Productional, operational and theoretical sensitivities of fatigue damage assessment in shipbuilding

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ABSTRACT

Firstly, this paper summarizes some of the theoretical and practical aspects of fatigue assessments in shipbuilding. The basics of the spectral fatigue analysis procedure for ship structures are mentioned. The simplified procedures are presented in more detail, due to their practical merit. The article is primarily concerned with the fatigue design procedures used by Classification Societies, as well as with possible standardizations under the auspices of IACS. Secondly, an example of fatigue damage assessment for the chemical tanker recently built in Croatian shipyards is provided in order to illustrate and compare the capabilities and differences of available procedures currently used by major Classification Societies. Finally, parametric studies are performed in order to investigate the effects of productional structural elements misalignement, constructional and fabricational tolerances, of corrosion during operations at sea, shape parametres of theoretical distributions, of selections of the S-N curves and of the combinations of local and global loads. The sensitivity analysis presented in the article provides suggestions for improving design and production of the critical parts of the ship hull construction with respect to fatigue damage.

NOMENCLATURE

ABS - American Bureau of Shipping
BV - Bureau Veritas
CCS - China Classification Society
CRS - Croatian Register of Shipping
DNV - Det Norske Veritas
GL - Germanischer Lloyd
HSE – Health and Security Executive
IACS – International Association of Classification Societies
IMO - International Maritime Organisation
IIW - International Institute of Welding
KR - Korean Register
LR - Lloyd's Register of Shipping
NK - Nippon Kaiji Kyokai
NL – neutral line
RINA - Registro Italiano Navale
RS - Russian Maritime Register of Shipping

1. INTRODUCTION

Fatigue, i.e. crack initiation and propagation due to cyclic loading, has been identified as a source of large number of failures occurring in welded ship structural details. The disasters of bulk carriers observed in the period 1990. – 1998. were in all probability caused mainly by the cracking of side structures (IMO 1995). Numerous fatigue cracks have also appeared on relatively new VLCCs and the other types of ships (ISSC 2000, Hansen 1995, Hughes 1993).

In addition to the bad experiences over the last decade, there are several other reasons that have caused the shipping industry to reconsider its attitude towards the fatigue of critical structural details. The reasons are: higher weight-optimization of new ship structures with simplification of structural detail and fabrication methods, the intensified usage of high tensile steel, an increasing number of ageing structures with lack of maintenance and increased public sensitivity with respect to protection of human lives and the environment.

In the past, the rules made by classification societies treated the problem of fatigue strength in an indirect way by keeping overall stress levels within permissible limits, particularly those where stress concentration could occur. With the new designs, this is not always sufficient and fatigue should be considered throughout the design stage. Methods for improving fabrication stage should only be considered as remedial measures. With an improving knowledge of fatigue loads and the rapid development of stress analysis, classification societies have developed calculation-based methods for the fatigue assessment of ship structures and introduced them into their rules. Two types of procedures have been developed: direct (spectral) and simplified (deterministic).

The direct calculation of fatigue life is a laborious task and can easily lead to an intolerable calculation time, especially if the structural model is complex. On the other hand, simplified procedures significantly reduce calculation time but are less accurate. Individual IACS Members have their own comprehensive, but different, simplified procedures of assessing fatigue strength of ship structures. During the past several years, IACS attempted to harmonize these procedures. Some progress has been made but harmonization of the approaches is not yet achieved. Recently all these procedures have been revised and updated. This paper reviews the features of the simplified fatigue assessment procedures and presents the analysis of several key issues.

2. FATIGUE ASSESSMENT PROCEDURES FOR SHIP STRUCTURES

Calculation of fatigue damage requires two sets of information: material properties (i.e. fatigue capacity of welded steel structures) and long-term stress distribution of ship structure. There are two approaches for assessment of fatigue capacity: S-N curve approach and fracture mechanics approach. The S-N curve approach is based on experimental measurements of the fatigue life in terms of cycles to failure (N) for different stress ranges (S). Fracture mechanics approach bases its analysis on the existence of an initial crack in the structure. In this approach, the fatigue crack growth rate is required instead of the S-N curves. In current procedures used by Classification Societies, material properties are given in the form of the S-N curves.

Depending on how the long-term stress distribution is determined, there are two types of fatigue assessment procedures that differ in computational effort and accuracy:

- Spectral (direct) procedure,
- Simplified (deterministic) procedure.

When the long-term stress distribution is known and appropriate S-N curve is selected, fatigue damage can be determined based on Palmgren-Miner cumulative damage rule which says: "If the damage contributed by one cycle of stress range S_i is $1/N_i$, where N_i is the mean fatigue life under a constant amplitude stress range S_i, by superposition the cumulative damage D caused by stress ranges S_1, S_2, ... S_n applied n_1, n_2, ... n_k cycles equals to" (BV 1999):

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

where:

n_i - number of cycles of stress range S_i,
N_i - number of cycles to failure at stress range S_i.
n_k - number of equal length intervals.

2.1 Spectral procedure

In the spectral procedure the long-term stress distribution of ship structure is given in the form of stress spectrum. This spectrum is determined by the hull structural response to expected seaway loading, taking into account the various ship loading conditions (cargo distribution), speed and sea state in the ship's lifetime, i.e. required stress distribution for fatigue calculations is constructed based on specified wave data.

