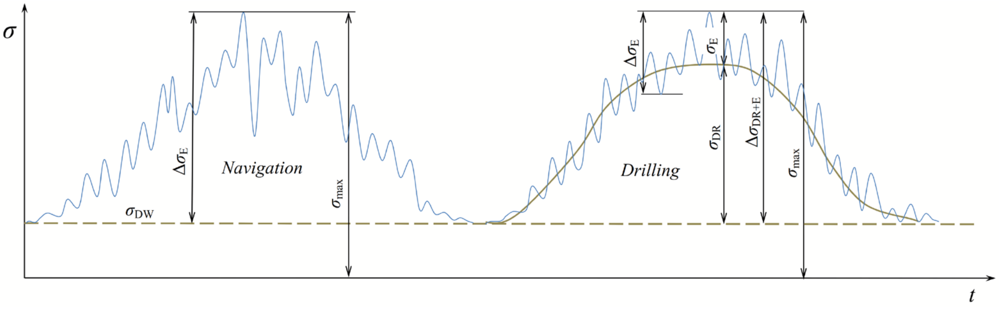

Figure 5. Definition of stress values on a system point which are used for fatigue validation (schematic).

Slika 5. Definicija vrijednosti naprezanja na pojedinom mjestu tornja, koja se koriste za provjeru pogonske čvrstoće (shematski).

The stress values used for fatigue validation must be based on drillship usage, and should correspond to a conservative approach by the assumed combination of extreme loading condition as well with regard to the stress values as to the number of cycles and shape of the specific stress spectrum.

In Fig.6 the stress spectra for individual loading case and a Woehler curve, used for fatigue validation, are presented in stress (σ)-cycles (n) diagram.

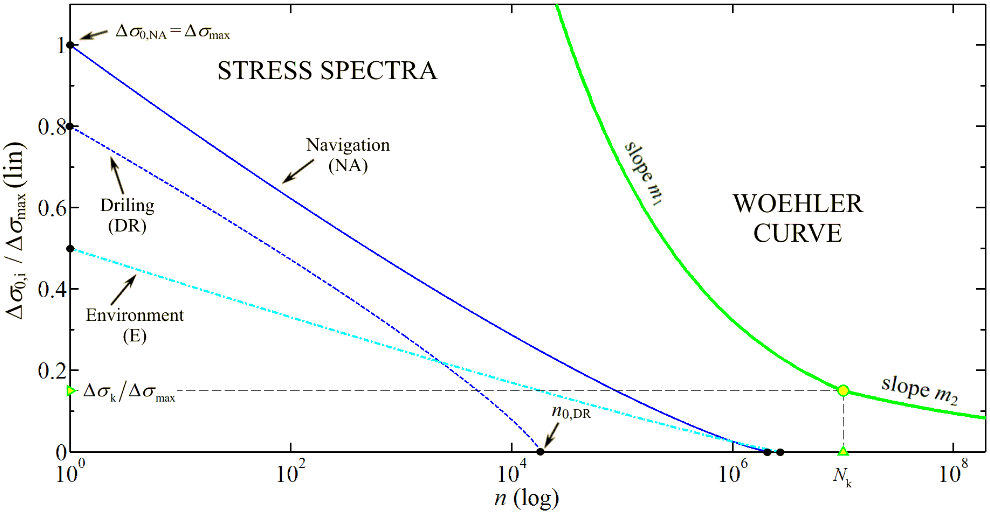

Figure 6. Stress spectra and Woehler curve for fatigue validation

Slika 6. Spektri naprezanja i Woehlerova krivulja za provjeru zamorne čvrstoće.

The fatigue life estimation is made according to the modified Palmgren-Miner damage accumulation hypothesis [1], since the fatigue strength of structures in service is continuously decreasing at high number of stress cycles. The Woehler curve is in this case presented in the stress-cycles diagram as a bilinear curve,Fig. 6; N_k represents the number of cycles at so called 'endurance limit' (knee point of the Woehler curve) having the value for the fatigue validation of welded structures usually $N_k = 10^7$ cycles.

