Probabilistic Analysis Approach of Uncertainties in Fatigue Life Simulations of an Oil Tanker Vessel

Ozgur Ozguc

Fatigue damage is known to occur more commonly in certain ship types and hull construction element categories. The significance of prospective fatigue damage is proportional to the number of potential damage points of the investigated type for the ship structure in question, as well as the consequences of such damage. The present study introduces an overview of different fatigue analysis methods and provides advice on the accuracy of different methods for different locations on a vessel and a ranking of the methods. A probabilistic analysis of hopper knuckle fatigue analysis is supported by example uncertainty calculations, using four different fatigue methods for the hopper knuckle of an oil tanker vessel. The calculation of bias and uncertainty is supported by creating input to PROBAN tool, where the uncertainty calculations are being performed. The calculations show that the resulting fatigue damage distributions vary significantly. The median (50%) varies between 0.7 and 1.1 for the four methods, where 1.0 is the assumed correct damage for the calculations. The most probable damage varies between 0.4 and 0.9 for the four methods.

KEY WORDS

~ Probabilistic method
~ Uncertainty
~ Bias
~ Fatigue capacity,
~ Tanker hull structure

Istanbul Technical University, Faculty of Naval Architecture and Ocean Engineering, Turkey

e-mail: ozguco@itu.edu.tr

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1. INTRODUCTION

Fatigue is an important criterion for evaluating the adequacy of vessel structural details, and there is a great interest in the methods for predicting fatigue life with a view to crack growth. Oscillatory stresses cause fatigue at the welded joints. Because all fatigue design factors are subject to considerable uncertainty, a reliability procedure to management of such uncertainty seems reasonable. Li et al. (2014) compared five typical procedures for fatigue evaluation of ship structures, in which two container ships operating in the North Atlantic were employed under case studies. The numerical findings were compared with the full-scale measurements. Different measures of wave environment and the variance in wave models were also investigated.

For inspection, monitoring, and optimization of maintenance information under fatigue effects, Soliman et al. (2016) suggested a probabilistic method. The cost of the life cycle covers the costs of survey, monitoring and repair steps, and the costs of specification failure. A side shell elements of a steel ship was used in the solution proposed. For the fatigue analysis on the basis the probabilistic linear elastic fracture mechanics, Souza and Ayyub (2000) provided a methodology. Probabilistic analysis included the use of reliability methods to calculate fatigue life, taking into account the processes of crack propagation and their related uncertainties. The main features of probability methods developed for inspection a planning based on consistent fatigue analysis, and probabilistic methodologies were defined by Lotsberg et al. (2016). The predictive crack growth lives can be dramatically influenced by minor changes in the basic assumptions of fatigue calculation. Calculated fatigue lives are sensitive to input parameters based on the S – N method. For ship design development, approval, and operations, Papanikolaou et al. (2014) discussed the understanding and modelling uncertainties relating to shiploads and responses. Throughout the synthesis, testing, and evaluation of decision-making parameters, stochastic probabilistic methods were employed.

Wang (2010) estimated, by spectral approach, the fatigue life of a structural component. The spectral approach compares the predicted fatigue life value with that calculated with the IACS R 56, and several factors, which cause uncertainty in the spectral method, are further defined and examined.

Li et al. (2013) proposed a time-domain procedure for fatigue evaluation of vessel side-shell structures. The procedure was a combination of global loads analysis and the local procedure. The sensitivity and feasibility of the proposed time-domain procedure were performed. A comparative analysis between the time and frequency methods was performed. A new local stress measurement method for fatigue evaluation was proposed.

Zhao et al. (2002) presented a critical review of latest developments in the probabilistic modelling of the uncertainties related to the fatigue reliability evaluation. A number of probabilistic models for the principal parameters in the S-N curve, fatigue crack growth functions, and fracture analysis were addressed with a particular emphasis on the identification of future needs for the development of suitable procedures for offshore structures. Garbatov (2016) developed a complicated fatigue strength and reliability evaluation model for the calculation of an oil carrier vessel by different local structural finite element approaches, which account for the associated uncertainties and the correlation between load cases and coating life and corrosion degradation.

Ozguc (2020a) described fatigue analysis procedures that were supported by a developed model. Three local fine mesh model details were investigated: deck erection butt weld, longitudinal stiffener through web-frame, and bottom erection butt weld. The issue of fatigue has been a major concern for ship-owners, designers, and classification societies, among others. The fatigue assessment procedure is quite complicated and time demanding; however, it is a very important item for maintenance purposes (Ozguc 2017a, 2018, 2020c).

Ozguc (2020b) investigated the conversion of an oil tanker into a floating production and storage unit (FPSO) for the use in the Gulf of Mexico (GoM), using fatigue simulations. The analyses included a verification of the longitudinal material amidships and were performed in accordance with the approved design, using 'as measured' scantlings derived from UTM measurements.

