Universitetet i Stavanger

FACULTY of SCIENCE and TECHNOLGY

MASTER'S THESIS

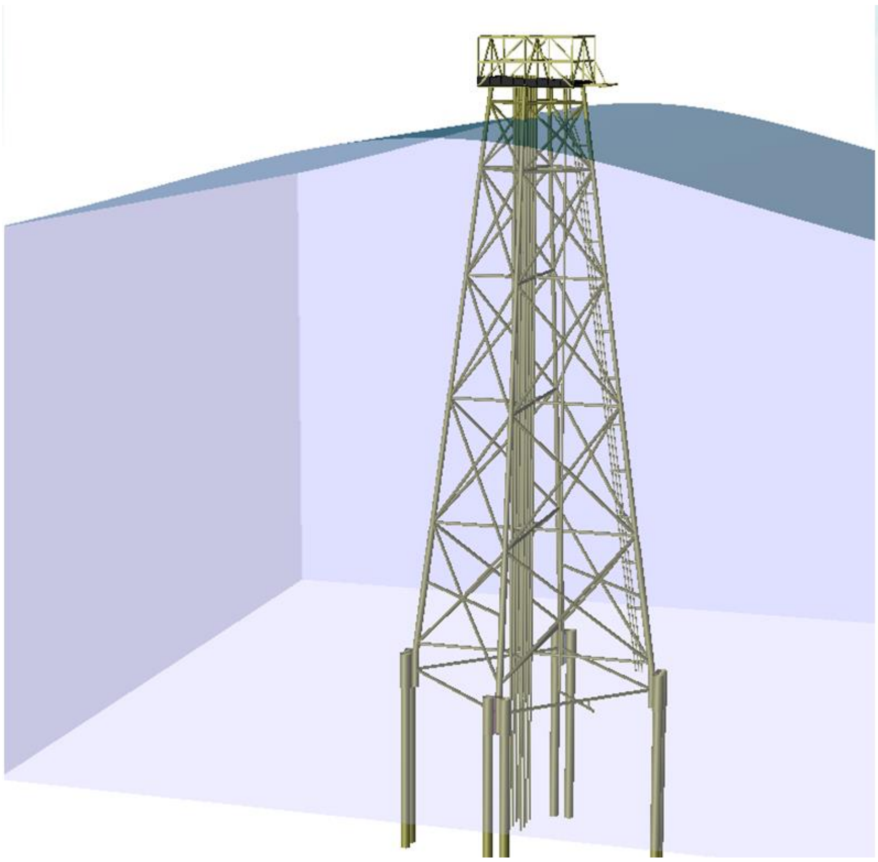
Study program/specialization: MSc in Offshore Technology, Marine and Subsea Technology	Spring semester, 2016 Open/~~Restricted~~
Author: Simon Palviainen Breivik	…………………………………………. (signature author)
Intern supervisor: Dimitrios Pavlou, UiS Extern supervisor: Bjørn Melhus, Kværner Jacket Technology	
Title of Master's Thesis: Evaluation of fatigue in single sided x – joint welds on Oseberg UWP	
ECTS: 30	
Subject heading: - Single sided weld fatigue assessment - SN – fatigue - Fracture mechanics - FE – modeling/analysis	Pages: ………………… + attachments/other: ………… Stavanger, ……………….. date/year

UNIVERSITY OF STAVANGER

Evaluation of fatigue in single sided x-joint welds on Oseberg UWP

Simon Palviainen Breivik

6/15/2016



Preface

Since upper secondary school I have been an employee of Kværner Verdal AS working with constructing and building offshore steel jackets for the oil & gas industry. I became a certified sheet metal worker and have now acquired over 5 years of experience within the industry. When I contacted Kværner about a potential master thesis, I was excited to hear they had a problem regarding the lifespan of an offshore steel jacket they wanted me to investigate.

This way I could also acquire knowledge regarding the design phase of offshore steel jackets as well as the knowledge I have around the construction and assembly phase.

I am very grateful for the help offered by my supervisor, Dimitrios Pavlov, at the University of Stavanger. I am also very grateful for the valuable help my supervisor, Bjørn Melhus at Kværner Jacket Technology has contributed.

In addition I would like to thank Preben Gellein at Kværner Jacket Technology for aid regarding the software used in this report.

Stavanger, June 2016

…………………………………………..

Simon Palviainen Breivik

Abstract

This report assesses the challenges regarding fatigue calculations on the inside of a single sided weld on the Oseberg UWP. SN – fatigue and FM – fatigue calculations are performed on two different models to establish a foundation/basis for evaluation of the inside.

Model one is a beam model used to identify the most critical joint on the Oseberg UWP. Model two is a FE – model of the critical joint identified. A comparison of the fatigue results from the two models provided a good foundation/basis for evaluating the inside of the single sided weld.

The calculated fatigue life on the outside of the single sided weld is 447 years using FE - fatigue. With a DFF of 3,0 this correspond to a design life of 149 years. For the inside of the single sided weld with a DFF of 10,0 to have the same safety level as the outside, the inside fatigue life is calculated to be 1490 years which correspond to a design life of 149 years.

For a fatigue life of 1490 years the critical initial crack size on the inside is calculated to be:

a_i = 6,35 mm
c_i = 63,5 mm

This crack size is larger than the smallest detectable crack size of 5,0 mm according to DNVGL – RP – C203 [4].

Table 1: Overview of the fatigue assessment approaches and their corresponding fatigue life results (without DFF)

Approach	Beam model (outside)	FE –model (outside)	FE – model (inside)	Error rate (Beam model/ FE – model (outside))
SN – fatigue life Curve	546 years T - curve	612 years T - curve	263 years W3 - curve	0,89
FM – fatigue life a_i x c_i	410 years 3 x 7,5	447 years 3 x 7,5	2220 years 5 x 50	0,92
Error rate (FM – fatigue/ SN – fatigue)	0,75	0,73	8,44	

Following the procedure described in standard DNVGL – RP – C203 using a W3 – curve the calculated fatigue life is only 263 years, which differ significant from the FM – fatigue results. Therefore there is a belief that the procedure is too conservative and a parameter study based on the approach in this report is recommended for further work.

Table of Contents

Preface II

Abstract III

Table of Contents V

Abbreviations VII

Symbols VII

Greek symbols IX

1 Background 1

2 Objectives 2

3 Method and execution 3

4 The Oseberg UWP 4

5 Fatigue 6

5.1 Introduction to fatigue 6

5.2 Total – life approach (SN-fatigue/Miner-Palmgren approach) 7

5.3 Defect - tolerant approach (fracture mechanics) 10

5.4 DFF 13

6 The Poisson effect and β - ratio 14

7 DETFAT 15

7.1 Description of DETFAT 15

7.2 SN – fatigue approach 17

7.3 Fracture mechanics approach 17

8 Identifying the critical x-joint using SN – fatigue 18

8.1 Short summary 23

9 Fracture mechanics on JtRw1_31 24

9.1 Short summary 27

10 FE - model 28

10.1 Geometry 28

10.2 Mesh – MPC – Supernodes 29

10.3 Integrated FE – model 30

11 Fatigue analysis of integrated FE – model (outside) 31

11.1 Outside hotspot stress amplitude 31

11.2 SN – fatigue 33
11.3 Fracture mechanics 33
11.4 Short summary 33
12 Fatigue analysis of integrated FE – model (inside) 34
12.1 Inside hotspot stress amplitude 34
12.2 Fatigue analysis approaches 36
12.3 a) Regular approach 36
12.4 b) Simplified approach 37
12.5 c) Fracture mechanics approach 37
13 Critical initial crack size 38
13.1 Short summary 38
14 Summary of all fatigue results 39
15 Discussion 40
16 Conclusion 42
17 Reference list 43
18 Appendix 44
18.1 Wave rose 44
18.2 Wave directions 44
18.3 DETFAT 45
18.4 Outside hotspot stress ranges from FE – analysis 47
18.5 Inside hotspot stress ranges from FE – analysis 50
18.6 Hotspot stress amplitudes form chapter 8 53
18.7 Schematic crack growth analysis procedure 55
18.8 SN – curves in air 56
18.9 SN curves in seawater with cathodic protection 57
18.10 Fracture mechanics results for the inside 58
18.11 Sketch of crack dimensions 61
18.12 Fracture mechanics results for the outside 62

Abbreviations

CTOD	Crack Tip Opening Displacement
DFF	Design Fatigue Factor
DOB	Degree of Bending
DOF	Degree of Freedom
EPFM	Elastic Plastic Fracture Mechanics
FE	Finite Element
FM	Fracture Mechanics
IMR	Inspection, Maintenance and Repair
LEFM	Linear Elastic Fracture Mechanics
MPC	Multiple Point Constraint
NDT	None Destructive Testing
SCF	Stress Concentration Factor
UWP	Unmanned Wellhead Platform

Symbols

a	Crack depth
a_f	Crack size when fracture occurs
a_i	Initial crack depth
A_X	Cross sectional area of brace
c	Half crack width
c_i	Initial half crack width
C,m	Crack growth parameters in fracture mechanics
D	Total fatigue damage
D_B	Diameter brace
D_C	Diameter chord
D_i	Fatigue damage contribution at wave block i to (i + 1)
E	Elasticity modulus
F_x	Axial force in brace
H	Wave height
I_y	Moment of inertia of brace about transformed y-axis
I_z	Moment of inertia of brace about transformed z-axis
k	Number of stress blocks
K_I	Total stress intensity factor
K_{mat}	Material toughness
K_r	Fracture ratio
K_{rmax}	Critical fracture ratio
L	Fatigue life
L_r	Load ratio

