Utilizing a Robust Fatigue Screening Process for Initial Design and Throughout the Ship Life-Cycle

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Abstract

The paper presents methodologies, procedures, and results from conducting an analysis using a simplified fatigue assessment rooted in beam theory as well as a spectral-based fatigue analysis procedure implemented in MAESTRO to globally screen for fatigue damage. The paper presents how the MAESTRO software open framework and the MAESTRO Spectral Fatigue Analysis implementation serve as key enabling technologies to the vision of implementing a fully functional life-cycle framework for maintenance, monitoring, and reliability of ship structures. It will discuss how a completely implemented and functional life-cycle framework can mitigate, among other things, extensive fatigue damage in the hull girder.

1. Introduction

It is well documented that a primary limiting component for a ship's service life is the hull structure. The fatigue life (or damage due to fatigue) is one of the major design issues naval architects and owners must contend with. Structural fatigue life is assessed during early stage design and often revisited through its operating life in order to mitigate further damage and keep ships operational throughout the intended service life or beyond. Over the years there have been many methods used to conduct fatigue damage assessment ranging from simplified methods to spectral-based methods. Like most complex analysis problems, each method has pros and cons as well as varying levels of uncertainties. These uncertainties are introduced from both the analysis methodologies themselves, as well as from the engineers executing the methods. It is well established that the costs associated with in-service fatigue damage are significant. This reality continues to drive industry to find more accurate and robust methods to predict these structural inadequacies. Therefore, it is an important objective for designers and owners to exercise an accurate process that can perform global fatigue screening of details in the primary hull structure early in the design process and throughout the ship's service life. This process should begin at preliminary design and can result in great insight for the designer regarding the fatigue distribution of the structural hull system. This knowledge, learned early in the design process, reduces some burden of the detail design phase with respect to structural fatigue. In this respect, the insight and knowledge serves as an excellent jumping-off point for downstream detailed design and the associated detailed fatigue analysis.

2. Process Overview

The following two sections describe the process for performing fatigue assessment using a spectral-based global screening approach and a simplified approach respectively. Each section will present the approach by addressing the main steps in the process. The objective of both approaches is to compute the fatigue demand on a structural entity and compare it to the predicted fatigue strength of that entity, *ABS (2003)*. The main steps can be identified as: Initialization of Structural Arrangements/Scantlings, Generation of Structural Analysis Model, Determination of Loads, Computation of Stress Range, and Computation of Fatigue Damage/Life. This procedure is shown in Fig.1. The following sections will describe steps 2 through 5 for both approaches. Step 1, Initialization of Structural Arrangements/Scantlings, is presented in the figure to illustrate that the designer should begin the process of fatigue assessment by understanding what details are used (or envisioned to be used) for the ship structural system. At the very least, an awareness of the structural details is important because proper detailing and proven details are an effective way of extending the fatigue life of a structural connection, *Glen et al. (1999)*.

