Probabilistic lifetime predictions Using Total Stress Concept, Remote Monitoring & Global Wave Forecast Models

Fatigue Analysis of Damen's FCS5009 Vessels

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Probabilistic Lifetime Predictions Using Total Stress Concept, Remote Monitoring and Global Wave Forecast Models

Fatigue Analysis of Damen's FCS5009 Vessels

by

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Abstract

At Damen's Research and Development department, continuous improvements are made to existing design practices using recent technological developments and fatigue design is currently on the anvil. Damen high speed craft operating around the globe are subject to millions of load cycles (resulting from ocean waves) and therefore suffer from metal fatigue. As per current practice, such vessels are designed for fatigue using inhouse software with a nominal stress approach supported by static sea-state scatter data and judgement based operational profiles.

Recently, new data sources with real time sea-state data over the whole globe have come available. Damen also has got continuous access to the GPS locations of its ships. Together, this enables it to generate real time operational profiles for its ships. A total stress concept has been developed by J.H. den Besten [1] based on results from a JIP called VOMAS. This approach has shown to provide optimistic fatigue lifetimes for arc-welded aluminium joints. Similar results are expected for steel joints as well.

The main goal of this thesis was to explore possible improvements to fatigue design methodology at Damen. A tool called Tanaav was developed for this purpose which makes use of both remote monitoring data and the total stress concept and provides an estimate of the yearly fatigue damage and fatigue lifetime. The tool has been used to predict fatigue lifetime for three fatigue sensitive details in 46 FCS5009 vessels. Results have been compared to corresponding predictions using current and past fatigue analysis practices at Damen. It was observed that both remote monitoring as well as total stress concept lead to significant improvements in predicted fatigue life.

Damen was also interested in predicting fatigue damage in a probabilistic sense by incorporating uncertainties in fatigue influence parameters. This thesis proposes a method for this and presents two cases as a proof of concept. Work done in this thesis will be validated by Damen in future with the help of full-scale testing on actual FCS5009 vessel during an offshore measurement campaign. After validation, this method will help in improving the fatigue design practice at Damen, increasing design flexibility and in optimizing their vessel weights in a responsible way.

Preface

Prior to this research, I had mostly worked on design of fixed offshore structures and had negligible knowledge about the structural design of a vessel. This research provided me with the opportunity to expand my profile into floating structures. I learnt a lot about fatigue design concepts as well. In addition, it gave me an insight into the workings of a Damen as a company.

My contribution to this topic has been supported by some amazing professionals. First, I would like to thank Henk den Besten for answering my doubts in a pleasant way, and always being available for discussions. I learnt the most about fatigue design through his course Fatigue and Fracture. I would also like to thank both my current and interim company supervisors Don Hoogendoorn and Ewoud Huiskamp for facilitating my work by providing all necessary input data in a timely manner and also providing direction to my results. I also wish to thank Tim Cheung for helping me to filter the input data.

I would like to thank my girlfriend Narayani Deshpande for her help in presenting my references efficiently. I also would like to thank her for her patience with me, especially in the last week.

I would also like to mention my parents without whose support, I would not be here doing my graduation. I know that they would be very proud that I am about to complete my second Masters.

Finally, thanks to all my colleagues at TU Delft and Damen Shipyards for the fun I had during my graduation.

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Acronyms

ABS – American Bureau of Shipping

CDF – Cumulative Distribution Function

ESA – European Space Agency

FCS – Fast Crew Supplier

GoM – Gulf of Mexico

GL – Germanisher Lloyd

GWS – Global Wave Statistics

JIP – Joint Industry Project

JS – JONSWAP (Spectrum)

MoI – Moment of Inertia

MMSI - Maritime Mobile Service Identity number

PDF – Probability Density Function

PM – Pierson Moskowitz (Spectrum)

VOMAS – VermoeiingsOntwerpMethodiek voor snelle Aluminium Schepen[2]

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1
Introduction

Fatigue analysis is an important aspect of the design of vessels as associated failures can lead to costly maintenance or even catastrophic accidents. High speed craft can be vulnerable to fatigue damage due to many factors, such as an increased number of load cycles due to higher speeds, lightweight scantlings, operation is harsh environments etc.

As in the case of any design, fatigue analysis requires engineers to deal with uncertainties in the input data. This is done by using assumptions & simplifications and involving safety factors. This can in turn lead to increased requirements on plate thickness or weld quality which can add to the production cost as well as manufacturing time. So, it is beneficial to reduce the safety factors without reducing the reliability of the structure. This can be achieved by improving the accuracy of the analysis and by taking the governing variables into account thereby reducing the assumptions and simplifications.

This thesis investigates possible improvements to the fatigue lifetime predictions at Damen by making use of recent technological developments and state-of-the art research carried out at TU Delft in collaboration with Damen. In this study, a new method has been developed which can use data from remote monitoring data & global wave forecasting models as well as the Total Stress fatigue assessment concept. The method has been applied on 46 FCS5009's (a type of Fast Crew Supplier vessels) and the results have been compared with previous results to showcase how the new method compares to the old one.

Chapter 2 provides a brief background as to the relevance of and the reason for choosing this thesis topic. Chapter 3 outlines the thesis scope. Chapter 4 presents a theoretical background based on literature. Chapter 5 describes the features and flow of the new method, incorporated in a MATLAB tool (Tanaav). Chapter 6 details the various case studies carried out to answer the research questions. Finally, conclusions and recommendations are presented in Chapter 7 & 8 respectively.

2
Problem Definition

The FCS5009 is a type of Fast Crew Supplier Vessel used for operations such as transportation of personnel and cargo, patrols, safety stand-by etc. It is one of a wide variety of vessels manufactured by Damen Shipyards. This vessel has been selected for analysis because remote monitoring data for 46 such vessels has been recently acquired by Damen. A typical FCS5009 vessel is shown in Figure 1. Its hull is made of steel whereas superstructure is made of aluminium.

Figure 2.1: Photo of a typical FCS5009 Vessel[3]

Fatigue design is currently carried out at Damen using a MATLAB tool called Alufastship in conjunction with certain fatigue design guidelines [4]. Another tool called FLOAT is also available at Damen which calculates the fatigue damage using a spectral approach. Some recent developments, Damen wants to have an updated fatigue tool, as they believe it would improve their fatigue life prediction accuracy. Possible opportunities for improving the current method are as follows:

1. Data from Vessel Monitoring and Global Wave Forecasting models
2. Total Stress Concept
3. Probabilistic approach to Fatigue

These possibilities are briefly described below:

2.1 Vessel Monitoring Data

The rapid advancement of technology has significantly improved the methods of monitoring and tracking the ships in the recent past. The fast-developing satellite services have enabled the ship tracking across the globe easier now. Currently, several websites such as 'Marine-Traffic'[5] and 'FleetMon'[6] provide ship tracking using an Automatic Identification System (AIS) to display the real-time location of the ships. This gives companies like Damen access to real time locations, speeds and orientations of their ships.

Data from Marine-Traffic is used for this thesis. They provide following parameters for each ship position at a maximum rate of an update every two minutes:

1. Vessel Location (Latitude and Longitude)
2. Vessel Speed
3. Vessel Course
4. Vessel Heading
5. Timestamp (UTC)
6. Vessel Identification Number (MMSI)

During a data validation study carried out at Damen [7], it was found that coverage of AIS data was good and operational profiles were remarkable similar to GPS data.

Cost of purchasing this data is a function of the volume of records (datapoints) purchased. Two data sets with different sampling rates were used in this study. First data set is for 46 FCS5009 vessel with a sampling rate of approximately 1 data row per hour for a period of 2.5 years (2016-2018). Second data set is for 4 of the 46 vessels with a higher sampling rate of approximately 20 data rows per hour for the same duration. The grey in Figure 2.2 below shows the routes taken by 46 FCS5009 vessel during a period of 2.5 years (2016-2018).

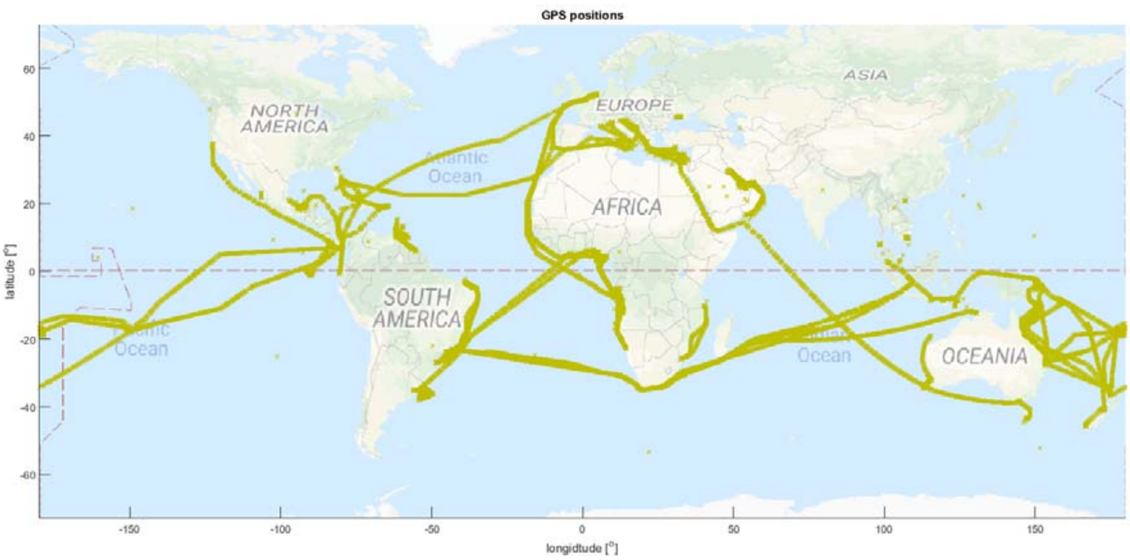


Figure 2.2: Routes for 46 FCS5009 Vessel from remote monitoring (superimposed using google maps)

2.2 Global Wave Forecasting Models

Since the pioneering development of wave forecasting relations by Sverdrup and Munk (1947) [8], operational wave analysis and forecasting has reached quite a sophisticated level. National Meteorological Services of many maritime countries now operationally use numerical wave models which provide detailed sea-state information at given locations. COPERNICUS is the European Program for the establishment of a European capacity for Earth Observation and Monitoring. It has a monitoring component which is based on data from its space component (ESA's Sentinels) and its In-situ component (maps, ocean buoys, ground based whether stations etc.). The Copernicus Marine Environment Monitoring Service (CMEMS) has become operational in May 2015. It provides following sea-state parameters at closely spaced grid points around the world at three hourly intervals:

1. Significant Wave Height,
2. Wave peak periods,
3. Spectral moments,
4. Dominant Wave Direction etc.

Combined with the location data from vessel monitoring system, this provides a reasonable estimate of the sea-states encountered by a vessel in real-time as well as for the past few years since it has become operational. So far Copernicus has shown very good accuracy in predicting significant wave heights and wave periods in the validations performed by Copernicus themselves and in also in validations performed by Damen over the past 1.5years [7][9][10]. Nevertheless, few cases were observed where wither the significant wave height or wave peak period did not match with other data sources especially for low significant wave heights. However, this may not affect the fatigue results much as sea-states with low significant wave heights have less energy and cause negligible hourly fatigue damage compared to higher sea-states. Figure 2.3 below shows the significant wave heights encountered by FCS5009 vessels along their route.

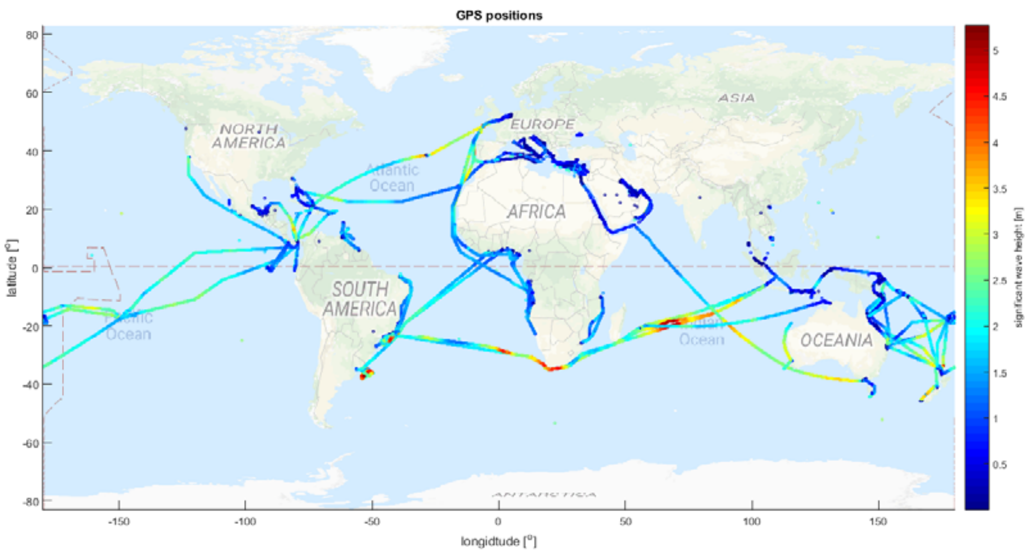


Figure 2.3: Significant wave heights along ship routes using wave forecasting models (superimposed using google maps)

2.3 Total Stress Concept

The current fatigue design practice at Damen (as well as industry practice) for welded joints involves either the nominal stress concept or the hot-spot stress concept, both of which have many drawbacks.

To improve this practice, the total stress (TS) concept was initially developed in a JIP called VOMAS, in which fatigue resistance of all aluminium welded joint details was combined in a single SN curve. The concept was validated with about 1000 aluminium welded joint fatigue resistance data points[1]. During the trials, it was also found that the fatigue life time estimate of welded aluminium joints using the total stress concept is significantly higher than in current fatigue design methods. The concept is currently being extended to steel joints and similar results are expected.

2.4 Probabilistic Fatigue Analysis

Fatigue crack development is a stochastic process and there are different kinds of uncertainty – physical variability, data uncertainty and modelling errors, associated with it. Despite this, the current design practice is to calculate fatigue damage as a deterministic accumulative phenomenon. The reliability level for each fatigue lifetime prediction is factored into the SN-Curve used for damage calculation. This approach may be able to capture the uncertainty on the resistance side. However, uncertainties in loading should also be included in the reliability of fatigue lifetime predictions. This can be achieved by treating fatigue damage as a random variable with a certain probability distribution. This will not only improve the accuracy of the analysis but also give the designer more control over the cost vs reliability level trade-off.

The goal of this thesis is to predict the probabilistic fatigue life distribution for 46 FSC5009 vessels based on real time vessel monitoring, global wave forecasting models and total stress concept.

3
Thesis Definition

3.1 Research Objective

The research objective of this study is to predict the probabilistic fatigue lifetime using total stress concept, remote monitoring and global wave forecast models.

3.2 Research Questions

The research questions of this thesis are:

RQ1: *How does the fatigue lifetime of a single-sided steel butt joint, on the deck of an FCS5009, calculated using the total stress concept compare with its fatigue lifetime calculated using total stress concept ?*

RQ2: *How does the fatigue lifetime of a single-sided steel butt joint, on the deck of an FCS5009, calculated using design operational profiles and sea-states compare with its fatigue lifetime calculated using vessel monitoring data combined with global wave forecasting model Copernicus ?*

RQ3: *How does hourly fatigue damage of a single-sided steel butt joint, on the deck of an FCS5009 vary with following fatigue influence parameters ?*

1. *Significant wave height and Wave Peak Period*
2. *Vessel Speed and Vessel heading with respect to mean wave direction*
3. *Plate thickness and bending stress ratio*

RQ4: *How do the CDFs of fatigue damage and fatigue lifetime of a single-sided steel butt joint, on the decks of FCS5009s compare with the deterministic fatigue lifetime predicted using current design practice at Damen ?*

3.3 Intermediate Steps

- To present the results of the improved fatigue analysis
- To compare the results of the improved fatigue analysis to results obtained with conventional methods
- To elaborate the improvements of the new method
- To highlight the ambiguities which remain in the new tool, providing directions for future work

3.4 Research Boundaries

The boundaries in this project mainly due to time constraint are:

- Only fatigue of steel welded joints is considered.

  The hulls of FCS5009 which are the main structural component are made up of steel, which makes this a valid limitation. In any case, the same method remains applicable to aluminium welded joints as well. In addition, the TS concept has already been applied to aluminium joints in previous work [11], so this would be an opportunity to apply the results of recent research on steel joints.

- Only linear global hull girder induced bending will be taken into account.

  Effect of shear forces, local water pressures and whipping are excluded. For FCS5009's, the contribution to fatigue damage due to these effects would be minimal due to the ship's slender design. Also, the sea-states considered in analysis have low to medium significant wave heights which further reduces the significance of non-linear load response effects.

- Total Stress Concept is only applied to toe-induced failure in single-sided butt-welded joints:

  Single-sided butt joints represent majority of weld length in vessels and are used as representative joints during preliminary fatigue analysis at Damen. Local geometry of such welds as per Damen drawings is such that root induced failure in the traditional sense is unlikely. Also, the total stress concept curve for steel is currently in developmental and has only been calibrated for single-sided butt welds.

4
Theoretical Background

4.1 Fatigue damage process

Metal structures, when subjected to repeated loading induces cyclic strains, become weaker and eventually develop cracks. If the repeated loading continues, the cracks grow through the member thickness. This phenomenon is called Fatigue. Local plasticity caused due to micro- and meso-scopic stress concentrations is the driving factor in fatigue crack initiation and growth. Metals have a polycrystalline grain structure with varied grain sizes, orientations and yield strengths. As a result, even an elastic far-field stress can lead to local plasticity which cannot be treated predicted deterministically.

Crack initiation is typically a near surface phenomenon. This is because the causes of micro stress concentrations such as persistent slip bands, corrosion, manufacturing defects and even far-field stresses (especially bending) are more pronounced near the surface.

Fatigue life of a member in a large structure is defined as the time it takes for the cracks to form and grow until fracture occurs. The initiation growth and propagation of fatigue damage is directly proportional to number of load cycles. The fatigue damage process can be divided into three phases, crack initiation phase, crack growth and propagation phase and fracture phase. (Refer Figure 4.1 below).

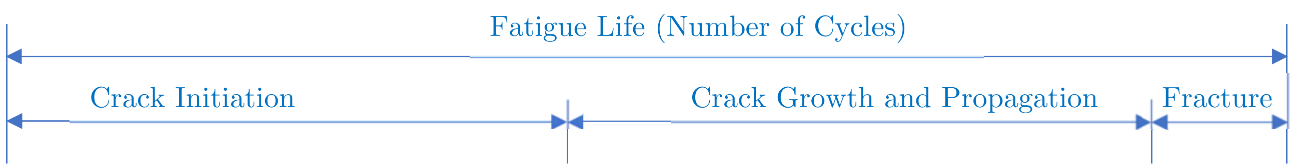


Figure 4.1: Fatigue life phases

The fracture phase is typically very short and can be safely neglected while calculating fatigue life. For a member without welds or discontinuities, the crack initiation phase is the longest and governing phase for fatigue life. Whereas for member with discontinuities and notches, the fatigue life is dominated by the crack-growth and propagation phase since the crack initiation phase is shortened due to higher local stress concentrations. A similar phenomenon is observed at weld-locations as welding introduces defects which again lead to higher local stress concentrations. As a result, fatigue damage in large structures normally accumulates faster at joints and discontinuities.

4.2 Fatigue Assessment Concepts

As explained, fatigue is a stochastic process which is too complex to accurately predict in real structures based on purely analytical procedures. Hence, fatigue life prediction methods are based on empirical results of fatigue testing done on representative samples. Stress based methods are most commonly used for designing structures for fatigue.

Joints in a real structure are classified as butt-joints, T-joints, cruciform joints etc. based on similarities in structural geometries. Constant amplitude cyclic loading is then applied to test specimen with similar geometry until failure. The number of load cycles required till failure is the fatigue life for that specimen. There are slight differences in geometry of multiple specimen, which leads to different number of cycles to failure even in experimental conditions. A stress vs cycles to failure curve (called as SN-curve) is then fitted to the results. The SN-curve is then applied to joints in real structures.

For actual structures such as ships, the cyclic load cycles are of varying amplitude. The generally accepted rule to design such structures for fatigue is called as the Palmgren-Miner's Rule where, each cycle with an amplitude S_i is considered to cause a damage equal to $1/N_i$, where N_i is the number of cycles to failure for constant amplitude loading cycles with amplitude S_i based on the SN-curve for that particular type of joint. The total fatigue damage, D is defined as follows:

$$D(t) = \sum_{i} \frac{n_i}{N_i}$$

where, ‘i' stands for all possible stress cycle amplitudes encountered by the structure in time t.

This neglects the sequence in which the stress cycles are encountered. This assumption is justified for fatigue damage due to random loading which does not have specific trends in the loading order. And for the case of ships, loading cycles are due to waves so this assumption is generally applicable.

The S-N curve can be based on various types of stress definitions. Some commonly used definitions for creating and using SN-curves for steel are briefly described below along with the recently developed total stress concept:

4.2.1 Nominal stress concept

In this approach, S-N curves are derived using specimen which are similar to real joints on a macro-scale. For this approach, structural details are classified based on their quality and configuration. Each detail is then represented by a unique SN-curve. This approach assumes that all welded steel has same fatigue life with the variation coming from stress concentration resulting from geometry and quality. It works well if the detail has similar stress pattern and imperfections to the test specimen. A major benefit is that it has low complexity and does not require much computational effort[12].

The drawbacks of this method are:

1. It is not always possible to find an SN-curve matching exactly with the detail as there are infinite possibilities.
2. Nominal stress is hard to define in case of complex geometries and loading patterns.
3. Effect of discontinuities and defects may not be captured correctly. (Design can be under as well as overconservative).

4.2.2 Structural hotspot stress concept

For this concept, the SN curves are based on stress at the possible crack location (typically the weld-toe). A stress concentration factor is defined at the crack location. The structural hotspot stress S_h is a fictitious stress derived by extrapolating the stress from extrapolation points. Location of extrapolation points and extrapolation method (surface extrapolation, through thickness extrapolation etc.) depends on geometry of the weld as well as the plate thicknesses [12].

The drawbacks for this method are:

1. In an FE model, the crack location is often a singularity and as such the stress at that location needs to be extrapolated based on stress values nearby. As a result, fine meshes are required near the crack location.
2. The stress concentration in the FE model may not accurately represent the stress concentration in the specimens as welds are idealised in FE models.

4.2.3 Total stress concept

Fatigue life of welded joints is governed by crack growth behaviour as crack initiation time is shortened due to welding-induced defects. Stress in the weld-notch cross-section is a superposition of an equilibrium equivalent stress and a self-equilibrating stress. The equilibrium equivalent stress is governed by the far-field stress whereas the self-equilibrating stress consists of a non-linear notch stress and the weld load carrying stress. Micro-crack growth is controlled by notch affected stress intensity whereas macro-crack growth is driven by far-filed affected stress intensity. The total stress concept is based on an equivalent structural response parameter, S_T developed using a two-stage crack growth model [1].

$$S_T = \frac{\Delta\sigma_s}{t_p^{(\prime)\,\frac{2-m}{2m}} * I_N^{\frac{1}{m}} * (1-r_l)^{1-\gamma}}$$

where,

$$I_N = \int_{\left(\frac{a_i}{t_p^{(\prime)}}\right)}^{\left(\frac{a_f}{t_p^{(\prime)}}\right)} \frac{1}{\left\{Y_n(\frac{a}{t_p^{(\prime)}})\right\}^n * \left\{Y_f(\frac{a}{t_p^{(\prime)}})\right\}^m * \left(\frac{a}{t_p^{(\prime)}}\right)^{\frac{m}{2}}} \, d\left(\frac{a}{t_p^{(\prime)}}\right)$$

This method was initially developed for aluminium welds. A single-slope, dual slope as well as random fatigue limit curve for aluminium were developed first. Coen de Korte compared the fatigue damage in a typical aluminium welded joint using nominal stress and total stress approach and found that damage using total stress concept was factor 10 lesser than damage calculated using nominal stress concept for that particular geometry [11].

Currently, a single-slope total stress SN-curve for steel has been developed based on fatigue tests carried out on T-joints, Cruciform joints and butt joints. The parameters of the SN-curve are given in table 4.1. Using these parameters an SN-curve can be generated corresponding to any reliability value. Figure 4.2 below shown the total stress steel SN curves corresponding to 50% and 99.7% reliability.

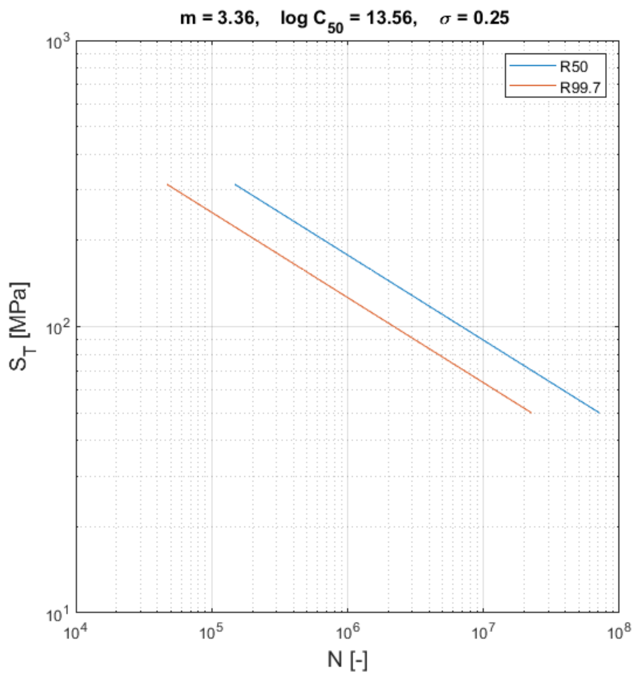


Figure 4.2: Single-Slope Total Stress SN Curves for steel

Table 4.1: Inputs for base case

Sr No.	Parameter	Value	Unit
1	m	3.36	-
2	log C	13.56	-
3	n	3.84	-
4	σ	0.25	-
5	γ	0.84	-

4.3 Fatigue Influence Parameters

Factors which can influence the magnitude of the fatigue damage at a detail in the ship are called as fatigue influence parameters in this thesis. The qualitative relationship between these factors and fatigue damage is explained below. The factors are divided into two types:

4.3.1 Environmental Parameters

These include factors which describe the sea-state being experienced by the ship. They are:

1. wave height
2. wave period
3. sea-state spectral shape
4. ship speed
5. ship's heading relative to the dominant direction of waves and
6. mass distribution along the length of the ship
7. moment of inertia distribution along the length of the ship

The ship is assumed to act as a beam floating in water. The global hull girder bending moment at any section along the length of the ship is due to opposing actions of water pressure and self-weight. The water pressure distribution is influenced by all the above factors except the last one, but it is most sensitive to the wave height and ship's heading relative to the dominant wave direction. The average stress in any cross section is directly proportional to the global hull girder bending moment at that section and inversely proportional to moment of inertia at that section. Another way in which these parameters influence the fatigue damage is that, the number of loading cycles is a function of the wave period (which affects the wave speed and wave length) and the vessel speed. The higher the wave frequency and vessel speed, the more would be the number of load cycles in a given duration.

All these factors can change with time (the mass distribution can change due to operational requirements and the moment of inertia can change due to shrinkage or plastic deformations accumulating over time). However, for the purpose of this thesis, mass and moment of inertia distribution are assumed constant with respect to time (except for the probabilistic fatigue part in which shrinkage is explicitly considered).

4.3.2 Geometry Parameters

Figure 4.3 shows the geometry used in this study.

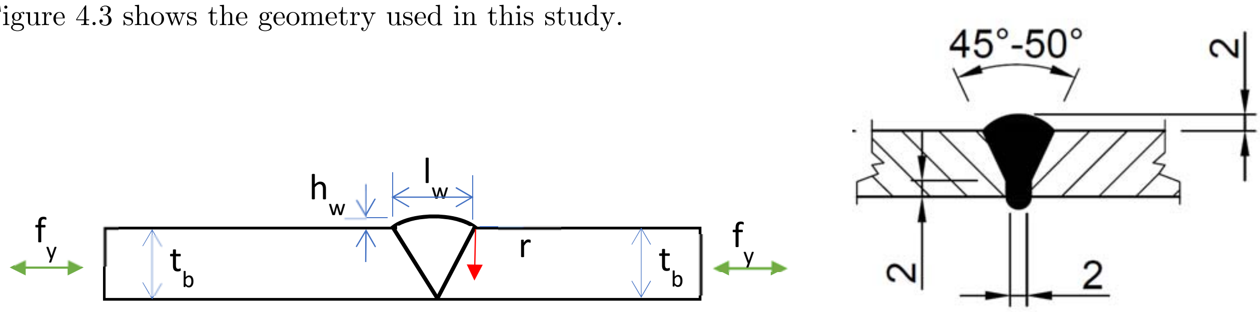


Figure 4.3: Full Penetration Single-sided Butt Weld geometry.

(left – as modelled in this study ; right – from Damen's welding manual)

Geometry parameters are the factors which are specific to the fatigue detail under consideration. They are given below:

1. Joint Type (T-Joint, Butt-joint, Cruciform Joint)
2. Weld Type (Single-sided or Double sided)
3. Penetration (Partial or Full)
4. Crack location (Toe or Root)
5. Plate thicknesses
6. Weld Dimensions (length, width, notch radius, notch angle, quality, inspection etc.)
7. Load Ratio (mechanical mean stress component)
8. Bending Ratio (ratio of bending stress to membrane stress)
9. Misalignment (both angular as well as offset)

In the nominal stress approach, factors 1 to 4 are to be considered in selecting the FAT class. Plate thickness is accounted for using an amplification factor. Weld dimensions per se are not addressed but weld quality and inspection are again a selection criterion to choose FAT class. Load ratio can be considered using a correction factor. Misalignments are included in the SN-curves up to a certain extent. Bending ratio is considered in the peak stress value or the SN-curve itself. All these factors are accounted for because all of them can influence the stress distribution and peak stress value at the notch location.

All these factors are assumed to be constant over time. Although they can only vary from detail to detail.

4.4 Fatigue Damage Calculation Methods

In practice, the design duration of a structure is divided into unit intervals (most commonly of an hour). The fatigue damage for that interval is then calculated, assuming environmental fatigue influence parameters to be constant, using one out of a variety of methods. The total fatigue damage is then calculated as a linear summation of all hourly fatigue damages in the design duration. The methods relevant for this thesis are described below:

4.4.1 Method used in Alufastship

Inputs four Hourly Damage Calculation:

- Significant wave height (Hs), in m
- Wave Peak Period (Tp), in s
- Vessel speed, in m/s
- RAO(ω)'s corresponding to vessel speed at transverse section where fatigue sensitive detail is located, in kNmm/m
- Section Modulus at the same transverse section(Z), in mm^3
- Stress Concentration Factor at fatigue sensitive detail (Kg), (no unit)
- FAT class for the detail according to GL 2004 guidelines.

Procedure:

It is assumed that the vessel encounters regular waves of constant wave height equal to the significant wave height at a relative heading of 180 degrees (waves coming towards the ship bow) for the entire duration.

Wave length and wave velocity are calculated from wave period using the deep-water dispersion relation ($\omega^2 = gk$) and wave speed relation ($v^2 = \sqrt{g/k}$). The relative speed of the ship with respect to the waves is summation of vessel speed and wave speed. The number of waves encountered by the ship is calculated by dividing the total time duration of an hour by the relative speed for the ship. The number of stress cycles is the number of waves encountered times a factor (0.5) to account for wave spreading and relative heading angles other than 180 degrees.

Note that the mean zero crossing period should ideally be used here instead of the peak period (although using the peak period seems convenient from a seakeeping perspective). RAO's to be provided at discrete frequency points.

Since waves on only 1 wave height and period are considered in the hourly interval, resulting stress cycles have a constant amplitude for each frequency, $\Delta\sigma(\omega)$ in MPa:

$$\Delta\sigma(\omega) = \frac{0.71 * RAO(\omega) * Hs * Kg}{Z}$$

0.71 is the irregular wave correction factor.

Once, the number of cycles of each stress range are known, the fatigue damage is calculated as per the FAT class using Palmgren-Miner's Rule. The SN-curves corresponding to all FAT classes provided in GL2004 are already provided in the tool.

4.4.2 Method used in FLOAT

Inputs four Hourly Damage Calculation: (Differences from Alufastship are highlighted in **bold**)

- Significant wave height (Hs), in m
- Wave Peak Period (Tp), in s
- **Wave Spectrum Type (PM or JS)**
- Vessel speed, in m/s
- **Vessel Heading, in degrees**
- RAO(ω)'s corresponding to vessel speed **and vessel heading** at transverse section where fatigue sensitive detail is located, in kNmm/m
- Section Modulus at the same transverse section(Z), in mm^3
- Stress Concentration Factor at fatigue sensitive detail (Kg), (no unit)
- Dual slope SN-Curve parameters ($\log C_1$, $\log C_2$, m_1, m_2)

Procedure:

FLOAT uses a spectral approach. It generates a unidirectional wave spectrum from the specified significant wave height and wave period using standard formulas for PM or JS spectrum as specified in the input. {Refer Appendix A for formulas}.

The wave spectrum is then transformed into a stress spectrum by multiplying with the square of the amplitude of the transfer function between wave height and stress amplitude, H(ω) which is calculated as:

$$\mathrm{H}(\omega) = \left|\frac{RAO(\omega) * Hs * Kg}{Z}\right|$$

The spectral moment and mean zero crossing period for the stress spectrum are then calculated using following formulae:

$$T_{0,\sigma} = 2\pi \sqrt{\frac{m_{0,\sigma}}{m_{0,\sigma}}}$$

where,

$$m_{i,\sigma} = \int_0^{\infty} \omega^i * S_\sigma(\omega) d\omega$$

The hourly fatigue damage is calculated using the following analytical formulation for a dual slope SN-curve.

$$D(t) = f_p \, . \, t \, . \left[\frac{(8m_{0,\sigma})^{\frac{m_1}{2}}}{C_1} \, . \, \Gamma_{upper}\left(\frac{m_1}{2} + 1; \sigma_t\right) + \frac{(8m_{0,\sigma})^{\frac{m_2}{2}}}{C_2} . \Gamma_{lower}\left(\frac{m_2}{2} + 1; \sigma_t\right) \right]$$

Where, σ_t is the stress at the slope transition or knuckle point defined by equating the number of cycles to failure using the two lines in the SN curve as follows:

$$\log(C_1) - m_1 log(\sigma_t) = \log(C_2) - m_2 log(\sigma_t)$$

Thus,

$$\log(\sigma_t) = \frac{\log(C_1) - \log(C_2)}{m_1 - m_2}$$

And,

Γ_{upper} and Γ_{lower} are incomplete conjugate gamma functions defined as:

$$\Gamma_{upper}\,(z, b) = \int_b^{\infty} (t^{z-1} * e^{-t})dt \;\; ; \quad \Gamma_{lower}(z, b) = \int_0^{b} (t^{z-1} * e^{-t})dt$$

This method does not require any factor to account for relative heading or irregular waves as both are accounted for in the method. However, directional spreading is not included in the generated spectrum. Hence, this might be thought of as a discrepancy in the method. But it is still a conservative assumption to neglect directional spreading of waves, especially when the relative headings themselves may not be the constant in the hourly interval.

4.4.3 Rainflow counting

The Rainflow-counting algorithm (also known as the rain-flow counting method) is used in the analysis of fatigue data in order to reduce a spectrum of varying stress into an equivalent set of simple stress reversals. The method successively extracts the smaller interruption cycles from the sequence. This simplification allows the fatigue life of a component to be determined for each rainflow cycle using Miner's rule to calculate the fatigue damage.

For this method, a time signal of the wave must be made according to the theory of random vibrations. Then using the rainflow count algorithm the number of fatigue cycles and their amplitude is determined. In the algorithm it is considered that not each following wave peak and trough is a cycle for the material, two large peaks that are separated further apart can form a large fatigue cycle. This method is used in this thesis as a reference for validating the analytical formulation for spectral fatigue analysis.

5

Modelling

5.1 Tanaav

A new MATLAB tool had been prepared during this thesis to study the effect of using remote monitoring and wave forecasting data combined with total stress concept on the fatigue lifetime prediction. The new tool is called as 'Tanaav'. The name originates from the Hindi words "Tana" meaning steel and "Naav" meaning ship and combined together "Tanaav" also means tension or stress.

Remote monitoring and wave forecasting models together can generate a sequence of loading intervals of the ship. The sequence can either be ignored and resulting load conditions grouped into bins or they can be retained and fatigue accumulation over time can be seen as a result. Both Alufastship and FLOAT were not deigned to use remote monitoring data and as such did not incorporate the sequence of occurrences of various load conditions in hourly intervals. Tanaav can retain the sequence of occurrences of various load conditions (sea-states and operational profiles).

In order to do this more efficiently, Tanaav calculates a 5-dimensional hourly fatigue damage table as an initial step so that damage calculation for similar loading conditions is not carried out only once during an analysis. The five dimensions of the damage table are fatigue detail number, vessel speed, vessel heading, significant wave height and wave peak period. In order to make this table, the tool lets the user decide the extents and intervals of each of the five dimensions. This is the main difference in analysis procedure of Tanaav as compared to Alufastship and FLOAT. This additional step of creating an hourly fatigue damage table may add to the computation time if the analysis needs to be carried out for short time durations, for example to calculate the damage for 1 year with hourly fatigue intervals. But this step can reduce the time significantly for a detailed analysis with say 3-min intervals for 15 years. Tanaav can generate the fatigue damage using both nominal and total stress approaches. Another positive is that Tanaav lets the user customize the intervals for wave heights as well as time periods. These features do not exist in previous tools.

The following flow chart shows the basic working of the new tool where you can see the two possible paths that the tool can take.

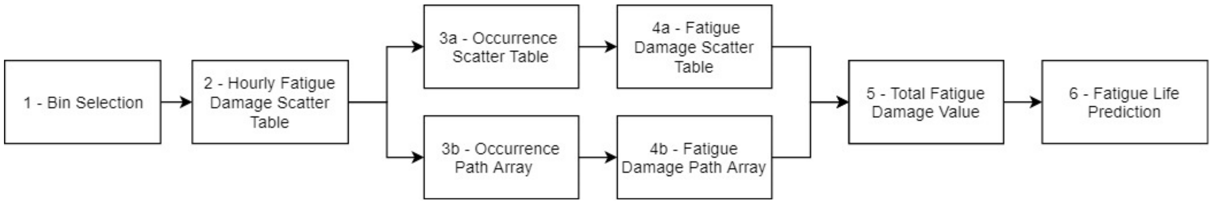


Figure 5.1: Basic Workflow Diagram for new MATLAB tool

This process is followed separately for each location of interest (hereafter called as 'detail') on the vessel.

A 'Bin' is a representation of a unique sea state in combination with a unique operational profile. For example, a bin could be defined with following parameter values:

Speed: *2.5 to 5 kn;* ***Heading:*** *15 to 25 deg;* ***Significant Wave Height:*** *1.5 to 2.5 m;*
Mean Wave Zero Crossing Period: *5.5 to 6.5 s*

First step is the initialisation or 'Bin selection'. In this the user would be able to decide the width and extents of each parameter and the total number of bins to be considered in the analysis. A default value is already provided in the tool. (Refer Table 1 for default parameter values used in the tool).

After the bins are decided, the next step is the calculation of hourly fatigue damage for each bin. For a chosen detail, the hourly damage is calculated and the damage values for each bin are stored in a 4-Dimensional scatter table. Till this point the calculations are hypothetical meaning the actual sea-states and operational profiles for design of from remote monitoring are not considered yet.

In the third step, the actual occurrences of each bin are counted either with ('b') or without ('a') preserving their sequence of occurrence in time.

The fourth step is just multiplying the hourly damage values for each bin with corresponding number of occurrences to get the total damage in each bin. Thereafter the damage in each bin is added together to arrive at the total damage. This is done in the fifth step. The duration is the summation of the total number of occurrences times the duration considered for each bin (an hour by default). Dividing the duration by the damage values gives us the predicted fatigue life time for the detail in the final step.

Module-I: Initialization
Module-I defines the Bins and various other input parameters.