L_0	The time for the total number of stress cycles $n_0 = \sum_{i=1}^{i=k} n_i$
$\log\bar{a}$	The intercept of the logN axis
m	The inverse negative slope of the SN – curve
M_{ba}	Plane plate shape factor at crack tip due to bending loading
M_{bc}	Plane plate shape factor at crack edge due to bending loading
M_{ma}	Plane plate shape factor at crack tip due to axial loading
M_{mc}	Plane plate shape factor at crack edge due to axial loading
Mk_{ba}	Weld toe magnification factor crack tip due to bending loading
Mk_{bc}	Weld toe magnification factor crack edge due to bending loading
Mk_{ma}	Weld toe magnification factor crack tip due to axial loading
Mk_{mc}	Weld toe magnification factor crack edge due to axial loading
M_y	Moment about transformed y-axis in the brace
M_Z	Moment about transformed z-axis in the brace
n	Cumulative number of cycles
n_i	Number of stress cycles in stress block i with constant stress range $\Delta\sigma_i$
N_i	Number of cycles to failure at constant stress range $\Delta\sigma_i$
p	Probability
P	Applied load
P_c	Critical load
r	Outer radius of brace
RF_a	Reduction factor
Sc	Axial loading SCF in brace or chord at the crown location
Ss	Axial loading SCF in brace or chord at the saddle location
Sipb	In plane bending SCF at the brace or chord side
Sopb	Out of plane bending SCF at the brace or chord side
T	Thickness
t	Time
T_c	Thickness of material
t_c	Time until fracture
t_{eff}	Effective thickness
t_{ref}	Reference thickness
Y	Finite size correction factor
ΔK	Stress intensity factor range
ΔK_a	Stress intensity factor range at crack tip
ΔK_c	Stress intensity factor range at crack edge

Greek symbols

$\Delta\sigma$	Stress amplitude
$\Delta\sigma_{HS}$	Hotspot stress amplitude
σ_m	Membrane stress
σ_b	Bending stress
σ_o	Outside stress
σ_i	Inside stress
σ_y	Yield stress
ν	Poisson ratio
$\rho(a)$	Plasticity correction factor

1 Background

Since the beginning of the oil adventure the search for offshore hydrocarbons has moved to deeper and deeper depths. This has resulted in the development of new technology, such as subsea solutions for the retrieval of hydrocarbons. But during the last ten years the cost for subsea wells has tripled and combined with the record low oil prices, oil & gas companies has again started to look for new and innovate solutions [9]. Statoil's response to this challenge was to develop a new concept called "subsea on a stick." Statoil wants to use this concept on the Oseberg oilfield located in the North Sea, where Kværner is one of the contractors competing for the contract. The concept involves relocating the subsea equipment up to the surface and installing it on an unmanned wellhead platform. When expenditure regarding the equipment, construction, wells and maintenance is included, the total cost would be several millions less than for a traditional subsea solution.

Compared to a regular offshore steel jacket, the unmanned wellhead platform is much slimmer and the structural steel has smaller dimensions. This is because it does not need to carry a large and heavy topside. The downside is that the smaller dimensions come with some extra challenges. The diameters of the bracings are too small for a welder to get on the inside to perform a double sided weld. Therefore Kværner wants to perform single sided welds on some of the joints, which results in positive ergonomically effects as well as a significant reduction in production costs.

Control and approval of welds are required to document the quality of the unmanned wellhead platform. Using methods within NDT, such as ultrasonic testing, inspectors can check for cracks on the inside. For single sided welds the ultrasonic testing is performed from the outside and detecting cracks and initial flaws on the inside is a challenging task. The minimum detectable crack can be found with a probability of 95 %, which is a relatively large probability. In accordance to DNVGL – RP – C203 this minimum detectable crack must have at least a depth of 5 mm [4].

2 Objectives

- Establish a foundation/basis for fatigue assessment on the inside of the weld

  - Analyze the jacket using SN – fatigue and fracture mechanics
  - Generate a FE – model for a more thorough analysis
  - Perform SN – fatigue and fracture mechanics on the FE – model

- Determine whether the critical initial crack size for the required lifespan of the jacket is larger or smaller than the ultrasonic inspection can detect

- Determine the inside design life based on the calculated fatigue life

- Discuss the results from the analyses

- Establish a recommendation for further analyses/investigations

3 Method and execution

The approach in this report is to first identify the most critical joint by performing a global fatigue analysis on a beam model using both SN – fatigue theory and fracture mechanics theory to see if they produce the same result.

Thereafter a FE – model of the critical joint is modelled and integrated in the global model for a more thorough analysis. The FE – model makes it possible for a fatigue analysis on the inside of the weld to be performed by extracting the hotspot stress amplitudes on the inside. But first a SN – fatigue and FM – fatigue analysis on the outside of the FE – model is performed to check if it produces the same results as the beam model. If the results are within the same range the FE – model is a good representation for the joint and a reliable basis for fatigue assessment of the inside is established.

After this check a fatigue analysis on the inside according to DNVGL – RP – C203 [4] will be performed. Thereafter a fracture mechanics analysis on the inside of the FE – model will give the critical crack size and the lifespan of the joint and the jacket.

The global model of the Oseberg UWP jacket as well as all software required for the analyses is provided by Kværner Jacket Technology.

The FE – modelling of the x – joint, which was a major part of the workload, was modelled by the author of this report.

4 The Oseberg UWP

The Oseberg UWP is an unmanned offshore steel jacket designed for production of oil and gas in the North Sea. The UWP jacket is similar to a regular offshore steel jacket used for oil production, except there is no heavy topside installed. Only a light installation for production of hydrocarbons will be permanently located on the topside. Therefore the dimensions of the UWP are much smaller and the construction slimmer.

A jack up rig will temporarily place itself next to the UWP for drilling of the wells and then the production is controlled from onshore.

Planned maintenance is performed approximately every six months by a maintenance crew transported to the jacket by boat. The access for maintenance is easy since the equipment is not subsea and therefore also less expensive.

Table 2: *Jacket key data [12]*

Number of legs	4
Top of jacket geometry	14m x 14m
Bottom of jacket geometry	38m x 38m
Number of piles	8 x Ø84” at 36 meters into sea bottom
Topside interface	25 meters above sea level
Topside minimum weight	400 tonnes
Topside maximum weight	800 tonnes
Design life	25 years
Water depth	108 m
Maximum 100 year design wave	28 m
Material quality	F_y = 355MPa

The UWP is subjected to different load types during its operational time. These loads are environmental loads such as waves, current, wind and earthquake. It could also be subjected to accidental loads due to vessel impact. But in this report only fatigue damage during normal operational mode is taken into consideration to determine the lifespan of the structure. During normal operational mode, wave loads is the primary contributor to fatigue damage. Statistical data regarding wave heights and directions from the installation location is therefore used in the fatigue analysis. See **Appendix 18.1** for a wave rose from the installation area.

Figure 1: An illustration of the UWP and an offshore maintenance vessel at the Oseberg field [12]

5 Fatigue

5.1 Introduction to fatigue

"The word *fatigue* originated form the Latin expression *fatigare,* which means to tire" [10]. Fatigue is generally referred to as a process in which damage is accumulated in a material undergoing fluctuating or cyclic loading and eventually resulting in a failure even if the varying stress range is well below the yield strength of the material [6]. The cyclic loading can cause fatigue failure in different types of materials which is receptive to crack growth, such as metallic alloys, polymers and composites. For fatigue to occur in any of these materials there must exist an initial crack of a certain size. Fatigue is a progressive process in which the damage or the crack size develops slowly in the early stages and accelerates quickly towards the end. During the crack growth the cross sectional area of the component will decrease and therefore the local stress will increase and this will eventually cause failure/fracture. A simple measure of fatigue is the size of the crack, but it will only be easily measurable at the late stage in life of the component. Usually the early phase with crack initiation may occupy 90 – 95 percent of the total lifetime before failure.

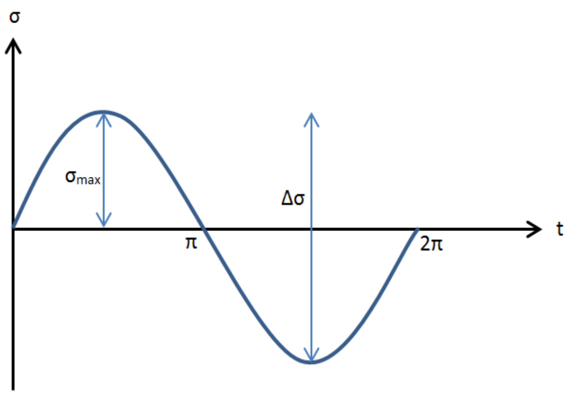


Figure 2: Stress amplitude and period

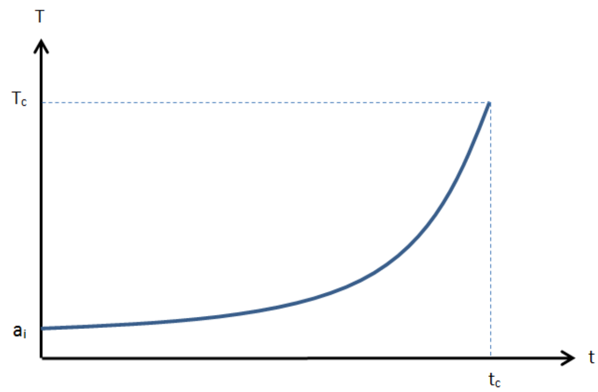


Figure 3: Crack growth curve

During the fatigue lifetime of a component there are several stages the propagation of damage can be divided into [10]:

1. "Substructural and microstructural changes which cause nucleation of permanent damage."
2. "The creation of microscopic cracks."
3. "The growth and coalescence of microscopic flaws to form "dominant" cracks, which eventually lead to catastrophic failure. (From a practical standpoint, this stage of fatigue generally constitutes the demarcation between crack initiation and propagation.)"
4. "Stable propagation of the dominant crack."
5. "Structural instability or complete fracture."