Random sea state is represented by a set of wave spectra varying wave heights and wave periods. Each wave spectrum can be described by a series of regular waves of varying frequency and amplitude with random phase angles. Wave loads, necessary for structural analysis, are calculated for all regular waves of unit amplitude for a range of wave periods and several wave headings. To calculate load transfer functions, usually a linear ship motion analysis (strip method) is performed. At a given wave heading and ship speed, two wave positions (90^o out of phase) are required for load calculations. Resulting number of load cases for structural analysis is very large. For an example of a tanker, approx. 300 wave load cases may be investigated (Fricke 1997).

The connection between wave spectrum and response stress spectrum is expressed through stress transfer functions. Stress transfer functions are calculated for each critical structural location, based on the above load transfer functions. Calculation is performed for each combination of cargo distributions, wave directions and ship speed. The required structural analysis is performed using finite element methods.

By multiplying sea spectrum by square of stress transfer function for the short-term response spectrum is obtained (Hughes 1983). Based on specified ship route and wave conditions in different geographical areas, the frequency of occurrence of different sea states during the ship's lifetime can be found. Afterwards, the long-term stress spectrum, needed for lifetime fatigue prediction, is calculated by weighting each short-term spectrum with its probability of occurrence. (Violette 1998). When the long-term stress distribution is known fatigue damage can be calculated directly from the response spectrum with the specified S-N curve and based on Palmgren-Miner linear cumulative damage rule (1).

From this short description of spectral fatigue assessment procedure it is obvious that determination of long-term stress distribution, in the form of response spectrum, involves large amount of data and calculational efforts due to large number of investigated load cases in a lifetime. The process itself is time-consuming and requires a large number of input data, and these are main drawbacks of the spectral procedure. On the other hand, this procedure gives more accurate predictions of fatigue life of ship structure.

2.2 Simplified (deterministic) procedure

Calculation of the fatigue damage in ship's structure using simplified procedure is also based on the application of the S-N curves together with Palmgren-Miner cumulative damage rule. The main difference between spectral and simplified procedure is in the way in which long-term stress distribution is obtained. In simplified procedure, it is assumed that probability density function of the long-term distribution of stresses may be represented by the two-parameter Weibull distribution. Probability density function p(s) and cumulative distribution function of the Weibull distribution, P(s), of stress ranges (S) are given as follows:

$$p(s) = \frac{k}{w}\left(\frac{S}{w}\right)^{k-1} e^{-\left(\frac{S}{w}\right)^k} \qquad (2)$$

$$P(s) = 1 - e^{-(S/w)^k} \qquad (3)$$

where:

k – Weibull shape parameter, the value varies between 0,7 to 1,3.

$w = \dfrac{S_R}{(\ln N_R)^{1/k}}$ – characteristic value of stress range

S_R – most probable extreme stress range in N_R cycles (i.e. at the probability of exceedance $1/N_R$)

S_R and k are the two parameters of the Weibull distribution of stresses.

N_R – number of cycles corresponding to the probability of exceedance $1/N_R$ – the value varies between 10^{-2} to 10^{-8}.

Simplified practical procedure generally consists of the following steps:

- determination of loads and loading conditions,
- selection and correction of the S-N curve,
- selection of the stress approach and
- calculation of the fatigue damage.

2.2.1 Loads and loading conditions

Current simplified practical procedures implemented by Classification Societies consider only static and wave induced loads regarding the calculation of the long-term distribution of stresses (IACS 1999), including following load components:

- hull girder loads (i.e. vertical bending and torsion moments and shear forces)
- external hydrodynamic pressures
- internal inertia and fluctuating loads resulting from ship motion

It is assumed that impact loads may be avoided by modifying the ship route, speed, etc., and they may be disregarded for the purpose of simplified fatigue analyses. Together with other loads such as residual stresses, they still require further study.

Fatigue analyses must be performed for all relevant loading conditions that may occur during ship's life depending on the type of ship. As a minimum two loading conditions must be considered: full load condition and ballast condition (IACS 1999).

2.2.2. Design S-N curves

Fatigue capacity of steel welded joints is characterized by experimentally determined S-N curves. For ship structural details, S-N curves are given by formula:

$$(S)^m \cdot N = C \qquad (4)$$

where m and C are constants depending on material, weld type, type of loading, geometrical configuration and environmental conditions.

S-N curves are defined by their mean fatigue life and standard deviation in log N or log C. The mean S-N curve indicates that for a stress range S the structural detail will fail with a probability level of 50% after N cycles. S-N curves used in fatigue assessment of ship structural details represent two standard deviations below the mean lines, which correspond to a survival probability of 97,5%.

There is a wide variation of S-N curves available for ship structure application. Most commonly used sets of design S-N curves are those of U.K. Health and Security Executive (former DEn - Department of Energy curves) and of International Institute of Welding.

The HSE's basic design S-N curves consist of eight curves, each representing a class of welded details depending on the geometrical arrangement of details, the direction of the fluctuating stress relative to the details and the method of fabrication and inspection of the details.

IIW has established 14 S-N curves identified by the values of detail categories. Each curve represents a detail category of different joint configuration.

Keeping in mind that S-N curves are determined experimentally in laboratories and that these curves will be used to calculate fatigue damage of actual structures some adjustments are inevitable. Several issues should be considered:

- Corrosion
- Plate thickness
- Weld improvement
- Residual stresses
- Mean stresses
- Workmanship

These effects are usually included by modification of the C parameter of the basic S-N curve and by change of the slope of the S-N curve after a certain number of cycles. These adjustments are left at the discretion of each Society.

The stresses used in the S-N data are the calculated nominal stresses based on the applied loads and sectional properties of the specimens. Therefore, when using the design S-N curves in fatigue assessment, the calculated stresses should correspond to the nominal stresses.

