



NTNU – Trondheim
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Fatigue Analysis of Mooring Lines on the Floating Wind Turbine Hywind Demo

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Submission date: June 2013

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Preface

This report is a result of the course “TMR4900 – Marine Structures, Master Thesis” at the department of Marine Technology at the Norwegian University of Science and Technology spring semester 2013. The major part of the work has been done at Statoil’s offices in Bergen; the rest has been done in my office at “Marinteknisk Senter” at Tyholt, Trondheim. The report is a follow-up on the project thesis written in the fall semester 2012.

The work on this report has been both difficult and interesting. Establishing the proper model with the right conditions has been time consuming, but the programming itself has represented the major part of the time consumption. Throughout the work on this report I have experienced different programming/computer- difficulties, but eventually they got all sorted out.

I have worked with several people during the work on this report; each and every one of them deserves to be mentioned. First of all I would like to thank my supervisor at NTNU Professor Carl M. Larsen for great advice and guidance while writing this report. I would also like to thank my supervisor at Statoil, Tor David Hanson for help and encouragement during the work. Arne Rekdal (Statoil) deserves a great thank for all the help he has contributed with, especially with computer related issues. And to the last but not least I would like to thank my fellow student Martin Lågstad for help, tips and discussions related to this report.

Bergen, 10th June 2013



Hans Ranøyen Homb

Summary

In the last decades the focus on developing renewable energy has increased tremendously. The main reason for this is the rapid increase of population, which requires enormous amounts of energy. Eventually we will run out of non-renewable energy which makes us reliable of the renewable energy, for example wind energy.

Statoil's response to this has been to design and create the Hywind Demo concept. An almost conventional wind turbine placed on top of a SPAR-buoy creates the basic idea.

The Hywind Demo presents many interesting and challenging problems, where fatigue is one of them. It shall withstand harsh and rough weather over a long period of time. It is self-explanatory that this challenge not can be solved too quickly, but solved with focus on the correct results. The mooring lines on the Hywind Demo introduce big issues, both regarding design and cost. As the depth increases, the required length of the mooring lines increases more, and this may cause problems.

This report investigates three main methods of approaching fatigue damage: Linear Time Domain, Non-linear Time Domain and Frequency Domain. The Linear Time Domain analyses were discarded due to the fact that the turbine rotor cannot rotate in a linear time domain analysis (the stiffness matrix for the rotor needs to be updated, which it can't in a linear time domain analysis). A way of solving this problem would require a lot of work on the model, and linear analyses were hence not carried out.

After the non-linear time domain simulation of the Hywind Demo, a fatigue calculation was done. The Rainflow counting method was used in order to calculate the fatigue damage. The results from this fatigue calculation showed similar results as Statoil's own results (compared with a fatigue evaluation based on the Rainflow technique). The expected life time for the "As-Built"-model (15 degree offset) was calculated to be 93.7 [years].

The worst sea state was done by first simulating 13 different sea states and then doing a peak parameter study. From the first study I found the significant wave height that produced most fatigue, while the second study consisted of a sensitivity study on the peak periods. The final result was that the most yearly damage occurs when $H_s = 3.0$ [m] and $T_p = 8.0$ [s].

The next topic discussed in my report was a "rotation matrix method". In the Metocean specification for the Hywind Demo location, the probability and angles for the waves are presented. The basic idea is to calculate total fatigue damage from the Metocean specification with only doing analyses on a few directions. The only requirement for doing this method is that

the system must have at least one symmetry place. This method was demonstrated as a possible way of reducing number of calculations needed. The expected life time based on the wave directions and probability was 92.7 [years].

A parameter study of the clump weights revealed that it is not optimized in terms of fatigue. The existing weight of a single clump weight is 66645 [kg in air]. The highest fatigue was found with only 2 [tons] lighter clump weight (64645 kg in air). Therefore, introducing a clump weight weighing less than 63645 [kg in air] or more than 66645 [kg in air] will reduce the fatigue damage. A requirement of enough yaw-stiffness for the Hywind Demo will favor an increase of the clump weights.

Calculating the fatigue damage in the frequency domain was based on a closed form solution. This requires that the S-N curve is linear and that the time series is narrow banded. In this case the time series from the stresses were not narrow banded, it was assembled by the “slow-motion” and the “wave-motion”. The solution was to filter these two processes apart, then calculating the contributions from the two processes individually. It is important to emphasize that this is a very simplified way of solving the problem, normally weight functions are applied when calculating like this. The results from this method gave only slightly lower results (4.6%) than the results from the rainflow-technique on the non-linear time domain analyses. This means that both of the methods works for the mooring line system on the Hywind Demo and that the solution from the Rainflow-technique is slightly more conservative. Both methods are very computational efficient.

Sammendrag

I de siste tiårene har fokuset på fornybar energi økt voldsomt. Hovedgrunnen til dette er den raske befolkningsveksten vi opplever. Dette i kombinasjon med økende velstand krever voldsomme energimengder. En dag vil vi ha brukt opp alle ikke-fornybare energiresursene vi disponerer, og vi blir avhengig av å ha bærekraftig fornybar energi.

Statoil sitt svar på denne utviklingen har vært å utvikle og designe Hywind Demo-konseptet. Konseptet tar en så og si konvensjonell vindturbin opp på en SPAR-bøye og ut i havet.

Hywind Demo står ovenfor mange interessante og vanskelige utfordringer, hvor blant annet levetiden er i sterk fokus. Den skal takle dårlig vær over lang tid, og da sier det seg selv at dette ikke er en oppgave som er løst på 1-2-3. Ankerlinene på Hywind Demo representerer de største utfordringene, både med tanke på design av ankerlinene og på kostnadene knyttet til dem. Når

dybden øker, øker kravet om lengde på ankerlinene enda mer. Selve «foot-printen» til ankerlinene (nesten 2 [km] diameter) medfører store utfordringer sett ut fra ett helhetlig perspektiv hvis det kunne tenkes å bygge en vindmølle-park.

Denne masteroppgaven diskuterer utmattings-analyser basert på simuleringer i 3 forskjellige plan: lineære tidsplanet, ikke-lineær tidsplanet og i frekvensplanet. Simulering i det lineære tidsplanet ble raskt forkastet på grunn av at rotoren ikke kan rotere når man gjør en lineær tidsplananalyse, stivhetsmatrisen må oppdateres for at dette skal fungere. En lineær tidsplan analyse baserer seg på at den ikke oppdaterer stivhetsmatrisen når ting beveger seg, noe som ikke fungerer på rotoren. Hvis dette skulle bli simulert (uten rotor bevegelse), ville det også krevd mye arbeid med å lage en modell.

Etter den ikke-lineære tidsplan simuleringen av Hywind Demo, ble det utført en levetidsanalyse. Levetidsanalysen fra den ikke-lineære tidsplan simuleringen ble gjort ved hjelp av «Rainflow»-telling. Resultatene fra «Rainflow»-tellingen samsvarte med Statoils egne resultater (sammenlignet med deres resultater fra Rainflow-telling). Den forventede levetiden for «As-Built»-modellen (15 graders offset) ble beregnet til å være 93.7 [år].

Den verste sjøtilstanden ble funnet etter å ha kjørt en analyse med 13 forskjellige sjøtilstander med en varierende signifikant bølgehøyde fra 1-13 [m]. Bølgeperiodene for de 13 signifikante bølgehøydene ble bestemt ut fra Metocean-spesifikasjonen, hvor den bølgeperioden med flest opptrer ble valgt. Tilslutt ble det gjennomført en sensitivetsanalyse av bølgeperioden for å regne ut hvilken bølgeperiode (relatert til den signifikante bølgehøyden funnet først) som bidro mest til utmatting. Størst utmattingskade per år skjer når sjøtilstanden har en $H_S = 3.0$ [m] og $T_P = 8.0$ [s].

Det neste som ble diskutert i rapporten min var en slags «rotasjons-matrise»-metode. I Metocean spesifikasjonen for stedet hvor Hywind Demo er lokalisert er det beskrevet sannsynligheter for bølger relatert til retningene de kommer fra. Poenget med denne «rotasjons-matrisen»-metoden er å finne en total utmattingskade basert på disse dataene fra Metocean spesifikasjonen. Hvis det finnes noen form for symmetri i konstruksjonen, er det mulig å redusere antall analyser. I dette tilfellet trengs det bare 3 forskjellige retninger (med 30 graders inkrement) for å representere alle retningene (fra 0 til 330 grader med 30 graders inkrement). Denne metoden demonstrerer en mulig måte å redusere antall analyser for slike typer beregninger. Fra denne metoden ble den forventede levetiden beregnet til å bli 92.7 [år].

En parameterstudie av klumpvektene avslørte at de ikke er optimalisert med tanke på utmatting. Nåværende vekt på en klumpvekt er 66645 [kg i luft], mens høyest utmatting ble

oppnådd med bare 2 [tonn] lettere klumpvekt. For å forbedre levetiden med å gjøre endringer på klumpvekten må vekten enten senkes til å bli lavere enn 63545 [kg i luft] eller tyngre enn 66645 [kg i luft]. Ett krav om nok rotasjons-stivhet i selve konstruksjonen favoriserer en liten økning av klumpvektene.

Levetids-analysen gjort i frekvensplanet baserte seg på en forenklet formel. Denne formelen forlanger at S-N kurven er lineær og at tidsserien er smal-båndet. I dette tilfellet ble det vist at tidsserien ikke er smalbåndet, den er bygd opp av to bidrag. De to forskjellige bidragene som gjør at tidsserien ikke er smal-båndet er den «langsomme» responsen og bølge-responsen. Løsningen ble å filtrere disse to prosessene fra hverandre, for så å regne ut de individuelle bidragene fra de ved hjelp av den forenklete formelen. Det er viktig å nevne at denne formelen er en forenkling, og normalt ved slike tilfeller må en slags vekting bli brukt. Resultatene fra denne metoden produserte noe lavere utmattings-skade, sammenlignet med svarene fra «Rainflow»-tellingen. Dette betyr at begge metodene fungerer for å regne utmatting på Hywind Demo. Det er mest naturlig å bruke «Rainflow»-tellingen siden den gir ett noe mer konservativt svar sammenlignet med den forenklete formelen. Begge metodene har bevist at de er veldig effektive rent regneteknisk.

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Nomenclature

COB – Center of Buoyancy

COG – Center of Gravity

DAF – Dynamic Amplification Factor (DNV)

DFF – Design Fatigue Factor (DNV)

ZCOG – Center of Gravity Z-direction

FD – Frequency Domain

FFT – Fast Fourier Transform

FLS – Fatigue Limit State

H_s – Significant wave height [m]

Hz – Hertz = 1/[s]

JONSWAP – Joint North Sea Wave Project

PDF – Probability Density Function

SCF – Stress Concentration Factor (DNV)

S-N – Stress/Number of Cycles diagram

TD – Time Domain

T_p – Peak Period [s]

ULS – Ultimate Limit State

γ – “Gamma”, Peakedness parameter for a JONSWAP-spectrum

1 INTRODUCTION

In the recent years the focus on renewable energy has increased tremendously. Statoils response to this has been to design and create the Hywind Demo concept.

Offshore wind turbines are nothing new; it has been around for several years. The difference between the existing offshore wind turbines and the Hywind Demo concept is the SPAR buoy design. The wind turbines that exists today is either resting on the seabed or they have a type of flotation system. The floating system for wind turbines like the SPAR buoy design has been introduced in the recent years. Since the Ocean does not only consist of shallow depths we need to design offshore wind turbines that can operate on not only on the shallow depths.

The SPAR buoy design is more or less conventional wind turbine place on top of a SPAR buoy, which then is more suitable for larger depths. The SPAR buoy offers great advantages with respect to stability and simplicity.

After testing their prototype Hywind Demo for a couple of years now, they have produced a lot of measurement data. The goal for Statoil for this has been to investigate the possibilities for a market friendly offshore wind turbine design.

The sea is a rough and harsh environment and this causes fatigue to every structure. This requires that the design is thoroughly investigated, everything from the big parts of the structure all the way to the small bolts. The repeated stress induces a certain degree of fatigue, which has to be within certain rules and regulations not only for the sake of the insurance companies but also for the safety for humans.

The object for this thesis is to perform a fatigue analysis on the mooring system for the Hywind Demo. The theory applied in the analyses performed will be covered. All the fatigue calculations will be based on simulations done in the software-program SIMA.

2 HYWIND DEMO

2.1 GENERAL DESCRIPTION

This section covers the main dimensions and principles of the Hywind Demo.

The Hywind Demo offshore wind turbine is based on a SPAR buoy type design. The buoy's stability is very good; due to the long distance between the center of gravity (COG) and center of buoyancy (COB). It is known for its deep draft which gives the buoy very stable and good hydrodynamic characteristics (Pettersen, 2007).

Hywind Main Dimensions and Data	
Wind Turbine Generator	2.3 [MW]
Turbine Weight	138 [t]
Height Of Nacelle	65 [m]
Rotor Diameter	82.4 [m]
Hull Draft	100 [m]
On-sight water Depth	210 [m] (+-10[m])
Displacement	5300 [m ³]
Diameter water line	6 [m]
Maximum diameter under water	8.3 [m]
No. Of Mooring lines	3
Pitch Control	Dynamic

TABLE 1 - HYWIND DEMO MAIN DIMENSIONS AND DATA



FIGURE 1 - HYWIND DEMO PHOTO

2.2 LOCATION

Hywind Demo is located approximately 11 kilometers west of Karmøy. The exact location of the wind turbine is (STATOIL, 2012):

Reference system	:	ED50, UTM zone 31N
UTM East	:	616016
UTM North	:	6557696
Water depth	:	210 m

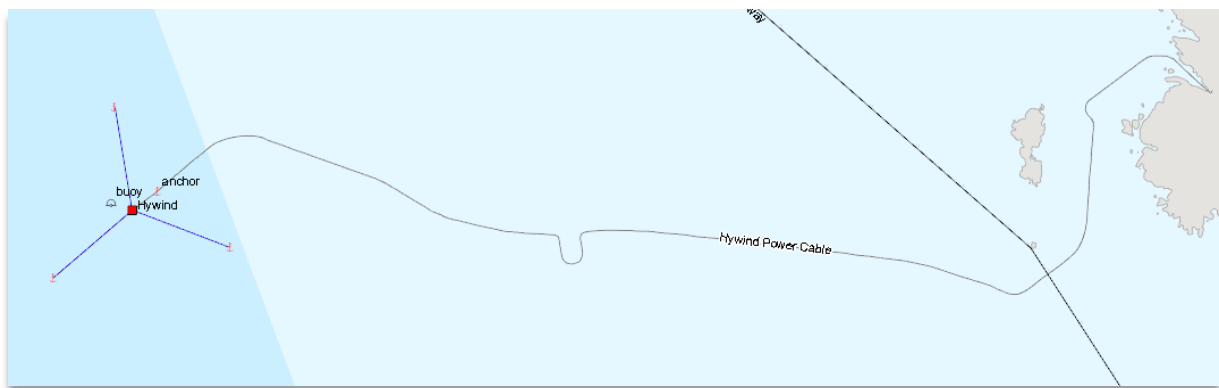


FIGURE 2 - HYWIND DEMO LOCATION (STATOIL)

2.3 MOORING SYSTEM

2.3.1 GENERAL DESCRIPTION

Every floating structure needs to be restrained from moving (Langen and Sigbjörnsson), this is of course also very important for the Hywind Demo. The mooring system used on the Hywind Demo is a conventional catenary mooring system. The catenary mooring system provides restoring forces because of the weight of the mooring lines. The lines have been equipped with extra clump weights described later in the thesis.

The mooring system for Hywind Demo consists of 3 mooring lines. The mooring lines are very long, which is normal for a conventional mooring system with an anchor that not is designed to

withstand vertical forces. A more detailed picture of the mooring line layout follows (STATOIL, 2012):

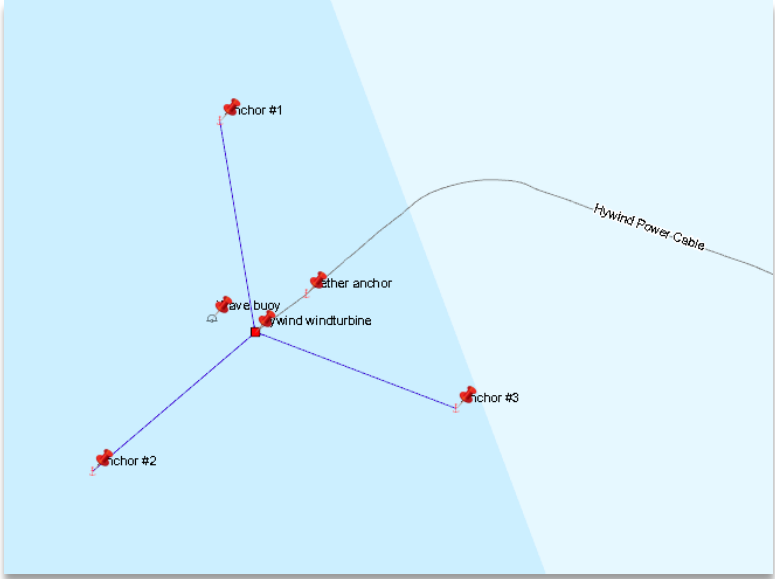


FIGURE 3 - MOORING SYSTEM LAYOUT (STATOIL)

The specific coordinates is described in the table below:

Mooring Line NO.	Depth [m]	UTM East [m]	UTM North [m]	XM [m]	YM [m]
1	202	615970.9	6558579.8	-45.1	883.8
2	220	615544.4	6556965.1	-471.6	-730.9
3	203	617141.7	6557391.4	1125.7	-304.6

TABLE 2 - MOORING LINE COORDINATES

The mooring systems global orientation is exactly 15 [degrees] counter-clock-wise offset (for mooring line No.1, from north).

The mooring line is built up by different sections and is as described below:

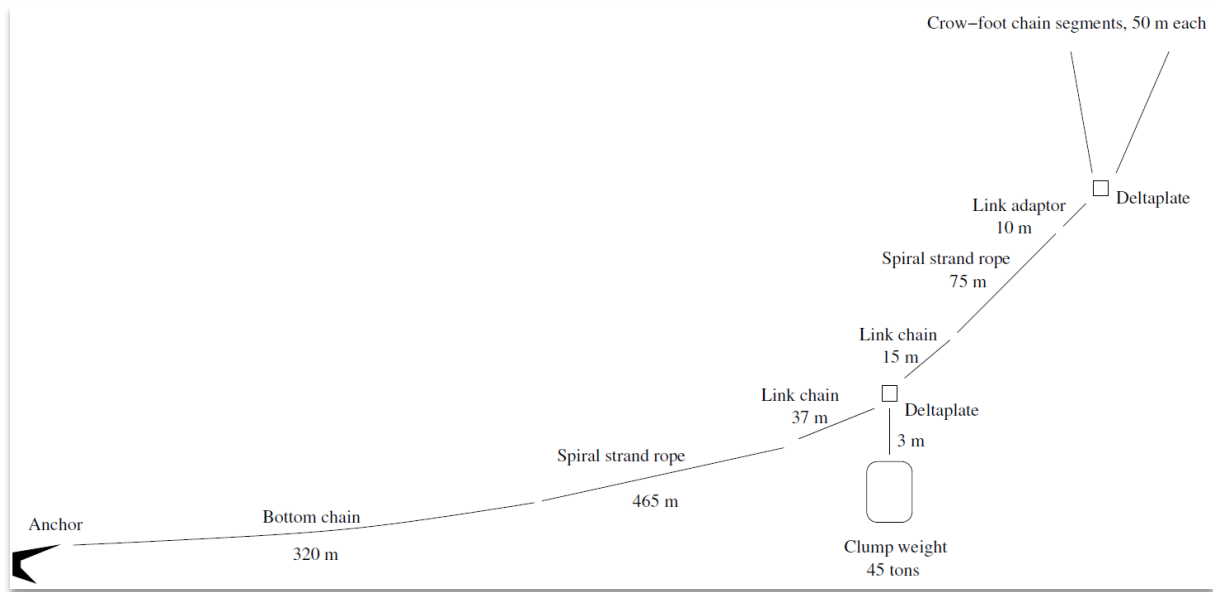


FIGURE 4 - MOORING LINE SEGMENTS (STATOIL)

The specific weight/lengths and placements are as follows:

Item	Description	Wia (kg)	Wiw (kg)	Length (m)	Length (m)	Diam. (mm)
1	16 T Stevshark Anchor	16000	0	0	0	
2	Ø76mm 5 Link Adaptor c/w open special end link one end	0	0	0	0	76
3	Ø76mm Trident Thin Kenter Shackle	0	0	0	0	76
4	Ø76mm L = 191m Studded Chain	40300	35100	320	0	76
5	Ø76mm Trident Thin Kenter Shackle	0	0	0	0	76
6	Ø76mm 5 Link Adaptor c/w open special end link one end	0	0	0	0	76
7	Ø78 L = 450 m Unsheathed Spiral Strand Rope	15100	12300	465	0	78
8	Ø76mm L = 35 m Studded chain c/w open special link both ends	4700	4100	37	0	76
9	Ø76mm Trident Thin Kenter Shackle	70	61	0	0	76
10	Ø76mm 5 Link Adaptor c/w open special end link one end	240	209	0	0	76
11	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0	95
12	Deltaplate	199	173	0	0	
13	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0	95
14	85 T SWL GP Shackle	42	36	0	0	
15	Ø78mm L = 3m Studless Chain (NVR3)	378	328	0	0	76
16	85 T ROV Shackle	150	130	0	0	
17	Concrete Clump Weight	65125.82794	45000	0	0	5000
18	Ø76mm L = 15 m Studded chain c/w open special link both ends	1890	1642	15	0	76
19	Ø78 L = 90 m Unsheathed Spiral Strand Rope	2400	2000	75	0	78
20	Ø76mm L = 10m c/w 5 Link Adaptor Both Ends	1260	1095	10	0	76
21	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0	95
22	Deltaplate	199	173	0	0	
23	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0	95
24	Ø76mm L = 50m Studded chain c/w open special link both ends	6300	5475	50	0	76
25	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0.3	95
26	Ø76mm L = 50m Studded chain c/w open special link both ends	6300	5475	0	50	76
27	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0	
28	Ø95mm LTM Joining Shackle with Round Pin	220	191	0	0.3	
29	Ø100mm Masterlink, Type GN Rope Fittings No 1210 000 or Similar	0	0	0	0.7	
30	Ø100mm Masterlink, Type GN Rope Fittings No 1210 000 or Similar	0	0	0	0	
31	Mooring Bracket on Structure, Pin Ø280mm, 2 off	0	0	0	0	

TABLE 3 - MOORING LINE SPECIFICATIONS (STATOIL)

“W ia” is weight in air, and “W iw” is weight in water [kg]. The information used from the table above are the different chain diameters (for calculation of stresses), and the weight of the clump weight (used for a clump weight analysis later in the report).

2.4 SUB STRUCTURE

The sub-structure is divided into four mass elements: Primary Structure, Secondary Structure, Water Ballast and Fixed Ballast (STATOIL, 2012).

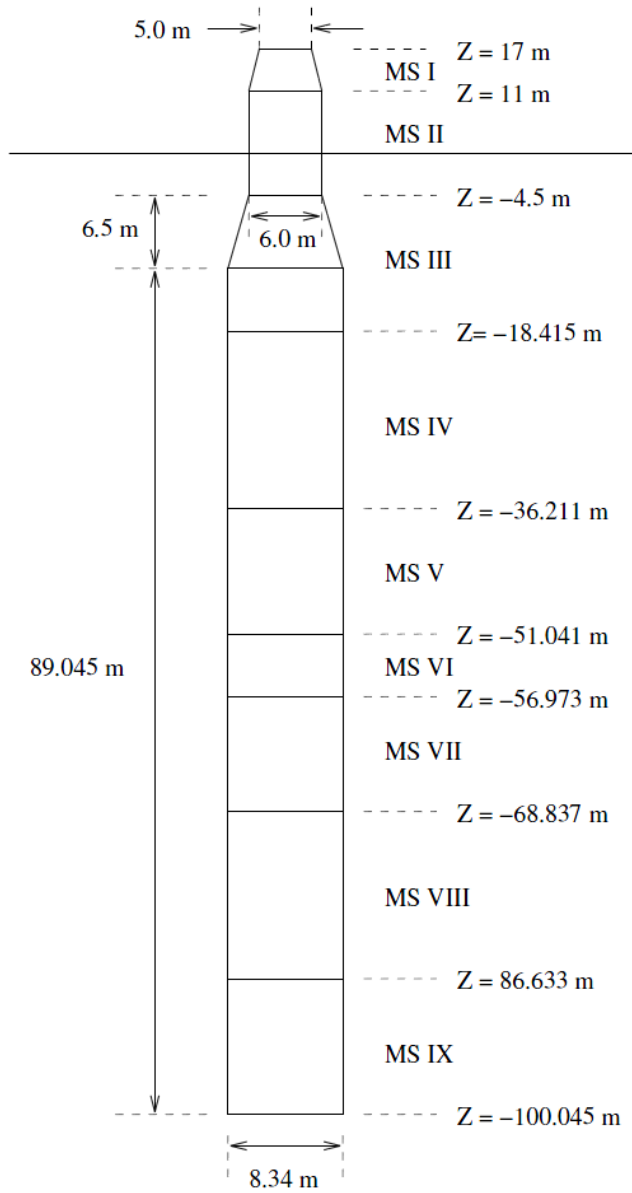


FIGURE 5 - HYWIND DEMO SUB-STRUCTURE (STATOIL)

3 FATIGUE THEORY

3.1 GENERAL

The increasing demand of safety and reliability brings up the importance of fatigue. Every marine structure built today is designed to last at least 20 – 30 years, so it is self-implied that this subject is thoroughly investigated. The Hywind Demo is positioned at a location where the weather is not particularly “big”, but it is not necessarily the largest waves that produce the highest fatigue-loads.

Fatigue is classified on the form in which it occurs: mechanical, creep, thermo mechanical, rolling contact, corrosion and fretting fatigue. Fatigue can also be classified by the duration of the fatigue, life in other words: repeated number of loads. Normally the loads are much lower than the yield stress for the material. These cycles will accumulate and may lead to material failure (Berge, 2006).

3.2 CRACK MODES

A fatigue crack can propagate in three different modes, depending on the relative orientation of loading to the crack. The most common crack growth used is Mode I (figure below) (Berge, 2006).

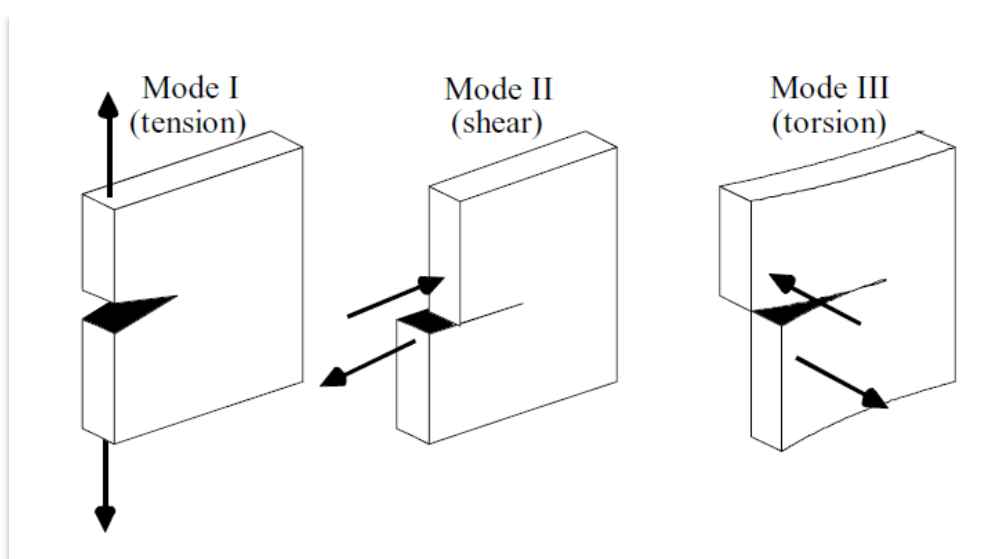


FIGURE 6 - CRACK PROPAGATION MODES (BERGE, 2006)

3.3 CALCULATION OF FATIGUE DAMAGE

The relation between the stress S_i and number of cycles N_i can be decided from a S-N curve which is defined by Paris's law (Larsen, 2009).

$$\frac{da}{dN} = C * \Delta K^m \quad 3.1$$

Where: $\frac{da}{dN}$ - The crack growth rate

ΔK^m - The stress intensity factor

C - Material constant

The S-N curve is decided with respect to materials and the design of the structure to be analyzed. DNV describes in their rules how much the individual damages can be, and this is covered later in the report.

Fatigue damage as a result of varying level of tension bandwidth can be calculated by Miner – Palmgren's hypothesis (Larsen, 2009).

$$D = \sum \frac{n_i}{N_i} \quad 3.2$$

Where: D is the accumulated fatigue damage on all tension bandwidths

n_i is the number of stress ranges with level S_i

N_i is the number of stress ranges on level S_i which leads to fatigue damage.

For a load scenario with narrow bandwidth the tension bandwidth is almost equal to the double of the tension amplitude. This is a conservative approach which gives bigger calculated fatigue load compared to the actual fatigue.

3.3.1 SHORT TERM FATIGUE ANALYSIS

Short term fatigue can be calculated from a TD (time domain) analysis or FD (frequency domain).

With a stochastic FD analysis it is possible to calculate the fatigue damage in two different ways, both ways using a stress spectrum found in the actual cross section of the test object. The two different ways are:

- Think of the Gaussian process as a narrow banded process and then apply the Rayleigh distribution on peaks and stress ranges.
- Generate a stress history from the stress spectrum using FFT (Fast Fourier Transform). This will result in a broad banded Gaussian process. From this the fatigue damage can be calculated by analyzing the stresses by counting the cycles and ranges (normally Rainflow-counting) which will lead to a total fatigue damage result.

From the TD analysis the results can also be analyzed in two different ways:

- Perform a Rainflow-counting, leads to results very fast (Rain-flow does not require too much computational resources).
- Choose a probability distribution where you estimate its parameters on the basis of the load history. Then it is possible to calculate the fatigue damage by integrating the probability density function and the S-N curve.

Regardless of the two different ways of calculating the fatigue damage (TD or FD) the biggest uncertainty factor from these analyses will be the wave loading. Here the drag coefficient represents the largest uncertainty factor, but also the modeling of the waves close to the sea surface in combination to the current is important (Larsen, 1992).

3.3.2 LONG TERM FATIGUE ANALYSIS

When we want to perform a long term fatigue analysis, we need to consider all the relevant information connected to environmental and operational conditions the structure will experience during its lifetime. It is important to cover the operational aspects such as installation, modification and repair.

The environmental data which the structure is to be designed for is usually based on wave and current statistics. These data can be presented as a frequency distribution of significant wave heights (H_s) and zero up-crossing, peak or average periods. For the Hywind Demo it is been used a Metocean specification which include wind, wave, current, temperature and salinity data. The data is measurement data from the area the Hywind Demo is located.

If the long term fatigue analysis is performed in the FD (and stochastic linearization is carried out), the transfer function for the response on the structure will be depending on the wave condition. In other words, the transfer function must be established for each wave condition. A way to solve this is to divide all the sea states into blocks. For each block of sea states one transfer function is used for the calculation of the response. The advantage of this is fewer sea states to iterate, and the computation time will depend on how many blocks the sea states are divided into. When the long term fatigue analysis is performed this way, it becomes really important to select the right size of the iteration blocks (Larsen, 1992).