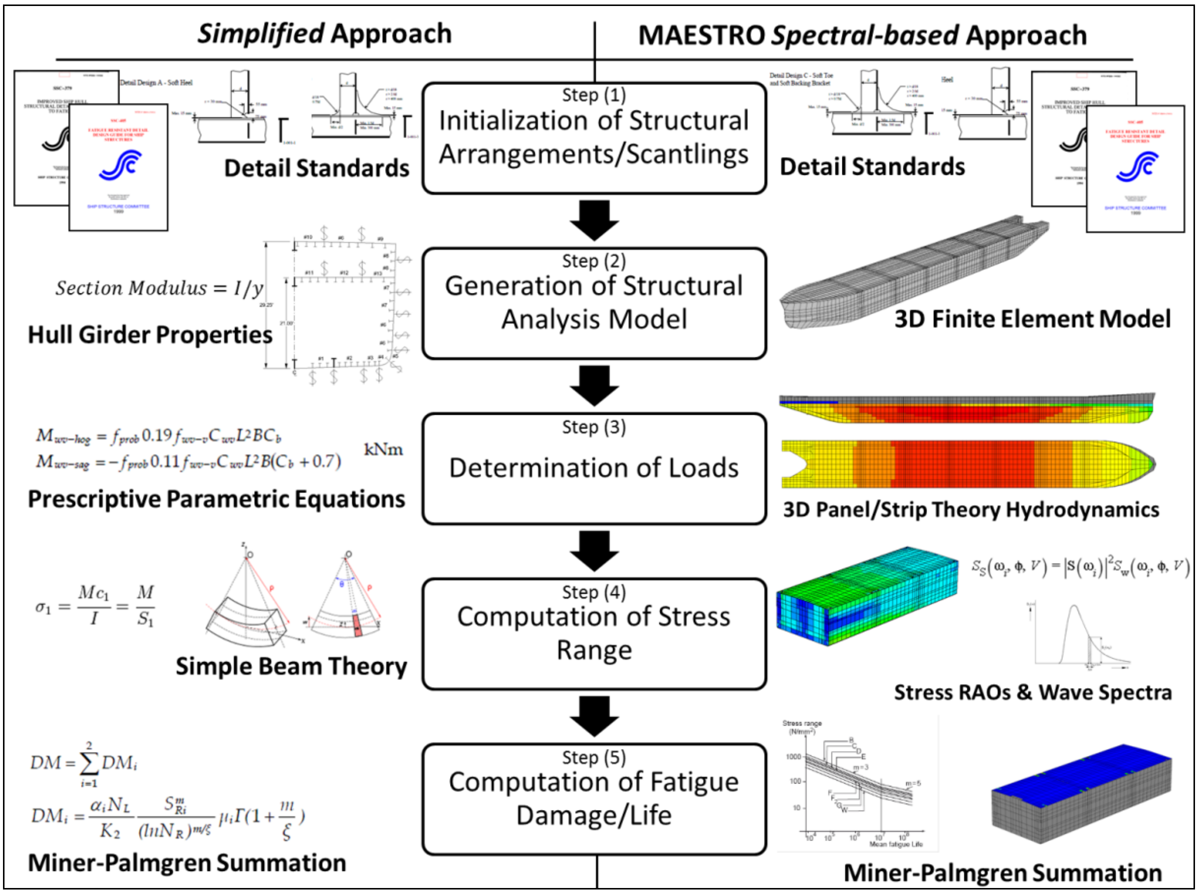


Fig. 1: Fatigue design and assessment procedure

The following section describes how the software suite MAESTRO, http://www.maestromarine.com, has implemented a spectral-based fatigue assessment approach. MAESTRO (Method for Analysis, Evaluation, and STRuctural Optimization) is a structural design tool specifically tailored to suit naval architects and their finite element analysis and limit-state (failure mode) evaluation needs. MAESTRO has seamlessly integrated all the necessary analysis methodologies to execute a *spectral*-based global fatigue screening procedure through a single Windows-based GUI. This MAESTRO-based procedure seamlessly integrates the structural modeling (preprocessing), the ship-based loading (including seakeeping loads), the finite element analysis, stress range computation, fatigue damage computations, and the post-processing. A key enabling aspect of this MAESTRO-based method is its efficiency which permits this high fidelity fatigue screening approach to be used as an intrinsic aspect of the early-stage (e.g., preliminary design) structural design process.

2.1 MAESTRO Spectral-based Global Fatigue Screening

2.1.1 Generation of the Structural Analysis Model

The generation of a global three dimensional (3-D) finite element model (FEM) that represents the entire hull structure is the first major step in the fatigue assessment process. The global model must sufficiently capture the stiffness and inertial properties of the entire structure. Further, the model must be generated in such a way to accurately compute (through FEA) the nominal stress or provide sufficient boundary conditions for fine-mesh models that may be generated as the design matures. This can be accomplished through course-mesh finite element modelling and the representation of stiffened panels through orthotropic shell elements (i.e., smeared stiffener approach). For a global screening process that makes use of the nominal stress it is unnecessary to generate a very fine mesh model to determine the required local nominal stress, *ABS (2003)*. Fig.2 shows a MAESTRO global model that illustrates the above approach for course-mesh modelling.

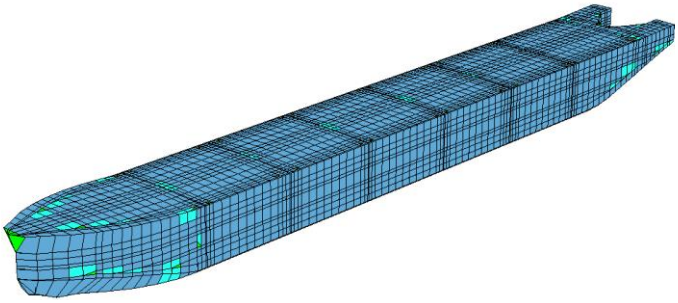


Fig. 2: MAESTRO Global Course-mesh FEM

Although the subject of this paper is global fatigue screening, it is important to note that MAESTRO's fatigue analysis can extend to local fine-mesh analyses. MAESTRO has functionality to either generate or import local fine-mesh models, which serve as substructures or super-element(s) in the global model. At the time of computing fatigue damage, the user has the option to include all fine-mesh models.

In addition to the generation of the structural FEM, all base loading conditions (e.g., Full Load, Ballast, etc.) must be captured in the FEM. These base loading conditions are the conditions the vessel will see through the envisioned life-cycle. MAESTRO facilitates the modelling of the common loading patterns that collectively make up the base loading condition. Examples of these loading patterns are shown in Fig.3.

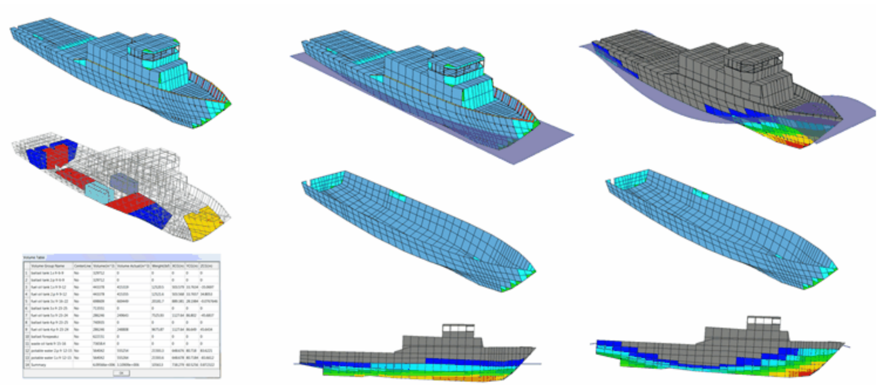


Fig. 3: Tank, still-water, and quasi-static wave loading

2.1.2 Determination of the Loads

For the *spectral*-based fatigue approach, a rigorous process is undertaken to compute the seakeeping hydrodynamic loads. To accomplish this, MAESTRO exercises a linear seakeeping model based on either 3-D potential flow theory or 2-D strip theory; this is an end-user decision. A full explanation of the implementation of this theory, and in particular, the manner in which loads are transferred to the structural model resulting in equilibrium is presented in *Ma et al. (2012a,b)*.