2.2.3. Stress approaches for fatigue damage assessment

Three approaches are used for fatigue damage assessment depending on type of stress applied in calculation:

- Nominal stress approach,
- Hot-spot stress approach and
- Notch stress approach.

Nominal stress approach

The nominal stress is defined as a general stress in structural detail calculated by beam theory and taking into account the gross geometric changes of detail (e.g. cut-outs, brackets, changes of scantlings, misalignments, etc.). Stress concentrations due to abrupt changes in geometry and the presence of welds are not directly calculated; these effects are included by the selection of an appropriate S-N curve. This means that nominal stress approach is applicable in cases where considered structural detail can be easily categorized into some detail category for which S-N curve is being established experimentally. Unfortunately, ship structural details are more complex than the test specimens, both in geometry and in applied loading, making it difficult to find a correspondence between the S-N data and the structural detail.

Hot-spot stress approach

The hot-spot stress is usually defined as a local stress at the hot spot (a critical point) where cracks may be initiated. This approach takes into account the influence of structural discontinuities due to geometry of the connection. The exact weld toe geometry and non-linear stress peak due to the local notch at the weld toe are disregarded, because their calculation is time-consuming and weld geometry is usually not known in advance although it may be given in documentation. The hot-spot stress is used directly with a single S-N curve for calculating fatigue damage of various structural details. The design S-N curve no longer applies for a detail category, but for a weld type. Hot-spot stress approach is suitable for cases in which nominal stress cannot be clearly defined and the considered structural detail is not comparable to any classified detail of the design S-N curve. The most important issue here is whether a single S-N curve can be used to determine fatigue damage at many different structural locations. The finite element method (FEM) is usually performed to obtain hot-spot stresses.

Notch stress approach

Notch stress is defined as a peak stress at the root of a weld. It is determined by taking into account stress concentrations due to effects of the structural, as well as the weld toe geometry. Fatigue damage assessment based on notch stress approach also uses only one S-N curve for all types of structural details. This curve is different from the S-N curve used in hot-spot stress approach. Notch stresses are calculated by finite element method with an extremely fine mesh model for definition of weld toe geometry, making the calculation more complex and time-consuming than that of the hot-spot approach.

The connection between different types of stresses can be established through the stress concentration factors, which are determined for various structural details by the finite element analyses and experiments.

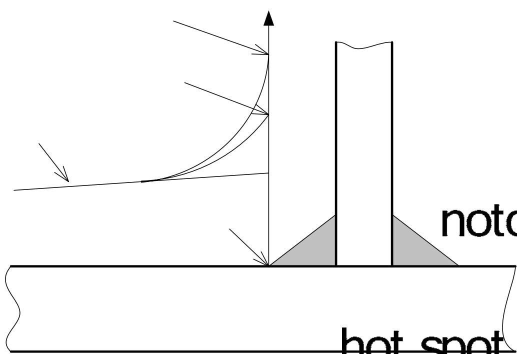


Fig.1 Stresses at weld toe location (Andersen 1998)

For structural details for which the nominal stress, S_n, can be easily calculated, the hot-spot stress, S_g, is equal to:

$$S_g = K_g \cdot S_n \tag{5}$$

where K_g is stress concentration factor due to geometrical configuration of the structural detail.

Figure 2 shows geometric stress concentration factors used in calculation of fatigue damage further in this paper.

The notch stress, S_l, is given by formula:

$$S_l = K_f \cdot S_g \tag{6}$$

where K_f is stress concentration factor, which includes effects associated to the weld geometry. This factor is usually calculated by parametric formulas such as (BV 1999):

$$K_f = 2\left(\theta / 30\right)^{0.5} \tag{7}$$

where θ is mean weld toe angle, expressed in degrees. It is important to apply the appropriate stress concentration factors according to the type of applied loads, and geometry of the structural detail considered.

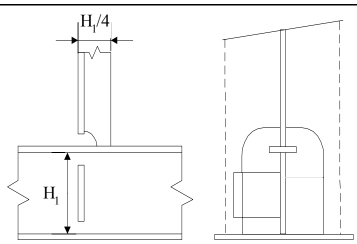
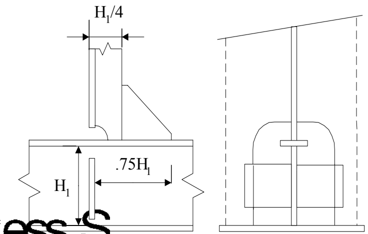
Structural detail	K_{g1}, axial	K_{g2}, bending
	2.57	1.21
	1.53	1.26

Fig.2 Stress concentration factors (BV 1999)

2.2.4 Calculation of the fatigue damage

Assuming that the probability density function of long-term stress distribution (hull girder + local bending) may be represented by a two-parameter Weibull distribution, fatigue damage D_i for each relevant loading condition based on Palmgren-Miner's rule is given by:

$$D_i = \frac{\alpha_i N_L}{C} \frac{S_R^m}{\left(\ln N_R\right)^{m/k}} \mu \Gamma\left(1+\frac{m}{k}\right) \tag{8}$$

where:

N_L – number of cycles for the expected ship's life,

μ – coefficient taking into account the change in slope of the design S-N curve,

Γ (x) – Euler's gamma function,

α_i – part of ship's life in considered loading condition (e.g. ballast, full load, etc.)

Total fatigue damage, D, for considered structural location is then obtained by summing up fatigue damages for all relevant loading conditions:

$$D = \sum_i D_i \tag{9}$$

Fatigue life is then:

$$\text{Fatigue life} = \frac{\text{Design life}}{D} \tag{10}$$

where design life is usually 20 years.