How and how fast the nucleation and microdefects will propagate and form the dominant crack, which further on will propagate and cause fracture, is highly dependent on a wide range of mechanical, microstructural and environmental factors, as well as the load frequency and stress amplitude.

5.2 Total – life approach (SN-fatigue/Miner-Palmgren approach)

There are two main approaches to fatigue design. The classical and most used is the *Total - life approach* or Miner – Palmgren as named after the inventor A. Palmgren and popularised by M. A. Miner. This approach is based on stress amplitude – life curves or better known as SN-curves to calculate fatigue life.

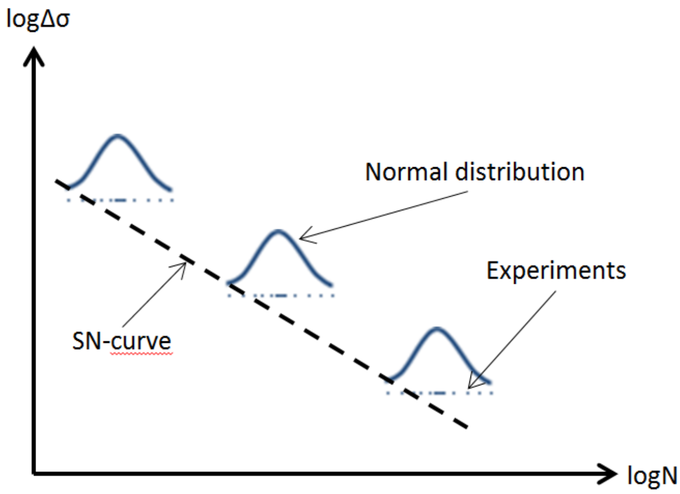


Figure 4: SN-curve generated by experiments

SN – curves are based on experimental data, gathered from several experiments performed in a laboratory. The way they are derived is by subjecting test pieces to a cyclic load with the same amplitude until fatigue limit is reached and fracture occurs. The number of cycles until fracture is registered. This is done for several test pieces and a normal distribution will develop. Then the load amplitude is altered and the same procedure is performed. The SN – curve is drawn by subtracting two standard deviations to the left for all the normal distributions and then drawing a line through all the points. This way around 97,5 % are on the right side of the curve, which implies that 2,5 % will fail. A DFF is therefore implemented as a safety barrier, see chapter **5.4 DFF**. Based on the profile, joint type with or without cathodic protection, environment etc. there are different SN – curves.

For constant load amplitude the SN – curve directly gives the number of cycles to failure. For a given stress range Δσ, the number of cycles, N, until failure is determined by going in to the SN – curve as shown in **Figure 6**.

The equation describing the curve is:

$$logN = log\bar{a} - m * log\Delta\sigma \rightarrow N = \bar{a}(\Delta\sigma)^{-m}$$ **Equation 1**

The test pieces used for deriving the SN-curves had a standard thickness. The reference thickness for tubular joints is 32 mm and for plane joints 22 mm [1]. When increasing the thickness of the structure the fatigue life will decrease. As mentioned earlier fatigue is related to cracks and when the thickness increases the probability of cracks being present in the structure also increases. Meaning statistically there will be more cracks in a thicker structure. Also the stress at the crack tip will be higher in a thicker plate, resulting in a shorter fatigue life, see **Figure 5**. This effect is automatically accounted for in fracture mechanic analysis, but for SN – fatigue an empiric formulation is given to increase the effective stress.

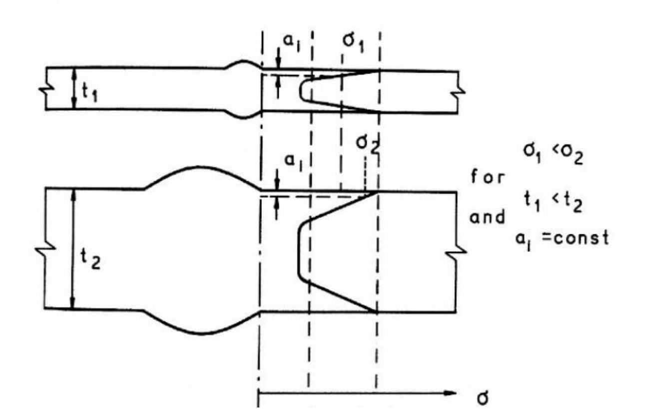


Figure 5: The crack tip in the thicker plate will experience a higher stress causing a shorter fatigue life [1]

Therefore this effect needs to be taken into account using the thickness effect formula:

$$t_{eff} = (\frac{T}{t_{ref}})^{0,25}$$ **Equation 2**

The above situation is not likely for a real life situation. In a real life situation the stress range would be distributed according to the corresponding number of cycles they occur. Therefore the contribution from all the different stress ranges needs to be summed up to calculate the total fatigue life.

The total fatigue damage is calculated by the Miner – Palmgren formula:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}$$ **Equation 3**

When the accumulated damage ratio, $D = 1$, the Minor – Palmgren formula assumes fracture. The usual criterion is $D \leq 1$, but usually a DFF is predetermined for each case.

The calculated fatigue life is then calculated as:

$L = \frac{L_0}{D}$ **Equation 4**

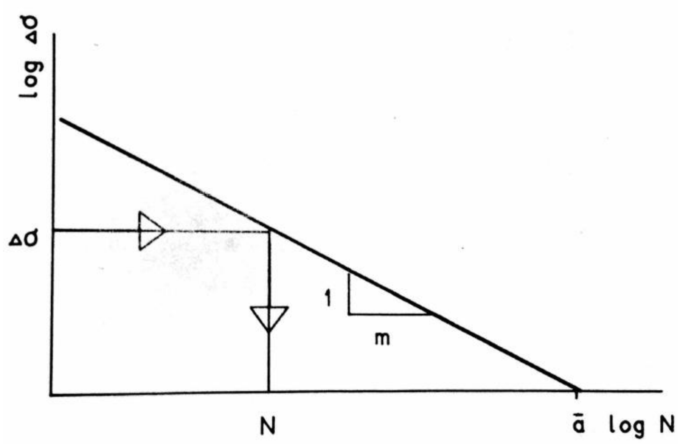


Figure 6: Number of cycles to failure for a constant stress amplitude [1]

As shown in **Figure 7** the stress distribution is divided into stress blocks. The damage corresponding to the number of cycles within each block is calculated and the summation is carried out using the Miner – Palmgren formula (**Equation 3**).

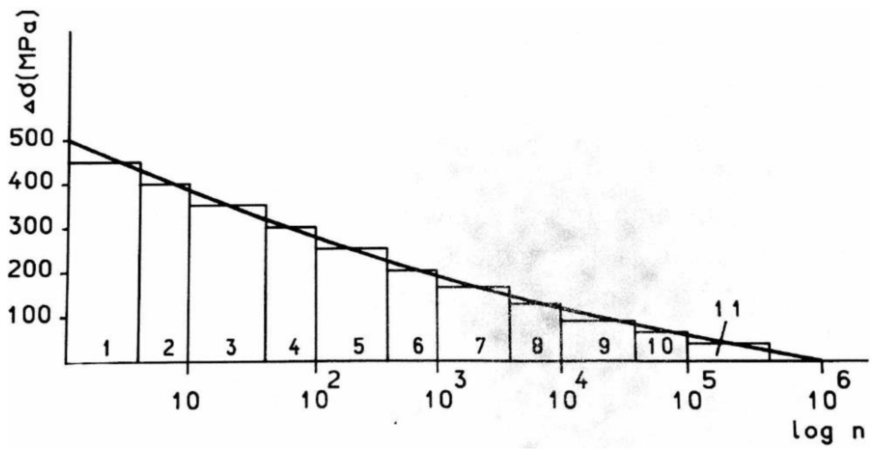


Figure 7: Stress amplitudes divided into blocks [1]

The Δσ is easy to calculate if the structure is uniform with an even cross sectional area, but often the geometry is more complex. The stress distribution will therefore not be uniformly distributed and a hotspot stress will occur. To calculate the hotspot stress, the nominal stress is multiplied with a SCF, which is calculated using Efhymiou's parametric equations [4], depending on the type of situation.

$\Delta\sigma_{HS} = SCF * \Delta\sigma$ **Equation 5**

5.3 Defect - tolerant approach (fracture mechanics)

The other approach is called *Defect – tolerant approach* which relies on fracture mechanics. Fracture mechanics is the study of crack propagation in solid materials using mathematics and theories within solid mechanics. Using these methods the speed of the crack growth through a material can be described and the fatigue life of the structure is determined. There are two different approaches to fracture mechanics, LEFM and EPFM depending on the type of situation. LEFM is used when analysing materials with relatively low fracture resistance which will fail when exposed to cyclic loads well below their tensile strength. The LEFM approach will be used in this report [3].

In the LEFM approach crack growth (a) per cycle (N) is described by Paris law [10]:

$$\frac{da}{dN} = C(\Delta K)^m \qquad \textbf{Equation 6}$$

The ratio da/dN describes the change in length of the fatigue crack per load cycle. The terms C and m are empirical constants which are functions of material properties, microstructure, loading mode, fatigue frequency, load ratio, environment and temperature. ΔK is the stress intensity factor range and is expressed as:

$$\Delta K = K_{max} - K_{min} \qquad \textbf{Equation 7}$$

where K_{max} and K_{min} correspond to the maximum and minimum load expressed as:

$$K_{max} = Y\sigma_{max}\sqrt{\pi a} \qquad \textbf{Equation 8}$$

$$K_{min} = Y\sigma_{min}\sqrt{\pi a} \qquad \textbf{Equation 9}$$

Y is the finite size correction factor and a is the crack depth.