Module-II: Expected Hourly Fatigue Damage Scatter Table (Loop)
Module-II calculates the expected hourly fatigue damage for each bin of all specified 'Details'. It has the following 6 submodules which are executed in a loop for each bin:

- A: Wave Spectrum
- B: Transfer Function from Wave Height to Nominal Stress
- C: Transfer Function from Nominal Stress to Total Stress
- D: Stress Spectrum and Spectral Moments
- E: Hourly Damage using Spectral Formulations
- F: Hourly Damage using Rainflow Counting (Optional – only for verification)

Module-III: Occurrence Counting
Module-III segregates the provided environmental data and operational profile into Bins (pre-defined in Module 1). The user can either choose to provide design data, path 'a' or remote monitoring data

associated with timestamps, path ‘b’. Design data would contain only the number of occurrences ignoring the sequence in which they would occur). Path ‘a’ would result in an occurrence scatter table whereas path b would result in an occurrence array.

Module-IV: Actual Fatigue Damage Scatter

Module-IV calculates the actual fatigue damage accumulated in each bin as a product of the expected hourly damage of a bin and the number of hours spent by the vessel in that bin during the period in consideration. Like Module 3, this module has two possible paths. In path ‘a’, the tool would compute only the design damage as in the total damage in each bin at the end of the specified design duration. In path ‘b’ the tool would additionally calculate how the fatigue damage accumulated vs time for the entire duration.

Module-V: Post-processing

Module-V calculates the total fatigue damage at the specified details and the corresponding design life prediction. It also generates relevant graphs and scatter diagrams.

A detailed explanation of all modules and work-flow for Tanaav is provided in Appendix C. Module II, which is the core module, is described below.

Module II calculates the expected hourly fatigue damage for each bin specified in module 1 for each detail. The module consists of multiple matlab script files which are run in a loop as through the main file called “LoopRunAll”. This is illustrated in flowchart below:

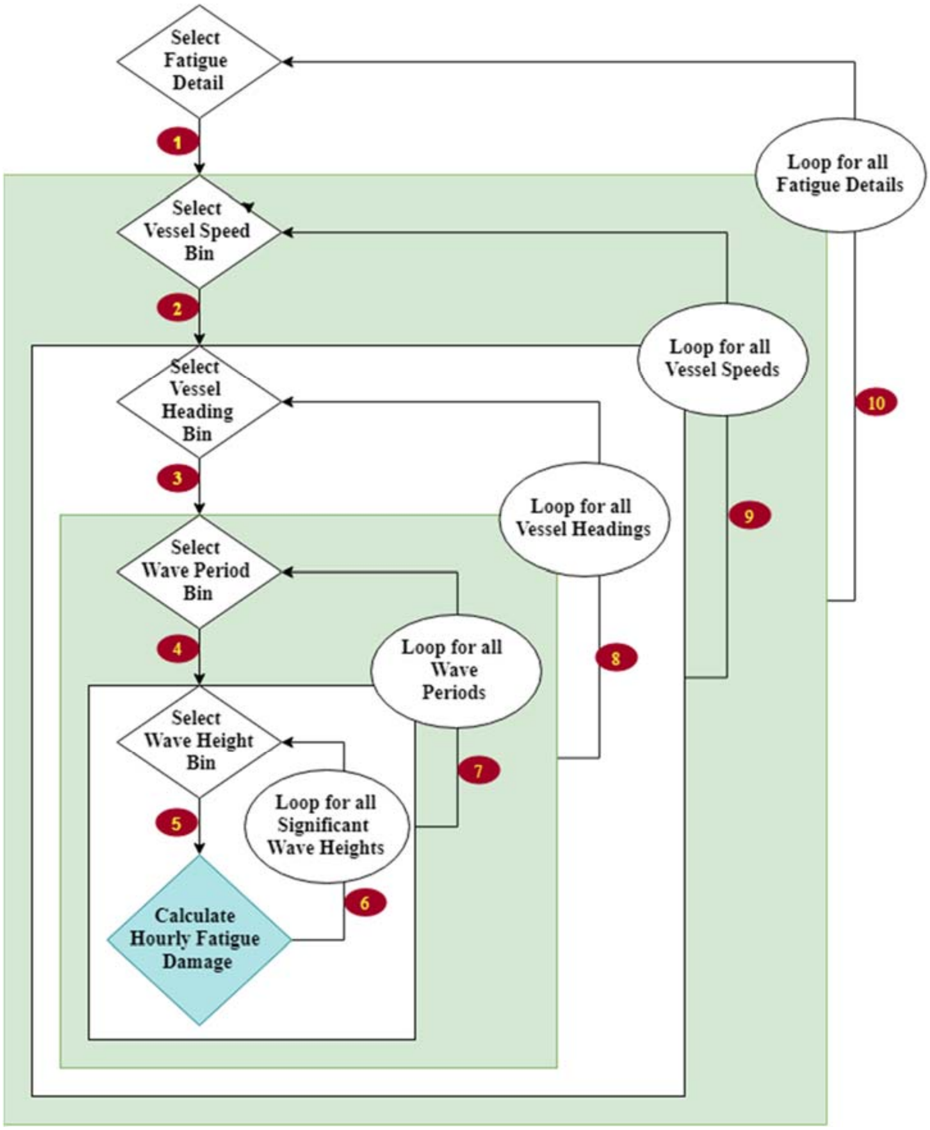


Figure 5.2: Flow Diagram for Module-II Loop.

The hourly fatigue damage calculation is broken up into 5 standard and 1 optional submodule.

The process to calculate the hourly fatigue damage is presented in figure below:

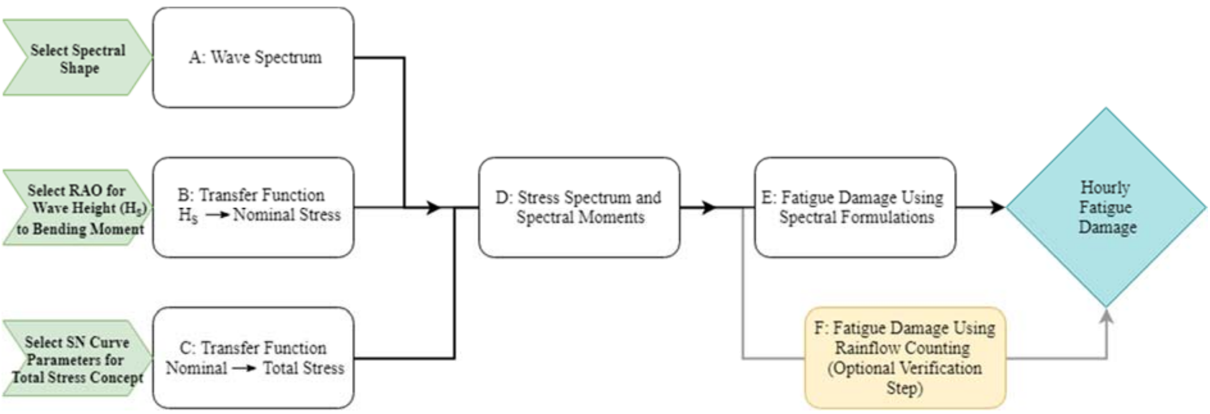


Figure 5.3: Flow Diagram for Hourly Fatigue Damage Calculation for 1 Bin.

Inputs required for this tool and their default values are shown in table 5.1 below:

Table 5.1: Inputs with default values

Sr. No.	Input	Default Values	Units
1	Bins for Speeds	0:2.5:25	kn
2	Bins for Heading	0:10:180	deg
3	Bins for Wave Periods	3.5:1:14.5	s
4	Bins for Significant Wave Heights	0.5:0.5:6	m
5	Spectrum Type	PM or JS	-
6	Frequencies for RAOs	0.05:0.05:2.5	rad/s
7	Location IDs for Fatigue Details	[“Loc^{XX}m” ()]	-
8	Section Moduli for Fatigue Details	[3.45E+8]	mm^3
9	SCFs for Fatigue Details	[1.5]	-
10	Filename for RAOs*	‘ReferenceRAOs.xlsx’	

^{XX} stands for the longitudinal distance from aft.

**The RAOs would be imported from a excel file.*

Each submodule is described below. It is also mentioned where and how the method differs from Alufastship and FLOAT.

5.1.1 Submodule II-A: Wave Spectrum

The module uses functions from a toolbox of MATLAB routines called “WAFO” [13] to generate a Pierson Moskowitz or JONSWAP Spectrum. Typical wave spectrums generated using this module are presented in Figure 5.4 below.

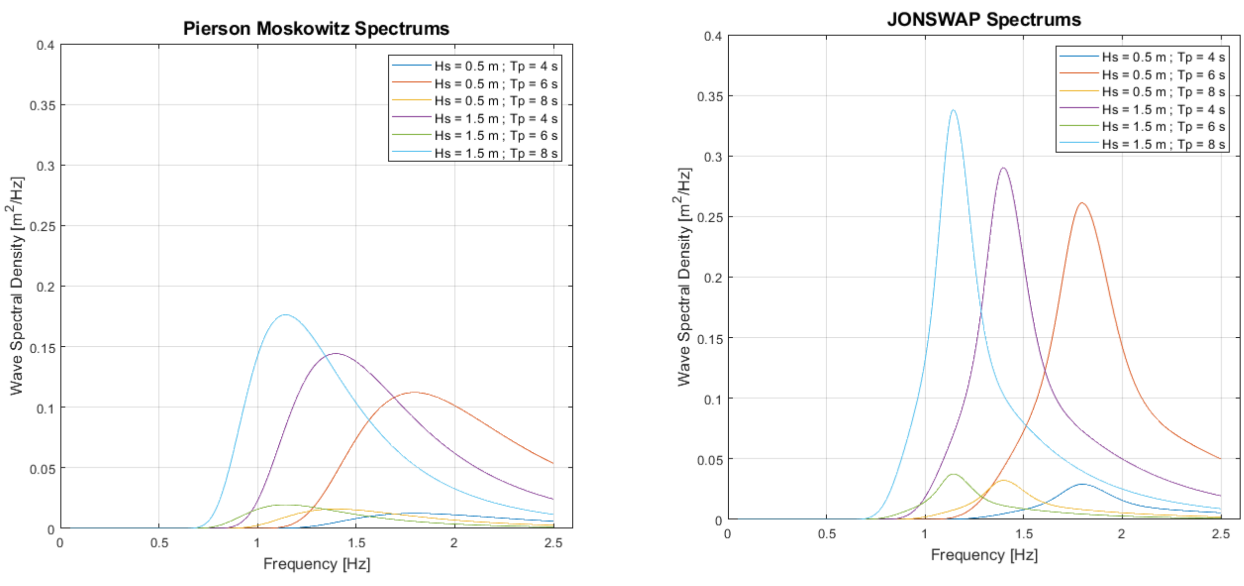


Figure 5.4: Typical wave spectrums generated by Module II-A of Tanaav

As mentioned earlier in section 4.5, Alufastship uses regular waves with a reduction factor (0.71) irrespective of the wave spectrum to be used, instead of generating a wave spectrum. FLOAT generates wave spectrums similar to Tanaav. This makes FLOAT and Tanaav more accurate than Alufastship. Tanaav and FLOAT are also more flexible in terms of being able to incorporate more types of wave spectrums in future.

5.1.2 Submodule II-B: Transfer Function from Wave Height to Nominal Stress

Following linear load response relationship is assumed for this calculation.

$$Nominal\ Stress(\omega) = \frac{RAO(\omega)}{Z} * K_g$$

Where,

Z is the section modulus at the cross-section,

ω is the radial frequency (RAOs are a function of radial frequency),

Results of FEM analysis can also be incorporated with the help of Stress Amplification Factor (Kg) which relates the average stress in a cross-section to the peak nominal stress at a fatigue sensitive detail.

Figure 5.5 below shows typical RAOs (generated by 'Qship') for varying values of vessel speed (V) and vessel heading relative to waves (θ).

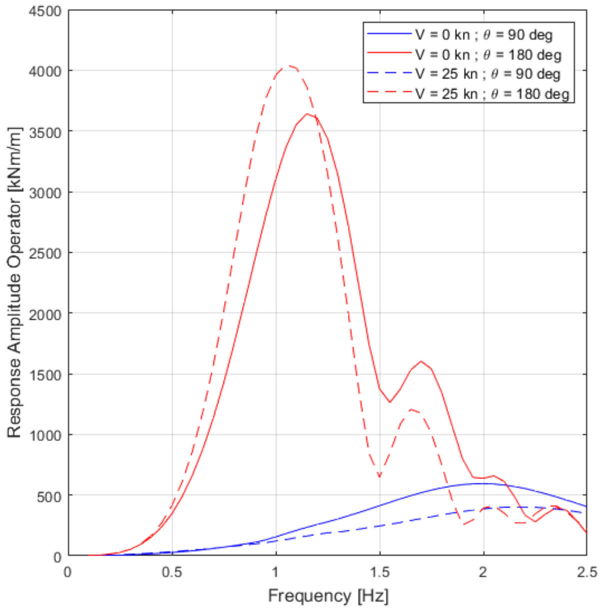


Figure 5.5: Typical RAOs generated in Qship to be used as inputs for Module II-B of Tanaav

Alufastship uses only the RAO value at the peak frequency of the spectrum instead of the entire RAO. FLOAT calculates nominal stress spectrum similar to Tanaav. Once again, this makes Tanaav and FLOAT more accurate than Alufastship.

5.1.3 Submodule II-C: Transfer Function from Nominal Stress to Total Stress

Nominal stress at a detail is taken as the far-field structural stress to estimate the total stress. The module uses MATLAB functions developed by Prof. Henk den Besten which are already available at Damen. The transfer function is calculated based on his research into the total stress concept. The formulae used in these functions are provided below for reference. The formulae used in this module are given in Appendix C. Figure 5.6 shows the geometry of the weld-cross-section used in this thesis. Figure 5.7 shows the stress distribution, notch factor and far-field factors calculated based on formulae given in Den Besten's PhD dissertation [1]. Plate and weld dimensions are chosen to match fatigue sensitive details on the deck of an FCS5009 vessel.

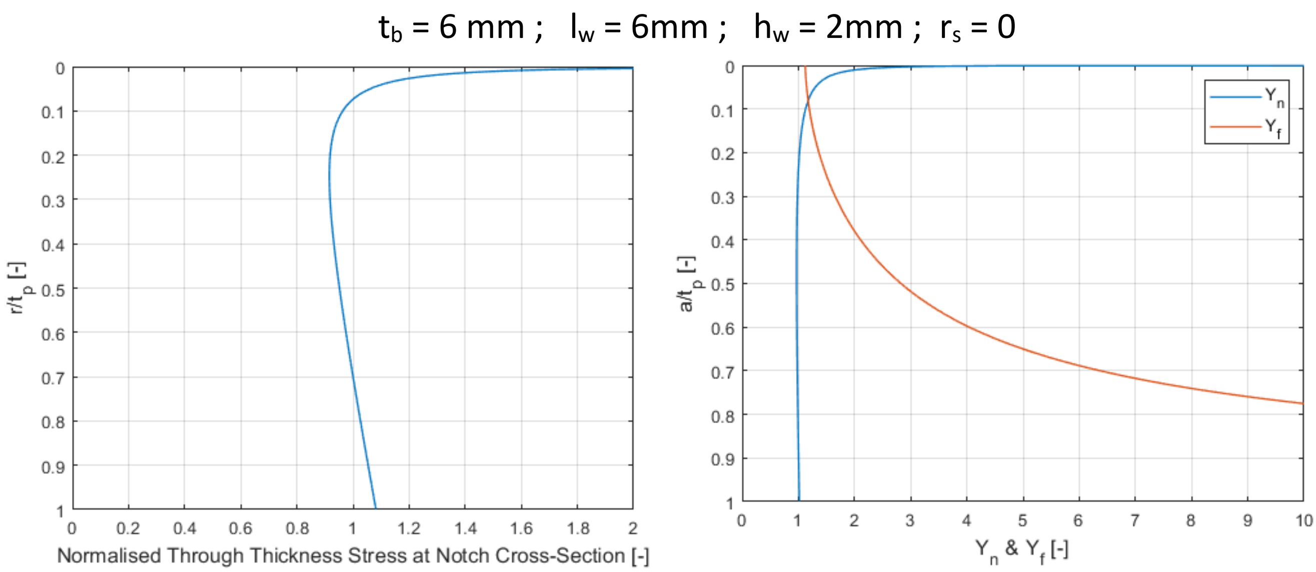


Figure 5.7: Analytical Weld Toe Stress distribution and corresponding notch factor and far-field factors

Bending stress (r_s) is assumed as zero as deck plates in such a vessel are designed mainly to resist normal stresses. Bending component should be marginal if spans are correctly designed. The weld load carrying coefficient was calculated using a formulation developed recently by Yanxin Qin as a part of continuing research on the Total Stress Concept under Den Besten. The formulation is also provided in Appendix C.

The tool is designed to handle only single sided butt welds connecting plates of similar thicknesses as the formulations for C_{bw} and the Total Stress SN curve data (m, C, n, σ and γ) are available only for such a joint. Remaining joints can be incorporated as and when data becomes available for them. Other types of joints such as T-joints, Cruciform joints etc. would be included in later versions of the tool.

Total stress approach is more accurate than nominal stress approach in the sense that it takes into account full stress distribution which including the size effect, mean stress effect, the notch affected as well as far field affected crack growth behaviours. Total stress concept is not a part of either Alufastship or FLOAT. Tanaav can calculate fatigue life based on nominal stress as well as total stress approaches. Thus, Tanaav is a definite improvement in this aspect.

5.1.4 Submodule II-D: Stress Spectrums and Spectral Moments

Wave spectrum generated previously is transformed into nominal and total stress spectrums in this submodule by multiplying them with square of amplitude of transfer functions. Spectral moments and corresponding mean zero crossing wave periods and expected number of waves in an hour are also calculated.

Alufastship takes the expected number of waves as inverse of peak period. FLOAT calculates it similar to Tanaav. One issue still pending with this method is that the resulting stress spectrums and expected waves per hour needs to be corrected for the vessel velocity. Another issue is that neither FLOAT nor Tanaav take into account wave spreading. 3D wave spectrums should be used in place of 2D wave spectrums. These will need to be addressed in future versions. For now, not including wave spreading is ok as it gives conservative results.

5.1.5 Submodule II-E: Hourly Damage using Spectral Formulations

This submodule uses the spectral moments calculated in the previous submodule as well as SN curve data provided as input to estimate the hourly fatigue damage using spectral formulations available in literature for narrow banded spectrums [14].

Formulae Used:

<u>Double Slope Nominal Stress Curve Damage:</u>

$$D(t) = f_p \,.\; t \,.\left[\frac{(8m_{0,\sigma})^{\frac{m_1}{2}}}{C_1} \,.\; \Gamma_{upper}\left(\frac{m_1}{2}+1;\sigma_t\right) + \frac{(8m_{0,\sigma})^{\frac{m_2}{2}}}{C_2} \,.\, \Gamma_{lower}\left(\frac{m_2}{2}+1;\sigma_t\right)\right]$$

Where, σ_t is the stress at the slope transition or knuckle point defined by equating the number of cycles to failure using the two lines in the SN curve as follows:

$$\log(C_1) - m_1 log(\sigma_t) = \log(C_2) - m_2 log(\sigma_t)$$

Thus,

$$\log(\sigma_t) = \frac{\log(C_1) - \log(C_2)}{m_1 - m_2}$$

And,

Γ_{upper} and Γ_{lower} are incomplete conjugate gamma functions defined as:

$$\Gamma_{upper}(z,b) = \int_b^{\infty} (t^{z-1} * e^{-t})dt \;;\quad \Gamma_{lower}(z,b) = \int_0^{b} (t^{z-1} * e^{-t})dt$$

Single Slope (Steel) Total Stress Curve Damage:

$$D(t) = f_p \; . \; t \, . \frac{(8m_{0,\sigma})^{\frac{m}{2}}}{C} \; . \; \Gamma(\frac{m}{2} + 1)$$

where,

Γ is the complete gamma function defined as:

$$\Gamma(z) = \int_0^\infty (t^{z-1} * e^{-t})dt$$

Alufastship uses regular waves to calculate fatigue damage and hence does not require using spectral formulations. FLOAT uses only the dual slope formulation for nominal stress approach. Tanaav has both the dual slope as well as single slope formulations. It also has a multi-slope formulation for cases where a Random Fatigue Limit model needs to be applied.

5.1.6 Submodule II-F: Hourly Damage using Rainflow Counting

Rainflow counting is a slow (heavy on computation) but more accurate and transparent method to calculate hourly fatigue damage. Hence, this module was added to calculate the hourly fatigue damage using Rainflow counting for the same inputs as the previous module. This module is optional as increases the computation time significantly especially when the number of bins is high. It can be used for verification during development stages of the tool and turned off during later use to make the tool more efficient.

The module generates a stress time series for a 3-hour duration and calculates the number of occurrences for predefined stress intervals to calculate the 3-hourly fatigue damage which is divided by 3 to an accurate hourly fatigue damage.

Formulae Used:

Frequency domain to Time domain

$$\eta(t) = \sum_p a_p \cos(\omega_p t + \varepsilon_p)$$

Where,

$$a_p = \sqrt{2S(\omega_p)\Delta\omega}$$

$$\varepsilon_p = \; rand(0{,}2\pi)$$

Time domain to Frequency domain

$$A_p = \frac{2}{T} * \int_0^T \eta(t) * \sin(\omega_p t) \; dt$$

$$B_p = \frac{2}{T} * \int_0^T \eta(t) * \cos(\omega_p t) \; dt$$

$$S(\omega) = \frac{1}{2\Delta\omega}\{A_p^2 + B_p^2\}$$

A frequency range of 0 to 2.5 rad/s with an interval of 0.05 rad/s is used to generate the time series. Both the frequency range and interval can be customised by the user. Also, the time series generated as a result is converted back to the frequency domain to and plotted against the initial spectrum to observe the match between the input stress spectrum and the resulting time series.

All 6 subroutines of Module II together lead to estimation of the hourly fatigue damage of a bin given seastate information, operational profile, corresponding RAO and local details of the joint. Thus, by running these subroutines in a loop, a 5-Dimensional Fatigue Table is generated with each value corresponding to the hourly fatigue damage of a unique Bin of a Fatigue Detail. Rainflow counting is not possible in either Alufastship or FLOAT.

To summarize, Tanaav extends the hourly fatigue damage calculation method used in FLOAT to total stress concept and makes it compatible with remote monitoring data.

The drawbacks in the tool are:

- it has only been tested on single-sided butt joints for total stress.
- it does not have a GUI (yet)
- it is not able to generate histogram plots of damage vs stress range as fatigue damage is calculated using analytical spectral fatigue formulations.
  drawbacks in the tool

5.2 Probabilistic Fatigue

The current fatigue analysis method used by Damen estimates one value of fatigue damage in the considered duration or inversely estimates one values of the required section modulus to satisfy the design life. In both these cases, the calculations are based on a certain reliability level which is incorporated mostly in the SN-curve. An additional safety factor is also used but it is based on engineering judgement and is not supported by probabilistic calculations. This is the also the industry practice. However, this method does not provide enough insight into the relative level of reliability at various details. It also restricts the designer from choosing a higher or lower level of reliability depending on the criticality of a certain detail.

Most of the inputs considered for a fatigue analysis are stochastic and have inherent uncertainties. These uncertainties can be either Aleatory – that is depending on chance or Epistemic -meaning related to knowledge (validation). Fatigue analysis accuracy can be improved by taking this into consideration. Also, such a method will give more flexibility to designers and help in ensuring similar reliability levels for various analysis. A probabilistic fatigue analysis method is proposed as an added feature.

If we assume the use of total stress concept as well as Palmgren Miners rule for damage calculation, then following inputs are required for fatigue analysis (Ref Figure 5.8).

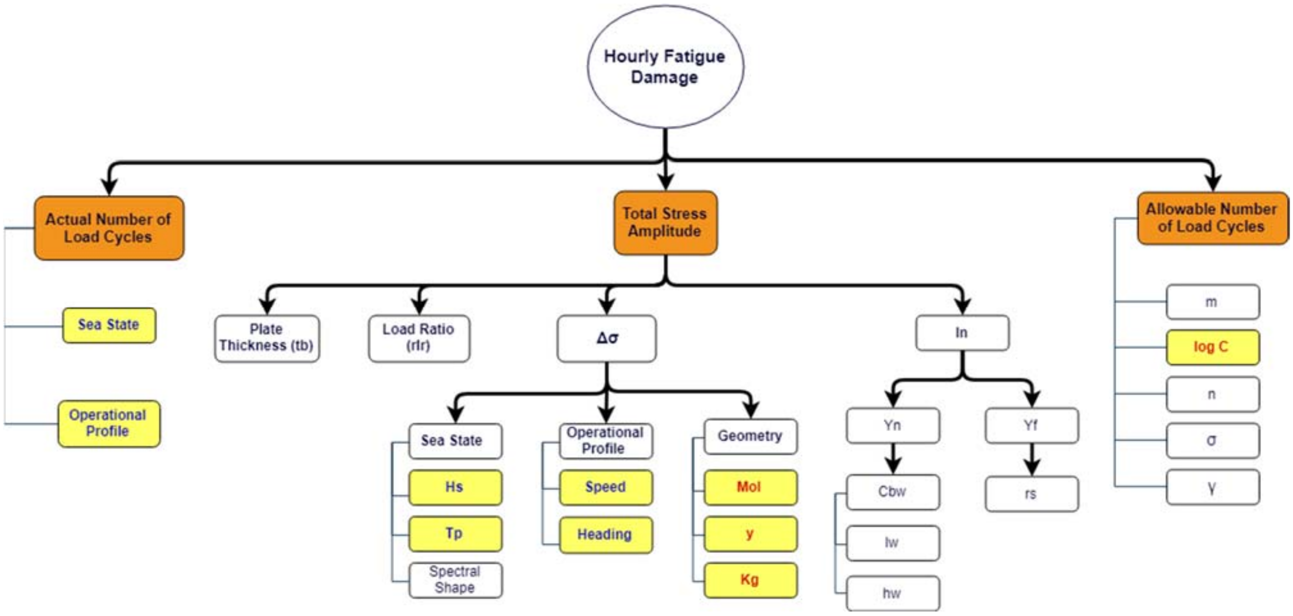


Figure 5.8: Inputs for Fatigue Damage Calculation for an arc-welded joint on a vessel like FCS5009.

Each of these inputs can have a probability distribution instead of a deterministic value. Only a few of these uncertainties have been included in this study. The values in red are considered for hourly damage calculation and uncertainties in blue values are considered in yearly damage calculation using remote monitored data and wave forecast models. The remaining inputs are kept deterministic. The goal here was to illustrate how input uncertainties can be handled to generate a cumulative distribution for fatigue damage instead of a single value.

Monte Carlo simulations are used to generate a range of fatigue damage values corresponding to pre-set levels of reliability. Section 6.6 describes a case study using this module.

Procedure:

This procedure is an extension to the hourly damage calculation procedure described in section 5.1 (Refer figure 5.2). Instead of calculating one value for hourly fatigue damage of a bin by using a deterministic value for each input, a CDF is calculated for hourly fatigue damage of each bin by using CDFs of uncertain input variables to generate large number of (1000) samples for each uncertain input variable using inverse transform sampling.

For e.g. if a random number has a given CDF, a sample value of the random variable can be generated by taking a random seed value from a standard uniform distribution (between 0 and 1) and taking the value of the random number corresponding to a probability equal to the seed value from its CDF.

After calculating the hourly damage values of each bin as a CDF, the CDF of the total damage is simply a summation of CDF of each hourly damage value encountered by the vessel during its lifetime.

6
Case Studies

6.1 Nominal Stress vs Total Stress Concept

A transverse single-sided butt weld on the deck of an FCS5009 vessel has been analysed using both the nominal stress and total stress concept. GWS scatter data for Gulf of Mexico and DNV-3 sea-state specified in Damen guidelines are chosen for analysis. GoM sea-state was chosen because FCS5009s were originally designed for the GoM region. Both sea-states are cut-off at 2.5m significant wave-height as per Damen Guidelines for High Speed Craft. Operational profile is assumed as per current Damen Guidelines [4]. The inputs used are presented in table below:

Table 6.1: Inputs for Case Study 1

Sr. No.	Parameter	Value	Unit	Remark
		Inputs - Environmental		
1	Design Lifetime	15	*years*	5000 operational hours/year
2a	Seastate scatter data (Case 1)	GWS scatter data for GoM	-	Wave Height restricted to 2.5m as per reference report
2b	Seastate scatter data (Case 2)	DNV-3	-	
3	Type of Wave Spectrum	JONSWAP		-
4	Vessel Speed Distribution	10 (30% time) 17.5 (20% time) 22.5 (50% time)	*kn*	As per Damen Guidelines for HSC
5	Vessel Relative Heading	180 (100% time)	*deg*	0.5 factor for Heading & spreading
6	Vessel Displacement	50% Consumables with Deck Load	*T*	Total Displacement = 468 T (including lightship weight of 250 ton)
7	RAOs for hull girder bending moment from wave height	Refer Appendix B]	*kNm/m*	RAOs generated using 'Qship ' (strip theory)
		Inputs – Geometry & SN Curve		
1	Detail Type	Single-sided Butt Weld	-	
2	Detail Distance from Aft	28	*m*	This influences which RAO to use.
3	Stress Concentration Factor	1.48	-	From FEM (y = 2.35 m; Iref = 8.11+E11 mm^4)
4	SN Curve for Nominal Stress	FAT 71	-	Assuming toe notch failure (GL2004)
4	SN Curve for Total Stress	Single Slope Steel	-	$m = 3.36$; $C = 13.56$; $n = 3.84$; $\sigma = 0.25$; $\gamma = 0.84$; $a_i/t_p = 1.0$
5	Local Geometry Dimensions	$t_b = 6$; $l_w = 5.73$; $h_w = 2$	*mm*	$r_l = 0.5$; $r_s = 0.0$

The results of the comparison are given in Table 6.2 below:

Table 6.2: Results of Case Study 1

Sr No	Stress Concept	Operational Profile	Sea State	Yearly Fatigue Damage (-)	Predicted Fatigue Life (Years)	Fatigue Damage Ratio (NS / TS)
			Design Lifetime: 15 Years			
1A	**NS**	Damen Guidelines	Gulf of Mexico	0.0310	32	3.5
1B	**TS**			0.0088	113	
2A	**NS**	Damen Guidelines	DNV-3	0.0121	83	3.2
2B	**TS**			0.0038	262	

NS: Nominal Stress ; TS: Total Stress

It can be observed that for all other factors remaining constant the fatigue damage calculated using nominal stress concept is more than three times higher than the fatigue damage calculated using total stress concept. This can pe partially attributed to the fact that the plate thickness is 6 mm whereas the reference plate thickness for nominal stress SN-Curve in design codes is 25 mm. A reduction in plate thickness is known to reduce the fatigue damage (thickness effect) [15]. Another factor is that the total stress concept uses more geometric information leading to higher accuracy (lesser conservatism) albeit introducing more complexity in the calculation.

6.2 Design Sea-states vs Data from Global Wave Forecasting models

To study how design sea-states compare with data for global wave forecasting models, same analysis as case 1 was carried out for varying sea-states. Here the GWS scatter data for GoM was compared to the average sea-states encountered by 13 of Damen's FCS5009 vessels operating in the GoM. Figure 6.1 below shows a comparison of these sea-states via scatter diagrams.

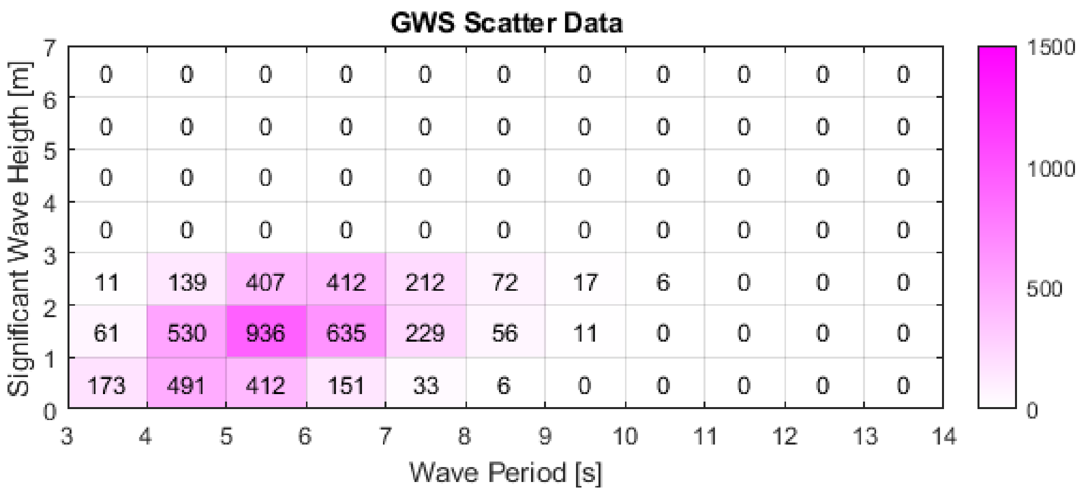


Figure 6.1a: GWS Scatter Data for GoM cut-off at 2.5m wave height

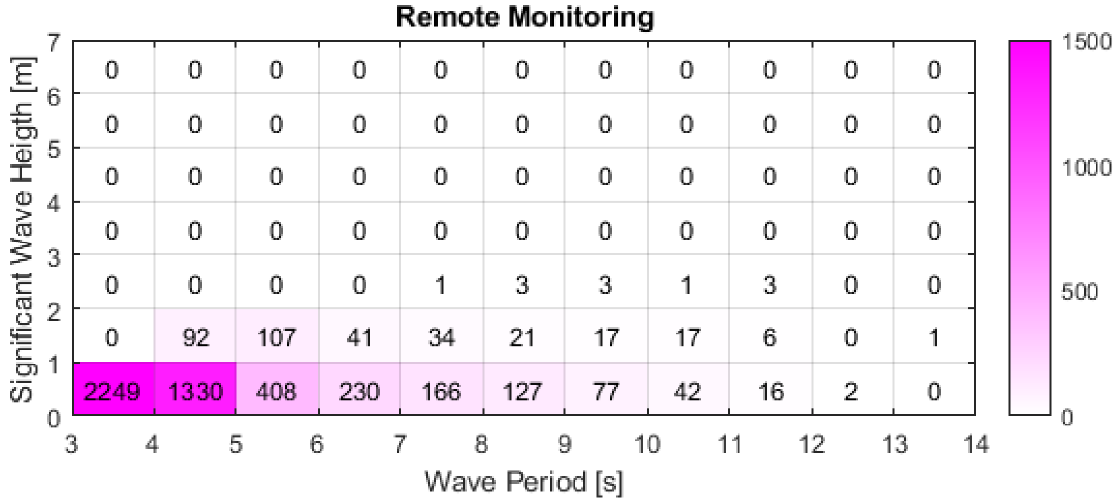


Figure 6.1b: Average sea-states encountered by FCS5009 vessels operating in GoM region for past 2.5 years as per Global Wave Forecasting Model (Copernicus)

It is evident from the figure that wave forecasting combined with remote monitoring predicts milder sea-states for FCS5009 vessels than design sea-states. It should be noted that wave forecasting models (although calibrated using buoy and satellite measurements) may not be able to capture milder sea-states especially in shallow to intermediate depth seas. More research is required to validate these sea-states. However, it taken at face values, this predicts that FCS5009s at Damen are currently being designed for significantly harsher sea-states than necessary.

Results of the study are presented in table 6.3 below:

Table 6.3: Results of Case Study 2

Sr No	Stress Concept	Operational Profile	Sea State	Yearly Fatigue Damage (-)	Predicted Fatigue Life (Years)	Fatigue Damage Ratio (NS / TS)
			Design Lifetime: 15 Years			
1A	NS	Damen Guidelines	**GWS Scatter Data**	0.0310	32	105.0
1B			**Wave Forecasting**	0.0003	3385	
2A	TS	Damen Guidelines	**GWS Scatter Data**	0.0121	113	71.9
2B			**Wave Forecasting**	0.0002	5953	

Results show that fatigue damage predicted using design sea-states is huge as compared to predictions using data from wave forecasting models. This indicates immense conservatism in current design practice. However, as states earlier these results should be taken with a pinch of salt in the sense that averaged sea-states for a small sample size of vessels for a short duration of time are not necessarily representative of all FCS5009 vessels operating worldwide. Sample size needs to be much higher if these results are to be formalized into some design guidelines.

6.3 Design Operational Profile vs Data from Remote Monitoring

To study how design operational profiles compare with remote monitoring data, in terms of fatigue damage prediction, same analysis as case 2 was carried out with carrying operational profiles. Figure 6.2 below shows a comparison of the operational profiles recommended in design guidelines vs the operational profiles collected through remote monitoring.

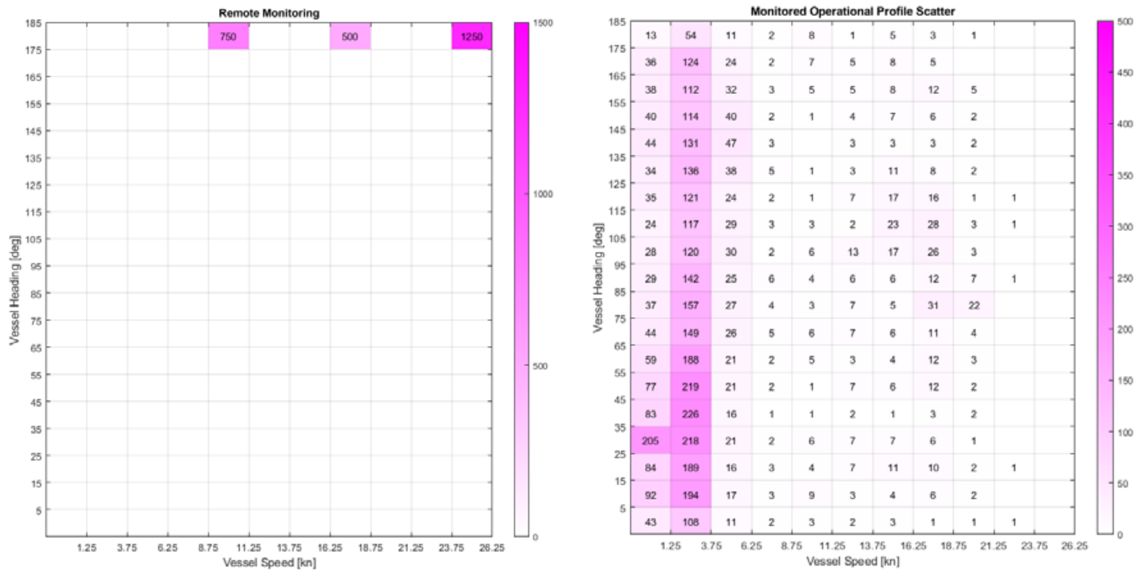


Figure 6.2: Design operational profile scatter(left) vs Average operational profiles recorded for FCS5009 vessels operating in GoM region for past 2.5 years (right)

It is evident that the vessel speeds and vessel headings assumed in design are vastly different to the actual scenario if remote monitoring is to be believed. Table 6.4 below presents the results of this study.

Table 6.4: Results of Case Study 3

Sr No	Stress Concept	Operational Profile	Sea State	Yearly Fatigue Damage (-)	Predicted Fatigue Life (Years)	Fatigue Damage Ratio (NS / TS)
Design Lifetime: 15 Years						
1A	TS	Damen Guidelines	**Wave Forecasting**	0.0002	5953	1.4
1B		Remote Monitoring		0.0001	8466	

Results show that fatigue damage predicted using design operational profiles is comparable to predictions using data from remote monitoring. Although there is a factor of 1.4 in the fatigue damage prediction, the factor is small when the relatively small sample size is considered. Design guidelines need to be conservative in the absence of certain data about possible vessel speeds and headings during operation. Hence, a factor of 0.5 on damage calculated using head waves seems ok for design.

6.4 Fatigue Damage Sensitivity

A study was carried out to access sensitivity of fatigue damage to some of the fatigue influence parameters. This sensitivity study is based on hypothetical hourly damage calculations. The influence factors are classified into three categories:

1. Environmental Factors (Sea-state and Operational Profile)
2. Local Geometry and Loading (Plate thickness and Bending ratio)
3. Monitoring Intervals (i.e. the sampling frequency for remote monitoring data)

6.4.1 Environmental Factors

Figure 6.3 below shows how hourly fatigue damage varies with vessel operational profile. Fatigue damage is scaled using design hourly damage for a 15-year design life (design hourly damage = 1.33E-5 considering 5000 operating hours/year). Vessel Heading is relative to dominant wave direction.