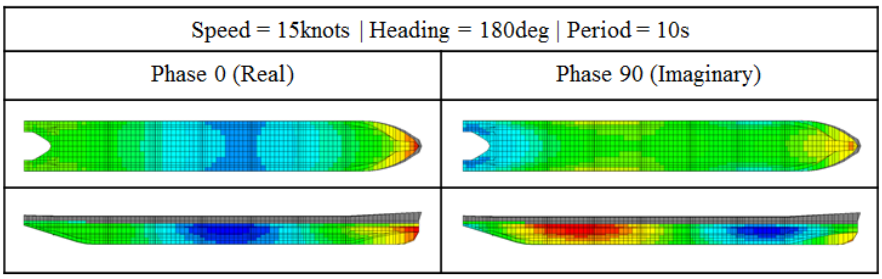


Fig. 4: Hydrodynamic pressure loads on global structural model

This theory is implemented as a plug-in component called MAESTRO-Wave. Because MAESTRO-Wave is a plug-in component, the MAESTRO model's wetted panel definition, evaluation patch definition, tank definition and weight distribution, are used to generate regular unit wave responses in the form of a database (i.e., exists as a separate *.smn file), which includes ship motions, accelerations and dynamic pressure acting on the hull for each speed, heading and wave frequency. For the computation using 3-D potential theory, the user has the ability to make use of three different wetted panel discretization methods: the original finite element mesh, the evaluation patch mesh, and the section based re-panelization mesh, for the linear seakeeping analysis. After MAESTRO-Wave generates the unit wave hydrodynamic load database, the hull girder load response RAOs, such as vertical bending moment, shear force and torional moment, as well as the element stress RAOs, can be obtained. The hull girder load response RAOs form the basis for conducting extreme load analysis while the element stress RAOs form the basis for conducting spectral fatigue analysis. This is computed in step 4 shown in Fig.1 and will be discussed in the next section. Fig.4 shows the real and imaginary components of the complex hydrodynamic loads transferred onto the MAESTRO structural model

2.1.3 Computation of Stress Range

After the database of complex pressures are computed (as described in the previous section), the next step for the designer is to compute the stress range distributions for each hydrodynamic case. However, prior to computing the stress range, it is necessary to find the stress transfer function (i.e., stress RAOs) for the entire global model as well as any fine-mesh models that may be included in the MAESTRO FEM. MAESTRO accomplishes this by decomposing the complex load vector into two vectors: the real component and the imaginary component, followed by conducting a finite element analysis for each component. This will establish the relationship between the stress in each element within the FEM and the wave frequency, heading, and speed for each base loading condition defined in step 2 of Fig.1. Depending on the number of base loading conditions and wave frequencies, headings, and speeds, the database that holds this information can become quite large. MAESTRO stores this information in a binary file called the *.sfa file.

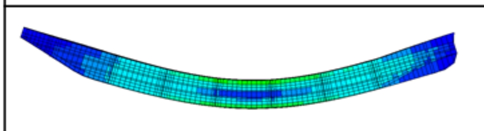
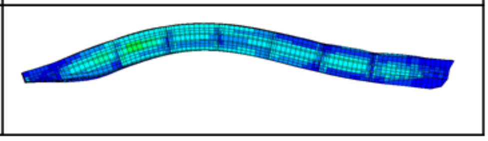
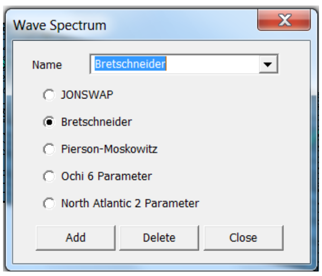
Speed = 15knots | Heading = 180deg | Period = 10s	
Phase 0 (Real)	Phase 90 (Imaginary)
	

Fig. 5: Stress transfer function FEA response

Once the stress transfer function is established, the next step is to incorporate wave data to generate the stress-range spectra. The wave data comes in the form of wave distributions as a wave scatter diagram as well as wave spectra. MAESTRO provides the option of choosing from five standard wave spectra: JONSWAP, Bretschneider, Pierson-Moskowitz, Ochi 6 Parameter, and North Atlantic 2 Parameter. Wave scatter diagrams can be chosen from a library incorporated into MAESTRO or the user can define a custom wave scatter diagram.



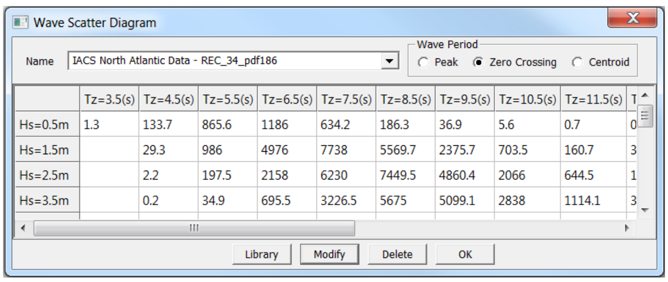


Fig. 6: MAESTRO wave data dialogs (Wave spectra and wave scatter diagram)

With this information defined by the user, MAESTRO can then perform direct integration of the stress range for each cell of the wave scatter diagram. Summed together, this produces a long-term stress range distribution for the global structure.

2.1.4 Computation of Fatigue Damage/Life

The final step in the procedure, step 5 in Fig.1, requires the user to define the operational profile, the exposure time, the particular structure to be screened, its associated S-N curves, and finally the stress concentration factor (SCF). The operational profile consists of the probabilities of speeds and headings at each wave height, as shown in Fig.7. The exposure time and the probabilities of speeds and headings together will provide the number of stress range cycles for a given cell in the wave scatter diagram. This information is defined in the MAESTRO Spectral Fatigue Analysis dialog, as shown in Fig.8.