3.4 CUMULATIVE DAMAGE

Data from a fatigue analysis is normally presented in an S-N diagram. The stress/strain ($\Delta S/\Delta \epsilon$) range is plotted versus cycles to failure (N). We differentiate between low cycle fatigue life and high cycle fatigue life:

- Low cycle range is below 10^5 cycles
- High cycle range is above 10^5 cycles

The S-N data in the high cycle range tend to follow a log-linear relationship:

$$N(\Delta S)^m = Const. \tag{3.3}$$

When the load cycles occur with constant amplitudes, the S-N diagram will look like this:

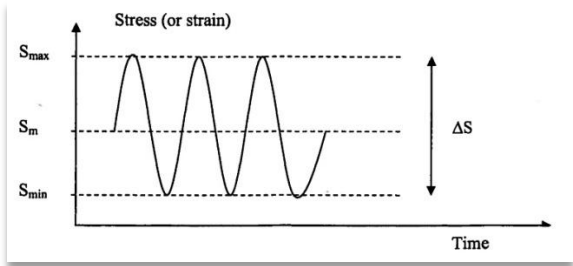


FIGURE 7 - CONSTANT AMPLITUDE LOADING (LARSEN, 2009)

3.3.3 CHARACTERIZATION OF FATIGUE LOADING

Fatigue is a cumulative process made from an irregular (usually) load history. Normal design life time for a typical offshore structure spans up to a period of 20-30 years. If we assume a load with frequency 0.2 [Hz] the number of cycles will be in the magnitude of 10^8 . Therefore it is important that the time history is reduced to a convenient format to make the fatigue calculations a lot easier (Berge, 2006).

When we talk about fatigue loading we usually differentiate them on the loading characteristics. In addition to the constant amplitude loading mentioned it exists:

- *Variable amplitude loading/spectrum loading or irregular loading.* These three names are used on any type of loading that have non-constant amplitude (most common).
- *Block loading;* composed of blocks of constant amplitude cycles.
- *Random loading/stochastic loading;* a variable amplitude loading from a random process.

This is an example on how the S-N curve may look like with variable loading:

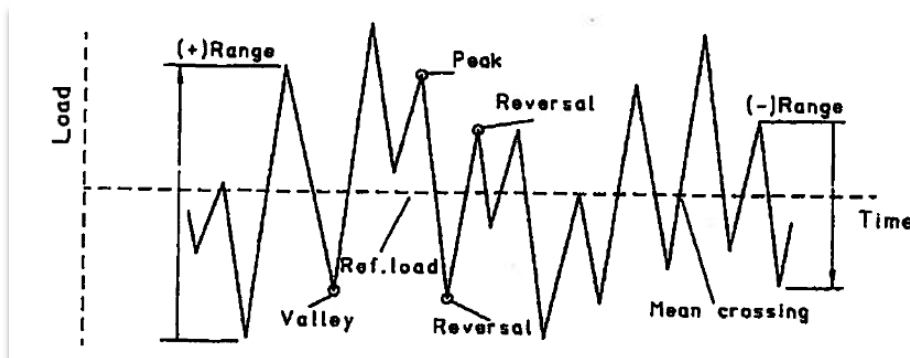


FIGURE 8 - VARYING LOADING AMPLITUDES (BERGE, 2006)

Explanation:

- *Peak* is the point where the first derivative of the loading/time history changes from positive to negative sign.
- *Reversal* is the point where the first derivative of the loading/time history changes sign.
- *Valley* is the point where the first derivative of the loading/time history changes from negative to positive sign.
- *Range* is the difference between the valley and the peak loading or between a successive peak and valley. Ranges can vary in terms of the definition applied. Overall range is the difference between the highest peak point and the lowest valley point.

- *Mean crossings* is where the number of times the loading history crosses the mean load level.

Irregularity factor is a measurement of the irregularity on the data, in other words the bandwidth (stress range) of the signal. The bandwidth is defined as the ratio between the positive mean crossings to the number of valleys or peaks in that given load history. In a fatigue analysis of welds the mean stresses can normally be neglected, so the mean-crossings are defined as the zero-crossings (Berge, 2006).

3.5 CYCLE COUNTING

In cumulative damage analysis the stress-time history is broken down into individual cycles, which are summed up to a distribution of the different stress ranges. Various methods of cycle counting exist, each with their own cons and pros. In many cases it is important to use a counting method that physically represents the fatigue process most correct. Cycle counting can be represented by different spectra's:

- *Occurrences spectrum* is a representation of a variable amplitude loading, by the number of times a specific loading parameter (range, peak, level, etc.) occurs within a set interval. In statistics this is called frequency functions or probability density functions (PDF).
- *Exceedances spectrum* is a presentation of a spectrum loading situation by the number of times the value equals or exceeds a particular loading parameter.

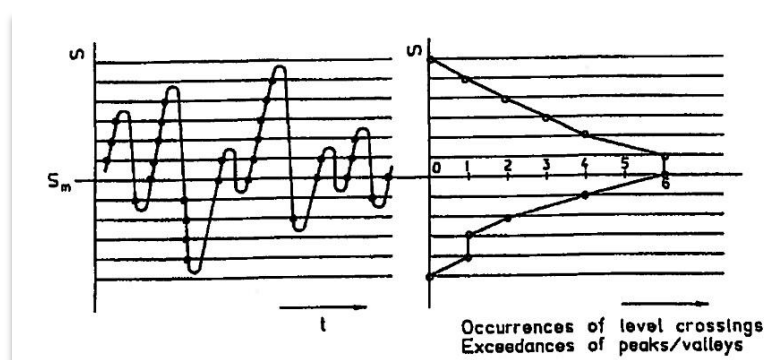


FIGURE 9 - EXCEEDANCES SPECTRUM (BERGE, 2006)

How we count the cycles and amplitudes can vary with the situation, and the different methods of counting can achieve different results. The basic cycle counting methods will be described in the next chapters (Berge, 2006).

3.5.1 LEVEL CROSSING COUNTING

This counting method counts when the value crosses/reaches different levels (of load). How many levels the counting is divided into is crucial for this methods accuracy. In order to reduce the counting events by a factor of two, positive-going level-crossings are recorded at and above the mean load and negative-going crossings below the main load. The difference between the counts for two neighboring levels on the positive side of the mean level is equal to the number of peaks in the corresponding interval of stress. But regardless, the occurrences spectrum of the stress levels is the same as the exceedances spectrum of the peak levels.

The main flaw with the *level crossing counting* method is that there is no information obtained about the irregularity of the load.

Figure explained: (a) represents a broad-banded load history. The result from the counting (of (a), without dead band) is presented in (c), while in (b) a dead band has been introduced. The reason the dead band is introduced is that for many cases the small stresses may be assumed to be non-damaging, so they can be neglected in the counting procedure.

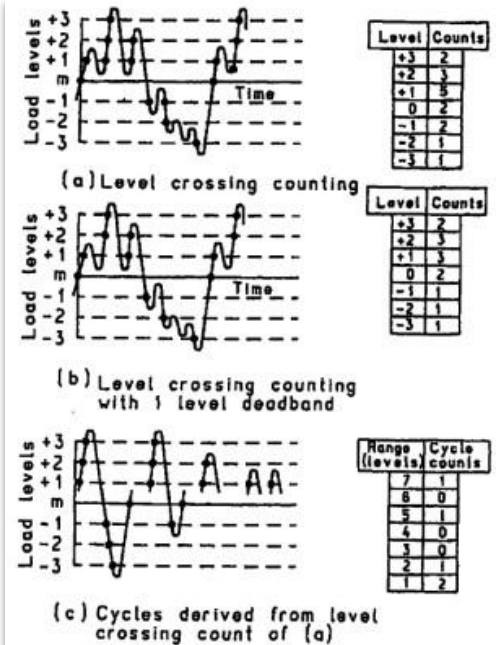


FIGURE 10 - LEVEL CROSSING COUNTING (BERGE, 2006)

A normal method of counting cycles is to construct the largest possible cycle followed by the second largest and so forth until all the level crossings are demonstrated. The reversal points are normally assumed to occur halfway between the levels, and with this method a narrow-band process are represented in a realistic way. However, for a broad banded loading the stress ranges with mean values different from the mean level from the loading will be combined in an unrealistic way. For this process the level count method tends to be a bit conservative.

3.5.2 PEAK COUNTING

All the values above the mean level are counted as a peak, and all values below the mean level are counted as a valley. The peaks and valleys are usually separated from each other in the results. A regular variation of this method is to count all the peaks and valleys without respect to the mean level. The two different peak counting methods are presented below.

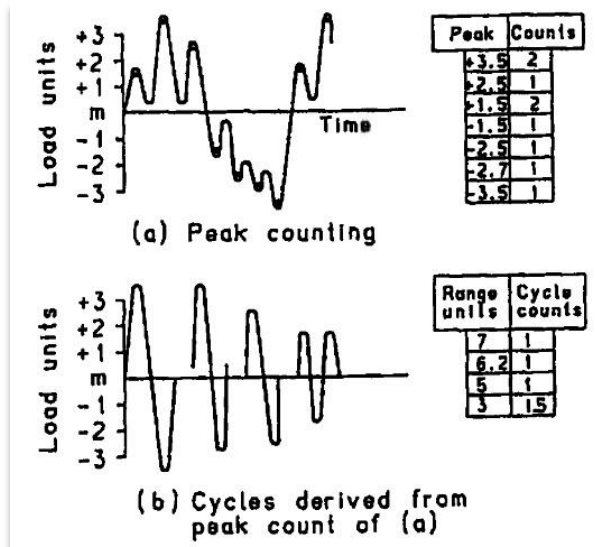


FIGURE 12 - PEAK COUNTING (BERGE, 2006)

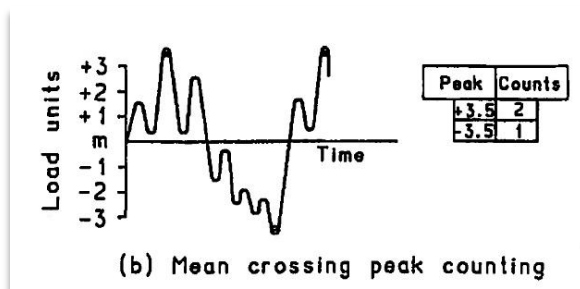


FIGURE 11 - MEAN CROSSING PEAK COUNTING
(BERGE, 2006)

As with the level counting, the peak counts are combined by constructing the largest possible cycle then then second largest cycle and so forth. This is, as mentioned above a conservative counting method. An alternative to this is to combine pairs of peaks and valleys in a random way.

3.5.3 SIMPLE RANGE COUNTING

In this method a range is defined as the stress difference between two reversals. It distinguishes between positive and negative ranges. If the mean of each range is counted the method is called *range-mean counting*. If only positive ranges are counted, each range is counted as a cycle. When both positive and negative ranges are counted each range is counted as a half-cycle.

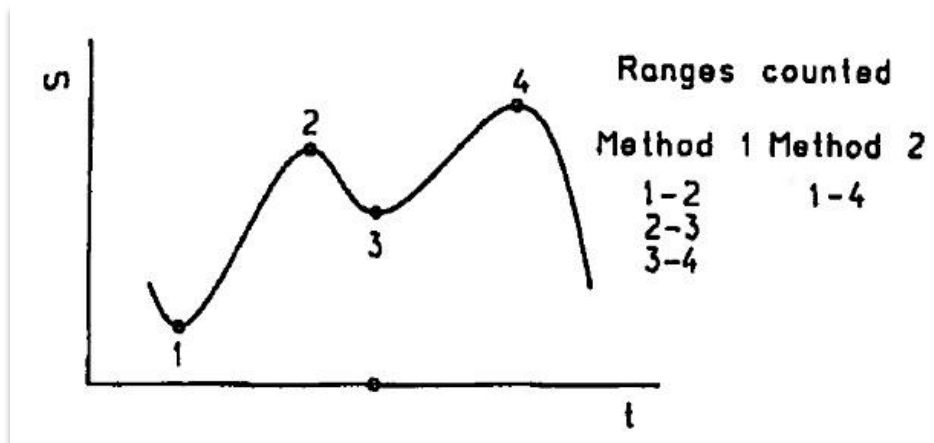


FIGURE 13 - SIMPLE RANGE COUNTING (BERGE, 2006)

A problem with this method is how to take care of the small cycle's in-between the larger cycles. The sequence above can be counted as three individual half cycles or one large half cycle. The final damage summation will depend significantly on the choice of the threshold level for counting small cycles.

3.5.4 RAINFLOW COUNTING ALGORITHM

Rain flow counting itself is used as a common name for a large class of counting methods, such as: *range-pair counting*, *the Hayes method*, *the original rain-flow method*, *ordered overall range counting*, *racetrack counting* and *hysteresis loop counting*. If the load history begins and ends with its maximum peak or minimum valley point, these methods gives identical results (number of counts). I will cover the original rainflow method.

This method is used in the analysis of fatigue data in order to reduce the measured statistics into a smaller set of stress reversals. There are multiple methods and algorithms which give the same results, but this is the most popular one.

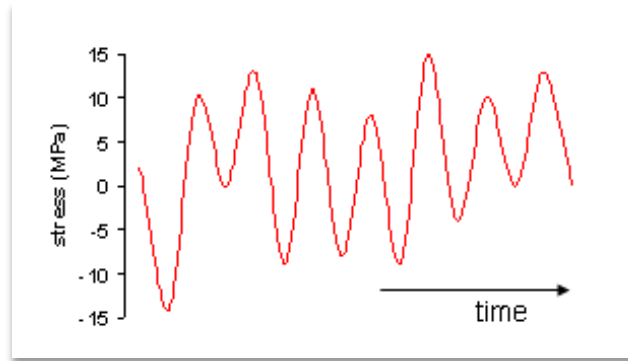


FIGURE 14 - LOAD HISTORY

It is important that this algorithm allows the Miner's rule, in order to evaluate the fatigue life of the structure. The algorithm was created by Tatsou Endo and M. Matsuishi in 1968. For simple periodic loadings rain-flow counting is unnecessary, since it can easily be modeled and estimated by a simple application of the S-N curve (given that the stress amplitude is known).

This method is well suited for a broad banded load history.

The algorithm is performed this way:

- 1) Reduce the time history to a sequence of tensile peaks and compressive troughs.
- 2) Imagining that the time history is a template for a rigid sheet
- 3) Turning the sheet clockwise 90 degrees (earliest time on top)
- 4) Each tensile peak is imagined as a source of water that drips down to the "ground underneath"
- 5) Count the number of half-cycles by looking for terminations in the flow occurring when either:
 - a. It reaches the end of the time history
 - b. It merges with a flow that started at an earlier tensile peak
 - c. It flows opposite a tensile peak of greater magnitude.
- 6) Repeats step 5 for compressive troughs
- 7) Assigns a magnitude to each half-cycle equal to the stress difference between its start and termination time.

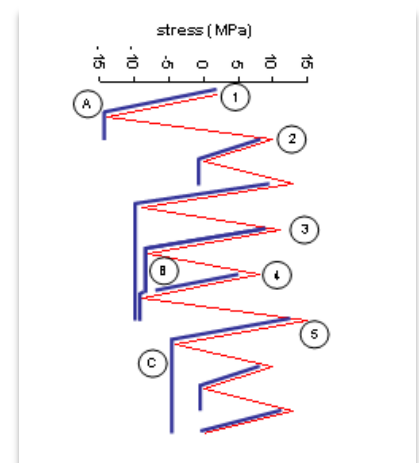


FIGURE 15 - RAINFLOW ANALYSIS FOR TENSILE PEAKS

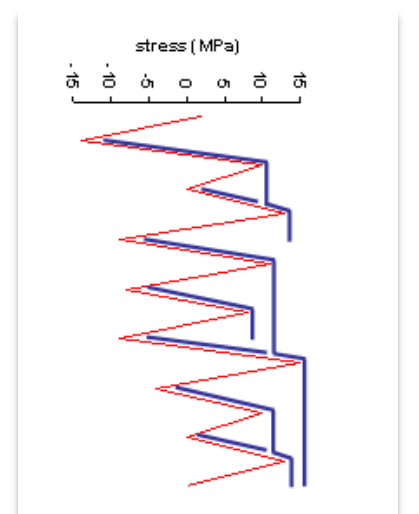


FIGURE 16 - RAINFLOW ANALYSIS FOR COMPRESSIVE TROUGHS

- 8) Pair up all the half-cycles of identical magnitude (but opposite sign) to count the number of complete cycles. Typically there will exist some residual half-cycles

The result from using this algorithm will give the user number of cycles at the different amplitudes, as shown on the figure below.

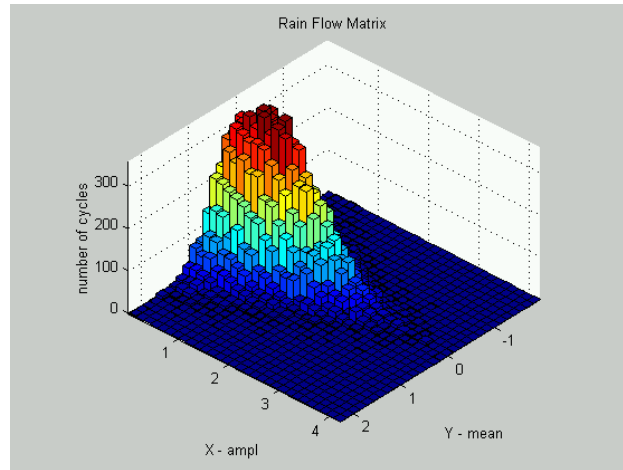


FIGURE 17 - RAIN FLOW MATRIX EXAMPLE RESULT

3.6 ANALYTICAL FATIGUE DAMAGE CALCULATION

It is possible to perform an analytical fatigue damage assessment, but it requires certain prerequisites. However, when these are met this method is way faster than counting methods discussed previously in this report. The analytical formula is derived as follows:

As described earlier the total damage can be calculated with the Miner – Palmgren’s hypothesis:

$$D = \sum \frac{n_i}{N_i} \quad 3.4$$

If the size of each block is reduced the expression can be written as:

$$D = \int_0^{\infty} \frac{dn}{N} \quad 3.5$$

Expected damage can be found by the integral:

$$E(D) = \int_0^{\infty} \frac{1}{N} E \, dn \quad 3.6$$

Where $E \, dn$ is expected number of stress ranges given by:

$$E \, dn = f_s(s) ds * N_{tot} \quad 3.7$$

Where:

- $f_s(s)$ is the probability density function for specific stress range

If the long term distribution can be described as a Weibull distribution (2-parameter), the closed form expression for fatigue damage can be written as:

$$E(D) = \frac{N_{tot}}{K} \lambda^m \Gamma\left(\frac{m}{\beta} + 1\right) \quad 3.8$$

Where:

- N_{tot} is total number of stress cycles in the time history
- $\Gamma(\dots)$ is the gamma function
- λ, β are parameters in the Weibull distribution
- K, m are parameters from the S-N curve

If the stress ranges are Rayleigh distributed, the closed form solution for expected damage:

$$E(D) = \frac{N_{tot}}{K} * (2\sqrt{2} * \sigma)^m * \Gamma\left(\frac{m}{\beta} + 1\right) \quad 3.9$$

Where:

- σ is the standard deviation to the stress process

The main criteria for using these two formulas are that the stress process is narrow-banded. Furthermore, the two expressions can only be used if the S-N curve has a constant slope and no fatigue limit. In other words the S-N curves equation is valid for all positive values of the stress range.

If the S-N curve has a fatigue limit, all the stress ranges below this limit will not contribute to the fatigue damage ($n_i = \infty$). It is possible to derive an expression that takes this into account, but I will not discuss this here.

4 DNV RULES AND REGULATIONS

“The aim of fatigue design is to ensure that the structure has sufficient resistance against fatigue failure i.e. it has an adequate fatigue life. Prediction of fatigue lives is used in fatigue design to fulfill this aim. Prediction of fatigue lives can also form the basis for definition of efficient inspection programs, both during manufacturing and during the operational life of the structure” (DNV, September,2012).

This chapter is to be considered as a summary of important rules and regulations stated by DNV. The specific DNV document used is mentioned in the different sub-chapters.

4.1 GENERAL WIND TURBINE RECOMMENDATIONS

In the document “Design of Offshore Wind Turbine Structures” (DNV-OS-J101) written by DNV, they describe different parameters which are important in the designing of the Hywind Demo. The document contains all the different parts on an offshore wind turbine and the individual demands for these components. However, I have only looked at the part that describes the FLS.

4.1.1 FATIGUE LIMIT STATES

The basis of the DNV fatigue design is the S-N curve and cumulative damage. The S-N curve is usually based on fatigue tests in the laboratory. For best interpretation of the S-N curves from the fatigue tests, the fatigue failure is defined to have occurred when a fatigue crack has grown through the thickness of the structure or structural component. The characteristic S-N curve shall in general be taken as the curve that corresponds to 2.3% quantile of N given S, for example the S-N curve that provides 97.7% probability of survival. The design fatigue life for all the structural components (like the anchor pin joints and all the connection parts for the mooring line system) should be based on the specified service life of the structure. Common rule is to design it for 20 years. The fatigue analysis shall be carried out for each individual member subjected fatigue load. Critical parts are to be analyzed more detailed to ensure correct data (DNV, September 2012).

4.1.2 CHARACTERISTIC STRESS RANGE DISTRIBUTION

Every significant stress range that will contribute to fatigue damage to the structure is important to consider. The stress range from the wave loading shall be based on site-specific wave statistics. Discrete wave statistics can be applied for this purpose and usually imply that the number of waves are specified from eight different compass directions in one-meter wave height intervals. For the wave heights between 0 [m] and 1 [m], a finer discretization with 0.2 [m] wave height intervals is recommended in order to enhance the accuracy of the fatigue damage predictions (DNV, September 2012).

For water depths less than 15 [m], higher order stream function theory is to be used. Since the Hywind Demo operates on a much deeper sea level, this is not important. DNV states that for depths of 30 [m] and deeper, Stokes 5th order theory is to be applied. As with wave statistics, the wind loading shall also be established from site-specific wind statistics.

Stresses caused by the operation and the control of the Hywind Demo shall be included. Examples on this may be rotor stopping and starting, generator connection and disconnection. All these situations may cause transient loads and yaw-loads (rotational) to the whole structure.

When it is appropriate, all the stress-ranges from the long-term stress range distribution shall be multiplied by a stress concentration factor (SCF). The SCF factor depends on the structural geometry and can be calculated from parametric equations or by finite element analysis (DNV, September 2012).

For fatigue analysis of regions where the base material is not significantly affected by the residual stresses due to welding, the stress range may be reduced prior to the fatigue analysis (depending on whether the mean stress is a tensile stress or a compressive stress, see figure below).

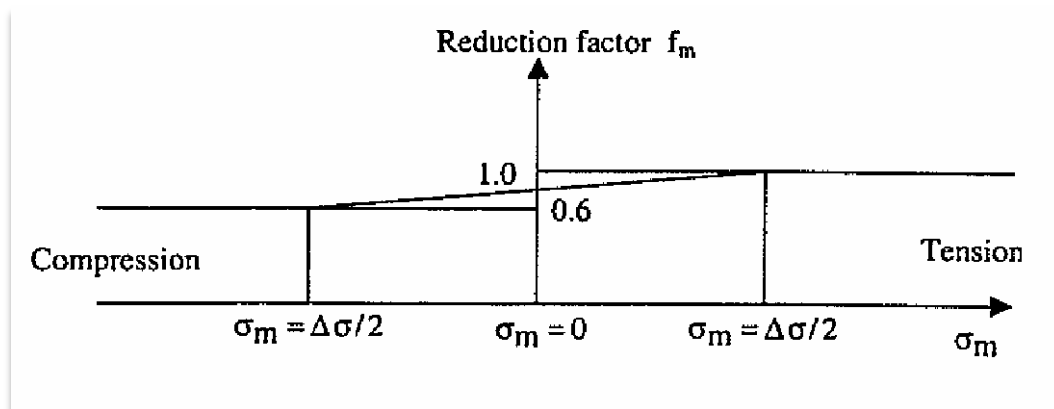


FIGURE 18 - DNV STRESS REDUCTION FACTOR (DNV)

Another part of the fatigue and stress range analyses are the dynamic effects. These effects can be large due to all the rough motions these types of structures experience. When the natural period of the Hywind Demo or the mooring lines is less or equal to 2.5 [s], a dynamic amplification factor (DAF) may be applied to the wave load on the structure (when it is modeled as a single-degree of freedom system).

$$DAF = \frac{1}{\sqrt{(1 - \Omega^2)^2 + (2\Omega\zeta)^2}} \tag{4.1}$$

Where: Ω = Ratio between applied frequency and natural frequency

ζ = Damping ratio relative to critical damping

If the natural period for the mooring lines on the Hywind Demo are greater than 2.5 [s], a time domain analysis shall be carried out to determine the dynamic amplification factors.

The stress ranges in the stress range distribution must be compatible with the stress ranges of the S-N curve that the distribution is to be used for fatigue damage predictions.

4.1.3 CHARACTERISTICS AND DESIGN CUMULATIVE DAMAGE

The predictions of the total fatigue life should be based on calculations of cumulative fatigue damage under the assumption of linearly distributed cumulative damage (DNV, September 2012).

The first method DNV is pointing at is the Miner sum calculation method. This one does not need any further explanation since it's already been discussed earlier in this report. The second method they mention is a modified Miner sum formula. They introduce a design fatigue factor (DFF) which is to be multiplied with the characteristic cumulative damage.

$$D_d = DFF * D_c \tag{4.2}$$

Where: D_d is the design cumulative damage
 DFF is the design fatigue factor
 D_c is the characteristic cumulative damage

The design fatigue factors from DNV:

Table J2 Requirements for S-N curves and design fatigue factors, DFF			
<i>Location</i>	<i>Accessibility for inspection and repair of initial fatigue and coating damages (2)</i>	<i>S-N curve</i>	<i>DFF</i>
Atmospheric zone	Yes	“In air”, for surfaces with coating “Free corrosion”, for surfaces protected by corrosion allowance only	1.0
Splash zone (1)	Yes	Combination of curves marked “In air” and “Free Corrosion” (3)	2.0
	No		3.0
Submerged zone	Yes	“In seawater”, for surfaces with cathodic protection.	2.0
	No		3.0
Scour zone	No	“Free corrosion”, for surfaces protected by corrosion allowance only.	3.0
Below scour zone	No	“In seawater”	3.0
1) Splash zone definition according to Sec.11 B200. 2) If the designer considers the steel surface accessible for inspection and repair of initial fatigue damage and coating this must be documented through qualified procedures for these activities. See also Sec.11 and Sec.13. 3) The basic S-N curve for unprotected steel in the splash zone is the curve marked “free corrosion”. The basic S-N curve for coated steel is the curve marked “in air”. It is acceptable to carry out fatigue life calculations in the splash zone based on accumulated damage for steel considering the probable coating conditions throughout the design life – intact, damaged and repaired. The coating conditions shall refer to an inspection and repair plan as specified in Sec.13. For coating systems with a specified coating life of 15 years and without any qualified coating repair procedure, it is acceptable to use the “in seawater” S-N curve as a representative fatigue curve throughout a service life of 20 years.			

TABLE 4 - DNV DESIGN FATIGUE FACTORS (DNV)

The reason for the red color on the table above is that it is not 100% validated from DNV.

In method 2 they also apply a material factor γ_m . This factor is applied to all stress ranges before calculating the corresponding numbers of cycles to failure that are used to obtain the design fatigue damage. They are presented in relation to the DFF:

Table J3 Material factors, γ_m, to be applied to all stress ranges for calculation of design fatigue life	
<i>DFF</i>	<i>γ_m</i>
1.0	1.0
2.0	1.15
3.0	1.25

TABLE 5 - DNV MATERIAL FACTOR (DNV)

The overall design requirement is (the Miner sum):

$$D_D \leq 1.0 \qquad 4.3$$

4.2 MOORING SPECIFIC RULES

This is a summary of a selected set of rules from the DNV document “Position Mooring” (DNV-OS-E301). This sub-chapter covers environmental conditions that may come to an importance regarding the boundary for an analysis together with fatigue rules and recommendations that are mooring line specific.

4.2.1 ENVIRONMENTAL RULES AND RECOMMENDATIONS

When analyzing the mooring system, detailed metocean specifications should be used to perform the analysis.

In general, when we are analyzing a structure that is meant for the Norwegian water (and some other extra-tropical locations), a combination employing both wind and waves with a 100-year return periods combined with current with a 10-year return period is usually acceptable. However when we are investigating an offshore wind turbine, it is common to use a 50-year return period for the waves. A long term fatigue analysis on mooring systems require that a set of environmental states shall be specified, to ensure that all conditions are accounted for so that the fatigue damage calculation has adequate accuracy.

Waves

The effects from the loads are based on the predicted tensions in the mooring lines. This is normally obtained by calculations. The analysis of the mooring line tensions shall cover the motion of the floating unit induced by environmental loads and the response of the mooring lines to these motions. Characteristic load effects are obtained for stationary, environmental states. Each environmental state may be specified in terms of:

- Peak wave period – T_p
- Significant wave height - H_s
- Wave spectrum (JONSWAP or double-peaked)
 - o In the North Sea and North Atlantic the Torsethaugen double peak spectrum can be applied. This spectrum is based on measured spectra for Norwegian waters.
- Wave energy spreading function
- Main wave direction
- Mean wind speed (over a 1 [hour] averaging period 10 [m] above sea level)
- Wind spectrum function
- Wind direction
- Surface current speed (V_c)
- Current profile over depth
- Current direction

As mentioned above the sea states with return periods of 100 years shall be used (50 years for offshore wind turbines). The wave conditions shall include a set of combinations of significant wave heights (H_s) and peak periods (T_p) along the 100-year contour line. The contour line is defined by the inverse FORM technique.

The joint probability distribution of significant wave height and peak wave periods at the mooring system location is necessary when establishing the contour line. If the joint distribution is not available, the range of combinations based on a contour line for the North Atlantic may be used.