By solving the integral of **Equation 6**:

$$N = \int_{a_i}^{a_f} \frac{da}{C(\Delta K)^m}$$

the number of cycles (N) to fracture can be found and the fatigue life is determined.

For this report the following approach and formulas will be used to calculate the fatigue life [8].

$$\frac{da}{dN} = C\Delta {K_a}^m \qquad \textbf{Equation 10}$$

$$\frac{dc}{dN} = C\Delta {K_c}^m \qquad \textbf{Equation 11}$$

Equation 10 and **Equation 11** describe the crack growth depth (a) and crack growth width (c) per cycle (N), see **Appendix 18.11** for a sketch. The stress intensity factor is based on evaluating the shape factor for a plate and then a correction factor for weld toe magnification is specified for a tubular joint configuration.

There are two fracture types, brittle and plastic fracture. Brittle fracture occurs when the crack grows spontaneously without any prior apparent plastic deformation and the stress intensity factor at the crack tip exceeds the material toughness. Plastic collapse occurs when deformation takes place ahead of the crack and the crack is growing in a controlled manner through the thickness of the material. This is the preferred collapse type. Material toughness is expressed as:

$$K_{mat} = \sqrt{\frac{2\sigma_y E * CTOD}{1-\upsilon^2}} \qquad \textbf{Equation 12}$$

In order to assess the risk of brittle fracture a fracture ratio is defined. The fracture ratio expressed as:

$$K_r = \frac{K_I}{K_{mat}} + \rho(a) \qquad \textbf{Equation 13}$$

ρ(a) is a plasticity correction factor that takes into account the residual stresses in the material. K_I is the total stress intensity factor. If $K_r > 1.0$ brittle fracture will occur. But the value 1.0 is reduced by the critical fracture ratio, K_{rmax}, which is expressed as:

$$K_{rmax} = (1 - 0{,}14L_r^2)\left(0{,}3 + 0{,}7e^{-0{,}65L_r^6}\right),\ L_r < 1{,}0 \qquad \textbf{Equation 14}$$

Fracture will occur when $K_r \geq K_{rmax}$

The load ratio, L_r must be lower than 1,0 otherwise **Equation 14** is not valid. The load ratio is defined as:

$$L_r = \frac{P}{P_c RF_a} \qquad \textbf{Equation 15}$$

where RF_a is the reduction factor defined as:

$$RF_a = \left(1 - \frac{Cracked\ area}{Total\ area}\right)$$ **Equation 16**

The cracked area is calculated as:

$$Cracked\ area = \frac{1}{2}\pi ac$$ **Equation 17**

P is the applied load and P_c is the critical load.

The DOB factor accounts for the stress not being constant over a cross section when being subjected to bending. It has a value between 0 – 1,0. The DOB is the ratio of stress contribution from bending compared to the total stress and is expressed as:

$$DOB = \frac{\sigma_b}{\sigma_m + \sigma_b}$$ **Equation 18**

The stress intensity factor for **Equation 10** and **Equation 11** is as follows:

$$\Delta K_a = [M_{ma}Mk_{ma}(1 - DOB) + M_{ba}Mk_{ba}DOB]\Delta\sigma_{HS}\sqrt{a\pi}$$ **Equation 19**

$$\Delta K_c = [M_{mc}Mk_{mc}(1 - DOB) + M_{bc}Mk_{bc}DOB]\Delta\sigma_{HS}\sqrt{a\pi}$$ **Equation 20**

Equation 18 is inserted in **Equation 19** and **Equation 20.** The M and Mk factors are a function of the crack growth a, and based on curve fitting of results from a 3D FE-model comprising the weld geometry. The shape and magnification factors are also dependent on the crack growth, which is constantly increasing during the load cycles, therefore these factors are solved for each increment of the crack growth. The factors are calculated in accordance to "Fracture mechanics assessment of fatigue cracks in offshore tubular steel structures" [2]. The increment calculation is done by the fatigue analysis software DETFAT.

The crack growth parameters C and m, defining the crack growth velocity are important parameters. In the standard BS7910 [11] there are a number of different proposals provided for the calculation of these depending on various factors such as load ratio, environment and the need for accuracy. But a major drawback is that the parameters defined for sea water are considered to produce overly conservative results compared to the SN – fatigue approach. In order to overcome this problem a study by Kværner has been performed to evaluate the crack growth parameters [8]. The approach was to equilibrate the parameters to a corresponding SN – curve. For example the slope of the SN – curve corresponded to the parameter m in the Paris law. Then the remaining parameter C was found on the basis of the two approaches having equal fatigue lives. This way the results found are not extremely conservative and will be approximately the same as a corresponding SN – fatigue analysis. This will lead to a more cost effective design.

5.4 DFF

To design for adequate fatigue life a design fatigue factor is implemented. In both SN – fatigue and fracture mechanics there is uncertainty involved. The design fatigue factor is implemented to reduce this uncertainty [5].

The DFF usually has a value between 1,0 and 10,0 depending on the criticality of the joint, consequence of a fatigue failure and the possibility for IMR.

6 The Poisson effect and β - ratio

When a material is exposed to an axial load in one direction, it will try to deflect perpendicular in the two other directions. This Phenomenon is called the Poisson effect and is denoted by *v*. This effect can cause different stress distributions through the material.

For a pipe fully fixed to a plate subjected to an axial load the stress on the outside will be greater than the stress on the inside, due to the Poisson effect. The pipe wall will displace outwards/inwards depending on the load direction resulting in bending stress and axial stress. This is true for a plate or when the diameter of the plate is high compared to the pipe fixed on the plate. This ratio is called β. The β – ratio is a number between 0 and 1 [5].

$$\beta = \frac{d}{D}$$ **Equation 21**

For β – values lower than 0,90 normally $\sigma_o > \sigma_i$
For β – values going towards 1,0 → $\sigma_o \approx \sigma_i$

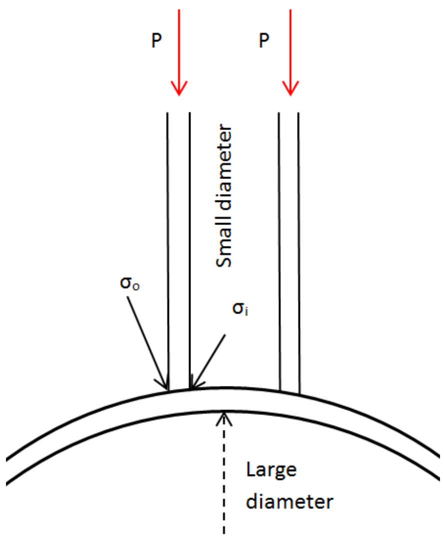


Figure 8: Low β – value

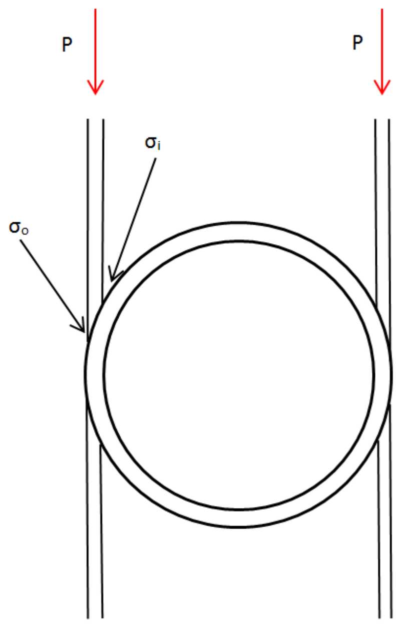


Figure 9: High β – value

7 DETFAT

7.1 Description of DETFAT

DETFAT is a fatigue analysis software developed by Kværner Jacket Technology to calculate the fatigue life of offshore steel jackets and other structures. The software uses input information from Sestra such as material properties, geometrical data and the rigidness of the structure. The jacket is modelled in Sestra and environmental loads are also applied there. The environmental data is based on statistical data for the installation location. An analysis with the wave loads applied on the jacket is run, which provides an output file containing information about the member forces in the jacket. This file is then inserted into DETFAT which calculates stresses at 24 points during one wave cycle in all the joints. This is done for 9 wave heights ranging from 2 – 24 meters and 12 equidistant wave angles (every 30 degree). This will give 2592 (9*12*24) different load cases. Based on these load cases, SCF's and a suitable SN – curve or fracture mechanics, DETFAT calculates the fatigue life. The software displays numerical results and relevant graphs are plotted manually [7].

