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Fatigue strength assessment of container ships

SUMMARY

A procedure of fatigue strength assessment of container ships is described in the paper. The so called "direct approach" procedure was developed on the basis of different methods of long-term total stress range prediction (step-wise approximation, Weibull distribution and direct summation of accumulated fatigue damages for all sea states). The proposed procedure was applied to a currently designed container ship and its results will be published in second part of the paper.

INTRODUCTION

The evaluation of fatigue strength under variable load amplitudes is based on the generalized results of the sample constant amplitude fatigue investigations (i.e. S-N curves) and on the Palmgren-Miner's hypothesis on linear summation of variable amplitude fatigue damages. According to the hypothesis the total structure damage may be represented by a sum of damages generated at each load cycle on different stress levels, independent of the sequence of the stress cycles.

The ship lifetime (in respect of fatigue strength) is usually assumed not less than 20 years. The accepted level of the dimensionless sum of fatigue damages, D, expressed by the so called usage coefficient η, should not exceed 1.0. The appropriate fatigue strength criterion is based on the design S-N curves derived from the mean values of corresponding results of experimental investigations, decreased by two standard deviations of the statistical sample of stress.

The direct procedure of fatigue strength assessment, presented in this paper, is based on that developed by Det Norske Veritas [1] and implemented into SANKO3 computer program package described in [6]. The main task of the package is to make it possible to predict the cyclic total stresses and hatch deformations due to sea-wave loads acting on longitudinal hull structure during the ship life. The new (current) version of the package enables also to assess the fatigue strength of the structures[7].

FATIGUE ANALYSIS

In the case of the constant amplitude cyclic stresses σ the number of cycles N to fatigue failure is experimentally determined for specimens of steel and other materials. The results of the tests are presented in the form of S-N curves which may be used for evaluation of the number of stress cycles to failure with a given stress range (double amplitude $\Delta\sigma = 2\sigma$). It can be described by an exponential expression of the following type:

$$\Delta\sigma_N = \left(\frac{\bar{a}}{N}\right)^{1/m} \tag{1a}$$

or presented in the logarithmic form :

$$\log N = \log\bar{a} - m\log\Delta\sigma_N \tag{1b}$$

where:

- N - expected number of cycles to failure at the stress range $\Delta\sigma$
- m - negative inverse slope of S-N curve (S-N fatigue curve parameter)
- $\log\bar{a}$ - intercept of log N-axis by S-N curve

$$\log\bar{a} = \log a - 2\log s$$

where:

- a - constant factor appropriate to the mean S-N curve
- $\bar{a}$ - S-N fatigue curve parameter
- s - S-N fatigue stress range ($\Delta\sigma$)
- log s - standard deviation of log N (from test results log s = 0.20).

Design S-N curves are currently used for the base material (with ground cut edges) and for controlled weld joints (free of significant defects) in air (or with the anticorrosive cathodic protection) and in the corrosive environment (4 sets of log a and m values may be found in [1]). In practice single-range S-N curves may be used of the following parameter values:

$\log \bar{a} = 12.76$ - for welded joints
$\log \bar{a} = 13.00$ - for base material
$m = 3$ - both for welded joints and base material (used in air or with anticorrosive cathodic protection).

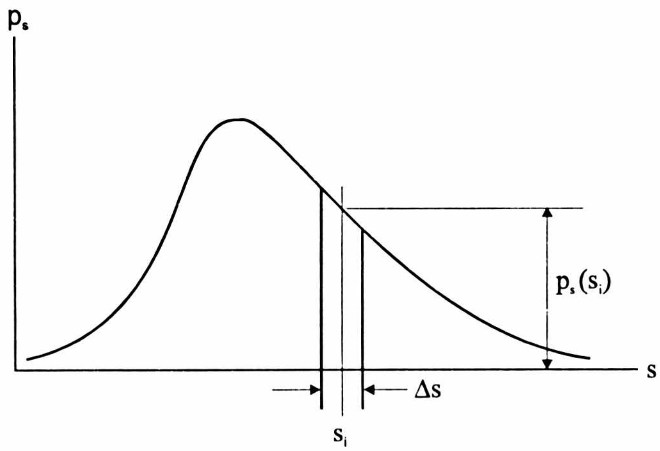
The design S-N curve was developed on the basis of the experimental investigation of smooth samples with the stress concentration factor K = 1.0. In practice the fatigue strength of structural elements is calculated on the basis of the nominal stress range multiplied by the stress concentration factor:

$$\Delta\sigma = K \cdot \Delta\sigma_{nom} \tag{2}$$

where σ_{nom} is the nominal stress.

The K-factors may be determined from FEM calculations or tables of K factor values for typical ship structure elements [1]. The stress concentration factors for containership hatch corners may be calculated with the use of the DECKFRAME program [3].

The S-N curves are valid for the constant amplitude stress cycles whereas the hull stress range is a random variable described by the probability density function $p_s(s)$ schematically presented in figure (s means here the stress range, i.e. $s = \Delta\sigma$). The characteristic stress range value S_c which corresponds to a given small probability of exceedence, is a parameter of the probability density function p_s.



Probability density function of the wave-induced stress ranges s

The application of S-N curves to the evaluation of ship structure fatigue strength requires using the Miner's linear damage summation hypothesis. According to it the fatigue damage caused by one stress cycle of the range S_i is equal to $1/N_i$, where: N_i - number of cycles up to the total failure at a constant stress range S_i (determined from the S-N curves). The fatigue damage accumulated during k blocks of stress ranges S_i is equal D.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{3}$$

The total failure occurs when the above defined sum reaches a critical value, e.g. D = 1.

The fatigue strength criterion, if the long term stress range distribution is presented in the form of a histogram composed of an appropriate number of blocks of $\Delta\sigma_i$ stress ranges (each of the number of repetitions n_i), is as follows:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i \cdot (\Delta\sigma_i)^m \le \eta \tag{4}$$

where:
D - accumulated fatigue damage
k - number of stress range blocks
n_i - number of cycles in i-th block
N_i - number of cycles up to the total failure at $\Delta\sigma_i$ constant stress range
η - usage factor (allowable value: $\eta = 1.0$).

Another method is the application of (3) to a long term stress range probability distribution given by the probability density function $p_s(s)$ [4]. (Here s stands again for the stress range $\Delta\sigma$. The customary probabilistic notation is used in which the random variable s is written in the lower case when indefinite.) The distribution is divided into a large number of narrow stress blocks of the width Δs, as shown in the figure. For each block the number of cycles n_i is the following:

$$n_i = N p_s(s_i) \Delta s \tag{5}$$

where N is the total number of stress cycles during the ship life.

If the denotation of [4] is assumed: $S_N = \Delta\sigma_N$ and $C = \bar{a}$, the expression (1a) takes the form:

$$N S_N^m = C \tag{6}$$

Substituting (5) and (6) to (3) and performing the integration (with $\Delta s \to 0$) one obtains a general fatigue strength formula:

$$D = \frac{N}{C} E(S^m) \tag{7}$$

where:

$$E(S^m) = \int_0^\infty s^m p_s(s) ds \tag{8}$$

is the expected value of the random variable s^m.

The long term stress range distribution function $P_s(s)$ (i.e. the integral of the density $p_s(s)$) is assumed in the form of a two-parameter Weibull distribution:

$$P_s(s) = 1 - \exp\left\{ -(\ln N)\left(\frac{s}{S_c}\right)^k \right\} \tag{9}$$

where:
$P_s(s)$ - probability that the stress range s will not be exceeded
S_c - characteristic value of *s* for which the exceedance probability is of a given small value
k - Weibull distribution shape parameter.