It is important to perform the calculations for several sea states along this 100-year contour line to check whether mooring system is properly designed. Normally, ship-shaped units are very sensitive to low frequency motion and therefore the sea states with short peak periods can be critical. Which sea states along the contour line it is important to investigate is described in the figure below (DNV, October 2010):

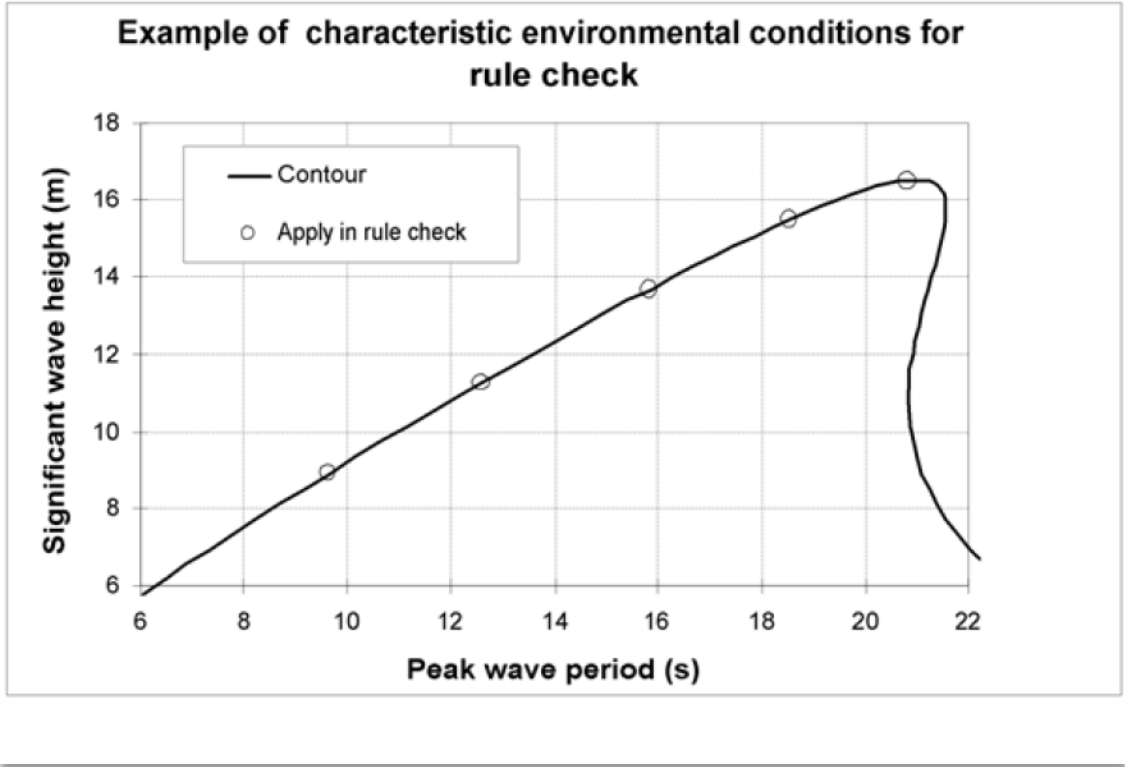


FIGURE 19 - SEA STATE SELECTION (DNV)

Wind

Normally a wind speed 10 [m] the water surface with a return period of 100-years should be used. It is also based on the marginal distribution of wind speeds at the specific location. The wind loads shall be treated as a steady component in combination with the time varying component wind gust. The wind gust creates low frequency motions. Time varying winds is described by a wind gust spectrum. The NPD/ISO wind spectrum shall be applied for all locations, and the formulation is given in NORSOK N-003 and in ISO-19901-1. The steady component of the wind speed is represented by a 1 [hour] average mean wind 10 [m] above sea level.

Typical 1 [hour] mean wind speeds with a return period of 100 years 10 [m] above sea level:

Location	Wind speed [m/s]
Norwegian Sea (Haltenbanken)	37.0
North Sea (Troll field)	40.5
North Sea (Greater Ekofisk area)	34.9
Hywind location (50 year return period)	35.0

TABLE 6 - TYPICAL WIND SPEEDS (DNV)

Squall events should normally be analyzed in the time domain using the time histories of squalls. It shall include variation in both wind speed and direction. Normally the duration of a squall is set to 1 [hour]. The scaling shall be done in a way so the squall has a 100 [year] return period. The time axis can be scaled to preserve the rate of increased wind speed. The extreme values of the mooring line tension (and offset) shall be taken as the maximum values for the time series for the actual response. If squall time series are not available the squall can be represented by a one minute average constant wind speed with a return period of 100 [years]. Below is a figure of a squall time series plotted with respect to the wind speed:

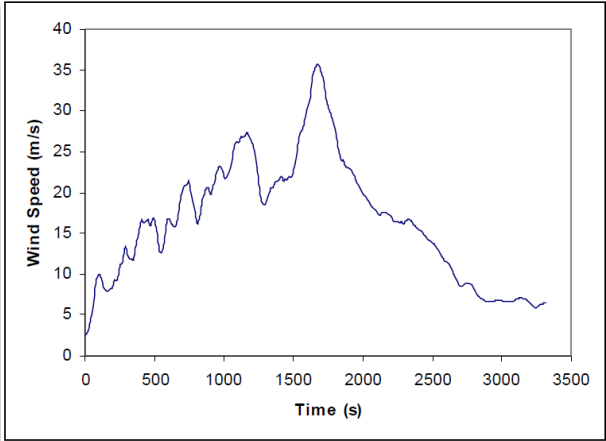


FIGURE 20 - SQUALL TIME SERIES (DNV)

Current

Normally a surface current speed with a 10-year return period shall be used. The basis of the surface current speed should be the marginal distribution of the current speed at the specific location.

We divide the currents into different categories:

- Circulation currents (oceanic circulation patterns)
- Tidal currents
- Wind generated currents
- Loop and eddy currents
- Soliton currents (created by difference in density)

These are put into a total current vector, where speed and directions are specified for the different depths. In open areas the wind generated current at surface level may be calculated as follows:

$$V_{C_{Wind}} = 0.015 * U_{1hr,10m} \quad 4.4$$

Typical surface current speeds with a return period of 10 years:

Location	Current Velocity [m/s]
Norwegian Sea (Haltenbanken)	0.90
North Sea (Troll)	1.50
Hywind Demo location	1.00

TABLE 7 - TYPICAL CURRENT VELOCITIES (DNV)

WIND, WAVES AND CURRENT COMBINED

DNV states that for a column-stabilized unit (directionally fixed) the loads from wind, waves and current are assumed acting from the same direction. And for units with a symmetrical mooring line pattern at least head, quartering and beam load directions should be analyzed in addition to the case mentioned above (all in one direction). In these cases, a directional distribution of wind, waves and current may be applied.

4.2.2 ACCUMULATED FATIGUE DAMAGE

Characteristic fatigue damage for a mooring line component is a result of the cyclic loading history. The fatigue damage is summed up from the different sets of environmental states chosen for the long term environment:

$$d_c = \sum_{i=1}^{i=n} d_i \quad 4.5$$

Where:

- d_i is the fatigue damage to the component in the environmental state i
- $i=1, \dots, n$ is the different environmental states

Each environmental state is defined in terms of wind, heading angles, wave and current parameters. The probability of occurrence P_i is required for each environmental state.

If the effects of mean tension can be neglected, the accumulated fatigue damage for each environmental state may be computed as:

$$d_i = n_i \int_0^{\infty} \frac{f_{Si}(s)}{n_c(s)} ds \quad 4.6$$

Where:

- n_i is the number of stress cycles in the current environmental state (during the design life)
- $f_{Si}(s)$ is the probability density of the nominal magnitudes (peak-to-through) of the stress cycles applied to the component in state i .
- $n_c(s)$ is the number of stress cycles of magnitude s that would lead to failure of the component.

The nominal magnitudes of the stress cycles are computed by dividing the magnitudes of the corresponding tension by the nominal cross-section area of the component. For chains and ropes we got:

$$A_{chain} = \frac{2 \pi d^2}{4} \tag{4.7}$$

$$A_{rope} = \frac{\pi d^2}{4} \tag{4.8}$$

Then the number of stress cycles in each environmental state can be calculated:

$$n_i = v_i * P_i * T_D \tag{4.9}$$

Where:

- v_i is the mean-up-crossing rate [Hz] of the loading process in the state i
- P_i is the probability of the occurrence in the state i
- T_D is the design life time for the mooring line component [s]

4.2.3 FATIGUE PROPERTIES

To calculate the capacity against tension fatigue on the component level the following equation can be used:

$$n_C(s) = a_D * s^{-m} \tag{4.10}$$

The equation can be linearized by writing it logarithmic:

$$\log(n_C(s)) = \log(a_D) - m * \log(s) \tag{4.11}$$

Where:

- $n_C(s)$ is the number of stress ranges
- s the stress range (double amplitude) [MPa]
- a_D is the intercept parameter of the S-N curve
- m is the slope of the S-N curve

Fatigue Curve Parameters	a_D	m
Stud Chain	$1.2 * 10^{11}$	3.0
Stud less Chain (open link)	$6.0 * 10^{10}$	3.0
Stranded Rope	$3.4 * 10^{14}$	4.0
Spiral Rope	$1.7 * 10^{17}$	4.8

TABLE 8 - FATIGUE CURVE PARAMETERS (DNV)

Now the fatigue life for long term mooring can be calculated by using the curve parameters. It is important to use appropriate stress concentration factors (SCF). Other types of connection elements shall not be used in long term mooring systems unless the fatigue life is well documented. The design S-N curves from the table:

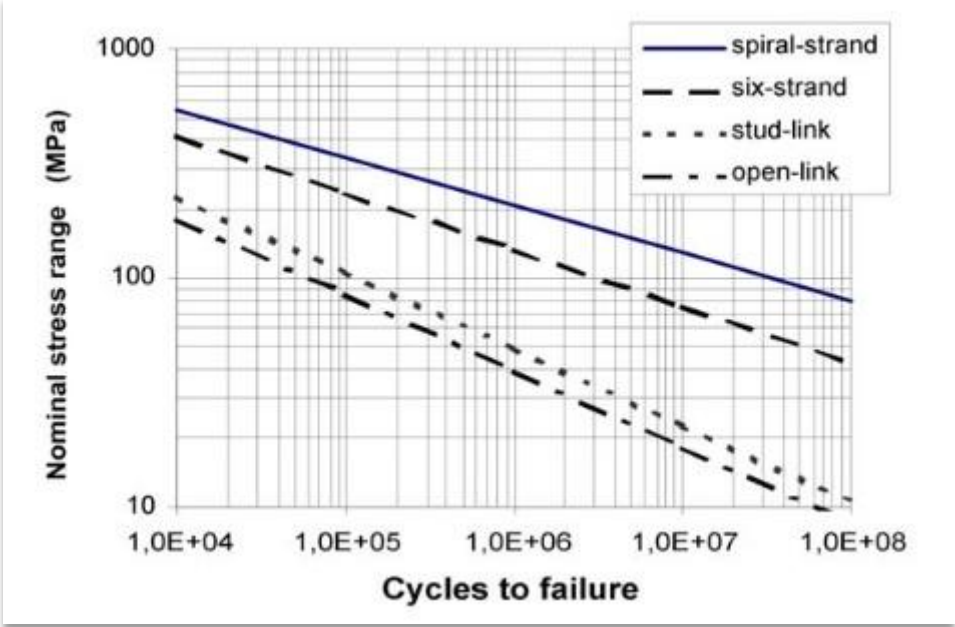


FIGURE 21 - DESIGN S-N CURVES (DNV)

The S-N curves for chain (stud-link and open-link) are intended to be applicable in sea water, while the S-N curves for the steel wire ropes is based on the fact that the rope is protected from the corrosive effect of sea water.

An alternative to the linear S-N curve shown above is a two-slope S-N curve. It can be explained as:

$$N = \begin{cases} \bar{a}_1 * S^{-m_1} & S > S_{sw} \\ \bar{a}_2 * S^{-m_2} & S < S_{sw} \end{cases}$$

Where:

- \bar{a}_1 and \bar{a}_2 are the characteristic fatigue strength. It is defined as the mean minus two standard deviation curve.
- S_{sw} is the stress at the “knee-point” on the curve (corresponding N_{sw} is the number of cycles at the “knee-point”).

The two-slope S-N curve from DNV is as follows:

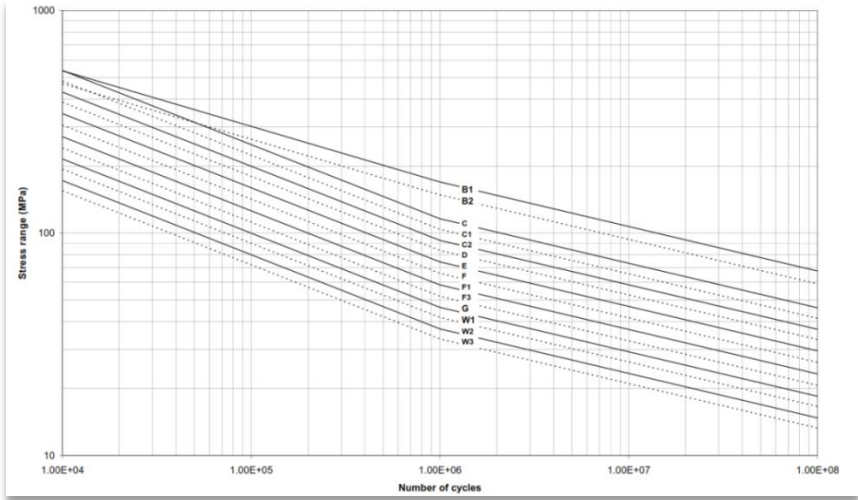


FIGURE 22 - TWO SLOPE S-N CURVES, IN AIR (DNV)

The different curves represent the different categories of material. The anchor chains used on the Hywind Demo falls under the category “B1”.

The mooring lines for the Hywind Demo consist mainly of studed chains and spiral stranded ropes.

4.3 ULS CHECK

In the DNV rules and regulations (DNV-OS-E301) requirements for ULS is described. The two most important check points are:

- The mooring line tension (on the most critical part) shall be within certain limits.
- Horizontal (of the line itself) and vertical offset (of the anchor) shall be investigated.

Mooring line tension shall meet the requirements of the following equation:

$$S_C - T_{C-mean} * \gamma_{mean} - T_{C-dyn} * \gamma_{dyn} \geq 0 \tag{4.12}$$

Where:

- S_C is the characteristic capacity, defined by $S_C = 0.95 S_{mbs}$. The S_{mbs} represents the minimum breaking strength for the component.
- T_{C-mean} is the characteristic mean mooring line tension, from a static analysis of the model
- T_{C-dyn} is the characteristic dynamic mooring line tension, from a dynamic analysis of the model.

- γ_{mean} is a partial safety factor on mean mooring line tension.
- γ_{dyn} is a partial safety factor on dynamic mooring line tension.

In DNV-OS-E301 two different consequence classes are defined for ULS. Quoted from the document:

Class 1: “Where mooring system failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsize or sinking.

Class 2: “Where mooring system failure may well lead to unacceptable consequences of these types”

The safety factors related to these two classes:

Partial Safety Factors for ULS			
Consequence Class	Type of Analysis of Wave Frequency Tension	Partial Safety Factor on Mean Tension γ_{mean}	Partial Safety Factor on Dynamic Tension γ_{dyn}
1	Dynamic	1.10	1.50
2	Dynamic	1.40	2.10
1	Quasi-Static	1.70	
2	Quasi-Static	2.50	

TABLE 9 - PARTIAL SAFETY FACTORS FOR ULS (DNV)

As shown in the table above, the safety factors for quasi-static analysis is much higher compared to the safety factors for the dynamic analysis. However, the model will only be simulated dynamically.

Regarding horizontal and vertical offset of the anchor, the most important parameter is the vertical offset of the anchor. Described in D800 (Permissible Line Length, DNV-OS-E301), the following applies:

- “The mooring lines shall have enough length to avoid uplift at anchors for all relevant design conditions in the ULS”.
- “Vertical forces on the anchors can be accepted in the ALS, if it is documented that these vertical forces will not significantly reduce the characteristic resistance of the anchors”.

This applies to anchors not designed to take vertical forces. The anchors used on the mooring lines for the Hywind Demo are Stevshark anchors, which are not designed to take vertical forces. This will be checked by investigating the point on the mooring chain closest to the anchor. If the point closest to the anchor has no vertical displacement, there is no uplift of the anchor itself.

5 RIFLEX

5.1 IN GENERAL

This theory part will cover the main essence behind the programming code RIFLEX. The program itself is made and developed at MARINTEK.

The program is designed to perform load effect analysis on flexible riser systems. The program can describe the typical or linear response of the flexible risers, but also the responses under extreme conditions where nonlinearities play an important role. Usually these computations is very time consuming, so it was therefore important that this program was created for this use to optimize the computational requirements.

These were the requirements for the program (Engseth et al.)

- Simple but general description of the physical system
- 3D problem description
- Bending, axial and torsional deformations including coupling between these effects
- Large displacements and rotations consistently handled both with regards to stiffness, mass and load description
- Non-linear relation between cross section forces and deformations
- Non-linear load formulation
- Use of simplifications without loss of accuracy when possible

The program computes the static and dynamic behavior of flexible risers. The program itself consists of four program modules which communicate by a file system. Schematically it looks something like this:

The different sub-scripts are:

- INPMOD: Input and data base organization
- STAMOD: Static Analysis
- DYNMOD: Dynamic Analysis
- OUTMOD: Post-processing and output by print/plot

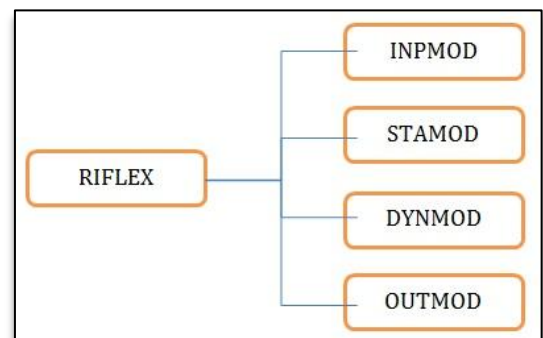


FIGURE 23 - RIFLEX FLOWCHART

5.2 A QUICK OUTLINE OF THE ANALYSIS (ENGSETH ET AL.):

- 1) **STAMOD:** Establishes an equilibrium position of the riser subjected to the static loads. This is the basis for the dynamic analysis.
- 2) **CAT-procedure:** The unstiffened catenary solution is used to approximate the initial static equilibrium configuration. In most cases the bending stiffness will have a minor effect on the overall static configuration. This fact plus the fact that the catenary configurations are easy to calculate makes the problem very convenient with regards to obtaining a fairly accurate static equilibrium configuration. A positive side is that it also demands minimum computational resource.
- 3) **CATFEM-procedure:** This step is an iteration process for equilibrium by the FEM-method. Its initial conditions are the catenary solution. This step establishes rapidly the initial static equilibrium, where only the weight and buoyancy loads are included.
- 4) **FEM-procedure:** This is the traditional way for the incremental loading procedure from the given stress-free configuration to the specified equilibrium configuration. The loads applied are: volume loads, prescribed displacements, specified nodal point forces and current forces.

5.3 BASIC THEORY

The analysis part of the program is based on a nonlinear FEM modeling of the riser. This theory allows large displacement and rotation, which is essential for the whole problem. Two different types of elements may be used for the modeling of the riser; a 3D cable element or 3D beam element. A total Lagrangian description for the motion is used for the cable element while for the beam element it uses a modified Lagrangian formulation.

The displaced position of each nodal point is uniquely defined by the initial position vector \mathbf{X} and the nodal displacement vector \mathbf{u} . It's important to emphasize that large rotations in space must be handled very carefully (not vector quantities). In the current formulation it is assumed that each node is assigned with own specific nodal coordinate. This coordinate system moves with the nodes.

Incremental rotations utilized during a load step are used to update the transformation. And in the current formulation the general motion of a nodal point is described by the three

displacement components and the nine elements of the rotation matrix. The 12 nodal degrees of freedom for each beam element are defined in relation to the local element coordinate system. It is assumed that the deformations relative to these local elements coordinate systems are small.

Cubic interpolation is assumed for bending in the transverse directions where the axial displacements and the torsional rotation are interpolated linearly (Engseth et al.).

5.4 SIMA

SIMA is and 3Dgraphically interface program based on RIFLEX and SIMO. Before this program existed, making input to RIFLEX or SIMO was entirely done by text editing. Instead of only using text editors, you now are able to see what you are modeling in 3D. The program also validates the code you are writing, to minimize the risk of making any input errors which may cause calculation errors.

The program is being developed as a joint industry project by MARINTEK and Statoil. Currently the program supports these types of codes:

- SIMO – Used to model marine operations.
- RIFLEX – Used to model a system consisting of slender elements (risers, anchors and such).
- RIFLEX coupled – SIMO and RIFLEX coupled. Used to model slender elastic structures within a marine operation.
- MULDIF2 – Used to model input to a hydro dynamical software package MULDIF2.
- SIMLA JLayer – Used to model pipeline laying operations.
- HLA – Used to set up an interactive HLA simulation.

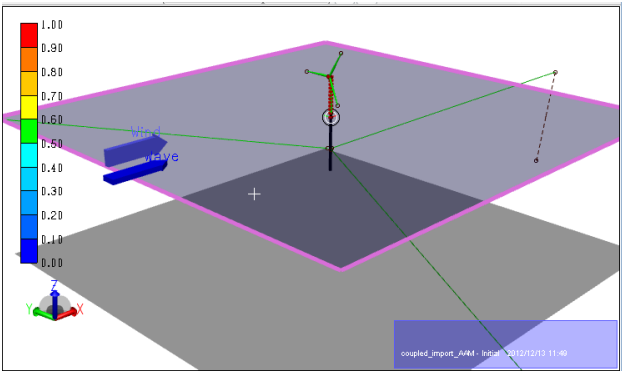


FIGURE 24 - MARINTEK OC3 MODEL

The picture above is the OC3 model made by MARINTEK. The model represents a 5-megawatt offshore wind turbine. The model has at this point only been used to familiarize myself in the program.

6 THE MODEL

6.1 GENERAL

This chapter contains a detailed description of the model used in SIMA.

In SIMA, a pitch-controller has been added to simulate the real pitch-controller used on the Hywind Demo. The pitch-controller alters the thrust (angle of blades) in relation to the pitch-movement of the structure. The controller makes the Hywind Demo much more pitch stable. The cutout-speed where the turbine goes to an idle-mode is 25 [m/s].

Designated wind-files are used in SIMA. The wind-files describe a more realistic turbulence and intensity compared to a constant wind all over the blades. The waves are based on a JONSWAP 3-parameter spectrum.

The model used is Statoils "As-Built"-model for the Hywind Demo. The input of model into Sima is a coupled Riflex- and Simo-import.

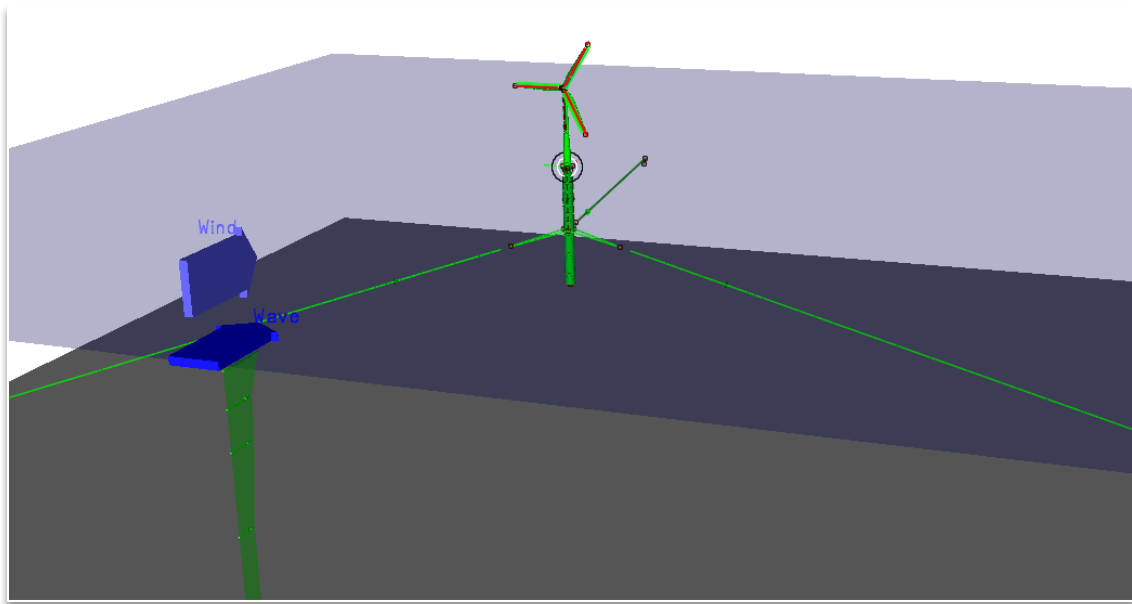


FIGURE 25 - STATOIL'S AS-BUILT-MODEL

All the line segments in the mooring lines are modeled as bar-elements in SIMA. This means that the elements only can receive forces in axial direction.

6.2 INITIAL CONDITIONS

The mooring lines are modeled with 7 different segments (without the delta lines) in SIMA. Only minor changes have been done compared to the real model, and the area that has been modified is the area around the clump weight. Below is a schematic view of the SIMA-model:

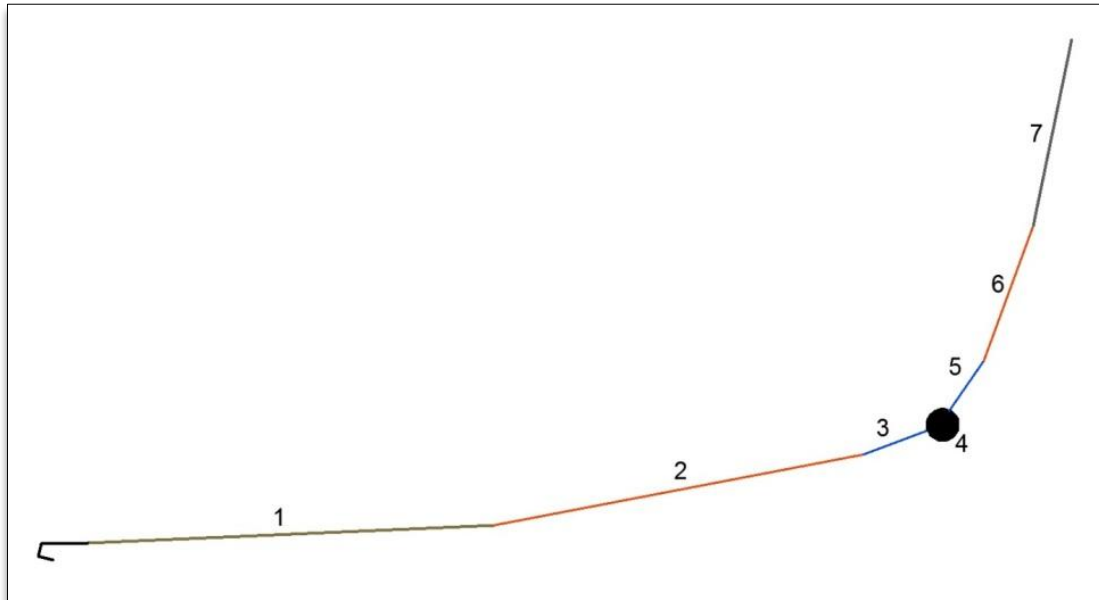


FIGURE 26 - SIMA MODEL SCHEMATIC, SIDE-VIEW

The delta-lines are connected to the end of segment 7.

Segment	Description	Length [m]	Cross-Section	Number of Elements
1	Bottom Chain	320	CS1_91	10
2	Spiral Strand Rope Bottom	465	CS1_92	30
3	Link Chain Bottom	37	CS1_93	5
4	Clump Weight	1*	CS1_94	1
5	Link Chain Top	15	CS1_95	5
6	Spiral Strand Rope Top	75	CS1_96	9
7	Link Adaptor	10	CS1_97	1

TABLE 10 - SIMA MOORING LINES SCHEMATIC EXPLANATION

*The length of the clump weight is set to 1 [m], and the density and volume is set to achieve correct mass

As with the segment numbering, the element numbering starts from the point closest to the anchor. For example, element 1 in “Link Chain Bottom” is the element closest to the “Clump Weight” while element 5 is the element closest to the “Spiral Strand Rope Top”.

Each segment (1-7) is assigned its own cross-section parameter in SIMA:

Cross Section	Area [m]
CS1_91	$1.585 \cdot 10^{-2}$
CS1_92	$5.875 \cdot 10^{-3}$
CS1_93	$1.582 \cdot 10^{-2}$
CS1_94	19.83
CS1_95	$1.613 \cdot 10^{-2}$
CS1_96	$5.203 \cdot 10^{-3}$
CS1_97	$1.893 \cdot 10^{-2}$

TABLE 11 - SIMA, CROSS SECTION AREAS

These cross-section parameters are not to be confused with the actual cross-section used for stress calculation. This parameter is used in the hydro-dynamical calculation in SIMA. The reason I mentioned this cross-section parameter is that it is easy to misinterpret the data from SIMA, in other words it is easy to think that these cross sections presented above were the actual cross-sections in real life.

The actual cross sections used for stress calculations are:

Part	Area
Delta Line	$2 \frac{\pi}{4} * (76mm)^2$
Mooring Line, Studded Chain	$2 \frac{\pi}{4} * (76mm)^2$
Mooring Line, Spiral Strand Rope	$\frac{\pi}{4} * (76mm)^2$

TABLE 12 - ACTUAL CROSS SECTION AREAS

In the table above, **76 mm** is the cross section on the Studded Chain and the Spiral Strand Rope.

Below is a schematic representation of the SIMA-model. The black number represents a line-segment, while the blue numbers represent a node. The default direction for the “As-Built”-model used in Statoil’s analysis is 45 degrees offset from one mooring line or 15 degrees offset from the mooring line on the far side.