Fatigue damage to ship structural elements is critical in the shipbuilding industry because it can cause cracks that threaten the structural integrity (Ozguc 2021). Based on an IACS scatter diagram for a 216,000 m3 LNG vessel, Ozguc (2017b) investigated long-term loads and fatigue damage accumulation for various trading routes related to North Atlantic operations. Ozguc (2020d) compared the fatigue damage capability of side shell longitudinals under the combined effects of hull girder bending and pressure. In the case of an FPSO vessel, fatigue evaluation approaches, such as component stochastic and a full spectral one, were examined.

It was discovered that the calculated fatigue life was sensitive to input parameters by standard design analysis approaches. In the case of structures under combined corrosion-fatigue degradation processes Han et al. (2019) suggested a method for risk management. Various uncertainties arising from material properties, coupled corrosion-fatigue modelling, loading conditions and inspection techniques have been considered in the proposed framework. In view of fatigue management, inspection, and maintenance decisions, and taking into account sources of uncertainties that affect the efficiency of life cycles, Zou et al. (2018) discussed the challenges of fatigue management of naval structural assets, employing a holistic approach. A risk-based and holistic approach was proposed for the joint optimization of fatigue design, inspection, and maintenance on the basis of the same fatigue deterioration model.

This study aims at addressing an overview of different fatigue analysis methods, where suggestions are given on the accuracy of the different methods for different locations on a ship and a ranking of the methods. Furthermore, a method is developed for calculation of bias and uncertainty in fatigue analyses for different locations on a ship, where a hopper knuckle detail - loaded condition is accounted for. The calculation of bias and uncertainty is supported by creating an input to PROBAN (2006), where the uncertainty calculations are performed. PROBAN is a general-purpose probabilistic analysis tool, covering the calculation needs of structural reliability, for example. PROBAN estimates the likelihood, distribution, probability of first passage, crossing rate, and related sensitivity measures. The method is supported by exemplary uncertainty calculations for four different fatigue methods for the hopper knuckle of an oil tanker vessel.

2. FATIGUE ANALYSIS METHOD OVERVIEW

A number of different fatigue analysis methods exist. A description of the main fatigue calculation methods is given according to Table 1.

Table 1.
Fatigue analysis overview.

NAME	DESCRIPTION
DIRECT	Direct full stochastic analysis
COMP-SCF-DIR	Component based stochastic-stress concentration model - direct load transfer
COMP-SCF-WAVE	Component based stochastic-stress concentration model - calculated wave loads and phasing
COMP-SCF-RULE	Component based stochastic-stress concentration model - rule phasing
DW-SC	Design wave - stress concentration model
COMP-K-DIR	Component based stochastic - K-factors - direct load transfer
COMP-K-WAVE	Component based stochastic - K-factors - calculated wave loads and phasing
COMP-K-RULE	Component based stochastic - K-factors - rule phasing
DW-K	Design wave - K-factors
RULE	Rule based fatigue - K-factors (e.g. DNV Fatigue)

When the critical areas, with respect to fatigue, are identified, it is time to select the fatigue calculation method. The methods range from a simplified method based on simplified analytical expressions to refined numerical simulations. The simplified fatigue calculation option is suitable for members where the total stress response can be defined as a sum of individual stress components due to global wave bending moments, external and internal local pressures. In the stress component stochastic fatigue method, Class Rule loads are substituted by direct calculated wave loads. The most sophisticated method is the full stochastic (spectral) analysis. Full stochastic (spectral) analysis employs both global and local finite element models to determine the stress response and may be used for any kind of structure.

3. DIRECT: DIRECT FULL STOCHASTIC ANALYSIS

A direct full stochastic analysis normally means that a structural model of the total ship is utilised. The wave loads are directly transferred to the structural model. Both external pressure and internal tank pressures are normally accounted for. The analysis is performed with a full global model (or a part model), direct load transfer from hydrodynamic analysis, Sub-model (stress concentration model) of detail, Stochastic fatigue calculations using FE tools. The advantages and disadvantages of the method are referenced below.

Advantages

- All linear effects automatically included. Both for global and local loading.
- Phasing between responses automatically included
- Can be used for all geometries.
- Shear lag effects included.

Disadvantages

- Global model of the vessel is needed.
- Difficult to include non-linearities for one load component as all load components are mixed into one stress response.
- A large number of load cases (periods x headings) have to be analysed using the global structural model and the sub-model(s). This may demand large CPU and storage capacity.
- Partly a black box procedure (program dependent). This makes it difficult to check intermediate results.

Suitable areas can be described, such as all structural parts, except those in the waterline region or other locations where the no-linear behaviour of the external pressure is important (for locations where transverse stresses dominate, like hopper knuckle structure).

