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# Assessment of Aframax Tanker Hull-Girder Fatigue Strength According to New Common Structural Rules

Original scientific paper

The paper describes the fatigue strength assessment of ship hull girder according to Common Structural Rules for Oil Tankers (CSR). Additional criteria for hull girder fatigue calculation have recently been introduced into CSR because of frequent crack appearances on the main deck structure of large tankers. Hull girder fatigue check in CSR is performed in two steps: preliminary "fatigue section modulus" verification and detail fatigue calculation of deck longitudinals. The analysis is performed for an Aframax oil tanker fully complying with "old" rules of classification societies. Since the results of fatigue calculation for initial structure have not been found acceptable, a significantly increased hull section modulus is necessary as the only practical way for the deck longitudinal fatigue life improvement. In practice, the vertical wave bending moment at midship, as the primary cause of hull girder fatigue damage, is calculated according to a simplified CSR formula. In order to improve the knowledge of its influence on the calculated fatigue life, the wave bending moment is also determined directly by a hydrodynamic and statistical analysis. In that analysis, the North Atlantic navigation is assumed as design wave environment for three predominant loading conditions. It is obvious that such an approach enables a more detailed and rational fatigue analysis than the one carried out according to the CSR rules.

**Keywords:** *Aframax tankers, bending moment, fatigue strength, hull girders, vertical waves*

## Procjena zamorne izdržljivosti uzdužnjaka palube *aframax* tankera prema novim usuglašenim pravilima klasifikacijskih društava

Izvorni znanstveni rad

Opisan je postupak analize zamorne izdržljivosti brodskog trupa kao grednog nosača u području glavnog rebra prema novim usuglašenim pravilima klasifikacijskih društava (CSR). Kriteriji za zamornu izdržljivost grednog nosača su uvedeni u CSR pravila zbog učestalih pojavljivanja pukotina na palubnim strukturama velikih tankera. Provjera grednog nosača na zamornu izdržljivost u CSR se provodi u dva koraka: preliminarna provjera "zahtijevanog momenta otpora na zamor" i detaljni proračun zamora uzdužnjaka palube. Analiza je provedena za *aframax* tanker koji se gradi u skladu s postojećim pravilima klasifikacijskih društava. Budući da rezultati proračuna zamora postojeće konstrukcije nisu zadovoljili, znatno je povećan moment otpora poprečnog presjeka trupa, kao jedini izvediv način poboljšanja zamornog vijeka uzdužnjaka palube. U cilju daljnjeg produbljivanja znanja o ovom problemu, vertikalni moment savijanja na sredini broda, kao temeljni uzrok zamornog opterećenja uzdužnjaka palube, izračunat je, osim prema pojednostavljenim CSR izrazima, također i izravno hidrodinamičkom i statističkom analizom. U tu svrhu pretpostavljena je plovidba u Sjevernom Atlantiku cijelo vrijeme službe za tri prevladavajuća stanja krcanja broda. Pokazuje se da ovakav pristup omogućava podrobniju analizu zamora od one koja je propisana CSR pravilima.

**Ključne riječi:** *aframax tanker, moment savijanja, uzdužnjaci palube, vertikalni valovi, zamorna čvrstoća*

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## 1 Introduction

The Common Structural Rules (CSR) for Double-Hull Oil Tankers have been developed by a group of IACS classification societies in response to a consistent and persistent call from industry for an increased standard of structural safety of oil tankers. The recently published statistics indicate a significant number of defects, especially fractures, occurring in tankers less than 10 years old. It is the intent of CSR rules to reduce the possibility of so many defects [1],[2]. New CSR rules implement advanced structural and hydrodynamic computational methods to establish new criteria applied in a consistent manner, which will result not only in a more robust, safer ship, but will also eliminate the possibility of using scantlings and steel weight as a competitive element when selecting a class society to approve a new design.

Possibly, the most important new CSR rule requirement is the one for ultimate vertical bending moment capacity of hull-girder, which was not prescribed in previous versions of ship classification rules (with the exception of the Rules of Bureau Veritas that adopted the ultimate strength criterion in the year 2000 [3]). A "net" thickness approach is also an important new feature of CSR, where the structural capacity for different failure modes is to be calculated by assuming that the thickness of structural elements is reduced because of corrosion effects. CSR proposes a corrosion deduction thickness for different structural elements and different levels of calculation. Design scantlings of structural elements are then obtained by adding this corrosion deduction thickness to the minimum calculated "net" thickness.