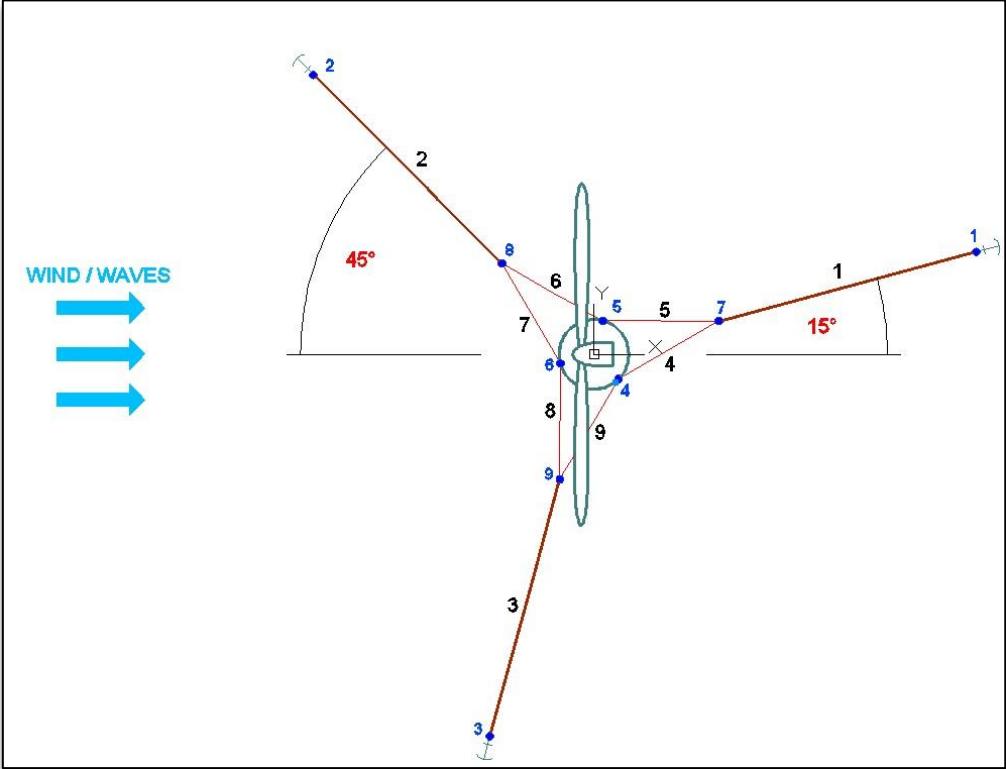


FIGURE 27 - SIMA MODEL SCHEMATIC, TOP-VIEW

The numbers in the figure above represents a line number in SIMA. The correspondence is as follow:

Number	Corresponding SIMA Line Number
1	Line_9
2	Line_10
3	Line_11
4	Line_3
5	Line_4
6	Line_5
7	Line_6
8	Line_7
9	Line_8

Number	Corresponding SIMA Node Number
1	Node 10
2	Node 11
3	Node 12
4	Node 4
5	Node 5
6	Node 6
7	Node 7
8	Node 8
9	Node 9

TABLE 13 - LINE AND NODE CORRESPONDANCE TABLES

6.3 STATIC ANALYSIS

The first step for SIMA is to perform a static analysis. After the static analysis step, the model is in equilibrium position as shown on the figure below:

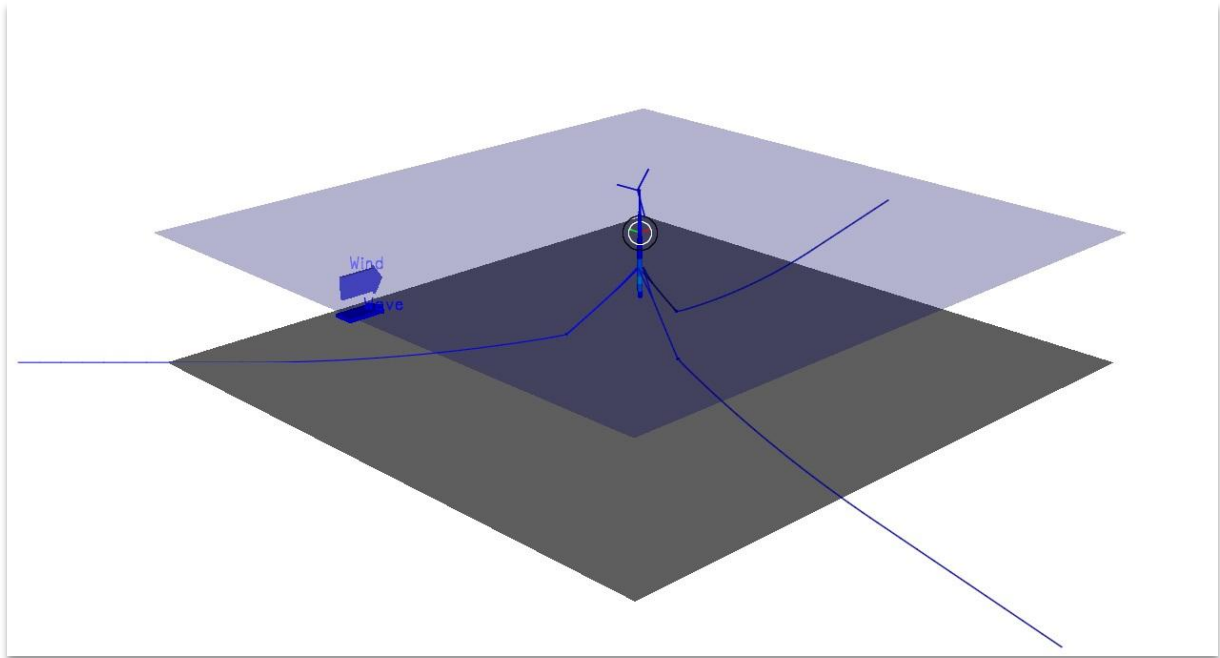


FIGURE 28 - HYWIND DEMO MODEL

In SIMA all the parameters useful for a full scale analysis is represented. However, I have chosen not to present all the different parameter since they are not very relevant. A few parameters worth taking a look at in the static calculation in SIMA are:

Load And Mass Formulation: Lumped load and mass formulation

Incremental loading sequence				
Number	Load Type	N step	Max Iterations	Accuracy
1	Volume Forces	10	10	1*10 ⁻⁷
2	Boundary Change	10	10	1*10 ⁻⁷
4	Specified Displacements	20	50	1*10 ⁻⁷
5	Current Forces	20	20	1*10 ⁻⁸

TABLE 14 - LOADING SEQUENCE, STATIC ANALYSIS

6.4 DYNAMIC ANALYSIS

The second and last step for SIMA is to perform the dynamic analysis of the model. As with the static analysis, there are different parameters to be set before an analysis can be done.

Most of the parameters has not been changed or modified. The reason for this is that the model I am using is Statoil's own model, and I will miss some important aspects by changing and modifying anything. The main aspect I would like to mention is the comparison-aspect. If I were to alternate how the calculation is done, I would not be able to tell if the solution I found was any better than the existing design. Nevertheless I would like to present the parameters I have modified/alterred:

- **Time Series Length/Simulation Length is set to 2000 [s]**
- **Time Increment/Time Step is set to $5 \cdot 10^{-3}$ [s]**

Apart from that **Displacements** and **Internal Forces** are stored from SIMA in the following manner:

Irreg. Analysis | Reg. Analysis | Procedure | Loading | **Storage** | HLA

Select what to store to file:

Displacements	Internal forces	Curvature response	Stroke response	Envelope curve	Visualisation responses
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

▼ Displacement response storage

Storage Step:

File format:

File Name:

Nodes:

Line	Segment	Node Number	All Nodes
line_1		1	<input checked="" type="checkbox"/>
line_9		1	<input checked="" type="checkbox"/>
line_10		1	<input checked="" type="checkbox"/>
line_11		1	<input checked="" type="checkbox"/>

+ - 🗑️ ✓ ↻

FIGURE 29 - SIMA STORAGE DISPLACEMENTS

The forces are stored in the similar way as the displacements:

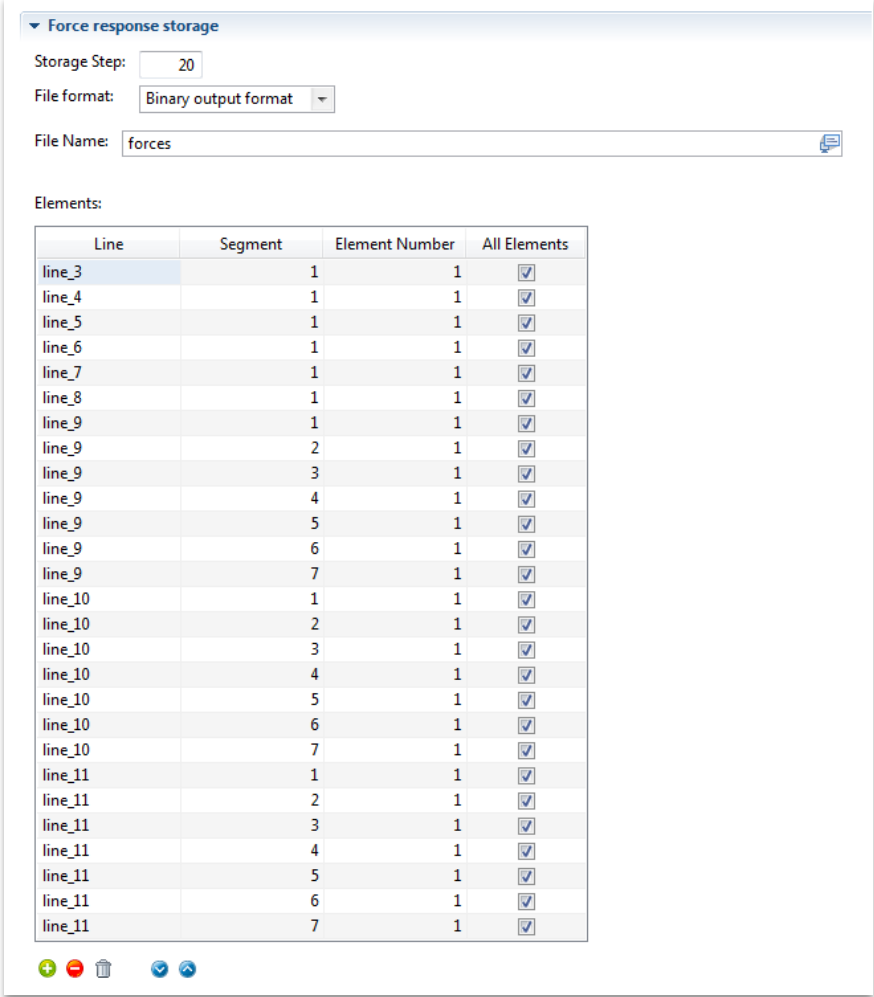


FIGURE 30 - SIMA STORAGE FORCES

Visualization responses were stored for cross checking purposes. These data were not used for any other reason than confirming the wind/wave/current and model direction.

The **Internal Forces** and **Displacements** are physically stored in either a “Displacements.bin” or “Forces.bin”. For each of these two files, a .text file is created. The .text-files relate the columns of data with which forces/displacements stored in them. This file is important for the interpretation of the data itself.

7 POST-PROCESSING

This chapter contains a description on how the data is processed after it is been processed in SIMA. The major part of the post-processing has been done in MATLAB, but Excel has also been used.

The bottle neck of the data processing has been the calculation in SIMA. One simulation takes around 5200 [s] to perform, and because of the multicore processor I used I was able to do three model simulations simultaneously. The time consumption of the MATLAB-scripts never exceeded 100 [s].

7.1 DATA FLOW

To easier understand the data-flow for my calculations, a flow chart for the data processing has been made. Note that the flow chart only describes the data-flow for the Rainflow counting method, and not the Linear-Time-Domain method or the Frequency method. This will be discussed later in the report.

The overall data flow:

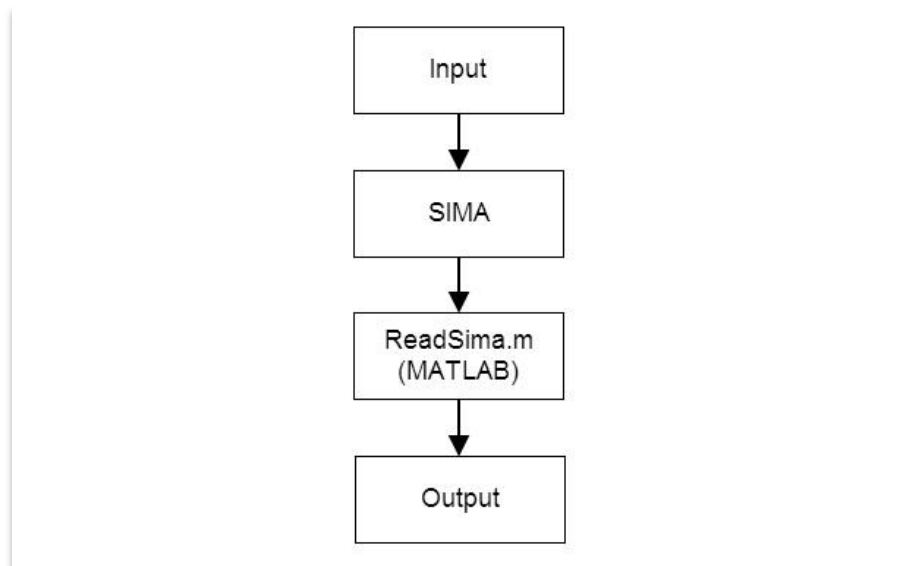


FIGURE 31 - OVERALL FLOW CHART, RAINFLOW

The *ReadSima.m* file contains different sub-scripts/functions. These are organized in a way that makes editing of input data more efficient:

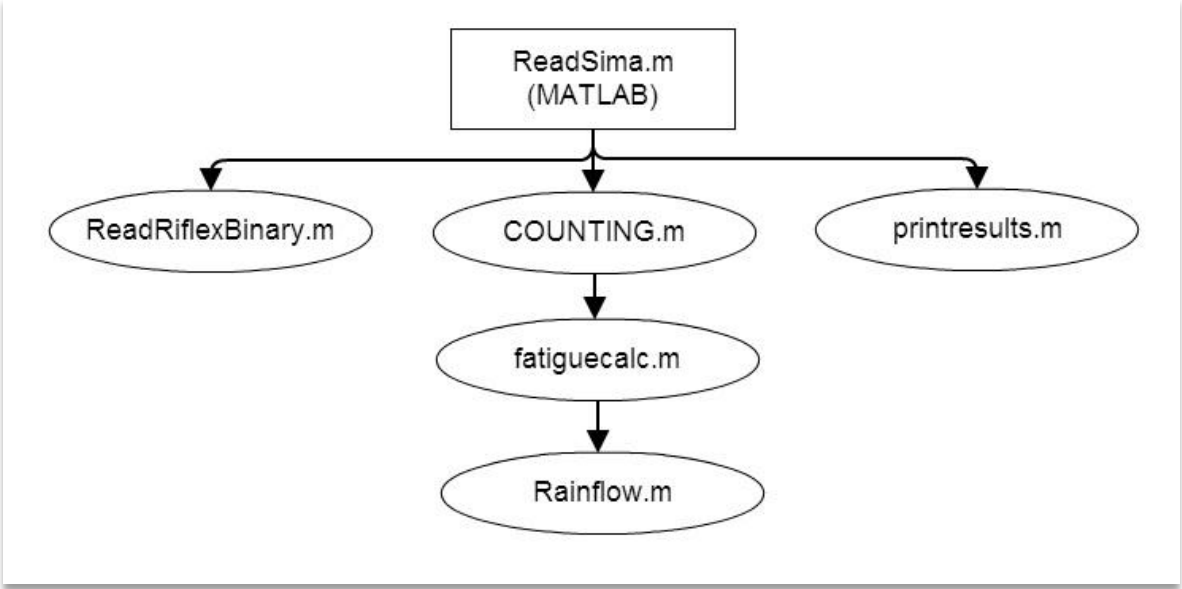


FIGURE 32 - FLOWCHART - READSIMA.M

7.2 MATLAB FILES

7.2.1 READSIMA.M

This function is the main function in my MATLAB-Post-Processing. The function executes the respective sub-functions as shown in the flow chart above. After it has executed the sub-functions, it collects and prints out the final graphs and numbers. The function contains the pathnames for where the data is located, and it is important that these paths are set correctly. When this function is executed, the user can choose between calculating the fatigue damage for case 1-13 or the “ T_p -test”. The “ T_p -test” is a model simulation in SIMA where only the T_p has been changed, to check which T_p that gives the most fatigue.

7.2.2 READRIFLEXBINARY.M

The input values required for this function is a *Forces.bin*- or a *Displacements.bin*-file. These two files are the data from the SIMA-analysis. For the *Forces.bin* file it also requires a *key_forces.text*, and for the *Displacements.bin* file it requires a *key_displacements.text* file. The “*key_...*” files contains information on where to find the specific forces/displacement information related to the lines/segment and element numbers from SIMA.

```

R I F L E X - KEY FILE
-----
This key-file describes the contents of : displacements.bin
The format of displacements.bin is BINARY
with numbers stored as real single precision (4 bytes)
The file displacements.bin contains a time series of nodal-displacements
The nodal-displacements are stored in columns on displacements.bin

Column no. 1 contains FORTRAN specific data (please ignore)
Column no. 2 contains the time.

For each node the following applies :
DOF 1 = displacement in x - direction
DOF 2 = displacement in y - direction
DOF 3 = displacement in z - direction

The response is stored as follows

```

Line Id	Local segment	Local node	No. of responses	Stored in column(s)
line_1	1	1	3	3 - 5
line_1	1	2	3	6 - 8
line_9	1	1	3	9 - 11
line_9	1	2	3	12 - 14
line_9	1	3	3	15 - 17
line_9	1	4	3	18 - 20
line_9	1	5	3	21 - 23
line_9	1	6	3	24 - 26
line_9	1	7	3	27 - 29
line_9	1	8	3	30 - 32
line_9	1	9	3	33 - 35
line_9	1	10	3	36 - 38
line_9	1	11	3	39 - 41
line_10	1	1	3	42 - 44
line_10	1	2	3	45 - 47
line_10	1	3	3	48 - 50
line_10	1	4	3	51 - 53
line_10	1	5	3	54 - 56
line_10	1	6	3	57 - 59
line_10	1	7	3	60 - 62
line_10	1	8	3	63 - 65
line_10	1	9	3	66 - 68

```

R I F L E X - KEY FILE
-----
This key-file describes the contents of : forces.bin
The format of forces.bin is BINARY
with numbers stored as real single precision (4 bytes)
The file forces.bin contains a time series of element-forces
The element-forces are stored in columns on forces.bin

Column no. 1 contains FORTRAN specific data (please ignore)
Column no. 2 contains the time.

For each bar element the following applies :
DOF 1 = Axial force

For each beam element the following applies :
DOF 1 = Axial force
DOF 2 = Torsional moment
DOF 3 = Mom. about local y-axis, end 1
DOF 4 = Mom. about local y-axis, end 2
DOF 5 = Mom. about local z-axis, end 1
DOF 6 = Mom. about local z-axis, end 2
DOF 7 = Shear force in local y-direction, end 1
DOF 8 = Shear force in local y-direction, end 2
DOF 9 = Shear force in local z-direction, end 1
DOF10 = Shear force in local z-direction, end 2

The response is stored as follows

```

Line Id	Local segment	Local element	No. of responses	Stored in column(s)
line_3	1	1	1	3
line_3	1	2	1	4
line_3	1	3	1	5
line_3	1	4	1	6
line_3	1	5	1	7
line_4	1	1	1	8
line_4	1	2	1	9
line_4	1	3	1	10
line_4	1	4	1	11
line_4	1	5	1	12

FIGURE 33 - KEY FILES

The output from the function is a matrix of information, either forces or displacements.

7.2.3 COUNTING.M

This function converts force to stress before it executes the function *fatiguecalc.m*. The function uses the data interpreted from *readRiflexBinary.m*. The function is used to keep track of the different parts of the model, related to which rows and columns in the .bin file it is related to.

7.2.4 FATIGUECALC.M

This function calculates the fatigue damage based on its input data from *COUNTING.m*. The first step for the function is to convert the “smooth” stress-signal into a time series which contains only minimums and maxima’s. It does that with a function called *sig2ext.m*.

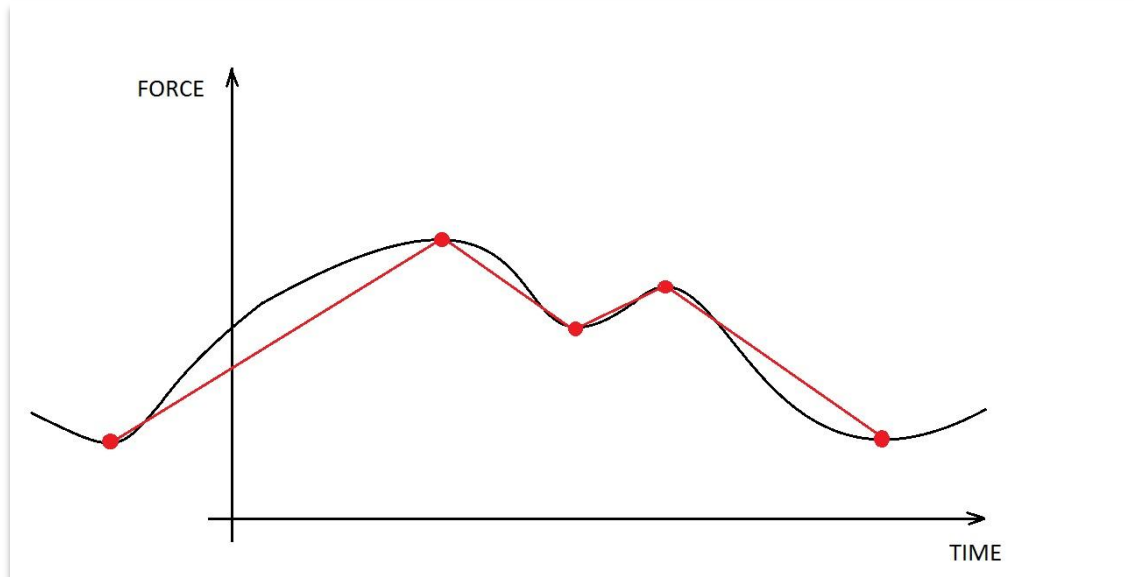


FIGURE 34 - IDENTIFICATION OF MINIMA'S AND MAXIMA'S

On the figure above, the original time series has been converted to a time series only containing maxima's and minimums. After the time series has been converted, *Rainflow.m* is used to perform a rainflow counting. The damage is then calculated by the formulas described in the fatigue chapter.

7.2.5 RAINFLOW.M

This is the main function used inside *fatiguecalc.m*. The function itself is made by Adam Nieslony (2009), and is designed to calculate fatigue damage by rainflow counting algorithm. The input used for this is the converted time series signal (which contains only minimums and maxima's). The output from this function is damage/mean stress and cycle (half of full cycle). The output is written for each half/full cycle.

7.2.6 PRINTRESULTS.M

This function writes the results in a .text file.

```
Results from conditionset NO: 1

Delta-lines
line_3 1.805870e-08, 1.795474e-08, 1.783072e-08, 1.769345e-08, 1.754498e-08,
line_4 1.761185e-08, 1.750584e-08, 1.737938e-08, 1.723716e-08, 1.708264e-08,
line_5 3.656848e-07, 3.660983e-07, 3.661989e-07, 3.659895e-07, 3.654552e-07,
line_6 1.948899e-07, 1.950868e-07, 1.951555e-07, 1.950985e-07, 1.949029e-07,
line_7 2.672847e-07, 2.676925e-07, 2.679104e-07, 2.679448e-07, 2.677916e-07,
line_8 2.485330e-07, 2.487304e-07, 2.487243e-07, 2.485148e-07, 2.480798e-07,

Link-Adaptor
line_9 5.275734e-08,
line_10 2.148397e-07,
line_11 2.182482e-07,

Link chain TOP
line_9 5.674556e-08, 5.610690e-08, 5.563383e-08, 5.525706e-08, 5.487824e-08,
line_10 1.837424e-07, 1.829820e-07, 1.822415e-07, 1.815185e-07, 1.808151e-07,
line_11 1.791653e-07, 1.785306e-07, 1.779120e-07, 1.773109e-07, 1.767255e-07,

Link chain BOTTOM
line_9 5.009666e-08, 5.037225e-08, 5.064519e-08, 5.091464e-08, 5.117998e-08,
line_10 2.101255e-07, 2.106067e-07, 2.110801e-07, 2.115458e-07, 2.120038e-07,
line_11 2.134685e-07, 2.139723e-07, 2.144672e-07, 2.149530e-07, 2.154303e-07,

Max values
Delta-lines 3.662e-07
Link-adaptor 2.1825e-07
Link chain TOP 1.8374e-07
Link chain BOTTOM 2.1543e-07

MAX VALUE: 3.662e-07
```

FIGURE 35 - PRINTRESULTS.M

Show above is an example on how the .text file looks like. It contains info about which dataset the results are from, along with the fatigue associated with the different parts. I also chose to write out the different max-values for comparison reasons.

7.2.7 OTHER FUNCTIONS

Other functions used that does not need further explanation:

- *CheckVerticalDisplacement.m, CheckVerticalDisplacement2.m*
- *Clumpweight_test.m, Clumpweight_test2.m*
- *frequencyFILTER.m*
- *AsBuiltClosedForm.m, ThirtyClosedForm.m, SixtyClosedForm.m, ParallelClosedForm.m*
- *createHywindAsBuiltModel.m* (used to rotate the model)
- *polyscatter.m*

If necessary, a short description is given within each function (.m-file)

8 RESULTS

8.1 OVERVIEW

All the calculations in SIMA have been analyzed on a Statoil-computer. The SIMA version used is a 03.01.2012-version. The MATLAB-calculation has been performed on my personal computer, with version "MATLAB R2012a".

The calculation of the fatigue damage is based on a linear S-N curve (Figure 21 - Design S-N Curves).

8.2 LINEAR TIME DOMAIN

As explained in the assignment text, a linear time domain analysis was to be performed for comparison with the other methods. However, some difficulties appeared along the way.

A fully linear time domain solution is possible to do without the movement of the wind turbine rotor, since the point of a fully linear time domain solution is that you don't update the stiffness matrix in the simulation. This does not work when the rotor rotates, since the stiffness matrix needs to be updated along the way. This means it would be possible to do this analysis with the rotor standing still and only the wave excitations working. A simulation of a wind turbine with no rotor movement loses one of the most valuable aspects, and I chose therefore to discard this method.

The method also becomes a little bit "out-of-bounds" for the relevance for this report, since I would have spent many hours just to create a model. The way it could have been performed described as follows:

- Constrain the floater from moving initially
- Release it dynamically

The solution from the linear time domain analysis would have given a solution on how much "loss" there is between the linear and non-linearity's in the mooring system. I would assume the differences to be quite large for this type of mooring system.

8.3 NON-LINEAR TIME DOMAIN

8.3.1 OVERVIEW

The first 200 [s] of the simulation was removed to get rid of transient effects. The model is not resting in the proper dynamic equilibrium position at the beginning of the simulation. This can be showed by looking at the variance of the forces on the mooring lines (the variance will stabilize/converge when the transient state is done).

For the “As-Built”-model, the mean wind speed was set to $U_{MEAN} = 20$ [m/s]. On all the other cases the wind-speed is set to $U_{MEAN} = 12$ [m/s]. This is not realistic, but it has been done to reduce number of variables. Realistically the wind speed will vary with significant wave heights.

When “As-Built” is mentioned, the direction of the incoming waves are 15 [degrees] offset from the far mooring line. This is based on data from the Metocean specification.

For the results presented in this chapter, specific names are used to refer to certain segments on the mooring line. To make it clear an explaining figure has been made:

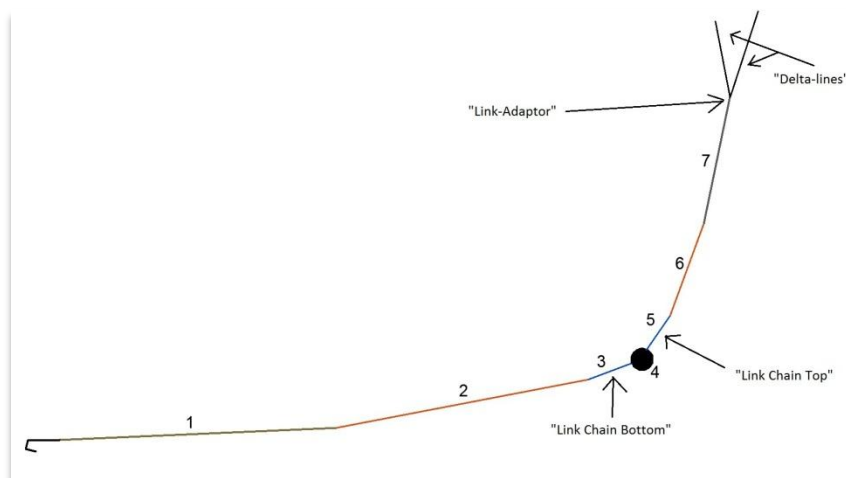


FIGURE 36 - SEGMENT NAMING, MOORING LINES

The numbers presented in the figure above is related to Table 10 - SIMA Mooring Lines Schematic on page 36. The element with the highest stresses in the segments, are used for the fatigue analyses. For example for the delta-lines, the element used for the calculation is the element closest to the “link-adaptor” not the element closest the connection to the structure.

For all the analyses in SIMA wave spreading and current has been kept the same. Wave spreading is set to 2. The current is chosen based on data from the Metocean specification given for Hywind Demos location:

No.	Level [m]	Direction	Velocity [m/s]
1	-3.0	0	1.700
2	-25.0	0	1.220
3	-50.0	0	1.140
4	-100.0	0	0.770
5	-200.0	0	0.730

TABLE 15 - SIMA CURRENTS

Where it is not mentioned any specific direction of the waves/current and wind, the direction is “default”. With “default” it is assumed the waves/current and wind comes in with an angle of 15 [degrees] offset from the mooring line on the far side as shown on Figure 27 page 38.

One of the first things I investigated during my analyses was if there was any room for improving the calculation time. The first thing I checked was whether lowering the number of storage points from SIMA could affect this. SIMA does not use significantly more computation power to save more numbers, but the reading and post-processing afterwards does. Therefore, a reduction of the matrix size can affect the total time significantly. The original results were written with a time step of 0.02 [s] and the newest results were written with a time step of 0.1[s]. In other words I decreased the amount of storage points in the matrix from 100000 to 20000 (in one direction). Below is an outtake of the fatigue results (from the 30 [min] analyses from the Link Chain Top:

Input parameters for this analysis:

$H_s = 4.0$ [m]
 $T_p = 9.5$ [s]

100000 Storage Points					
	Element 1	Element 2	Element 3	Element 4	Element 5
Line_9	2,2946e-09	2,2617e-09	2,2332e-09	2,2061e-09	2,1777e-09
Line_10	6,9913e-07	7,0484e-07	7,0960e-07	7,1194e-07	7,1125e-07
Line_11	5,2386e-08	5,2151e-08	5,1920e-08	5,1693e-08	5,1471e-08

TABLE 16 - FATIGUE 100000 STORAGE POINTS

20000 Storage Points					
	Element 1	Element 2	Element 3	Element 4	Element 5
Line_9	2,1920e-09	2,1621e-09	2,1351e-09	2,1093e-09	2,0826e-09
Line_10	6,8896e-07	6,8986e-07	6,9027e-07	6,8953e-07	6,8750e-07
Line_11	5,2437e-08	5,2197e-08	5,1959e-08	5,1725e-08	5,1497e-08

TABLE 17 - FATIGUE 20000 STORAGE POINTS

Both of the tables above are rounded to the closest 4 decimals for visual purposes (after the percentage calculation). The values are intended for comparison means only. These results were produced on an early stage, and later changes in my program codes may have changed the results. However, the differences shown here will still be the same.

The percentage difference (100000 storage points matrix divided by the 20000 storage point's matrix) is shown in the table below. Positive represents how much bigger the fatigue calculated from the 100000 storage point's matrixes is compared to the fatigue calculated from the 20000 storage point's matrix.

	Element 1	Element 2	Element 3	Element 4	Element 5
Line_9	4,68%	4,61%	4,59%	4,59%	4,57%
Line_10	1,48%	2,17%	2,80%	3,25%	3,45%
Line_11	-0,10%	-0,09%	-0,07%	-0,06%	-0,05%

TABLE 18 - PERCENTAGE DIFFERENCE 100000 AND 20000 STORAGE POINTS

With a discrepancy of maximum **4.59%**, I choose to continue calculating with 20000 elements in the matrixes. The time saving on the main routine in MATLAB was almost 60 [s]. Therefore, every calculation performed from this point and on will be done with the usage of **20000 storage points of forces**.

8.3.2 H_s 1 – 13 [M]

The first simulations that were done were to examine which sea states that contributes the most to the fatigue damage on the mooring lines. I decided to investigate 13 sea states, with a H_s of 1-13 [m] with an 1[m] increment (1, 2, 3,..., 13 [m]). Which peak periods associated with the significant wave heights were decided based on the scatter diagram found in the Metocean spec from the Hywind location:

H _s	T _p											
	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17
0-1	6363	6983	6380	5180	3888	2767	1899	1271	837	545	352	227
1-2	5219	8233	9609	9172	7622	5745	4038	2698	1737	1089	669	405
2-3	880	2256	3659	4343	4138	3366	2439	1621	1011	600	343	191
3-4	77	387	1004	1643	1933	1786	1378	929	564	317	167	84
4-5	3	38	192	501	811	920	800	567	344	184	89	40
5-6	0	2	20	97	249	387	411	325	205	107	49	20
6-7	0	0	1	10	50	122	177	169	118	63	28	10
7-8	0	0	0	1	6	26	59	75	63	37	16	6
8-9	0	0	0	0	0	4	14	27	30	21	10	4
9-10	0	0	0	0	0	0	2	7	11	10	6	2
10-11	0	0	0	0	0	0	0	1	3	4	3	1
11-12	0	0	0	0	0	0	0	0	1	1	1	1
12-13	0	0	0	0	0	0	0	0	0	0	1	0
13-14	0	0	0	0	0	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0	0	0	0	0	0
	12542	17899	20865	20947	18697	15123	11217	7690	4924	2978	1734	991

TABLE 19 - SCATTER DIAGRAM

The reason I chose out one peak period for each significant wave height was because I did not have time to perform an analysis on every single sea state. I selected the peak periods that have most occurrences within each significant wave height (1-13). An alternative to this have been to choose the average peak period based on occurrences.