4. COMP-SCF-WAVE: STRESS COMPONENT BASED STOCHASTIC ANALYSIS USING SCF-MODEL

A stress component based stochastic analysis using SCF-models normally means that a cargo hold model or similar models are used in combination with stress concentration models. The analysis is performed with cargo hold model, Unit loads applied to the model, Load transfer functions from hydrodynamic analysis, Sub-model (stress concentration model) of detail, load/stress ratio from structural analysis, and stochastic fatigue calculations using DNV POSTRESP -SESAM tool. The advantages and disadvantages of the method are addressed below.

Advantages

- Possible to separate each load component and thus include effects as reduced dynamic pressures around still water line.
- Only a few static load cases have to be analysed using the cargo hold model.

- Effect from different loads on the results can be found.

Disadvantages

- Manual definition of load cases.
- Simplifications are usually made in load calculation:
  - Constant pressure loading over the length of the cargo hold model. This means that the relative deformation of the transverse frames will be overestimated. Rotations of the longitudinals may be slightly underestimated for the wave periods, contributing most significantly to the fatigue damage. In general, the procedure is considered to be on the safe side.
  - The same load/profile is used for each wave heading/ period. However, the load profile is based on 10-4 probability level (referred to a Weibull long term distribution) which is not far from the load level that contributes most significantly towards fatigue damage.
- Errors may be made at several stages in the analysis procedures.
- Time consuming to check several sections of the ship.
- Global shear lag effects may not be included.

Suitable areas can be described, such as all areas where the total stress divided in several stress components related to different loads acting on the ship and areas where side pressure is of importance.

5. COMP-K-WAVE: STRESS COMPONENT BASED STOCHASTIC ANALYSIS USING K-FACTORS

This method is generally equal to COMP-SCF-WAVE except that load/stress ratios are found according to formulas or models where nominal stress is calculated. The hot-spot stresses are then found according to available K-factors for the detail in question (DNV-CG-0129, 2021). The analysis is performed with No model (as usual), load transfer functions from hydrodynamic analysis, load/stress ratio from formulas, stochastic fatigue calculations using POSTRESP-SESAM tool. The advantages and disadvantages of the method are similar to the COMP-SCF-WAVE, and only additional items are referred to below:

Advantages

- No models necessary for the analysis

Disadvantages

- May only be used if K-factor is available for the location
- May be used with available K-factors for locations where this is not applicable.
- May be difficult to separate axial and bending stress (different Kg factors may be used depending on geometry of the detail)

Suitable areas can be areas where K-factors are available.

6. RELATIVE DEFLECTION AND SECONDARY BENDING

The results from the COMP-K-WAVE method may vary significantly, depending on the method used for calculation of relative deflection and secondary bending (double hull bending). Depending on the geometry, relative deflection (and secondary bending) may be a significant contributor to the total fatigue damage (DNV Rules for classification: Ships — DNV-RU-SHIP Part 3 Chapter 3, 2021). The methods may be used for calculation of relative deflection and secondary bending, such as formulas for deflection and stress, formulas for stress due to a given deflection, deflections from a cargo-hold analysis transferred to a beam model where nominal stresses are calculated, and deflections from a cargo-hold analysis transferred to a local shell element model where nominal stresses are calculated.

7. RULE: RULE BASED FATIGUE

The rule based fatigue approach is the approach that will normally be used by the yards. The quality level of the analysis may vary. The K-factors are calculated from the DNV Nauticus Fatigue (2018) on the basis of selection of geometry. The analysis is performed according to cross section according to section scantlings, rule loads, and phasing, rule Weibull distribution, and load/stress ratio obtained from formulas. The advantages and disadvantages of the method are similar to the COMP-SCF-WAVE, and only the additional items are addressed as follows:

Advantages

- No models necessary for the analysis (e.g. DNV Section Scantlings/Nauticus Fatigue model used)

Disadvantages

- May only be used if K-factors are available for the locations
- May be used with available K-factors for locations where this is not applicable
- Rule loads
- Only longitudinal members

Suitable areas can be longitudinal members where K-factors are available. The results from the RULE method have the same uncertainties as the COMP-K-WAVE for Relative Deflection and Secondary Bending

8. FATIGUE METHOD SELECTION

The different fatigue methods as described are suited to different areas of a vessel. The selection of fatigue method to be used for different locations depends on several factors. Some of these factors are given, such as type of loading that is the main contributor to fatigue, response stress direction, detail type, required accuracy, and cost. A ranking of the four fatigue calculation methods as described is given in Table 2. The ranking is based on the accuracy of calculations. This is again based on the information on load importance, as given in Table 3, the response stress direction for the different details and the detail type. The cost associated with the different analysis methods is not included in the ranking.

Table 2.
Fatigue approach ranking for different locations.