Fatigue and corrosion are recognized as predominant factors which contribute to the structural failure observed on a ship in service. Fatigue may be defined as a process of cycle by cycle accumulating of damage in a structure subjected to fluctuating stresses. Until recently, the fatigue was considered as a serviceability problem rather than a hull girder strength problem [4], [5]. However, the latest researches conducted for the development of the new CSR showed that the majority of cracks are caused not only by local dynamic loads but also by global dynamic loads such as the wave bending moment. In other words, fatigue of the hull girder may be a governing strength criterion for oil tankers, in particular if higher tensile steel is implemented [6].

The aim of the present paper is to present the hull-girder fatigue analysis of an existing Aframax oil tanker according to new CSR.

A brief description of the Aframax tanker used in the present study is given in the first section of the paper. The following section describes the methodology proposed by CSR for fatigue life calculation of deck longitudinals of a double hull oil tanker. The next section presents results of the application of previously presented methodology to the Aframax tanker, showing that the fatigue life of the deck structure is significantly below 25 years. Although the fatigue life in general depends on many factors, such as design shape of structural details, material grade, scantlings of details, etc., a decrease in fatigue stresses is found to be the only convenient way to improve the global fatigue behaviour. Therefore, the section modulus of midship section is to be increased in order to reduce fluctuating stresses and to improve the fatigue behaviour of a ship as a hull girder. Finally, in the last section of the paper, the wave bending moment, as a primary cause of fatigue in the deck structure of oil tankers, is calculated by a direct hydrodynamic and statistical analysis using the linear strip theory and the IACS Recommendation No. 34 for extreme wave loads [7]. The obtained results are compared to those obtained by a pure "rule" approach and corresponding conclusions are drawn.

The main conclusion of the study is that a satisfactory fatigue life may be achieved only by a significant increase in the midship section modulus. Therefore, the study supports the opinion that fatigue becomes a governing criterion in ship design, requiring a lot of additional steel-weight to be added to the hull structure.

## 2 Ship description

The ship analyzed in the present study is an existing Aframax oil tanker with the centre line plane bulkhead fully complying with "old" rules for the design and construction of steel ships, including IACS UR S11. The main particulars of the Aframax tanker are presented in Table 1. Deck and bottom areas of the ship are made of higher tensile steel AH32, while the region around the neutral axis is made of mild steel ST235. Since this tanker has the ICE-1C class notation, the side shell in the ice belt region is made of higher tensile steel AH36. In addition, the whole center line bulkhead is made of higher tensile steel AH32 due to shear stress requirements.

The general arrangement of the vessel is shown in Figure 1, while the midship section of the vessel is presented in Figure 2.

Table 1 **Main characteristics of the Aframax tanker**
Tablica 1 **Osnovne značajke *aframax* tankera**

| | |
|---|---|
| Length between perpendiculars, *L*pp | 236 m |
| Moulded breadth, *B* | 42.0 m |
| Moulded depth, *D* | 21.0 m |
| Scantling draught, *T* | 15.6 m |
| Deadweight, *DWT* | 114000 dwt |

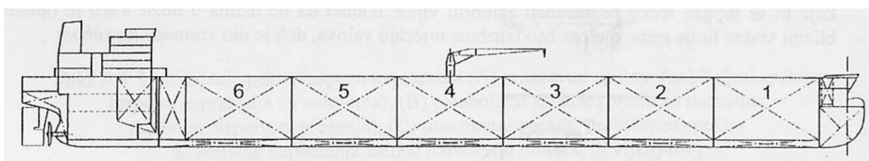
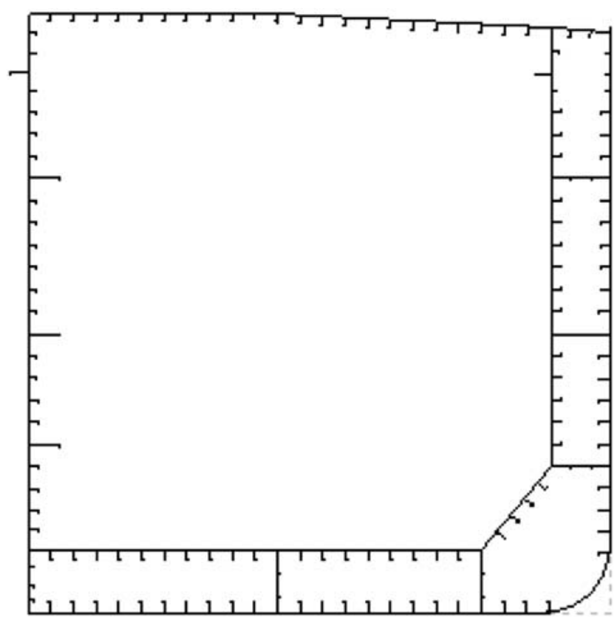