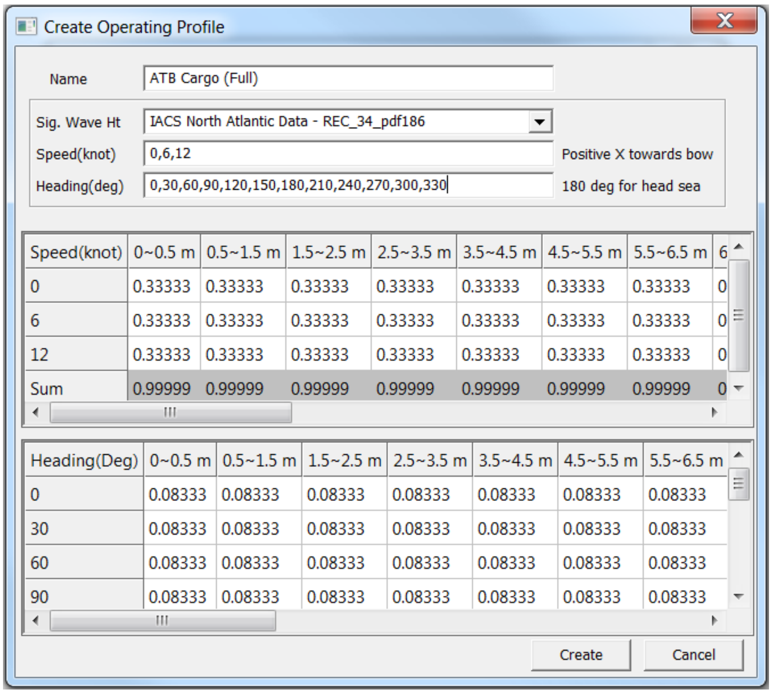


Fig. 7: MAESTRO operational profile dialog

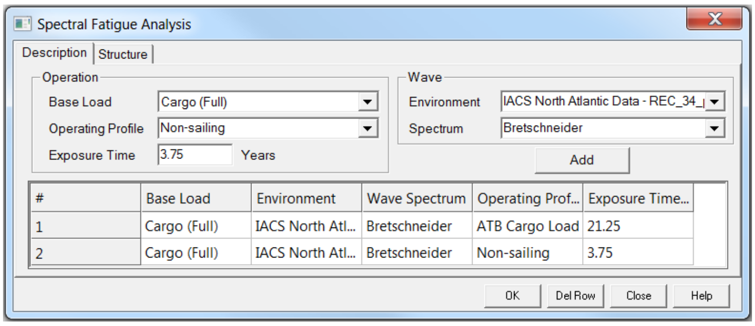


Fig. 8: MAESTRO spectral fatigue analysis dialog

Next, the user will select which portions of the FEM fatigue damage should be computed for. Here the user can select the entire global FEM, all fine-mesh FEM, or portions of the FEM. This is done by creating MAESTRO general groups of structure of interest. Once the user has defined these groups of structure, they can be collected in MAESTRO's Spectral Fatigue Analysis dialog where the user can associate the appropriate S-N curves and SCFs, as in Fig. 9. The S-N curves will define the fatigue strength of the structural component defined in the MAESTRO general group. In practice, the designer would typically begin with a single large area of structure to screen as opposed to the entire FEM all at once. For example, the designer may choose to first screen the main deck (or strength deck) within the 0.4L of mid-body. This step would inform the designer of the fatigue damage distribution throughout this portion of the hull structure. If the designer continues to add large portions of remaining structure in this manner, a true global fatigue damage screening model will emerge.

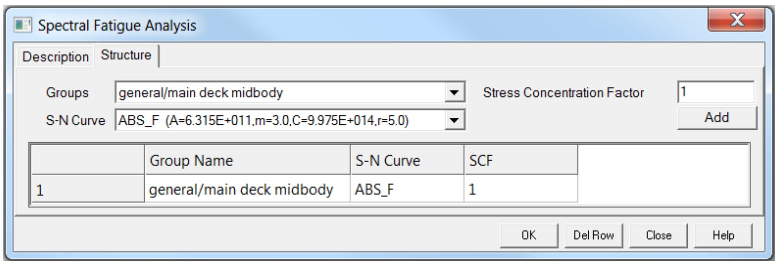


Fig 9: Associating structure groups with S-N Curves and SCFs

In the final step in the spectral-based global fatigue screening, MAESTRO uses the Palmgren-Miner's rule to compute damage. The Palmgren-Miner's cumulative fatigue damage rule assumes the cumulative fatigue damage (D) inflicted by a group of variable amplitude stress cycles is the sum of the damage inflicted by each stress range (d_i), independent of the sequence in which the stress cycles occur, *ABS (2007)*. Mathematically, this is expressed by the following equation:

$$D = \frac{T}{A}\left(2\sqrt{2}\right)^{m}\Gamma(m/2+1)\sum_{i=1}^{M}\lambda(m,\epsilon_i)\mu_i f_{0i} p_i (\sigma_i)^m \qquad (1)$$

where:

T =	design life, in seconds
m, A =	physical parameters describing the S-N curve
Γ =	complete gamma function with the argument (m/2+1)
λ =	rainflow factor of Wirsching
ε_i =	spectral bandwidth
μ_i =	endurance factor (between 0 and 1), measuring contribution of lower branch of damage
f_{0i} =	zero-up-crossing frequency of the stress response (Hz)
p_i =	joint probability of H_s and T_z
σ_i =	$\sqrt{m_0}$ for the *i*-th considered sea state

When the damage ratio is greater than 1, the fatigue capability of the structure in question is not acceptable. MAESTRO provides the user with the ability to plot the damage ratio (D) or the Fatigue Life, which is expressed as:

$$Fatigue\ Life = \frac{Design\ Life}{D} \qquad (2)$$

These results would be produced from this MAESTRO-based spectral fatigue screening method for typically hundreds (or thousands) of structural intersections depending on the elements included in the fatigue assessment group. The value to the designer comes in the form of the relatively short amount of time required to begin understanding the fatigue damage distribution via this global screening process. A timeline for this activity would entail generating the global FEM with base loading conditions (2-2.5 man-weeks) followed by performing linear frequency domain 3D panel hydrodynamic load computations (3 man-days). At this juncture, the engineer would begin to establish global fatigue screening groups and in effect begin the global fatigue screening process. In this amount of time, the designer would begin to benefit from a global view of the fatigue damage distribution.