Pos. no.	Location	DIRECT	COMP-SCF-WAVE	COMP-K-WAVE	RULE
1	Bilge hopper	+ +	+ +	+/- -	o/- -
2	Topside tank	+ +	+ +	- -	- -
3	Wing ballast tank				
3.1	Longitudinal - transverse bulkhead	- *	+ +	+ **	o **
3.2	Longitudinal - transverse web	- *	+ +	+ **	o **
3.3	Cut-outs in webs	- *	+	-	-
4	Bottom ballast tank				
4.1	Longitudinal - wt. floor (bhd)	+ + (+)	+ +	+ **	o **
4.2	Longitudinal - ordinary floor (frame)	+ + +	+ +	+ **	o **
4.3	Cut-outs on floors	+ +	+ +	- -	- -
4.4	Inner bottom long. in way of bilge wells	+ + +	+ +	-	-
5	Web frame in cargo tank				
5.1	Transverse web frame end brackets	+ +	+ +	-	- -
5.2	Cross ties and their end connections	+ + +	+ +	-	- -
5.3	Cut outs around transverse bracket ends	+ + +	+ +	-	- -
5.4	Tripping brackets	+ + +	+ +	-	- -
6	Transverse bulkhead in cargo tank				
6.1	Connection of hor. stringers to transverse web frames and side horizontal girders	+ + +/++	++	-	--
6.2	Connection of longs to hor. stringers	+ + +	+ +	-	- -
6.3	Connection of access trunk to inner bottom	+ + +	+ +	-	- -
6.4	Connection of transverse bulkhead vertical web to deck girder and inner bottom	+ + +	+ +	-	- -
6.5	Corrugated bulkhead connection to deck and inner bottom	+ + +	+ +	-	- -
6.6	Corrugated bulkhead connection to stool shelf plate	+ + +	+ +	-	- -
6.7	Connection of transverse bulkhead lower stool plating to inner bottom	+ + +	+ +	-	- -
6.8	Connection of transverse bulkhead to knuckle inner bottom	+ + +	+ +	-	- -
	Deck - longitudinal direction	+ + +	+	+	+
	Deck - transverse direction	+ +	+ +	+ +	- -

**Procedure for pressure reduction in direct analysis exists, **Assuming that relative deflections and secondary bending are calculated from beam/shell model. Note: COMP-K-WAVE may be used for more locations if relevant K-factors exist*

Description of symbols are represented such as + + +as good as can be with linear approach
+ +Very good, + Good, O may be used, - results may be way out, - - should not/cannot be used.

Table 3.
Fatigue load importance at different locations.

Pos. no.	Location	Main contributor	Second contributor	Third contributor
1	Bilge hopper	P-side	P-internal	P-bottom
2	Topside tank	P-side	P-internal	
3	Wing ballast tank			
3.1	Longitudinal - transverse bulkhead	P-side	MY/MZ/AX	P-internal
3.2	Longitudinal - transverse web	P-side	MY/MZ/AX	P-internal
3.3	Cut-outs in webs	P-side	MY/MZ/AX	P-internal
4	Bottom ballast tank			
4.1	Longitudinal - wt. floor (bhd)	MY	P-bottom	P-internal
4.2	Longitudinal - ordinary floor (frame)	MY	P-bottom	P-internal
4.3	Cut-outs on floors	MY	P-bottom	P-internal
4.4	Inner bottom long. in way of bilge wells	MY	P-bottom	P-internal
5	Web frame in cargo tank			
5.1	Transverse web frame end brackets	P-bottom	P-internal	P-side
5.2	Cross ties and their end connections	P-internal	P-bottom	
5.3	Cut outs around transverse bracket ends	P-internal	MY/AX	
5.4	Tripping brackets	MY/P-internal		
6	Transverse bulkhead in cargo tank			
6.1	Connection of hor. stringers to transverse web frames and side horizontal girders	P-internal/		
P-side	MY/MZ			
6.2	Connection of longs to hor. stringers	P-side	MY/MZ	
6.3	Connection of access trunk to inner bottom	MY	P-internal	
6.4	Connection of transverse bulkhead vertical web to deck girder and inner bottom	MY	P-external	P-internal
6.5	Corrugated bulkhead connection to deck and inner bottom	P-internal	MY	
6.6	Corrugated bulkhead connection to stool shelf plate	P-internal	P-external	
6.7	Connection of transverse bulkhead lower stool plating to inner bottom	MY	P-internal	AX/ P-external
6.8	Connection of transverse bulkhead to knuckle inner bottom	MY	P-internal	
	Deck - longitudinal direction	MY	MZ	AX
	Deck - transverse direction	PY	PZ	

Note: P-side: external side pressure, P-bottom: external bottom pressure, P-internal: internal tank pressure due to acceleration of the vessel, MY/Z: Bending moment about respective axes, AX: Axial load