The stresses in DETFAT are calculated by:

$$\sigma(\beta) = \frac{F_X}{A_X} * \sqrt{(Sc * cos\beta)^2 + (Ss * sin\beta)^2} + \frac{M_y}{I_y} * r * Sipb * cos\beta + \frac{M_Z}{I_Z} * r * Sopb * sin\beta$$

Equation 22

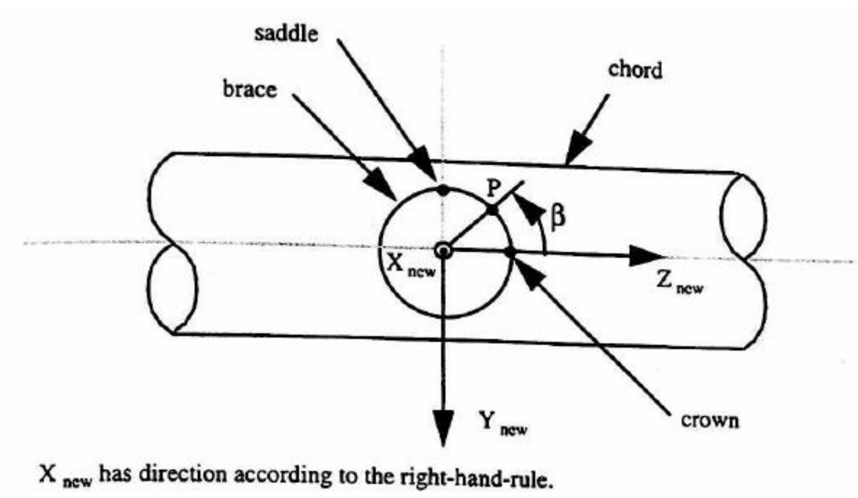


Figure 10: Definition of transformed axis system and angle β

DETFAT then creates a stress plot based on 24 points during the wave cycle as seen in **Figure 11.**

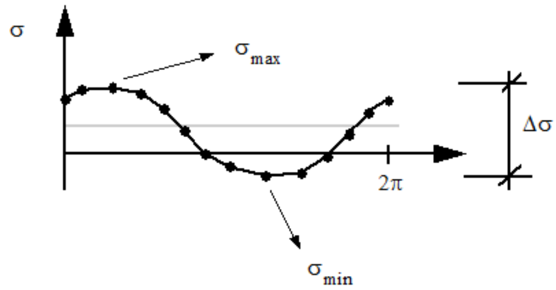
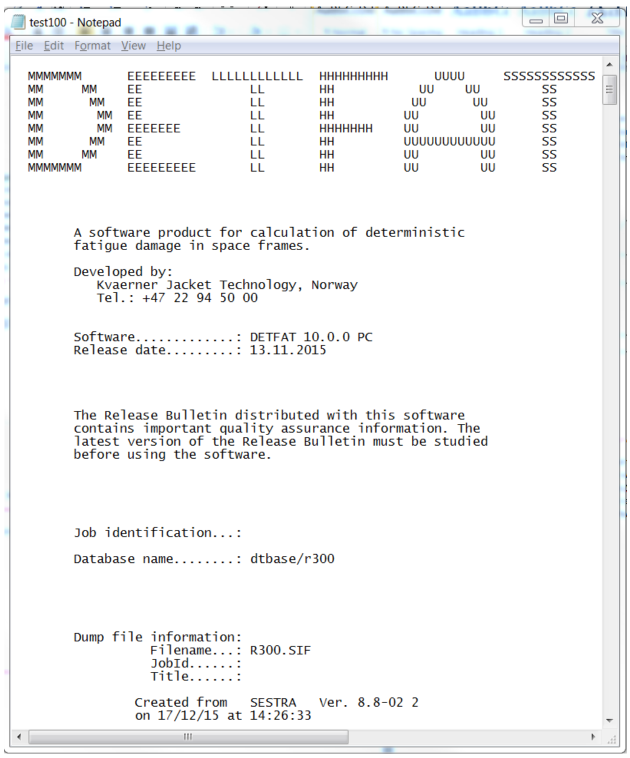


Figure 11: Stress variation at a given point in the structure as the wave passes by.

The software DETFAT will read an appropriate input file and perform fatigue analysis as requested, fracture mechanics or ordinary SN – fatigue. The input files are edited in notepad and run in the Windows Command Prompt, as can be seen in **Appendix 18.3**



test100 - Notepad
File Edit Format View Help

```
MMMMMMM      EEEEEEEEE  LLLLLLLLLLLL  HHHHHHHHH      UUUU      SSSSSSSSSSSS
MM     MM    EE                LL     HH          UU    UU          SS
MM      MM   EE                LL     HH         UU      UU         SS
MM       MM  EE                LL     HH        UU        UU        SS
MM       MM  EEEEEEE           LL     HHHHHHH   UU        UU        SS
MM      MM   EE                LL     HH        UUUUUUUUUUUU        SS
MM     MM    EE                LL     HH        UU        UU        SS
MMMMMMM      EEEEEEEEE         LL     HH        UU        UU        SS

      A software product for calculation of deterministic
      fatigue damage in space frames.

      Developed by:
         Kvaerner Jacket Technology, Norway
         Tel.: +47 22 94 50 00

      Software.............: DETFAT 10.0.0 PC
      Release date.........: 13.11.2015

      The Release Bulletin distributed with this software
      contains important quality assurance information. The
      latest version of the Release Bulletin must be studied
      before using the software.

      Job identification...:

      Database name........: dtbase/r300

      Dump file information:
                Filename...: R300.SIF
                JobId......:
                Title......:

              Created from    SESTRA   Ver. 8.8-02 2
              on 17/12/15 at 14:26:33
```

Figure 12: Front page of a typical output file [7]

7.2 SN – fatigue approach

The fatigue contribution from all the different wave heights and directions during one year is added up using the Miner – Palmgren's rule. The fatigue evaluation is performed for all activated joints and DETFAT will report fatigue lives for the different joints in sorted order [7].

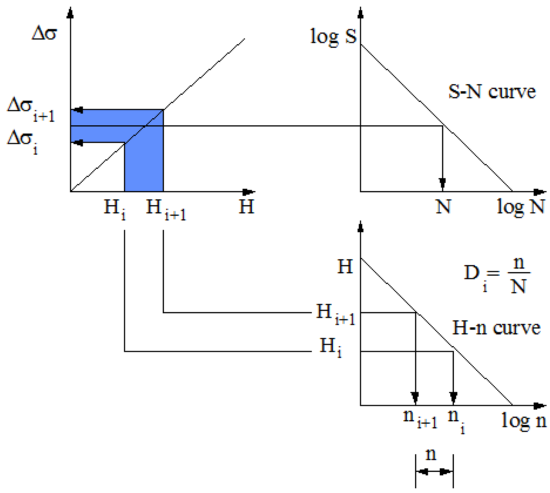


Figure 13: the basic concept of how DETFAT performs SN – fatigue [7]

The H – n curve describes the long term distribution of wave heights at the location of where the jacket is to be installed. The Δσ – H curve is generated by DETFAT based on the member forces caused by wave loads, which is calculated by Sestra using hydrodynamic equations. The S – N curve is already an input in the software. In this report the SN – curve T (tubular joint) for seawater with cathodic protection is chosen [4], see **Appendix 18.9**.

7.3 Fracture mechanics approach

By some simple updates of the input file of DETFAT a fracture mechanics evaluation can be performed using the principles as outlined in chapter **5.3 Defect - tolerant approach (fracture mechanics)**.

DETFAT can also perform fatigue analysis based on stresses obtained by an FE – analysis.

8 Identifying the critical x-joint using SN – fatigue

In order to identify the most critical joint connection an SN – fatigue analysis for all the joints was performed. The three most critical x – joints are listed in **Table 3** and their corresponding dimensions in **Table 4** The fatigue analysis is performed on a beam model with a T – curve in seawater with cathodic protection, see **Appendix 18.9**. The fatigue life results are therefore calculated on the outside of the pipe based on σ_o.

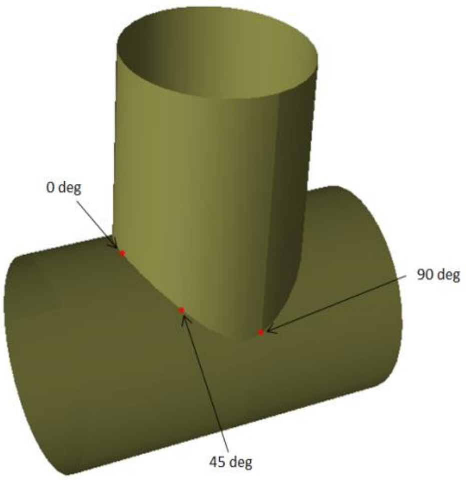


Figure 14: ISO – view of a T - joint

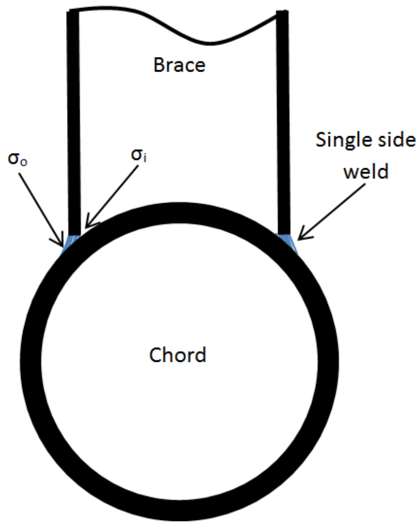


Figure 15: cross sectional view of a T - joint

Table 3: fatigue damage results

Joint	Chord	Brace	Wave direction	Point [deg]	Damage [per year]	Life [years]	Side
JtRw2_21	Rw2_226	Rw2_216	All	270,0	0,002105	475,0	Chord
JtRw1_31	Rw1_316	Rw1_327	All	45,0	0,001857	538,4	Brace
JtRw2_21	Rw2_226	Rw2_217	All	90,0	0,001822	548,8	Chord

Table 4: joint dimensions

Joint	Chord	Brace	Joint type	D_C [m]	T [m]	D_B [m]	t [m]	Angle [deg]	β [d/D]
JtRw2_21	Rw2_226	Rw2_216	X	0,840	0,055	0,700	0,020	85,091	0,83
JtRw1_31	Rw1_316	Rw1_327	X	0,770	0,050	0,700	0,015	89,578	0,91
JtRw2_21	Rw2_226	Rw2_217	X	0,840	0,055	0,700	0,020	85,091	0,83