The advantage of the simplified procedure is relatively fast calculation of the fatigue damage with acceptable results in practice, while the main disadvantage is required experimental data that may cause problems in application to the new types of ships.

3. FATIGUE ASSESSMENT PROCEDURES OF CLASSIFICATION SOCIETIES

Most of Classification Societies have their own simplified procedure for fatigue analysis, provided at least for the preservation of the correct ordering of calculated fatigue life of ship structural details. The key issues significantly differ from one procedure to another, especially in cases of determination of local loads, selection of stresses to be used, selection of design S-N curves and application of correction factors. In the past few years IACS made attempts to harmonize these procedures, and some progress has been achieved. IACS members agreed that a two-parameter Weibull distribution should be assumed as an interpretation of long-term distribution of stress. Individual load components are to be determined with a moderate probability of exceedance (10^{-3} to 10^{-5}). The shape parameter, k, of the Weibull distribution may be taken as (IACS 1999):

$$k = 1.1 - 0.35\frac{L-100}{300} \tag{11}$$

where L is the ship's length in m.

Table 1: Comparison of the simplified fatigue assessment procedures

Class. Soc.	Loads	Stress approach	S-N curves
ABS	$2\cdot10^{-8}$	nominal, hot-spot	HSE
BV	10^{-5}	notch	HSE
CCS	n/a	hot spot	HSE
CRS	10^{-6}	nominal, hot-spot	IIW
DNV	10^{-4}	notch	HSE[3]
GL	10^{-6}	nominal, hot-spot	IIW
LR[1]	n/a	hot-spot[2]	HSE[5]
NK	10^{-4}	nominal, hot-spot	BS[4]
RINA	10^{-8}	nominal, hot-spot	IIW
KR	10^{-4}	hot-spot	HSE
RS	10^{-3}	nominal, hot-spot	n/a

Table 2: Comparison of the simplified fatigue assessment procedures: special considerations

Class. Soc.	Special considerations
ABS	Corrosion, thickness
BV	Mean and residual stresses, corrosion, thickness above 16mm
CCS	Mean stress, corrosion
CRS	Mean stress, corrosion, thickness
DNV	Mean s., corr., thickness above 22mm
GL	Mean stress, corrosion and thickness
LR[1]	Corrosion, thickness above 22 mm
NK	Mean, corrosion included in the S-N data
RINA	Mean stress
KR	Mean s., corr., thickness above 22mm
RS	Mean stress, corrosion

1 – The procedure is available through the use of the ShipRight program
2 – The weld notch parameters are embedded in the S-N curve
3 – Modified C curve
4 – BS refers to British Standard 5400
5 – Modified curve - between C and D curve

The number of cycles N_L during expected ship's life should be taken between $0.5\cdot10^8$ to $0.7\cdot10^8$ for a design life of 20 years. Table 1 and Table 2 show current status of the simplified procedures of several IACS members.

4. EXAMPLE OF FATIGUE DAMAGE ASSESSMENT

Statistics show that more than 40% of the fatigue cracks are located in the side shell (Hansen 1995, ISSC 1997), more specifically in the connections of longitudinal to transverse web frames. Note that there is a wide dispersion of fatigue damage rate over the ship structure, mostly due to the uneven distribution of loadings and fatigue properties of the structural details

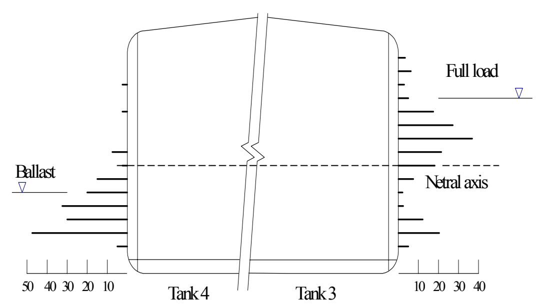


Fig.3 Number of cracks in tanker logitudinals

Most of the cracks were found immediately below the full load and ballast waterlines. This is due to pulsating hydrodynamic pressure on the ship's hull (induced by waves and ship motions) that is recognized as the main cause of the fatigue damage in side longitudinals. This study was focused primarily on the side longitudinals at connections to stiffeners. Comparative study was performed on one tanker built in Croatian shipyard in Split. Two critical locations in the side shell were investigated: both are connections of the side longitudinal with transverse frame stiffeners (Fig.4). Details are located at midship section (Fig.6) immediately below full load and ballast waterlines. Two investigated details differ only in size of side and inner hull longitudinals. In addition, one connection of double bottom longitudinal with the floor stiffener bracket was investigated (Fig.5). Since the shell longitudinal is a simply clamped beam, it was possible to calculate their stresses from simple beam theory. Material is mild steel, class A. Stresses taken into account are:

- Stresses from global loads (still water and wave bending moments and forces)
- Stresses from local loads (wave pressure)
- Secondary stresses due to relative deflection between frame and transverse bulkhead
- Secondary stresses due to double hull bending

Three fatigue assessment procedures were selected for the comparison:

- Germanischer Lloyd's (GL) procedure that uses both nominal and hot-spot stress approaches, together with application of IIW S-N curve (detail category 100), [11],
- Bureau Veritas (BV) procedure which is based on the notch stress approach and application of the HSE design S-N curve (class B) [3], [12],
- Lloyd’s Register of Shipping (LR) procedure that has unique stress approach (see Table 1) and uses modified HSE S-N curves. Calculation of the fatigue damage is performed with LR’s computer program – 'ShipRight© Fatigue Design Assessment', [13], [14] with permission of LR for the presented research.