Figure 1 **Aframax tanker**
Slika 1 ***Aframax* tanker**

Figure 2 **Midship section of the Aframax tanker**
Slika 2 **Glavno rebro *aframax* tankera**



## 3 Fatigue in CSR

Hull girder fatigue calculations in CSR are performed in two steps: a simplified check of hull girder fatigue section modulus and a detailed fatigue life assessment of main deck longitudinals. These two calculation methods are briefly described in the following sections.

### 3.1 Hull girder fatigue requirement

Hull girder fatigue strength is checked by a simplified fatigue control measure against dynamic hull girder stresses in the longitudinal deck structure. The required hull girder fatigue section modulus $Z_{v\text{-fat}}$ ($m^3$) is given in **CSR, Section 8.1.5**:

$$Z_{v-fat} = \frac{M_{wv-hog} - M_{wv-sag}}{1000 \cdot R_{al}} (m^3) \tag{1}$$

$M_{wv\text{-}hog}$ = hogging vertical wave bending moment for fatigue (kNm)
$M_{wv\text{-}sag}$ = sagging vertical wave bending moment for fatigue (kNm)
$R_{al}$ = allowable stress range (N/mm²)

$$R_{al} = 0.17L+86 \text{ for class F-details} \tag{2}$$

The actual section modulus to be compared to the minimum required value $Z_{v\text{-}fat}$ is calculated by deducting half of the rule corrosion wastage ($-0.5t_{corr}$) from the gross thickness of all structural elements contributing to the hull girder longitudinal strength. It should be pointed out that this requirement is not mandatory, but recommended to be applied in the early design stage in order to avoid significant reinforcements in the later design stage when detailed fatigue calculations are carried out.

Hogging and sagging vertical wave bending moments for fatigue are obtained by multiplying rule wave bending moments for strength assessment by a factor of 0.5. In that way, the representative probability level of wave bending moments is reduced from $10^{-8}$ to $10^{-4}$. This aspect is described in **CSR Section 7.3.4.1.3.**

### 3.2 Detailed fatigue assessment of deck longitudinals

The calculation of hull girder stress for the detailed fatigue strength assessment of deck longitudinals is based on the fatigue hull girder sectional proprieties calculated by deducting a quarter of the corrosion addition ($-0.25\ t_{corr}$) from the gross thickness of all structural elements comprising the hull girder cross section.

The capacity of welded steel joints with respect to fatigue strength is characterized by the Wöhler curves (S-N curves) which give the relationship between the stress ranges applied to a given detail and the number of constant amplitude load cycles to failure, with the zero mean stress. The hull detail which is taken into consideration for the fatigue assessment of deck structure is the connection of a deck longitudinal and a typical web frame, classed as F-detail, **CSR Table C.1.7-Classification of Structural Details.**

The fatigue assessment of the structural details is based on the application of the Palmgren-Miner cumulative damage rule. When the cumulative fatigue damage ratio, *DM*, is grater than 1, the fatigue capability of the structure is not acceptable. *DM* is determined according to **CSR Appendix C 1.4.1**.

$$DM = \sum_{i=1}^{2} DM_i \tag{7}$$

Where:

$DM_i$ = cumulative fatigue damage ratio for the applicable loading condition
i = 1 for full load condition
= 2 for normal ballast condition.