The distribution (9) is identical with the usual one when the denotation change is taken into account [1]:

$s = \Delta\sigma$ $\quad k = h$ $\quad S_c = \Delta\sigma_0$ $\quad N = n_0$

$$\frac{S_c}{(\ln N)^{1/k}} = \frac{\Delta\sigma_0}{(\ln n_0)^{1/h}} = q$$

According to [4] the Weibull distribution expected value is as follows:

$$E(S^m) = S_c^m (\ln N)^{-m/k} \Gamma\left(1 + \frac{m}{k}\right) \tag{10}$$

where Γ is gamma function.

Substituting (10) to (7) one obtains the accumulated fatigue damage D in the form:

$$D = \frac{N}{C} S_c^m (\ln N)^{-m/k} \Gamma\left(1 + \frac{m}{k}\right) \tag{11}$$

The value of D must not exceed 1 to protect structure against fatigue cracks.

It is necesary to substitute the fatigue usage factor η_L for D and solve (11) for S_c in order to determine the limit stress range characteristic value $(S_c)_L$ in relation to the fatigue strength. Taking into account that, due to (6), the following holds: $(N/C)^{1/m} = S_N$, one obtains:

$$\left(S_c\right)_L = \xi \frac{S_N}{\gamma_F} \tag{12}$$

where:

$$\xi = (\ln N)^{1/k}\left[\Gamma\left(1+\frac{m}{k}\right)\right]^{-1/m} \quad \text{and} \quad \gamma_F = \left(\eta_L\right)^{-1/m} \tag{13}$$

The factor ξ allows for the random variability of stress ranges as it links the S_N limit value, determined from a S-N curve for N cycles during the ship life, with the limit characteristic value $(S_c)_L$.

Returning to the previous denotations and generalizing (11) for several service load cases, one obtains (for Weibull distribution of wave-induced stress ranges):

$$D = \frac{\nu_0 T_d}{\bar{a}} \sum_{n=1}^{N_{load}} p_n q_n^m \Gamma\left(1+\frac{m}{h_n}\right) \tag{14}$$

where:

- n - load case number
- N_{load} - number of considered load cases
- p_n - fraction of design life corresponding to n-th load, normally $\Sigma p_n = 0.85$
- T_d - design ship's life in seconds (20 years = $6{,}3\cdot 10^8$ seconds)
- h_n - Weibull stress range distribution shape parameter
- q_n - Weibull scale parameter for stress ranges
- ν_0 - average zero crossing frequency (during the ship life)
- $\Gamma(1+m/h_n)$ - gamma function (see e.g. [5]).

The Weibull distribution scale parameter is determined from $\Delta\sigma_0$ stress range as:

$$q = \frac{\Delta\sigma_0}{\left(\ln n_0\right)^{1/h}} \tag{15}$$

where:

- $\Delta\sigma_0$ - reference stress range value which may be exceeded only once in n_0 cycles
- n_0 - number of cycles corresponding to the stress range $\Delta\sigma_0$.

It is usually assumed [1] that the $\Delta\sigma_0$ reference stress range value should correspond to $n_0 = 10^4$, because if $n_0 = 10^8$ then the accumulated fatigue damage D becomes very sensitive to the determination accuracy of the Weibull distribution shape parameter h.

The expressions (12) and (13) may be also rewritten with the other denotations used in the paper, namely:

$$(\Delta\sigma_0)_L = \xi\, \Delta\sigma_N \tag{12a}$$

where:

$$\xi = \left(\ln n_0\right)^{1/h}\left[\Gamma\left(1+\frac{m}{h}\right)\right]^{-1/m} \tag{13a}$$

Fatigue damage calculation for a given steady sea state and heading direction, with the use of the Rayleigh distribution for stress ranges, is an alternative to the application of Weibull distribution to the long term stress range prediction.