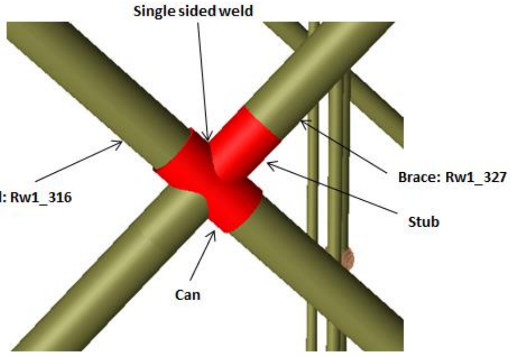


Figure 16: JtRw1_31

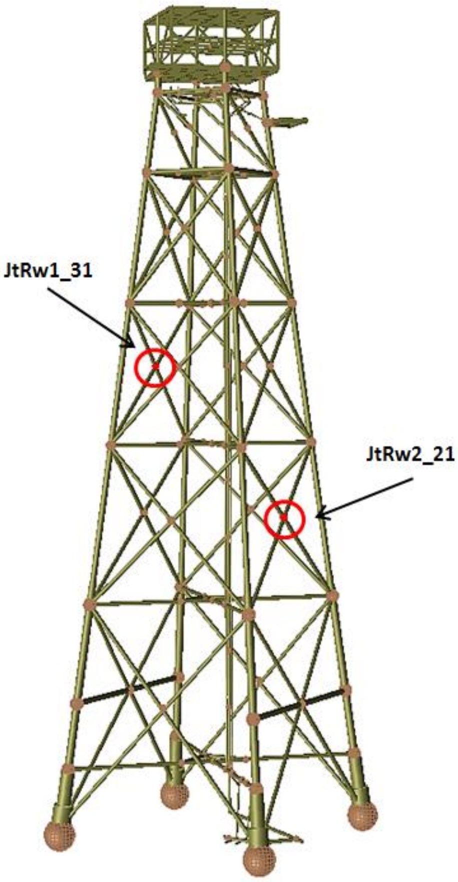


Figure 17: Overview of the Oseberg UWP and its two most critical joints

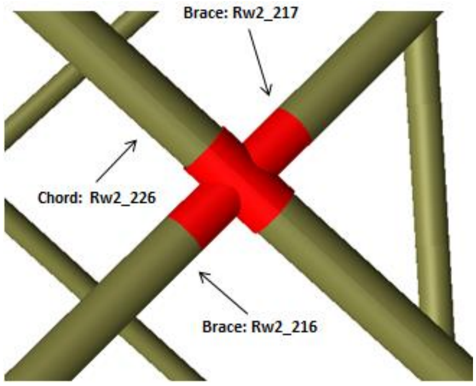


Figure 18: JtRw2_21

JtRw2_21 has the lowest calculated fatigue life of 475 years and a β – value of 0,83. JtRw1_31 with a fatigue life of 538 years and a β – value of 0,91 is identified to be the most critical x – joint since it has the highest β – value, and therefore the stress on the inside is closer to the outside stress because of the Poisson effect, see chapter **6 The Poisson effect and β - ratio**. This joint is chosen for further analysis in this report since the inside stresses will be used when calculating fatigue life on the inside. Both joints are within the design life of 25 years by a factor of 19 (475/25).

β – value for JtRw2_21: $\beta = \frac{d}{D} = \frac{0,7}{0,84} = 0,83$

β – value for JtRw1_31: $\beta = \frac{d}{D} = \frac{0,7}{0,77} = 0,91$

A detailed overview of what point on the brace which has the lowest fatigue life is given in **Table 5**.

Table 5: point fatigue damage results from JtRw1_31

Joint	Chord	Brace	Wave direction	Point [deg]	Damage [per year]	Life [years]	Side
JtRw1_31	Rw1_316	Rw1_327	All	0,0	0,000268	3731,4	Chord
JtRw1_31	Rw1_316	Rw1_327	All	0,0	0,001310	763,1	Brace
JtRw1_31	Rw1_316	Rw1_327	All	45.0	0,000793	1260,3	Chord
JtRw1_31	Rw1_316	Rw1_327	All	45,0	0,001857	538,4	Brace
JtRw1_31	Rw1_316	Rw1_327	All	90,0	0,001169	855,7	Chord
JtRw1_31	Rw1_316	Rw1_327	All	90,0	0,001831	546,1	Brace
JtRw1_31	Rw1_316	Rw1_327	All	135,0	0,000381	2627,2	Chord
JtRw1_31	Rw1_316	Rw1_327	All	135,0	0,001001	999,0	Brace
JtRw1_31	Rw1_316	Rw1_327	All	180,0	0,000057	17427,1	Chord
JtRw1_31	Rw1_316	Rw1_327	All	180,0	0,000468	2137,6	Brace
JtRw1_31	Rw1_316	Rw1_327	All	225,0	0,000117	8512,6	Chord
JtRw1_31	Rw1_316	Rw1_327	All	225,0	0,000442	2263,1	Brace
JtRw1_31	Rw1_316	Rw1_327	All	270,0	0,000345	2898,5	Chord
JtRw1_31	Rw1_316	Rw1_327	All	270,0	0,000696	1436,6	Brace
JtRw1_31	Rw1_316	Rw1_327	All	315,0	0,000316	3169,2	Chord
JtRw1_31	Rw1_316	Rw1_327	All	315,0	0,000970	1030,8	Brace

The two points highlighted have the lowest fatigue life and are most critical for the joint. The point located at 45,0 degrees on the brace side has a fatigue life of 538,4 years. The point located at 90,0 degrees has a fatigue life of 546,1 years, a difference of 7,7 years which is negligible when it comes to fatigue calculations. With increasing β – value the difference in stresses would affect the point at 90 degrees more than the one at 45 degrees, see chapter **6 The Poisson effect and β – ratio**. Therefore the point at 90,0 degrees is chosen for further analysis.

Waves coming from direction 270 degrees (north, see **Appendix 18.2**) give the highest hotspot stress amplitude in point 90 degrees on the brace side of the x – joint, see **Figure 20**. This corresponds well to wave rose which says that 21 percent of the waves comes from direction 270, see **Appendix 18.1**. With less than half the number of waves coming from direction 330 (west – north west), this result in 87,1 MPa lower hotspot stress amplitude, see **Figure 19**.

The difference in the hotspot stress amplitude is not significant, but the fatigue damage for waves coming from direction 270 is still much greater. The reason for this is that 21 percent of the waves come from this direction and only 8 percent from direction 330. This means that the number of waves in the fatigue contribution range is higher as well. This can be seen by comparing **Figure 21** and **Figure 22**. The bulk of fatigue damage is due to waves in the range of 6 – 13 meters as indicated in **Figure 23** and **Figure 24**.

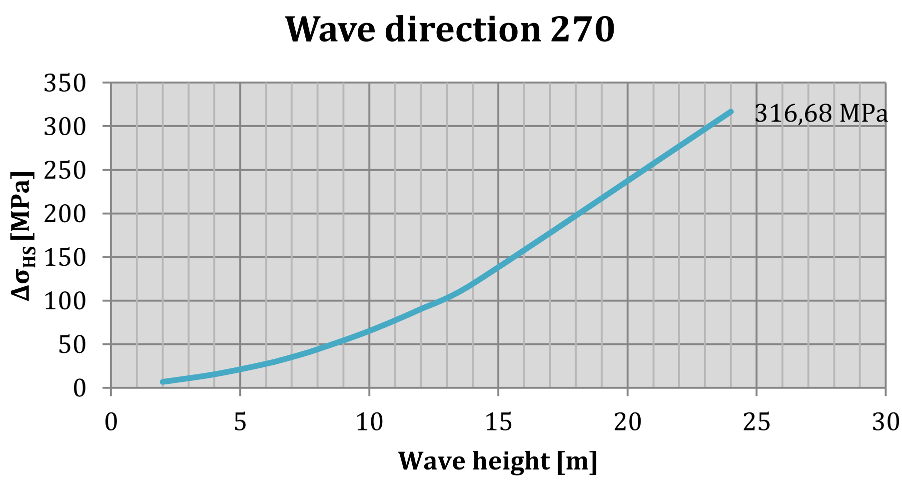


Figure 20: Hotspot stress - wave height 90 degrees on the brace side from wave direction 270

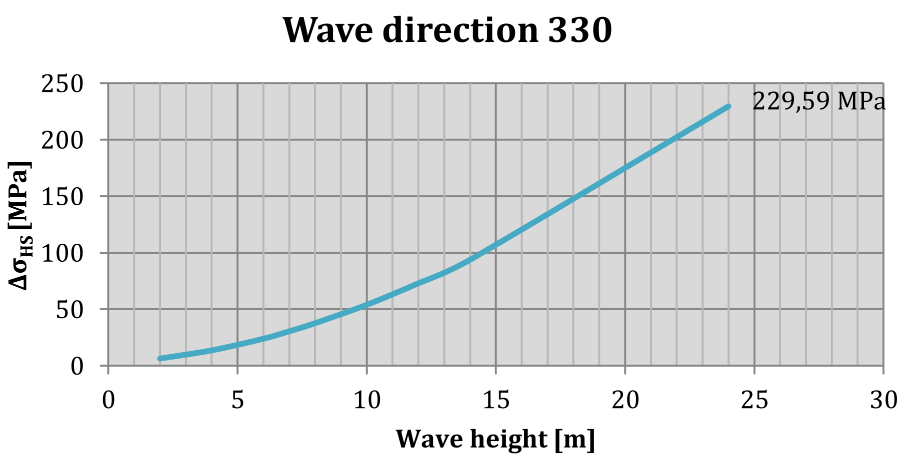


Figure 19: Hotspot stress - wave height 90 degrees on the brace side from wave direction 330