9. FATIGUE ANALYSES

Results from fatigue analyses may be used to find the information necessary for bias and uncertainty calculations of fatigue analyses. Some of the analyses performed during the past years may be used to locate information that can be used in calculation of bias and uncertainty for different locations. The information from these analyses may be of interest, such as fatigue damage (for comparison between different methods), unit stress calculations (for comparison between different methods), hydrodynamic loads (for comparison between different methods), information on relative importance of different effects, and correlation information. The different analyses have naturally focused on the calculation of fatigue damage. Some of the calculations are performed for more than one analysis approach. These may subsequently be used to see the difference in calculated fatigue damage between two analysis approaches. The number of such analyses is limited and may therefore only be used as examples on differences. It will, due to the limited number of comparisons that may be performed, not be possible to extract any statistical information on the fatigue calculations. An alternative, in order to achieve this, is to perform simplified analyses for some of the vessels where more detailed, and expensive, methods have been used in the fatigue calculations. Statistical information may be collected from hydrodynamic analyses and used as an input in the calculation of bias of uncertainty of different fatigue analysis methods. Most of the analyses performed have no relevance for this report since they only represent one single analysis for one vessel. It will thus be difficult to extract any statistical information about uncertainty in the hydrodynamic calculations from these analyses.

10. UNCERTAINTIES IN FATIGUE CALCULATIONS OF SHIPS

Realistic uncertainty calculations can only be made if the problem is broken down, in such a way that reasonable probability distributions can be estimated according to DNV Classification Note 30.6 (1992). The calculations are broken down according to the system listed, such as hydrodynamic loading and application to the structural model, stress calculations from the structural model, fatigue calculations based on the above loading and stress, missing fatigue effects, and calculation of relative deflection. This is made as a separate calculation since the calculation methods may vary significantly within some of the main fatigue calculation methods. This effect may also be significant for many fatigue sensitive areas. It is therefore isolated since this can be done without introducing any additional uncertainty

11. DETAILED OVERVIEW OF UNCERTAINTIES IN FATIGUE CALCULATIONS

The description focuses on the description of factors contributing towards the uncertainty of each item. Only a short description of each point is given.

Missing fatigue effects

- Springing/whipping
  - Fatigue damage from excitation of Eigen periods varying with global Eigen periods, and bow shape
- Low cycle fatigue
  - Fatigue damage from low cycle fatigue (normally negligible)
- Local vibration
  - Fatigue damage from vibration of stiffeners (close to machinery room)

Fatigue calculations

- SN-curve
  - Type of SN-curve
  - Uncertainty in the SN-curve (fatigue assessment)
- Wave spreading
  - Spreading function selection
  - Difference between actual spreading and estimated best spreading
  - Use of wrong spreading function
- Wave spectrum
  - Type of spectrum (PM/Jonswap)
  - Difference between actual spectrum and estimated best spectrum
- Scatter diagram
  - How the scatter diagram represents the physical wave data
  - Ship route compared to ship route for which the scatter diagram is calculated
  - Wrong use of scatter diagram
- Calculation method
  - Rayleigh: Summation of fatigue damage within each short term period
  - Weibull: Calculation of long term distributions from which fatigue damage is calculated
  - Rule distributions will vary from calculated => Larger uncertainty
- Effect of corrosion
  - Uncertainties in coating lifetime
  - Effect from corrosion on fatigue life
  - Inclusion of corrosion in analysis
- Thickness effect
  - Correctness of thickness effect
  - Correct use of thickness effect in analysis

Stress calculations

- Crack growth
  - Crack growth varies in dependence on whether the stress is membrane or bending stress, initial crack depth, etc. These effects are not differentiated in the fatigue calculations (are differentiated in crack propagation analyses)
- Extrapolation
  - Use of correct stress from the structural analysis in the fatigue calculations
- Mean stress effect
  - Inclusion of mean stress effect
  - Correctness of mean stress effect
- Load/stress ratio
  - Use of correct stress together with the actual load
  - Combine with correct K-factor (axial/bending)
- Other K-factors
  - Inclusion of relevant K-factors for the actual location (especially for stiffeners)
  - Correctness of other K-factors
- Stress concentration factor (SCF)
  - SCF-model
    - Correctness of SCF-model (mesh, size, boundary conditions, dimensions)
    - Load transfer (boundary displacements/ forces, local loads)
    - Use of correct stress
  - Nominal stress mod
    - As above
  - Beam model
    - As above
    - Combination with correct K-factor (axial/ bending)
  - Formulas
    - Correctness of formulas
    - Use of formulas
- Global str. model
  - Correctness of geometry, mass, dimensions, material properties
  - Use of inappropriate element types
  - Stress flow uncertainties due to initial deformations of plate fields (orthotropic material behaviour)
  - FE element description in used program
  - If simplified methods are used to calculate the stresses:
    - Uncertainty in simplified calculations (formulas + use of formulas + simplified models)
- Phasing (correlation)
  - Errors in correlation between different loads