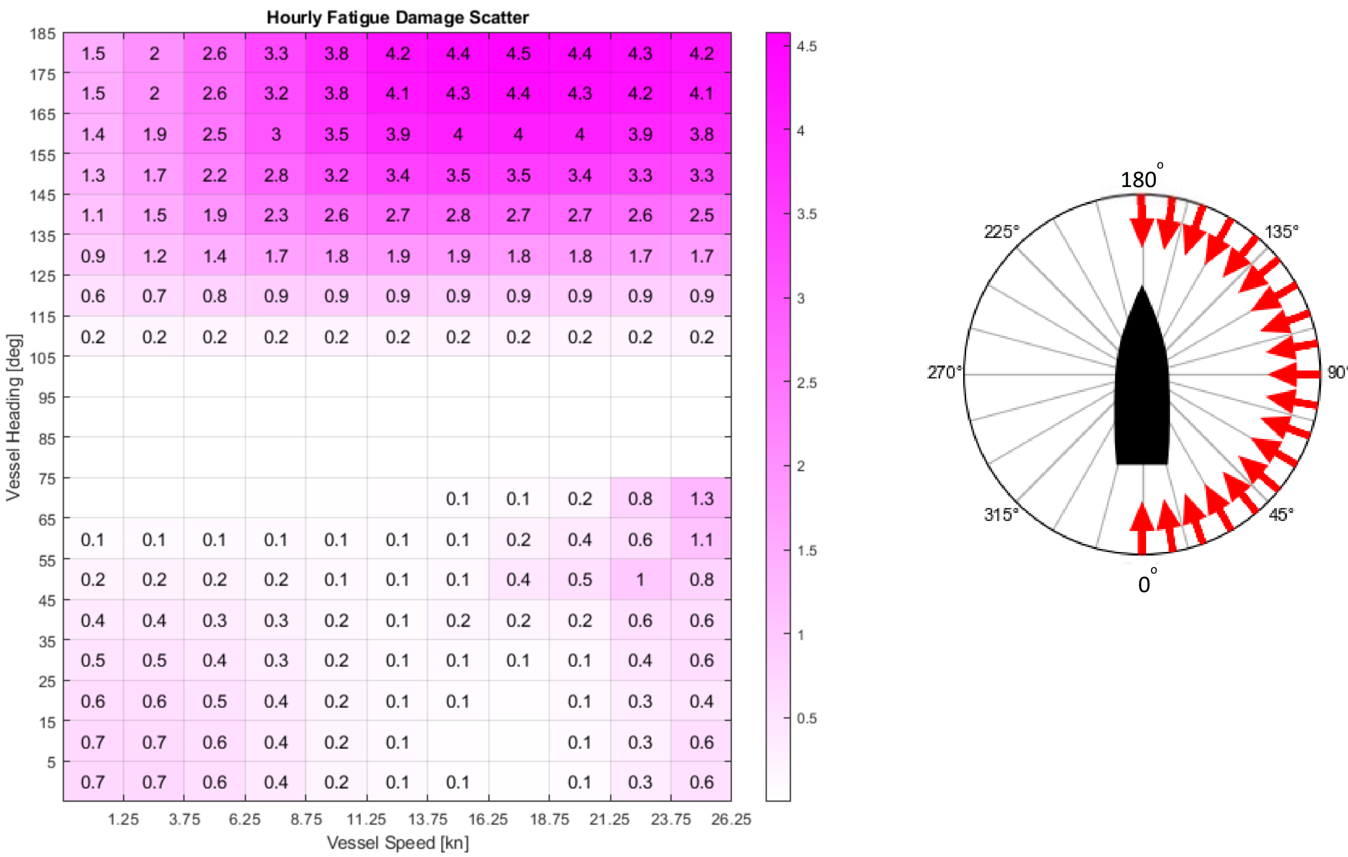


Figure 6.3: Hourly Fatigue Damage Scatter vs Vessel Operational Profile (left). Heading angles for a vessel (right). Red arrows indicate dominant wave direction. Black object is top view of a vessel.

Key takeaways from figure 6.3 are as follows:

- waves travelling from the vessel bow towards vessel aft (Heading angle between 100 to 180) cause significantly more fatigue damage per hour than waves travelling from vessel aft to vessel bow. This can be attributed in part to the fact that the number of load cycles encountered by a vessel would be increased for the first case and reduced for the latter due to doppler effect due to vessel velocity. However, this still does not explain why there is a difference in fatigue damage for 0 degree and 180 degree heading for zero vessel velocity.

- Beam sea-states cause negligible damage compared to head sea-states. This is obvious as fatigue damage is calculated from stresses caused as a result of pressure variation under the vessel which would be negligible for beam seas as compared to head seas.
- Fatigue damage for waves travelling in the same direction as the vessel becomes negligible near vessel speeds of 16 kn. This can be explained by the fact that the wave phase velocity corresponding to peak spectral frequency (1 - 1.5 rad/sec) is in the range of (13 to 19 kn) for deep water.
- Fatigue Damage is more sensitive to Vessel Heading angle than Vessel Velocity.

Figure 6.4 below shows how hourly fatigue damage varies with sea-states. Fatigue damage is once again scaled using design hourly damage for a 15-year design life (design hourly damage = 1.33E-5 considering 5000 operating hours/year). Wave period in the figure refers to the wave peak period.

Figure 6.3: Hourly Fatigue Damage Scatter vs sea-state

Key takeaways from figure 6.4 are as follows:

- Fatigue Damage is more sensitive to significant wave height than peak period of the sea-state.
- Fatigue Damage per hour increases steeply for increasing significant wave height whereas it has a peak and decreases towards both sides of the peak for wave period.
- Fatigue Damage can increase as much as 100 times when significant wave height changes from 1 m to 3 m. It can increase 10 time when wave period changes from 12.5 sec to 7.5 sec.
- Reducing the bin widths for significant wave height and wave period can significantly increase the accuracy of fatigue damage calculation. This is not easy for GWS scatter data as design data

is provided in pre-set bin widths. However, this is easy to apply for remote monitoring combined with global wave forecasting.

6.4.2 Local Geometry and Loading

This case study explores the dependence of the transfer function between nominal stress and total stress on two local geometry and loading parameters namely, the plate thickness and the bending ratio. Table 6.4 shows how the transfer function varies when the plate thickness is change from 5 mm to 10 mm for 0 and 20 percent bending ratio.

Table 6.4: Transfer function from nominal stress to total stress for varying plate thickness and bending ratio

Plate Thickness (t_b)	l_w	h_w	Cbw	I_n	Transfer Function (NS to TS)		
mm	mm	mm	-	-	$r_s = 0$	$r_s = 0.2$	Δ
5	4.8	2	0.18	6.77	1.21	1.25	3.3%
6	5.7	2	0.15	6.23	1.34	1.37	2.3%
7	6.7	2	0.13	5.97	1.44	1.47	1.6%
8	7.6	2	0.11	5.91	1.53	1.54	1.0%
9	8.5	2	0.09	5.97	1.60	1.61	0.6%
10	9.5	2	0.08	6.13	1.65	1.66	0.3%

It can be observed that the transfer function value increases with increasing plate thickness as well as increasing bending ratio. Increase in transfer function value indicates a corresponding increase in fatigue damage. A thickness effect is included in the nominal stress approach above a plate thickness of 25mm. However, it can be observed that similar phenomenon is observed for lesser plate thicknesses while using total stress concept. It is also seen that the effect of increasing bending ratio decreases with increasing plate thickness.

6.4.3 Monitoring Intervals

Remote monitoring can provide vessel speed and vessel heading data at a maximum rate of one update per every 2 min [5]. However, cost of procuring this data is proportional to the number of data points. So, it is desirable to check how sensitive yearly fatigue damage value is to the rate of remote monitoring data obtained. This case study compares the yearly fatigue damage for four vessels for two sampling rates (1hr interval vs 3min interval data). For the one hour data, vessel heading and velocity is assumed constant for an hour and updated each hour whereas for the 3min interval data, vessel velocity and heading is updated every 3mins. Results of the study are given in Table 6.5 below:

Table 6.5: Yearly Damage Comparison for 1-hour vs 3 min monitoring interval

IMO	**NS / TS**	**Yearly Fatigue Damage**					
		3 min Interval	**1 Hr Interval**	**Comparison**			
'9679115'	NS	0.0181	0.0201	1 Hr Interval Damage is	11%	**More**	than 3min
	TS	0.0044	0.0048		9%	**More**	
'9751767'	NS	0.0098	0.0107		9%	**More**	
	TS	0.0025	0.0027		8%	**More**	
'9751779'	NS	0.0461	0.0458		1%	**Less**	
	TS	0.0098	0.0097		1%	**Less**	
'9768318'	NS	0.0438	0.0407		7%	**Less**	
	TS	0.0093	0.0087		7%	**Less**	

It is observed that, the fatigue damage can either be higher or lower for a reduced sampling rate. However, the difference in fatigue damage is not very significant. Hence, a one-hour sampling interval with a 10 percent factor of safety seems sufficient until a more detailed study is conducted.

6.5 Deterministic vs Probabilistic Fatigue Damage

In this study, uncertainties in loading as well as resistance are analysed to calculate probability density function of resulting fatigue damage for 46 FCS5009 vessels. The aim of this case study was to illustrate how uncertainties can be captured in the analysis to generate a probabilistic fatigue damage prediction. Only a few of the numerous possible uncertainties have been included leaving it open for further development.

Following uncertainties were considered in the analysis:

6.5.1 Uncertainties in Far-field Loading

As explained in section 4.3, multiple factors can influence the far-field stress at a detail. Two of them namely, the change in moment of inertia of the transverse cross section and the stress variation along a weld due to stiffness variation are included as shown below.

<u>Shrinkage due to weld distortions</u>

The change in section modulus of the transverse cross section can be caused due to change in dimensions of the vessel as a result of shrinkage due to weld distortions. G.J. de Jong conducted a research into the shrinkage of High Speedo Craft. His findings are mentioned in a thesis report by C.W. Bouhuijs [16]. He analysed four vessels to study distribution of shrinkage in length, breadth and depth during hull construction. The causes of this shrinkage are not relevant for this study. Results of this thesis were used to generate a distribution for reduction in vessel depth as a result of this shrinkage. As the data for this is limited (4 measurement points only) the resulting distribution may not be very reliable. However, it will be useful as an example as to how such an uncertainty can be included in the analysis. Three distributions (normal, half-normal, uniform) were tried out to fit the data. The mean and standard deviations for each distribution were calculated using 'fitdist' function in MATLAB. 'fitdist' uses the maximum likelihood method to estimate the parameters of the distributions.

Probability density and cumulative distributions for all three distributions along with the empirical cumulative distribution for the measurements (assuming equal likelihood for all four measurements) are shown in figure 6.4 below.

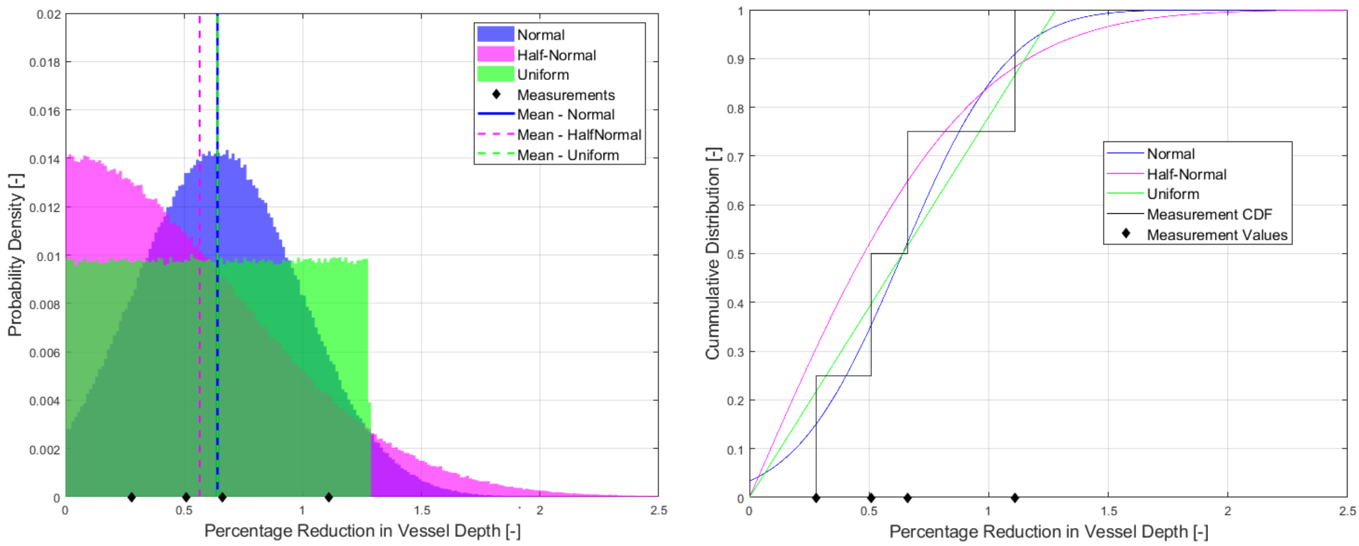


Figure 6.4 Pdfs and Cdfs of reduction in depth during hull construction

The half-normal distribution was chosen to represent the uncertainty in shrinkage because the uniform distribution has an upper bound which may not be the case for shrinkage, and the normal distribution does not have a lower bound and predicts expansion in some cases which is not feasible. The half-normal distribution has a lower bound and does not have an upper bound.

The total moment of inertia (I) of a vessel transverse section is composed of three components. First two are the rectangular moment of inertia ($bd^3/12$ and $db^3/12$) which is proportional to the cube of depth of longitudinal plates and the breadth of horizontal plates. The third component is due to shift in neutral axis (Ad^2) which is proportional to the square of depth of longitudinal plates. To estimate the relative effect of these components, hand calculations were carried out for two transverse sections (at 26 m and 28 m from aft respectively) using vessel drawings. It was observed that, the rectangular moment of inertia components combined contributed to only 10% of the total moment of inertia whereas the remaining 90% was the axis shift contribution. Hence, as an approximation, the moment of inertia was assumed to be proportional to the square of the vessel depth. The distance to the extreme fibre from neutral axis (y) is obviously linearly proportional to the vessel depth. Hence, the resulting section modulus ($Z = I/y$) would be linearly proportional to the vessel depth. Hence, the distribution of reduction in section modulus was assumed to be same as distribution of reduction in vessel depth.

Stress concentrations

In a conventional fatigue analysis, a weld detail with highest peak stress is considered to be the most critical without considering the distribution of stress amplitude along the entire weld length. For example, FEM model results below in Figures 6.5, 6.5 and 6.7 show the distribution of stress along the weld length for two transverse but welds on the deck (at 26 m and 28m from aft respectively).

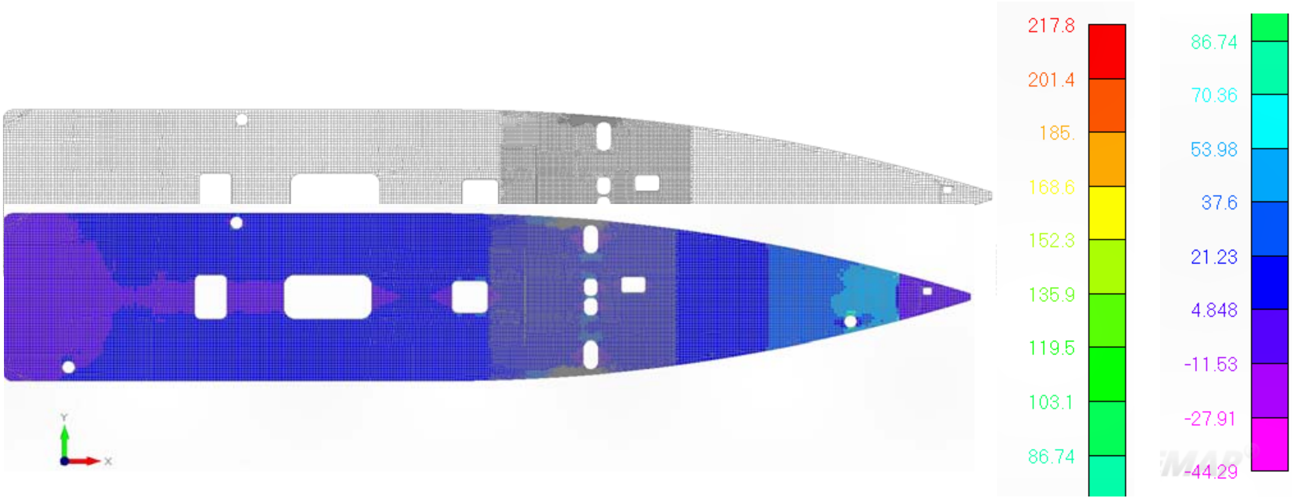


Figure 6.5 Top view of Deck from FEM Model of an FCS5009

(Top-Plain; Bottom - With Stress Contours)

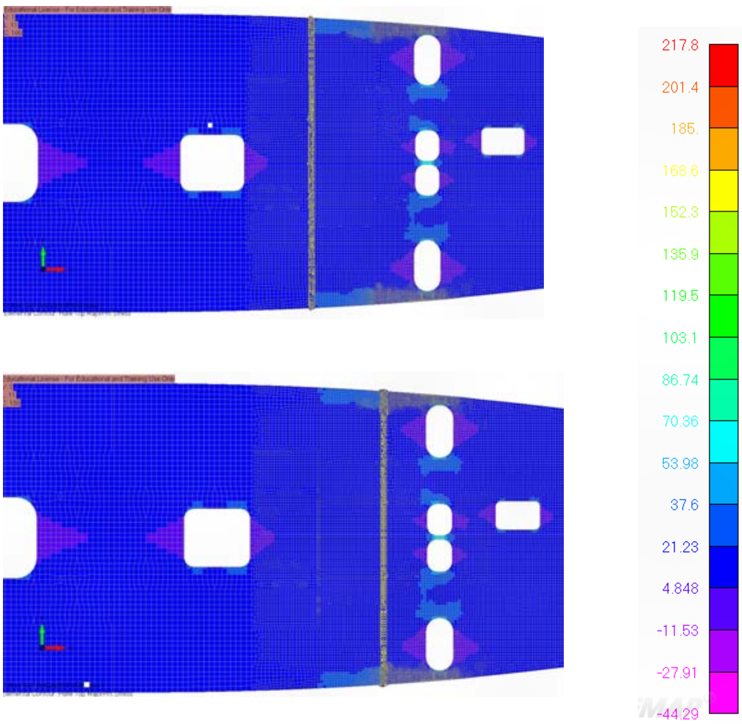


Figure 6.6 Zoomed view of Deck from FEM Model of an FCS5009

(Top figure highlights the Weld at 26 m from Aft; Bottom figure highlights the Weld at 28m from Aft)

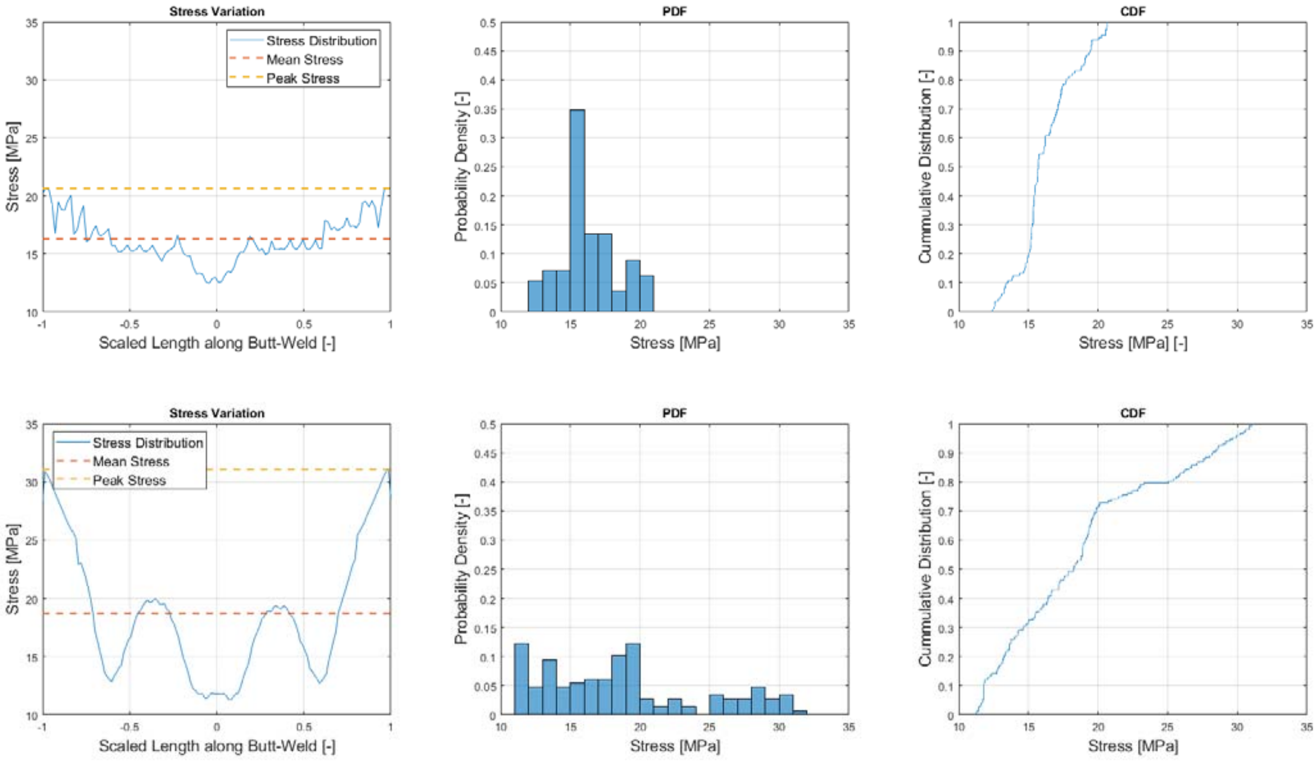


Figure 6.7 Stress Distribution along weld length

(Top-26m from Aft; Bottom – 28m from Aft)

It can be observed that, the peak stress in the weld at 28m (41 MPa) is much higher than the peak stress in the weld at 26m (27 MPa). However, the mean stress for both the welds is quite close to each other (19 MPa and 16 MPa respectively). Also, the Cdfs of both the stress distributions is very different. So, if a fatigue life of the weld length as a whole is to be estimated, then this stress distribution can be included in the analysis. This stress distribution is representative of the variation in far-field stress along the weld length and should not be confused with the variation in local stress distribution at a hot-spot in the weld.

Both the above uncertainties were included in the analysis when calculating the hourly fatigue damage table. Apart from these, the uncertainties in environmental parameters (Hs, Tp) were included using remote monitoring data. Uncertainties in speed and heading can similarly be included but were kept out as they would significantly increase the required analysis time.

6.5.2 Uncertainties in Resistance

Uncertainty in resistance is incorporated by providing a distribution for log C in the SN-curve. A mean of 13.56 with a standard deviation of 0.25 were used to generate this distribution as per values provided for the single slope total stress curve. These values are estimated from fatigue test results using a maximum likelihood approach. The PDFs and CDFs of distribution used for log C is given in figure 6.8 below:

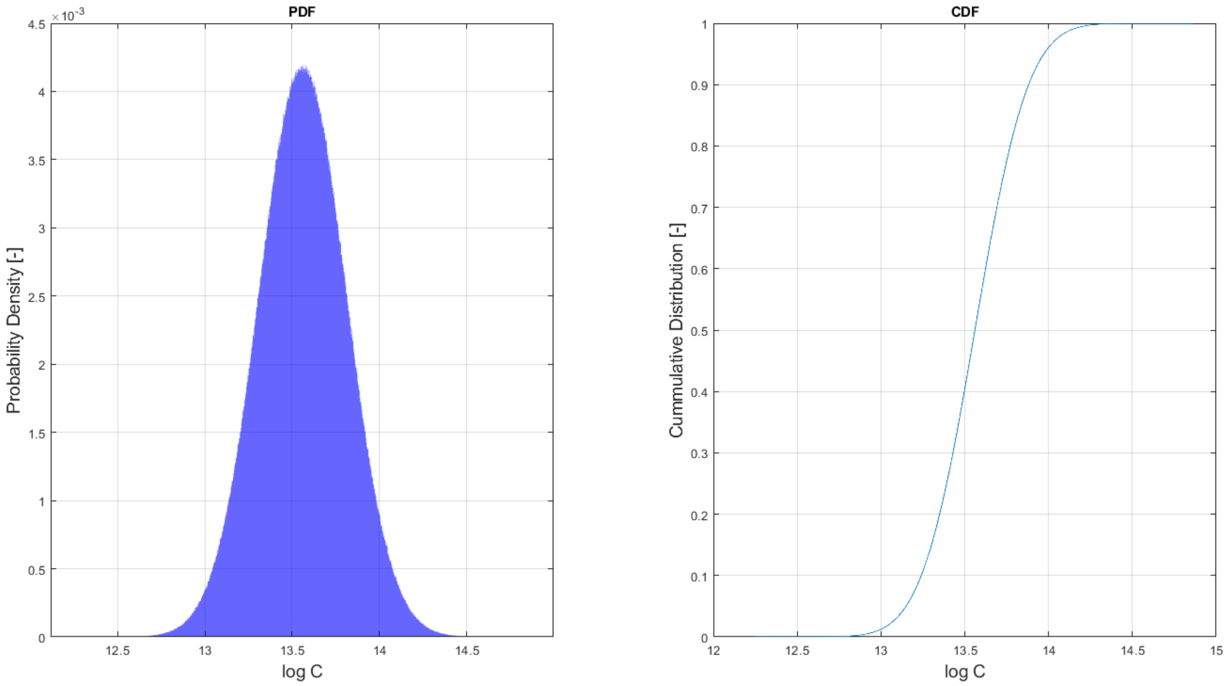


Figure 6.8 PDF and CDF for log C in the Total stress single slope steel SN curve

6.5.3 Probabilistic Analysis Case

Remote monitoring data for 46 FCS5009 ships for a 2-and-a-half-year period was provided by Damen for this thesis Yearly sea-state data scatter data for each ship was generated from remote monitoring by segregating the data into bins. Appendix B provides the complete sea-state scatter data for each ship. Analysis results (a cumulative distribution for fatigue damage and fatigue life for each ship) are presented in figures below. Each line represents the damage distribution for one ship.

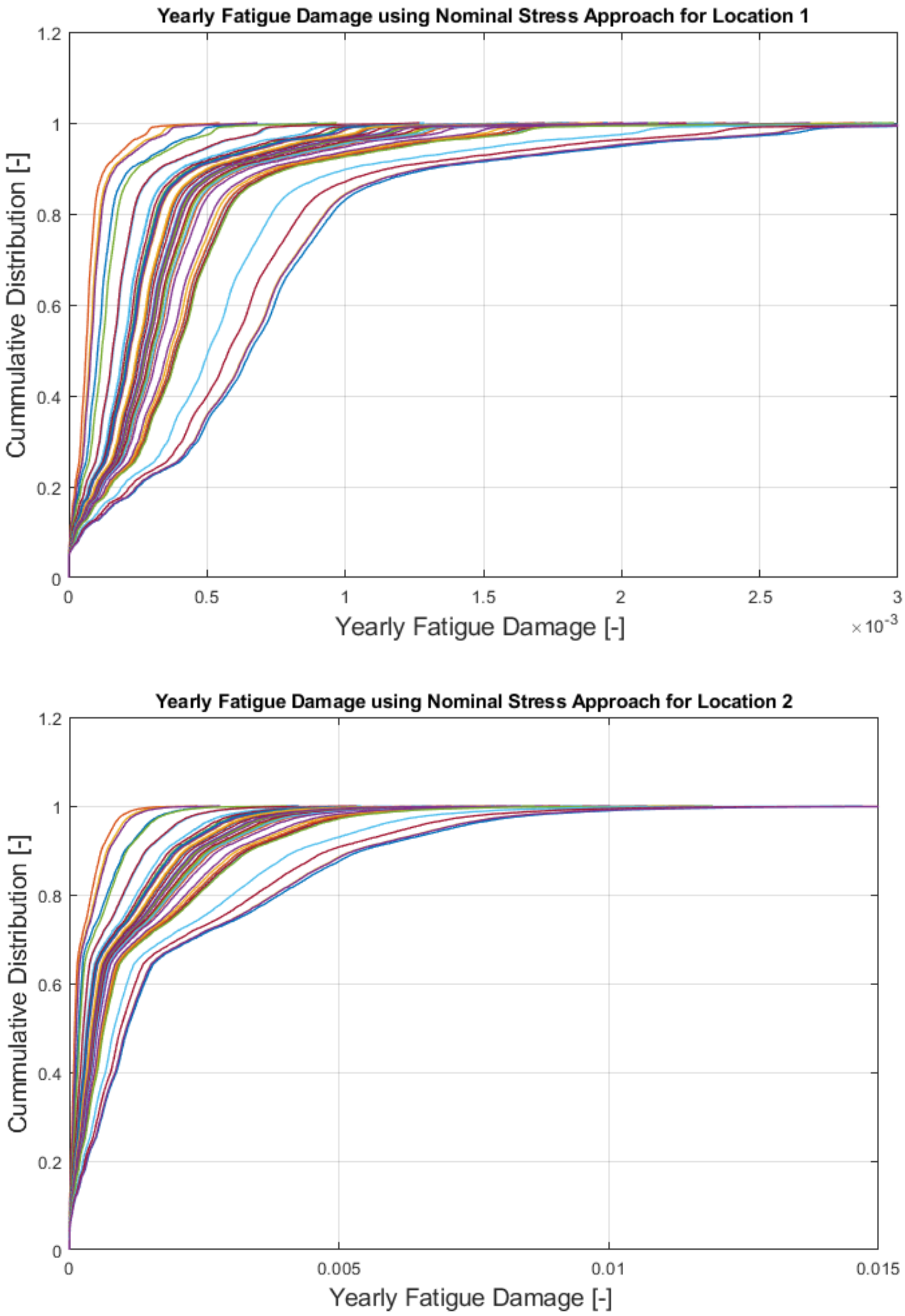
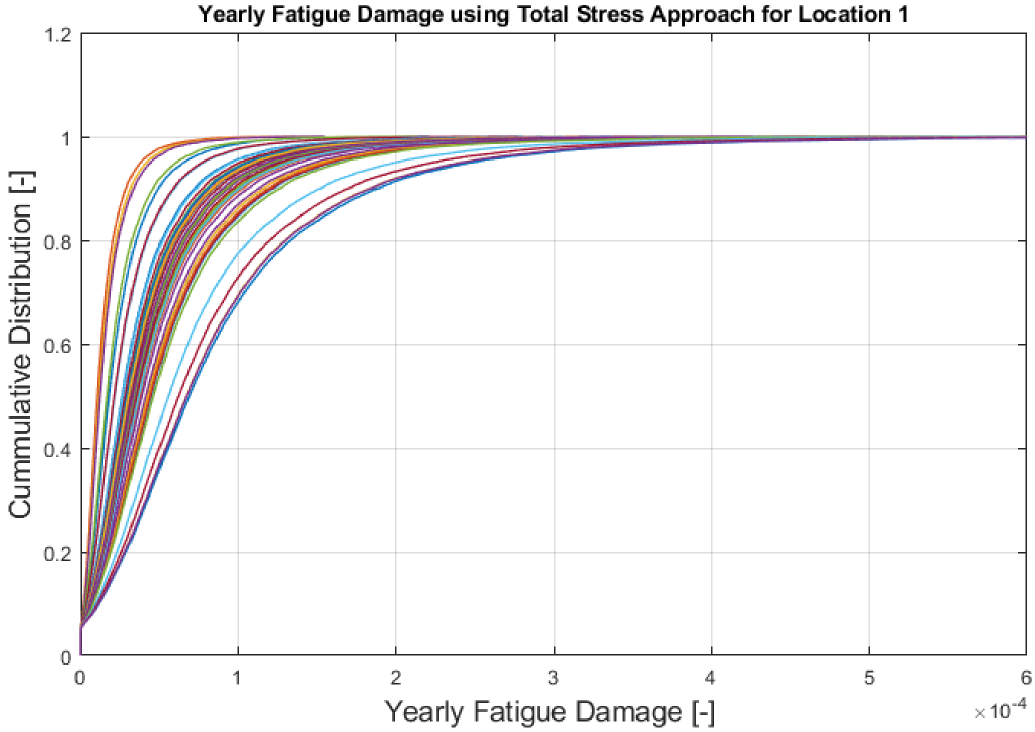


Figure 6.9 CDF for Yearly Fatigue Damage variation using Nominal stress approach



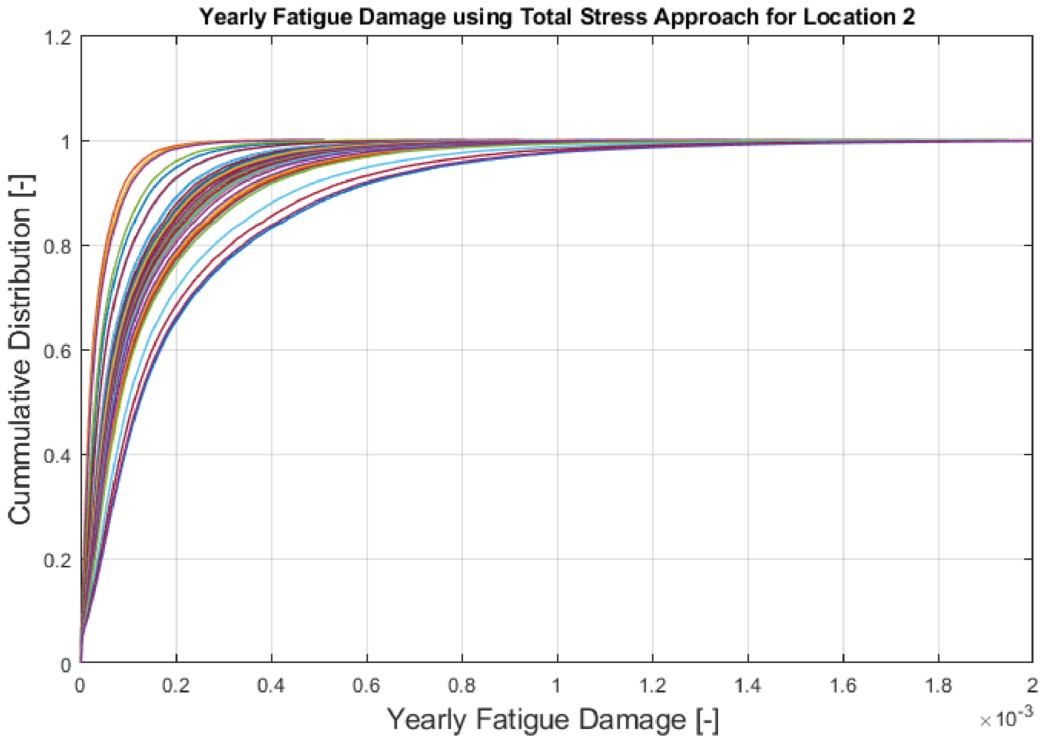


Figure 6.10 CDF for Yearly Fatigue Damage variation using Total stress approach

Nominal stress case only includes uncertainties on loading side (SCF) whereas total stress case includes uncertainties in both loading and resistance (SCF and log C)

The fatigue damage for a reliability level of 99 percent was calculated for each ship. A log-normal distribution was fitted to this data with 95 percent confidence bounds using the maximum likelihood approach. Figure 6.11 below shows the combined yearly fatigue damage CDF for a reliability of 95 percent. The mean, upper bound and lower bound of this CDF (inverse for lifetime) for a 95 percent reliability are presented in Table 6.6 below against corresponding deterministic fatigue lifetime mean and minimum values for 46 FCS5009 vessels.

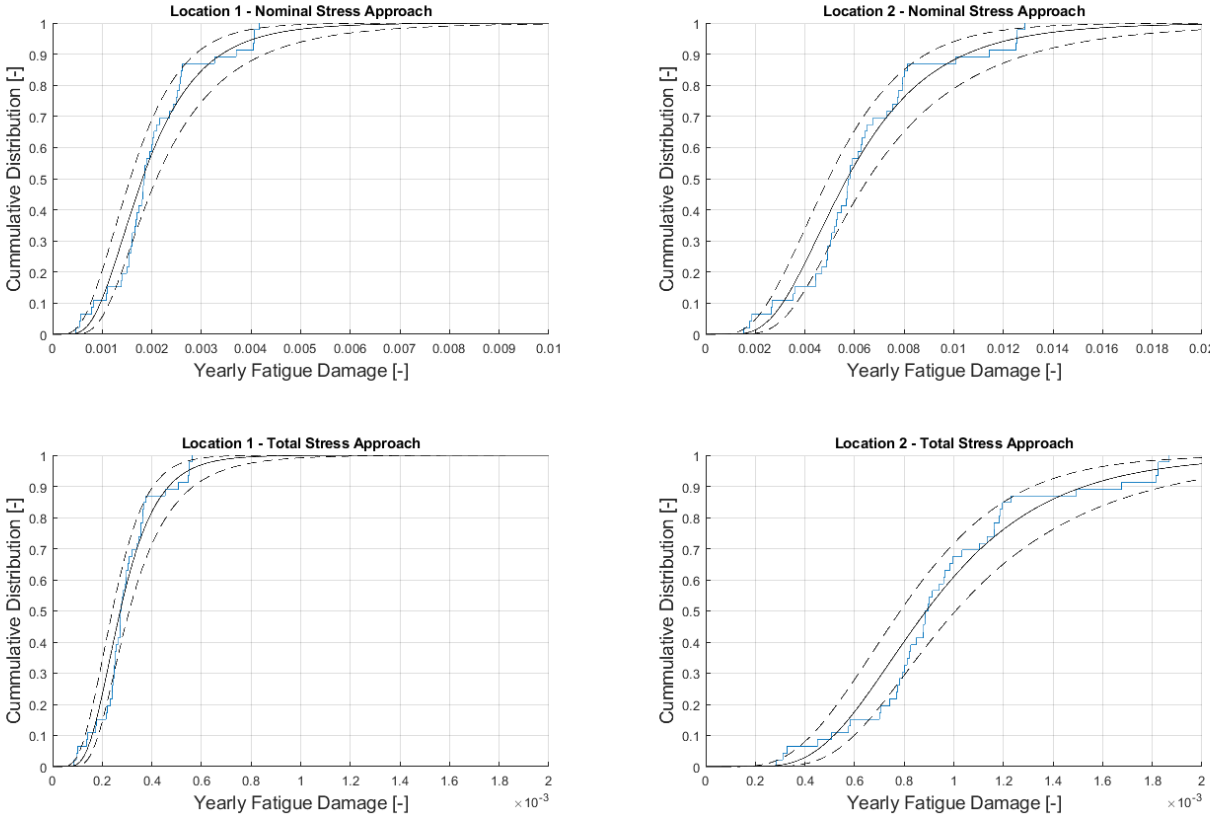


Figure 6.11 CDF for Yearly Fatigue Damage variation (99 percent reliability values for 46 vessels)

Table 6.6: Probabilistic vs Deterministic Fatigue Lifetime estimates

Sr No	Stress Concept	Location	Probabilistic Analysis			Deterministic Analysis	
			Fatigue Lifetime estimate (years)			Fatigue Lifetime estimate (years)	
			mean	Upper Bound	Lower Bound	mean	min
1	NS	1	142.1	185.2	96.8	846.1	105.3
2		2	47.4	61.2	32.7	331.9	42.5
3	TS	1	1150.2	1442.2	829.0	7437.4	1146.8
4		2	482.5	604.9	347.9	3748.4	577.1

This is a pilot case with a small sample size (only 46 vessels) and hence no generalised inferences are drawn from the comparison. However, for this specific case it can be said that the fatigue life for weld at location 1 (26m from aft) would be between 96 to 185 years based on nominal stress concept and between 829 to 1442 years based on total stress concept with a reliability level of 99 percent and confidence interval of 95 percent. Similar inferences can be drawn about the other location.

7
Conclusions

The objective of this master thesis is to make probabilistic fatigue life predictions by incorporating total stress concept, data from remote monitoring and global wave forecast models. A MATLAB program called Tanaav has been developed during this thesis based on existing software AluFastShip and FLOAT. Tanaav has been applied to predict fatigue lifetimes for FCS5009 vessels as a pilot case. In theory, the new program is better than the previous programs as it gives the designer more control over the inputs while maintaining best practices from previous software.

The following paragraphs summarize the work done in this study with reference to each research question.