2.2 Simplified Approach

As an alternative to a more extensive spectral-based fatigue assessment, many classification societies provide detailed guidance for performing simplified fatigue assessment, which serves to assess standard structural details as opposed to novel structural configurations or unusual wave environments. Further, this approach is used prior to detail design and provides the designer with insight regarding the structural system's measure against fatigue damage. The following section will describe a simplified approach as defined by the Common Structural Rules (CSR) for Oil Tankers that was developed by a group of International Association of Classification Societies (IACS) members, *IACS (2010)*. This fatigue assessment uses a nominal stress approach based on beam theory.

2.2.1 Generation of the Structural Analysis Model

The CSR simplified approach is based on beam theory; therefore, the analysis model can be thought of as simply the hull girder cross section. For this CSR procedure, the fatigue calculation is performed in two steps: (1) a simplified check of the hull girder section modulus compared to a required fatigue section modulus and (2) a fatigue life assessment of standard structural details.

The hull girder fatigue section modulus required is Z_{v-fat} [m^3] and is given in CSR Section 8.1.5:

$$Z_{v-fat} = \frac{M_{wv-hog} - M_{wv-sag}}{1000 * R_{al}} \ [m^3] \tag{3}$$

where:

M_{wv-hog} = hogging vertical wave bending moment for fatigue [kNm]

M_{wv-sag} = sagging vertical wave bending moment for fatigue [kNm)

R_{al} = allowable stress range [N/mm^2]

$R_{al} = 0.17 \cdot L + 86$ for class F-details (4)

The hogging and sagging vertical wave bending moments used for fatigue strength assessment are multiplying by a factor of 0.5, which accounts for the probability level of wave bending moments. This is described in CSR Section 7.3.1.2 and Section 7.3.4.1.3.

2.2.2 Determination of the Loads

As is the case with other industry-accepted simplified fatigue assessment approaches, the CSRs use parametric equations to determine the loads for use in fatigue assessment. These well-recognized parametric equations have no explicit relationship to the ship operations or the wave data that the ship will operate in. The hogging and sagging vertical wave bending moments for fatigue are M_{wv-hog} M_{wv-hog} and $M_{wv-saog}$ respectively as given in CSR section 7.3.4.1.3. However, the vertical bending moments calculated in CSR section 7.3.4.1.3 are for the life-time extreme and have an exceedance probability value of 10^{-8}, but for fatigue assessment purposes CSR uses a higher exceedance probability value (10^{-4}). This is accounted for using the parameter f_{prob} and is described in CSR section 7.3.4.1.3.

$$M_{wv-hog} = f_{prob} 0.19 f_{wv-v} C_{wv} L^2 B C_b \quad [kNm] \tag{5}$$

$$M_{wv-sag} = -f_{prob} 0.11 f_{wv-v} C_{wv} L^2 B (C_b + 0.7) \quad [kNm] \tag{6}$$

where:

f_{prob} = probability of exceedance factor (equal to 0.5 for fatigue analysis)
f_{wv-v} = distribution factor for vertical wave bending moment along vessel length
L = vessel length
B = vessel moulded breadth
C_b = block coefficient

2.2.3 Computation of Stress Range

The calculation of the hull girder stresses are attained through the use of simple beam theory. The application of simple beam theory is an expedient way of getting reasonable approximations of stress levels in the longitudinal hull girder. The hull girder stresses from simple beam theory have the following assumptions, *Glen et al. (1999)*:

- plane cross-sections remain plane;
- stresses remain in the elastic range and thus allow superposition;
- the beam is essentially prismatic (no openings or discontinuities; and
- there is no interaction between bending and other response modes (e.g., transverse and longitudinal deflections or shear and torsional distortions).

With the above simple beam theory assumptions, the nominal stress range can be calculated:

$$S_{Ri} = \frac{M_{wv-hog} - M_{wv-sag}}{Z_{v-net75}} \quad [\mathrm{N/mm^2}] \tag{7}$$

where:

$M_{wv\text{-}hog}$ = defined in Eq.(5)

$M_{wv\text{-}sag}$ = defined in Eq.(6)

$Z_{v\text{-}net75}$ = Net vertical hull girder section modulus of hull cross-section about transverse neutral axis. This is calculated based on gross thickness, minus the corrosion addition 0.25 t_{corr} of all effective structural elements.

The calculated stress range is assumed to have a long-term distribution that fits a two-parameter Weibull probability distribution. This assumption enables the use of a closed form equation to compute the fatigue life, *IACS (2010)*.

2.2.4 Computation of Fatigue Damage/Life

Assuming the stress range has a long-term distribution that fits a two-parameter Weibull probability distribution allows the fatigue damage ratio (DM_i) for the applicable base loading condition to be defined as, *IACS (2010)*:

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

where:

α_i = proportion of the ship's life

N_L = number of cycles for the expected design life

K_2 = S-N curve parameter as defined in CSR section C.1.4.5.5

S_{Ri} = stress range at the representative probability level of 10^{-4} [N/mm^2]

m = S-N curve parameter as defined in CSR section C.1.4.5.5

N_R = 10,000, number of cycles corresponding to the probability level of 10^{-4}

ξ = Weibull probability distribution parameter, defined in CSR section C.1.4.1.6

μ_i = coefficient taking into account the change in slope of the S-N curve, defined in CSR section C.1.4.1.4

Γ = Gamma function

Finally, the resultant cumulative damage is to be taken as:

$$DM = \sum_{i=1}^{2} DM_i \tag{9}$$

Where i = 1 for full load condition and i = 2 for normal ballast condition

3. Procedure Example

3.1 Vessel Description

The vessel analysed in this paper is an articulated tank barge (ATB), Table I. The deck, side shell, and bottom areas of the vessel are made of ABS Grade A steel, while the shear strake areas of the vessel's mid-body are made of ABS Grade D steel. The deck has a series of hatch openings outboard (both port and starboard) that are distributed through the length of the vessel.