Relative deflections/secondary bending

- Only one of the options below to be selected
- Local model
  - Modelling errors
  - Nominal stress definition
- Beam model
  - Modelling errors
  - Axial and bending stress separation
  - Deflection form (non-symmetric effects, angles)
- Formulas
  - Formulas according to DNV-CG-0129 fatigue assessment of ship structures (large uncertainties)

Section loads, hydrodynamic pressure, internal pressure, and acceleration of steel

- Shear lag
  - Global shear lag effects on the ship beam
- Boundary cond.
  - Errors introduced by boundary conditions on the "global" model
- Non-linearity
  - Section forces (bow flare, bottom slamming, deck wetness)
  - Hydro. pressures (Non-linear side pressure effects)
    - real versus calculated (error in theory)
    - application of hydrodynamic side pressure
  - Int. pressure
    - Sloshing in tanks
- Load point definition
  - The pressures that are used to scale the different effects. (Local bending - at stiffener, relative deflection/secondary bending - at middle of hold)
- Long. variation
  - Inclusion of varying load along the length of the vessel
- Load transfer: (errors in the load transfer)
  - Direct transfer
    - Hydrodynamic pressure transfer (Element mapping, element normal, trim, volume difference)

  - Component based
    - Definition of unit sectional forces
    - Pressure distribution definitions
    - Acceleration points used in the calculations
- Hydro calculations
  - Calculation theory (3D, 2D, Rule)
  - Errors in the calculations themselves.
  - Periods, headings, program, mass model, panel model, damping values
- Forward speed effects
  - Effects on the hydrodynamic loading from forward speed

The statistical information available for the calculation of bias and uncertainty in the fatigue calculations for ships is scarce. Such information will require several persons/groups to have performed equivalent analyses for the same problem.

12. CALCULATION OF BIAS AND UNCERTAINTY

The bias and uncertainty calculations are performed in PROBAN, which is a software tool for probabilistic analysis. Each variable is defined with bias and uncertainty, defined as distributions with assigned available distributions from the PROBAN "library" (2006). Normal distributions are defined and used to describe the uncertainty for all variables. All variables within one "main effect" are assumed to be mutually independent. The total uncertainty within on "main effect" is therefore the product of the individual variables. Each "main effect" is multiplied with their assumed/calculated importance and summed up below each higher level "main effect". The "Rel. deflection/secondary bending" part may easily be included. The effect depends on loading from external pressure, internal pressure, and acceleration of heavy loads/items. The complexity of this inclusion will be decided upon when some data on the relative importance of this effect has been evaluated.

13. EXAMPLE ANALYSIS

The analyses of bias and uncertainty in fatigue calculations of a hopper knuckle are described. Calculations are performed for four different analysis methods. These methods, which are described in detail, are DIRECT, COMP-SCF-WAVE, COMP-K-WAVE, and RULE. Loaded condition is analysed since most data available apply to this condition. Be aware that the hopper knuckle is normally not used as defined in this report for calculations made for the two last methods listed above. These methods will normally not employ a global structural model. The calculations are still expected to be representative for the two methods. The hopper knuckle detail is shown in Figure 1. This is one hopper knuckle configuration and crack type. Other configurations, crack locations, and types exist. The hydrodynamic loading causing the cracks will probably be the same. Their relative importance may however vary. The calculations of uncertainty are still assumed to be relevant also for these crack locations. External side pressure (P-side), external bottom pressure (P-bottom), and internal pressure (P-internal) are the main contributors to the fatigue damage. This data is extracted from two different analyses. The data is based on long-term stress amplitudes. Weibull slope parameters and the correlation between the different stresses are not included in the estimation of relative importance.

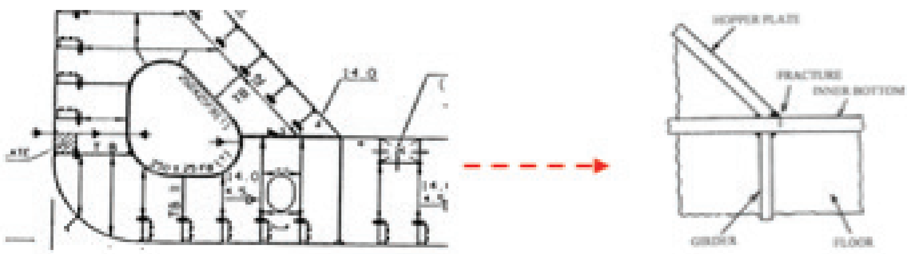

Figure 1.
A typical hopper knuckle of oil tanker vessel.