RQ1: *How does the fatigue lifetime of a single-sided steel butt joint, on the deck of an FCS5009, calculated using the total stress concept compare with its fatigue lifetime calculated using total stress concept ?*

The total stress concept has been successfully applied to predict fatigue life of single-sided butt welds between steel plates on decks of FCS5009 vessels. Similar methodology is applicable to all kinds of welds in steel as well as aluminium. It has been shown that, using total stress concept can lead to significant increase (factor 3) in predicted fatigue life of these welds as compared to the nominal stress approach.

RQ2: *How does the fatigue lifetime of a single-sided steel butt joint, on the deck of an FCS5009, calculated using design operational profiles and sea-states compare with its fatigue lifetime calculated using vessel monitoring data combined with global wave forecasting model Copernicus ?*

Vessel monitoring data coupled with global wave forecasting model predictions has been used to predict fatigue damage using both nominal stress and total stress approaches. In both cases, the predicted yearly fatigue damage is less than the yearly damage using GWS data. This has been shown to be caused due to large difference in sea-state data between forecasting and GWS for Gulf of Mexico region.

RQ3: *How does hourly fatigue damage of a single-sided steel butt joint, on the deck of an FCS5009 vary with following fatigue influence parameters ?*

1. *Significant wave height and Wave Peak Period*
2. *Vessel Speed and Vessel heading with respect to mean wave direction*
3. *Plate thickness and bending stress ratio*

Hourly fatigue damage scatter has been calculated for varying operational profile and sea-state parameters. Resulting distributions have been explained using seakeeping arguments. It has been shown that hourly fatigue damage is especially sensitive to significant wave height and vessel heading relative to dominant wave direction.

With respect to plate thickness and bending ratio, a parametric study has been carried out to calculate values of transfer function between nominal stress and total stress for varying values of plate thickness and bending ratio. It has been observed that the transfer function increases by 30 percent for increase in plate thickness from 5 mm to 10 mm. It has also been observed that bending ratio does not influence the transfer function value as much and its effect reduces with increasing thickness.

RQ4: *How do the CDFs of fatigue damage and fatigue lifetime of a single-sided steel butt joint, on the decks of FCS5009s compare with the deterministic fatigue lifetime predicted using current design practice at Damen ?*

Monte-Carlo simulations have been used to calculate hourly fatigue damage distribution while incorporating uncertainties in loading as well as resistance. Uncertainties in environmental parameters have been included using remote monitoring data. CDFs of fatigue damage have been calculated for 46 FCS5009 vessels considering vessel depth reduction due to shrinkage during manufacturing as a random variable. A method has also been proposed to analyse welds as a whole (include the variability in far-field stress along the weld length as a design parameter) instead of predicting fatigue life for only a small part of the weld with a high far-field stress. The methodology proposed can be seamlessly extended to include any number of input uncertainties if their probability distribution is available. This also adds importance to future measurements and research distributions of all fatigue influence parameters. Fatigue lifetime estimates using deterministic method lies within the bounds of fatigue life estimates predicted by probabilistic method.

8
Recommendations

Based on possibilities and limitations given in conclusions, following recommendations can be made for further research to improve the validity and range of application of developed methodology:

8.1 Validation

Full-scale measurements on actual vessels are required to validate the method at each stage such as monitoring data, RAOs, Stress Spectrums and eventually the fatigue life prediction. Damen already has access to some measurements towards this goal and more measurement campaigns are also planned. Data from both needs to be used to validate and calibrate the method where required.

8.2 Extension

More weld types, such as T-joints, Cruciform joints etc should be analysed using the software. The method should also be extended to dual slope and random fatigue limit SN-curves for total stress. Wave spectrums should be customized based on data from remote monitoring and also by splitting the spectrum into its components (swell and local wind generated) to improve accuracy. Wave spreading also needs to be included in the model by using directional wave spectrums. Another possible improvement for better accuracy that needs to be looked into is the sampling frequency for remote monitoring data and the bin widths used for segregating it. For the probabilistic module, more research is required to establish PDFs and CDFs of many for fatigue influence parameters. Apart from this a cosmetic improvement is required in the software as it currently does not have a GUI which it needs to be used regularly by engineers.

8.3 Optimization

Further research is required to improve the process flow and also use selective Monte-Carlo sampling to reduce the runtime. A study is also required to access the optimum number of samples for a certain error tolerance.

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Appendix - A

Wave Spectra

Pierson-Moskowitz Spectrum

This is a spectrum for a fully developed sea-state. The spectrum is related to the wind speed by following formula:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left(-\beta\left(\frac{\omega_0}{\omega}\right)^4\right)$$

But it has become standard to relate the variables to the main sea states parameters (significant wave height and peak frequency as follows:

$$S(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left(-\frac{5}{4}\left(\frac{f_m}{f}\right)^4\right)$$

where,

α is the Philips constant and

f_m is the peak frequency.

JONSWAP Spectrum

Data collected during the Joint North Sea Wave Observation Project JONSWAP, showed that the wave spectrum is never fully developed. It continues to develop through non-linear, wave-wave interactions even for very long times and distances. Hence an extra and somewhat artificial factor was added to the Pierson-Moskowitz spectrum in order to improve the fit to their measurements. The JONSWAP spectrum is thus a Pierson-Moskowitz spectrum multiplied by an extra peak enhancement factor γ

$$S_j(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^r$$

$$r = \exp\left[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right]$$

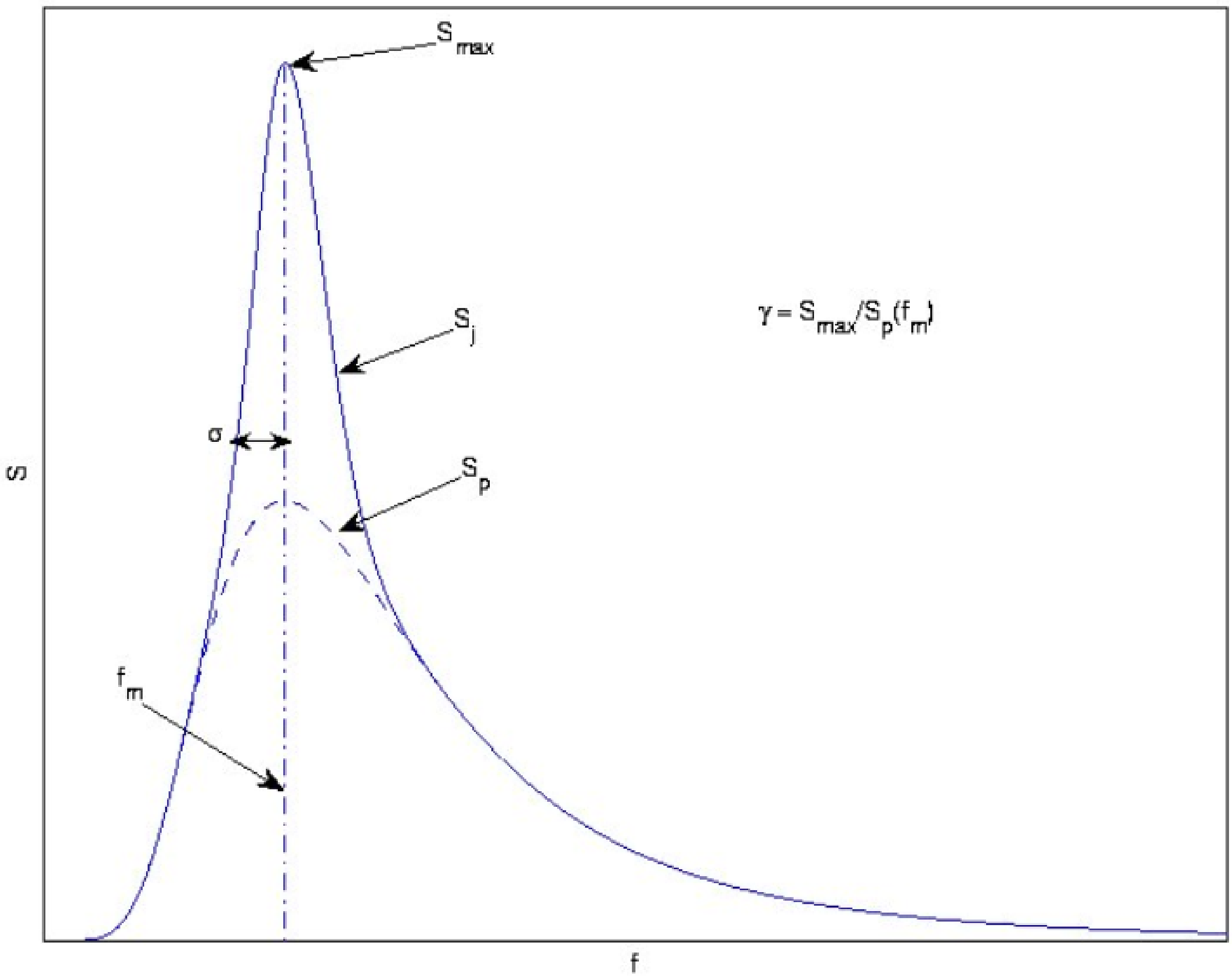


Figure A.1 JONSWAP and Pierson-Moskowitz spectra [17][18]

Appendix - B

Detailed Inputs for Case Studies

1. Response Amplitude Operators (RAOs)

omega (rad/s)	Speed 0 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	3	2	2	2	2	2
0.15	9	9	9	8	7	6	6	5	5	4
0.20	23	23	22	19	17	14	12	10	9	8
0.25	49	48	45	40	34	28	22	17	14	13
0.30	93	91	84	74	62	49	37	28	21	19
0.35	160	156	144	126	104	81	59	42	30	27
0.40	256	250	230	201	165	126	90	60	42	35
0.45	389	379	349	303	246	186	130	84	55	46
0.50	564	548	504	437	353	264	181	114	71	58
0.55	785	763	701	606	488	363	245	149	90	72
0.60	1056	1027	943	814	654	483	321	191	111	87
0.65	1377	1340	1230	1061	852	625	412	239	134	105
0.70	1748	1701	1563	1349	1081	791	516	294	160	125
0.75	2163	2105	1937	1673	1341	979	633	354	187	148
0.80	2613	2545	2345	2030	1630	1188	763	419	217	176
0.85	3085	3007	2779	2414	1944	1419	908	491	250	209
0.90	3560	3475	3225	2818	2282	1672	1069	572	287	251
0.95	4016	3930	3667	3232	2641	1950	1250	662	332	307
1.00	4430	4346	4087	3642	3016	2253	1451	766	387	373
1.05	4772	4697	4460	4031	3393	2572	1671	872	432	430
1.10	5018	4957	4757	4370	3752	2895	1901	976	465	480
1.15	5141	5100	4953	4634	4066	3209	2133	1078	487	523
1.20	5124	5106	5023	4797	4314	3492	2360	1178	498	561
1.25	4954	4962	4955	4841	4479	3728	2575	1275	502	596
1.30	4631	4668	4744	4756	4539	3904	2768	1371	499	634
1.35	4168	4235	4396	4540	4491	4005	2932	1461	489	675
1.40	3589	3683	3929	4213	4336	4029	3059	1544	472	720
1.45	2932	3049	3368	3784	4084	3972	3143	1616	444	769
1.50	2247	2376	2746	3274	3748	3839	3178	1674	405	820
1.55	1591	1719	2104	2709	3344	3637	3164	1718	352	874
1.60	1037	1141	1491	2120	2884	3376	3104	1749	287	928
1.65	673	728	967	1545	2386	3064	3003	1770	213	983
1.70	557	558	623	1029	1869	2710	2865	1784	155	1036
1.75	557	552	520	642	1359	2319	2694	1797	175	1087
1.80	505	524	532	474	893	1900	2490	1810	281	1134
1.85	356	401	495	486	530	1465	2254	1821	424	1175
1.90	169	207	361	496	370	1032	1984	1823	584	1208
1.95	248	173	159	421	410	629	1678	1805	749	1233
2.00	464	386	143	261	456	306	1343	1754	908	1247
2.05	607	555	351	50	423	217	988	1661	1054	1250
2.10	630	615	499	164	315	337	632	1519	1178	1242
2.15	535	551	543	334	168	420	295	1328	1276	1223
2.20	377	406	480	425	107	423	35	1096	1344	1195
2.25	286	280	343	423	208	365	242	832	1381	1159
2.30	348	302	227	339	288	281	404	556	1387	1117
2.35	418	387	258	212	305	227	491	298	1366	1070
2.40	402	404	340	143	258	233	508	190	1322	1021
2.45	297	330	361	210	165	259	469	353	1258	969
2.50	150	195	302	277	66	259	403	551	1182	916

omega (rad/s)	Speed 0 [kn]								
	Headings[deg]								
	100	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**
0.10	2	2	2	2	3	3	3	3	3
0.15	5	5	6	6	7	8	9	9	9
0.20	9	10	12	14	17	19	22	23	23
0.25	14	17	22	28	34	40	45	48	50
0.30	21	28	38	50	63	75	85	91	94
0.35	31	43	61	83	107	129	147	158	162
0.40	43	63	93	130	170	207	237	256	263
0.45	57	89	137	195	257	315	362	393	403
0.50	75	122	195	282	374	460	530	575	590
0.55	97	165	269	394	526	648	746	810	832
0.60	122	218	362	536	716	883	1017	1103	1133
0.65	153	283	478	710	951	1171	1346	1459	1498
0.70	190	362	618	921	1231	1513	1737	1879	1929
0.75	234	458	786	1170	1560	1910	2186	2360	2420
0.80	287	572	984	1460	1936	2359	2688	2894	2965
0.85	351	704	1211	1788	2356	2853	3232	3468	3547
0.90	424	852	1463	2150	2813	3379	3802	4060	4147
0.95	504	1008	1735	2541	3298	3922	4374	4644	4733
1.00	588	1174	2026	2956	3798	4463	4922	5187	5272
1.05	657	1338	2341	3391	4300	4974	5411	5649	5724
1.10	712	1510	2675	3842	4779	5421	5800	5990	6046
1.15	762	1699	3029	4283	5205	5766	6051	6169	6199
1.20	813	1909	3394	4692	5547	5974	6126	6151	6148
1.25	871	2137	3754	5044	5767	6013	6000	5915	5874
1.30	938	2376	4094	5317	5845	5865	5661	5453	5370
1.35	1014	2617	4396	5489	5763	5525	5112	4780	4655
1.40	1096	2853	4647	5541	5512	4991	4376	3930	3769
1.45	1181	3077	4831	5461	5094	4292	3498	2960	2774
1.50	1267	3282	4938	5244	4523	3467	2539	1948	1751
1.55	1351	3460	4957	4893	3825	2571	1574	981	792
1.60	1430	3605	4883	4419	3044	1670	692	171	86
1.65	1503	3710	4712	3845	2233	841	177	504	610
1.70	1567	3769	4449	3203	1452	281	633	869	916
1.75	1618	3776	4102	2534	793	551	912	962	944
1.80	1653	3729	3690	1891	476	856	943	806	730
1.85	1669	3626	3237	1336	649	957	755	470	360
1.90	1662	3473	2775	954	865	859	418	92	135
1.95	1630	3277	2339	812	949	611	30	365	479
2.00	1573	3051	1961	851	891	285	339	642	716
2.05	1491	2812	1664	921	723	102	585	752	773
2.10	1387	2577	1454	945	496	347	676	685	655
2.15	1266	2362	1316	905	281	508	613	480	415
2.20	1131	2179	1222	812	210	544	431	216	156
2.25	988	2035	1145	686	291	468	190	137	215
2.30	842	1931	1067	553	354	311	89	315	377
2.35	701	1858	980	434	352	117	264	410	428
2.40	575	1807	886	340	293	73	362	387	365
2.45	482	1762	793	267	202	216	357	276	232
2.50	447	1711	713	201	124	292	268	149	138

omega (rad/s)	Speed 2.5 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	3	3	2	2	2	2
0.15	9	9	9	8	7	6	6	5	5	4
0.20	23	23	21	19	17	14	12	10	8	8
0.25	49	48	44	40	34	27	22	17	14	13
0.30	91	89	83	73	61	48	37	27	21	19
0.35	158	154	143	124	103	80	58	41	30	26
0.40	254	247	228	198	162	124	88	59	41	35
0.45	386	376	346	300	243	183	127	82	54	45
0.50	561	546	501	433	350	261	178	111	69	57
0.55	782	761	699	603	485	359	241	146	87	71
0.60	1054	1025	941	812	651	479	317	187	107	86
0.65	1377	1340	1230	1061	850	622	407	234	129	103
0.70	1750	1703	1565	1350	1081	790	512	287	153	123
0.75	2167	2110	1941	1678	1345	980	630	347	180	145
0.80	2619	2551	2352	2038	1637	1192	762	411	208	172
0.85	3092	3015	2787	2424	1953	1424	906	482	238	204
0.90	3567	3483	3232	2825	2289	1674	1064	559	271	244
0.95	4022	3935	3671	3232	2638	1943	1238	645	310	295
1.00	4433	4346	4082	3630	2996	2230	1429	744	359	357
1.05	4767	4690	4445	4005	3357	2535	1642	849	401	410
1.10	5002	4941	4736	4339	3709	2852	1873	959	433	456
1.15	5112	5073	4929	4608	4034	3177	2115	1071	456	497
1.20	5077	5066	5001	4788	4309	3486	2362	1185	467	534
1.25	4887	4907	4931	4852	4510	3761	2606	1298	471	567
1.30	4545	4594	4709	4777	4605	3983	2836	1414	465	603
1.35	4061	4139	4341	4554	4579	4129	3042	1528	453	642
1.40	3467	3570	3849	4201	4423	4186	3212	1640	434	684
1.45	2803	2925	3263	3736	4147	4144	3336	1745	405	729
1.50	2124	2254	2630	3193	3769	4003	3404	1840	365	777
1.55	1493	1617	1997	2612	3321	3772	3409	1921	313	827
1.60	984	1081	1412	2027	2828	3466	3351	1984	247	879
1.65	676	722	932	1476	2316	3106	3233	2028	166	931
1.70	577	582	640	1001	1807	2712	3061	2052	69	982
1.75	543	551	552	665	1325	2298	2845	2056	46	1032
1.80	458	486	533	529	902	1877	2594	2041	172	1078
1.85	317	354	461	521	595	1460	2317	2007	312	1119
1.90	256	241	319	493	469	1063	2022	1957	463	1154
1.95	399	330	204	388	476	711	1715	1890	618	1180
2.00	582	512	298	228	477	452	1398	1803	774	1197
2.05	697	650	465	143	409	356	1079	1695	924	1203
2.10	714	697	585	268	278	392	767	1563	1062	1199
2.15	638	648	624	406	112	428	478	1403	1180	1185
2.20	518	537	579	488	69	410	255	1215	1276	1162
2.25	438	436	474	499	207	336	216	1003	1344	1130
2.30	447	415	374	441	303	229	326	775	1384	1093
2.35	481	454	356	340	344	141	419	548	1394	1051
2.40	459	459	397	257	326	151	456	363	1377	1005
2.45	361	389	409	262	257	214	437	313	1336	957
2.50	218	258	352	308	166	255	376	420	1274	907

omega (rad/s)	Speed 2.5 [kn]								
	Headings[deg]								
	100	110	120	130	140	150	160	170	180
0.10	2	2	2	2	3	3	3	3	3
0.15	5	5	6	6	7	8	9	9	9
0.20	9	10	12	15	17	20	22	23	24
0.25	14	17	22	29	35	41	46	49	50
0.30	22	28	39	51	64	76	87	93	95
0.35	31	43	62	85	109	131	150	162	166
0.40	43	64	95	134	174	212	242	262	269
0.45	58	91	140	201	264	324	372	403	414
0.50	76	125	200	291	386	474	546	592	608
0.55	98	169	277	407	543	670	771	837	860
0.60	124	224	375	555	743	916	1055	1145	1176
0.65	156	292	496	738	989	1219	1402	1520	1561
0.70	193	375	644	961	1286	1581	1815	1965	2017
0.75	239	476	822	1225	1635	2003	2293	2477	2540
0.80	294	596	1030	1531	2034	2481	2829	3047	3121
0.85	360	733	1267	1877	2481	3008	3411	3661	3746
0.90	432	882	1527	2258	2967	3573	4023	4298	4389
0.95	509	1037	1807	2672	3488	4159	4641	4927	5020
1.00	587	1202	2112	3117	4029	4743	5232	5511	5600
1.05	650	1373	2451	3587	4569	5291	5756	6006	6084
1.10	706	1562	2814	4071	5078	5766	6169	6367	6425
1.15	760	1774	3197	4537	5526	6128	6428	6548	6577
1.20	820	2007	3586	4966	5882	6339	6494	6511	6504
1.25	890	2258	3967	5334	6108	6368	6339	6231	6180
1.30	970	2518	4326	5618	6181	6190	5945	5699	5601
1.35	1058	2780	4644	5794	6080	5798	5317	4931	4787
1.40	1153	3034	4907	5841	5791	5191	4483	3972	3789
1.45	1252	3275	5096	5742	5316	4400	3499	2894	2687
1.50	1351	3492	5199	5489	4672	3481	2448	1801	1588
1.55	1448	3678	5201	5087	3896	2508	1436	825	640
1.60	1540	3821	5094	4553	3049	1580	628	362	405
1.65	1623	3912	4877	3920	2209	833	497	740	820
1.70	1692	3942	4557	3237	1465	562	829	994	1021
1.75	1743	3907	4154	2560	933	770	1002	1004	973
1.80	1772	3805	3694	1949	746	954	966	812	733
1.85	1774	3641	3212	1456	827	983	766	492	383
1.90	1747	3427	2742	1128	933	868	465	140	76
1.95	1692	3176	2312	974	959	646	158	259	358
2.00	1609	2908	1947	943	888	375	248	514	587
2.05	1503	2637	1659	950	737	174	467	640	670
2.10	1378	2381	1451	938	540	272	575	617	601
2.15	1239	2155	1310	885	346	414	550	460	409
2.20	1090	1972	1214	790	236	466	409	231	172
2.25	935	1837	1136	669	256	416	200	114	177
2.30	778	1752	1055	545	299	285	76	280	344
2.35	625	1706	963	436	295	109	241	391	417
2.40	487	1685	860	353	240	68	346	390	378
2.45	386	1670	756	283	155	206	354	299	263
2.50	359	1647	667	209	96	281	281	178	155

omega (rad/s)	Speed 5 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	3	3	2	2	2	2
0.15	9	9	9	8	7	7	6	5	5	4
0.20	22	22	21	19	16	14	12	10	8	8
0.25	47	46	43	38	33	27	21	17	14	13
0.30	89	87	80	71	59	47	36	26	21	19
0.35	154	150	138	121	100	77	56	40	29	26
0.40	248	242	222	193	158	120	85	57	40	35
0.45	378	368	338	293	238	179	124	80	53	45
0.50	550	535	491	424	342	255	173	107	67	57
0.55	768	747	686	592	476	351	234	141	84	70
0.60	1037	1008	926	798	640	470	310	181	104	85
0.65	1357	1319	1212	1045	837	612	399	227	125	102
0.70	1725	1678	1543	1333	1067	778	502	279	148	121
0.75	2136	2080	1915	1657	1329	968	620	338	172	143
0.80	2580	2515	2321	2014	1620	1181	752	401	198	169
0.85	3042	2969	2749	2395	1934	1413	896	470	226	201
0.90	3505	3425	3183	2790	2266	1661	1053	546	256	239
0.95	3943	3860	3607	3184	2608	1923	1223	628	291	287
1.00	4331	4250	3999	3564	2949	2197	1405	721	335	345
1.05	4641	4568	4336	3914	3284	2479	1602	822	372	395
1.10	4846	4789	4597	4216	3603	2767	1815	930	403	438
1.15	4922	4889	4759	4454	3896	3062	2044	1045	425	476
1.20	4853	4850	4802	4609	4148	3353	2288	1166	437	511
1.25	4629	4662	4712	4662	4346	3631	2541	1291	441	544
1.30	4261	4326	4479	4593	4462	3878	2794	1423	434	577
1.35	3761	3856	4104	4384	4472	4070	3034	1555	423	613
1.40	3163	3279	3603	4038	4354	4183	3248	1691	403	653
1.45	2515	2641	3011	3566	4099	4194	3423	1825	376	695
1.50	1866	1995	2377	3000	3712	4088	3541	1951	340	739
1.55	1288	1403	1764	2395	3224	3861	3590	2067	296	786
1.60	850	936	1233	1816	2681	3528	3559	2165	245	835
1.65	611	651	833	1314	2138	3111	3448	2240	192	884
1.70	536	544	602	920	1644	2652	3259	2289	153	933
1.75	481	495	514	647	1224	2191	3005	2308	162	981
1.80	369	407	472	505	878	1759	2700	2294	229	1026
1.85	226	265	391	470	611	1372	2368	2248	331	1067
1.90	229	189	247	443	461	1032	2026	2172	452	1102
1.95	396	329	153	343	444	737	1691	2069	584	1130
2.00	549	500	312	160	453	508	1373	1942	721	1149
2.05	627	601	484	135	390	397	1076	1796	858	1159
2.10	617	611	566	338	234	407	805	1636	991	1159
2.15	541	550	550	464	21	434	570	1464	1113	1149
2.20	451	466	488	480	185	404	400	1285	1220	1130
2.25	408	408	429	429	320	303	338	1102	1307	1103
2.30	419	394	379	386	360	166	371	919	1371	1070
2.35	427	409	343	357	330	102	418	746	1409	1032
2.40	385	397	356	298	293	185	428	599	1421	990
2.45	286	321	373	247	274	251	388	506	1406	945
2.50	157	191	312	285	235	271	307	492	1367	898

omega (rad/s)	Speed 5 [kn]								
	Headings[deg]								
	100	110	120	130	140	150	160	170	180
0.10	2	2	2	2	2	3	3	3	3
0.15	5	5	6	7	7	8	9	9	9
0.20	9	10	12	15	17	20	22	23	23
0.25	14	18	23	29	35	41	46	49	50
0.30	22	29	39	52	65	77	87	94	96
0.35	31	44	63	86	110	133	151	163	168
0.40	44	65	97	136	177	215	246	266	273
0.45	59	93	143	205	269	330	379	410	422
0.50	77	128	205	297	394	485	558	605	622
0.55	99	173	284	418	558	688	792	860	883
0.60	126	230	386	572	766	945	1089	1181	1213
0.65	158	301	512	764	1024	1262	1453	1575	1618
0.70	197	388	668	998	1336	1644	1888	2045	2098
0.75	245	494	855	1276	1704	2090	2394	2587	2653
0.80	302	618	1072	1597	2126	2597	2964	3194	3273
0.85	369	759	1316	1959	2598	3159	3586	3851	3940
0.90	440	908	1584	2360	3118	3764	4243	4533	4630
0.95	513	1062	1878	2804	3678	4395	4907	5209	5308
1.00	586	1232	2206	3285	4260	5021	5541	5836	5930
1.05	647	1418	2575	3791	4838	5607	6101	6366	6448
1.10	705	1628	2969	4307	5380	6113	6539	6746	6807
1.15	766	1863	3380	4804	5855	6494	6806	6926	6953
1.20	836	2120	3797	5259	6230	6707	6855	6857	6843
1.25	917	2394	4204	5647	6458	6711	6649	6509	6446
1.30	1009	2675	4584	5939	6511	6479	6172	5878	5762
1.35	1110	2958	4917	6106	6361	6002	5437	4995	4832
1.40	1218	3231	5182	6118	5996	5293	4500	3940	3742
1.45	1329	3483	5356	5959	5429	4413	3452	2827	2616
1.50	1441	3704	5421	5625	4700	3449	2413	1787	1587
1.55	1549	3879	5362	5137	3875	2498	1493	958	809
1.60	1649	3996	5177	4532	3030	1651	826	585	580
1.65	1736	4043	4876	3863	2237	1001	632	750	804
1.70	1804	4014	4483	3182	1554	699	807	940	965
1.75	1847	3912	4029	2531	1048	767	949	964	943
1.80	1861	3743	3546	1948	806	907	936	814	748
1.85	1843	3522	3061	1469	815	946	770	532	434
1.90	1794	3265	2600	1132	897	853	497	198	111
1.95	1715	2987	2183	962	926	652	199	206	295
2.00	1612	2704	1831	922	865	395	209	452	523
2.05	1490	2428	1559	929	722	188	414	581	611
2.10	1352	2174	1371	917	531	247	520	563	550
2.15	1204	1956	1256	860	347	375	498	416	371
2.20	1048	1787	1182	762	243	418	363	206	161
2.25	887	1675	1120	640	250	365	168	137	198
2.30	724	1619	1046	522	275	236	102	291	349
2.35	563	1605	951	427	256	69	254	390	412
2.40	417	1613	841	357	190	96	345	383	372
2.45	313	1624	729	294	105	219	347	297	265
2.50	304	1620	635	218	82	280	275	184	163

omega (rad/s)	Speed 7.5 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	3	2	2	2	2	2
0.15	9	9	9	8	7	6	6	5	5	4
0.20	21	21	20	18	16	13	11	10	8	8
0.25	45	44	41	37	31	26	20	16	14	13
0.30	85	83	77	68	57	45	34	26	20	19
0.35	147	143	132	116	95	74	54	38	29	27
0.40	237	232	213	185	151	115	82	55	39	35
0.45	363	353	325	281	228	172	119	77	51	45
0.50	529	515	473	409	330	245	166	103	66	57
0.55	741	720	662	571	459	339	226	136	82	70
0.60	1001	973	894	771	619	455	299	174	100	85
0.65	1310	1274	1172	1011	811	593	386	219	120	101
0.70	1665	1621	1493	1290	1036	756	487	269	142	120
0.75	2062	2007	1851	1605	1291	943	603	326	165	142
0.80	2485	2423	2241	1950	1575	1151	733	388	189	168
0.85	2922	2852	2648	2317	1880	1379	876	456	215	200
0.90	3352	3278	3056	2693	2201	1622	1031	529	242	236
0.95	3751	3675	3450	3064	2527	1877	1197	608	273	282
1.00	4092	4022	3802	3416	2851	2139	1372	697	313	337
1.05	4347	4289	4096	3729	3158	2403	1557	792	346	383
1.10	4491	4451	4305	3988	3443	2663	1749	893	374	424
1.15	4503	4489	4410	4177	3692	2918	1951	1004	396	460
1.20	4370	4387	4395	4278	3895	3163	2166	1124	408	494
1.25	4089	4141	4249	4280	4044	3395	2394	1253	412	525
1.30	3672	3758	3970	4169	4120	3608	2634	1393	405	555
1.35	3145	3258	3565	3936	4111	3788	2881	1539	395	589
1.40	2547	2677	3054	3579	3998	3918	3119	1693	377	626
1.45	1925	2062	2471	3114	3767	3973	3338	1851	354	665
1.50	1343	1470	1867	2563	3413	3927	3517	2008	326	706
1.55	868	970	1308	1975	2948	3764	3633	2157	295	750
1.60	571	630	862	1417	2406	3472	3670	2293	266	796
1.65	467	487	590	963	1834	3060	3610	2407	248	842
1.70	432	445	486	676	1319	2558	3448	2493	251	889
1.75	349	377	434	541	936	2018	3185	2543	284	935
1.80	201	248	353	466	718	1515	2836	2551	345	979
1.85	44	79	227	388	597	1128	2426	2516	429	1019
1.90	182	125	69	295	486	893	1992	2435	528	1054
1.95	318	279	120	185	376	757	1581	2311	638	1083
2.00	386	373	280	45	309	623	1233	2152	755	1104
2.05	386	390	379	151	262	459	976	1964	874	1117
2.10	343	350	388	312	170	327	804	1758	992	1120
2.15	300	306	329	395	93	314	676	1546	1105	1114
2.20	283	287	281	370	240	343	557	1340	1210	1099
2.25	272	270	280	280	378	308	445	1150	1300	1077
2.30	223	233	256	246	409	226	376	986	1375	1048
2.35	119	164	202	276	324	250	371	853	1429	1014
2.40	124	99	170	249	206	377	389	756	1462	975
2.45	173	199	136	173	222	449	372	696	1471	933
2.50	121	132	238	147	280	407	303	672	1457	889

omega (rad/s)	Speed 7.5 [kn]								
	Headings[deg]								
	100	110	120	130	140	150	160	170	180
0.10	2	2	2	2	2	2	2	3	3
0.15	5	5	6	6	7	8	8	9	9
0.20	9	10	12	15	17	19	21	23	23
0.25	14	18	23	29	35	41	46	49	50
0.30	22	29	39	52	65	77	87	93	96
0.35	32	45	64	87	111	133	152	164	168
0.40	44	66	98	137	178	216	248	268	275
0.45	60	94	145	207	273	334	383	415	426
0.50	78	130	208	302	401	493	568	616	633
0.55	101	177	291	427	570	703	810	879	904
0.60	128	236	396	587	787	971	1119	1215	1248
0.65	161	309	528	788	1057	1304	1501	1628	1672
0.70	202	401	691	1033	1385	1706	1960	2124	2180
0.75	251	511	886	1324	1772	2177	2496	2699	2769
0.80	311	639	1111	1660	2216	2715	3103	3346	3429
0.85	378	781	1361	2039	2719	3315	3769	4049	4144
0.90	448	930	1641	2468	3278	3966	4475	4783	4885
0.95	517	1087	1956	2947	3881	4644	5189	5510	5615
1.00	586	1270	2314	3466	4505	5316	5869	6183	6284
1.05	647	1474	2714	4009	5124	5943	6466	6746	6833
1.10	709	1706	3139	4562	5702	6477	6922	7135	7195
1.15	778	1965	3581	5090	6200	6863	7174	7283	7305
1.20	857	2245	4025	5568	6576	7046	7163	7135	7109
1.25	950	2540	4455	5961	6772	6977	6853	6667	6587
1.30	1054	2842	4848	6231	6752	6632	6247	5906	5776
1.35	1167	3143	5176	6340	6495	6032	5404	4937	4768
1.40	1286	3426	5411	6261	6013	5232	4422	3872	3681
1.45	1409	3678	5527	5993	5354	4323	3401	2814	2616
1.50	1531	3882	5507	5556	4584	3386	2420	1838	1651
1.55	1647	4022	5351	4999	3770	2483	1542	1030	883
1.60	1751	4086	5076	4369	2958	1666	865	594	572
1.65	1836	4068	4708	3709	2193	1011	613	712	764
1.70	1896	3972	4280	3050	1520	679	776	912	939
1.75	1925	3809	3819	2420	1011	741	928	949	930
1.80	1921	3596	3344	1850	772	891	922	806	743
1.85	1882	3348	2874	1383	798	933	759	529	435
1.90	1812	3078	2428	1066	890	839	490	204	122
1.95	1716	2797	2027	927	917	637	204	199	281
2.00	1599	2515	1696	912	849	386	207	427	492
2.05	1467	2245	1452	928	701	195	392	541	567
2.10	1323	1999	1300	912	513	246	482	514	498
2.15	1171	1793	1219	846	341	354	450	366	324
2.20	1012	1643	1170	740	252	382	314	173	145
2.25	847	1557	1120	616	253	319	132	161	222
2.30	680	1530	1048	503	260	188	129	306	360
2.35	515	1546	949	420	225	30	271	392	411
2.40	363	1580	830	361	148	127	348	378	366
2.45	261	1610	710	301	66	236	341	292	263
2.50	276	1619	612	223	93	283	268	187	168

omega (rad/s)	Speed 10 [kn]									
	Headings [deg]									
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
0.10	3	3	3	3	3	3	2	2	2	2
0.15	9	8	8	8	7	6	6	5	5	5
0.20	20	20	19	17	15	13	11	9	8	8
0.25	42	41	38	34	29	24	20	16	14	13
0.30	79	77	72	63	53	43	33	25	20	19
0.35	137	134	124	108	90	70	52	37	29	27
0.40	222	216	199	174	142	109	78	53	39	36
0.45	340	331	305	264	215	162	113	74	50	46
0.50	497	484	445	385	311	232	158	99	64	57
0.55	697	678	623	539	434	321	214	129	80	70
0.60	942	917	843	729	587	432	284	166	97	85
0.65	1232	1200	1105	957	770	565	368	208	116	102
0.70	1564	1524	1406	1220	984	721	466	257	136	121
0.75	1929	1882	1741	1516	1227	900	578	311	158	143
0.80	2316	2262	2099	1839	1495	1101	704	371	181	169
0.85	2706	2647	2469	2176	1782	1319	843	437	204	200
0.90	3078	3018	2832	2517	2081	1551	993	508	228	234
0.95	3407	3349	3168	2847	2381	1793	1155	585	256	277
1.00	3664	3616	3456	3149	2671	2039	1324	671	291	330
1.05	3823	3788	3672	3407	2943	2283	1499	759	321	373
1.10	3860	3852	3795	3598	3185	2519	1675	853	346	412
1.15	3756	3780	3806	3719	3390	2740	1853	955	366	446
1.20	3506	3566	3690	3744	3536	2944	2036	1067	377	478
1.25	3111	3213	3449	3663	3626	3128	2225	1191	382	508
1.30	2609	2738	3082	3478	3643	3289	2425	1328	376	536
1.35	2025	2177	2604	3174	3577	3422	2636	1478	367	569
1.40	1423	1580	2050	2758	3414	3514	2851	1644	353	603
1.45	891	1025	1473	2257	3143	3545	3070	1821	335	639
1.50	576	637	953	1706	2766	3493	3269	2005	316	678
1.55	584	557	623	1174	2296	3343	3431	2190	301	718
1.60	670	639	569	754	1771	3083	3533	2369	295	761
1.65	639	639	609	574	1251	2708	3548	2532	306	805
1.70	441	490	564	570	836	2237	3459	2669	337	849
1.75	81	194	406	544	627	1713	3254	2769	389	893
1.80	435	252	145	436	593	1206	2930	2824	460	935
1.85	655	700	264	270	560	822	2506	2824	544	974
1.90	628	639	621	88	454	664	2008	2765	639	1010
1.95	601	638	614	331	308	664	1488	2643	741	1039
2.00	580	597	589	787	174	643	1030	2462	847	1062
2.05	512	534	352	632	94	534	756	2230	955	1076
2.10	438	500	485	572	312	372	733	1960	1061	1083
2.15	618	760	390	557	636	231	806	1672	1164	1080
2.20	417	511	363	490	878	154	816	1392	1259	1070
2.25	294	341	620	413	893	89	719	1149	1345	1051
2.30	234	240	375	361	507	178	539	974	1419	1026
2.35	225	204	234	313	383	400	341	883	1478	996
2.40	233	219	174	313	310	596	228	860	1520	961
2.45	219	229	178	295	241	672	230	868	1543	922
2.50	165	190	221	218	134	606	218	873	1547	881

omega (rad/s)	Speed 10 [kn]								
	Headings[deg]								
	100	110	120	130	140	150	160	170	180
0.10	2	2	2	2	2	2	2	2	2
0.15	5	5	6	6	7	8	8	9	9
0.20	9	10	12	14	17	19	21	22	23
0.25	15	18	23	29	35	40	45	48	49
0.30	23	29	39	52	64	76	86	92	94
0.35	33	45	64	87	110	133	151	163	167
0.40	45	67	99	138	178	217	248	268	275
0.45	61	95	147	209	275	336	386	418	430
0.50	80	133	211	307	407	500	576	625	642
0.55	103	180	296	436	582	717	827	898	923
0.60	131	241	405	602	807	997	1150	1249	1283
0.65	165	318	544	812	1090	1346	1551	1684	1729
0.70	207	413	714	1068	1434	1769	2036	2208	2267
0.75	259	527	915	1371	1840	2267	2605	2820	2893
0.80	319	658	1146	1722	2312	2841	3253	3511	3599
0.85	386	799	1406	2126	2851	3486	3968	4266	4366
0.90	453	950	1705	2589	3452	4185	4726	5054	5163
0.95	518	1117	2047	3105	4099	4911	5492	5833	5945
1.00	586	1316	2435	3663	4768	5629	6215	6546	6652
1.05	649	1541	2866	4243	5425	6287	6833	7119	7207
1.10	718	1795	3322	4829	6027	6825	7268	7470	7525
1.15	796	2076	3791	5379	6521	7170	7444	7519	7529
1.20	885	2377	4259	5857	6851	7257	7302	7225	7182
1.25	988	2693	4698	6216	6952	7050	6842	6612	6519
1.30	1104	3011	5080	6409	6801	6566	6125	5768	5635
1.35	1228	3321	5368	6408	6413	5877	5246	4795	4634
1.40	1358	3601	5534	6207	5844	5060	4289	3770	3590
1.45	1490	3833	5555	5839	5158	4177	3307	2747	2559
1.50	1619	3999	5436	5348	4405	3274	2349	1784	1602
1.55	1739	4085	5198	4782	3620	2390	1475	974	830
1.60	1842	4085	4873	4169	2830	1580	802	556	544
1.65	1920	4005	4488	3530	2078	936	591	714	768
1.70	1968	3860	4063	2889	1416	644	784	918	943
1.75	1980	3665	3614	2273	933	748	934	947	925
1.80	1956	3436	3153	1719	745	902	917	795	730
1.85	1899	3183	2695	1278	808	932	745	516	423
1.90	1814	2914	2262	1004	903	827	476	203	130
1.95	1706	2637	1880	911	919	621	205	206	280
2.00	1582	2360	1575	923	838	375	215	413	471
2.05	1445	2095	1367	942	683	204	379	510	530
2.10	1299	1856	1254	918	497	251	452	471	453
2.15	1145	1664	1205	840	337	340	409	320	280
2.20	984	1534	1176	724	261	352	269	143	133
2.25	817	1475	1133	598	257	280	101	185	245
2.30	646	1478	1059	491	249	146	155	323	373
2.35	477	1520	952	417	199	20	290	398	412
2.40	322	1574	824	364	113	156	354	374	361
2.45	226	1617	697	305	45	253	338	287	261
2.50	269	1634	597	223	116	288	263	189	173