Assuming the Rayleigh probability density function for stress range s in the form:

$$p_s(s) = \frac{s}{4m_0}\exp\left(-\frac{s^2}{8m_0}\right) \tag{16}$$

one obtains (after performing the integral calculation in accordance with (8)) the expected value $E(S^m)$ as follows:

$$E\left(S^m\right) = \left(2\sqrt{2m_0}\right)^m \Gamma\left(1+\frac{m}{2}\right) \tag{17}$$

and the accumulated fatigue damage $\overline{D}$ for the given sea state by means of (7):

$$\overline{D} = \frac{\overline{N}}{C}\left(2\sqrt{2m_0}\right)^m \Gamma\left(1+\frac{m}{2}\right) \tag{18}$$

where:

- m_0 - response spectrum zero-order moment (variance)
- $\overline{N}$ - number of stress cycles for the given sea state.

Assuming that the total accumulated fatigue damage D (in the whole ship life) may be estimated as the sum of the partial failures $\overline{D}$ for all sea states and wave directions, one finally obtains:

$$D = \frac{\nu_0 T_d}{\bar{a}} \Gamma\left(1+\frac{m}{2}\right) \sum_{i=1}^{all}\sum_{j=1}^{all} r_{ij}\left(2\sqrt{2m_{0ij}}\right)^m p_{ij} \tag{19}$$

for one loading condition, and

$$D = \frac{\nu_0 T_d}{\bar{a}} \Gamma\left(1+\frac{m}{2}\right) \sum_{n=1}^{N_{load}} p_n \sum_{i=1}^{all}\sum_{j=1}^{all} r_{ij}\left(2\sqrt{2m_{0ij}}\right)^m p_{ij} \tag{20}$$

for N_{load} loading conditions,

where:

- p_{ij} - probability of the occurrence of i-th sea state for j-th wave direction
- r_{ij} - relation between zero crossing frequency in a given sea state and average zero crossing frequency $r_{ij} = \frac{\nu_{ij}}{\nu_0}$
- ν_0 - average zero crossing frequency $\nu_0 = \sum p_{ij}\cdot \nu_{ij}$
- ν_{ij} - response zero crossing frequency in i-th sea state and j-th wave direction $\nu_{ij} = \frac{1}{2\pi}\sqrt{\frac{m_{2ij}}{m_{0ij}}}$
- m_n - n-th order moment of the response spectrum $m_n = \int \omega^n \cdot S_\sigma(\omega)d\omega$
- ω - wave frequency
- $S_\sigma(\omega)$ - stress response spectrum

The above given expressions were derived on the assumption that an average number of cycles for i-th sea state and j-th heading direction is $\overline{N}_{ij} = \nu_{ij} T_d p_{ij}$.

PRACTICAL APPLICATION

A newly developed version of SANKO3 program package may be used for the calculation of :

- the dimensionless sum of the accumulated fatigue damage D
- the time T to the development of fatigue cracks
- the Weibull distribution shape factor h and
- the total number of wave-induced stress cycles N, for two selected loading conditions (usually full ship and ballast condition) simultaneously.

All the calculations are performed for the same data set as in the previous package version, SANKO2, but supplemented with the number of loading conditions (1 or 2) and the sailing region indicator (0 - worldwide, 1 - North Atlantic). An example of its practical application will be given in the next part of the paper.

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Appraised by Janusz Kolenda, Prof.,D.Sc.,M.E.

Miscellanea

STEELS AND AL-ALLOYS APPLICABLE TO SHIP HULL STRUCTURES

The book under that heading, written by two outstanding specialists of material science : Prof. Konstanty Cudny of Technical University of Gdańsk and Norbert Puchaczewski, D.Sc., of Polish Register of Shipping, has recently enriched the Polish proffesional shipbuilding literature. The book is especially interesting and useful to the production engineers and designers who work in the maritime industry. It can be also helpful in education of shipbuilding engineers.