The selected H_s and T_p –s from the scatter diagram:

H_s [m]	T_p [s]
1	6.5
2	7.5
3	8.5
4	9.5
5	10.5
6	11.5
7	12.0
8	12.5
9	13.5
10	13.5
11	14.5
12	15.0
13	15.5

TABLE 20 - ASSOCIATED SIGNIFICANT WAVE HEIGHTS AND PEAK PERIODS

The probability for each different sea state is based on the scatter diagram from the metocean-spec for the Hywind Demo.

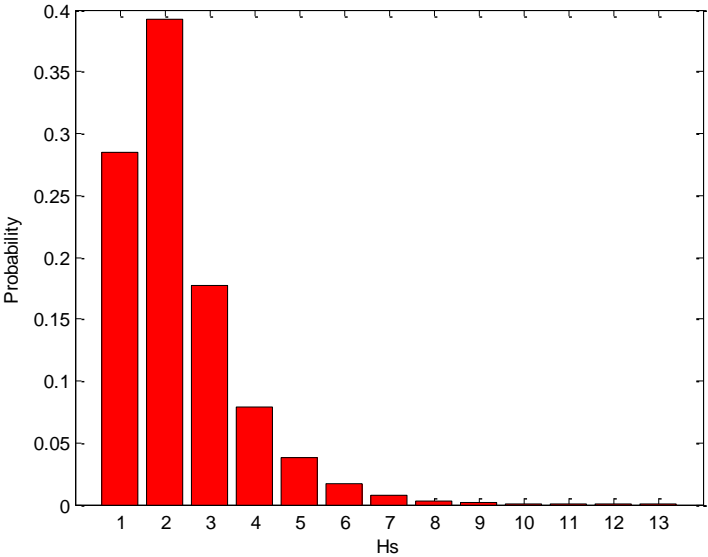


FIGURE 37 - SEA STATE PROBABILITY

H_s	Probability
1	0,2851
2	0,3923
3	0,1773
4	0,0789
5	0,0376
6	0,0168
7	0,0071
8	0,0031
9	0,0012
10	0,0004
11	0,0001
12	4,0826e-05
13	4,0826e-05

TABLE 21 - PROBABILITY TABLE

The yearly damage for the 13 different cases are presented on the tables on the next page. The different significant wave heights (H_s) are along the horizontal axis while the different segments are presented on the vertical axis. The values from $H_s = 7$ [m] and up to $H_s = 13$ [m] are not shown here, for visual purposes (see Appendix B - results).

Segment/Hs	1	2	3	4	5	6
delta line_3	0,000017	0,000030	0,000018	0,000013	0,000011	0,000008
delta line_4	0,000021	0,000059	0,000052	0,000046	0,000037	0,000027
delta line_5	0,000335	0,001612	0,001584	0,001316	0,000915	0,000554
delta line_6	0,000189	0,000358	0,000226	0,000130	0,000082	0,000049
delta line_7	0,000182	0,000408	0,000329	0,000257	0,000208	0,000152
delta line_8	0,000206	0,000402	0,000321	0,000235	0,000208	0,000145
link adaptor line_9	0,000030	0,000072	0,000061	0,000045	0,000033	0,000021
link adaptor line_10	0,000255	0,002281	0,002650	0,002091	0,001436	0,000873
link adaptor line_11	0,000054	0,000361	0,000408	0,000340	0,000252	0,000165
link ch. top line_9	0,000032	0,000055	0,000035	0,000021	0,000013	0,000008
link ch. top line_10	0,000208	0,002053	0,002415	0,001878	0,001260	0,000750
link ch. top line_11	0,000041	0,000302	0,000342	0,000281	0,000203	0,000130
link ch. bot. line_9	0,000029	0,000068	0,000057	0,000042	0,000030	0,000020
link ch. bot. line_10	0,000252	0,002251	0,002612	0,002057	0,001410	0,000856
link ch. bot. line_11	0,000053	0,000355	0,000401	0,000333	0,000247	0,000161

TABLE 22 - RESULTS HS 1-13[M], YEARLY DAMAGE, AS BUILT DIRECTION

The results with the “worst” direction, the waves/current and the wind going parallel to one of the mooring lines (line_10):

Segment/Hs	1	2	3	4	5	6
delta line_3	0,000054	0,000132	0,000116	0,000120	0,000111	0,000094
delta line_4	0,000068	0,000236	0,000248	0,000256	0,000227	0,000179
delta line_5	0,000371	0,002244	0,002256	0,001680	0,001073	0,000606
delta line_6	0,000222	0,000930	0,000956	0,000633	0,000438	0,000253
delta line_7	0,000054	0,000175	0,000210	0,000213	0,000208	0,000158
delta line_8	0,000050	0,000078	0,000066	0,000061	0,000068	0,000057
link adaptor line_9	0,000006	0,000047	0,000063	0,000059	0,000050	0,000035
link adaptor line_10	0,000730	0,007507	0,008793	0,006543	0,004348	0,002575
link adaptor line_11	0,000005	0,000047	0,000062	0,000058	0,000049	0,000035
link ch. top line_9	0,000003	0,000026	0,000034	0,000031	0,000026	0,000018
link ch. top line_10	0,000656	0,007662	0,008929	0,006358	0,004088	0,002391
link ch. top line_11	0,000003	0,000027	0,000035	0,000031	0,000026	0,000018
link ch. bot. line_9	0,000005	0,000045	0,000060	0,000056	0,000048	0,000033
link ch. bot. line_10	0,000724	0,007425	0,008681	0,006452	0,004279	0,002531
link ch. bot. line_11	0,000005	0,000045	0,000059	0,000055	0,000047	0,000033

TABLE 23 - RESULTS HS 1-13[M], YEARLY DAMAGE, PARALLELL DIRECTION

Conclusion from both default direction and the parallel direction with the 13 different sea states:

- The largest fatigue damage occurs when $H_s = 3$ [m] ($T_p = 8.5$ [s]). For some segments, the fatigue damages is greatest when $H_s = 2$ [m], but these segments has a very small fatigue damage compared to some of the others.

- The three segments that represents the largest fatigue damage, sorted from highest to lowest:
 - o “link adaptor line_10”
 - o “link chain bottom line_10”
 - o “link chain top line_10”

In the further analysis I will therefore only focus on the worst segment (“link adaptor line_10”). It is however worth to mention the size of the fatigue damage on “delta line_5” compared to the other delta-lines. The dynamical effects because of its position from the incoming waves/current and wind, seems to contribute a lot to the fatigue damage. It is not unlikely that the yaw-rotation is the main contributing dynamic effect here.

To find the total accumulated damage, all the contributions from the different sea-states (1-13) are summed up. The life time for the “As-Built”-direction and the parallel direction:

	As-Built	Parallel
Link Adaptor line_10	93,7 years	29,7 years
Link Chain Top line_10	105,2 years	30,2 years
Link Chain Bottom line_10	95,2 years	30,1 years

TABLE 24 - EXPECTED LIFE TIME

The weighted damage for a year is presented in a graph below. When the direction is parallel, the other two lines does not experience fatigue damage at all. That behaves as expected. The weighted damage 1 year for the “link-adaptor” segment is also shown in a graph below.

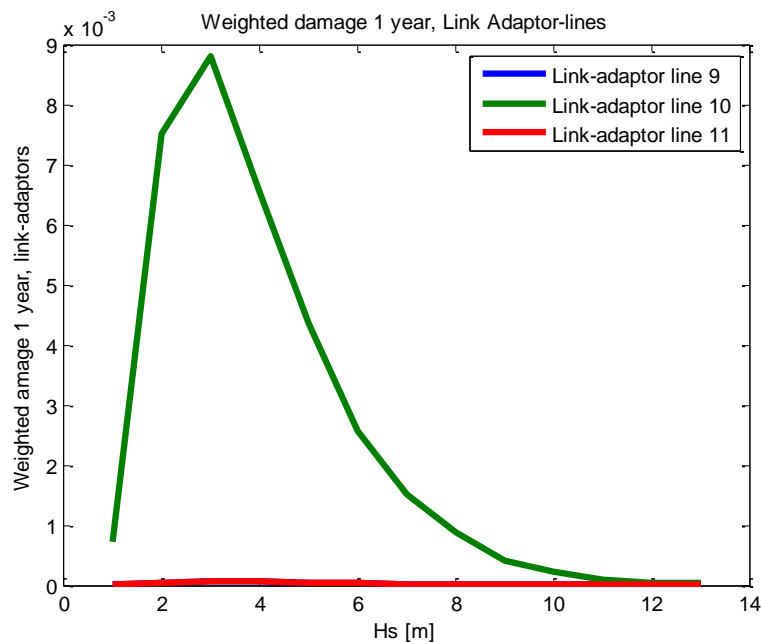


FIGURE 38 - WEIGHTED DAMAGE, PARALELL DIRECTION

When it comes to the question if the mooring lines are within the requirements of FLS, the design life time must be known. If a life time of 30 [years] is assumed the safety factors for the two different directions are:

Design Life Time = 30 [years]	
	Safety Factor
As - Built	3.123
Parallel	0.99

TABLE 25 - SAFETY FACTORS, FLS

The “As-Built” model is within the safety requirements, even with the DFF = 3.0. With the parallel direction it is not even 1.0, and with a DFF of above 1.0 it will be even worse. I conclude therefore with the fact that the “As-Built” model passed the FLS-test while the Parallel direction failed.

8.3.3 PARAMETER STUDY – PEAK PERIOD

This is a sensitivity study on which peak period related to the result in the previous chapter that gives the most fatigue damage. It has been performed on the segment of the mooring line that experience most fatigue damage: “link adaptor line_10”. The peak periods selected were:

H _s = 3 [m]									
T _p [s]	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5

TABLE 26 - TP-TEST, SEA STATES

Damage for one year calculated, and the respective probability for each peak period:

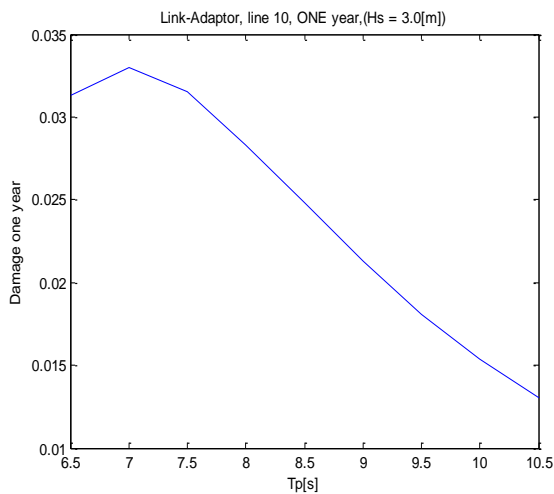


FIGURE 39 - PEAK PERIODS, DAMAGE ONE YEAR

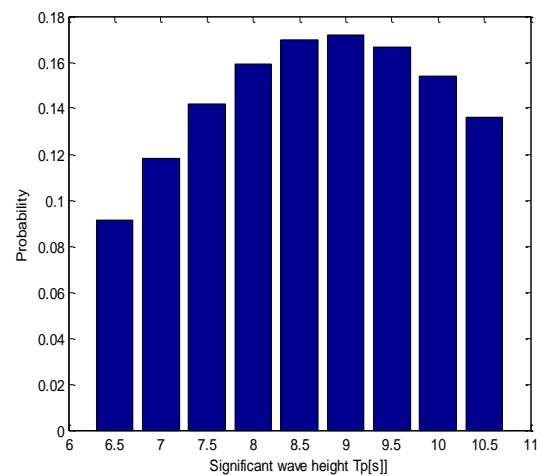


FIGURE 40 - PROBABILITY PEAK PERIODS, H_s = 3[M]

Combined with yearly damage and the probability for each sea state the result shows which of these sea states that contributes the most:

Damage weighted 1 year Link Adaptor line_10	
T _p = 6.5 [s]	0,0057
T _p = 7.0 [s]	0,0078
T _p = 7.5 [s]	0,0089
T _p = 8.0 [s]	0,0090
T _p = 8.5 [s]	0,0084
T _p = 9.0 [s]	0,0073
T _p = 9.5 [s]	0,0060
T _p = 10.0 [s]	0,0047
T _p = 10.5 [s]	0,0036

TABLE 27 - TP-TEST WEIGHTED DAMAGE, ONE YEAR

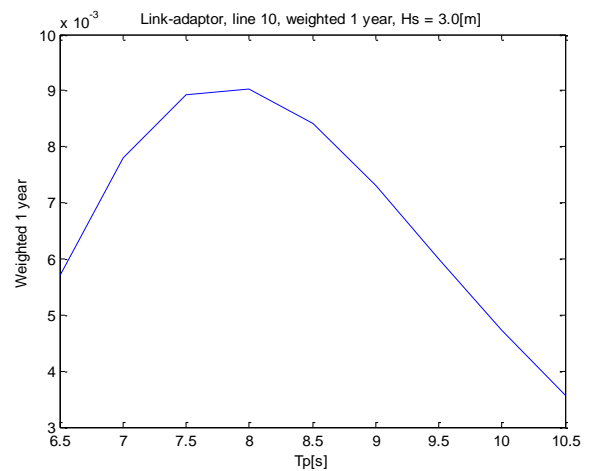


FIGURE 41 - PEAK PERIODS, WEIGHTED DAMAGE ONE YEAR

With this I can conclude on which sea state that is the worst with regards to fatigue damage on the mooring line system for the Hywind Demo:

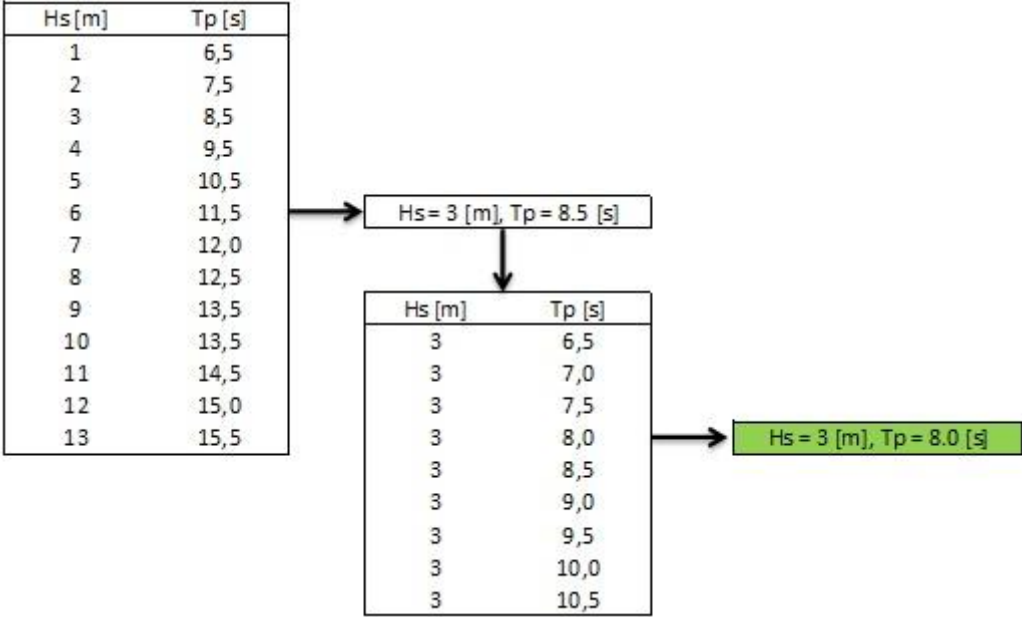


FIGURE 42 - FLOW CHART, WORST SEA STATE

The worst sea state is:

- **H_s = 3 [m], T_p = 8.0 [s]**
- **Most critical segment: "Link Adaptor line 10"**

The minimal change in peak period confirms that the way I selected the peak periods (based on maximum occurrence), was acceptable.

8.3.4 ROTATION MATRIX METHOD

The basic idea is to calculate total fatigue damage from the Metocean specification where wave directions, wave heights and probability are connected. The red lines drawn in the wave rose are the mooring lines:

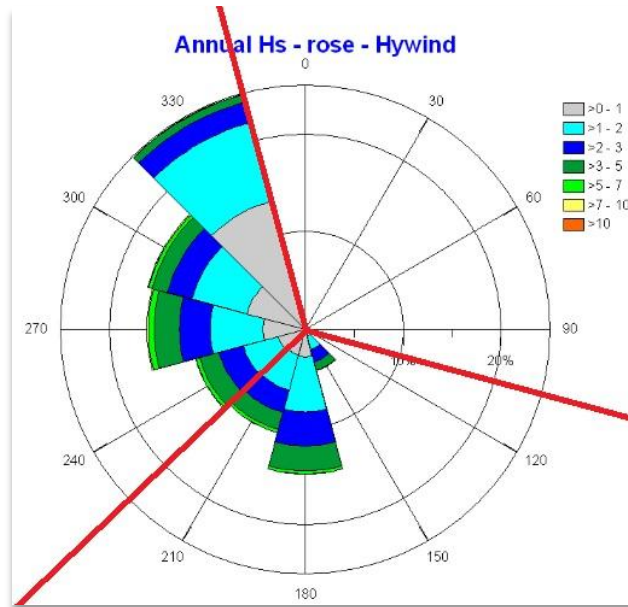


FIGURE 43 - ANNUAL WAVE ROSE FOR THE HYWIND LOCATION FOR THE PERIOD 1957-2002 WITH MOORING LINES

The probability for the significant wave heights and directions:

Significant wave height	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	Omni
< 1	0.30	0.05	0.05	0.04	0.08	0.61	2.81	2.72	2.82	4.24	6.06	13.88	33.66
< 2	0.33	0.06	0.06	0.04	0.14	1.88	8.47	6.45	6.50	9.59	11.84	22.39	67.75
< 3	0.33	0.06	0.06	0.04	0.14	3.02	12.05	8.80	9.07	12.73	14.42	24.60	85.33
< 4	0.33	0.06	0.06	0.04	0.14	3.59	13.87	10.03	10.46	14.47	15.51	25.23	93.80
< 5	0.33	0.06	0.06	0.04	0.14	3.79	14.64	10.60	11.12	15.29	16.04	25.40	97.51
< 6	0.33	0.06	0.06	0.04	0.14	3.83	14.88	10.86	11.40	15.73	16.29	25.44	99.07
< 7	0.33	0.06	0.06	0.04	0.14	3.84	14.97	10.93	11.50	15.90	16.41	25.45	99.65
< 8	0.33	0.06	0.06	0.04	0.14	3.84	14.98	10.95	11.54	15.99	16.47	25.45	99.87
< 9	0.33	0.06	0.06	0.04	0.14	3.84	14.99	10.95	11.55	16.03	16.50	25.45	99.96
< 10	0.33	0.06	0.06	0.04	0.14	3.84	14.99	10.95	11.56	16.05	16.52	25.45	99.99
< 11	0.33	0.06	0.06	0.04	0.14	3.84	14.99	10.95	11.56	16.05	16.52	25.45	100.00
< 12	0.33	0.06	0.06	0.04	0.14	3.84	14.99	10.95	11.56	16.05	16.52	25.45	100.00
< 13	0.33	0.06	0.06	0.04	0.14	3.84	14.99	10.95	11.56	16.06	16.52	25.45	100.00
< 14	0.33	0.06	0.06	0.04	0.14	3.84	14.99	10.95	11.56	16.06	16.52	25.45	100.00
Mean	0.59	0.78	0.78	0.81	1.04	2.21	2.10	2.04	2.12	2.09	1.73	1.13	1.78
Maximum	2.66	1.90	2.50	1.90	2.50	7.00	9.40	8.90	10.50	12.30	14.00	8.25	14.00

TABLE 28 - ANNUAL DIRECTION SAMPLE DISTRIBUTION OF NON-EXCEEDANCE (%) OF SIGNIFICANT WAVE HEIGHT AT THE HYWIND LOCATION

I assume that all the three mooring lines are 100% symmetrical. This symmetry makes it possible to calculate an overall fatigue damage with doing computations in a few directions:

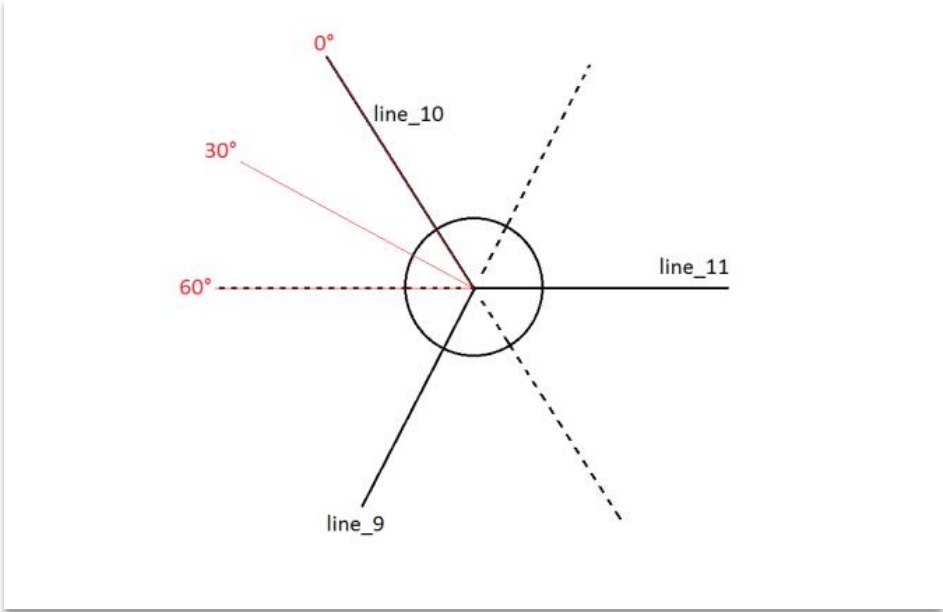


FIGURE 44 - ROTATION ANGLES

By assuming the angle increment needed from the metocean spec (30 degrees) along with the symmetry, the number of different directions is reduces down to 3. With these three angles it is possible to calculate the fatigue damage for all the angles from 0-330 degrees. It is important not to forget that the Hywind Demo is rotated 15 [degrees] clock wise compared to the figure above. The correct rotational position is show on Figure 2 - Hywind Demo Location on page 3.

The different rotations simulated are the red lines represented in the figure above. For each of the lines an equivalence matrix is assembled. This matrix explains the equivalent damage based on the calculations from the three angles.

I have only included the equivalent damage table for “link adaptor line_10”, since the most critical segment is represented here.

Line_10:

Damage on line_10	
Damage from angle	Equivalent damage
line_10, 0 degrees	line_10, 30 degrees
line_10, 30 degrees	line_10, 60 degrees
line_10, 60 degrees	line_11, 30 degrees
line_10, 90 degrees	(line_11 + line_9) / 2 parallel
line_10, 120 degrees	line_9, 30 degrees
line_10, 150 degrees	line_9, 60 degrees
line_10, 180 degrees	line_9, 30 degrees
line_10, 210 degrees	(line_11 + line_9/2) parallel
line_10, 240 degrees	line_11, 30 degrees
line_10, 270 degrees	line_10, 60 degrees
line_10, 300 degrees	line_10, 30 degrees
line_10, 330 degrees	line_10 parallel

TABLE 29 - EQUIVALENT DAMAGE, LINE 10

The 15 [degree] offset of the Hywind Demo (compared to the wave rose), has been compensated by interpolating the probability of the wave angles:

Angle (degrees)	Probability (%)
15	0,195
45	0,03
75	0,05
105	0,09
135	1,99
165	9,415
195	12,97
225	11,255
255	13,81
285	16,29
315	20,985
345	12,85
All	100,00

TABLE 30 - ADJUSTED DIRECTIONAL PROBABILITY

The damages calculated, H_s 1-13:

	Parallel		30 [degrees]		60 [degrees]	
	Damage	Lifetime [years]	Damage	Lifetime [years]	Damage	Lifetime [years]
link adaptor line_9	0.000308415	3242.3891	0.00021418	4668.9407	0.0005717	1748.9643
link adaptor line_10	0.033711464	29.6635	0.02190854	45.6443	0.009583	104.3437
link adaptor line_11	0.000305362	3274.8018	0.00075025	1332.888	0.009595	104.2182

TABLE 31 - DAMAGE PARALLEL-30-60 ROTATIONS

Damages on “link adaptor line_10”:

Rotation [degrees]	Inserted equivalent damages	Probability [%]	Damage
15	0,021908541	0,195	0,00427217
45	0,009583712	0,03	0,00028751
75	0,000750251	0,05	3,7513E-05
105	0,000306888	0,09	2,762E-05
135	0,000214181	1,99	0,00042622
165	0,000571767	9,415	0,00538319
195	0,000214181	12,97	0,00277793
225	0,000306888	11,255	0,00345403
255	0,000750251	13,81	0,01036096
285	0,009583712	16,29	0,15611867
315	0,021908541	20,985	0,45975072
345	0,033711464	12,85	0,43319231
Total Damage			0,01076089
Years			92,9291302

TABLE 32 - DAMAGE, DIRECTIONAL CALCULATION

8.3.5 PARAMETER STUDY - CLUMP WEIGHT

The clump weight has been studied for optimization of lowest possible fatigue damage. The weight (kg in air) has been changed to see if this affects the yearly fatigue damage of the mooring lines. The sea state and direction used in these analyses has been set to the worst fatigue wise, which has been researched earlier in this report:

- $H_s = 3.0$ [m] and $T_p = 8.0$ [s]
- Waves/currents and wind direction: Parallel to one mooring-line (“line_10”)
- “Link Adaptor Line_10” is the segment with most fatigue damage, and therefore this will be the segment studied.

The first analyzes were done with a 5 [ton] increment four times on “each side” of the current weight. The existing weight is marked green.

Mass in Air [kg]								
46645	51645	56645	61645	66645	71645	76645	81645	86645

TABLE 33 - MASS, CLUMP WEIGHT ANALYSIS #1

An important factor to mention is that the only parameter changed in SIMA, is the density of the clump weight. This means that the volume and displacement of the clump weight has not been changed. This has been done in order to reduce number of changing variables in the simulation.

The results from the first clump weight analysis:

Damage 1 Year	
Mass in air [kg]	Damage
46645	0,059
51645	0,061
56645	0,062
61645	0,063
66645	0,063
71645	0,061
76645	0,057
81645	0,055
86645	0,053

TABLE 34 - DAMAGE 1YEAR CLUMP WEIGHT ANALYSIS #1

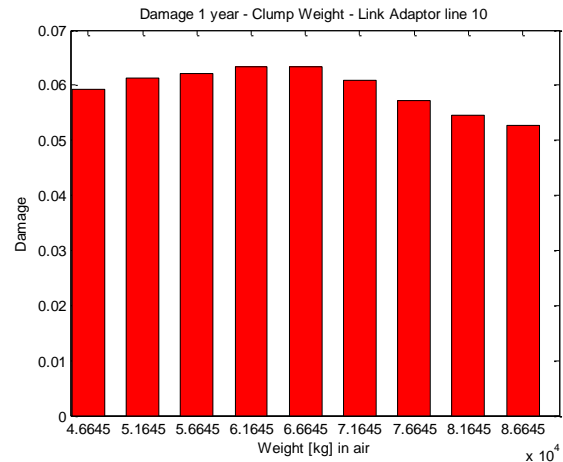


FIGURE 45 - DAMAGE 1 YEAR CLUMP WEIGHT ANALYSIS #1

As marked in the table, the largest fatigue damage occurs around 61645 – 66645 [kg]. This is particularly interesting since the existing design has a clump weight of 66645 [kg]. To investigate this closer the weight increments are reduced.

The second clump weight analysis were done with a 1 [ton] increment four times on “each side” of the current weight. The existing weight is also marked green here.

Mass in Air [kg]								
62645	63645	64645	65645	66645	67645	68645	69645	70645

TABLE 35 - MASS, CLUMP WEIGHT ANALYSIS #2

The results from the second clump weight analysis:

Damage 1 Year	
Mass in air [kg]	Damage
62645	0,06318
63645	0,06323
64645	0,06420
65645	0,06359
66645	0,06343
67645	0,06272
68645	0,06262
69645	0,06201
70645	0,06119

TABLE 36 - DAMAGE 1 YEAR CLUMP WEIGHT ANALYSIS #2

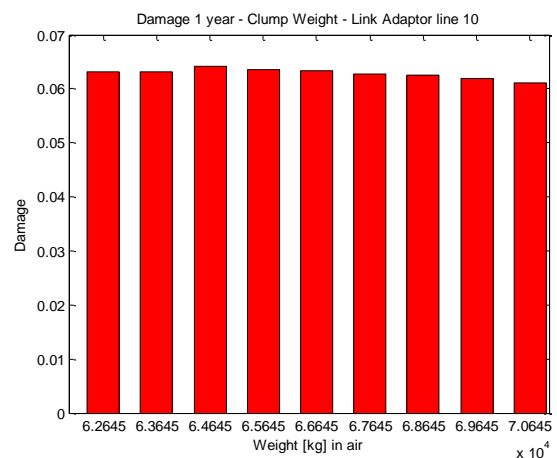


FIGURE 46 - DAMAGE 1 YEAR CLUMP WEIGHT ANALYSIS #2

The largest fatigue damage occurs when the clump weight is 64645 [kg in air]. An interesting thing to point out is that the drop of the fatigue damage is larger when the weight increases compared to when the weight is decreased.

The ballast were not changed during these two analyses, therefore I have chosen to investigate the draft difference of the hull. I checked this both by doing a quick hand-calculation and by checking the displacements from SIMA. For the hand calculations I assumed that all the weight introduced in the clump weight worked as a vertical force on the hull.

The water line area is $D = 6$ [m] and the water density is set to 1025 [kg/m³]. The results from the hand calculations gave the following results:

Weight [kg]	Total Weight Difference [kg]	Difference Draft [m]	Weight [kg]	Total Weight Difference [kg]	Difference Draft [m]
46645	-60000	-2,0703	62645	-12000	-0,4140
51645	-45000	-1,5527	63645	-9000	-0,3105
56645	-30000	-1,0351	64645	-6000	-0,2070
61645	-15000	-0,5176	65645	-3000	-0,1035
66645	0	0	66645	0	0
71645	15000	0,5176	67645	3000	0,1035
76645	30000	1,0352	68645	6000	0,2070
81645	45000	1,5527	69645	9000	0,31055
86645	60000	2,0703	70645	12000	0,4141

TABLE 37 - HAND CALCULATIONS, DRAFT DIFFERENCE

This was controlled checked from the “Displacements.bin” file from SIMA. The displacement is read at the bottom of the hull:

Weight [kg]	Position [m]	Draft Difference [m]	Weight [kg]	Position [m]	Draft Difference [m]
46645	-97,6472	-2,1856	62645	-99,3954	-0,4347
51645	-98,1957	-1,6372	63645	-99,5041	-0,3287
56645	-98,7400	-1,0909	64645	-99,6148	-0,218
61645	-98,2871	-0,5457	65645	-99,7241	-0,1087
66645	-99,8328	0,0000	66645	-99,8328	0
71645	-100,3776	0,5448	67645	-99,9426	0,1098
76645	-100,9182	1,0854	68645	-100,0517	0,2189
81645	-101,4574	1,6246	69645	-100,1605	0,3277
86645	-101,9945	2,1617	70645	-100,2692	0,4364

TABLE 38 - COMPUTER SIMULATION, DRAFT DIFFERENCE

The difference from the hand calculations and the actual simulation are very small. This means that the weight introduced works mostly as a vertical force on the hull. When the clump weight has a weight of 64645 [kg in air] the draft difference is only 0.218 [m], only minor changes in the dynamic behavior can therefore be assumed. This minor change makes the fatigue damage calculation more trustworthy.