Table I: Main characteristics of ATB

Length between perpendiculars Lpp	175.00 m
Moulded breadth B	22.50 m
Moulded depth D	12.20 m
Scantling draught T	8.90 m

3.2 MAESTRO *Spectral-based* Global Fatigue Screening

A global MAESTRO FEM was generated to properly represent the vessel's entire hull girder structure and main supporting members as well as the appropriate base loading conditions. In creating the global FEM, care was taken to choose nodes and elements to represent the stiffness and inertia properties of the hull structure, while keeping the size of the file to a manageable level (i.e., small data file), *ABS (2006)*. The FEM for this exercise is shown in Fig.2. Generally, a full MAESTRO model such as the one shown in Fig.2, with base loading conditions, can be generated by an experienced user in one to two weeks after the necessary input data (e.g., drawings, load distributions, etc.) is collected.

The next step was to generate a frequency loads database using MAESTRO-Wave's 3D potential theory approach (i.e., 3D panel code). As described in the previous section, the FEM wetted panels served as the MAESTRO-Wave hydrodynamic model and is shown in Fig.10. The matrix of hydrodynamic runs executed is shown in Table II and input via the MAESTRO-Wave setup dialog.

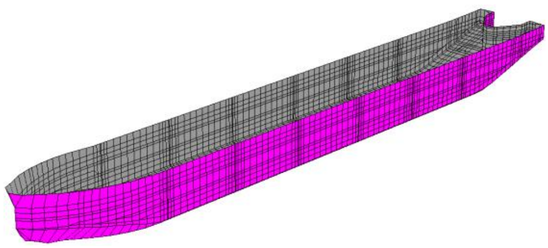


Fig. 10: MAESTRO-Wave panel model for hydrodynamic analysis

Table II: Matrix of hydrodynamic cases

Load Condition	Speeds (knots)	Headings (degrees)	Wave Frequencies (radians/second)
Full Load	0	0,30,…,330	0.2,0.3,…,1.8

Next, the process involved the establishment of the stress transfer functions for the database of frequency loads (both real and imaginary). Once this was established the computation of fatigue damage was initiated by defining the following: Wave Scatter Diagram (IACS North Atlantic), Wave Energy Spectra (Bretschneider), and Operating Profile (equal probabilities of wave headings and speeds). Per IACS guidance, the operating profile accounted for 85% of the life at sea. Finally, the procedure moved to deciding what portion of the structure was to be selected for fatigue damage screening (i.e., fatigue screening group) and the application of S-N data and exposure time. The parameters used for this exercise are captured in Table III. Table IV and Table V capture the fatigue screening group parameters and results respectively.

Table III: Spectral Fatigue Analysis Setup

Base Load	Environment	Wave Spectra	Operating Profile	Exposure Time
Full Load	IACS North Atlantic	Bretschneider	Equal Probabilities	21.25
Full Load	Not Applicable	Not Applicable	Non-sailing	3.75

Table IV: Global Fatigue Screening Group

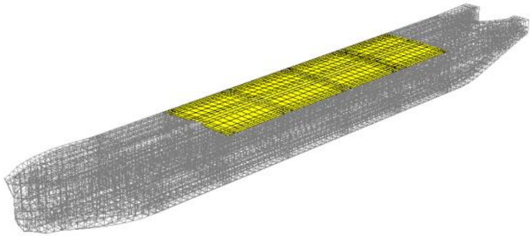
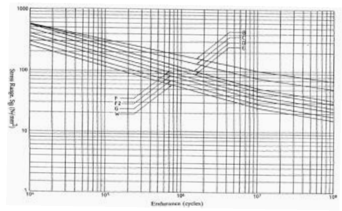
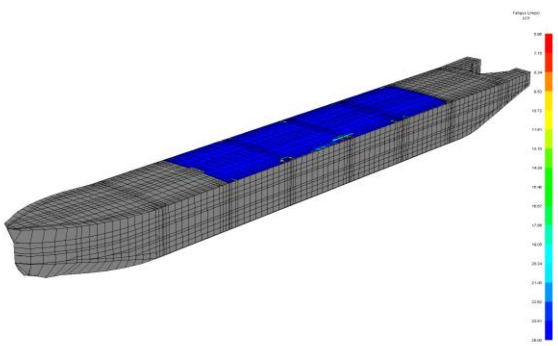
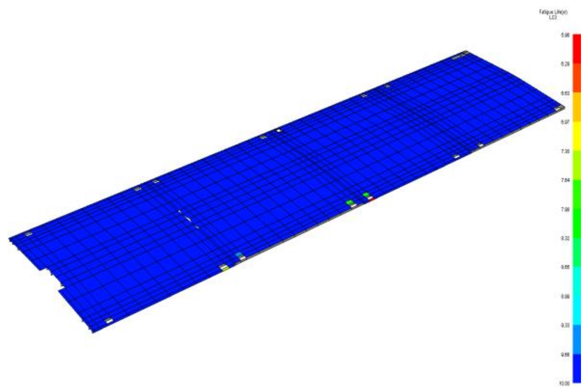
Screening Group	S-N Curve	SCF
	ABS Class F 	1.0

Table V: Global Fatigue Life Screening Results

Full Model Plot (< 25 years)	Fatigue Screening Group Plot (< 10 years)
	

3.3 *Simplified* Approach

Following the procedure discussed in the previous sections, the hull girder cross-sectional properties were calculated for a section of interest with the appropriate corrosion deduction, $Z_{v-net75}$, and compared to the required fatigue section modulus, Z_{v-fat}. Table VI and Table VII provide the input and results for Eq.(3).

Table VI: Input parameter to Z_{v-fat} calculation

M_{wv-hog}	546,158 [kNm]
M_{wv-sag}	-555,969 [kNm]
R_{al}	115.58 [N/mm^2)]

Table VII: Comparison of Z_{v-fat} and Z_{actual}

Z_{v-fat}	9.45 [m^3)
$Z_{v-net75}$	11.24 [m^3]

The stress range, which is computed using Eq.(7) and the input parameters from Table VI and Table VII resulted in 97 N/mm^2. Finally, using Eq.(8), the fatigue damage ratio can be computed. Table VIII provides the input parameters and results of this calculation.