omega (rad/s)	Speed 12.5 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	3	3	2	2	2	2
0.15	8	8	8	7	7	6	5	5	5	5
0.20	18	18	17	16	14	12	11	9	9	8
0.25	38	37	35	31	27	23	19	15	14	13
0.30	71	70	65	58	49	39	31	24	20	20
0.35	124	121	112	98	82	64	48	36	28	27
0.40	201	196	181	158	130	100	72	51	38	36
0.45	309	301	278	242	197	149	105	70	50	47
0.50	452	440	406	352	286	214	147	93	63	58
0.55	634	618	569	494	400	298	200	122	77	71
0.60	857	835	770	669	542	401	266	156	94	86
0.65	1118	1090	1008	877	711	526	344	196	112	103
0.70	1414	1379	1279	1118	909	672	437	242	131	122
0.75	1733	1693	1575	1383	1132	840	544	293	151	144
0.80	2060	2018	1887	1670	1376	1026	663	350	171	170
0.85	2380	2336	2199	1964	1634	1229	795	413	193	200
0.90	2668	2624	2492	2252	1898	1443	939	481	215	234
0.95	2889	2858	2747	2522	2158	1664	1093	556	239	275
1.00	3026	3012	2941	2754	2404	1886	1255	639	271	325
1.05	3052	3062	3053	2935	2626	2105	1419	722	296	365
1.10	2952	2999	3067	3050	2816	2312	1581	810	318	402
1.15	2727	2801	2972	3090	2967	2501	1742	904	335	435
1.20	2412	2505	2765	3033	3065	2673	1903	1006	346	466
1.25	2098	2177	2465	2881	3101	2826	2065	1118	350	495
1.30	1957	1943	2127	2626	3068	2957	2233	1246	345	521
1.35	2166	2012	1868	2294	2948	3060	2410	1389	339	551
1.40	2540	2444	1878	1914	2729	3120	2591	1556	329	583
1.45	2289	2475	2249	1635	2405	3120	2782	1742	318	617
1.50	2151	2310	2357	1644	1999	3028	2966	1947	311	653
1.55	2116	2094	2188	1977	1587	2840	3125	2164	312	691
1.60	2027	1977	2003	2136	1314	2538	3236	2387	328	730
1.65	1149	1421	1873	1945	1343	2135	3274	2604	361	771
1.70	509	681	1442	1779	1559	1672	3216	2802	414	813
1.75	63	174	666	1640	1703	1241	3048	2968	483	855
1.80	249	184	138	1049	1451	996	2764	3088	566	896
1.85	444	415	260	527	1291	1011	2372	3147	659	934
1.90	547	551	508	99	1016	1109	1899	3134	759	969
1.95	578	603	650	515	789	1106	1397	3040	864	998
2.00	558	589	695	765	1241	932	960	2862	971	1022
2.05	503	526	651	863	846	663	746	2602	1076	1039
2.10	431	441	538	838	1093	468	813	2270	1179	1048
2.15	359	376	414	710	1002	363	947	1887	1276	1048
2.20	309	333	369	528	1171	113	987	1487	1365	1041
2.25	301	291	364	405	989	709	894	1125	1445	1027
2.30	320	286	272	420	775	686	693	890	1514	1006
2.35	331	321	207	410	602	615	451	857	1570	979
2.40	309	317	296	244	549	518	254	971	1612	947
2.45	249	261	315	116	554	416	157	1107	1639	911
2.50	163	183	240	284	474	238	73	1187	1649	873

omega (rad/s)	Speed 12.5 [kn]								
	Headings[deg]								
	100	110	120	130	140	150	160	170	180
0.10	2	2	2	2	2	2	2	2	2
0.15	5	5	6	6	7	7	8	8	8
0.20	9	10	12	14	16	19	20	21	22
0.25	15	18	23	28	34	39	44	47	48
0.30	23	30	39	51	63	75	84	90	93
0.35	33	46	64	86	109	131	149	161	164
0.40	46	67	99	137	178	216	247	267	274
0.45	62	96	148	210	276	338	388	421	432
0.50	81	134	214	310	412	507	584	634	651
0.55	105	184	301	444	593	732	845	918	943
0.60	134	247	415	617	829	1025	1183	1285	1321
0.65	169	327	559	836	1125	1391	1606	1744	1792
0.70	213	425	735	1103	1485	1837	2119	2300	2363
0.75	266	542	943	1419	1914	2367	2725	2953	3031
0.80	327	673	1181	1790	2418	2981	3418	3693	3786
0.85	392	815	1456	2224	2996	3672	4184	4501	4608
0.90	456	972	1778	2721	3640	4419	4994	5342	5458
0.95	518	1153	2148	3276	4331	5191	5804	6163	6280
1.00	587	1370	2566	3870	5038	5941	6549	6888	6995
1.05	655	1616	3027	4483	5719	6603	7145	7420	7502
1.10	730	1891	3510	5090	6315	7094	7495	7660	7701
1.15	818	2192	4001	5638	6756	7332	7525	7548	7540
1.20	917	2512	4477	6077	6981	7269	7225	7103	7047
1.25	1030	2843	4904	6355	6943	6921	6657	6412	6317
1.30	1156	3170	5244	6432	6663	6358	5913	5569	5442
1.35	1290	3478	5461	6311	6201	5659	5060	4631	4478
1.40	1429	3739	5533	6021	5617	4870	4134	3635	3461
1.45	1568	3936	5461	5614	4951	4015	3172	2626	2441
1.50	1702	4051	5273	5124	4224	3129	2224	1671	1493
1.55	1822	4078	4999	4576	3458	2255	1361	879	744
1.60	1919	4023	4666	3982	2679	1460	723	533	541
1.65	1987	3902	4289	3358	1939	849	594	742	797
1.70	2020	3732	3877	2727	1299	631	812	938	959
1.75	2016	3528	3438	2123	861	776	950	950	925
1.80	1975	3298	2985	1590	740	924	917	786	719
1.85	1904	3049	2536	1184	834	938	734	503	412
1.90	1809	2784	2115	962	926	819	464	203	140
1.95	1695	2510	1752	915	927	607	208	216	283
2.00	1567	2235	1476	947	833	367	224	405	456
2.05	1429	1973	1307	964	671	213	370	485	500
2.10	1282	1742	1233	928	486	257	428	435	413
2.15	1127	1563	1210	838	337	330	374	279	239
2.20	964	1456	1195	714	269	328	229	119	130
2.25	795	1424	1154	586	260	246	78	208	267
2.30	622	1454	1074	484	239	109	180	340	387
2.35	449	1518	959	417	177	49	308	405	416
2.40	291	1588	823	367	83	183	362	373	359
2.45	205	1640	690	307	52	270	337	284	259
2.50	275	1660	588	221	141	295	259	191	178

omega (rad/s)	Speed 15 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	3	3	2	2	2	2
0.15	7	7	7	7	6	6	5	5	5	5
0.20	17	16	15	14	13	11	10	9	9	9
0.25	33	34	30	27	24	21	17	15	14	14
0.30	61	60	56	50	43	35	28	23	20	20
0.35	107	104	97	86	72	58	44	34	28	28
0.40	174	170	157	138	115	90	66	48	38	37
0.45	268	262	242	212	174	134	95	65	49	48
0.50	394	384	355	310	254	192	133	87	61	59
0.55	552	539	499	436	356	268	182	113	75	73
0.60	745	727	675	591	483	362	242	144	91	87
0.65	969	946	880	774	635	475	315	181	107	104
0.70	1217	1189	1112	983	811	609	401	223	125	123
0.75	1479	1450	1361	1213	1008	761	500	271	143	146
0.80	1741	1711	1617	1454	1222	930	612	324	162	172
0.85	1987	1958	1867	1699	1445	1113	734	383	181	202
0.90	2202	2179	2099	1936	1670	1303	868	449	200	234
0.95	2382	2365	2305	2157	1890	1499	1013	522	222	272
1.00	2546	2535	2486	2359	2102	1696	1165	601	249	320
1.05	2762	2735	2668	2547	2301	1894	1318	680	271	359
1.10	2380	2450	2897	2731	2493	2086	1468	763	290	394
1.15	2380	2450	3256	2932	2682	2265	1619	851	304	425
1.20	2380	2450	2577	3174	2864	2446	1772	946	313	456
1.25	2380	2450	2577	3498	3024	2628	1930	1050	317	484
1.30	2380	2450	2577	2832	3164	2809	2099	1168	313	508
1.35	2380	2450	2577	2832	3261	2974	2282	1304	309	536
1.40	2380	2450	2577	2832	3310	3098	2474	1466	305	566
1.45	2379	2450	2577	2832	3432	3151	2681	1655	304	598
1.50	1663	1918	2577	2832	3094	3087	2883	1870	310	631
1.55	1162	1335	2088	2832	3094	2921	3057	2109	330	666
1.60	810	923	1423	2832	3094	2679	3176	2364	366	703
1.65	554	624	949	2116	3094	2484	3213	2624	420	742
1.70	351	398	605	1356	3094	2543	3143	2873	491	782
1.75	171	211	351	836	3094	2997	2952	3096	576	821
1.80	19	45	166	478	2059	2947	2642	3275	673	860
1.85	170	124	16	242	1170	2947	2242	3392	778	897
1.90	318	289	153	91	664	2800	1821	3431	888	931
1.95	430	421	353	64	360	2611	1499	3380	1002	961
2.00	489	481	496	280	162	2514	1419	3232	1116	986
2.05	487	478	501	510	37	1067	1561	2986	1227	1004
2.10	432	439	429	610	256	828	1737	2647	1333	1015
2.15	346	371	396	490	513	455	1779	2233	1432	1018
2.20	274	292	366	321	711	74	1607	1774	1521	1014
2.25	260	255	293	370	718	266	1245	1323	1599	1003
2.30	286	270	241	394	468	552	836	979	1665	986
2.35	303	292	253	295	247	768	645	884	1716	962
2.40	288	286	269	214	464	879	653	1035	1752	934
2.45	253	256	257	230	505	842	505	1251	1775	901
2.50	212	220	227	234	321	639	541	1410	1782	865

omega (rad/s)	Speed 15 [kn]								
	Headings[deg]								
	100	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**
0.10	2	2	2	2	2	2	2	2	2
0.15	5	5	5	6	6	7	7	8	8
0.20	9	10	12	14	16	18	19	20	21
0.25	15	18	23	28	33	38	42	45	46
0.30	24	30	39	50	62	73	82	88	90
0.35	34	46	64	85	108	129	146	158	162
0.40	47	68	99	137	177	215	246	266	273
0.45	63	98	149	211	277	340	390	423	435
0.50	83	136	216	314	417	514	593	644	662
0.55	107	187	307	453	606	749	866	941	967
0.60	137	252	425	633	852	1056	1220	1328	1365
0.65	173	335	575	861	1162	1441	1667	1813	1864
0.70	219	437	756	1139	1541	1913	2212	2404	2470
0.75	273	555	969	1471	1996	2477	2858	3099	3182
0.80	333	686	1218	1866	2535	3134	3598	3889	3988
0.85	396	832	1513	2332	3153	3870	4413	4748	4861
0.90	457	999	1860	2864	3838	4661	5267	5631	5753
0.95	519	1196	2258	3453	4566	5466	6101	6468	6587
1.00	590	1432	2704	4079	5297	6222	6828	7156	7259
1.05	663	1697	3190	4713	5975	6841	7343	7583	7651
1.10	747	1991	3694	5319	6523	7229	7551	7662	7686
1.15	843	2309	4195	5833	6862	7319	7424	7400	7379
1.20	952	2645	4662	6196	6952	7120	7020	6881	6822
1.25	1074	2985	5052	6362	6793	6701	6430	6193	6103
1.30	1210	3311	5325	6328	6448	6132	5710	5382	5261
1.35	1352	3605	5455	6127	5976	5459	4885	4469	4320
1.40	1498	3836	5444	5808	5412	4695	3977	3486	3315
1.45	1642	3986	5312	5406	4769	3854	3023	2485	2303
1.50	1777	4049	5095	4933	4057	2976	2084	1543	1369
1.55	1894	4027	4818	4401	3299	2112	1241	784	662
1.60	1983	3937	4494	3817	2528	1338	656	535	563
1.65	2040	3796	4128	3199	1802	773	619	783	836
1.70	2058	3620	3724	2575	1191	640	850	965	981
1.75	2039	3417	3290	1984	810	815	972	958	929
1.80	1986	3192	2840	1475	756	952	921	781	712
1.85	1906	2945	2397	1111	870	949	727	495	405
1.90	1805	2682	1988	943	953	816	456	205	150
1.95	1688	2407	1646	936	939	599	214	226	288
2.00	1559	2133	1403	979	832	363	234	399	445
2.05	1420	1873	1273	990	663	223	364	466	475
2.10	1273	1650	1232	942	480	263	408	404	378
2.15	1117	1487	1231	840	339	322	344	242	202
2.20	953	1403	1223	709	277	307	194	103	133
2.25	781	1398	1179	580	262	216	67	231	288
2.30	605	1452	1093	481	230	76	204	357	401
2.35	429	1534	969	419	158	79	326	412	420
2.40	270	1615	824	370	57	209	370	372	357
2.45	197	1673	686	307	73	287	337	281	257
2.50	289	1693	583	216	167	303	256	193	183

omega (rad/s)	Speed 17.5 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	3	3	4	3	2	2	2	2
0.15	6	6	6	6	6	6	5	5	5	5
0.20	13	14	13	12	11	10	10	9	9	9
0.25	26	27	25	23	20	18	16	15	14	14
0.30	49	48	45	41	36	30	26	22	20	21
0.35	86	84	79	71	60	49	39	32	28	29
0.40	142	139	129	115	96	77	58	44	37	38
0.45	221	216	201	178	148	115	84	60	48	49
0.50	326	319	297	262	217	166	118	79	60	61
0.55	461	450	420	370	306	233	161	103	73	74
0.60	625	611	570	504	417	316	215	131	87	89
0.65	817	799	747	662	550	417	280	164	102	106
0.70	1036	1015	950	844	705	537	359	202	118	126
0.75	1286	1258	1178	1050	880	674	449	246	135	148
0.80	1578	1541	1437	1277	1072	827	552	295	151	174
0.85	1946	1893	1745	1533	1282	993	666	350	168	204
0.90	2179	2380	2145	1837	1512	1171	791	412	184	235
0.95	2179	2193	2720	2228	1775	1362	929	483	203	271
1.00	2179	2193	2429	2771	2094	1569	1077	560	227	317
1.05	2179	2193	2429	3559	2499	1804	1227	636	245	353
1.10	2179	2193	2429	2710	3028	2075	1380	717	260	386
1.15	2179	2193	2429	2710	3739	2380	1545	804	271	417
1.20	2179	2193	2429	2710	4638	2761	1727	898	278	447
1.25	2179	2193	2429	2710	3384	3207	1936	1003	282	474
1.30	3141	2193	2429	2710	3384	3716	2177	1124	279	496
1.35	2412	2646	2429	2710	3384	4252	2455	1265	281	524
1.40	1827	2005	2712	2710	3384	4763	2761	1434	285	552
1.45	1363	1502	2036	2710	3384	5184	3087	1634	296	582
1.50	1011	1115	1523	2649	3384	4129	3407	1866	320	612
1.55	760	839	1143	1974	3384	4129	3685	2126	359	645
1.60	599	650	871	1484	3384	4129	3881	2407	416	680
1.65	493	516	658	1123	2842	4129	3964	2697	489	716
1.70	393	410	477	835	2097	4129	3892	2982	579	754
1.75	265	304	360	568	1535	4129	3685	3241	681	791
1.80	100	157	292	354	1088	4129	3397	3459	794	828
1.85	89	44	153	313	704	4005	3169	3612	914	864
1.90	266	228	99	282	386	2609	3237	3684	1040	897
1.95	403	375	288	141	279	1692	3754	3662	1169	927
2.00	472	459	412	260	329	1046	3685	3538	1296	952
2.05	459	469	464	426	249	589	3685	3309	1420	971
2.10	372	406	460	473	273	336	3541	2985	1538	984
2.15	259	297	399	457	513	306	3317	2584	1646	990
2.20	219	223	298	430	605	283	3203	2146	1741	989
2.25	260	248	227	375	516	162	2156	1730	1823	981
2.30	274	274	242	293	407	362	936	1431	1888	966
2.35	240	250	268	239	392	693	718	1347	1937	946
2.40	213	210	244	251	379	811	518	1458	1966	921
2.45	241	217	194	264	320	636	307	1635	1978	891
2.50	283	262	189	226	271	348	83	1763	1973	857

omega (rad/s)	Speed 17.5 [kn]								
	Headings[deg]								
	100	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**
0.10	2	2	2	2	2	2	2	3	3
0.15	5	5	5	6	6	7	7	7	7
0.20	10	10	12	13	15	17	18	19	19
0.25	16	19	22	27	32	36	40	43	44
0.30	24	30	39	49	60	71	79	85	87
0.35	35	46	63	84	106	127	144	155	159
0.40	48	69	99	136	176	214	245	265	272
0.45	65	98	150	212	279	342	394	427	439
0.50	85	138	219	318	424	524	604	657	676
0.55	110	190	313	463	621	770	890	969	997
0.60	140	258	436	651	878	1091	1264	1377	1416
0.65	178	344	590	888	1203	1497	1736	1891	1945
0.70	224	447	776	1177	1602	1998	2315	2519	2589
0.75	278	566	997	1529	2088	2599	3001	3257	3345
0.80	337	698	1261	1952	2662	3295	3786	4093	4198
0.85	398	851	1577	2449	3317	4072	4643	4994	5112
0.90	457	1031	1950	3013	4037	4897	5524	5899	6022
0.95	519	1245	2374	3631	4790	5714	6352	6713	6829
1.00	594	1498	2843	4278	5526	6441	7015	7314	7404
1.05	674	1781	3350	4917	6167	6972	7403	7593	7644
1.10	766	2091	3866	5499	6627	7224	7461	7526	7535
1.15	871	2425	4363	5948	6843	7184	7230	7187	7162
1.20	989	2770	4801	6212	6818	6914	6801	6666	6611
1.25	1118	3112	5134	6275	6597	6488	6231	6007	5920
1.30	1263	3428	5331	6167	6242	5942	5537	5218	5099
1.35	1412	3700	5385	5939	5789	5290	4726	4316	4168
1.40	1564	3892	5318	5625	5243	4538	3824	3337	3167
1.45	1710	3996	5162	5239	4611	3701	2875	2343	2164
1.50	1844	4015	4944	4778	3904	2828	1947	1418	1249
1.55	1956	3961	4675	4252	3151	1975	1129	703	598
1.60	2037	3853	4360	3671	2385	1225	611	560	602
1.65	2081	3708	4000	3055	1676	718	659	830	881
1.70	2086	3534	3597	2438	1098	668	893	996	1007
1.75	2055	3335	3163	1861	782	859	998	971	937
1.80	1993	3112	2715	1380	787	984	930	780	710
1.85	1908	2866	2277	1062	913	963	725	490	401
1.90	1804	2601	1881	946	985	818	452	210	162
1.95	1687	2325	1563	969	956	595	221	236	294
2.00	1558	2050	1355	1016	836	363	244	396	438
2.05	1420	1794	1262	1019	661	233	360	449	455
2.10	1272	1579	1249	959	478	270	392	376	348
2.15	1114	1433	1263	847	343	316	318	207	168
2.20	948	1372	1257	708	284	290	161	96	143
2.25	774	1393	1209	578	264	191	71	254	310
2.30	594	1468	1114	482	222	45	228	374	416
2.35	415	1565	981	422	140	108	344	421	425
2.40	257	1653	829	373	37	233	379	373	355
2.45	199	1713	686	306	97	303	338	279	256
2.50	308	1732	582	211	192	310	253	195	188

omega (rad/s)	Speed 20 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	3	3	4	3	3	3	2	2	2	2
0.15	5	6	5	5	5	5	5	5	5	5
0.20	10	11	10	9	9	9	9	9	9	9
0.25	19	22	18	17	16	15	14	14	14	15
0.30	37	36	34	31	28	25	22	21	21	22
0.35	67	66	62	55	48	40	34	29	28	30
0.40	115	112	104	92	78	63	49	40	37	40
0.45	185	180	167	147	122	95	71	54	47	51
0.50	283	276	255	222	183	140	100	70	58	63
0.55	417	405	372	323	263	199	138	91	71	76
0.60	596	577	527	453	367	275	186	115	84	92
0.65	837	808	729	619	496	369	246	144	97	109
0.70	1174	1127	1001	832	655	483	318	178	111	128
0.75	1666	1578	1378	1109	851	618	403	218	126	151
0.80	2044	1931	1921	1493	1097	777	502	262	139	177
0.85	2496	2492	2348	2038	1414	964	614	315	153	206
0.90	2496	2492	2714	2852	1841	1190	742	376	167	235
0.95	2496	2492	2714	2947	2448	1468	890	448	182	269
1.00	2496	2492	2714	2947	3312	1823	1060	525	202	313
1.05	2496	2492	2714	2947	3470	2289	1245	603	217	347
1.10	2496	2492	2714	2947	3470	2901	1454	687	228	380
1.15	2496	2492	2714	2947	3470	3681	1706	783	236	410
1.20	3547	3766	2714	2947	3470	4695	2017	890	242	439
1.25	3029	3198	3876	2947	3470	6026	2401	1013	246	466
1.30	2568	2699	3221	2947	3470	4392	2855	1159	248	487
1.35	2137	2243	2654	3810	3470	4392	3392	1333	257	514
1.40	1725	1814	2149	3043	3470	4392	3992	1540	273	540
1.45	1336	1417	1698	2395	4634	4392	4636	1783	301	568
1.50	997	1076	1319	1861	3629	4392	5280	2061	345	596
1.55	741	810	1037	1446	2818	4392	5862	2372	405	627
1.60	591	625	810	1172	2161	4392	6309	2706	483	659
1.65	514	522	597	972	1696	4392	6565	3051	577	694
1.70	437	456	477	718	1397	4089	6614	3390	686	729
1.75	313	353	432	464	1182	3193	5638	3701	807	765
1.80	141	191	336	419	894	2510	5638	3964	941	800
1.85	115	75	163	421	504	2005	5638	4156	1082	834
1.90	313	257	93	294	338	1609	5638	4256	1230	867
1.95	471	431	283	101	476	1229	5638	4247	1381	896
2.00	532	523	441	181	444	789	5638	4122	1531	921
2.05	485	508	520	351	248	332	5413	3879	1677	941
2.10	385	417	502	466	165	360	3706	3537	1816	956
2.15	345	350	415	510	317	561	2571	3132	1942	964
2.20	383	369	345	476	432	492	1762	2734	2053	965
2.25	394	399	357	395	492	318	1146	2441	2146	960
2.30	323	356	385	341	503	389	662	2353	2218	948
2.35	192	238	352	353	464	524	348	2477	2265	931
2.40	135	124	247	372	394	555	340	2726	2287	908
2.45	256	198	119	337	346	533	413	2939	2284	881
2.50	376	328	161	236	348	513	336	3003	2258	850

omega (rad/s)	Speed 20 [kn]								
	Headings[deg]								
	100	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**
0.10	2	2	2	2	2	2	1	2	2
0.15	5	5	5	6	6	6	6	7	7
0.20	10	11	12	13	15	16	17	18	18
0.25	16	19	22	26	31	35	38	41	42
0.30	25	31	38	48	59	69	77	82	84
0.35	36	47	63	83	105	125	142	153	157
0.40	50	69	99	136	176	214	246	266	273
0.45	66	100	151	214	283	347	400	435	447
0.50	87	140	223	324	433	536	620	675	695
0.55	112	194	320	474	639	794	921	1004	1033
0.60	143	264	447	670	908	1132	1315	1434	1476
0.65	182	351	605	916	1248	1561	1814	1978	2035
0.70	229	456	797	1220	1672	2091	2427	2642	2716
0.75	283	575	1029	1594	2187	2727	3152	3422	3514
0.80	340	712	1310	2044	2794	3461	3975	4297	4406
0.85	398	874	1649	2570	3482	4270	4862	5224	5345
0.90	456	1068	2045	3161	4228	5113	5750	6123	6246
0.95	521	1298	2490	3801	4992	5917	6535	6876	6984
1.00	601	1568	2979	4459	5706	6580	7098	7354	7429
1.05	688	1866	3500	5084	6282	6996	7348	7492	7529
1.10	788	2190	4017	5618	6636	7124	7298	7339	7343
1.15	902	2534	4496	5985	6743	7007	7033	6989	6965
1.20	1026	2885	4891	6156	6652	6724	6618	6492	6439
1.25	1164	3222	5159	6147	6418	6317	6071	5853	5769
1.30	1315	3522	5287	6009	6078	5789	5390	5073	4955
1.35	1470	3763	5288	5783	5641	5146	4583	4172	4025
1.40	1625	3916	5197	5482	5104	4397	3681	3195	3026
1.45	1773	3981	5038	5107	4475	3559	2735	2209	2032
1.50	1904	3969	4827	4651	3766	2690	1820	1303	1141
1.55	2009	3898	4567	4125	3014	1849	1030	641	556
1.60	2081	3786	4256	3541	2256	1128	590	601	652
1.65	2113	3643	3895	2927	1565	686	709	881	928
1.70	2108	3473	3490	2316	1026	709	939	1030	1036
1.75	2069	3276	3054	1755	776	908	1027	987	949
1.80	2002	3054	2606	1305	829	1019	943	784	711
1.85	1913	2806	2175	1034	959	981	727	489	400
1.90	1809	2538	1794	965	1019	824	452	217	175
1.95	1692	2259	1501	1011	975	595	231	247	301
2.00	1564	1983	1328	1058	844	365	254	394	432
2.05	1426	1730	1270	1052	662	244	358	436	437
2.10	1277	1526	1280	980	479	276	378	352	320
2.15	1118	1398	1302	857	349	312	295	175	136
2.20	949	1361	1296	712	292	275	130	100	158
2.25	772	1405	1242	580	266	168	86	277	331
2.30	589	1498	1139	486	215	19	252	390	430
2.35	408	1605	996	428	125	136	361	430	431
2.40	252	1698	837	377	27	257	388	373	354
2.45	209	1758	689	305	121	320	339	277	256
2.50	329	1774	585	205	216	318	250	197	194

omega (rad/s)	Speed 22.5 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	2	3	4	2	3	3	3	2	2	2
0.15	4	5	4	4	4	5	5	5	5	5
0.20	7	10	7	7	7	8	8	9	9	10
0.25	16	16	14	13	12	12	13	14	15	16
0.30	35	34	31	26	22	19	19	20	21	23
0.35	70	68	61	51	40	32	27	27	29	32
0.40	128	123	110	91	70	52	40	36	37	42
0.45	220	211	187	153	116	83	58	47	47	53
0.50	361	344	303	245	183	128	84	60	57	65
0.55	574	547	475	379	277	189	120	77	68	79
0.60	898	851	732	567	407	271	166	98	80	94
0.65	1150	1311	1108	840	585	379	226	123	91	112
0.70	1808	1692	1688	1230	827	518	301	154	103	131
0.75	2763	2704	2150	1824	1164	698	393	192	115	154
0.80	3160	3214	3015	2277	1640	931	505	235	126	180
0.85	3160	3214	3227	3260	2328	1237	640	289	136	208
0.90	3160	3214	3227	3527	3350	1648	805	353	147	236
0.95	3160	3214	3227	3527	3832	2204	1009	433	160	266
1.00	3160	3214	3227	3527	3933	2967	1264	519	176	309
1.05	4329	3214	3227	3527	3933	4027	1565	608	186	342
1.10	3920	4094	3227	3527	3933	5527	1939	711	194	374
1.15	3607	3730	4265	3527	3933	4876	2412	833	200	403
1.20	3312	3412	3815	5087	3933	4876	3021	975	205	431
1.25	3008	3093	3420	4378	3933	4876	3770	1146	212	459
1.30	2662	2743	3033	3790	3933	4876	4698	1349	223	478
1.35	2268	2346	2620	3264	5215	4876	5821	1598	245	505
1.40	1840	1917	2173	2741	4313	4876	7151	1884	279	530
1.45	1407	1493	1738	2225	3553	4876	8679	2220	327	556
1.50	1018	1109	1368	1755	2865	4876	5998	2600	392	583
1.55	732	802	1055	1423	2248	5449	5998	3024	474	611
1.60	587	617	780	1191	1744	4304	5998	3471	572	642
1.65	533	545	597	925	1470	3371	5998	3936	687	674
1.70	468	491	531	655	1337	2617	5998	4396	817	707
1.75	334	377	473	521	1097	2067	5998	4824	961	741
1.80	153	198	347	492	727	1763	5998	5190	1117	775
1.85	241	176	164	417	462	1634	5998	5455	1284	808
1.90	481	411	189	262	457	1439	4996	5614	1458	839
1.95	643	602	421	109	454	1018	4025	5616	1636	868
2.00	684	678	597	260	335	493	3267	5458	1814	893
2.05	638	652	664	465	150	367	2701	5153	1988	914
2.10	593	598	635	598	144	552	2279	4757	2153	929
2.15	605	595	582	631	337	537	1899	4370	2304	939
2.20	623	619	571	591	497	343	1466	4194	2435	942
2.25	570	597	591	546	585	117	928	4427	2542	940
2.30	421	481	573	542	592	190	372	5145	2620	931
2.35	201	282	475	555	548	361	387	4951	2665	916
2.40	68	56	299	532	507	487	639	4592	2677	896
2.45	290	204	78	443	501	558	620	4399	2653	871
2.50	473	402	157	285	507	569	405	4282	2594	843

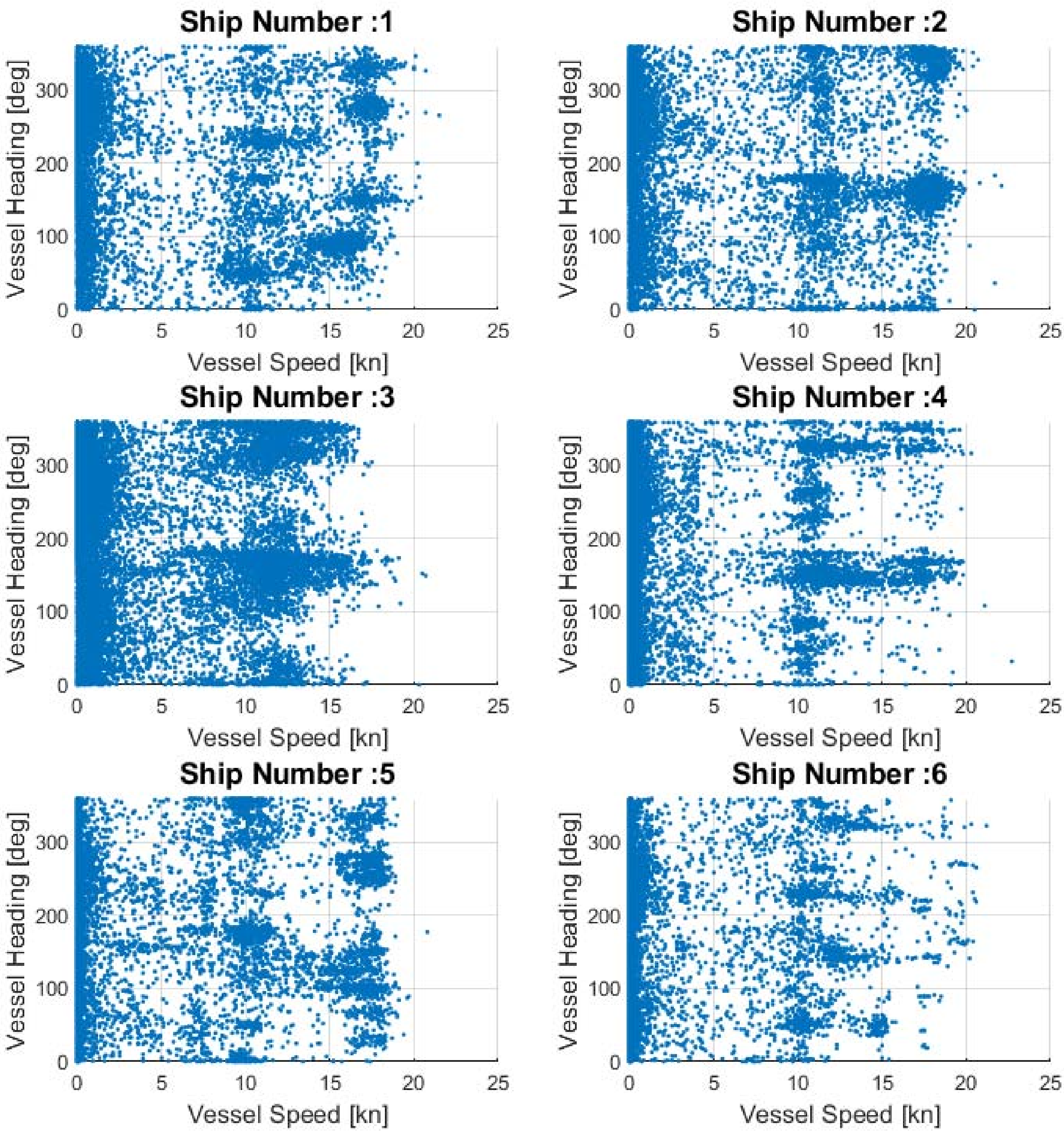
omega (rad/s)	Speed 22.5 [kn]								
	Headings[deg]								
	100	110	120	130	140	150	160	170	180
0.10	2	2	2	2	2	2	3	2	2
0.15	5	5	5	6	6	6	6	6	6
0.20	10	11	12	13	14	15	16	17	17
0.25	17	19	22	26	30	34	37	39	40
0.30	26	31	38	47	58	68	76	81	83
0.35	37	47	63	83	104	125	143	154	158
0.40	51	70	100	137	178	217	249	271	278
0.45	68	101	153	218	288	356	411	447	459
0.50	89	142	227	332	446	553	642	699	720
0.55	115	198	328	488	661	824	957	1045	1076
0.60	147	270	459	691	941	1178	1372	1499	1543
0.65	186	359	622	948	1300	1631	1899	2072	2132
0.70	233	464	820	1269	1748	2191	2544	2770	2848
0.75	286	585	1065	1665	2291	2859	3304	3586	3682
0.80	341	728	1365	2141	2927	3623	4158	4490	4603
0.85	398	902	1724	2691	3641	4455	5060	5426	5548
0.90	456	1110	2141	3304	4404	5300	5930	6293	6410
0.95	525	1355	2605	3959	5162	6065	6646	6955	7050
1.00	610	1640	3108	4615	5834	6640	7091	7304	7366
1.05	705	1950	3635	5209	6325	6943	7231	7345	7374
1.10	813	2285	4145	5680	6580	6986	7131	7166	7169
1.15	933	2636	4594	5965	6614	6844	6870	6832	6810
1.20	1065	2987	4937	6065	6501	6573	6476	6355	6304
1.25	1208	3315	5145	6021	6276	6184	5942	5725	5640
1.30	1366	3593	5221	5880	5951	5665	5263	4945	4826
1.35	1525	3803	5194	5665	5523	5022	4453	4041	3893
1.40	1683	3920	5099	5374	4987	4270	3549	3064	2896
1.45	1830	3956	4945	5003	4353	3430	2607	2086	1912
1.50	1958	3927	4742	4545	3643	2564	1705	1201	1045
1.55	2056	3850	4485	4015	2892	1737	948	601	539
1.60	2118	3739	4174	3428	2141	1047	594	653	709
1.65	2142	3600	3810	2814	1470	677	765	934	978
1.70	2128	3432	3400	2210	974	759	988	1066	1068
1.75	2083	3237	2961	1667	790	959	1058	1006	965
1.80	2013	3012	2515	1250	879	1056	959	791	717
1.85	1925	2761	2090	1028	1008	1003	732	491	402
1.90	1821	2489	1726	999	1055	834	455	226	188
1.95	1705	2207	1461	1059	998	598	241	258	308
2.00	1577	1931	1322	1103	855	370	264	394	428
2.05	1438	1682	1293	1087	667	256	358	425	422
2.10	1288	1490	1321	1003	484	283	367	330	294
2.15	1127	1381	1348	870	356	309	274	144	105
2.20	955	1367	1339	719	301	262	101	112	176
2.25	775	1431	1278	585	269	147	107	300	352
2.30	589	1538	1165	492	209	20	276	407	445
2.35	406	1652	1014	434	111	164	379	438	436
2.40	253	1748	847	381	33	280	397	374	353
2.45	224	1807	695	305	145	336	340	275	255
2.50	352	1819	590	199	240	327	247	200	199