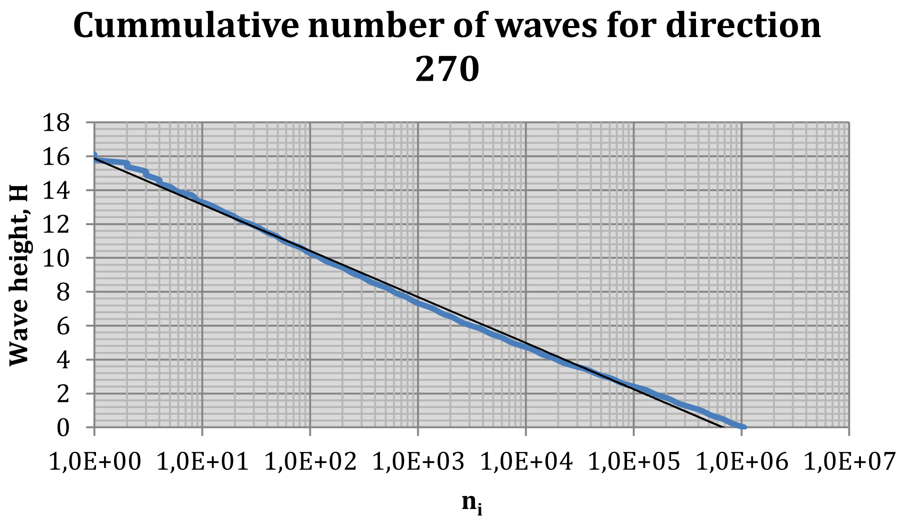


Figure 22: environmental data, number of waves coming in from direction 270 degrees

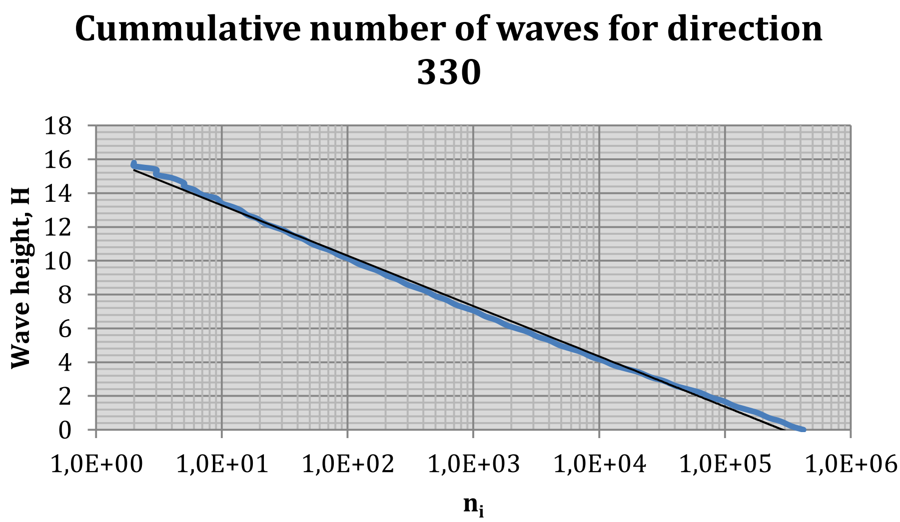


Figure 21: environmental data, number of waves coming in from direc-tion 330 degrees

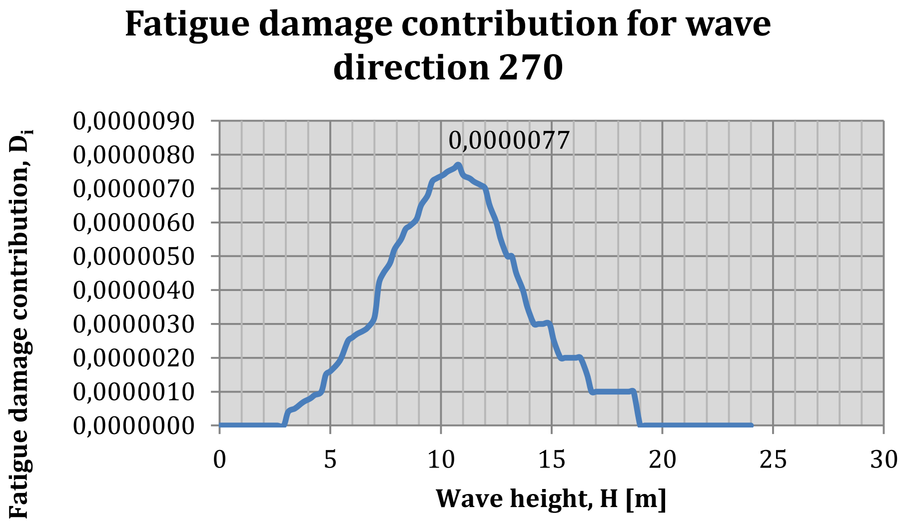


Figure 24: Fatigue damage contribution from wave direction 270 degrees

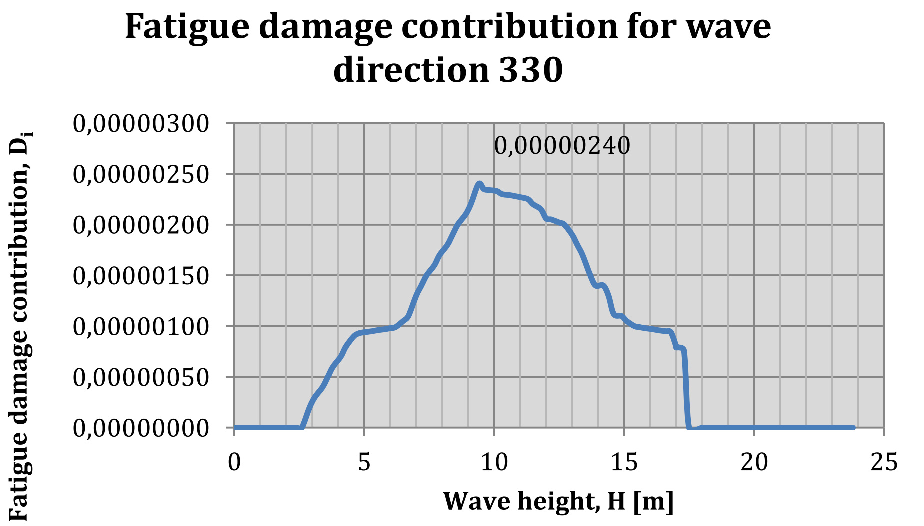


Figure 23: Fatigue damage contribution from wave direction 330 degrees

By summing up the fatigue damage contribution from all the wave heights during one year (area under the fatigue damage contribution graphs), the accumulated damage from wave direction 270 degree is 0,000234 and 0,000088 for wave direction 330 degree, which means the contribution is 2,66 (0,000234/0,000088) times greater for wave direction 120 degree.

8.1 Short summary

Using SN – fatigue on the beam model, joint JtRw1_31 with has a maximum calculated fatigue life of 546 years in point 90,0 degrees on brace side. The β – value is 0,91. This joint is chosen for further analysis.

9 Fracture mechanics on JtRw1_31

A fracture mechanics analysis on the critical x – joint JtRw1_31 identified in chapter **8 Identifying the critical x-joint using SN – fatigue** is performed in DETFAT. A beam model is the basis for the analysis and therefore the calculations are based on the outside hotspot stress, σ_o. By changing the input file DETFAT utilizes equations from fracture mechanics theory to calculate crack growth and fatigue life.

The input parameters used in the analysis are listed in **Table 6**.

Table 6: input parameters used for a fracture mechanics analysis in DETFAT

Input parameters	Value
Initial crack depth, a_i	3,0 mm
Initial half crack width, c	7,5 mm
Weld angle	60 degrees
Crack growth constant, C (stage A)	1,44*10^-17
Crack growth exponent, m (stage A)	5,0
Crack growth constant, C (stage B)	1,53*10^-12
Crack growth exponent, m (stage B)	3,0
Yield Stress	355 MPa
Ultimate stress	470 MPa
Material CTOD value	0,25 mm
DOB	0,33

The initial crack depth, initial half crack width, crack growth constants and crack growth exponents are chosen on the basis of the "Fracture Mechanics Evaluation Report" so they correspond to the safety level of a SN – curve, which means 2,5 % will fail [8]. The DOB factor (0,33) is automatically calculated by DETFAT.

A detailed overview of the most critical point on the joint is listed in **Table 7**. DETFAT is programed to stop calculating fatigue life if it reaches 620 years.

Table 7: fracture mechanics results

Joint	Chord	Brace	Point [deg]	Depth, a [mm]	Width, c [mm]	Cycles ,N	Life [years]	Side
JtRw1_31	Rw1_316	Rw1_327	0,0	3,88	12,31	3062897664	620.0	Chord
JtRw1_31	Rw1_316	Rw1_327	0,0	15,00	234,29	2825502208	571.6	Brace
JtRw1_31	Rw1_316	Rw1_327	45,0	8,45	26,74	3062897664	620.0	Chord

JtRw1_31	Rw1_316	Rw1_327	45,0	15,00	229,86	1976637312	400,0	Brace
JtRw1_31	Rw1_316	Rw1_327	90,0	22,07	62,52	3062897664	620,0	Chord
JtRw1_31	Rw1_316	Rw1_327	90,0	15,00	234,98	2025621888	410,0	Brace
JtRw1_31	Rw1_316	Rw1_327	135,0	4,38	14,52	3062897664	620,0	Chord
JtRw1_31	Rw1_316	Rw1_327	135,0	10,08	37,85	3062897664	620,0	Brace
JtRw1_31	Rw1_316	Rw1_327	180,0	3,11	8,41	3062897664	620,0	Chord
JtRw1_31	Rw1_316	Rw1_327	180,0	4,24	11,59	3062897664	620,0	Brace
JtRw1_31	Rw1_316	Rw1_327	225,0	3,28	9,43	3062897664	620,0	Chord
JtRw1_31	Rw1_316	Rw1_327	225,0	3,80	10,26	3062897664	620,0	Brace
JtRw1_31	Rw1_316	Rw1_327	270,0	3,92	12,59	3062897664	620,0	Chord
JtRw1_31	Rw1_316	Rw1_327	270,0	4,53	12,37	3062897664	620,0	Brace
JtRw1_31	Rw1_316	Rw1_327	315,0	4,08	13,21	3062897664	620,0	Chord
JtRw1_31	Rw1_316	Rw1_327	315,0	9,09	30,42	3062897664	620,0	Brace

As calculated using SN – fatigue in chapter **8 Identifying the critical x-joint using SN – fatigue**, the same two points highlighted in **Table 7** are found to be the most critical points on the x – joint. The point 45,0 degrees on the brace side with a fatigue life of 400 years is the lowest, but point 90,0 degrees on the brace side with a fatigue life of 410 years is identified as the most critical point. The difference in fatigue life is 10 (410 – 400) years which is negligible in terms of fatigue calculations. Also the high β – value is the reason for choosing point 90 degrees. This is because the hotspot stress on the inside will become equal to the outside hotspot stress with increasing β – value, see chapter **6 The Poisson effect and β – ratio**.