Assuming that the long term distribution of stress ranges fits a two-parameter Weibull probability distribution, the cumulative fatigue damage $DM_i$ for each relevant condition is taken as follows (**CSR Appendix C, Sec.1.4.1.4**):

$$DM_i = \frac{\alpha_i N_L}{K_2} \cdot \frac{S_{Ri}^m}{(\ln N_R)^{\frac{m}{\xi}}} \cdot \mu_i \cdot \Gamma\left(1 + \frac{m}{\xi}\right) \tag{8}$$

Where:

$N_L$ = number of cycles for the expected design life. The value is generally between $0.6 \times 10^8$ and $0.8 \times 10^9$ cycles for a design life of 25 years.

$$N_L = \frac{f_0 \cdot U}{4 \cdot \log L} \tag{9}$$

$f_0$ = 0.85, factor taking into account non-sailing time for operations such as loading and unloading, repairs, etc.
$U$ - design life (s) = $0.788 \times 10^9$ for a design life of 25 years
$L$ = rule length [2]
$m$ = 3-S-N curves exponent as given in **CSR Table C.1.6**
$K_2$= $0{,}63 \cdot 10^{12}$ - S-N curves coefficient as given in **CSR Table C.1.6**
$\alpha_i$ - proportion of the ship's life:
$\alpha_1 = 0.5$ for full load condition
$\alpha_2 = 0.5$ for ballast condition
$S_{Ri}$ - stress range at the representative probability level of $10^{-4}$ (N/mm²)
$N_R$ = 10000, number of cycles corresponding to the probability level of $10^{-4}$
$\xi$ - Weibull shape parameter
$\Gamma$ - Gamma function
$\mu_i$ - coefficient taking into account the change in the slope of the S-N curve

$$\mu_i = 1 - \frac{\gamma\left(1 + \frac{m}{\xi}, \upsilon_i\right) - \upsilon_i^{-\frac{\Delta m}{\xi}} \cdot \gamma\left(1 + \frac{m + \Delta m}{\xi}, \upsilon_i\right)}{\Gamma\left(1 + \frac{m}{\xi}\right)} \tag{10}$$

$$\upsilon_i = \left(\frac{S_q}{S_{Ri}}\right)^{\xi} \cdot \ln N_R \tag{11}$$

$S_q$ - stress range at the intersection of two segments ("knee") of the S-N curves, **CSR Table C.1.6.**

$\Delta_m$ = 2 - slope change of the upper-lower segment of the S-N curve

$\gamma(a, x)$ - incomplete Gamma function, Legendre form

The Weibull shape parameter $\xi$ is calculated as:

$$\xi = f_{Weibull} \cdot \left(1.1 - 0.35 \cdot \frac{L-100}{300}\right) \quad (12)$$

The cumulative fatigue damage ratio, DM, is finally converted into a calculated fatigue life:

$$Fatigue\ life = \frac{Design\ life}{DM} \text{(years)} \quad (13)$$

According to CSR requirements, the calculated fatigue life should be more than 25 years.

## 4 Result of the analysis

Stress range $S_{Ri}$, required for the calculation of accumulated damage in Eq. (8), is calculated by the simple beam theory assumptions, i.e.:

$$S_{Ri} = \frac{M_{Ri}}{Z_{v-net75}} \quad (14)$$

where $Z_{v-net75}$ is the "net" section modulus (-0.25 $t_{corr}$) of the midship cross section, while $M_{Ri}$ is the range of wave bending moment at a representative probability level of $10^{-4}$. $M_{Ri}$ is calculated as:

$$M_{Ri} = M_{wv-hog} - M_{wv-sag} \quad (15)$$

where $M_{wv-hog}$ and $M_{wv-sag}$ are hogging and sagging vertical wave bending moments for fatigue, respectively, as given in **CSR Section 7.3.4.1.3**. For the Aframax tanker analysed in the present paper, the range of the vertical wave bending moment reads 3864 MNm. It should be noted that the stress range and all calculation parameters are the same for ballast and full load conditions. Consequently, the same results have been obtained for both conditions.

### 4.1 Initial structure

The existing "net" section modulus of the midship section calculated with the appropriate corrosion deduction, **CSR Table 6.3.1-Corrosion addition**, should be over the CSR minimal required fatigue section modulus. However, as may be seen from the results presented in Table 2, the actual section modulus should be increased by more than 15% to comply with the CSR minimal required value.