Loads are calculated according to each Society Rules. Two loading conditions were investigated – ballast and full load condition. The stress concentration factors for GL and BV procedures are obtained from a table of standard details. The shape parameter of the Weibull distribution is calculated according to (11).

4.1. Details investigated

Ship particulars:
Length overall L_{oa} = 182.5 m
Length between perpendiculars L_{pp} = 174.8 m
Rule (construction) length L = 173.15
Breadth moulded, B = 32.2 m
Depth moulded, D = 17.5 m
Draught design, T = 11 m
Block coefficient, C_b = 0.82
Maximum service speed, v = 15 kn,
Web frame spacing 3.4m,
Max. permissible S.W.B.M., sagging, 868000 kNm
Max. permissible S.W.B.M. hogging,1074900 kNm
Deadweight = Δ = 47400 tdw
Section modulus at deck, W_D = 16.14 m^3
Section modulus at bottom, W_B = 21.25 m^3
Height of NL above base line = 7.552m
Maximum draught (full load), d_1 =12.20 m
Ballast draught, d_2 = 7.20 m

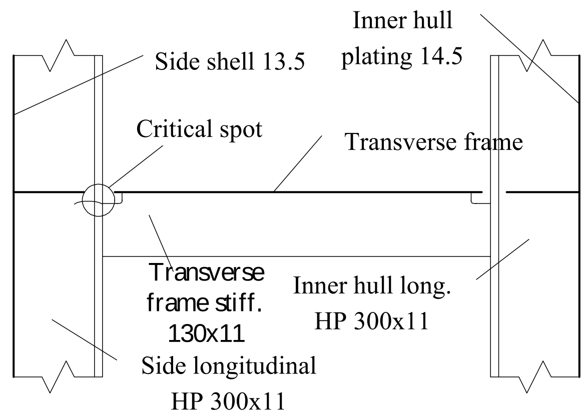


Fig.4 Side shell – location 1

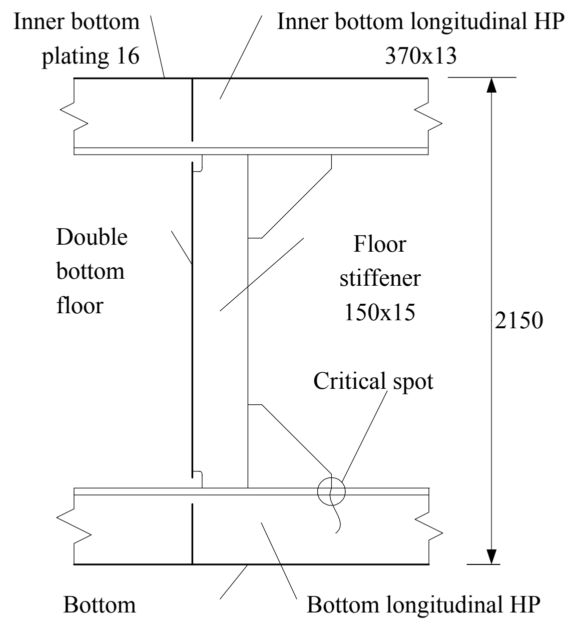


Fig.5 Double bottom – location 3

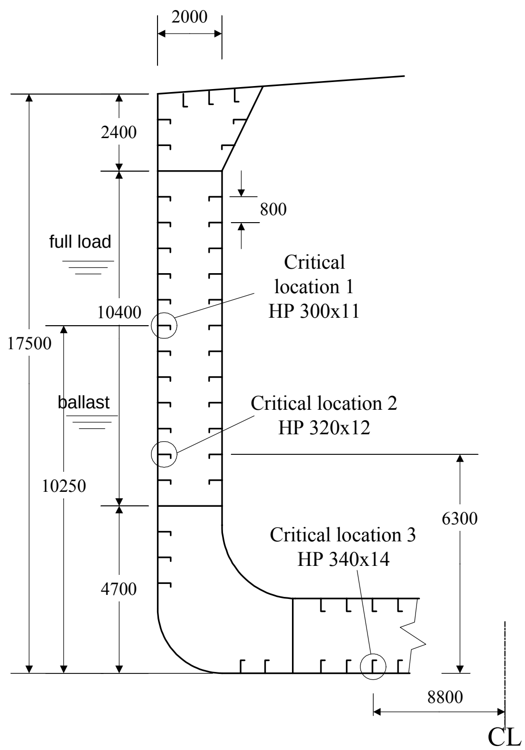


Fig.6 Midship section of a tanker

4.2. Calculated fatigue damage

Fig. 7 shows calculated fatigue damage, and Fig.8 shows corresponding fatigue life of investigated structural details.

Results show significant difference for each one of the three investigated locations. The highest fatigue damage is obtained at the first location, which was expected due to large local load fluctuations of the nearby full load waterline. Higher damage in longitudinal located in the double bottom (in cases of GL and LR procedure) than that in the ballast waterline region does not coincide with observations in practice – that implies the necessity of different combination of global and local fatigue loads for various locations on ship.