Table VIII: Fatigue damage calculation input and results

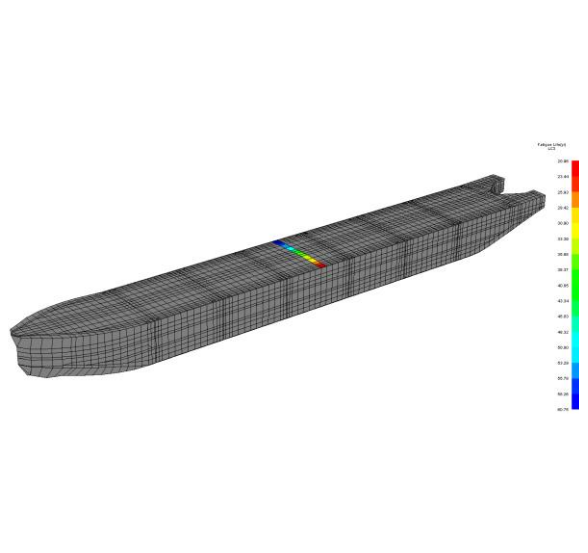
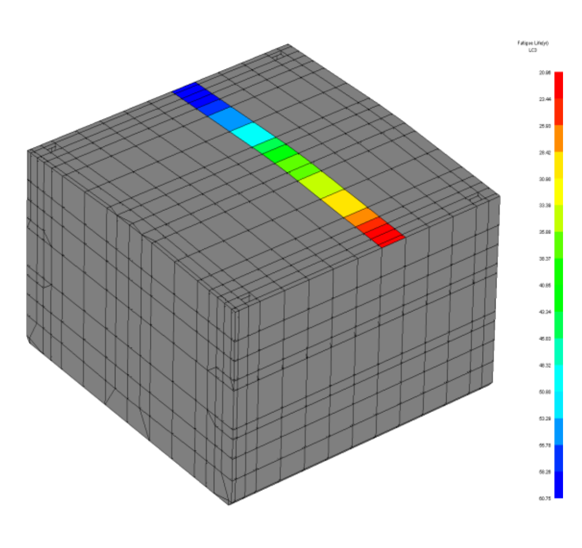
α_i	N_L	K_2	S_{Ri} [N/mm^2]	N_R	ξ	μ_i	DM_i	DM	Fatigue Life (years)
0.5	$7.48 \cdot 10^7$	$6.30 \cdot 10^{11}$	97	10,000	1.014	0.742	0.323	0.645	39

Note: S-N curve data, in-air for a Class F detail was used (see CSR Table C.1.6)

4. Contrast between Screening and Simplified

The following two sections summarize the MAESTRO Spectral-based Global Fatigue Screening and the Simplified approach in an attempt to provide a context to view each of these levels of fatigue assessment. It is obvious that a spectral-based approach is more robust due to the direct hydrodynamic loads computations and the consideration of operating profiles and wave environment data; however, it may be less obvious to the reader how accessible this procedure becomes in MAESTRO, making this approach very manageable and appealing to the designer. Overall, the results between the two approaches described in this example were comparable. As shown in Table VIII, the fatigue life for the simplified approach was 39 years. To compare these results to MAESTRO spectral-based fatigue analysis results, a fatigue screening group that collected elements within a single deck transverse *strip* was defined and fatigue life results computed. These results are graphically shown in Table IX and the fatigue life ranges from 20.96 years to 60.75 years. The range in fatigue life (in each element) is due to the asymmetric nature of the internal structure that was modeled and follows the stress distribution of a previously run static Full Load condition. On average, the fatigue life across this deck strip is 41 years. This fatigue distribution is something you can easily attain through global screening.

Table IX: Deck Strip Fatigue Screen (< 25 years)

Full Model Plot	Fatigue Screening Group Plot
	

4.1 Global Screening Approach

Global screening for fatigue provides the designer with a high-level assessment of fatigue damage and the distribution of fatigue damage in the hull structure. In this manner, the designer does not have to depend purely on the experience or guidance from classification society to determine on which particular areas to perform fatigue assessment. The designer would certainly review these areas, but the full global screening process described in previous sections provides the opportunity to find other areas that may be problematic. Further, after the hydrodynamic analysis step and the stress range computation step, this database is readily available for on demand fatigue analysis. This provides a practical and cost-effective way to bring spectral-based fatigue analysis into the early design stage of structural assessment. Although the determination of hydrodynamic loads, per step 3, can be computationally expensive, the increasingly large computing power of typical engineering PCs makes this a practical step to execute. Further, the analysis time required doesn't necessarily consume the engineers time as the processors are performing the computation. One can conclude that the major time expended for global screening is post-processing results and perhaps performing sensitivity studies and general effort with respect to the application of S-N curves, SCFs (if used), and other general parameters used for the analysis procedure. However, the time spent performing a global screening process should highlight potential problematic areas and provide an opportunity for the engineer to gain an improved understanding of the design's adequacy with respect to fatigue strength. The results also enable a mature starting point from which more detailed fatigue analysis of specific structural details can be conducted during design or during the ship's service life.

4.2 Simplified Approach

Many of the commonly used simplified ship fatigue analysis procedures are based on the same knowledge base and can be traced back to other non-marine or offshore standards. This knowledge base and existing standards have been applied with varying degrees of customization, detail, and interpretation, *Glen et al. (1999)*, by classification societies such ABS, DNV, GL and Lloyds. This approach makes use of simple beam theory for computing nominal stress in the hull girder and can be done so very easily very early in the design process. This procedure can be leveraged as part of the design evolution of the hull girder cross-sectional properties without much effort. The simplified approach has its merits in this regard and should be undertaken as a first data point for the designer.