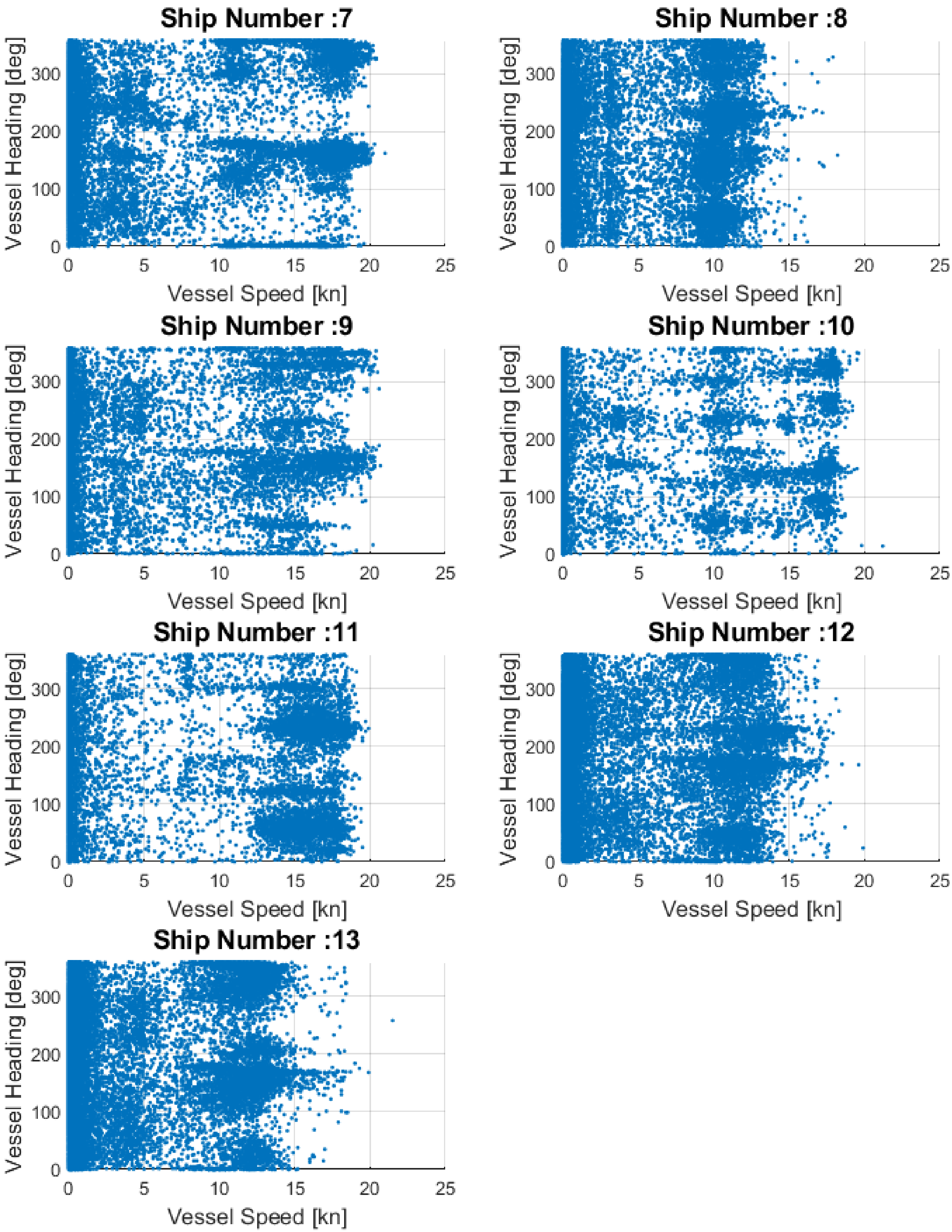
omega (rad/s)	Speed 25 [kn]									
	Headings [deg]									
	0	10	20	30	40	50	60	70	80	90
0.10	**2**	**3**	**6**	**2**	**2**	**2**	**3**	**3**	**3**	**3**
0.15	**3**	**4**	**3**	**3**	**4**	**4**	**5**	**5**	**6**	**6**
0.20	**10**	**13**	**8**	**7**	**6**	**6**	**7**	**9**	**10**	**11**
0.25	**27**	**26**	**22**	**17**	**12**	**10**	**11**	**13**	**15**	**17**
0.30	**60**	**58**	**49**	**39**	**27**	**18**	**15**	**18**	**22**	**25**
0.35	**119**	**114**	**98**	**77**	**53**	**33**	**22**	**24**	**29**	**34**
0.40	**219**	**208**	**179**	**139**	**96**	**58**	**34**	**31**	**37**	**44**
0.45	**382**	**363**	**311**	**238**	**163**	**98**	**53**	**39**	**46**	**55**
0.50	**646**	**611**	**516**	**391**	**262**	**156**	**82**	**50**	**55**	**68**
0.55	**1077**	**1006**	**841**	**623**	**412**	**241**	**122**	**64**	**65**	**82**
0.60	**1439**	**1341**	**1358**	**976**	**627**	**358**	**178**	**83**	**75**	**97**
0.65	**2473**	**2268**	**1781**	**1524**	**939**	**519**	**252**	**107**	**85**	**114**
0.70	**3368**	**3257**	**2989**	**1955**	**1395**	**740**	**348**	**139**	**94**	**134**
0.75	**3497**	**3558**	**3727**	**3122**	**2071**	**1042**	**472**	**179**	**103**	**157**
0.80	**3497**	**3558**	**3727**	**3906**	**2588**	**1462**	**631**	**228**	**110**	**183**
0.85	**3497**	**3558**	**3727**	**3906**	**3942**	**2035**	**832**	**290**	**117**	**210**
0.90	**3497**	**3558**	**3727**	**3906**	**4577**	**2852**	**1087**	**368**	**124**	**237**
0.95	**3497**	**3558**	**3727**	**3906**	**4577**	**4018**	**1423**	**467**	**134**	**266**
1.00	**4077**	**4238**	**3727**	**3906**	**4577**	**4902**	**1854**	**576**	**146**	**309**
1.05	**3877**	**3982**	**4458**	**3906**	**4577**	**5510**	**2398**	**695**	**153**	**340**
1.10	**3737**	**3809**	**4142**	**5294**	**4577**	**5510**	**3098**	**837**	**158**	**371**
1.15	**3593**	**3653**	**3895**	**4730**	**4577**	**5510**	**4015**	**1012**	**165**	**400**
1.20	**3401**	**3462**	**3680**	**4308**	**6700**	**5510**	**5224**	**1222**	**173**	**428**
1.25	**3130**	**3200**	**3430**	**3955**	**5702**	**5510**	**6821**	**1473**	**188**	**455**
1.30	**2773**	**2847**	**3098**	**3607**	**4977**	**5510**	**8962**	**1779**	**218**	**473**
1.35	**2340**	**2418**	**2672**	**3208**	**4376**	**5510**	**6673**	**2152**	**259**	**498**
1.40	**1860**	**1950**	**2206**	**2706**	**3819**	**7714**	**6673**	**2581**	**314**	**523**
1.45	**1379**	**1481**	**1764**	**2190**	**3250**	**6336**	**6673**	**3079**	**385**	**548**
1.50	**961**	**1057**	**1356**	**1772**	**2631**	**5235**	**6673**	**3646**	**472**	**572**
1.55	**684**	**746**	**995**	**1453**	**2051**	**4314**	**6673**	**4277**	**576**	**599**
1.60	**596**	**613**	**734**	**1150**	**1688**	**3479**	**6673**	**4961**	**697**	**627**
1.65	**596**	**601**	**625**	**861**	**1513**	**2701**	**6673**	**5672**	**835**	**657**
1.70	**534**	**562**	**605**	**677**	**1302**	**2054**	**6673**	**6406**	**989**	**688**
1.75	**349**	**410**	**541**	**620**	**1004**	**1733**	**6525**	**7102**	**1159**	**721**
1.80	**159**	**183**	**371**	**579**	**743**	**1706**	**5145**	**7718**	**1342**	**753**
1.85	**398**	**306**	**158**	**465**	**629**	**1595**	**4048**	**8198**	**1538**	**785**
1.90	**682**	**602**	**326**	**266**	**589**	**1263**	**3180**	**8482**	**1742**	**815**
1.95	**856**	**810**	**608**	**167**	**506**	**838**	**2562**	**8524**	**1950**	**843**
2.00	909	895	797	409	346	565	2240	8312	2159	868
2.05	897	894	869	643	155	541	2153	6929	2362	889
2.10	892	882	863	779	238	540	2059	6929	2553	906
2.15	904	895	850	815	471	445	1728	6685	2727	917
2.20	877	887	854	800	649	274	1148	2810	2876	922
2.25	757	804	845	789	734	106	548	6929	2994	921
2.30	539	620	770	794	742	229	413	6720	3076	914
2.35	258	358	610	775	718	429	601	5957	3117	902
2.40	58	73	377	702	707	580	614	4667	3115	885
2.45	334	229	108	559	705	656	458	4105	3069	862
2.50	570	478	177	353	685	662	233	3260	2982	836

omega (rad/s)	Speed 25 [kn]								
	Headings[deg]								
	100	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**
0.10	2	2	2	2	2	2	3	2	2
0.15	6	6	6	6	6	6	6	6	6
0.20	11	11	12	13	14	15	16	17	18
0.25	18	20	22	26	30	34	37	40	40
0.30	27	32	38	48	58	68	77	83	85
0.35	39	48	63	84	106	128	146	158	162
0.40	53	71	101	140	183	224	257	280	287
0.45	70	102	156	224	298	368	426	464	478
0.50	91	145	233	343	462	576	669	730	751
0.55	117	203	338	505	686	858	1000	1093	1125
0.60	150	276	472	716	980	1231	1436	1569	1616
0.65	190	367	640	984	1357	1706	1988	2171	2233
0.70	237	473	847	1322	1828	2293	2663	2899	2981
0.75	289	597	1105	1740	2397	2989	3452	3744	3843
0.80	342	747	1423	2239	3058	3777	4327	4667	4781
0.85	398	932	1801	2809	3790	4621	5230	5594	5714
0.90	458	1154	2235	3439	4559	5450	6061	6404	6513
0.95	530	1413	2714	4100	5296	6158	6689	6962	7044
1.00	621	1709	3227	4741	5909	6637	7027	7207	7259
1.05	722	2031	3755	5293	6315	6851	7100	7201	7228
1.10	837	2374	4248	5696	6493	6854	6991	7027	7032
1.15	964	2730	4660	5913	6493	6715	6747	6713	6692
1.20	1101	3077	4953	5970	6383	6460	6367	6246	6194
1.25	1250	3391	5111	5917	6171	6080	5836	5615	5530
1.30	1413	3644	5155	5783	5855	5562	5153	4830	4710
1.35	1576	3825	5118	5578	5427	4914	4337	3921	3772
1.40	1735	3915	5027	5292	4887	4156	3430	2945	2777
1.45	1882	3932	4881	4919	4247	3313	2492	1975	1803
1.50	2005	3895	4682	4456	3533	2452	1604	1114	964
1.55	2097	3818	4425	3919	2783	1640	883	585	546
1.60	2151	3711	4110	3329	2041	985	618	713	771
1.65	2167	3575	3740	2716	1393	689	825	990	1030
1.70	2148	3409	3325	2120	943	817	1038	1105	1103
1.75	2100	3212	2883	1597	821	1013	1093	1029	984
1.80	2030	2983	2438	1216	935	1096	978	802	725
1.85	1941	2728	2023	1039	1060	1027	741	495	407
1.90	1839	2452	1676	1043	1094	846	460	236	202
1.95	1724	2167	1440	1112	1023	605	253	269	316
2.00	1596	1891	1333	1151	870	377	275	395	425
2.05	1457	1648	1329	1124	675	268	358	415	408
2.10	1305	1469	1369	1028	490	291	357	310	270
2.15	1141	1379	1399	886	365	307	255	115	76
2.20	966	1386	1385	728	310	251	74	131	196
2.25	783	1467	1316	592	272	129	131	323	373
2.30	594	1586	1193	500	205	43	299	424	459
2.35	410	1706	1033	442	99	190	397	447	442
2.40	261	1802	859	386	48	303	406	375	352
2.45	243	1858	703	305	168	352	342	273	254
2.50	375	1866	598	193	263	335	245	203	204

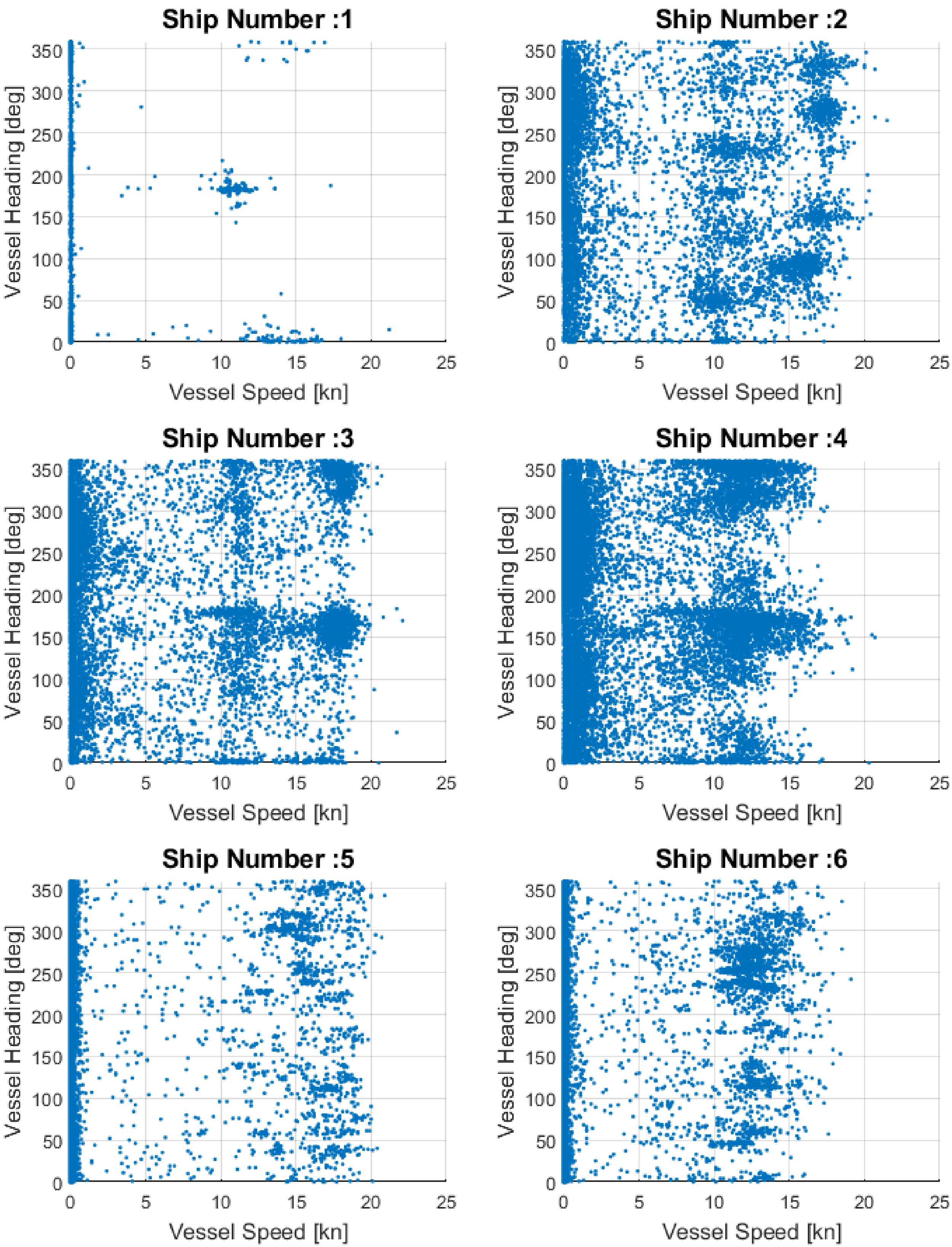
2. Vessel Operational Profiles

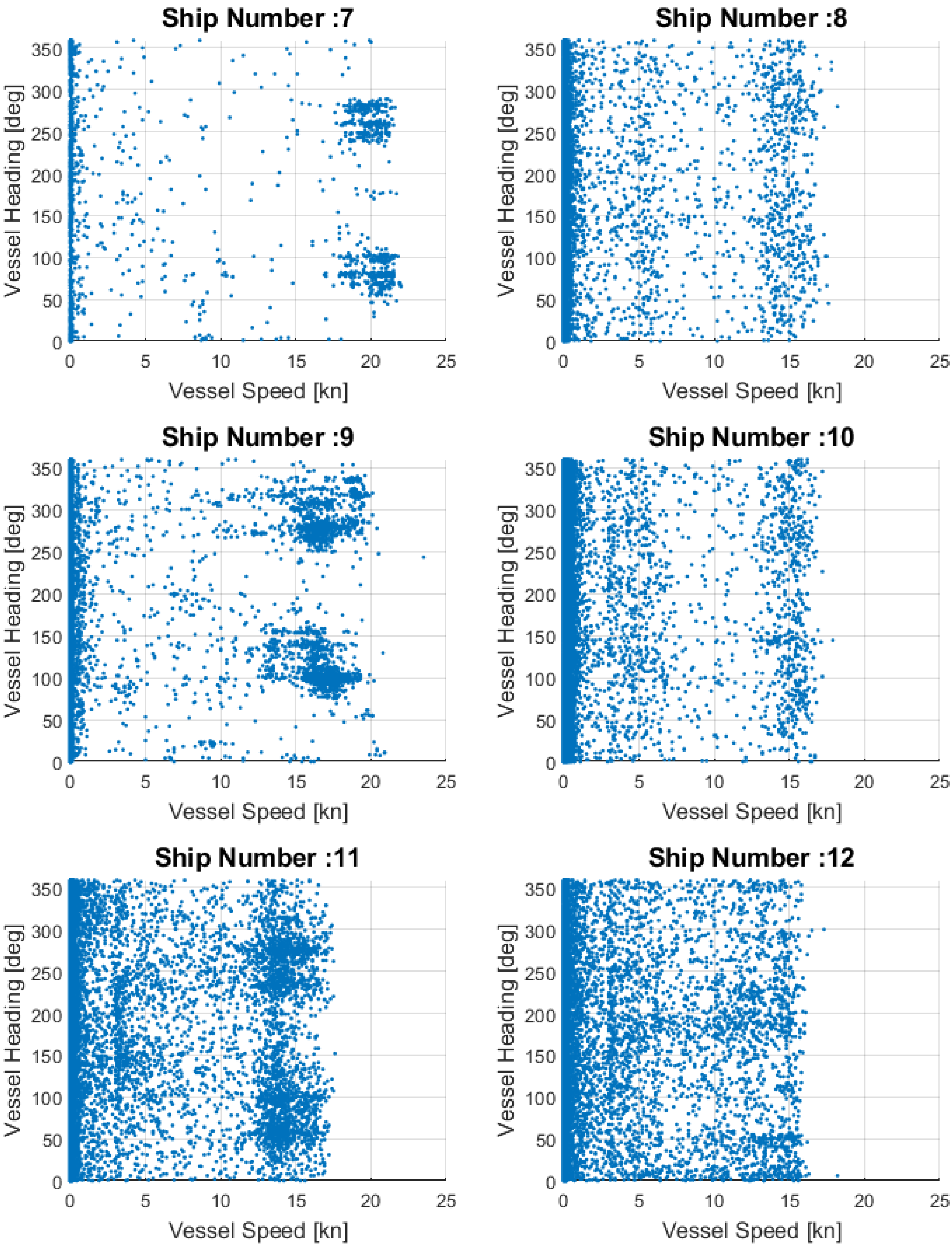
2.1. Scatter Diagrams for FCS5009s in Gulf of Mexico

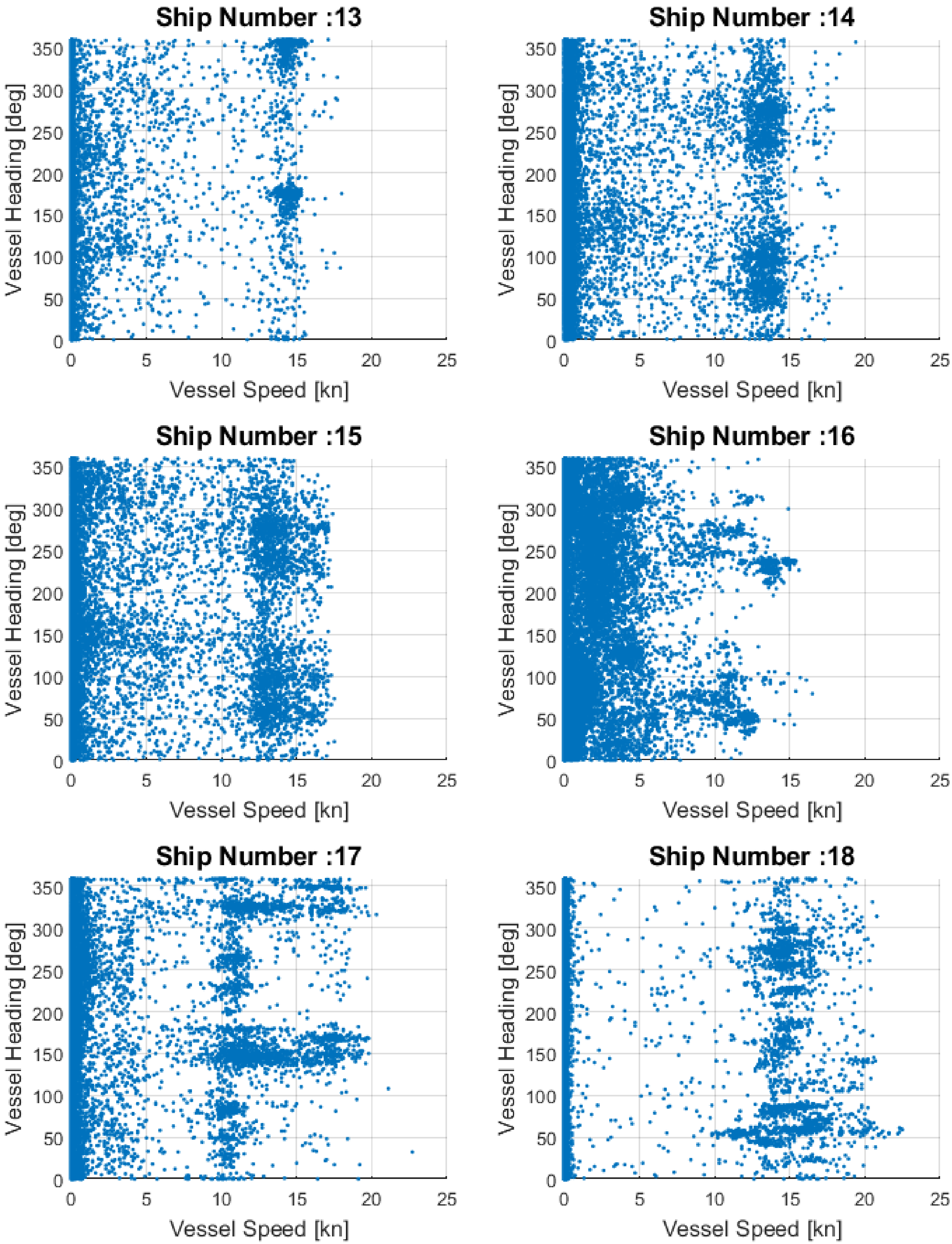


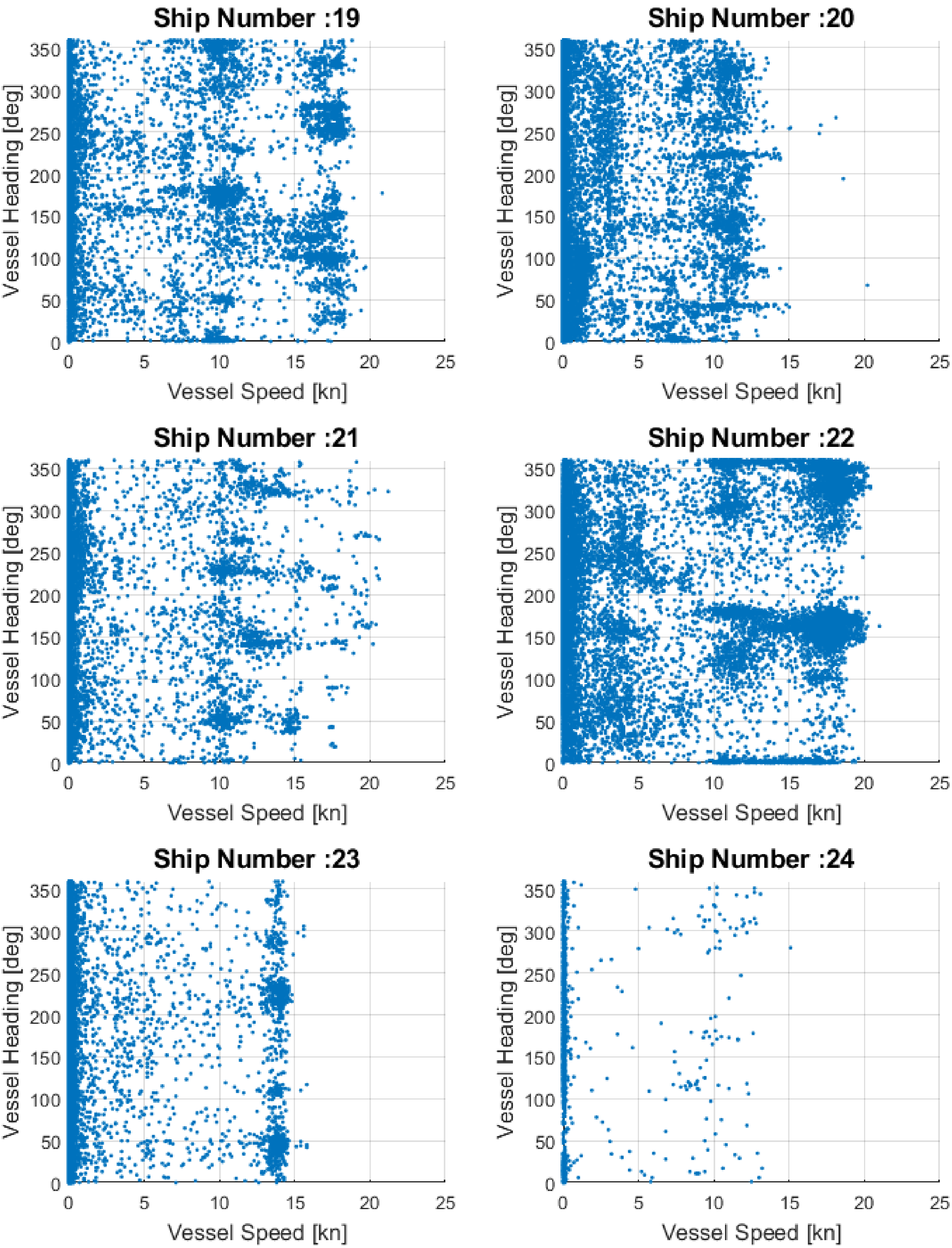

Ship Number :7
Ship Number :8
Ship Number :9
Ship Number :10
Ship Number :11
Ship Number :12
Ship Number :13
Vessel Heading [deg]
Vessel Speed [kn]
0
100
200
300
0
5
10
15
20
25

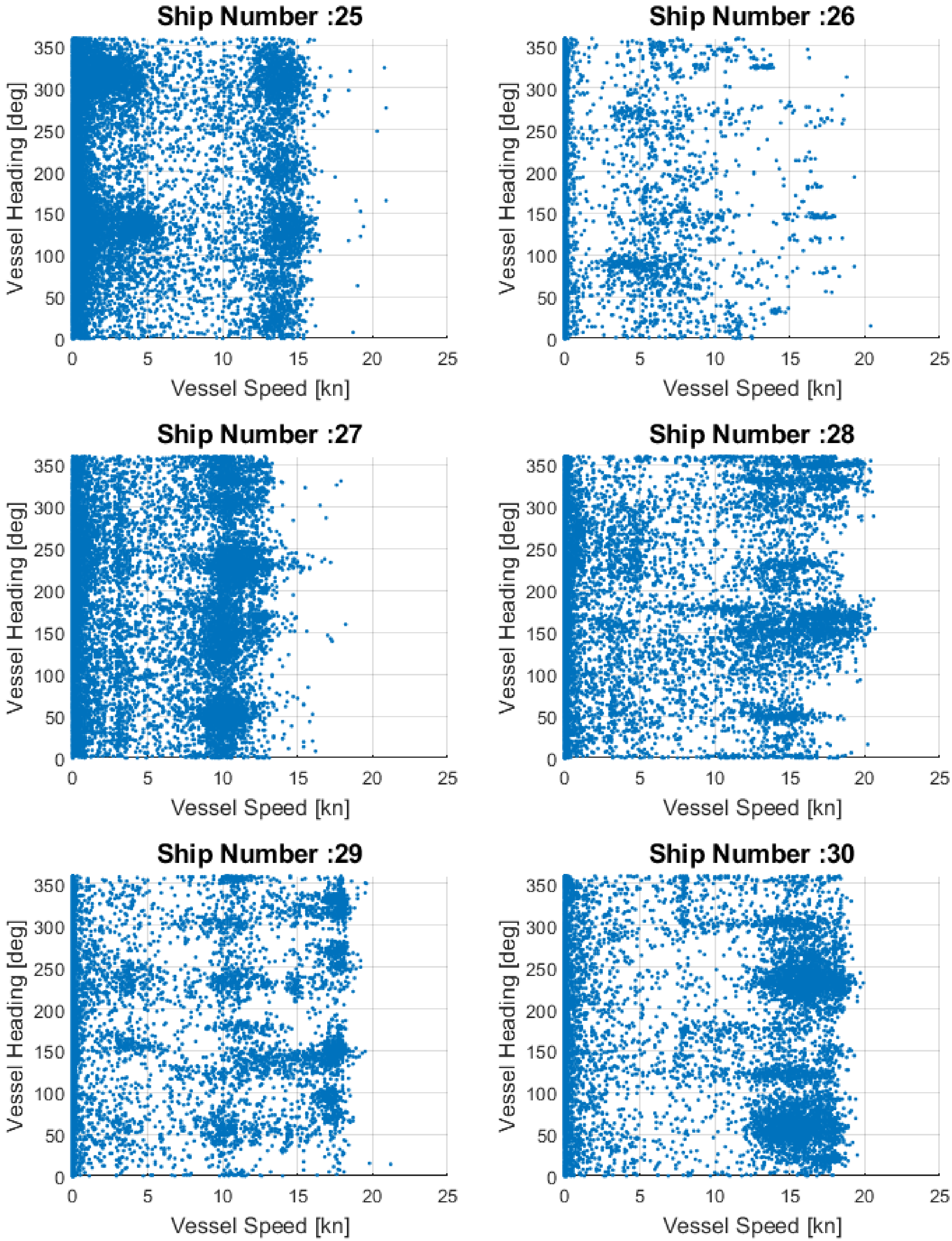
2.2. Scatter Diagrams for FCS5009s worldwide

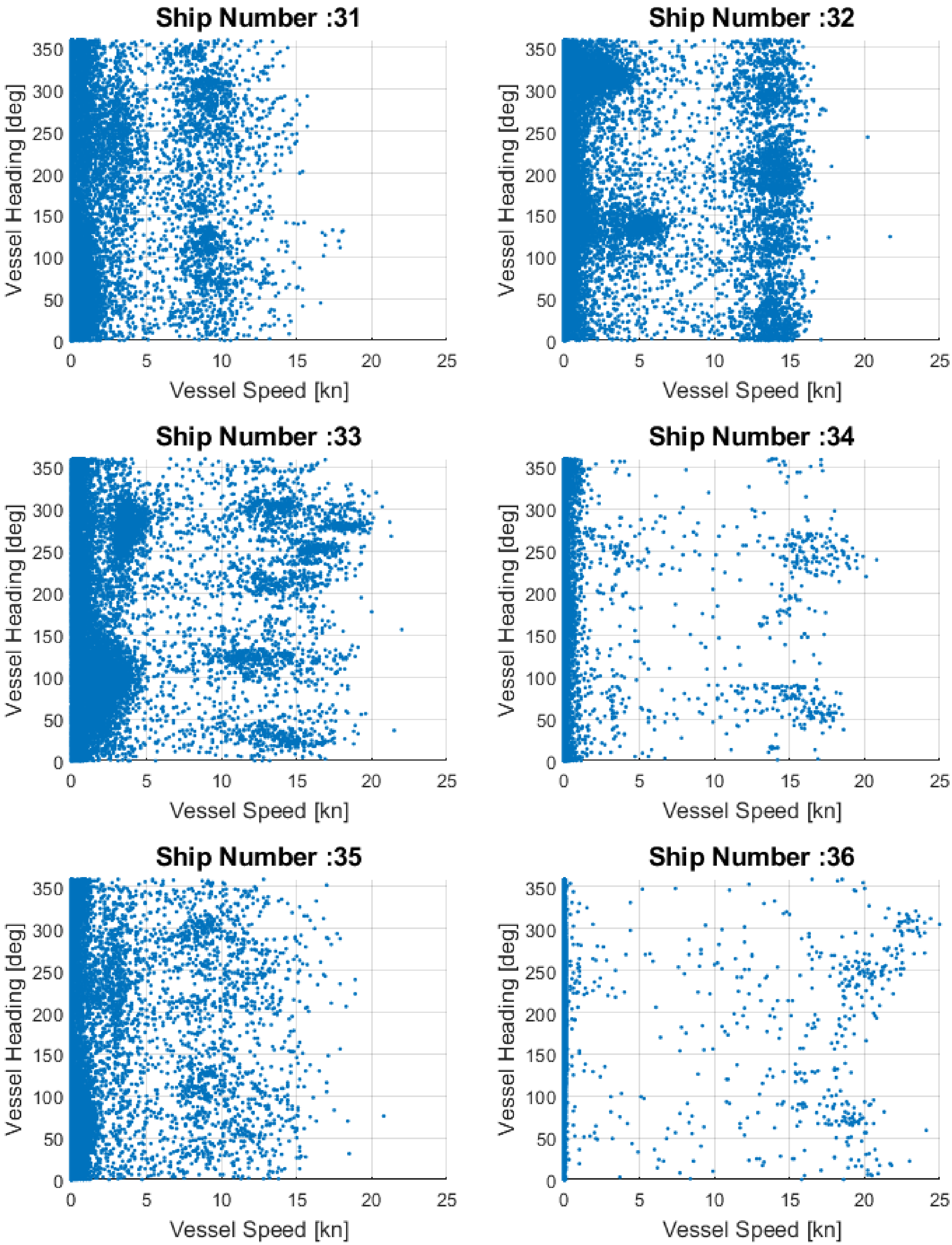


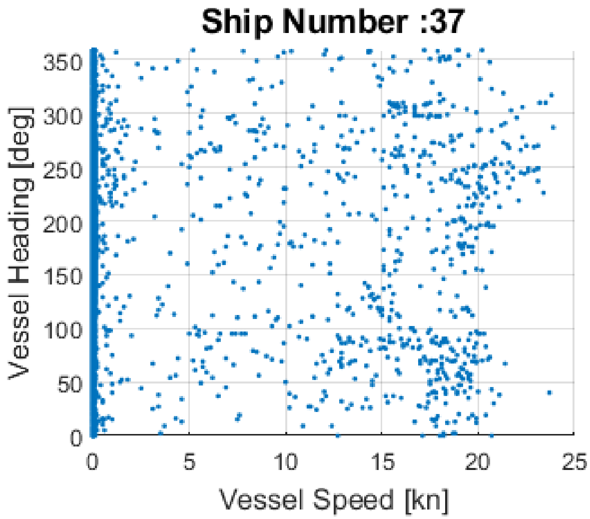

Ship Number :7
Ship Number :8
Ship Number :9
Ship Number :10
Ship Number :11
Ship Number :12
Vessel Heading [deg]
Vessel Speed [kn]
0
50
100
150
200
250
300
350
0
5
10
15
20
25

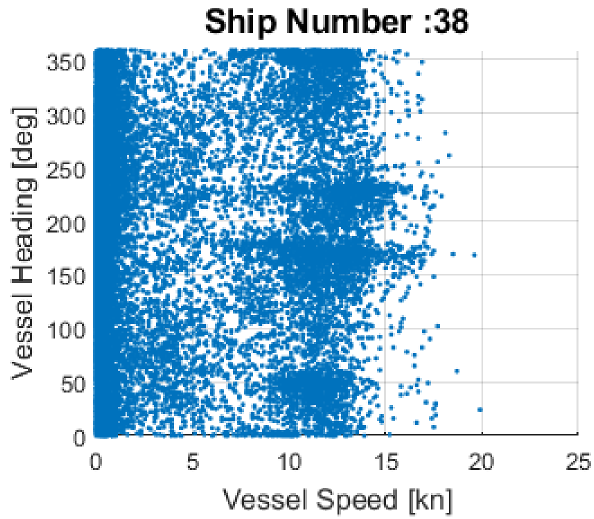

Ship Number :13
Vessel Heading [deg]
Vessel Speed [kn]
Ship Number :14
Vessel Heading [deg]
Vessel Speed [kn]
Ship Number :15
Vessel Heading [deg]
Vessel Speed [kn]
Ship Number :16
Vessel Heading [deg]
Vessel Speed [kn]
Ship Number :17
Vessel Heading [deg]
Vessel Speed [kn]
Ship Number :18
Vessel Heading [deg]
Vessel Speed [kn]

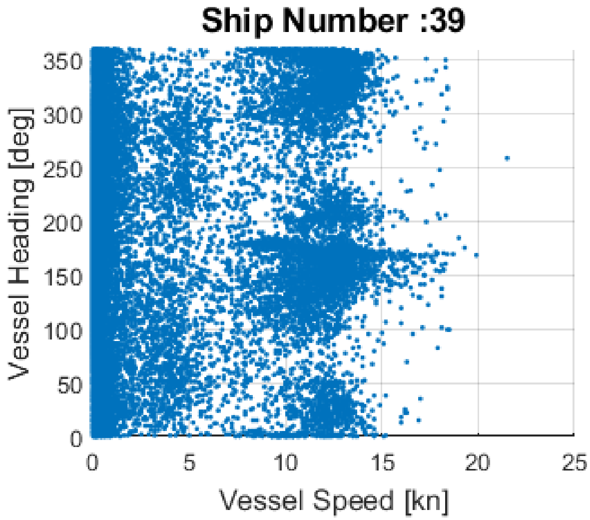

Ship Number :19
Ship Number :20
Ship Number :21
Ship Number :22
Ship Number :23
Ship Number :24
Vessel Heading [deg]
Vessel Speed [kn]
0
50
100
150
200
250
300
350
0
5
10
15
20
25

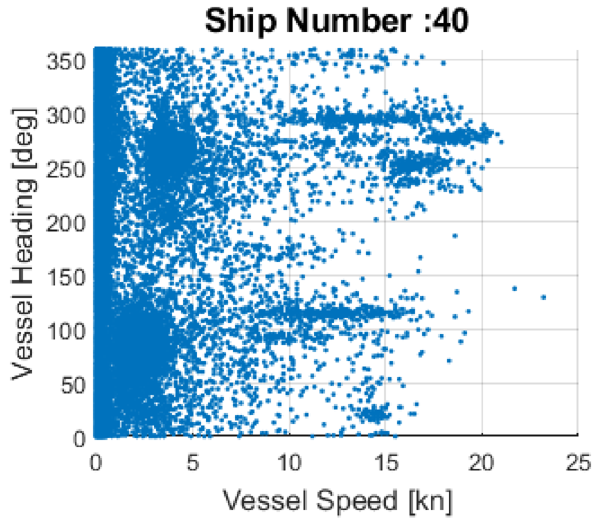

Ship Number :25
Ship Number :26
Ship Number :27
Ship Number :28
Ship Number :29
Ship Number :30
Vessel Heading [deg]
Vessel Speed [kn]
0
50
100
150
200
250
300
350
0
5
10
15
20
25

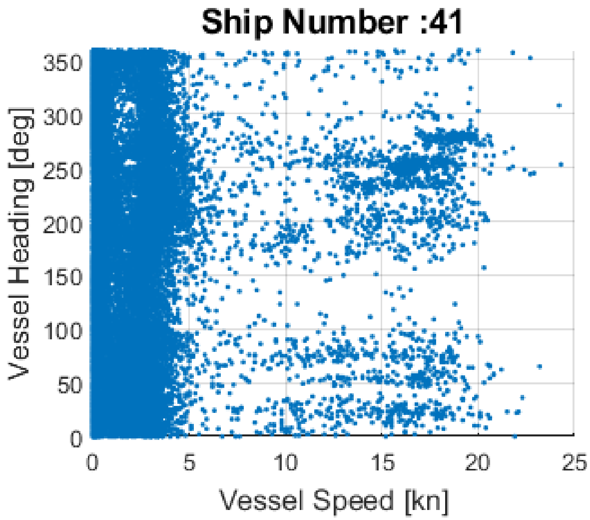

Ship Number :31
Ship Number :32
Ship Number :33
Ship Number :34
Ship Number :35
Ship Number :36
Vessel Heading [deg]
Vessel Speed [kn]
0
50
100
150
200
250
300
350
5
10
15
20
25

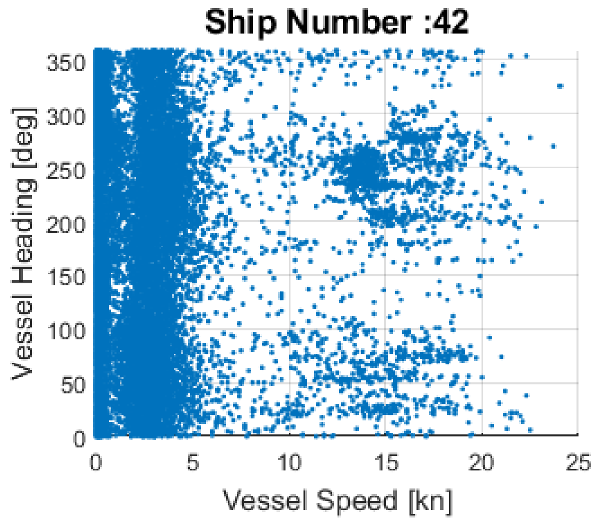

Ship Number :37
Vessel Heading [deg]
Vessel Speed [kn]