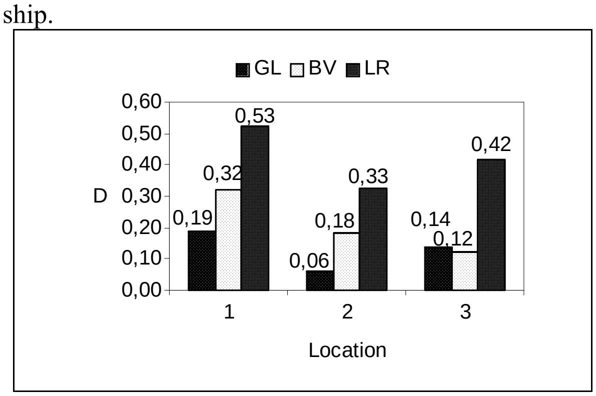


Fig.7 Calculated fatigue damage, D

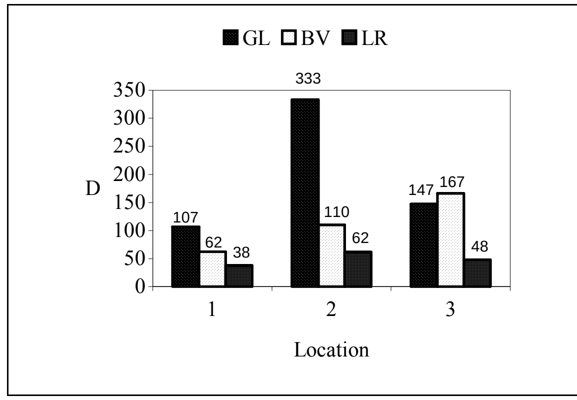


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Fig.8 Calculated fatigue life (in years)

In this example one conclusion is clear: all considered details have satisfactory fatigue strength – the lowest fatigue life is approx. 38 years. However, this result opens a possibility of structural detail optimization regarding fatigue.

5. ANALYSIS OF THE MOST INFLUENTIAL PARAMETERS

The following research was performed by using finite difference method (FDM) for parametric studies and assessments of sensitivities of practical fatigue damage calculational procedures to some productional, operational and theoretical parameters.

5.1 Constructional tolerances (workmanship)

The most important factor at construction stage, which affects fatigue life of the structure, is a misalignment of structural elements (Mitsubishi 2000).

The effect of actual maximum constructional tolerances is considered through an example of misalignment of web frame stiffener and side longitudinal at location 2. In case of BV procedure the influence of structural misalignment (Fig. 9) is included by adjusting the geometric stress concentration factor K_s:

$$K_{s,tol} = K_s \cdot \left(1 + 3e/t\right) \qquad (12)$$

where e is eccentricity and t thickness of thinner element in connection.

Results are shown at Fig.10 and Fig.11. One can notice a significant increase of fatigue damage caused by a very small increase in structural misalignment.

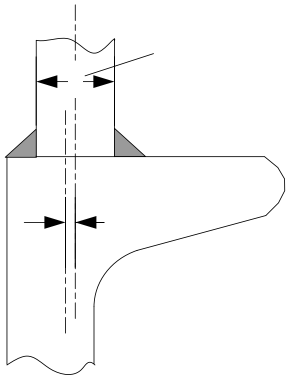

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Fig.9 Misalignment of structural elements

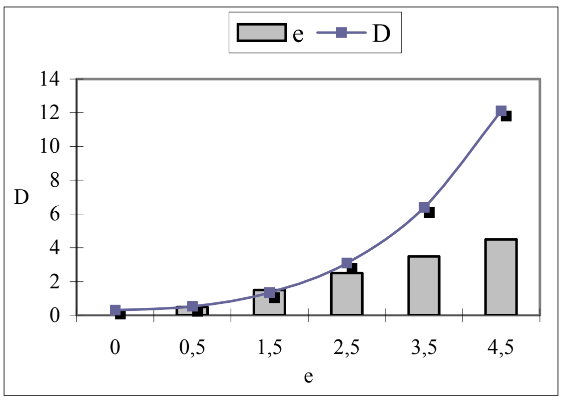


Fig.10 Influence of constructional tolerances on fatigue damage

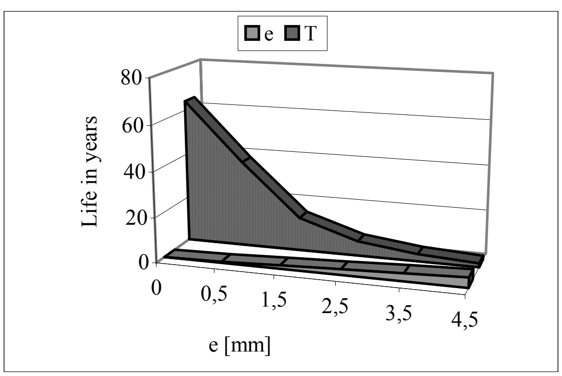
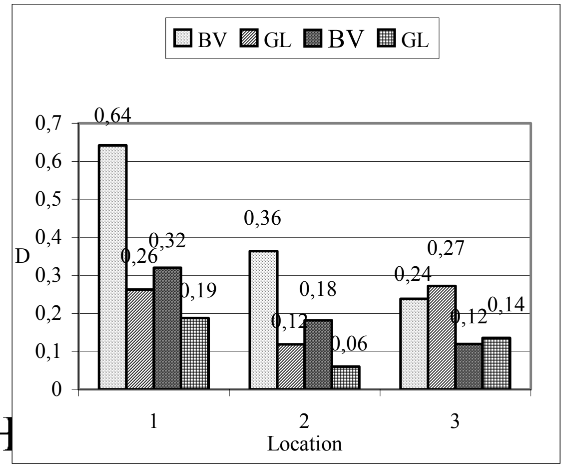


Fig. 11 Fatigue life as function of eccentricity

5.2 Corrosion

Fig.12 shows the effect of corrosion on fatigue damage calculated with BV and GL procedures. The Bureau Veritas includes this effect by dividing constant C of the S-N curve by 2. In this case the S-N curve is assumed to be without the change of slope. For the same purpose, the Germanischer Lloyd multiplies detail category referent value, $\Delta\sigma_R$, by 0.8, together with application of the S-N curve without change of slope. As expected, results show large rise of the fatigue damage in seawater environment.