The ULS check was performed on the different clump-weight sizes to reveal any major flaws in the design. The characteristic line tension is not checked against the criteria's in the ULS, only the vertical displacements have been checked.

Two different MATLAB-scripts were written in order to control that no vertical displacement occurs at the anchor, and the results were.

ULS Vertical Displacement				ULS Vertical Displacement			
Weight [kg]	Position [m]	Min Value [m]	Max Value [m]	Weight [kg]	Position [m]	Min Value [m]	Max Value [m]
46645	-204	-204	-204	62645	-204	-204	-204
51645	-204	-204	-204	63645	-204	-204	-204
56645	-204	-204	-204	64645	-204	-204	-204
61645	-204	-204	-204	65645	-204	-204	-204
66645	-204	-204	-204	66645	-204	-204	-204
71645	-204	-204	-204	67645	-204	-204	-204
76645	-204	-204	-204	68645	-204	-204	-204
81645	-204	-204	-204	69645	-204	-204	-204
86645	-204	-204	-204	70645	-204	-204	-204

TABLE 39 - ULS, VERTICAL DISPLACEMENT

8.4 FREQUENCY DOMAIN

The results in this chapter are based on the theory from chapter 3.6 (page 18).

As mentioned in chapter 3.6 (page 18), there are two main criteria's for doing an analytical fatigue calculation:

- S-N curve with no fatigue limit
- Narrow-banded stress process

In my calculations I have used the linear S-N curves specified by DNV. It is most common to use a linear S-N curve for structures like this (Larsen, 2013). A linear S-N curve has no fatigue limit.

The second criterion requires a bit more investigation, the determination whether the stress process is narrow-banded or not. For this I have used a routine in MATLAB (spegen_t.m, written by Finn Gunnar Nielsen 1995), to generate a power spectrum from the time history created in SIMA. From this power spectrum it will be possible to determine what type of process it is. The power spectrum $S(f)$ is the one-sided power spectrum as a function of frequency.

The simulation was done with a sea state with $H_s = 3$ [m] and $T_p = 8.5$ [s]. This produced the following power spectrum:

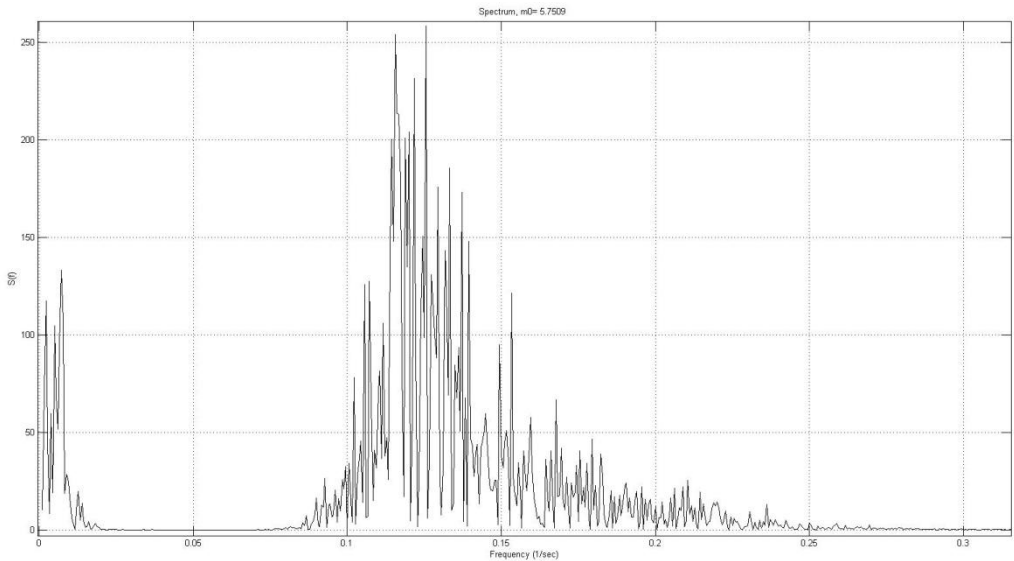


FIGURE 47 - POWER SPECTRUM

The smaller peaks to the left (with frequency $4 \cdot 10^{-3} - 7 \cdot 10^{-3}$) represents the slow motion and the peaks to the right represents the wave motion:

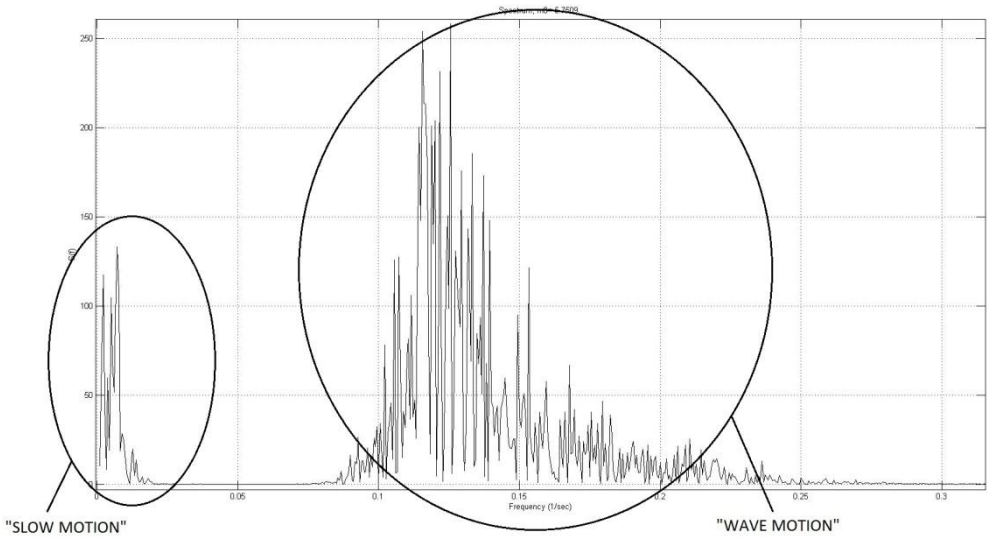


FIGURE 48 - POWER SPECTRUM, EXPLAINED

This proves that the stress process is **not narrow-banded**. The analytical formula (3.8) derived in chapter 3.6 (page 18) cannot be used without further modification of the formulas. Without

investigating a more in depth method described in “Probabilistic Analysis of Fatigue due to Gaussian Load Processes” (Jiao and Moan, 1990), I have chosen to investigate a very simplified modification of my current analytical formula. The simplified modification (proposed by T.Hanson (2013)) is as follows:

- Separate the “slow motion” and “wave motion” by applying a filter.
- Calculate the analytical fatigue contribution from each of the two different motions, based on the individual standard deviation
- Sum up the two different contributions
- Compare this to the damage calculated by the Rainflow-technique

The modified analytical fatigue formulas:

$$\frac{T}{T_Z} = N_{tot} \tag{8.1}$$

For the “wave motion”:

$$E_{wave}(D) = \frac{T}{T_{Z,wave}K} * (2\sqrt{2} * \sigma_{wave})^m * \Gamma(\frac{m}{\beta} + 1) \tag{8.2}$$

For the “slow motion”:

$$E_{slow}(D) = \frac{T}{T_{Z,slow}K} * (2\sqrt{2} * \sigma_{slow})^m * \Gamma(\frac{m}{\beta} + 1) \tag{8.3}$$

Total fatigue damage:

$$E_{tot} = E_{wave} + E_{slow} \tag{8.4}$$

This was performed on four different cases: “As-Built”, parallel, 30 [degree] and 60 [degree]. For every sea-state, the standard deviation and zero up-crossing period for both the “slow-motion” and “wave-motion” had to be found. After calculating all these parameter (with help from the filter), the damage was calculated from the closed form solution. The results from the closed form solution were:

	“As-built”		Parallel		30 [degrees]		60 [degrees]	
	Damage	Lifetime [years]	Damage	Lifetime [years]	Damage	Lifetime [years]	Damage	Lifetime [years]
link adaptor line_10	0.0103	97.0134	0.03277	30.5199	0.02139	46.7516	0.00916	109.1448

TABLE 40 - DAMAGE CLOSED FORM SOLUTION, AS-BUILT, PARALLEL-30-60 ROTATIONS

The solutions here are obtained by a very simplified formula, and usually these types of load history have to be treated with some sort of weight functions.

9 CONCLUSION

The first method investigated in this report was based on a Linear Time Domain model. The mooring system for the Hywind Demo is, however, considered to be a non-linear system, and a Linear Time Domain solution would hence be inadequate. However, a possible way of still doing a Linear Time Domain in Sima was investigated. The way of solving this problem would require a lot of work on the model, and linear analyses were hence not carried out.

After establishing the non-linear model, analyses were done to find the worst sea state with respect to fatigue. All the fatigue analyses from the non-linear time domain analyses were done by the Rainflow counting method. Significant wave heights from 1-13 [m] were simulated and from this I found out that a $H_S = 3.0$ [m] and $T_P = 8.5$ [s] created the largest fatigue damage per year on the mooring system. A sensitivity study on $H_S = 3.0$ [m] were done to check whether the peak period of $T_P = 8.5$ [s] was the worst peak period. The results showed that a $T_P = 8.0$ [s] produced slightly more fatigue damage. In other words, the worst sea state for Hywind Demo's existing mooring system is when **$H_S = 3.0$ [m]** and **$T_P = 8.0$ [s]**. This significant wave height is within the expected values for significant wave heights and peak periods for largest fatigue damage per year.

From the $H_S = 1-13$ [m] simulation on the "As-Built model, a fatigue life of **93.7 [years]** were found. The most fatigue damage occurs on the segment "link-adaptor line_10". Both the fatigue life and localization of it matches Statoil's results (compared with a fatigue evaluation based on the Rainflow technique). This means my MATLAB-codes for calculating fatigue damage with the Rainflow counting method works.

The results from the rotation matrix method gave an expected life time of **92.9 [years]**. An interesting observation is that it is almost no difference compared to the results from the $H_S = 1-13$ [m] simulations ("As-Built"-model, default direction). I had not expected that they would be that similar but there are different reasons that may explain the coincidence. The reason why they should not be that similar is that the weighted wave direction from the Metocean specification is different from the direction used in the "As-Built"-model. The weighted wave direction for the waves of 3 [m] and smaller are calculated to be 264 [degrees], while the wave direction for the "As-Built" model is 300 [degrees]. Another point to mention is that the mean wind speed for the two cases are different, it is $U_{MEAN} = 20$ [m/s] for the "As-Built" model and $U_{MEAN} = 12$ [m/s]. The most optimal wave direction for the Hywind Demo is 285 [degrees] (right in between two mooring lines). Based on the weighted direction, the fatigue damage produced in line_10 should be lower. That means that the $U_{MEAN} = 12$ [m/s] may produce more fatigue in the mooring lines than with a $U_{MEAN} = 20$ [m/s]. Another reason why the fatigue damage is greater

with at $U_{MEAN} = 12$ [m/s] can be linked to the constant pitch-controlling the Hywind Demo does around the $U_{MEAN} = 12$ [m/s]. This is only assumptions, and a parameter study with varying U_{MEAN} should give a proper answer to this. The reason for this method was to investigate the possibility to reduce the number of calculations needed. The only requirement for doing this is that the system must have at least one symmetry place. But after all, the solution from this method seems very reasonable.

The clump weight simulations showed that most fatigue damage was produced close to the existing weight. With a weight of **64645 [kg]** (in air) most fatigue damage was achieved. With both a lower clump weight and a higher clump weight the fatigue damage was found to be **lower**. With the weight of 64645 [kg] the draft increased only 0.218 [m], only small changes in the dynamic behavior can therefore be assumed. The clump weight was mainly introduced to ensure sufficient yaw-stiffness for the Hywind Demo and a decrease of the weight of the clump weight will reduce the yaw stiffness. Therefore, it is reasonable to increase the weight of the clump weight to decrease the fatigue damage.

Calculating the fatigue with the closed form solution works only on a narrow banded process. The stress history for the mooring lines on the Hywind Demo was showed not to be narrow banded. This was solved by filtering out the “slow-motion” and “wave-motion” so the two contributions could be calculated individually. The results showed that calculating with this closed form solution in the frequency domain underestimates the fatigue damage for this system. But with a maximum discrepancy of 4.60 [%] the method proves fully usable.

	Rotation			
	“As-Built” [years]	Parallel [years]	30 degrees [years]	60 degrees [years]
Non-Linear Time Domain	93,7	29,7	45,6	104,3
Frequency Domain	97,1	30,5	46,7	109,1
Difference	3,63 %	2,69 %	2,41 %	4,60 %

TABLE 41 - COMPARISON NON-LINEAR TIME DOMAIN AND FREQUENCY DOMAIN

The main conclusion is that calculating the fatigue damage in the frequency domain works for this case. Both methods have low computational time, but since the Rainflow technique is slightly more conservative this is the more favorable method.

10 FURTHER WORK

I suggest doing an optimization of the direction the Hywind Demo, with respect to the weighted wave directions found from the Metocean specification. The optimal orientation found from the Metocean specification is 261 [degrees], which is over 20 [degrees] off compared to the current optimal position of the Hywind Demo (the current optimal direction is 285 [degrees]).

When doing the clump weight simulations the hull was not re-ballasted. This was done to not spend too much time changing the model. However, it would be interesting to see how much the fatigue damage can be reduced by increasing the clump weights while re-ballasting. Simulation of more than one sea state should also be done, to check whether the increase of the clump weights does not produce any irregularities (on the other sea states besides $H_S = 3.0$ [m], $T_P = 8.0$ [s]). When doing clump weight simulations the volume of the clump weights needs to be changed, as it most probably will in the real world.

The downside by a fully linear time domain solution is that the motion of the rotor cannot be included. But comparing a linear time domain solution and a non-linear time domain solution on just the mooring system could maybe bring up some interesting results.

I also suggest doing a comparison between the simplified formula used in the frequency domain and the “weight”-based formulas. The “Jiao-Moan method” (1990) and “Tovo-Benasciutti method” (2002-2005) are both good examples on such, and they both have proved good accuracy.

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APPENDICES

APPENDIX A – SCATTER DIAGRAM

H _s (m)	Spectral peak period (T _p) - (s)																				Sum
	0-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	> 20		
0-1	294	1766	4314	6363	6983	6380	5180	3888	2767	1899	1271	837	545	352	227	146	94	60	110	43476	
1-2	18	381	2069	5219	8233	9609	9172	7622	5745	4038	2698	1737	1089	669	405	243	145	86	125	59302	
2-3	0	11	172	880	2256	3659	4343	4138	3366	2439	1621	1011	600	343	191	104	56	30	32	25252	
3-4	0	0	6	77	387	1004	1643	1933	1786	1378	929	564	317	167	84	41	19	9	7	10350	
4-5	0	0	0	3	38	192	501	811	920	800	567	344	184	89	40	17	7	3	2	4519	
5-6	0	0	0	0	2	20	97	249	387	411	325	205	107	49	20	7	2	1	0	1882	
6-7	0	0	0	0	0	1	10	50	122	177	169	118	63	28	10	3	1	0	0	753	
7-8	0	0	0	0	0	0	1	6	26	59	75	63	37	16	6	2	0	0	0	292	
8-9	0	0	0	0	0	0	0	0	4	14	27	30	21	10	4	1	0	0	0	110	
9-10	0	0	0	0	0	0	0	0	0	2	7	11	10	6	2	1	0	0	0	40	
10-11	0	0	0	0	0	0	0	0	0	0	1	3	4	3	1	0	0	0	0	14	
11-12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	5	
12-13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	
13-14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
14-15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Sum	312	2158	6561	12542	17898	20866	20948	18697	15124	11217	7692	4923	2978	1735	992	566	325	189	276	145997	

APPENDIX B – RESULTS

Damage Hs1-13 [m], As-Built – Model:

Segment/Hs	1	2	3	4	5	6	7	8	9	10	11	12	13
delta line_3	0,000017	0,000030	0,000018	0,000013	0,000011	0,000008	0,000005	0,000004	0,000002	0,000001	0,000001	0,000000	0,000000
delta line_4	0,000021	0,000059	0,000052	0,000046	0,000037	0,000027	0,000017	0,000010	0,000006	0,000003	0,000001	0,000000	0,000000
delta line_5	0,000335	0,001612	0,001584	0,001316	0,000915	0,000554	0,000340	0,000203	0,000107	0,000055	0,000024	0,000008	0,000010
delta line_6	0,000189	0,000358	0,000226	0,000130	0,000082	0,000049	0,000025	0,000014	0,000007	0,000003	0,000002	0,000001	0,000001
delta line_7	0,000182	0,000408	0,000329	0,000257	0,000208	0,000152	0,000089	0,000056	0,000030	0,000014	0,000007	0,000002	0,000003
delta line_8	0,000206	0,000402	0,000321	0,000235	0,000208	0,000145	0,000082	0,000056	0,000031	0,000016	0,000010	0,000003	0,000005
link adaptor line_9	0,000030	0,000072	0,000061	0,000045	0,000033	0,000021	0,000012	0,000007	0,000004	0,000002	0,000001	0,000000	0,000000
link adaptor line_10	0,000255	0,000281	0,000265	0,000209	0,000143	0,000087	0,000051	0,000030	0,000014	0,000007	0,000003	0,000001	0,000000
link adaptor line_11	0,000054	0,000361	0,000408	0,000340	0,000252	0,000165	0,000103	0,000062	0,000032	0,000016	0,000007	0,000002	0,000003
link ch. top line_9	0,000032	0,000055	0,000035	0,000021	0,000013	0,000008	0,000004	0,000002	0,000001	0,000001	0,000000	0,000000	0,000000
link ch. top line_10	0,000208	0,002053	0,002415	0,001878	0,001260	0,000750	0,000446	0,000260	0,000121	0,000065	0,000028	0,000008	0,000012
link ch. top line_11	0,000041	0,000302	0,000342	0,000281	0,000203	0,000130	0,000081	0,000048	0,000025	0,000013	0,000006	0,000002	0,000002
link ch. bot. line_9	0,000029	0,000068	0,000057	0,000042	0,000030	0,000020	0,000012	0,000007	0,000003	0,000002	0,000001	0,000000	0,000000
link ch. bot. line_10	0,000252	0,002251	0,002612	0,002057	0,001410	0,000856	0,000505	0,000297	0,000140	0,000074	0,000032	0,000009	0,000013
link ch. bot. line_11	0,000053	0,000355	0,000401	0,000333	0,000247	0,000161	0,000100	0,000060	0,000031	0,000016	0,000007	0,000002	0,000003

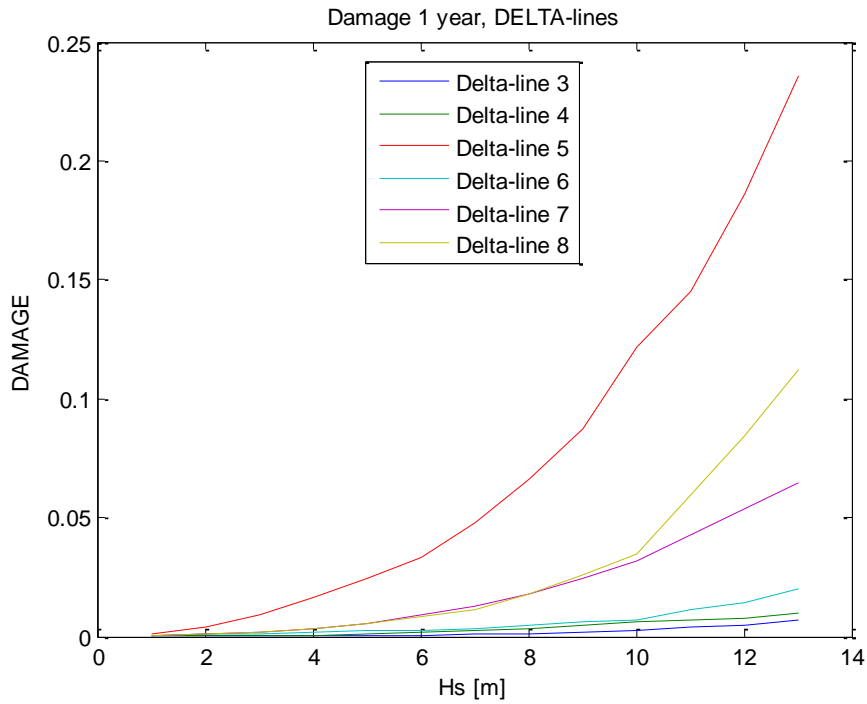
Hs 1-13 [m], Parallel Direction:

Segment/Hs	1	2	3	4	5	6	7	8	9	10	11	12	13
delta line_3	0,000054	0,000132	0,000116	0,000120	0,000111	0,000094	0,000063	0,000041	0,000024	0,000012	0,000006	0,000002	0,000002
delta line_4	0,000068	0,000236	0,000248	0,000256	0,000227	0,000179	0,000116	0,000071	0,000038	0,000018	0,000008	0,000002	0,000003
delta line_5	0,000371	0,002244	0,002256	0,001680	0,001073	0,000606	0,000358	0,000208	0,000110	0,000057	0,000024	0,000007	0,000009
delta line_6	0,000222	0,000930	0,000956	0,000633	0,000438	0,000253	0,000137	0,000081	0,000037	0,000021	0,000011	0,000004	0,000006
delta line_7	0,000054	0,000175	0,000210	0,000213	0,000208	0,000158	0,000097	0,000061	0,000030	0,000014	0,000006	0,000002	0,000002
delta line_8	0,000050	0,000078	0,000066	0,000061	0,000068	0,000057	0,000036	0,000024	0,000014	0,000007	0,000003	0,000001	0,000001
link adaptor line_9	0,000006	0,000047	0,000063	0,000059	0,000050	0,000035	0,000022	0,000013	0,000007	0,000003	0,000002	0,000001	0,000001
link adaptor line_10	0,000730	0,007507	0,008793	0,006543	0,004348	0,002575	0,001506	0,000884	0,000418	0,000227	0,000104	0,000030	0,000047
link adaptor line_11	0,000005	0,000047	0,000062	0,000058	0,000049	0,000035	0,000022	0,000013	0,000007	0,000004	0,000002	0,000001	0,000001
link ch. top line_9	0,000003	0,000026	0,000034	0,000031	0,000026	0,000018	0,000011	0,000007	0,000004	0,000002	0,000001	0,000000	0,000000
link ch. top line_10	0,000056	0,007662	0,008929	0,006338	0,004088	0,002391	0,001393	0,000818	0,000394	0,000217	0,000100	0,000028	0,000046
link ch. top line_11	0,000003	0,000027	0,000035	0,000031	0,000026	0,000018	0,000011	0,000007	0,000004	0,000002	0,000001	0,000000	0,000000
link ch. bot. line_9	0,000005	0,000045	0,000060	0,000056	0,000048	0,000033	0,000021	0,000013	0,000007	0,000003	0,000001	0,000000	0,000001
link ch. bot. line_10	0,000724	0,007425	0,008661	0,006452	0,004279	0,002311	0,001479	0,000869	0,000411	0,000224	0,000103	0,000029	0,000047
link ch. bot. line_11	0,000005	0,000045	0,000059	0,000055	0,000047	0,000033	0,000020	0,000013	0,000007	0,000003	0,000002	0,000000	0,000001

Results Hs 1-13 [m], As-Built-Model:

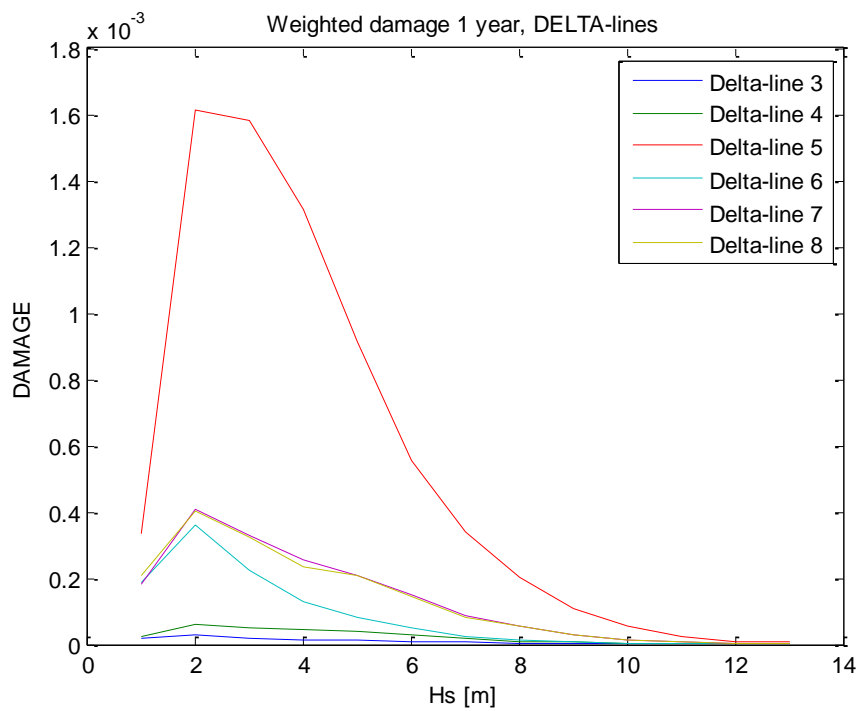
Delta Lines:

Yearly Damage



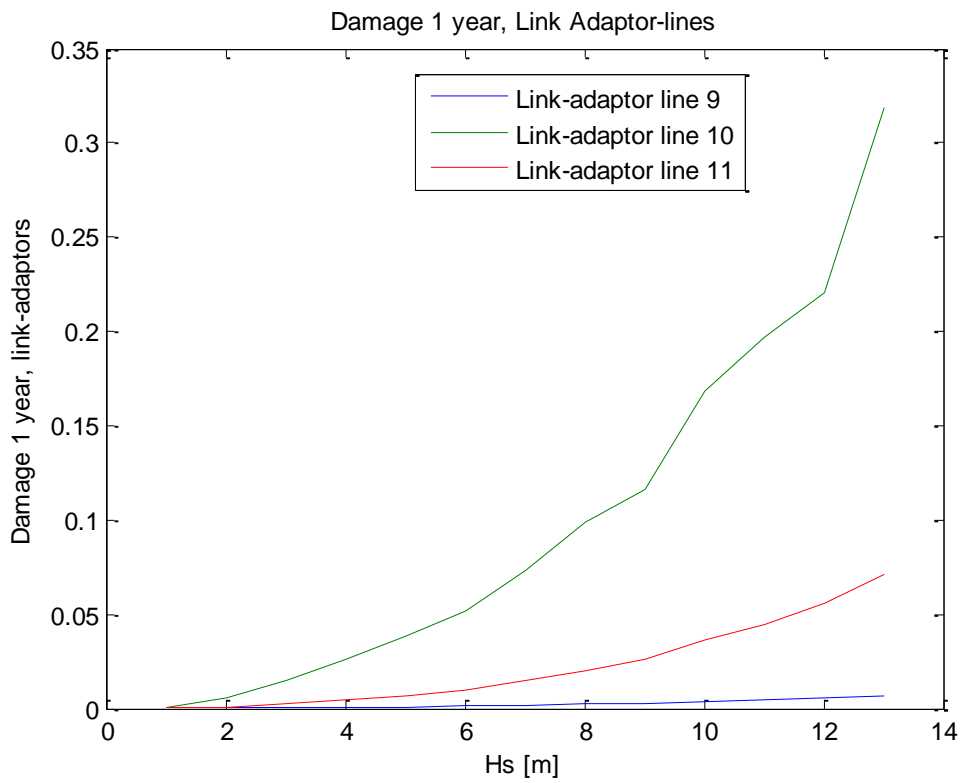
Delta-Lines

Weighted Damage

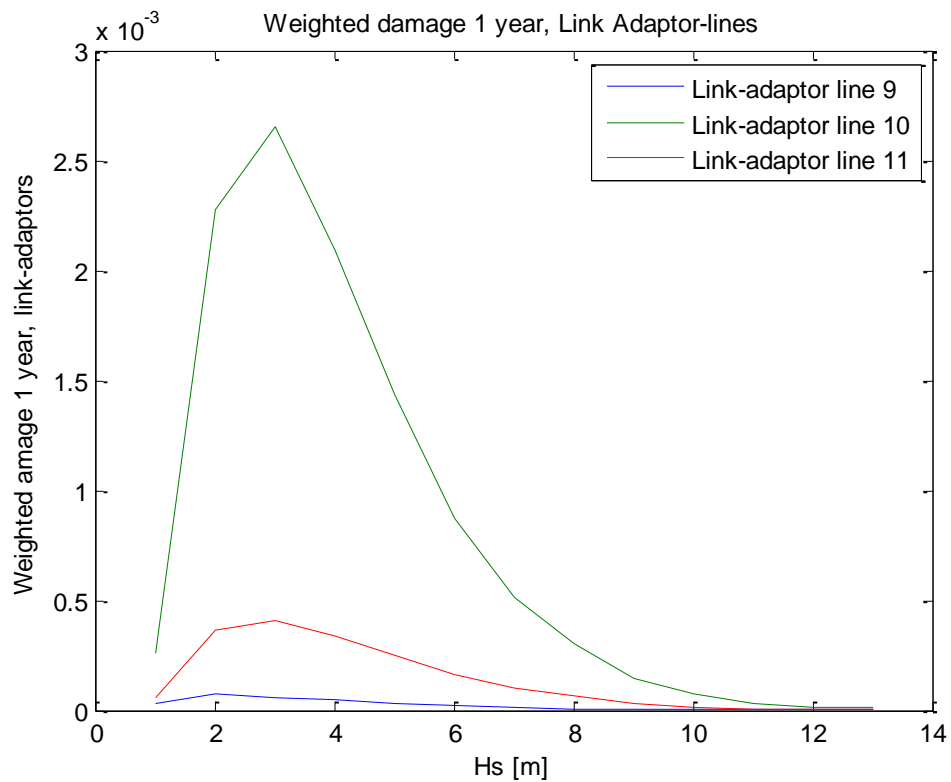


Link Adaptor

Yearly damage:

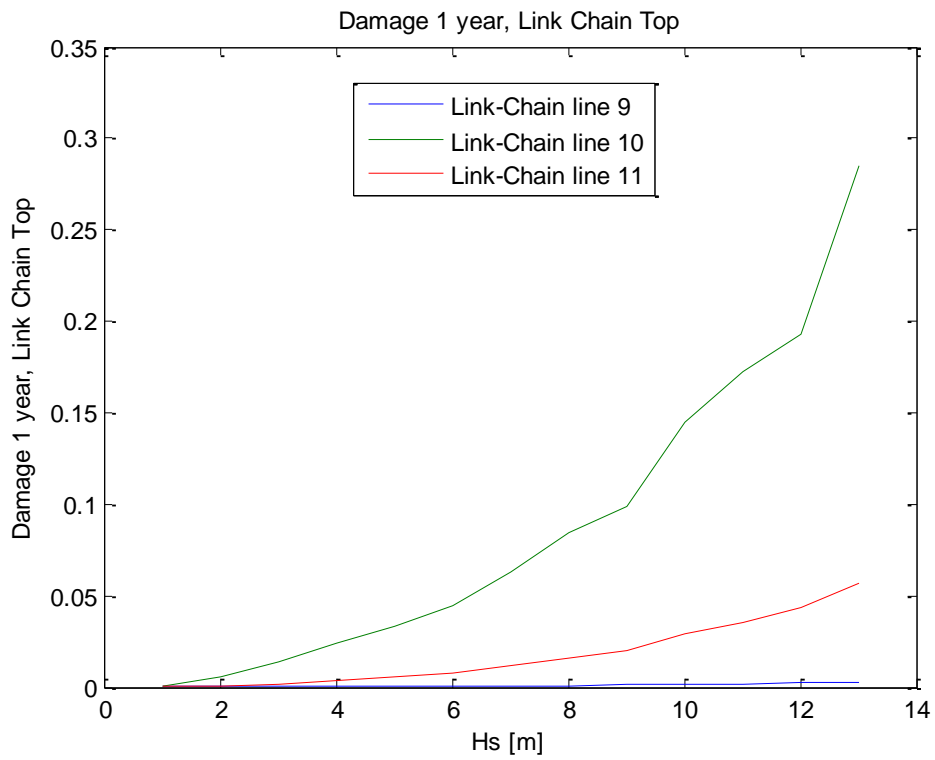


Weighted damage:

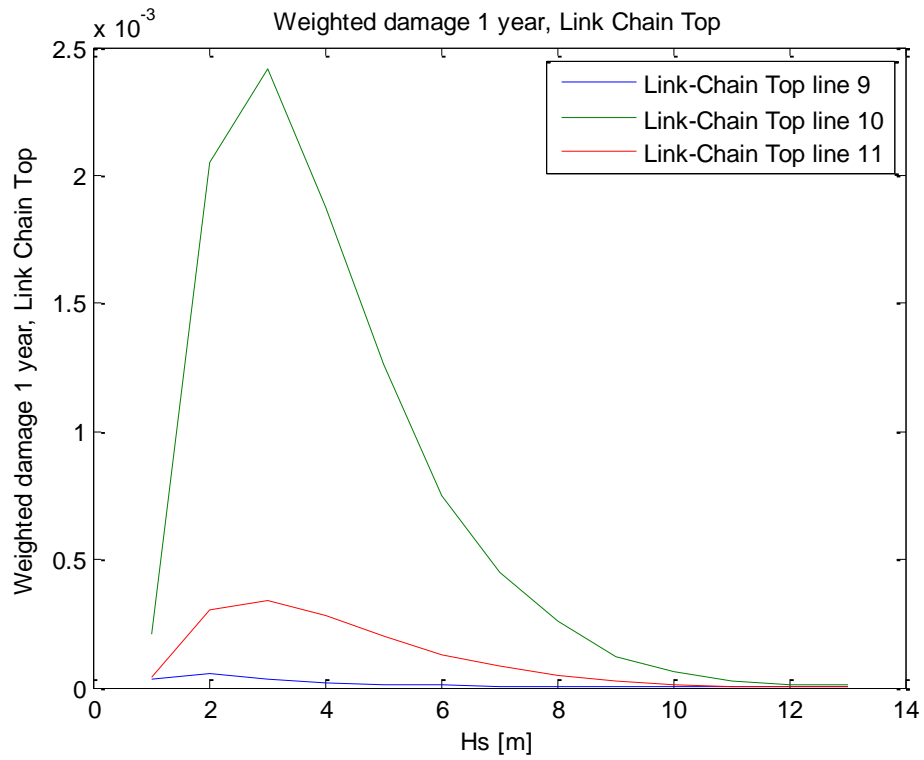


Link Chain Top

Damage yearly:

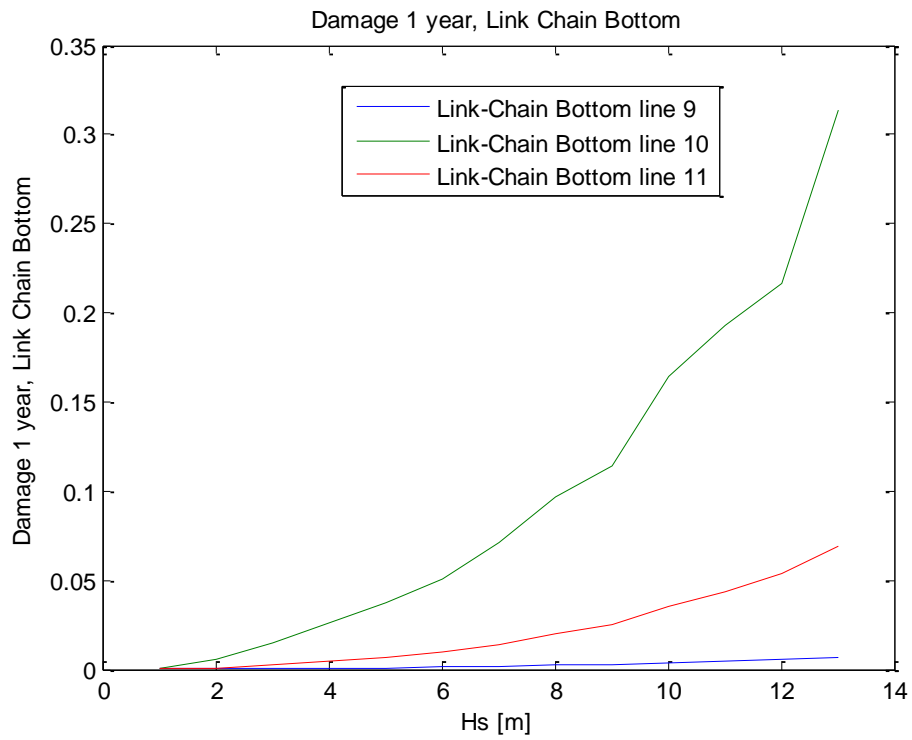


Weighted:

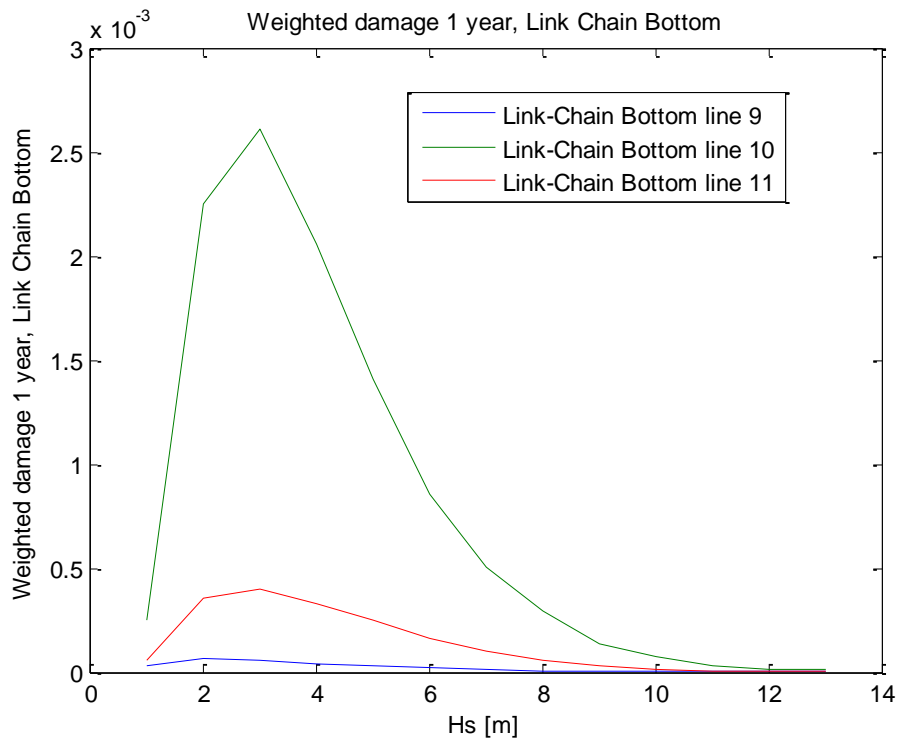


Link Chain Bottom

Damage yearly:



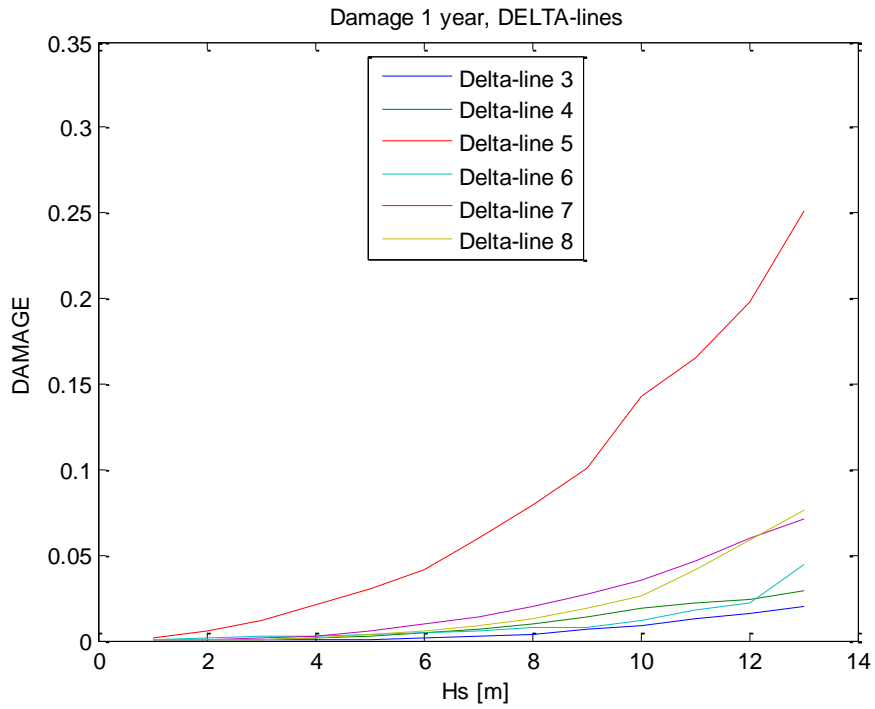
Weighted:



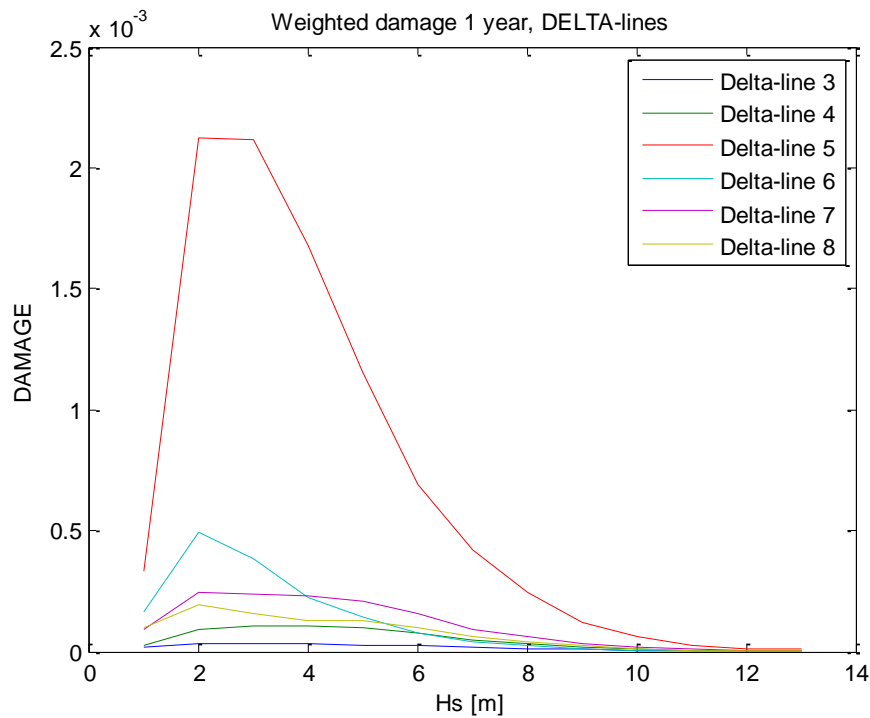
Results Hs 1-13 [m], 30 [degrees]:

Delta-lines

Damage yearly

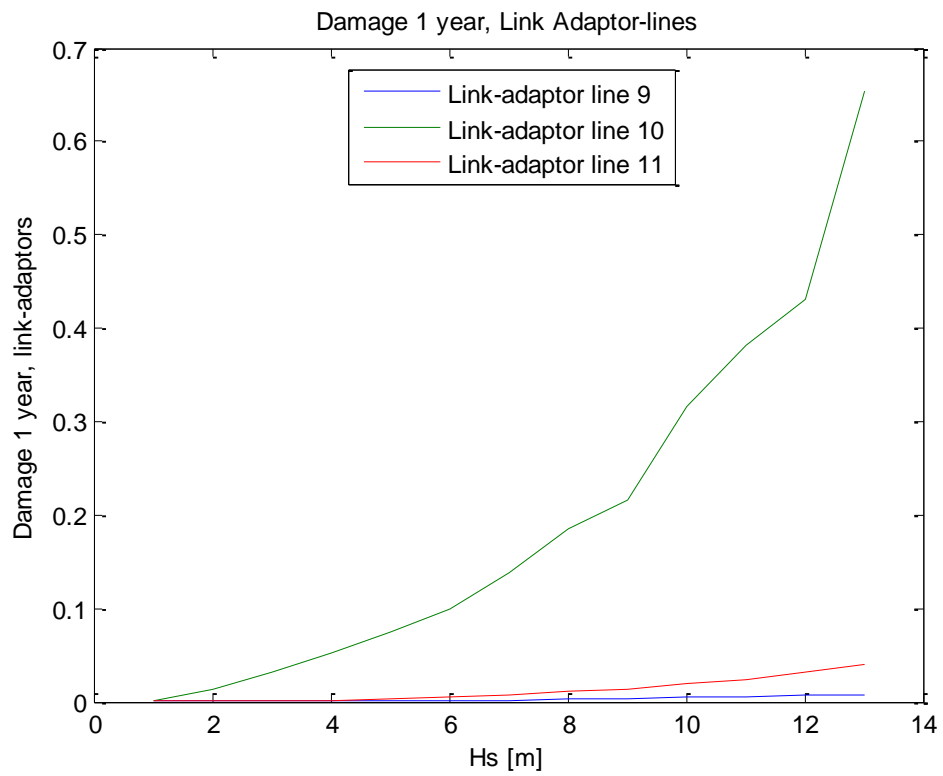


Weighted damage:

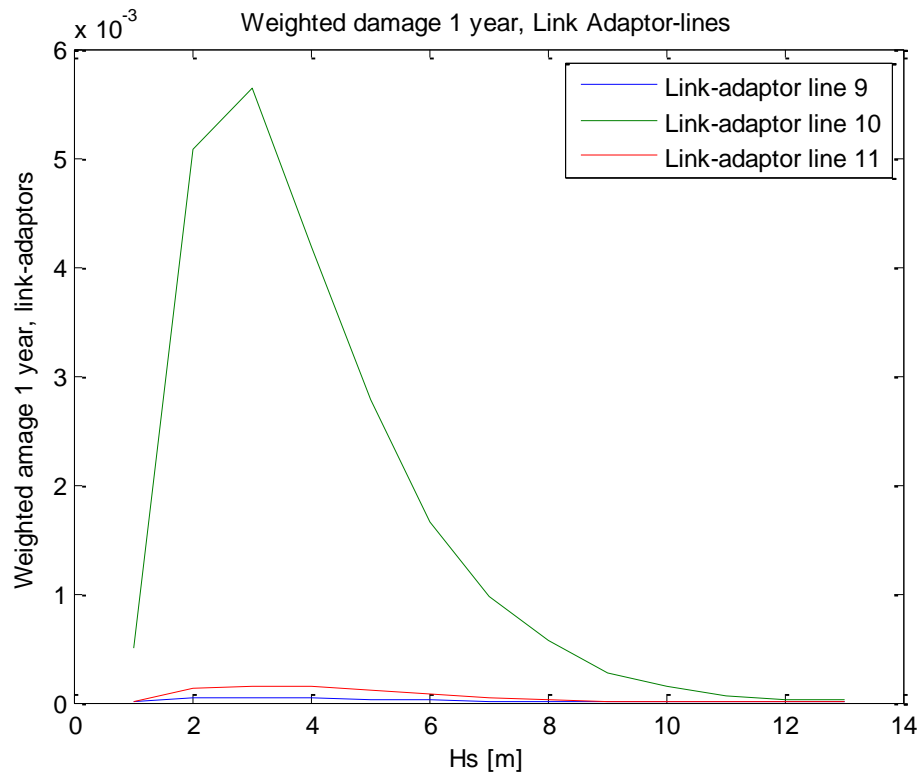


Link Adaptor

Yearly damage:

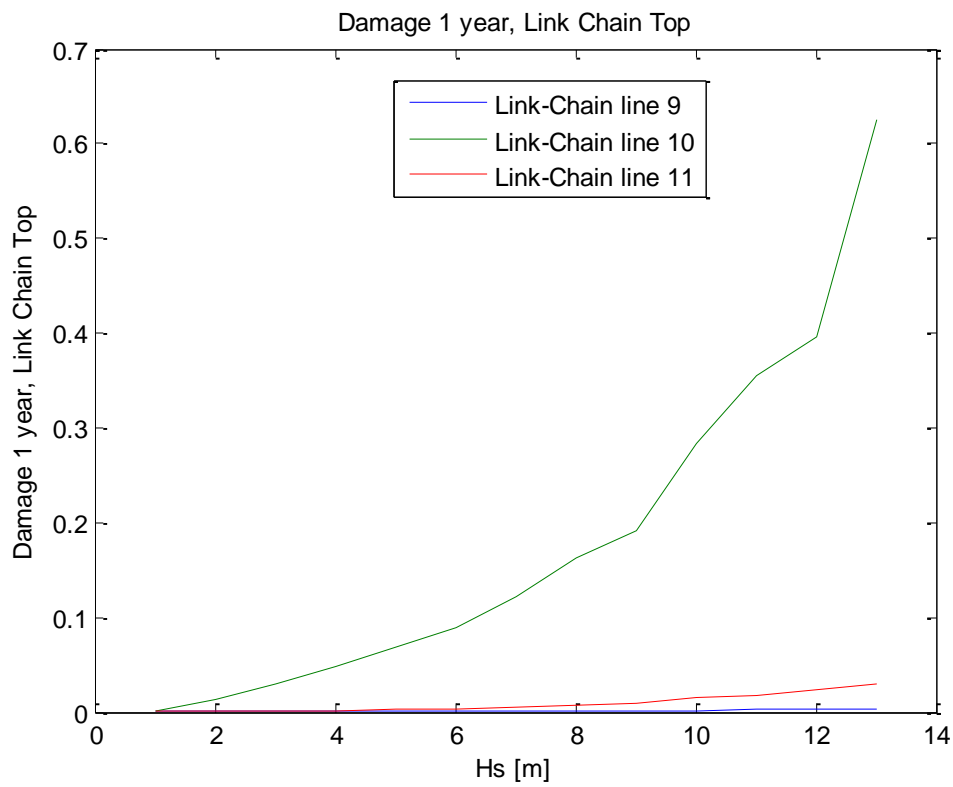


Weighted damage:

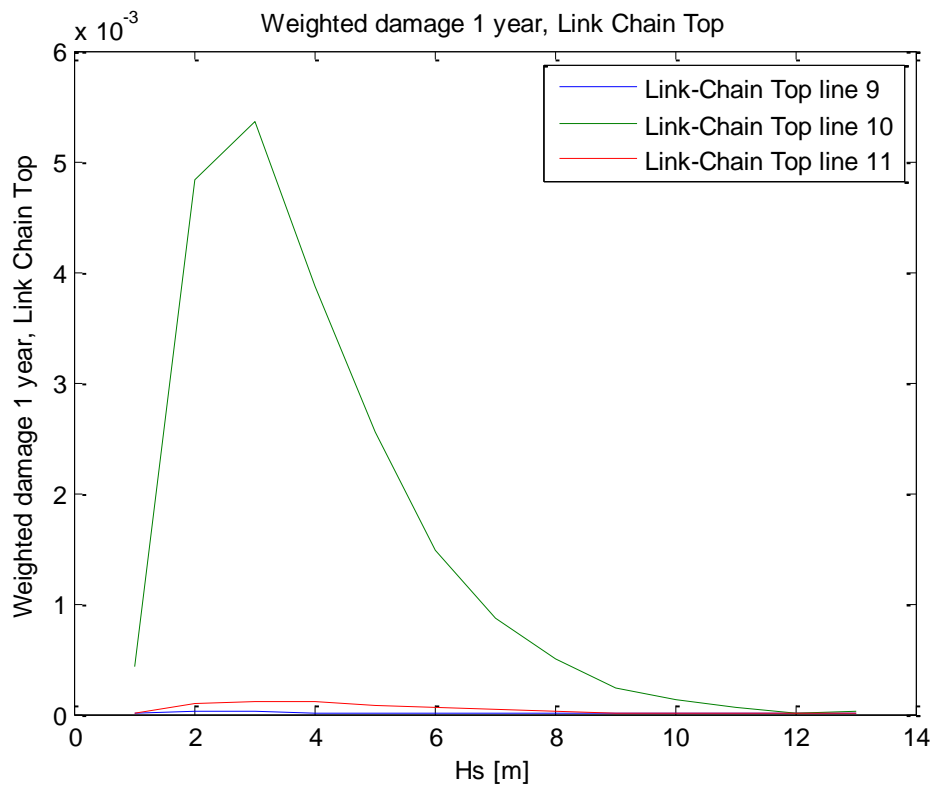


Link Chain Top

Damage yearly:

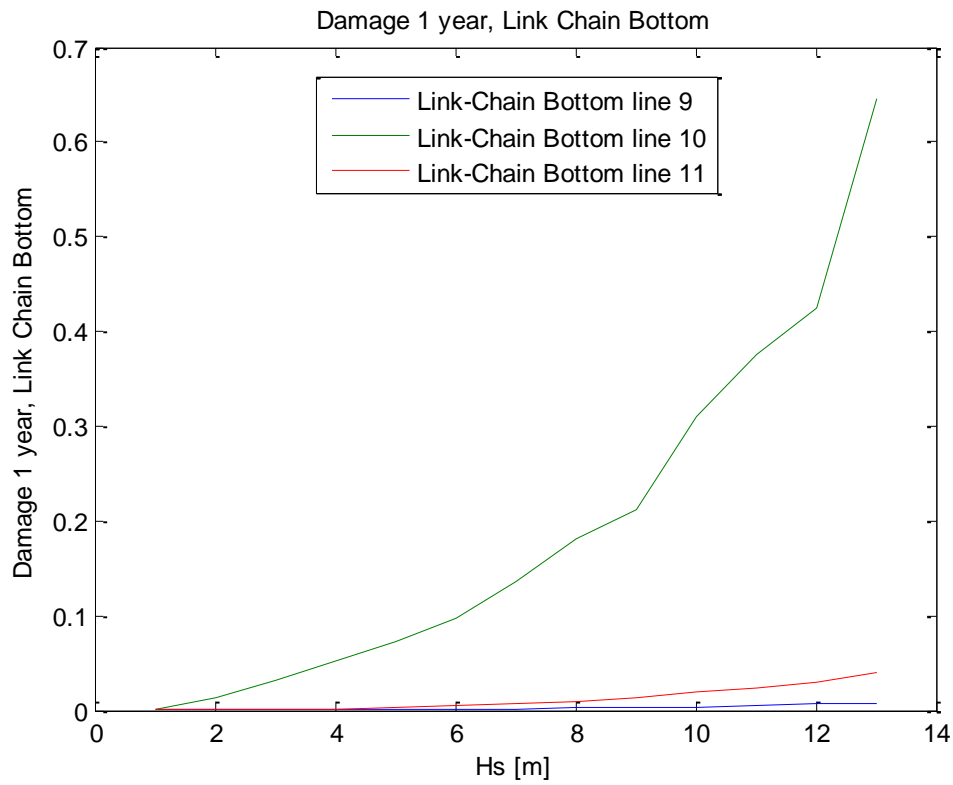


Weighted damage:

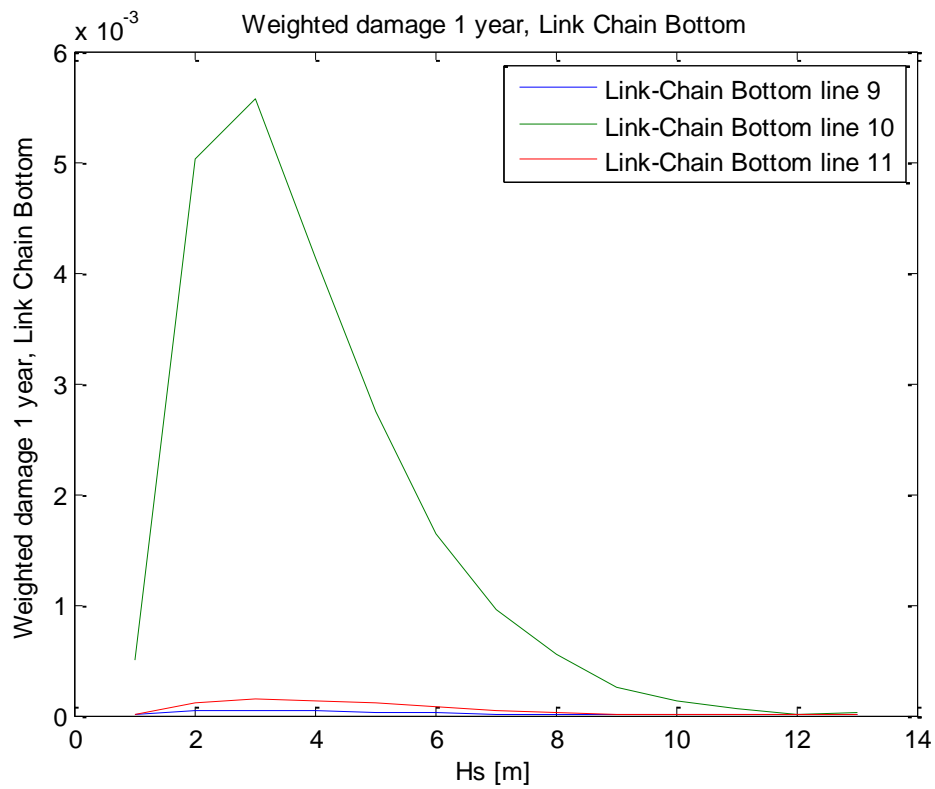


Link Chain Bottom

Damage yearly:



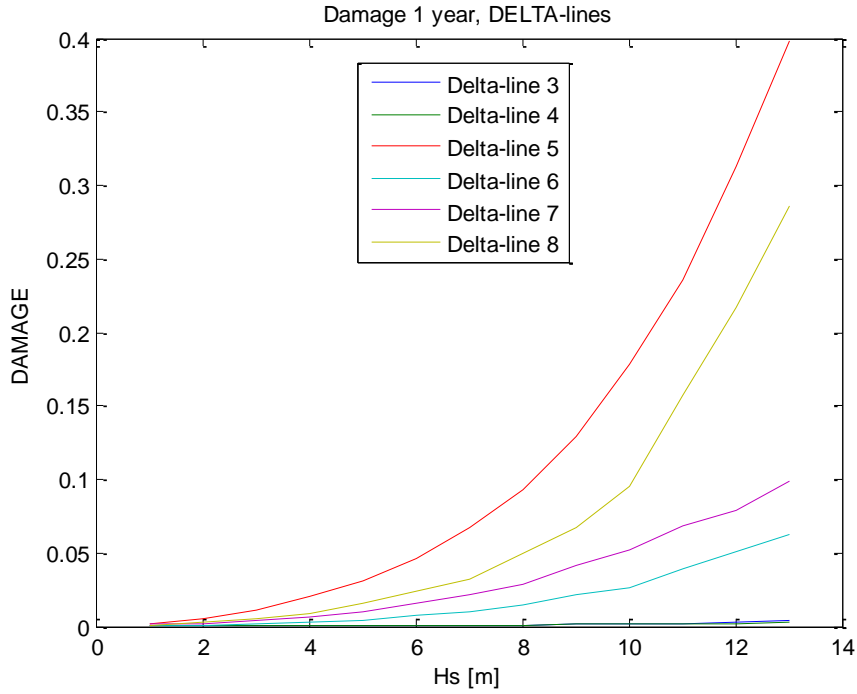
Weighted damage:



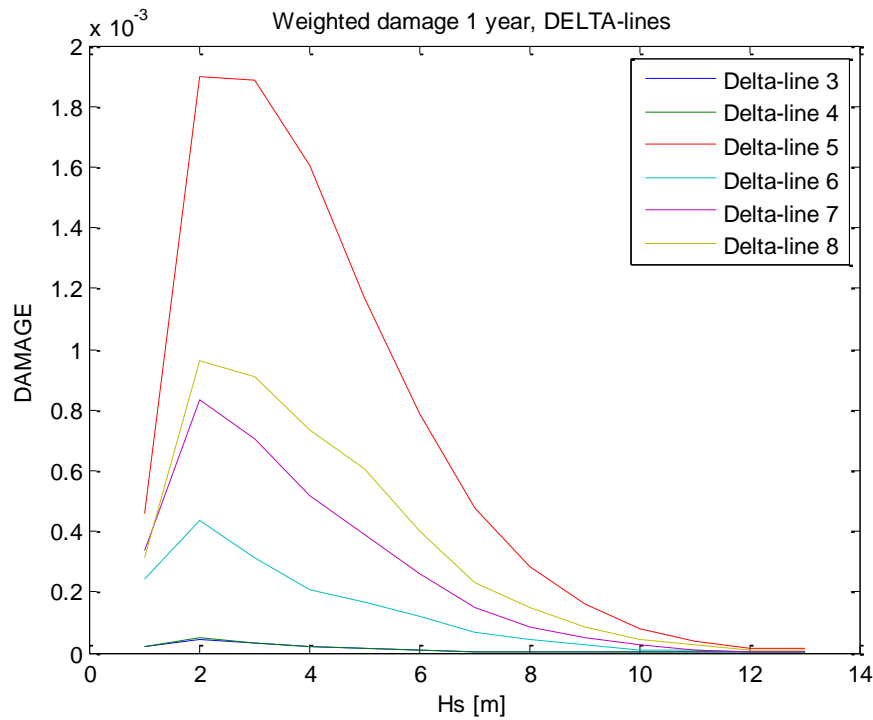
Results Hs 1-13 [m], 60 [degrees]:

Delta-Lines

Damage yearly

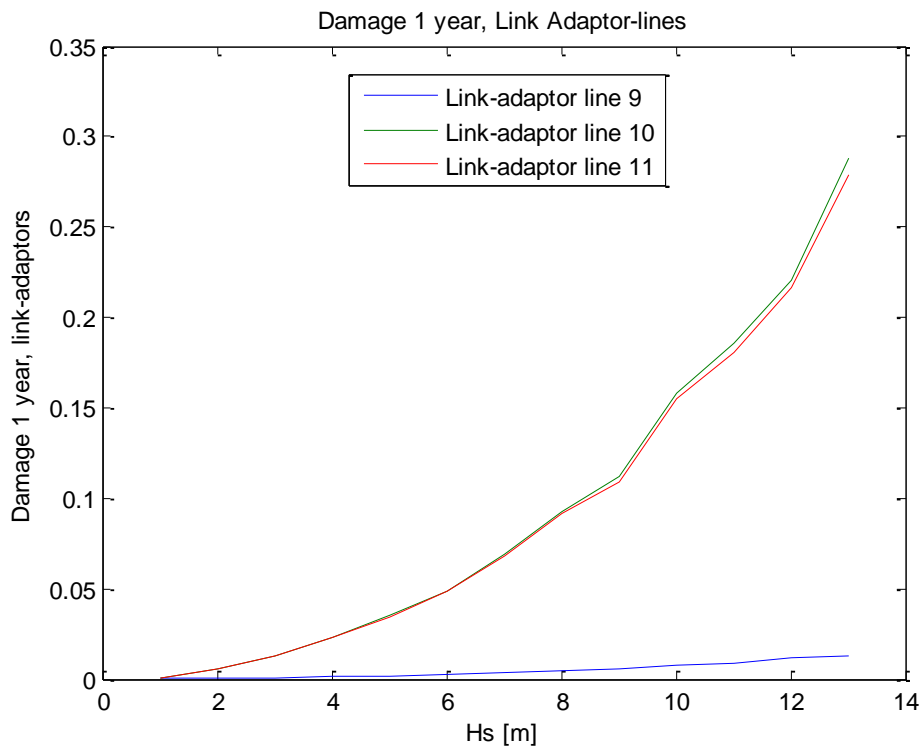


Weighted damage:

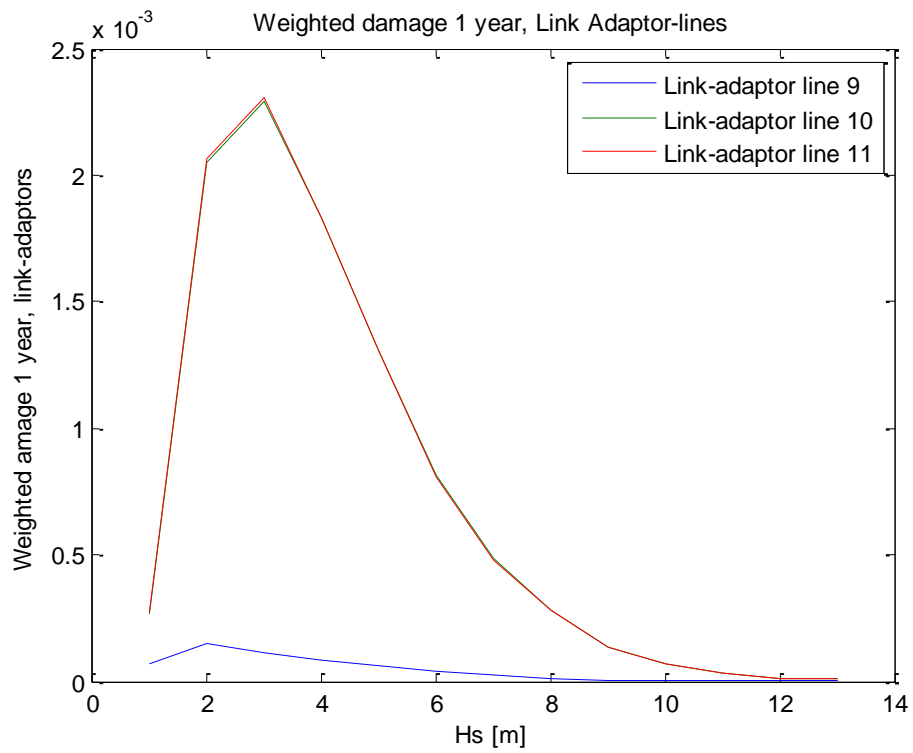


Link Adaptor

Yearly damage:

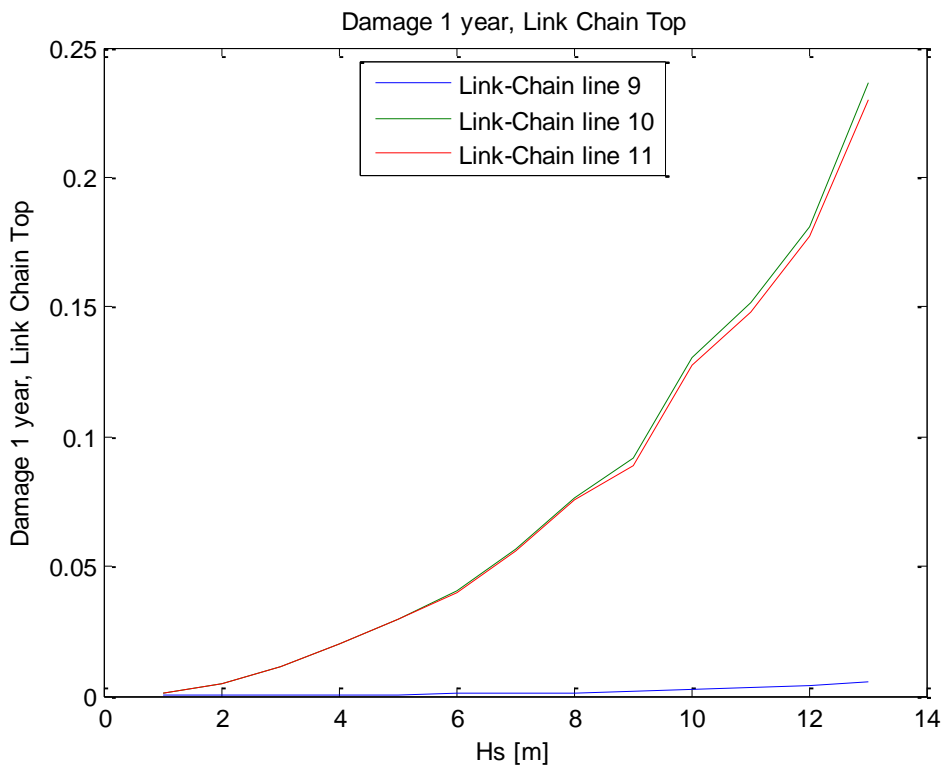


Weighted damage:

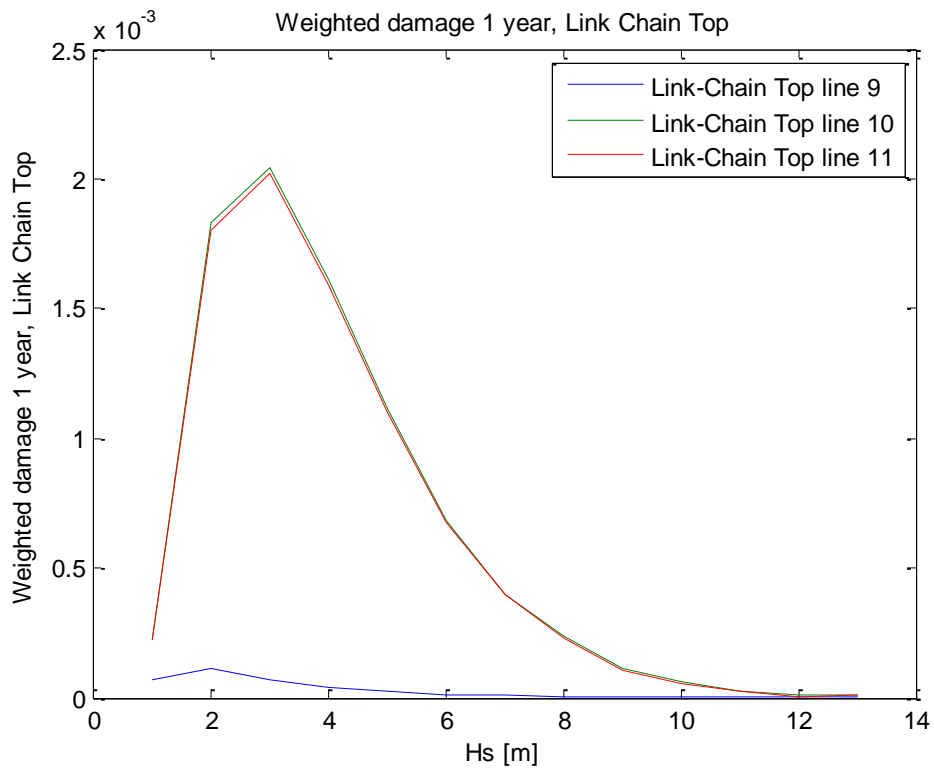


Link Chain Top

Damage yearly:

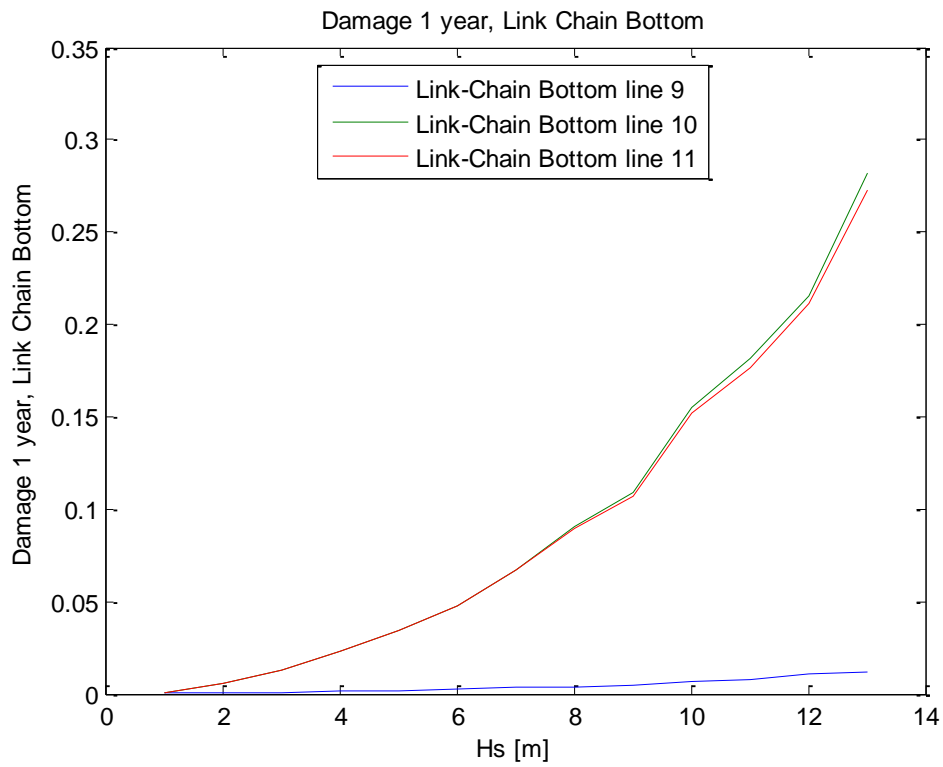


Weighted damage:

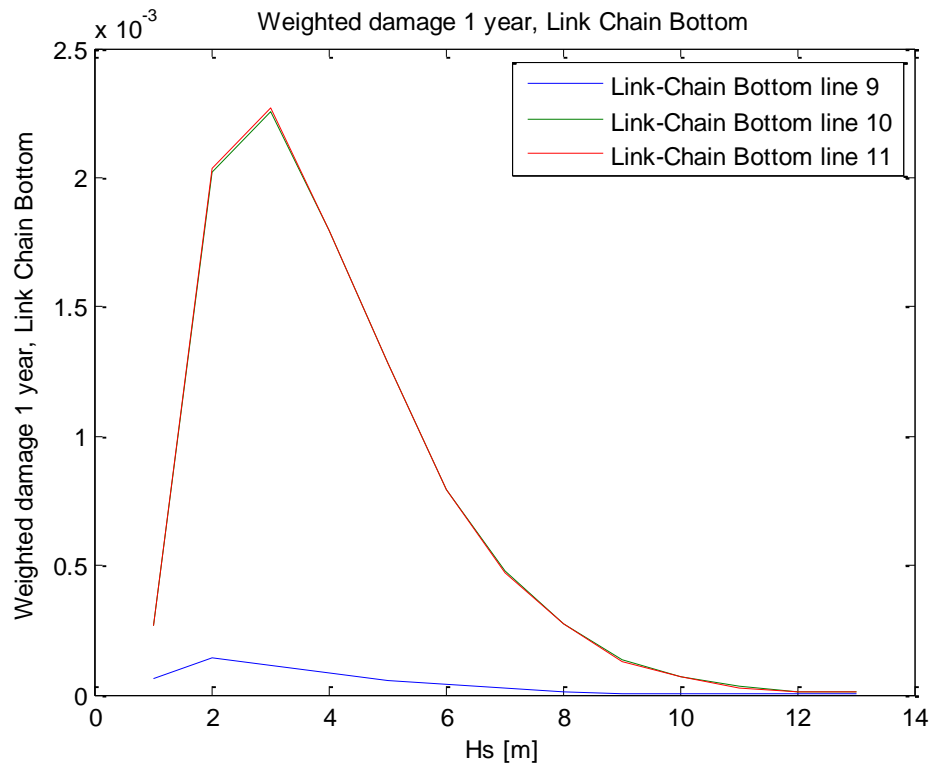


Link Chain Bottom

Damage yearly:



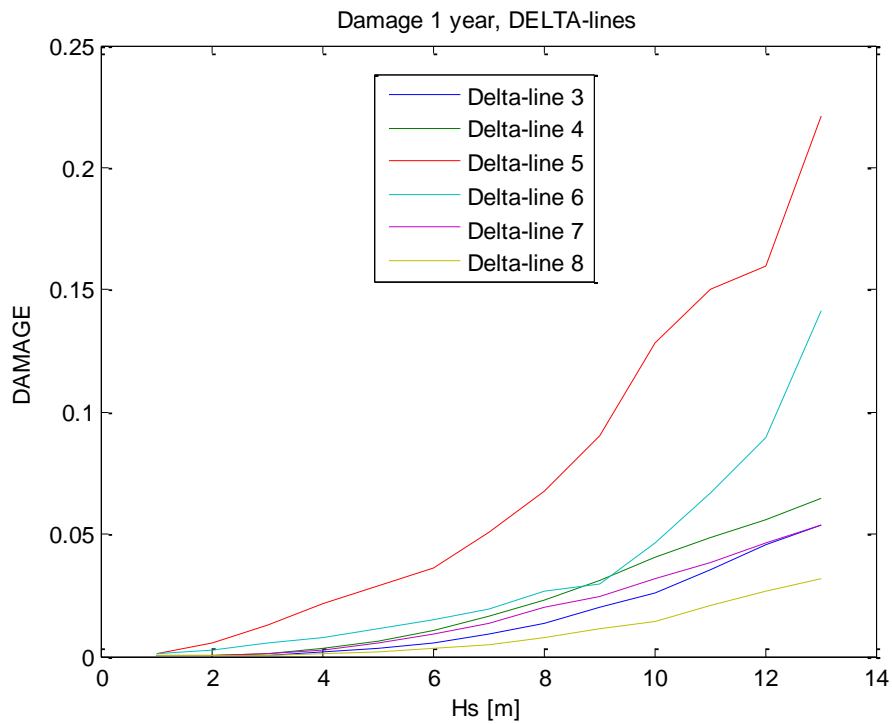
Weighted damage:



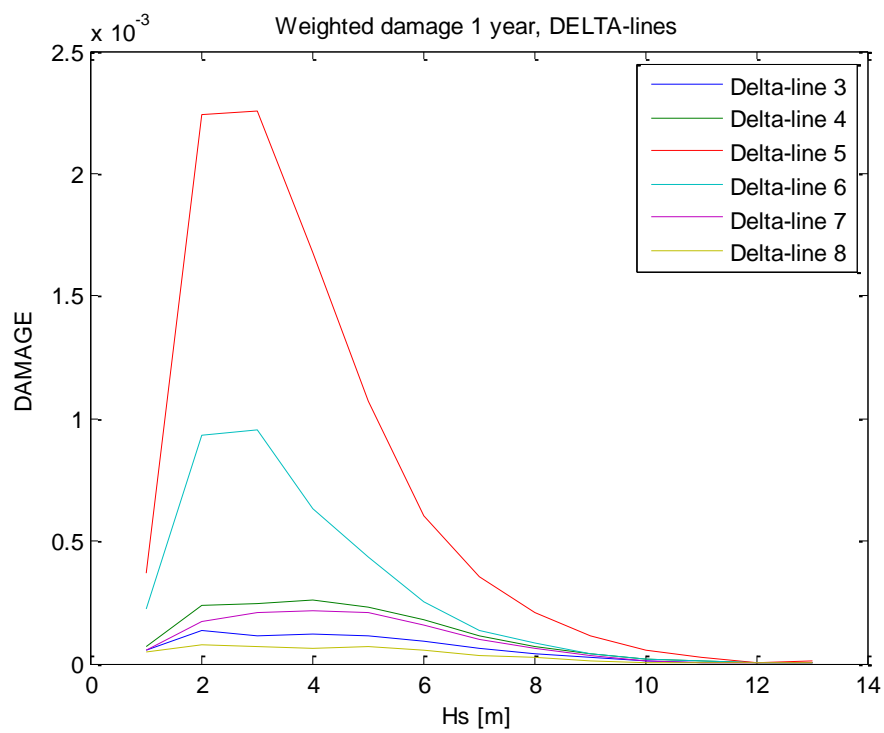
Results Hs 1-13 [m], Parallel direction

Delta Lines:

Yearly Damage

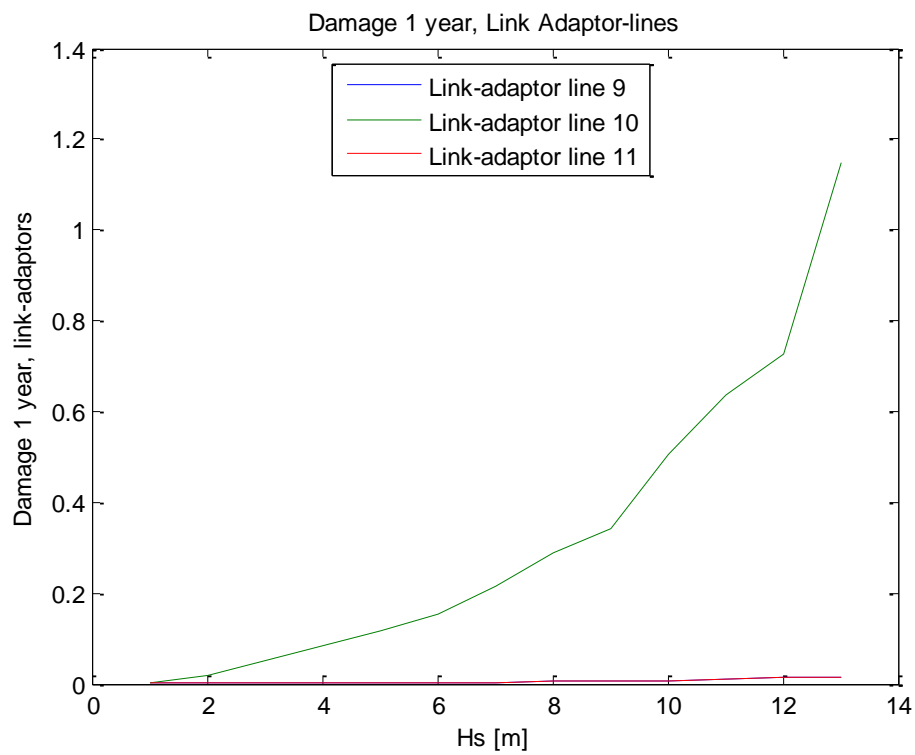


Weighted Damage

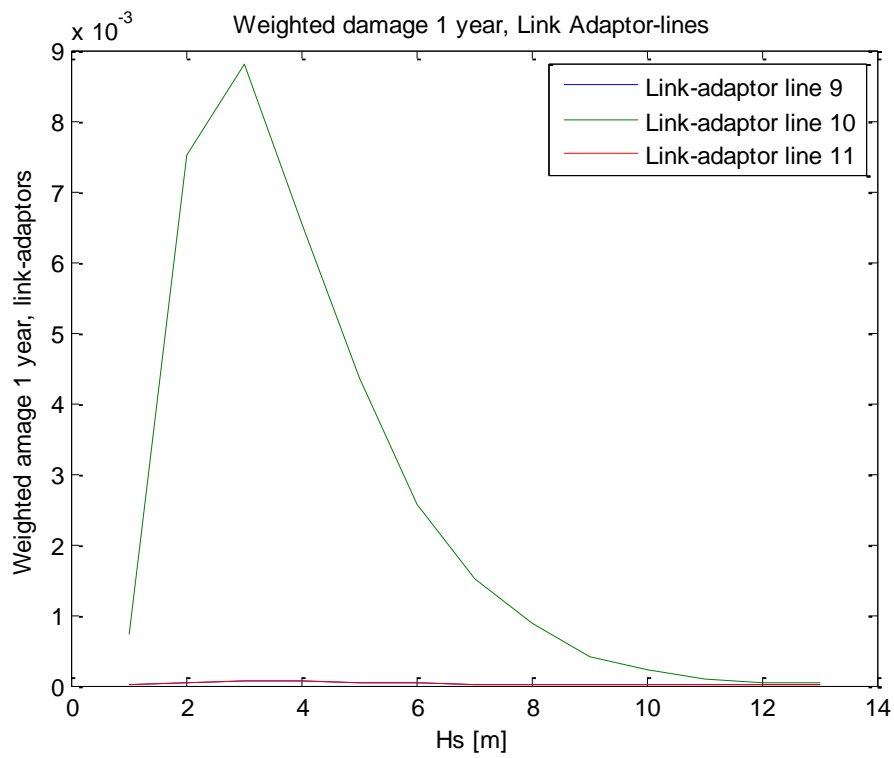


Link Adaptor

Yearly damage:

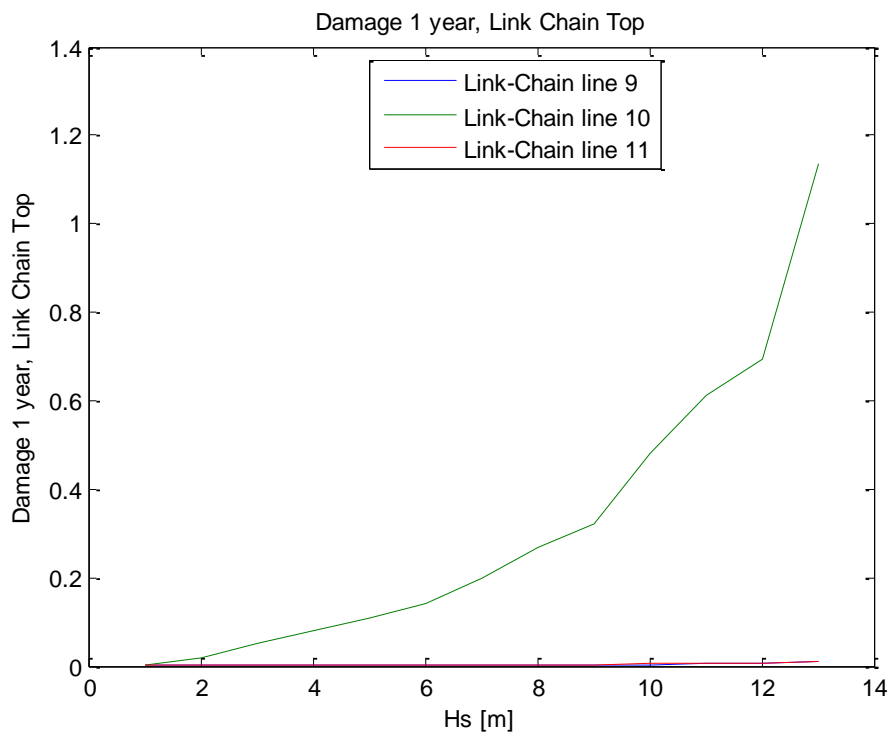


Weighted damage:

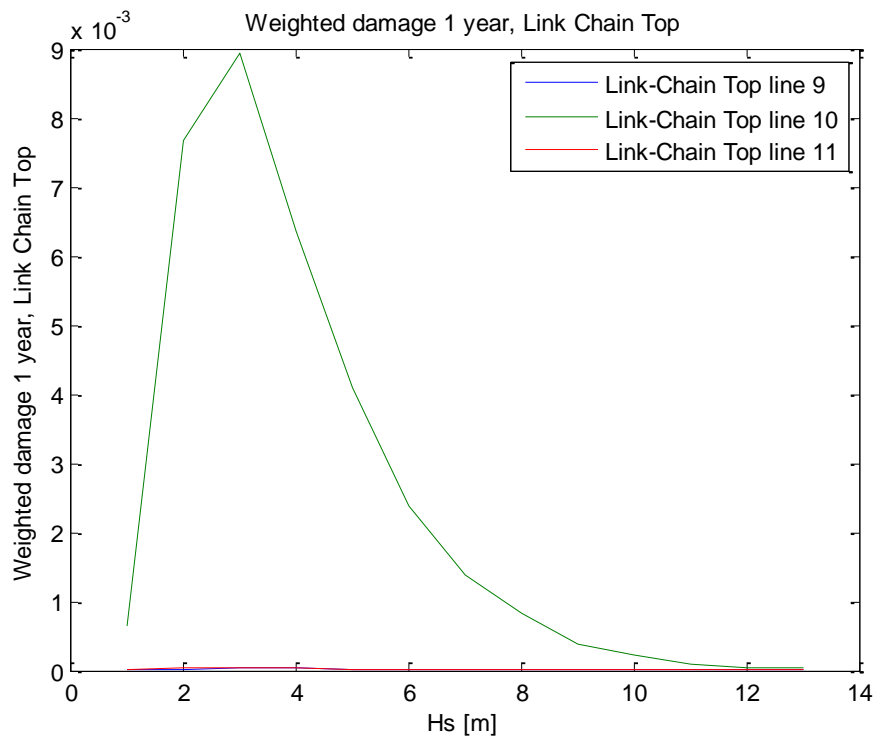


Link Chain Top

Damage yearly:

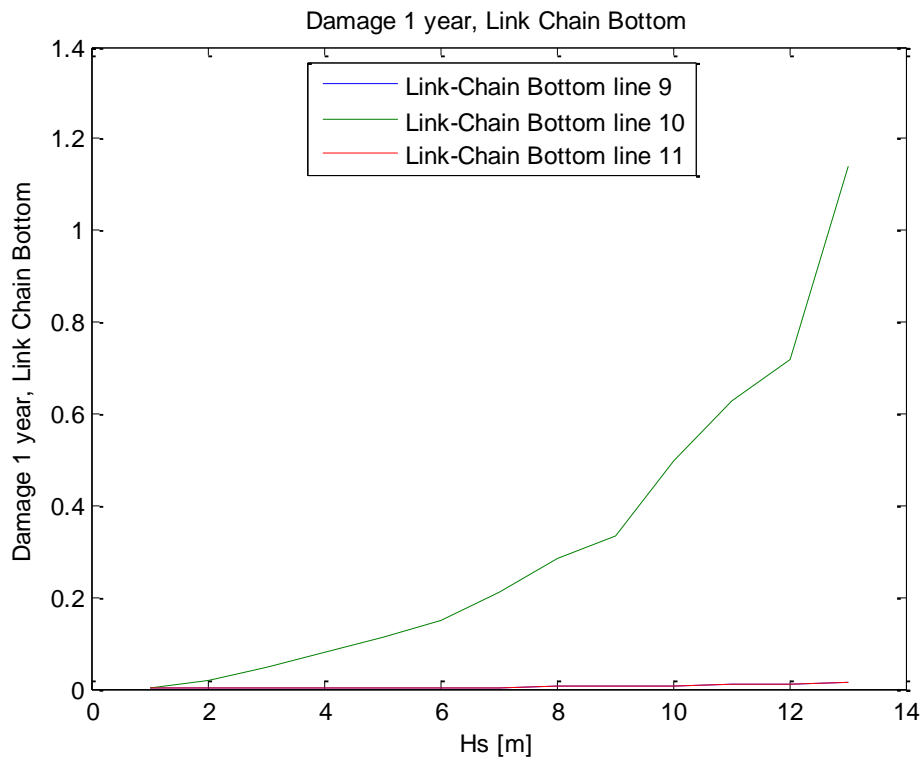


Weighted:

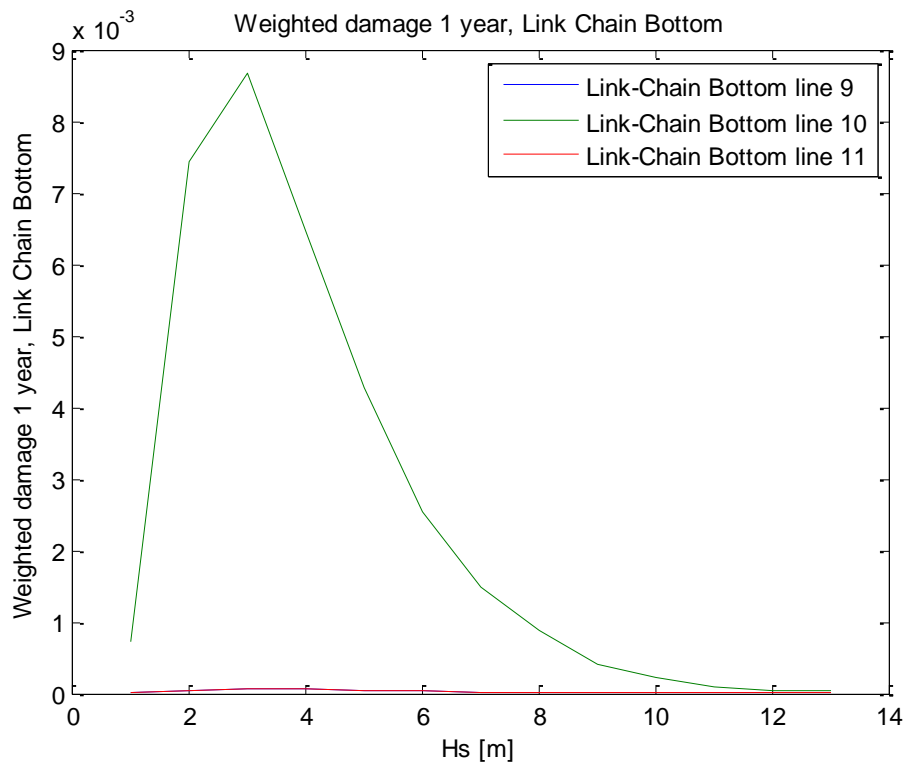


Link Chain Bottom

Damage yearly:



Weighted:



APPENDIX C – WEIGHTED WAVE DIRECTIONS

Significant wave height	0	30	60	90	120	150	180	210	240	270	300	330	OMNI	Probability	Weighted Direction
<1	0.30	0.05	0.05	0.04	0.08	0.61	2.81	2.72	2.82	4.24	6.06	13.88	33.66	0.3366	279,447,4153
<2	0.33	0.06	0.06	0.04	0.06	1.27	5.66	3.73	3.68	5.35	5.78	8.51	34.09	0.3409	260,214,139
<3	0.33	0.06	0.06	0.04	0.00	1.14	3.58	2.35	2.57	3.14	2.58	2.21	17.57	0.1757	243,414,918
<4	0.00	0.00	0.00	0.00	0.00	0.57	1.82	1.23	1.39	1.74	1.09	0.63	8.47	0.0847	237,272,723
<5	0.00	0.00	0.00	0.00	0.00	0.20	0.77	0.57	0.66	0.82	0.53	0.17	3.72	0.0372	237,419,348
<6	0.00	0.00	0.00	0.00	0.00	0.04	0.24	0.26	0.28	0.44	0.25	0.04	1.55	0.0155	243,870,967
<7	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.07	0.10	0.17	0.12	0.01	0.57	0.0057	248,421,0526
<8	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.06	0.00	0.22	0.0022	263,181,812
<9	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.03	0.03	0.00	0.08	0.0008	266,25
<10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.00	0.04	0.0004	277.5
<11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.0001	270
<12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	1E-04	270
<13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.0001	270
<14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0