5. Conceptual Integrated Life-Cycle System

Although fatigue analysis methods exist and have been utilized for many years, it is difficult to find them embedded in a comprehensive structural life-cycle framework system. This is not to suggest that such life-cycle systems do not exist; however, within the marine industry they largely reside only in the research and development community. For example, the U.S. Office of Naval Research is currently supporting a project at Lehigh University focused on the concept of an integrated life-cycle framework for ship reliability assessment, redundancy estimation, damage detection, and optimum inspection planning, *Frangopol et al.(2012)*. The notion of bringing together a full range of life-cycle analysis and management techniques into a set of linked technologies is nothing new. Ship Structure Committee (SSC) report SSC-427, illustrates how a complete set of analysis techniques can be linked to provide ship owners and operators with quantitative tools for design, construction, acquisition, repair, maintenance, and removal from service, *Dinovitzer (2003)*. However, these comprehensive tools aren't prevalent today. Even a key component to a life-cycle framework such as structural reliability still largely remains in the research community and not in practical ship design and assessment tools. These methodologies must find their way into practical tools that can be utilized by practicing naval architects even if all the necessary attributes aren't readily available.

For this, it is proposed that the MAESTRO software suite, which contains the necessary underpinnings for a structural life-cycle framework, can be used as a tool box from which to realize this vision of a user-friendly, practical, life-cycle assessment capability. By leveraging a tool that can contribute to the design process as well as the life-cycle assessment process, a single data model can be initiated and then populated and updated as the ship ages. Such an integration of external or 3rd-party technology is a concept that has been embraced by the MAESTRO software system from its inception and continues today. The core capability of MAESTRO is part of a larger open product model framework as shown in Fig.13 This open framework allows the interfacing (i.e., data input and data output) of MAESTRO with a variety of ship structural design and life-cycle assessment technologies for several technical domains including, but not limited to: Structural Life-cycle Assessment, Underwater Shock Assessment, Fatigue Analysis and Assessment, Hydrodynamic Loads Analysis, Ultimate Hull Girder Strength Assessment, and Ship Salvage Assessment. The implementation of a life-cycle system would represent an additional interface (or set of interfaces) with the MAESTRO open product model framework shown in Fig.11.

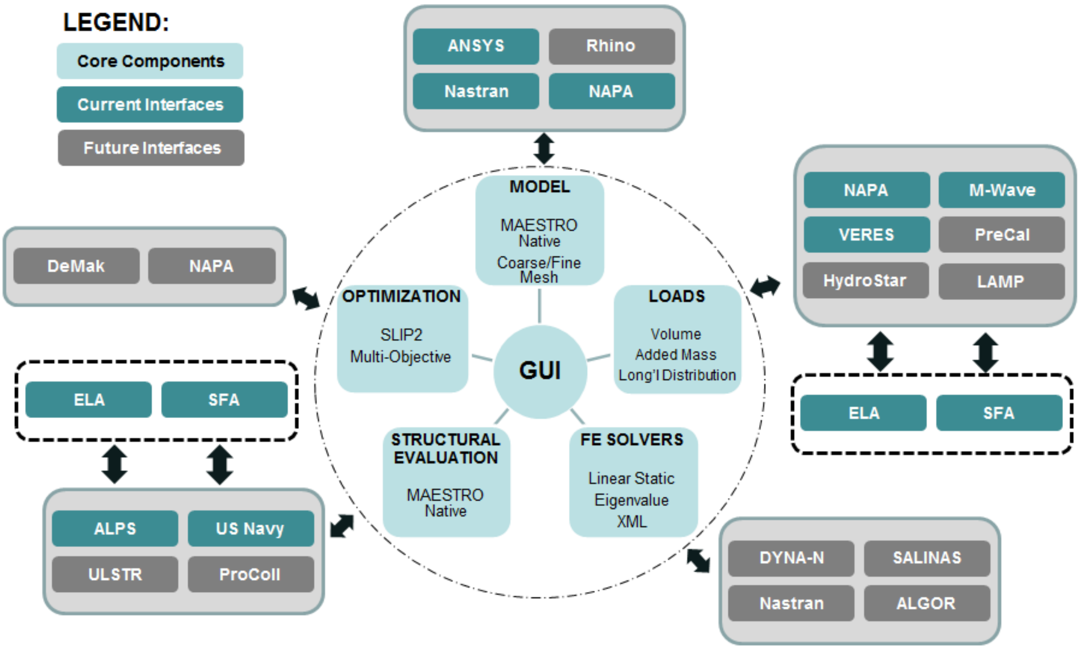


Fig. 11: MAESTRO Open Modeling/Analysis Framework

6. Conclusions

A primary limiting component for a ship's service life is the hull structure. In particular, a ship's fatigue life remains one of the major design issues naval architects are faced with in terms of how a design is initially assessed during early stage design, and what mitigating steps can be taken to control fatigue damage throughout the structural system's service life. To address this complicated subject, industry has implemented and exercised various long-standing approaches; however, many of these approaches are exercised during later stages in the design process, or after construction or even while a vessel is in service. Remediation of any issues that are found can be problematic and costly. Further these established approaches typically do not directly function within a larger structural life-cycle framework system as such systems still remain to a large extent only within the research and development community. Therefore, establishing an efficient and robust process that allows the naval architect to perform global fatigue screening of acceptable details in the primary hull structure early in the design process and throughout the service life is invaluable. Today, this can be accomplished by both designers and ship service-life manager who use the MAESTRO Spectral Fatigue Analysis technology.

In this respect, the benefits of performing global structural fatigue screening early in the design process should not be assumed to be small relative to the perceived complexity and required time for performing such a task. Dedicating three man-weeks of effort to *establish* an accurate initial understanding of how a ship structural system performs under fatigue demand is a small investment compared to the costs associated with *discovering* this during detail design or during the ship's in-service life. The lack of initial insight in this respect has the potential to also add to other costs such as repair and life extension activities.

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