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e

Fig. 12 Influence of the corrosion on fatigue damage

5.3 The effect of the shape parameter k

It is noted that calculated fatigue life is very sensitive to the variation of the Weibull shape parameter, k. This parameter can be accurately determined only through the spectral fatigue analysis or measurements. As a first approximation, the Weibull shape parameter k may be taken as (11). In practice, the value of the shape parameter usually varies between 0.7 to 1.3, depending on the dominant period of the hull structural response and the wave environments considered. For that range of values, the fatigue damage was calculated for three considered locations, and for better insight into this effect, the sensitivity analysis was performed.

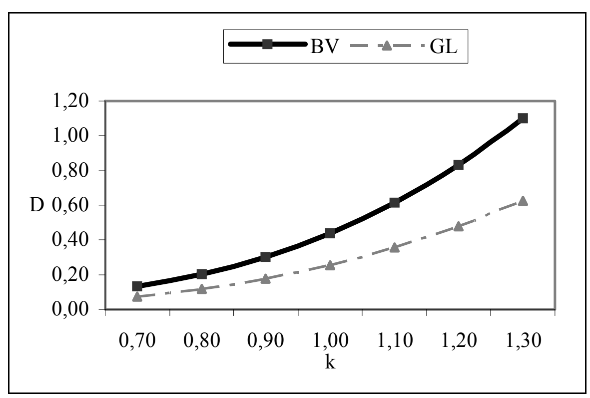

Fig.13 Influence of the shape parameter – location 1

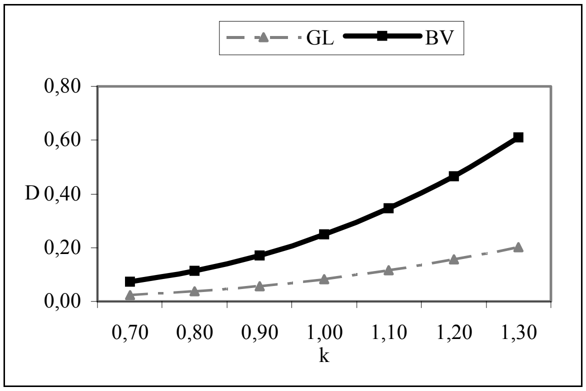

Fig.14 Influence of the shape parameter – location 2

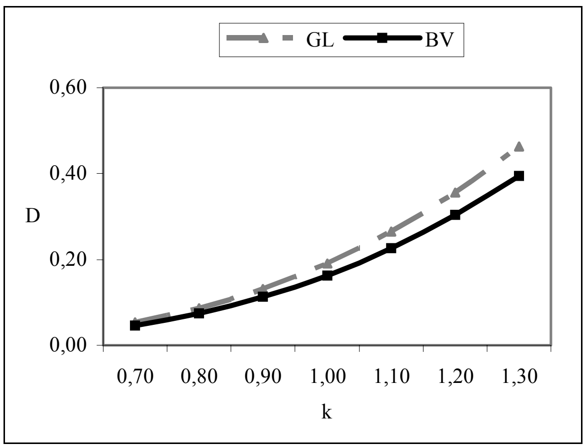

Fig.15 Influence of the shape parameter – location 3

5.3.1 Sensitivity analysis

For a simple evaluation of the influence of shape parameter on fatigue damage, it is practical to define a sensitivity factor as:

$$\frac{\Delta D}{\Delta k} = \frac{D(k + \Delta k) - D(k)}{\Delta k} \tag{13}$$

Very large sensitivity of the fatigue damage to small changes of the shape parameter was found, as shown in Table 3. For example: the change of value of the shape parameter from k=0,8 to k=0,9 (Δk = 0,1) at location 1 results in 50% increase of the fatigue damage!

Table 3: Sensitivity of the fatigue damage

Location	D(0.8)	D(0.9)	ΔD	ΔD/Δk
1	0.202	0.303	0.100	1.007
2	0.037	0.057	0.019	0.197
3	0.086	0.131	0.045	0.450

Location	D(1.1)	D(1.2)	ΔD	ΔD/Δk
1	0.413	0.832	0.419	4.19
2	0.116	0.156	0.040	0.40
3	0.265	0.355	0.090	0.90

Sensitivity analysis has also shown that the change of the shape parameter has larger influence on fatigue damage on location 1, where greater uncertainties in determination of fatigue loads are present.

5.4 Selection of design S-N curves

The effect of selecting the basic S-N curves is investigated. In both investigated procedures, BV and GL, only the hot-spot stress approach was used in order to avoid the influence of high values of notch parameters on results. To eliminate the influence of different corrections of the basic S-N curves, the analysis is performed with application of the same correction parameters in both cases – applied parameters are taken from GL procedure.

Conclusion can be drawn that selection of appropriate S-N curve is an important part of fatigue assessment procedure, since results deviate significantly regarding to the selected curve.

The result of analysis also shows the influence and the significance of selected stress approach as well as the selected number of correction parameters on fatigue damage. In this example fatigue damage obtained with BV procedure using the hot-spot stress approach is smaller than in case of GL procedure, which is significantly different from original results shown in fig.7.