Table 2 **Fatigue section modulus calculation for "initial" structure**
Tablica 2 **Proračun "zamornog" momenta otpora početne konstrukcije trupa**

| | "Initial" structure |
|---|---|
| Actual sectional area, $A_v$ (m$^2$) | 4.97 |
| Actual section modulus, $Z_v$ (m$^3$) | 26.59 |
| Allowable fatigue stress, $R_{al}$ (N/mm$^2$) | 125.7 |
| Required fatigue section modulus, $Z_{v-fat}$ (m$^3$) | 30.75 |

Input parameters and results of detailed fatigue calculations are presented in Table 3. As it can be seen, calculated fatigue life is estimated to 13.1 years, being much lower than the minimum requested fatigue life of 25 years.

Table 3 **Fatigue damage calculation for "initial" structure**
Tablica 3 **Proračun zamora materijala početne konstrukcije trupa**

| $M_w$ (MNm) | $N_L$ | $\alpha$ | $\xi$ | $K_2$ | $S_{Ri}$ (N/mm$^2$) | $DM_i$ | $DM$ | *Fatigue life* (years) |
|---|---|---|---|---|---|---|---|---|
| 3864 | $7.069 \cdot 10^7$ | 0.5 | 0.944 | $0.63 \cdot 10^{12}$ | 145.3 | 0.951 | 1.901 | 13.1 |

### 4.2 Reinforced structure

Since the initial design of Aframax structure has the fatigue life of much less than 25 years for the North Atlantic navigation, it is necessary to introduce some reinforcements. The only reasonable way to increase the fatigue life of deck longitudinals is to reduce the stress range $S_{Ri}$ by increasing the ship section modulus. For that purpose, the following reinforcements are proposed:

- Changing deck longitudinals from HP280x11 to T400x15/120x10
- Increasing the thickness of the main deck plate from 17.5 mm to 19.5 mm.

These reinforcements are sufficient to satisfy the hull girder fatigue strength, as it can be seen from results in Table 4.

Table 4 **Fatigue section modulus calculation for a "reinforced" structure**
Tablica 4 **Proračun "zamornog" momenta otpora pojačane konstrukcije trupa**

| | "Reinforced" structure |
|---|---|
| Actual sectional area, $A_v$ (m$^2$) | 5.30 |
| Actual section modulus, $Z_v$ (m$^3$) | 31.74 |
| Allowable fatigue stress, $R_{al}$ (N/mm$^2$) | 125.7 |
| Required fatigue section modulus, $Z_{v-fat}$ (m$^3$) | 30.75 |

Also, the detailed fatigue calculation of reinforced structure leads to a fatigue life of deck longitudinals of 25 years, which is satisfactory in accordance with the CSR (Table 5).

Table 5 **Fatigue damage calculation for a "reinforced" structure**
Tablica 5 **Proračun zamora materijala pojačane konstrukcije trupa**

| $M_w$ (MNm) | $N_L$ | $\alpha$ | $\xi$ | $K_2$ | $S_{Ri}$ (N/mm$^2$) | $DM_i$ | $DM$ | *Fatigue life* (years) |
|---|---|---|---|---|---|---|---|---|
| 3864 | $7.069 \cdot 10^7$ | 0.5 | 0.944 | $0.63 \cdot 10^{12}$ | 121.8 | 0.5 | 1.0 | 25.0 |

## 5 Fatigue analysis with loads from the hydrodynamic analysis

The vertical wave bending moment is the dominant dynamic loading component for the hull girder fatigue analysis. New CSR continue using simple IACS UR S11 formulae for the design wave bending moments in sagging and hogging. The rule vertical wave bending moments are defined as the bending moments with the exceeding probability of $10^{-8}$. In other words, the rule values are the most probable extreme values for the return period of 20 years, which is the ordinary ship lifetime. The rule design wave bending moments are based on the main dimensions of the ship: length, breadth and block coefficient. Operational profile, mass distribution and hull form are not taken into account by the rule formulae.

As an alternative to the application of IACS UR S11, a direct hydrodynamic analysis of ship motion and load may be performed to determine the long term distribution of wave bending moments for fatigue assessment. The direct analysis requires more detailed and elaborated input data and it is of interest to see its implication on the hull girder fatigue life.