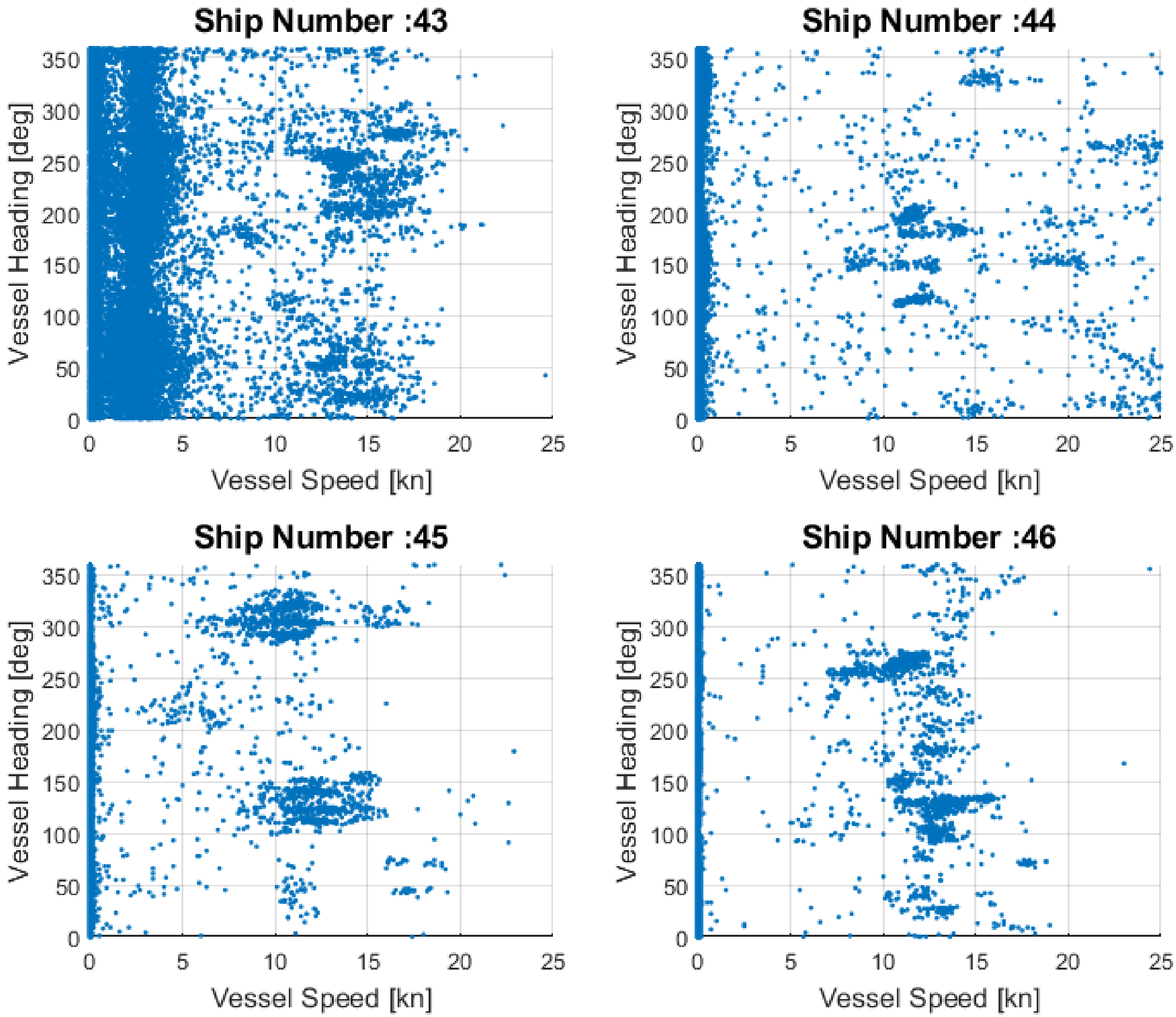

Ship Number :38
Vessel Heading [deg]
Vessel Speed [kn]


Ship Number :39
Vessel Heading [deg]
Vessel Speed [kn]


Ship Number :40
Vessel Heading [deg]
Vessel Speed [kn]

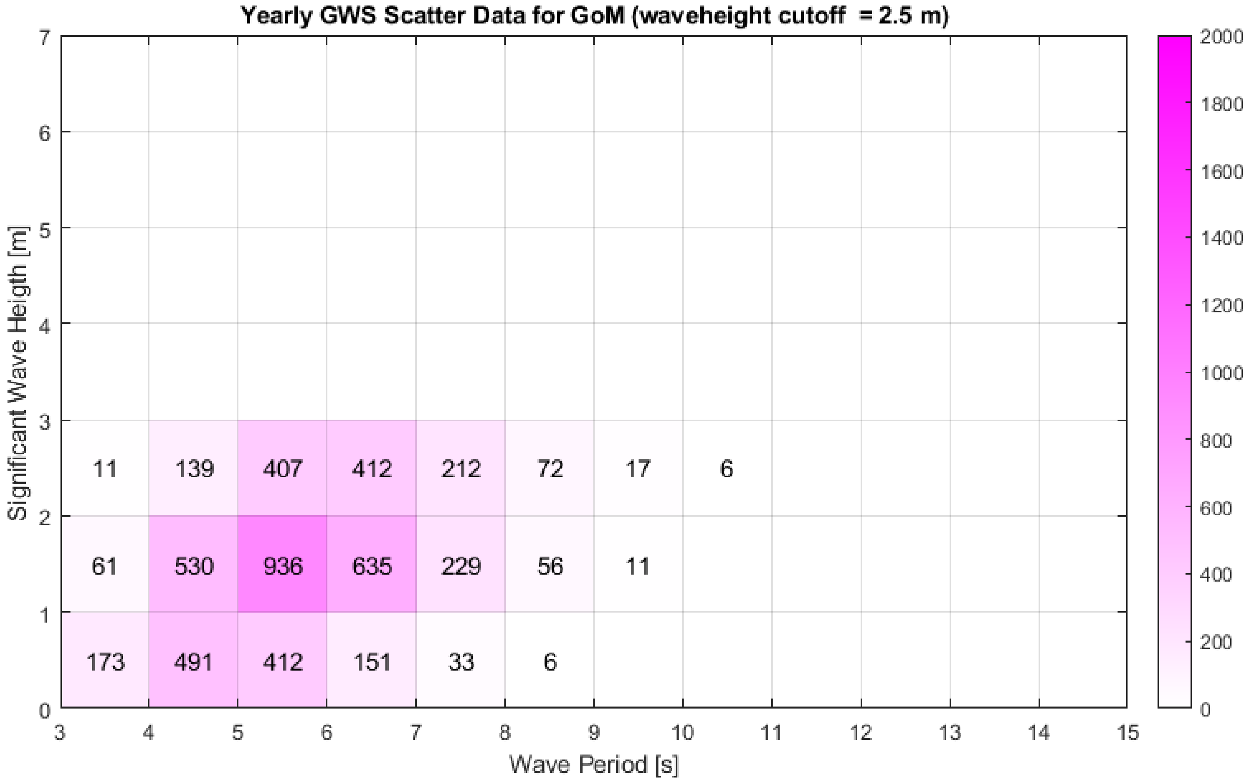

Ship Number :41
Vessel Heading [deg]
Vessel Speed [kn]


Ship Number :42
Vessel Heading [deg]
Vessel Speed [kn]

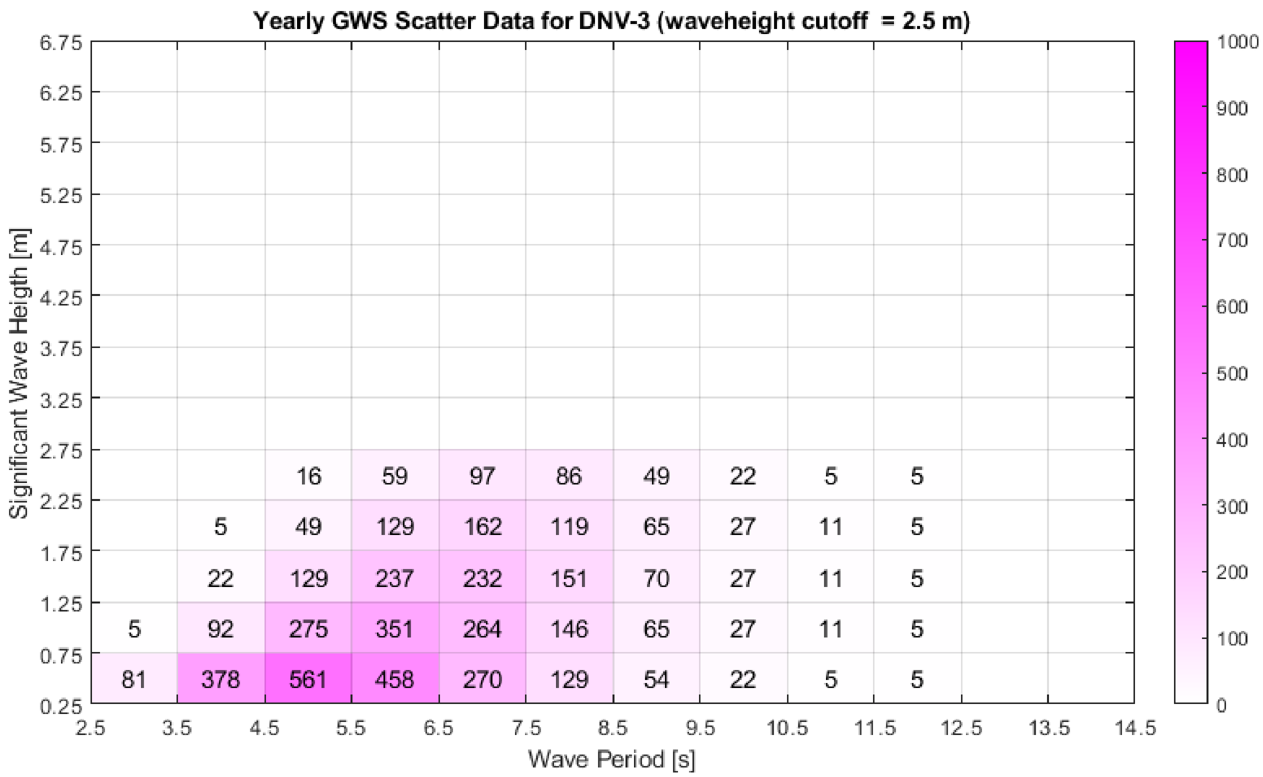

Ship Number :43
Ship Number :44
Ship Number :45
Ship Number :46
Vessel Heading [deg]
Vessel Speed [kn]
0
50
100
150
200
250
300
350
0
5
10
15
20
25

3. Sea State Scatter Diagrams

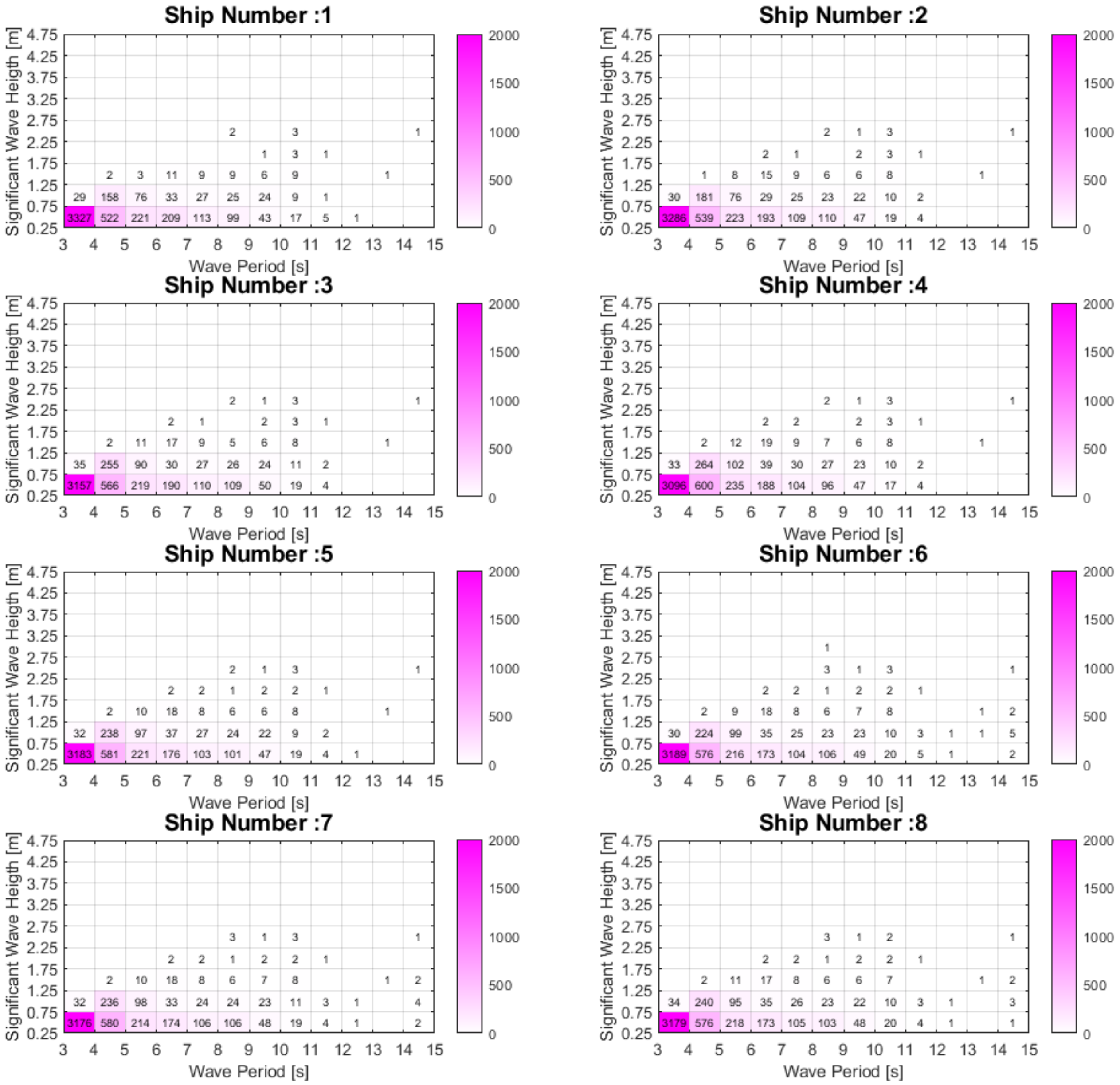
3.1. GWS Scatter Data for GoM (cut-off at 2.5 m wave height)

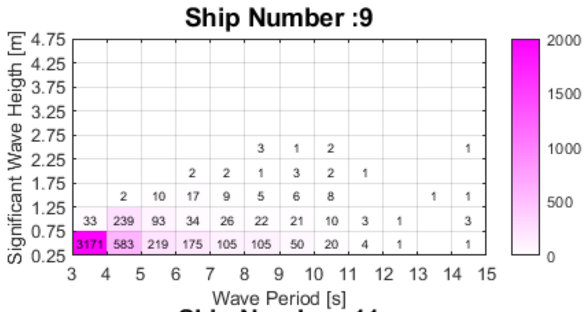


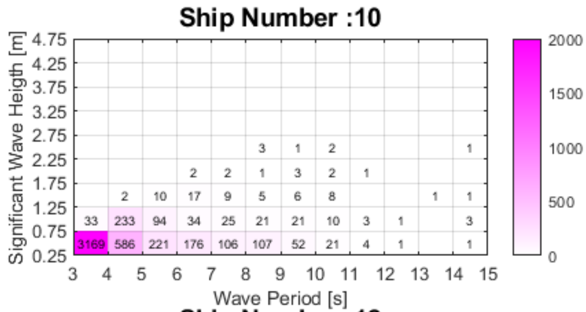
3.2. GWS Scatter Data for DNV-3 (cut-off at 2.5 m wave height)

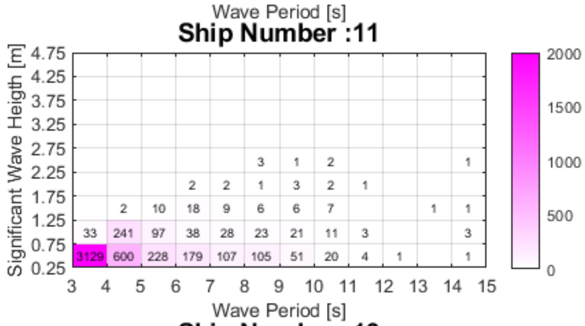


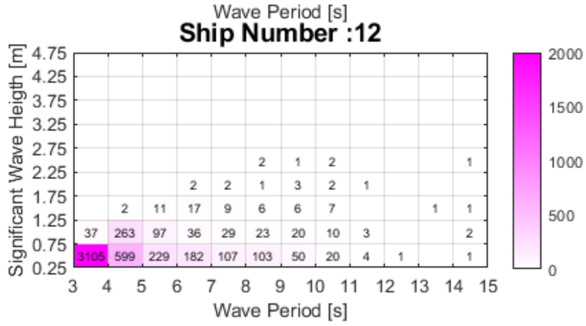
3.3. Remote Monitoring Data for FCS5009s in GoM

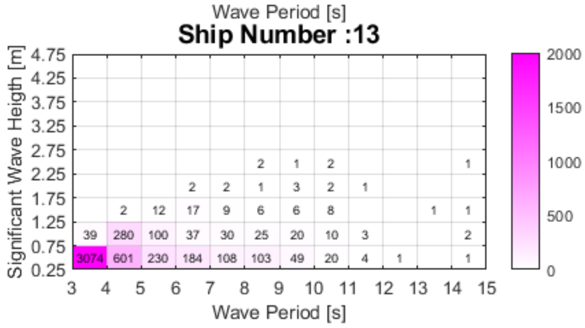



Ship Number :9
Significant Wave Heigth [m]
Wave Period [s]

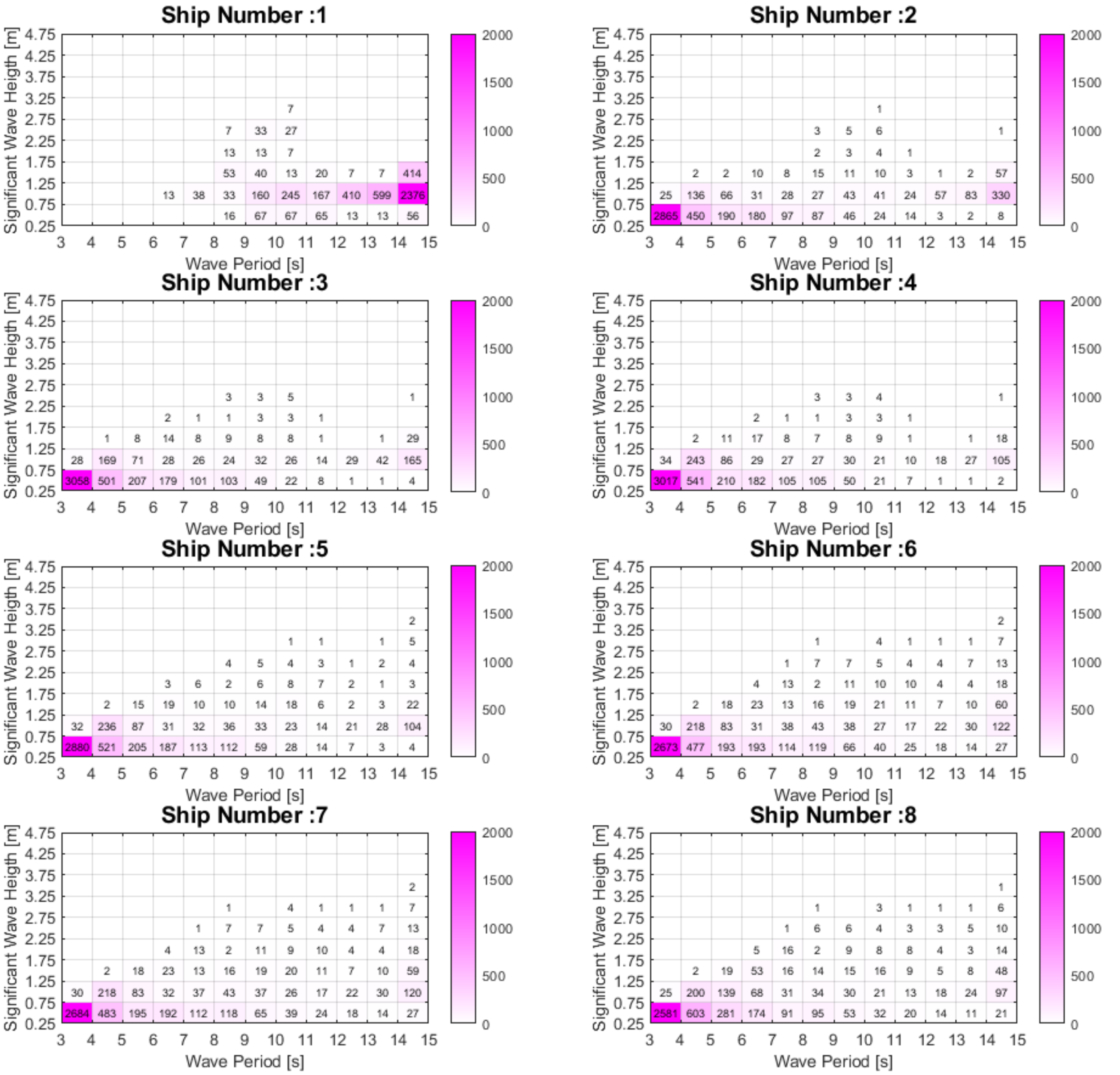

Ship Number :10
Significant Wave Heigth [m]
Wave Period [s]

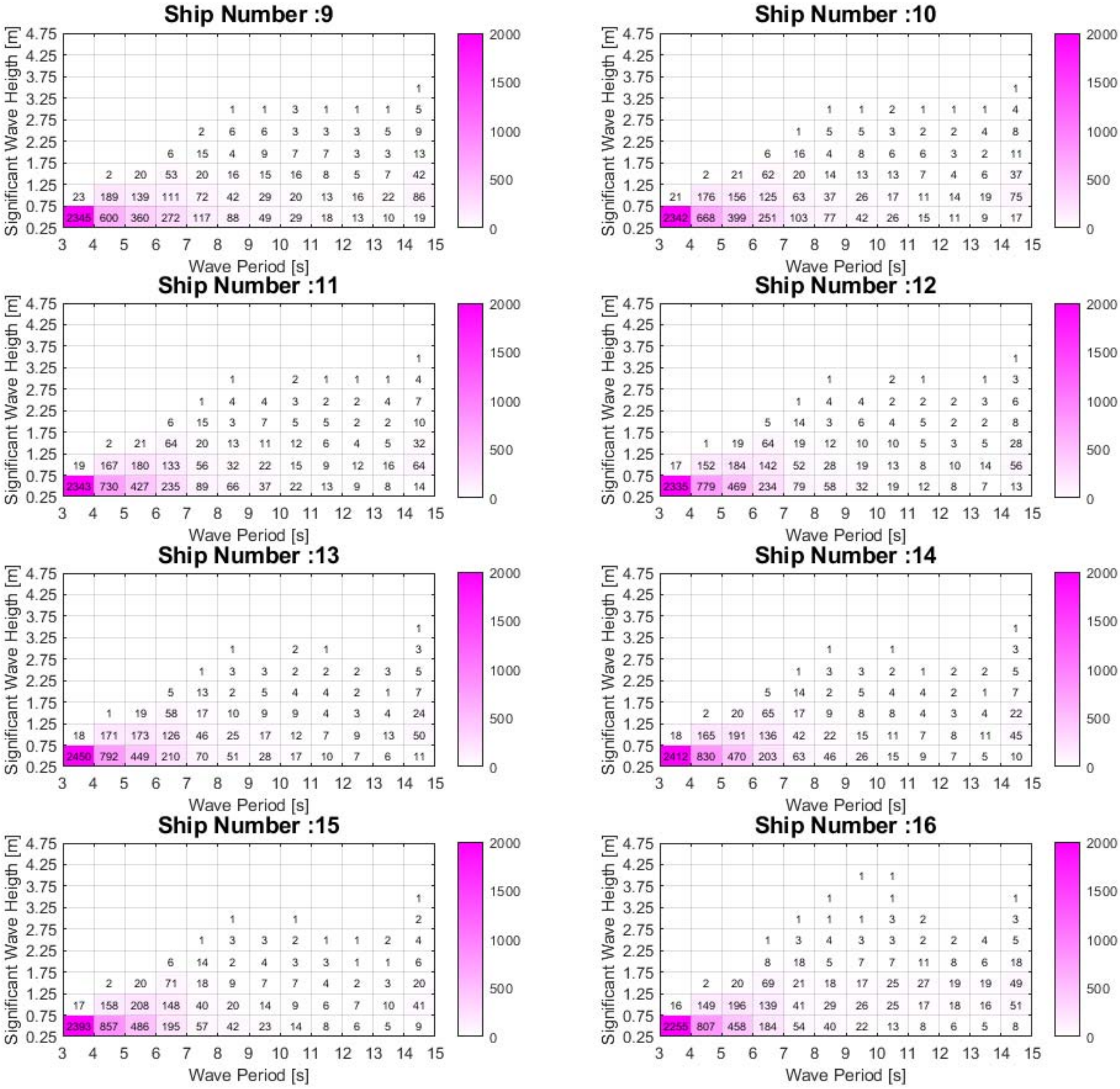

Ship Number :11
Significant Wave Heigth [m]
Wave Period [s]

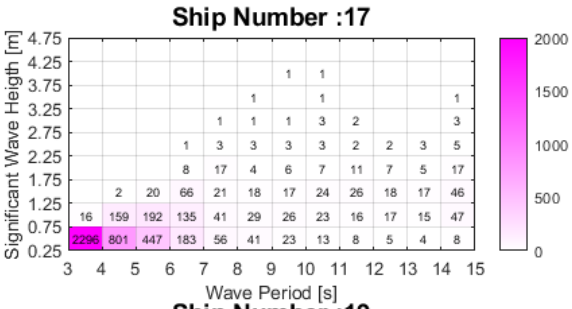

Ship Number :12
Significant Wave Heigth [m]
Wave Period [s]

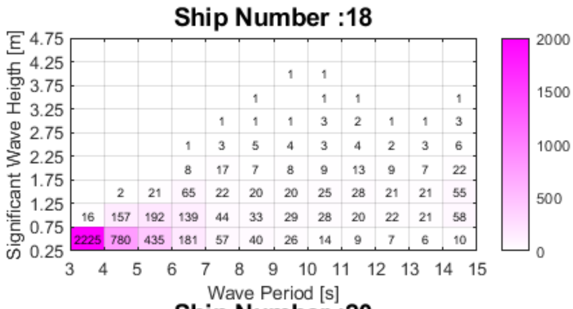

Ship Number :13
Significant Wave Heigth [m]
Wave Period [s]

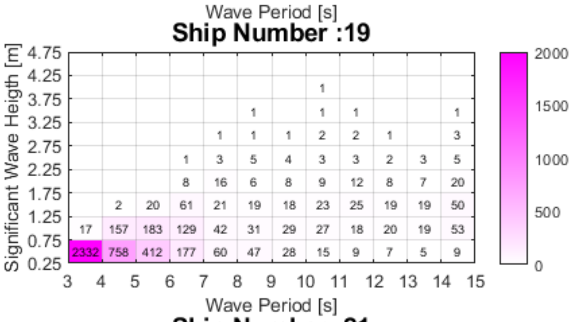
3.4. Remote Monitoring Data for FCS5009s Worldwide

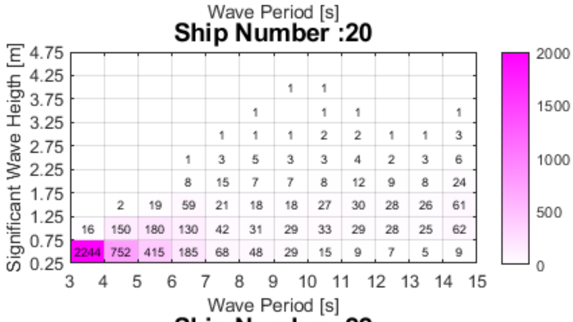


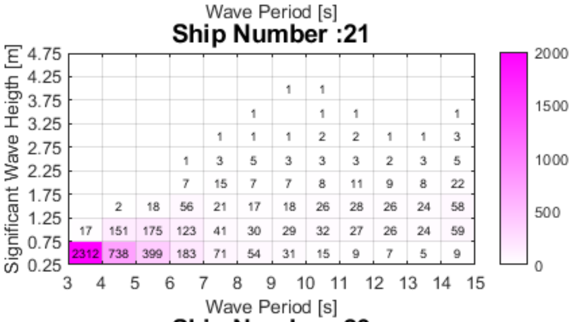

Ship Number :9
Ship Number :10
Ship Number :11
Ship Number :12
Ship Number :13
Ship Number :14
Ship Number :15
Ship Number :16
Significant Wave Heigth [m]
Wave Period [s]

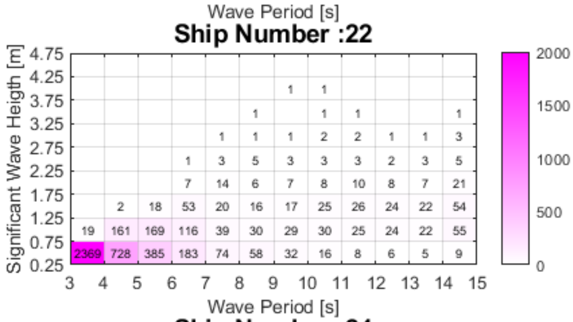

Ship Number :17
Significant Wave Heigth [m]
Wave Period [s]

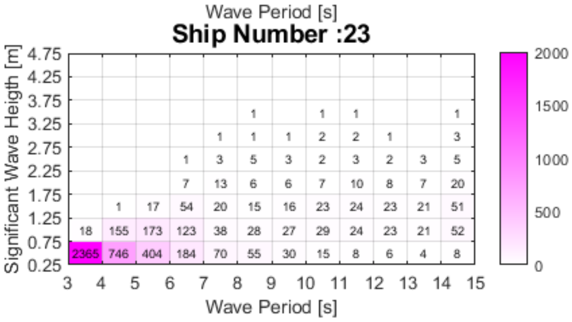

Ship Number :18
Significant Wave Heigth [m]
Wave Period [s]

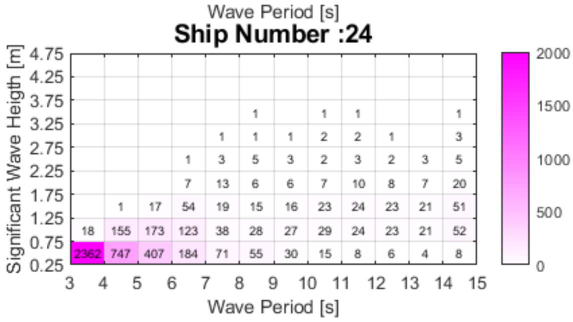

Ship Number :19
Significant Wave Heigth [m]
Wave Period [s]

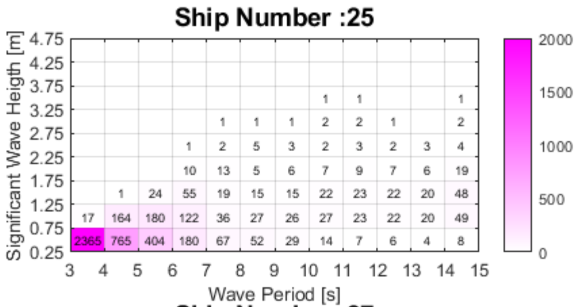

Ship Number :20
Significant Wave Heigth [m]
Wave Period [s]

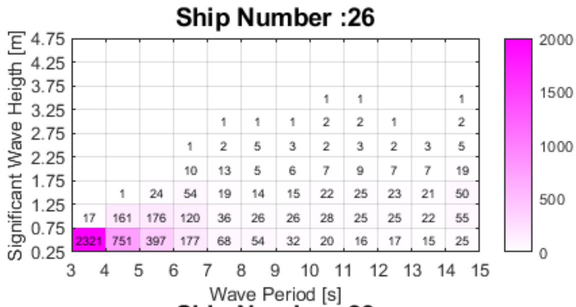

Ship Number :21
Significant Wave Heigth [m]
Wave Period [s]

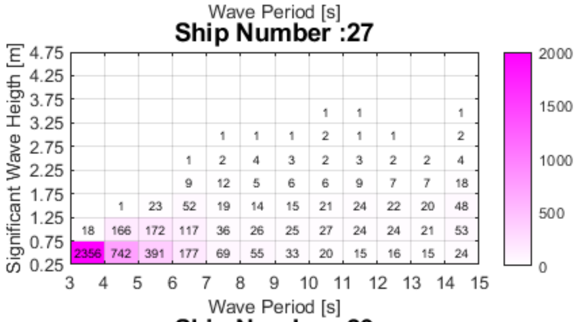

Ship Number :22
Significant Wave Heigth [m]
Wave Period [s]

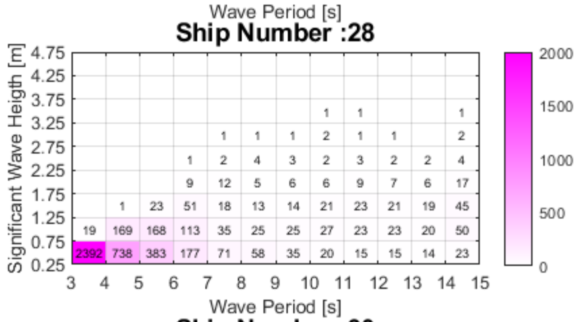

Ship Number :23
Significant Wave Heigth [m]
Wave Period [s]

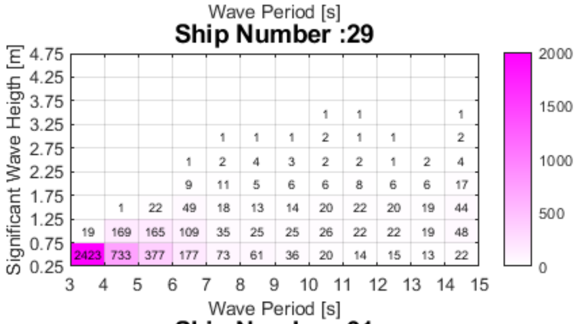

Ship Number :24
Significant Wave Heigth [m]
Wave Period [s]

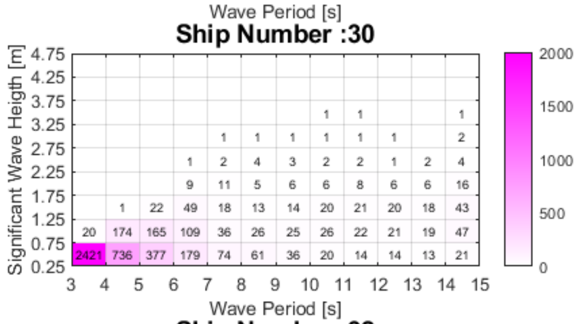

Ship Number :25
Significant Wave Heigth [m]
Wave Period [s]

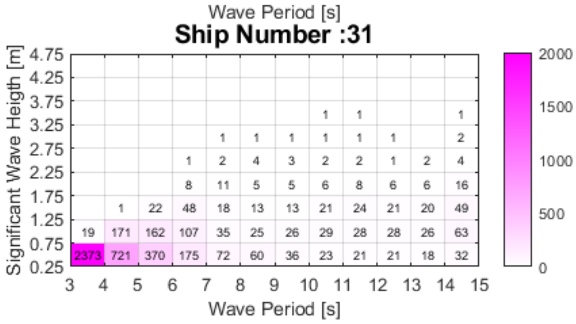

Ship Number :26
Significant Wave Heigth [m]
Wave Period [s]

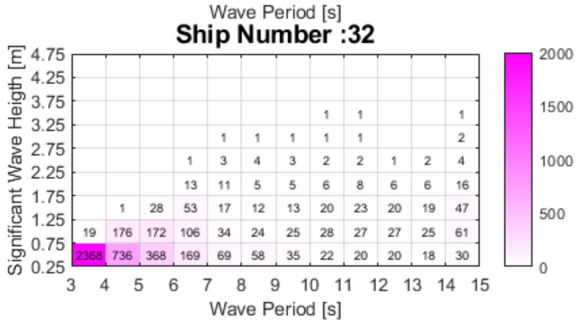

Ship Number :27
Significant Wave Heigth [m]
Wave Period [s]

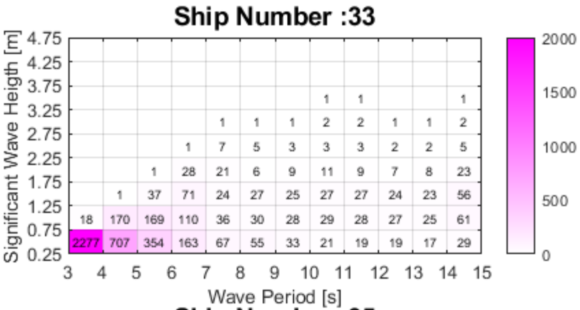

Ship Number :28
Significant Wave Heigth [m]
Wave Period [s]

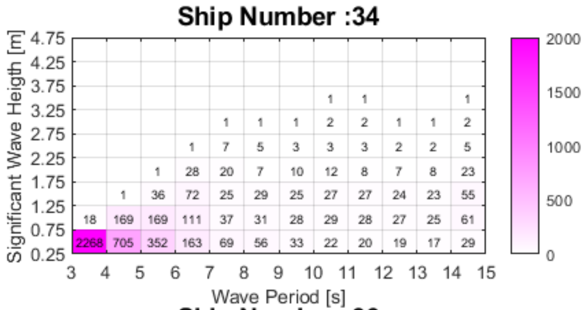

Ship Number :29
Significant Wave Heigth [m]
Wave Period [s]

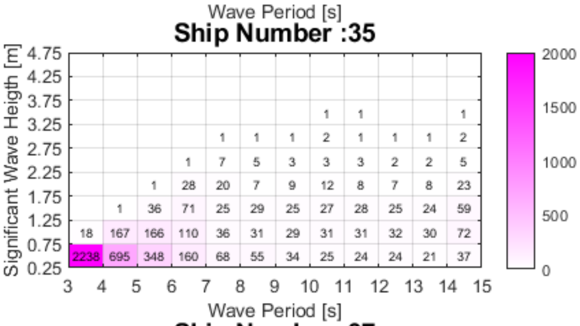

Ship Number :30
Significant Wave Heigth [m]
Wave Period [s]


Ship Number :31
Significant Wave Heigth [m]
Wave Period [s]


Ship Number :32
Significant Wave Heigth [m]
Wave Period [s]


Ship Number :33
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0


Ship Number :34
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0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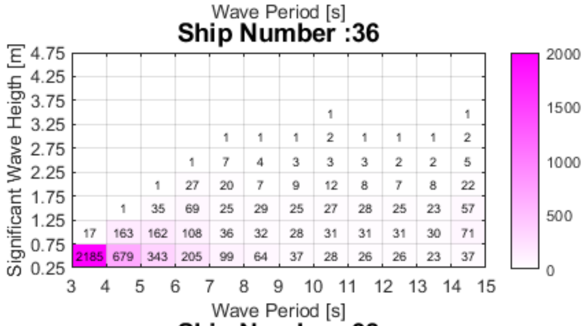
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0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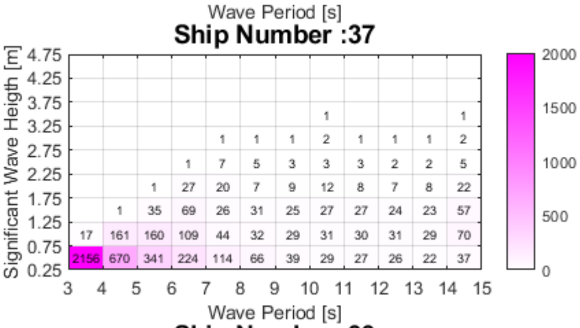
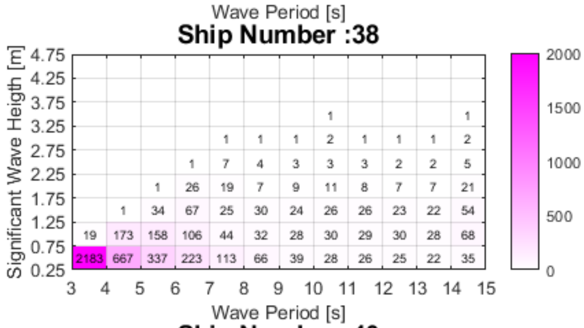
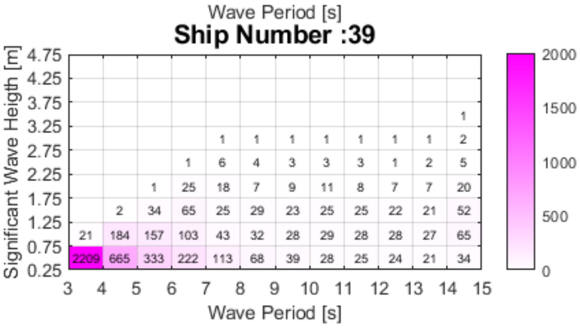
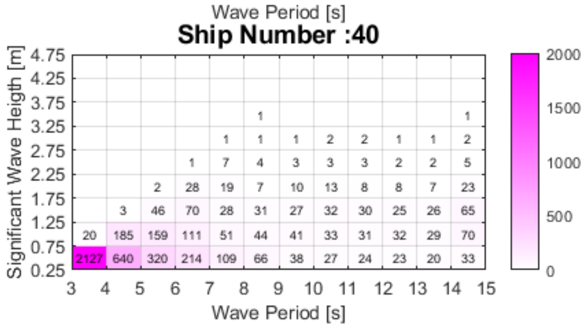
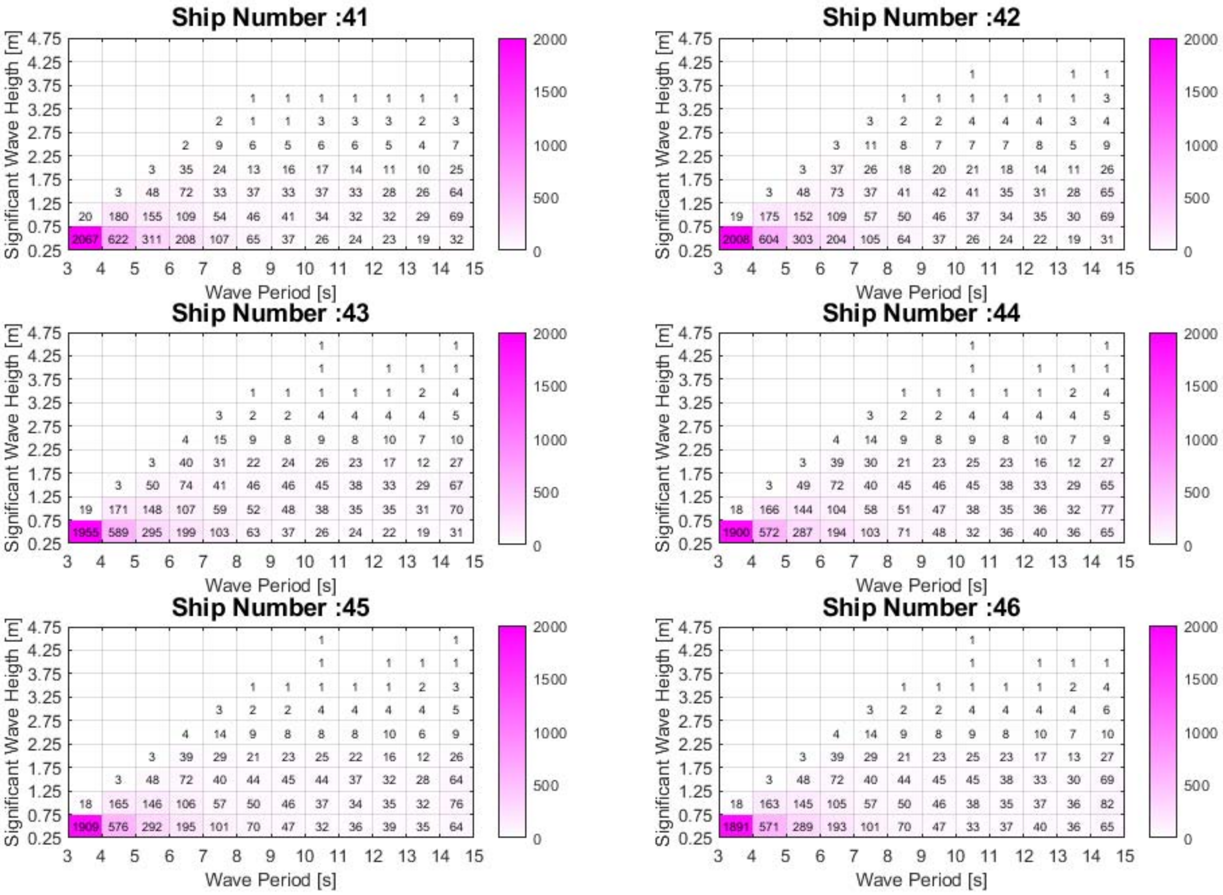
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0


Ship Number :37
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0


Ship Number :38
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0


Ship Number :39
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0


Ship Number :40
Significant Wave Heigth [m]
Wave Period [s]
2000
1500
1000
500
0


Ship Number :41
Ship Number :42
Ship Number :43
Ship Number :44
Ship Number :45
Ship Number :46
Significant Wave Heigth [m]
Wave Period [s]

Appendix - C

Explanation Note for Tanaav

1 Introduction

Fatigue Analysis is an important step in design of vessels. Damen Shipyards B.V. currently uses an in-house MATLAB tool called 'AluFastShip' for carrying out Fatigue Analysis for its vessels. The latest version of this tool (AluFastShip 2.0) uses a deterministic method to calculate fatigue analysis using a nominal stress approach. Following opportunities were could be incorporated in the next version of this tool:

1. Total Stress Concept
2. Remote Monitoring Tool (Actual Operational Profile Data)
3. ESA Tool (Actual Seastate Data)

As a part of a graduation thesis assignment a new tool called Tanaav has been developed to explore possible improvements to the current tool using the available opportunities.