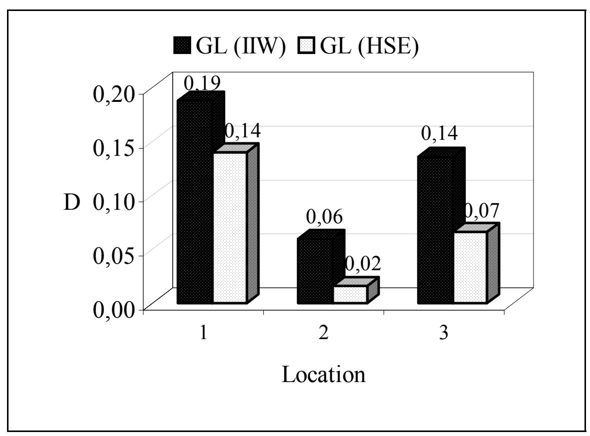

Fig.16 The effect of the S-N curves – GL procedure

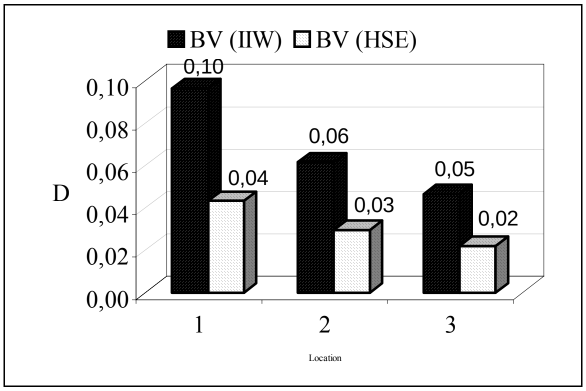

Fig.17 The effect of the S-N curves – BV procedure

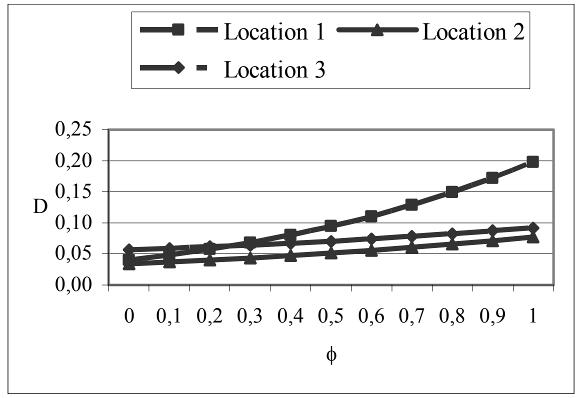

Fig.18 The effect of combination of loads

5.5. Combination of local and global loads

It is noted that the most probable extreme stress range should be calculated as the combination of the stress components from all loads acting on ship structure (IACS 1996). At present no agreement regarding this issue has been made between Classification Societies. In this paper the analysis of correlation of global and local loads is presented in order to illustrate some possibilities. Correlation between global and local loads is obtained with correlation factor, and analysis is performed by changing this factor in the range from 0 to 1.

Combination of loads on locations 1 and 2 (side shell):

$$\Delta\sigma_{total} = \Delta\sigma_{local} + \psi\Delta\sigma_{global} \tag{14}$$

Combination of loads on location 3 (bottom):

$$\Delta\sigma_{total} = \psi\Delta\sigma_{local} + \Delta\sigma_{global} \tag{15}$$

where ψ is the correlation factor between the global and local loads regarding possibility of their simultaneous acting.

The analysis is performed with BV procedure. The nominal stress range approach is used in order to eliminate the influence of the stress concentration factors on distribution of local and global stresses in overall stress of considered structural details.

Fig. 18 shows the results of the analysis. The significant influence of load combination is particularly evident on location 1, e.g. in the area with large local loads (wave pressure). The obvious conclusion from this analysis is that for various ship locations different correlation factor ψ should be applied. Nevertheless, for determination of the exact values of ψ, further research is necessary.

6. CONCLUSION

Up-to-date simplified procedures for fatigue design assessment have been outlined. Although fatigue design codes have been further developed during recent years, it can be stated that the difference between procedures of individual IACS members exists in every issue relevant for the assessment of the fatigue damage: the definition of the fatigue loads, the stress approach applied, the selection of the design S-N curves and a number of fatigue influencing parameters included in calculation (Tables 1 and 2).

The comparison of three typical approaches has shown high scatter in fatigue damage and fatigue lives at all investigated locations on a double hull tanker. The analysis has shown that the scatter is primarily due to different definition of fatigue loads, especially local loads, and due to different stress approaches applied. Similar results were obtained in application of simplified fatigue assessment procedures on the other types of ships (Fricke 2002, Blagojević 2002).

It is demonstrated in the paper how the workmanship and fabrication imperfections such as misalignments of structural elements, may dramatically reduce the fatigue strength of the ship's structure, giving even greater importance to production accuracy. Moreover, the effect of operational ageing with respect to corrosion in ship ocean-going service is proved to be quite significant.

Selection of the design S-N curves and of the correlation factor between local and global loads are also very influential and none of these effects should be disregarded in calculation. Parametric study has shown that extreme caution is necessary when selecting the theoretical shape parameter of the Weibull long-term distribution of stress range due to very large sensitivity of the fatigue damage to small changes of the shape parameter.

Significant efforts made by IACS towards harmonisation of fatigue assessment procedures have resulted in some progress. In order to determine a long-term distribution of stress ranges a two-parameter Weibull distribution should be assumed and, only as the first approximation, the Weibull shape parameter may be taken according to (11). In addition, the agreement has been reached that the individual load components should be determined with respect to moderate probability level of exceedance (10^{-3} to 10^{-5}). The analysis in this study has also shown that different approaches are well harmonized regarding the effect of corrosion (Fig.12). In spite of this effort, the key issues are still left to the discretion of the each classification society and further work is required in this respect.

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