Evaluation of the wave-induced load effects that occur during long-term operation of the ship in a seaway was carried out for sea areas in the North Atlantic in accordance with the IACS Recommendation Note No.34. Although this recommendation is basically concieved as guidance for the computation of extreme wave loads, it seems to be appropriate for fatigue analysis as well [7]. The basic assumptions proposed by IACS for the calculation of long-term extreme values of wave bending moments are:

- The IACS North Atlantic scatter diagram should be used. This scatter diagram covers areas 8, 9, 15 and 16, as defined in Global Wave Statistics (GWS). The data from the GWS are further modified by IACS in order to take into account the limited wave steepness more properly.
- Only ship speed equal to zero is to be taken into account.
- The two-parameter Pierson-Moskowitz spectrum (ITTC spectrum) is recommended.
- Short-crested waves with the wave energy spreading function proportional to $\cos^2(\upsilon)$ are to be used.
- All heading angles should have equal probability of occurrence and maximally 30° spacing between headings should be applied.

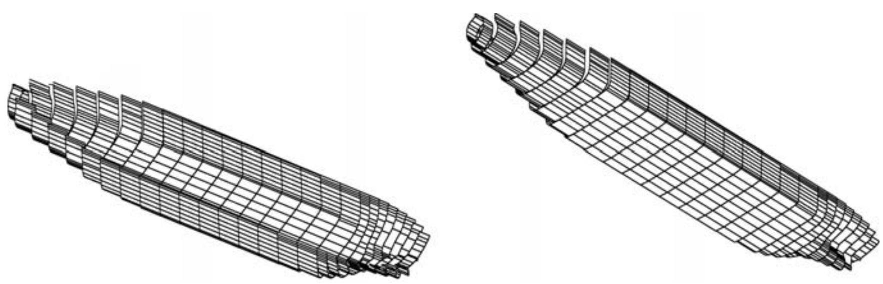
The calculation of transfer functions of wave-induced load effects is performed by the program WAVESHIP, based on the linear strip theory [8]. The strip model of Aframax tanker is shown in Figure 3, while the transfer functions of vertical wave bending moments for the full load condition and different headings are presented in Figure 4.

The long-term analysis according to IACS procedure is performed for three loading conditions: full load (FL), ship in ballast (BL) and partial loading condition (PL). The long-term analysis is performed by the computer program POSTRESP, which is a part of the SESAM package [9]. After that, the range of wave bending moments corresponding to the probability level of $10^{-4}$ required for fatigue analysis is easily determined. Parameters of Weibull distribution, used to approximate the long-term probability distribution of vertical wave bending moment, are also computed easily.

Fatigue analysis according to CSR considers that the tanker spends 85% of the time on sea, equally in ballast and full load condition. In the direct analysis, the partial loading condition is also considered. The percentage of time that a ship spends in either of these loading conditions may be estimated based upon the statistical analysis of load duration data for tankers performed by Guedes Soares [10], as presented in Table 6.

Finally, it should be mentioned that the results from hydrodynamic analysis are reduced by 10% for the application in fatigue calculation. This reduction is a consequence of the fact that the wave bending moments determined by linear strip theory overestimate the measured wave bending moments in average by 10% [11].

Input parameters and results of the detailed fatigue analysis of deck longitudinals are presented in Table 7. Calculated fatigue life is estimated to be 16.6 years, which is lower comparing to the CSR approach. It can be seen from Table 7 that the full load condition gives the largest contribution to the total fatigue damage.



a) looking from aft and above
a) pogled s krme odozgo

b) looking from bow and below
b) pogled s pramca odozdo

Figure 3 **Hydrodynamic "strip" model of *Aframax* tanker**
Slika 3 **Hidrodinamički "vrpčasti" model *aframax* tankera**

Figure 4 **Transfer functions of vertical wave bending moment at midship section for full load condition; $F_n$=0; μ =0°, 45°, 90°, 155°, 180°**
Slika 4 **Prijenosne funkcije vertikalnog valnog momenta savijanja glavnog rebra za stanje nakrcanog broda; $F_n$=0; μ =0°, 45°, 90°, 155°, 180°**