For the bi-linear or two-slope Whoeler curve, as noted in [3, Appendix], the fatigue damage can be calculated by

$$D = n_0 \left[\frac{q^{m_1}}{\bar{a}_1} \Gamma\left(\frac{m_1}{h} + 1; \left(\frac{\Delta\sigma_k}{q} \right)^h \right) + \frac{q^{m_2}}{\bar{a}_2} \gamma\left(\frac{m_2}{h} + 1; \left(\frac{\Delta\sigma_k}{q} \right)^h \right) \right] \tag{2}$$

where: $\Delta\sigma_k$*– stress range for which change of slope of Woehler curve occur;* N_k*– number of cycles for which change of slope of Woehler curve occur;* $\Gamma(\alpha;\ x)$*– the complementary incomplete gamma function;* $\gamma(\alpha;\ x)$*– the incomplete gamma function; m– negative inverse slope of the Woehler curve; ā intercept of the design Woehler curve with the log N axis;* $\bar{a}_1, m_1$*– Woehler curve fatigue parameters (* $\bar{a}_1 = N_k \cdot \Delta\sigma_k^{m_1}$*) for* $\Delta\sigma > \Delta\sigma_k$*;* $\bar{a}_2, m_2$*– Woehler curve fatigue parameters (* $\bar{a}_2 = N_k \cdot \Delta\sigma_k^{m_2}$*) for* $\Delta\sigma \le \Delta\sigma_k$*.*

The calculated fatigue damage D must be lower than the allowable value: $D_{calc} \leq D_{all} \leq 1$. Nevertheless of the modifications related to the calculation of damage accumulation by Palmgren-Miner hypothesis , the investigations and practical experience revealed damage values different from the theoretical value $D = 1$, depending on stress-time history, stress distribution and material behaviour. Therefore a damage sum of $D_{all} = 0.5$ is recommended for welded structures [1,3,5-8].

In order to perform a reliable validation, the scatter of the fatigue strength as the service loading spectra, must also be taken into account. Therefore, the service load spectra represent the extreme usage condition (that means that probability of occurrence of this spectrum will be very low $P_o \leq 1\%$) and the Woehler curve has a high probability of survival $P_s \geq 90\ \%$, so that the resulting probability of failure for the durability life will be low ($P_f \leq 0.1\%$.) if the calculated damage is $D \leq 0.5$.

The fatigue damage D should be calculated for the stress spectrum of each load case. Hence it will be possible to determine which load case is decisive for the fatigue strength of the specific derrick area.

The fatigue validation is influenced, beside of the service stress spectra, decisively from the structural fatigue properties for each critical system point of the derrick. For the welded structural details, being usually the critical points, the data for Woehler curves can be found in specific codes and norms [5,7,8]. Also bolted connections in highly stressed areas should be validated using specific data [5]. In specific cases also the influence of a low temperature at drillship usage or corrosion should be taken into account.

As an example for the described procedure a welded structural detail of the derrick the system point J 32, Fig. 4 is analysed. This structural detail correspond to detail category C1 , Ref. [4], with calculated maximum values of the stresses for loading case: $\Delta\sigma_0 = 320$ MPa at navigation, $\Delta\sigma_0 = 250$ MPa at drilling with superimposed environmental loading and $\Delta\sigma_0 = 220$ MPa due to the environmental loading alone.

The data used for the fatigue validation and results for individual loading case are summarized in Table 1. The Woehler curve are based on Ref. [5] with following data: for the fatigue strength $\Delta\sigma_k = 65.5$ MPa at $N_k = 10^7$ cycles and slopes of Woehler curve $m_1 = 3$ and $m_2 = 5$.

Specific data related to the stress spectra for individual loading condition per year and Woehler curve, used for calculation of fatigue damage are presented in Fig. 7.

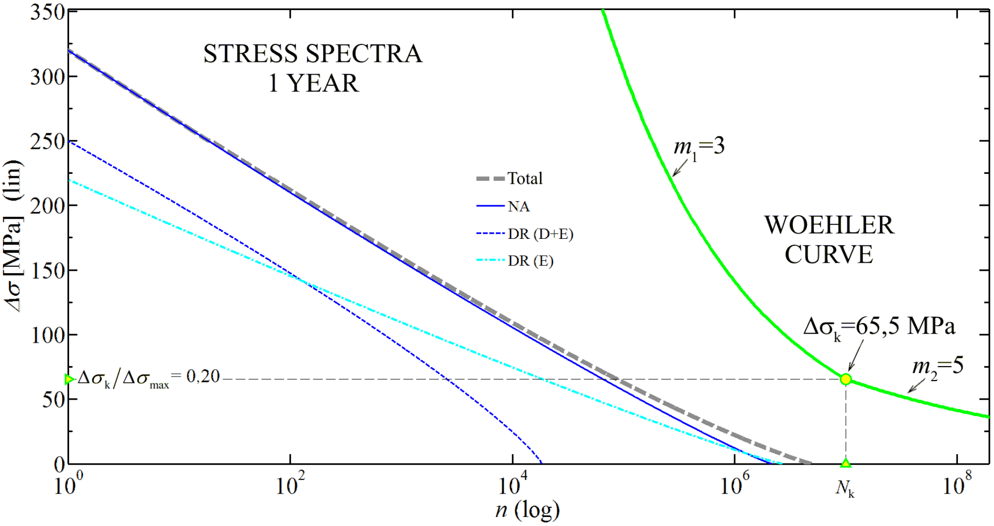

Figure 7 Stress spectra for one year and Woehler curve used for fatigue validation.