14. ANALYSIS DESCRIPTION

The input data is given to PROBAN as normal distributions with given mean values and coefficients of variation (CoV). The input in the developed tool is given as mean and uncertainty (z) at a given confidence level (x). A confidence level of 90 % is used in the analyses. This means that 90 % of all analysis should give results within mean value ± uncertainty (z) for the given item. Most values are found from engineering judgement as a limited amount of statistical data is available (Soliman et al. 2016 and Li et al. 2014). A summary of the statistical values for the different analysis methods is shown in Table 5 and Table 6 respectively.

It is noted that the 90 % of all calculations will give results within these intervals, with 5 % being lower and 5 % higher. Note: Conservative results are marked in bold print. A fatigue life of 40 years means that this is the fatigue life calculated with the given method. The assumed correct life is 20 years.

A stress of 0.9 means that the stress is underestimated by 10 % with the given method. The assumed correct stress level is 1. The calculations show that the resulting fatigue damage distributions vary significantly. The median (50 %) varies between 0.7 and 1.1 for the four methods, where 1.0 is the assumed correct damage for the calculations. The most probable damage varies between 0.4 and 0.9 for the four methods.

Table 4.
Calculated bias and uncertainty of fatigue damage for the different analysis methods.

Variable -->	DIRECT	COMP-SCF-WAVE	COMP-K-WAVE	RULE
Assumed correct damage/life	1 / 20			
Most probable (damage)	0.9	0.8	0.5	0.4
Median (50 %) (damage)	0.96	1.14	1.09	0.73
Mean value (damage)	1.06	1.36	1.46	0.94
CoV (StD/Mean)	0.49	0.66	0.88	0.82
90 % confidence level of calculated damage *	0.43 - 2.1	0.40 - 3.1	0.28 - 3.9	0.2 - 2.4
Most probable (fat. life)	24	24	40	50
Median (50 %) (fat. life)	21	18	18	27
Mean value (fat. life)	19	15	14	21
90 % confidence level of calculated fatigue life *	10 - 47	7 - 50	5 - 71	8 - 98

Table 5.
Calculated bias and uncertainty of stress level for the different analysis methods.

Variable -->	DIRECT	COMP-SCF-WAVE	COMP-K-WAVE	RULE
Assumed correct unit stress	1			
Most probable (damage)	0.98	1.03	1.00	0.89
Median (50 %) (damage)	0.99	1.05	1.04	0.91
Mean value (damage)	1.00	1.07	1.07	0.93
CoV (StD/Mean)	0.14	0.19	0.25	0.24
90 % confidence level of calculated stress level *	0.78 - 1.24	0.76 - 1.43	0.67 - 1.55	0.55 - 1.43

According to the results, the probability that a fatigue damage lower than 0.5 (or fatigue life above 40 years) is 10 % for the DIRECT method, while it is 30 % for the RULE method. This means that the probability that the calculated fatigue life shall be non-conservative with a factor of 2 or higher is 10 % and 30 % for the two methods. The different Weibull fitted distributions are shown in Figure 2. The results show the calculated stress compared to the expected stresses. The expected stress is thus 1.0.

It is noted that (L_TOTAL) means the fatigue damage calculations carried out by the methods studied in the present work, such as Direct method, COMP-SCF-WAVE method, COMP-K-WAVE method, and RULE method.