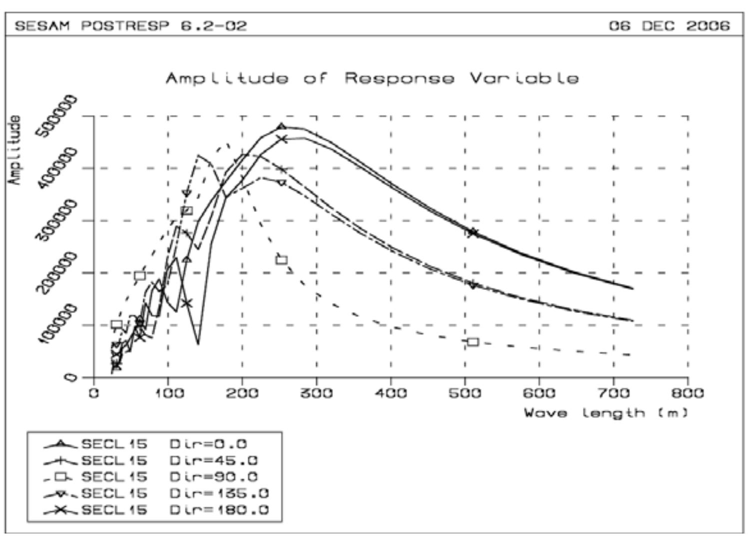


Table 6 **Operational profile adopted for tankers**
Tablica 6 **Pretpostavljeni scenarij službe tankera**

| Load cond. | Harbour | Full | Ballast | Partial |
|---|---|---|---|---|
| Percentage of spent time | 15% | 35% | 35% | 15% |
| Voyage duration (days) | ----------- | 23.5 | 23.5 | 2.0 |

Table 7 **Fatigue damage calculation as a result of hydrodynamic analysis for the reinforced structure.**
Tablica 7 **Proračun zamora materijala na osnovi rezultata hidrodinamičke analize za pojačanu konstrukciju trupa**

| | Full | Ballast | Partial |
|---|---|---|---|
| $M_w$ (MNm) | 4850 | 4470 | 4848 |
| $N_L$ | $7.44 \cdot 10^7$ | $7.73 \cdot 10^7$ | $7.58 \cdot 10^7$ |
| $\alpha$ | 0.35 | 0.35 | 0.15 |
| $\xi$ | 0.992 | 0.969 | 0.977 |
| $K_2$ | $0.63 \cdot 10^{12}$ | $0.63 \cdot 10^{12}$ | $0.63 \cdot 10^{12}$ |
| $S_{Ri}$ (N/mm$^2$) | 137.55 | 126.77 | 137.48 |
| $DM_i$ | 0.706 | 0.503 | 0.302 |
| *DM* | 1.511 | | |
| *Fatigue life* | 16.55 (years) | | |

## 6 Conclusion

The purpose of the paper is to point out that the fatigue failure is recognised as one of the governing failure modes in newly developed CSR for Double Hull Oil Tankers. Thus, fatigue is not only important for design of ship structural details, but also may be a governing criterion for the required section modulus at midship, i.e. for ship longitudinal strength, affecting thus the overall dimensions of structure subjected to fatigue.

Fatigue analysis of the connection of the main deck longitudinals and transverse web girders shows that the overall steel weight increase of 6.2% (620 tons increase for about 10000 weight of cargo hold area) would be necessary to reinforce the existing Aframax tanker to comply with the new CSR hull girder fatigue requirements.

It is shown in the paper that the non-mandatory hull girder fatigue strength criterion from CSR should be seriously considered in the early design stage. Otherwise, detailed fatigue calculations of the main deck longitudinals, which are normally carried out in a later stage, could lead to unsatisfactory results.

Finally, the paper proposes the methodology of how to efficiently use the results of the direct hydrodynamic analysis in the fatigue calculations. This could lead to more refined and more rational results of the fatigue analysis. To use direct calculation methods in the most efficient way, fatigue reliability could be employed to take into consideration various uncertainties in the load and the structural capacity and to estimate the probability of structural failure.

It should be mentioned that only the fatigue induced by the vertical wave bending moment is considered in this paper. Therefore, the presented results are relevant mostly for the main deck longitudinals in the centre-line area. To analyse the fatigue load of the main deck longitudinals located close to the side shell, the horizontal wave bending moment should be considered together with a statistical combination of vertical and horizontal wave bending moments. Such considerations are outside the scope of the present study. The same conclusion is valid for the connection of side shell longitudinals with web frames and transverse bulkheads, which are among the most important ship structural details from the fatigue point of view [12]. Since the governing fatigue loading of side shell longitudinals is the local dynamic pressure, a significantly different approach would be necessary, which is outside the scope of the present study.

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