Slika 7. Spektri pogonskih naprezanja za jednu godinu i Woehlerova krivulja za provjeru pogonske čvrstoće.

The results of the calculation are summarized in Table 1:

Table 1. The data for the fatigue damage calculation and resulting fatigue life estimation.

Tablica 1. Ulazne vrijednosti za proračun oštećenja i odgovarajuća procjena životnog vijeka.

$\Delta\sigma_k = 65{,}50$ MPa; $N_k = 10^7$; $m_1 = 3$; $m_1 = 5$					
Raturn period : 1 Year					
FLC	$\Delta\sigma_{0,i}$ (MPa)	$n_{0,i}$	h_i	D_i	%
NA	320,00	2.16E+06	0,9	2,47E-02	75,0%
DR (D+E)	250,00	1.84E+04	1,2	1,03E-03	3,1%
DR (E)	220,00	2.68E+06	0,9	7,22E-03	21,9%
Per Y =		4,86E+06		3,30E-02	
Estimated life : $D_{all} / \sum D_i = 0{,}5 / 0{,}033 = 15{,}15$ Years					

The expected fatigue life with respect to the criteria of an initial crack based on this calculation is about 15years.To assure a higher fatigue life an improvement in this area would be necessary. From the Table 1 it can be seen that 75% of the fatigue damage is generated by the stress spectra due to the navigation and 25% by the loading case of drilling, mainly due to the superimposed environmental loading at drilling.

4. CONCLUSION

For the fatigue validation of a drillship derrick it is of paramount importance to determine the representative service stress spectra for possibly critical, fatigue sensitive, system-points of the structure. Due to a very complex loading during operation, caused by ship motion in waves and wind blowing with changing direction and intensity (speed), reliable praxis related service stress spectra should be used for the fatigue validation.

Beside the stress spectra also the fatigue strength, to be used for fatigue validation, is of decisive importance. Predominantly the critical system-points are welds on which, on one side the stress concentration is present and on other side the fatigue strength is lower than in non-welded areas. Also the bolted connections could be critical and should be in such a case approved using the corresponding stress spectra.

It is proposed to verify the data used to derive the service stress spectra by service measurements, at which the stress time histories on selected system-points of the derrick should be determined in correlation to the wave and wind intensities.

It is also important that beside the described fatigue strength validation, during the usual periodical ship inspections the highly stressed system points of the derrick, determined at validation, are controlled regarding possible initial cracks.

Acknowledgment

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Postupak provjere pogonske čvrstoce tornja broda za podmorska bušenja

Sažetak

Provjera pogonske čvrstoće tornja broda za podmorska bušenja mora pored kontrole statičke čvrstoće pod maksimalnim opterećenjem, da sadrži također kontrolu čvrstoće na zamor pojedinih ,kritičnih mjesta strukture tornja. Ta mjesta strukture su opterećena promjenljivim naprezanjima nastalih djelovanjem valova,vjetra i bušenjem pri upotrebi broda sa brojem promjena u giga području. Usljed tih naprezanja mogu nastati zamorne naprsline a njihovo širenje uzrokovati lom čitave konstrukcije. Da bi se mogla izvršiti provjera čvrstoće na zamor, mora se definirati pogonsko naprezanje uzimajući u obzir upotrebu broda. Pri određivanju naprezanja potrebno je analizirati gibanje broda pri pogonskim opterećenjima i odrediti sile koje djeluju na strukturu tornja usljed valova, vjetra i bušenja. Za provjeru čvrstoće na zamor potrebno je odrediti naprezanja uzrokovana tim silama i njihov reprezentativni spektar (raspodjelu zbirne učestalosti naprezanja).

U ovom članku je prikazan postupak za određivanje spektra pogonskih opterećenja i provjeru životnog vijeka bušaćeg tornja broda za podmorska bušenja.

Ključne riječi: Radna opterećenja; Spektar opterećenja; Toranj broda za bušenje; Procjena životnog vijeka na zamor

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