The knowledge contained in the book meets half-way the needs connected with multidirectional development of various floating objects. Construction of such special ships as e.g. gas tankers, chemical carriers, floating units for sea bed oil resources exploration and production, high-speed craft (hydrofoils, catamarans, hovercraft) require materials of special properties in each case. The materials should demonstrate, apart from high levels of the typical mechanical properties, , e.g. good brittle crack resistance in very low temperatures, and fatigue resistance in marine environment conditions, dependent on an application.

The authors of the book thoroughly presented the material engineering problems of today shipbuilding. The entire content of the 190-page book is divided into the following six chapters:

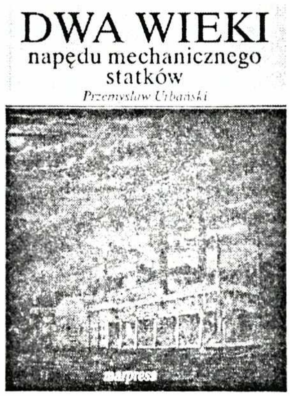
- Manufacturing processes of ship hull steels and their characteristics
- Steels applicable to ship hull structures
- Selection of steels for ship hull structures
- Steels for construction of liquefied gas tankers
- Application of aluminium alloys to ship hull structures
- Metal alloys applicable to ship hull structures

In the text of the book enriched by many tables and diagrams, the following topics can be found for instance:
metalurgical processes, material processing, material characteristic properties and their testing, actual material requirements and recommendations, principles of material selection for different structures, economic aspects of applicability of Al-alloys, role of the ship classification societies.

For prepartion of the book the authors made use of their own broad professional experience and of scores of Polish, English, German and Russian literature sources.

Miscellanea

INTERESTING BOOK



On 21 March 1997 the official promotion of the interesting book , titled „ Two centuries of the mechanical ship propulsion" was held at the Technical University of Gdańsk. The book was written (in Polish) by Przemysław Urbański, Assist.Prof., D.Sc., M.E. , connected with the University and engaged in education and scientific research in the field of ship powering and power plant exploitation for many years. His scientific outcome contains several ten research works on inland and sea ships as well as naval vessels; he is the author of many articles and scientific reports and two speciality books. For four years he lectured at University of Basrah, College of Engineering, Iraq, as well as at the Rivers State University of Science and Technology of Port Harcourt, Nigeria.

Prof.Urbański has been always very interested in historical aspects of his professional field, marine engineering, therefore he has devoted much time to looking for and gathering the historical issues on the mechanical ship propulsion inventions and their development. 200-year anniversary of the mechanical ship propulsion was the reason why Prof.Urbański prepared his interesting and valuable book which is a crowning achievement of his activity in the field of engineering history.

The ship mechanical propulsion history elaborated by the author is presented on 172 pages, divided into 12 chapters as follows:

I Towards the Birth of Mechanical Ship Propulsion
II The Invention of the Steam Engine
III Early Ideas, Experiments and Steamboats
IV Marine Reciprocating Steam Engines and the Evolution of Their Design
V Air Engines - Stirling and Ericsson Marine Engines
VI Electric Ship Propulsion
VII Steam Turbines for Ship Propulsion
VIII Marine Boilers and Their Development
IX The Invention of the Explosion Engine - First Motorboats
X Diesel Engines and Their Application to Marine Propulsion
XI Marine Gas Turbine Propulsion
XII Nuclear Ship Power Plants. Magnetohydrodynamic Ship Propulsion

The book, edited in the form of a nice album, is intended to serve a wide circle of readers connected with shipping and shipbuilding. It contains vast amount of the factographic materials (292 drawings and photos) often coming from hardly accessible sources, therefore it certainly will contribute to saving from oblivion the unique ship propulsion designs abandoned many years ago as no conditions for their development existed in those times.

It should be acknowledged that the main text of the book is supplemented not only by Bibliography but also by such valuable and useful appendices as:

@ Chronological Table of Important Dates (connected with the topic of the book)
@ Index of Subjects
@ Index of Proper Names
@ Index of Ship's Names.