Section 2 contains the objective of the report. An overview of the calculation process is given in section 3. It also lists and briefly describes the modules of the new tool. Sections 4-8 provide a detailed description of each module one by one.

2 Report Objective

This report is intended to describe the fatigue damage calculation procedure used in the new tool. The report will also present theoretical verification for the various modules of the new tool.

3 Process Overview

Fatigue damage at any location accumulates over time and as such the calculation is also divided into chunks of time which are added to each other to arrive at the cumulative fatigue damage vs time. By default, the tool assumes the smallest chunk of time for fatigue damage calculation to be one hour. The fatigue damage added to a location within that hour is calculated based on the environmental conditions (wave height, time period and wave spectrum) and operational profile of the vessel (vessel speed and vessel heading angle relative to the dominant wave direction). The above parameters would vary with time but are assumed to be constant during that hour. The effect of these parameters is same for the entire vessel. However, the fatigue damage calculation also considers the variation in longitudinal moment distribution along the length of the ship as well as local geometry influences on the stress amplitudes at the location for which fatigue damage is being calculated.

The following flow chart shows the basic working of the new tool where you can see the two possible paths that the tool can take.

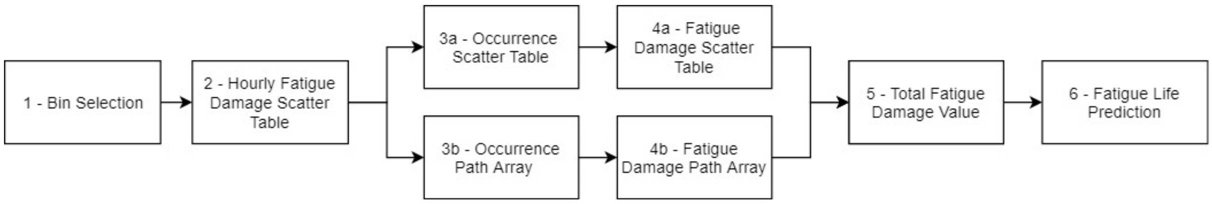


Figure 1: Basic Workflow Diagram for new MATLAB tool

This process is followed separately for each location of interest (hereafter called as 'detail') on the vessel.

A 'Bin' is a representation of a unique sea state in combination with a unique operational profile. For example, a bin could be defined with following parameter values:

Speed: *2.5 to 5 kn;* ***Heading:*** *15 to 25 deg;* ***Significant Wave Height:*** *1.5 to 2.5 m;*
Mean Wave Zero Crossing Period: *5.5 to 6.5 s*

First step is the initialisation or 'Bin selection'. In this the user would be able to decide the width and extents of each parameter and the total number of bins to be considered in the analysis. A default value is already provided in the tool. (Refer Table 1 for default parameter values used in the tool).

After the bins are decided, the next step is the calculation of hourly fatigue damage for each bin. For a chosen detail, the hourly damage is calculated and the damage values for each bin are stored in a 4-Dimensional scatter table. Till this point the calculations are hypothetical meaning the actual sea-states and operational profiles for design of from remote monitoring are not considered yet.

In the third step, the actual occurrences of each bin are counted either with ('b') or without ('a') preserving their sequence of occurrence in time.

The fourth step is just multiplying the hourly damage values for each bin with corresponding number of occurrences to get the total damage in each bin. Thereafter the damage in each bin is added together to arrive at the total damage. This is done in the fifth step. The duration is the summation of the total number of occurrences times the duration considered for each bin (an hour by default). Dividing the duration by the damage values gives us the predicted fatigue life time for the detail in the final step.

Module-I: Initialization

Module-I defines the Bins and various other input parameters.

Module-II: Expected Hourly Fatigue Damage Scatter Table (Loop)

Module-II calculates the expected hourly fatigue damage for each bin of all specified 'Details'. It has the following 6 submodules which are executed in a loop for each bin:

A: Wave Spectrum
B: Transfer Function from Wave Height to Nominal Stress
C: Transfer Function from Nominal Stress to Total Stress
D: Stress Spectrum and Spectral Moments
E: Hourly Damage using Spectral Formulations
F: Hourly Damage using Rainflow Counting (Optional – only for verification)

Module-III: Occurrence Counting

Module-III segregates the provided environmental data and operational profile into Bins (pre-defined in Module 1). The user can either choose to provide design data, path 'a' or remote monitoring data associated with timestamps, path 'b'. Design data would contain only the number of occurrences ignoring the sequence in which they would occur). Path 'a' would result in an occurrence scatter table whereas path b would result in an occurrence array.

Module-IV: Actual Fatigue Damage Scatter

Module-IV calculates the actual fatigue damage accumulated in each bin as a product of the expected hourly damage of a bin and the number of hours spent by the vessel in that bin during the period in consideration. Like Module 3, this module has two possible paths. In path 'a', the tool would compute only the design damage as in the total damage in each bin at the end of the specified design duration. In path 'b' the tool would additionally calculate how the fatigue damage accumulated vs time for the entire duration.

Module-V: Post-processing

Module-V calculates the total fatigue damage at the specified details and the corresponding design life prediction. It also generates relevant graphs and scatter diagrams.

4 Module-I

As explained in the previous section, this module allows the user to specify all basic inputs for the analysis. The inputs are provided default values in the code which the user is free to modify or leave as is. The inputs specified in this module are given in table below along with their default values:

Table 1: Input Values to be specified in Module-I

Sr. No.	**Input**	**Default Values**	**Units**
1	Bins for Speeds	0:2.5:25	kn
2	Bins for Heading	0:10:180	deg
3	Bins for Wave Periods	3.5:1:14.5	s
4	Bins for Significant Wave Heights	0.5:0.5:6	m
5	Spectrum Type	PM or JS	-
6	Frequencies for RAOs	0.05:0.05:2.5	rad/s
7	Location IDs for Fatigue Details	[“Loc^{XX}m” ()]	-
8	Section Moduli for Fatigue Details	[8.11E+11/2348]	mm^3
9	SCFs for Fatigue Details	[1.5]	-
10	Filename for RAOs*	‘ReferenceRAOs.xlsx’	

^{XX} *stands for the longitudinal distance from aft.*

**The RAOs would be imported from a excel file.*

Fatigue Details refers to the locations at which the user wishes to calculate the fatigue damage. Only one detail is specified as default, but user can specify multiple details in the array variable if corresponding section moduli and SCFs are also provided.

All the inputs are put into a structure variable named ‘PR’ which is then saved into a file called ‘ ParameterRanges.mat’ which can be loaded into the remaining modules as and when required.

5 Module-II

Module II calculates the expected hourly fatigue damage for each bin specified in module 1 for each detail. The module consists of multiple matlab script files which are run in a loop as through the main file called “LoopRunAll”. This is illustrated in flowchart below:

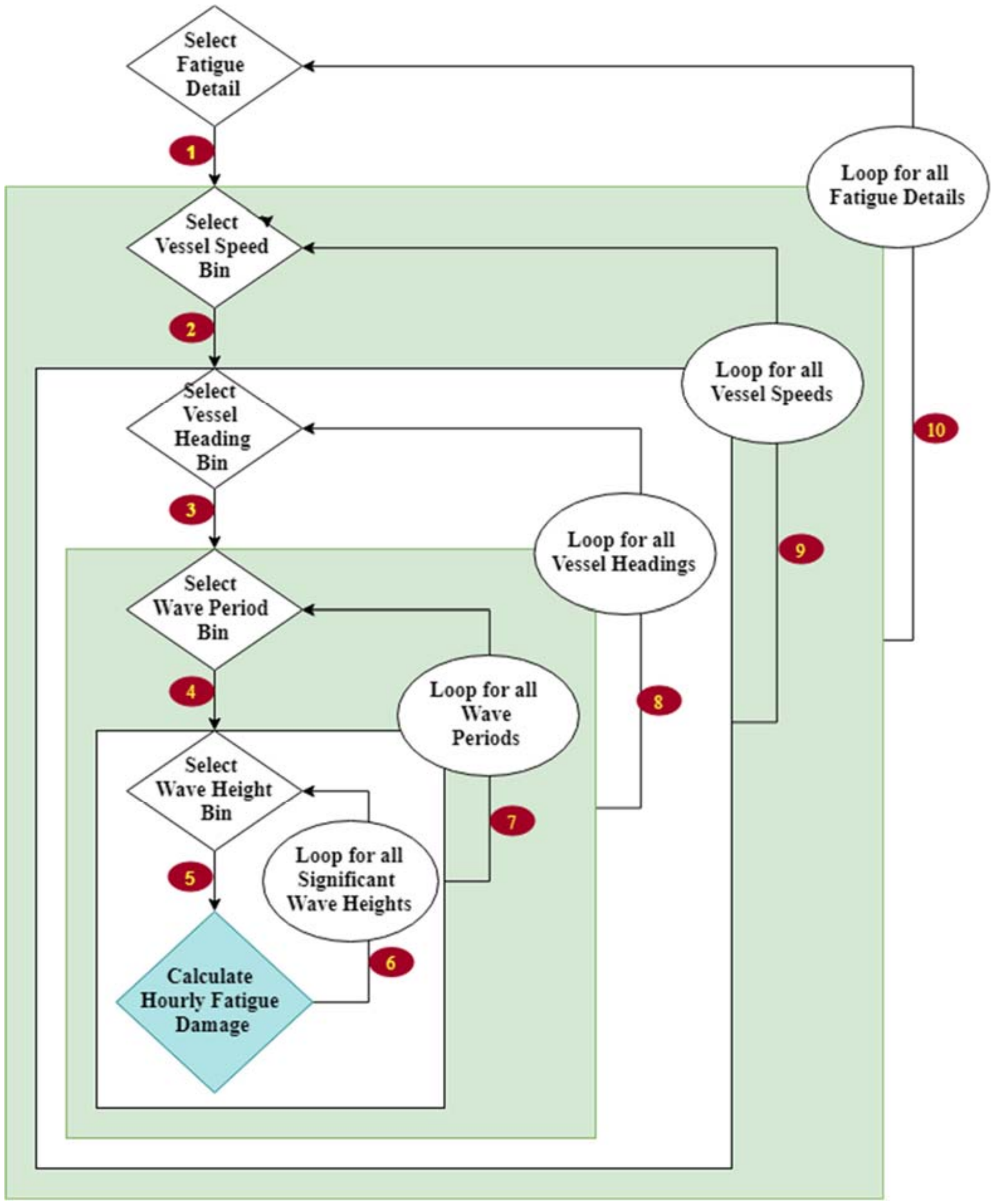


Figure 2: Flow Diagram for Module-II Loop.

The hourly fatigue damage calculation is broken up into 5 standard and 1 optional submodule.

The process to calculate the hourly fatigue damage is presented in figure below:

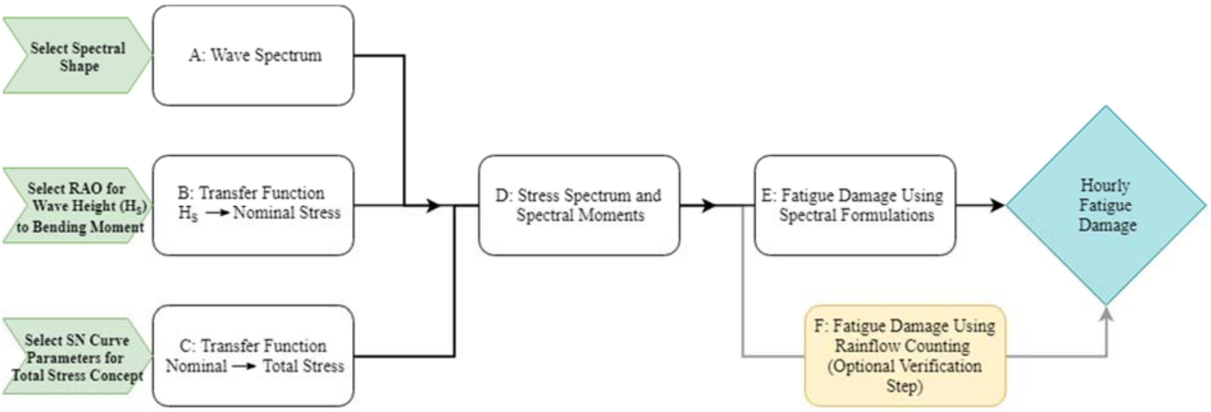


Figure 3: Flow Diagram for Hourly Fatigue Damage Calculation for 1 Bin.

5.1 Submodule II-A: Wave Spectrum

The module uses functions from a toolbox of MATLAB routines called "WAFO" [2] to generate a Pierson Moskowitz or JONSWAP Spectrum.

Table 2: Inputs and Outputs of Module II-A

Sr. No.	Parameter	Unit	Variable Name in MATLAB	Remark
		Inputs		
1	Significant Wave Height, H_s	m	*'Hw'*	-
2	Mean Wave Zero-Crossing Period, Tp	s	*'Tw'*	-
3	Discrete Frequencies for RAOs	rad/s	*'w'*	Array length should match with RAOs in Excel file
4	Type of Wave Spectrum	-	*'WaveSpecType'*	PM or JS
5	Spectral Parameters	-	*['gamma_ JS', 'sa', 'sb', Ag]*	Additional Parameters Required for JS Spectrum
		Outputs		
1	Wave Spectrum		*'Spec'*	Array with length same as number of frequencies.

5.2 Submodule II-B: Transfer Function from Wave Height to Nominal Stress

A linear load response relationship is assumed for this calculation. Results of FEM analysis can also be incorporated with the help of SCFs.

Table 3: Inputs and Outputs of Module II-B

Sr. No.	**Parameter**	**Unit**	**Variable Name in MATLAB**	**Remark**
Inputs				
1	RAO from Wave Height to Global Hull Girder Bending Moment	kNmm/m	*'RAO'*	Array length should match with Wave Spectrum
2	Section Modulus for Fatigue Detail, Z	mm^3	*'PR.Section Modulus'*	-
3	SCF for Fatigue Detail, K_g	-	*'PR.Kg'*	-
Outputs				
1	Transfer Function from Wave Height to Fatigue Detail		*'TF_NS2PM'*	Array with length same as number of frequencies.

Formula Used:

$$Nominal\ Stress(\omega) = \frac{RAO(\omega)}{Z/K_g}$$

5.3 Submodule II-C: Transfer Function from Nominal Stress to Total Stress

The module uses MATLAB functions developed by Prof. Henk den Besten which are already available at Damen. The transfer function is calculated based on his research into the total stress concept. The formulae used in these functions are provided below for reference.

Formulae Used:

$$\alpha = 0.5\{\pi + arctan(\frac{h_w}{l_w})\} \quad ; \qquad \beta = \alpha - \pi/2$$

$$\lambda_s \ and \ \lambda_a \ are \ aigenvalue \ solutions \ to \ the \ following \ equations \ with \ (0 < \lambda; \ \lambda \neq 1):$$

$$\lambda \sin(2\alpha) + \sin(\lambda 2\alpha) = 0 \ and \ \lambda \sin(2\alpha) - \sin(\lambda 2\alpha) = 0$$

$$w_{d1} = \frac{h_w}{l_w} \quad ; \quad w_{d2} = 0.5 * \frac{l_w}{t_p} + 2.5 * (\frac{h_w}{l_w} - 0.2) \quad ; \quad w_{d3} = 0.5 * \frac{l_w}{t_p} + (\frac{h_w}{l_w} - 0.2)$$

$$C_{bm} = -13.06 * e^{-0.03696 * w_{d1}} + 12.9638 + \frac{{w_{d2}}^3 + 0.7202 \, {w_{d2}}^2 + 0.7704 w_{d2} + 0.4817}{{w_{d2}}^4 + 4.249 \, {w_{d2}}^3 + 9.641 \, {w_{d2}}^2 + 8.654 w_{d2} + 5.701}$$

$$C_{bb} = -0.542 * e^{-2.141 * w_{d1}} + 0.3532 + \frac{1.029 {w_{d3}}^3 + 1.552 {w_{d3}}^2 + 1.917 w_{d3} + 1.838}{{w_{d3}}^4 + 3.094 {w_{d3}}^3 + 10.9 {w_{d3}}^2 + 8.73 w_{d3} + 11.51}$$

$$C_{bw} = (C_{bm} - r_s(C_{bm} - C_{bb}))$$

$$r_s \ is \ the \ bending \ stress \ to \ normal \ stress \ ratio$$

$$\chi_s = \frac{\cos\{(\lambda_s+1)\alpha\}}{\cos\{(\lambda_s-1)\alpha\}} \ ; \ \chi_a = \frac{\sin\{(\lambda_a+1)\alpha\}}{\sin\{(\lambda_a-1)\alpha\}}$$

$$\mu_s = \frac{C_{bw}(\lambda_a + 1) + 3(\lambda_a - 1)}{6(\lambda_a - \lambda_s)[cos\{(\lambda_s + 1)\beta\} - \ \chi_s cos\{(\lambda_s - 1)\beta\}]}$$

$$\mu_a = \frac{-C_{bw}(\lambda_s + 1) + 3(\lambda_s - 1)}{6(\lambda_a - \lambda_s)[sin\{(\lambda_a + 1)\beta\} - \ \chi_a sin\{(\lambda_a - 1)\beta\}]}$$

$$C_s = \frac{\pi}{2} * \lambda_s * (\lambda_s + 1) * \frac{\Gamma(\lambda_s/2)}{\Gamma((\lambda_s + 1)/2)} * \ [\cos\{(\lambda_s + 1)\beta\} - \ \chi_s * \cos\{(\lambda_s - 1)\beta\}]$$

$$C_a = \frac{\pi}{2} * \lambda_a * (\lambda_a + 1) * \frac{\Gamma(\lambda_a/2)}{\Gamma((\lambda_a + 1)/2)} * \ [\sin\{(\lambda_a + 1)\beta\} - \ \chi_a * \sin\{(\lambda_a - 1)\beta\}]$$

$$Y_n = \ C_s * \mu_s * (\frac{a}{t_p})^{\lambda_s - 1} + C_a * \mu_a * (\frac{a}{t_p})^{\lambda_a - 1}$$

$$Y_{fm} = \sqrt{\frac{2}{\pi}} * \sqrt{\tan(\frac{\pi a}{2t_p})} * \frac{0.752+2.02\left(\frac{a}{t_p}\right)+0.370*\{1-\sin(\frac{\pi a}{2t_p})\}^3}{\sqrt{(\frac{a}{t_p})*\cos(\frac{\pi a}{2t_p})}}$$

$$Y_{fb} = \sqrt{\frac{2}{\pi}} * \sqrt{\tan(\frac{\pi a}{2t_p})} * \frac{0.923+0.199\,\{1-\sin(\frac{\pi a}{2t_p})\}^4}{\sqrt{(\frac{a}{t_p})*\cos(\frac{\pi a}{2t_p})}}$$

$$Y_f = Y_{fm} - r_s(Y_{fm} - Y_{fb})$$

$$r_s \text{ is the bending stress to normal stress ratio}$$

$$I_N = \int_{\left(\frac{a_i}{t_p^{(\prime)}}\right)}^{\left(\frac{a_f}{t_p^{(\prime)}}\right)} \frac{1}{\left\{Y_n(\frac{a}{t_p^{(\prime)}})\right\}^n * \left\{Y_f(\frac{a}{t_p^{(\prime)}})\right\}^m * (\frac{a}{t_p^{(\prime)}})^{\frac{m}{2}}}\, d\left(\frac{a}{t_p^{(\prime)}}\right)$$

$$S_T = \frac{\Delta\sigma_s}{{t_p^{(\prime)}}^{\frac{2-m}{2m}} * I_N^{\frac{1}{m}} * (1-r_l)^{1-\gamma}}$$

So, the transfer function from nominal stress, $\Delta\sigma_s$ to total stress, S_T can be written as:

$$\textbf{Transfer function} = \frac{\mathbf{1}}{{t_p^{(\prime)}}^{\frac{2-m}{2m}} * I_N^{\frac{1}{m}} * (1-r_l)^{1-\gamma}}$$

The tool is designed to handle only single sided butt welds connecting plates of similar thicknesses as the formulations for C_{bw} and the Total Stress SN curve data (m, C, n, σ and γ) are available only for such a joint. Remaining joints can be incorporated as and when data becomes available for them. The types of joints which would eventually be included in the tool and their corresponding parameters are shown in figure below:

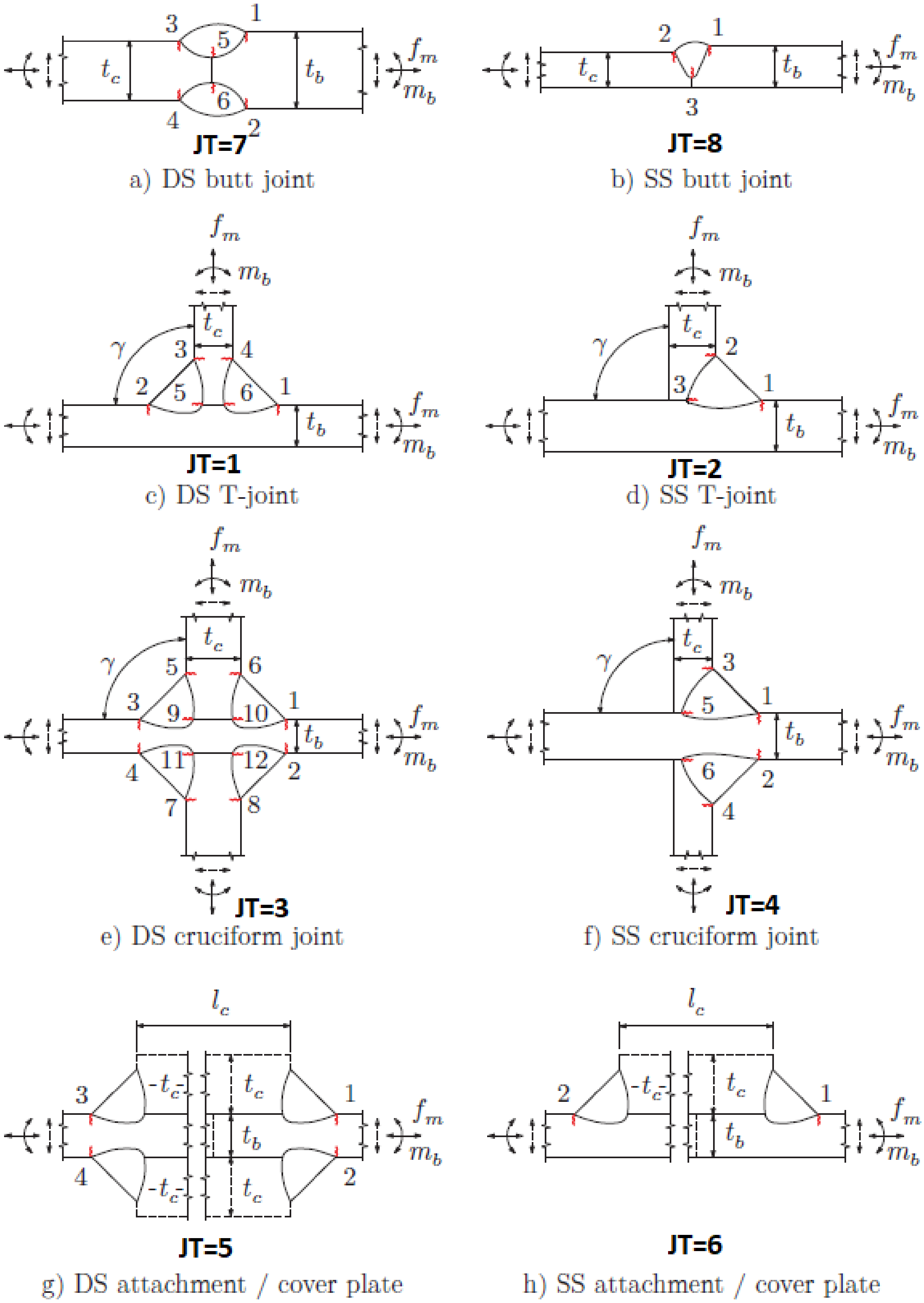


Figure 4: Types of joints to be included in the fatigue analysis tool.

Table 4: Inputs and Outputs of Module II-C

Sr. No.	**Parameter**		**Unit**	**Variable Name in MATLAB**	**Remark**
Inputs					
1	Local Joint Details	Joint Type	-	*"JT"*	
2		Notch Location	-	*"LF"*	
3		Weld Penetration	-	*"WT"*	Partial (2) or Full (1)
4		Plate Thickness	mm	*'tb, tc'*	
5		Weld Dimensions	Mm	*'lw,hw'*	
6		Notch Radius	mm	*"rho"*	
7		Notch Depth	mm	*"dn"*	
8	Load Details	Bending Ratio	-	*"rs"*	(m_x/f_y)
9		Load Ratio	-	*"Rl"*	Mean stress component
10	SN Curve Data	m	-	*"m_ TS"*	Single Slope Total Stress Curve
11		C	-	*"C_ TS"*	
12		σ	-	*"sigma_ TS"*	
13		n	-	*"n_ TS"*	
14		γ_{steel}	-	*"gamma_ TS"*	
15		a_i/t_p	-	*""aitp"*	
Outputs					
1	Transfer Function from Nominal to Total Stress			*'TF_ TS2NS'*	

5.4 Submodule II-D: Stress Spectrums and Spectral Moments

Wave spectrum generated previously is transformed into nominal and total stress spectrums in this submodule. Spectral moments and corresponding mean zero crossing wave periods and expected number of waves in an hour are also calculated.

Table 5: Inputs and Outputs of Module II-D

Sr. No.	Parameter	Unit	Variable Name in MATLAB	Remark
		Inputs		
1	Transfer Function from Wave Height to Fatigue Detail	?	*'TF_ NS2PM'*	Array with length same as number of frequencies.
2	Transfer Function from Nominal to Total Stress	?	*'TF_ TS2NS'*	
3	Wave Spectrum	?	*'Spec'*	Array with length same as number of frequencies.
		Outputs		
1	Nominal Stress Spectrum at Fatigue Detail	?	"Spec_NS"	Array with length same as number of frequencies.
2	Zeroth Order Spectral moment for Nominal Stress Spectrum	-	*"m0_ NS"*	
3	Mean Zero Crossing Period for Nominal Stress Spectrum	s	*"Tz_ NS"*	
4	Expected Number of Waves in an Hour for Nominal Stress Spectrum	-	*"HourlyExpected Waves_ NS"*	
1	Total Stress Spectrum at Fatigue Detail	?	"Spec_TS"	Array with length same as number of frequencies.
2	Zeroth Order Spectral moment for Total Stress Spectrum	-	*"m0_ TS"*	
3	Mean Zero Crossing Period for Total Stress Spectrum	s	*"Tz_ TS"*	
4	Expected Number of Waves in an Hour for Total Stress Spectrum	-	*"HourlyExpected Waves_ TS"*	

Formulae Used:

If, $$y(\omega) = |H(\omega)| * x(\omega)$$

Then,

$$S_{yy}(\omega) = |H(\omega)|^2 S_{xx}(\omega)$$

This result has been applied to convert the wave spectrum to a nominal stress spectrum and a total stress spectrum by multiplying with the square of corresponding transfer functions.

To calculate the spectral moments and time periods:

$$T_0 = 2\pi \sqrt{\frac{m_0}{m_2}}$$

where,

$$m_i = \int_0^\infty \omega^i * S(\omega) d\omega$$

Expected number of waves in a time duration (T) = $\frac{T}{T_0}$

5.5 Submodule II-E: Hourly Damage using Spectral Formulations

This submodule uses the spectral moments calculated in the previous submodule as well as SN curve data provided as input to estimate the hourly fatigue damage using spectral formulations available in literature.

Table 6: Inputs and Outputs of Module II-E

Sr. No.	Parameter	Unit	Variable Name in MATLAB	Remark
Inputs				
1	Zeroth Order Spectral moment for Nominal Stress Spectrum	-	*"m0_NS"*	
2	Zeroth Order Spectral moment for Total Stress Spectrum	-	*"m0_TS"*	
3	Expected Number of Waves in an Hour for Nominal Stress Spectrum	-	*"HourlyExpectedWaves_NS"*	
4	Expected Number of Waves in an Hour for Total Stress Spectrum	-	*"HourlyExpectedWaves_TS"*	
5	SN Curve for Nominal Stress	m1	*"m1_NS"*	
6		m2	*"m2_NS"*	
7		C1	*"C1_NS"*	
8		C2	*"C2_NS"*	
9	SN Curve for Total Stress	m	*"m_TS"*	
10		C	*"C_TS"*	
11		σ	*"sigma_TS"*	
12		n	*"n_NS"*	
Outputs				
1	Hourly Fatigue Damage using Nominal Stress	-	"HourlyDamage_NS_DS"	DS:double slope SN Curve for Nominal Stress.
2	Hourly Fatigue Damage using Total Stress	-	"HourlyDamage_TS_SS"	SS: single slope SN Curve for Total Stress.

Formulae Used:

Double Slope Nominal Stress Curve Damage:

$$D(t) = f_p \,.\; t \,. \left[\frac{(8m_{0,\sigma})^{\frac{m_1}{2}}}{C_1} \;.\; \Gamma_{upper}\left(\frac{m_1}{2} + 1; \sigma_t\right) + \frac{(8m_{0,\sigma})^{\frac{m_2}{2}}}{C_2} . \Gamma_{lower}\left(\frac{m_2}{2} + 1; \sigma_t\right) \right]$$

Where, σ_t is the stress at the slope transition or knuckle point defined by equating the number of cycles to failure using the two lines in the SN curve as follows:

$$\log(C_1) - m_1 log(\sigma_t) = \log(C_2) - m_2 log(\sigma_t)$$

Thus,

$$\log(\sigma_t) = \frac{\log(C_1) - \log(C_2)}{m_1 - m_2}$$

And,

Γ_{upper} and Γ_{lower} are incomplete conjugate gamma functions defined as:

$$\Gamma_{upper}\,(z, b) = \int_b^\infty (t^{z-1} * e^{-t})dt \;; \quad \Gamma_{lower}(z, b) = \int_0^b (t^{z-1} * e^{-t})dt$$

Single Slope (Steel) Total Stress Curve Damage:

$$D(t) = f_p \,.\; t \,. \frac{(8m_{0,\sigma})^{\frac{m}{2}}}{C} \;.\; \Gamma(\frac{m}{2} + 1)$$

where,

Γ is the complete gamma function defined as:

$$\Gamma(z) = \int_0^\infty (t^{z-1} * e^{-t})dt$$

5.6 Submodule II-F: Hourly Damage using Rainflow Counting

The MATLAB tool is currently in development and the results need to be verified from time to time whenever major changes are made in the code. Additionally, the hourly fatigue damage estimates calculated using numerical integration in the previous submodule. The formulations would later also be extended to multi-slope SN curves. Also, the incomplete gamma functions in MATLAB are tricky and opaque. Due to all these reasons it was essential to add a more accurate and transparent method to calculate hourly fatigue damage. Hence, this module uses Rainflow counting to calculate the hourly fatigue damage using the same inputs as the previous module. This module is optional as increases the computation time significantly especially when the number of bins is huge. It can only be used for verification during development stages of the tool and turned off during later use to make the tool more efficient.

The module generates a stress time series for a 3-hour duration and calculates the number of occurrences for predefined stress intervals to calculate the 3-hourly fatigue damage which is divided by 3 to an accurate hourly fatigue damage.

Formulae Used:

<u>Frequency domain to Time domain</u>

$$\eta(t) = \sum_p a_p \cos(\omega_p t + \varepsilon_p)$$

Where,

$$a_p = \sqrt{2S(\omega_p)\Delta\omega}$$

$$\varepsilon_p = rand(0,2\pi)$$

<u>Time domain to Frequency domain</u>

$$A_p = \frac{2}{T} * \int_0^T \eta(t) * \sin(\omega_p t)\ dt$$

$$B_p = \frac{2}{T} * \int_0^T \eta(t) * \cos(\omega_p t)\ dt$$

$$S(\omega) = \frac{1}{2\Delta\omega}\{A_p^2 + B_p^2\}$$

A frequency range of 0 to 2.5 rad/s with an interval of 0.05 rad/s is used to generate the time series. Both the frequency range and interval can be customised by the user. Also, the time series generated as a result is converted back to the frequency domain to and plotted against the initial spectrum to observe the match between the input stress spectrum and the resulting time series.

To summarize, all 6 subroutines of Module II together lead to estimation of the hourly fatigue damage of a bin given seastate information, operational profile, corresponding RAO and local details of the joint. Thus, by running these subroutines in a loop, a 5-Dimensional Fatigue Table would be generated with each value corresponding to the hourly fatigue damage of a unique Bin of a Fatigue Detail.

6 Module-III

Module-III can be operated along one of two paths depending on whether the user wishes to see the accumulation of fatigue damage vs time or just wants to calculate the total fatigue damage per bin at the end of a set duration.

6.1 Path 'a'

In this path, the user chooses to disregard the fatigue accumulation vs time curve. The input for this path would be a design sea-state scatter profile and an operational profile for the vessel. The module would generate a 5-dimensional table of occurrences in each bin compatible with the hourly fatigue damage table. This table would be provided as an input to the next module.

6.2 Path 'b'

In this path, the use would input an array of seastate and operational profile values one for each hour in the design duration and with a unique datetime stamp. This is the exact data which is obtained at Damen with a combination of remote monitoring of vessel operational profile and seastate data from an ESA tool.

The tool would then assign the closest matching bin to each hour of the array.

For example,

Sr No.	**Parameter**	**Actual Value**	**Bin Options**	**Bin Value Selected**
1	Vessel Speed	5.8 kn	0 : 2.5 : 25	5.5 kn
2	Vessel Heading	33 deg	0 : 10 : 180	30 deg
3	Significant wave height	1.3 m	0.5 : 0.5 : 7	1.5 m
4	Wave Period	5.6 s	3.5 : 1 : 14.5	5.5 s

7 Module-IV

Module-IV would automatically follow the same path selected in Module-III.

7.1 Path 'a'

By now, the tool would have generated hourly fatigue damage corresponding to all bins as well as calculated the number of hourly occurrences for each bin. The actual hourly damage per each bin is then simply the product of these two values. Thus, another 5-dimensional table would be generated as a product of the hourly damage table and the occurrence table. This would be provided as an input to the next module.

7.2 Path 'b'

By now, the tool would have generated hourly fatigue damage corresponding to all bins as well as assigned a bin ID to each hour in the design duration. The actual hourly damage in each hour is then simply the product of these two values. This path would thus generate a sequence of hourly damage values for the entire design duration. This would be used as an input in the final module.

8 Module-V

The total fatigue damage at a fatigue detail at the end of the design duration is calculated as a sum of fatigue damage in all bins of that detail. The predicted fatigue life is then calculated as the design duration divided by accumulated fatigue damage in that duration.

The user can also use the scripts in this module to generate graphs of fatigue damage vs time and scatter plots showing the distribution of fatigue in various sea-states and operational profiles.

References

1. J. H. den Besten. "*fatigue resistance of welded joints in aluminium high-speed craft: A TOTAL STRESS CONCEPT*". PhD thesis, Delft University of Technology, 2015.

2. Brodtkorb, Per & Johannesson, Pär & Lindgren, Georg & Rychlik, Igor & Ryden, Jesper & Sjo, Eva, "*WAFO - A Matlab toolbox for analysis of random waves and loads.*" Proceedings of the International Offshore and Polar Engineering Conference. 3. 343-350, 2000.

3. P. A. Brodtkorb, "*The probability of Occurrence of dangerous Wave Situations at Sea*". Dr.Ing thesis, Norwegian University of Science and Technolgy, NTNU, Trondheim, Norway, 2004.