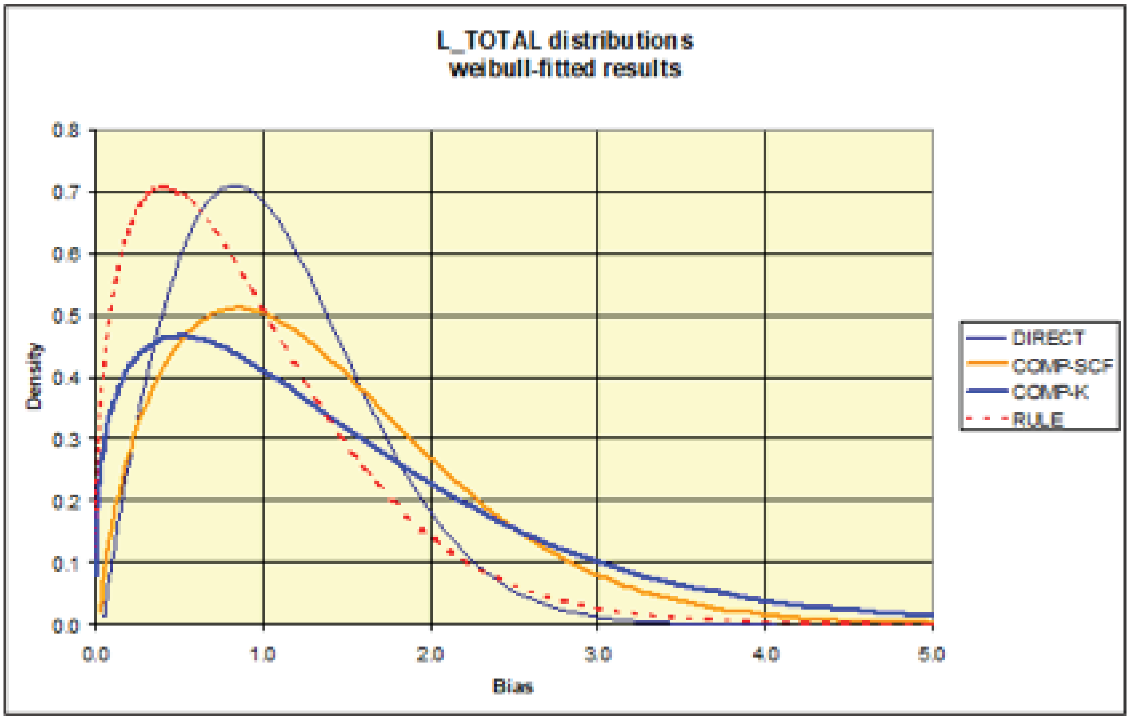

Figure 2.
Density for total fatigue damage for all methods.

15. DISCUSSION

The fatigue life is specifically related to the size of the dynamic stress level, the corrosiveness of the environment, and the magnitude of the notch and stress concentration factors of the structural details, all of which vary depending upon the ship type and structure being evaluated.

The small changes in basic assumptions that could have a significant impact on the anticipated crack growth have been shown. It was discovered that the calculated fatigue life was sensitive to input parameters by standard design analysis approaches. The calculated probability of fatigue failure by probabilistic methods was even more sensitive to analysis methodology and analysis input parameters. The importance factors will also vary according to longitudinal position on the ship. They will also vary with loading conditions and ship types. To find important factors for all possible combinations is a substantial task. It is therefore of vital importance that the necessary precision of the data should be decided upon.

It can be seen that a few variables dominate the calculated distribution of the total fatigue life. The following variables have an importance of more than 5 % for the minimum calculated distribution and probability level:

- L_EXTRAPOL Uncertainties in stress to be used in the fatigue calculations
- L-MEANSTRESS Uncertainty in mean stress effect
- L_SCF Uncertainties in calculation of SCF-factor (K-factors)
- L_GLOB_STR Uncertainties arising from the global structural model or formulas
- L_STRESS_PHA Uncertainty in calculation of correlation (phasing) between different load effects
- L_SNCURVE Uncertainties in SN-curve
- L_HYD_PHA Uncertainty in phasing between side pressure and bottom pressure
- L_SP_NONLIN Uncertainty in inclusion of non-linear side pressures
- L_SP_BOUND Uncertainties from boundary conditions related to side pressure
- L_SP_HYDRO Uncertainty in the calculation of linear side pressure

All of the calculated mean values are above 1.0. The results found from all the analyses will as a mean value be conservative. This is basically caused by the fact that the results vary between 0 and ∞. The moment from contributions above one will thus be larger than from those below one. The most probable value, which is the value that will be produced by most calculations, is below 1.0 for all methods (non-conservative). Some of the methods show large skewness factors. The skewness is not pronounced on the stress distributions and the large skewness on the fatigue damage distributions therefore mainly result from the fact that the stress distributions are raised to a power of three for calculation of fatigue damage. The use of normal distributions will lead to a small non-physical positive skewness since the density of input variables will be symmetrical about 1.0, i.e. the probabilities that the bias is below 0.8 or above 1.2 are identical for a non-biased distribution. This is not correct since a bias of 0.8 shall have the same probability as 1/0.8=1.25. The density is consequently too high for values below 1.0. The effect will be the larger the larger the uncertainty is for the input variables. However, this effect is small and is not supposed to influence the results significantly. Looking at DIRECT calculations and RULE calculations, the mean values are quite close to each other. Looking at the distributions it is found that the probability of calculated low fatigue damage (non-conservative) is much higher for the RULE method than for the DIRECT calculations.

16 CONCLUSION

The current paper has introduced an overview of various fatigue assessment procedures and provided some suggestions upon the accuracy of the various methods for various locations on a tanker vessel and a ranking of the methods. A probabilistic analysis of hopper knuckle fatigue analysis has been carried out using four different fatigue methods for the hopper knuckle of an oil tanker vessel. The calculation of bias and uncertainty has been supported by creating an input to PROBAN tool, where the uncertainty calculations have been conducted.

The analysis findings demonstrate that the resulting fatigue damage distributions have varied significantly. The median (50 %) has varied between 0.7 and 1.1 for the four methods, where 1.0 has been assumed a correct damage for the analyses. The most probable damage varies between 0.4 and 0.9 for the four methods applied.

CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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