Data results from the analysis of point 90 degrees on the brace side are presented below.

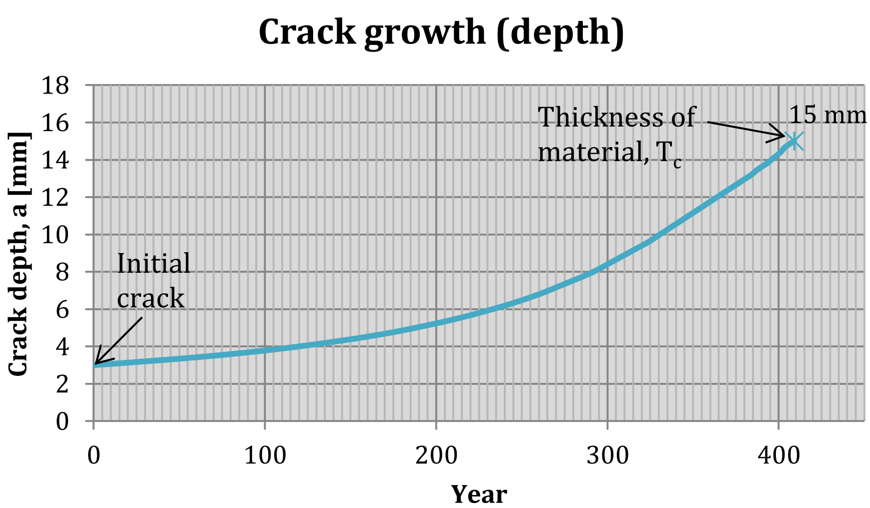


Figure 25: Crack growth on brace side at saddle location, i.e point 90 degree

The crack growth depth curve propagates as expected with an accelerated growth towards the end.

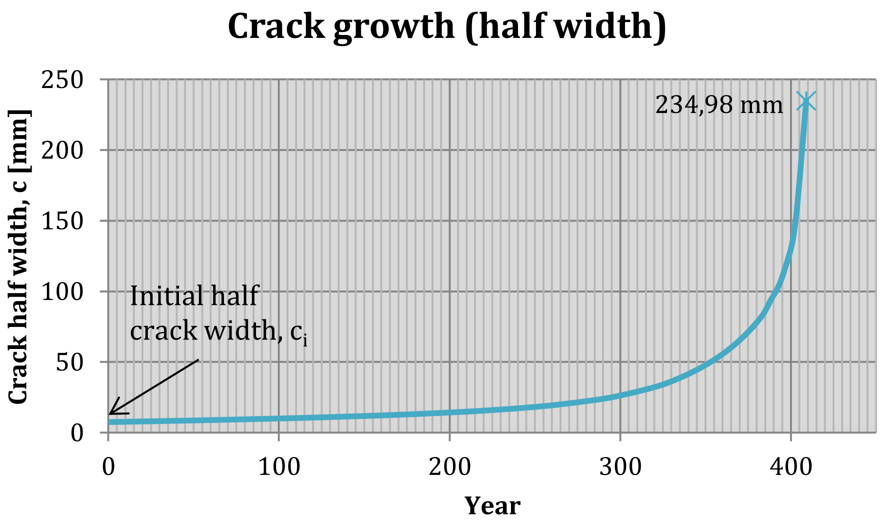


Figure 26: Crack growth half width in point 90 degrees on the brace side

The crack growth half width curve also propagates as expected with an accelerated growth towards the end. The total length of the width of the crack is 470 mm (2*234,98) and the total length of the weld is 2474 mm. This indicates that the failure is caused by a through thickness crack as indicated in **Figure 25**.

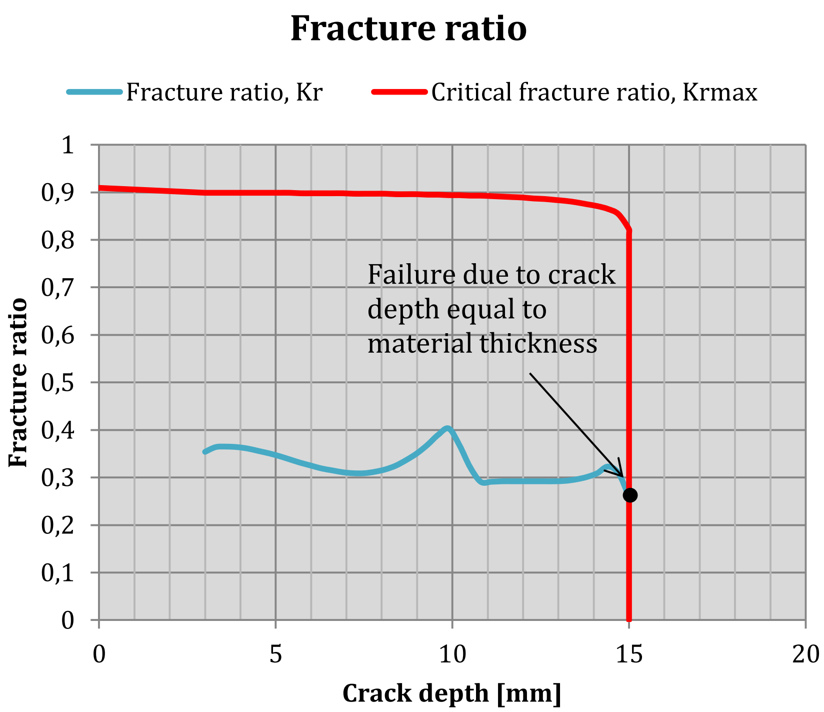


Figure 27: Fracture ratio as a function of crack depth

The fracture ratio plot in **Figure 27** shows the critical fracture ratio, K_{rmax}, and the fracture ratio, K_r, as a function of crack depth. When the critical fracture ratio is equal to the fracture ratio, the fatigue life of the x – joint is reached.

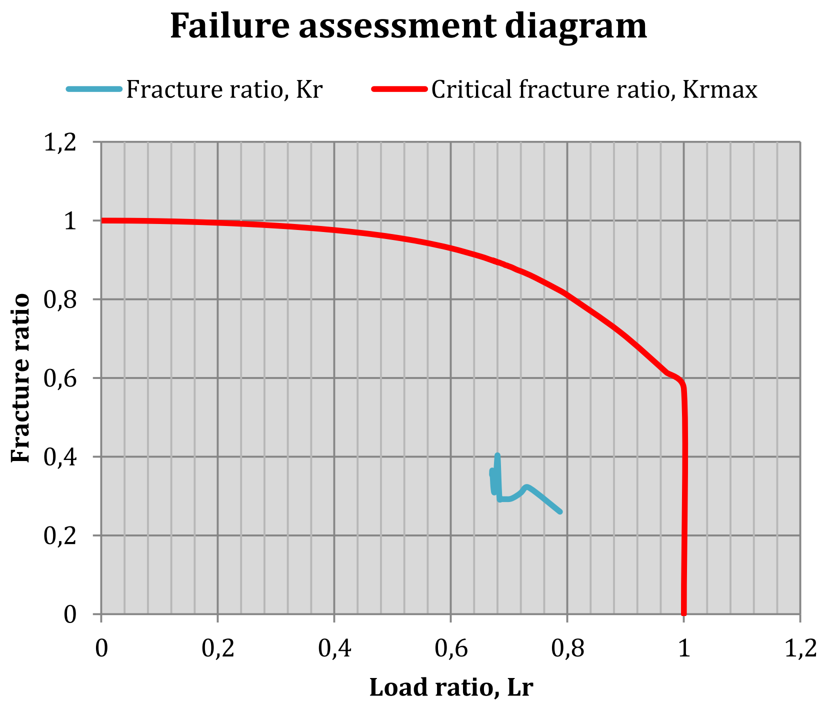


Figure 28: Failure assessment diagram

In the failure assessment diagram, seen in **Figure 28**, the critical fracture ratio, K_{rmax}, and the fracture ratio, K_r, is plotted as a function of the load ratio, L_r. The failure assessment diagram shows that the fracture ratio stays within the critical fracture ratio even though fatigue life is reached. This means that the x – joint still have structural integrity after the crack has grown through the material thickness. But fracture mechanics theory is not valid beyond this point, so the load ratio and fracture ratio cannot be evaluated any further. Regardless, the structural integrity of the jacket is maintained, but the remaining lifetime is most likely to be days or months since the crack propagation will only accelerate after having reached the material thickness. This is considered as ductile failure. Brittle fracture will be the case if failure occurs prior of having a through thickness crack.

9.1 Short summary

Using fracture mechanics on the beam model, Joint JtRw1_31 has a maximum calculated fatigue life of 410 years in point 90 degrees on the brace side.

10 FE - model

The FE – model is created in “Patran Sesam 2010”. This model will then be incorporated in the global model by use of the SESAM module Presel. Wajac is then used to subject the assembled model to the environmental loads. In Sestra a stiffness analysis is performed which gives the wanted stresses. A good FE – model will give a more accurate result of the stress distribution and the hotspot stress than a beam model. To view and identify the hotspot stresses Xtract is used. The global analysis will give the wanted hotspot stresses both on the inside and outside of the weld. These stresses will be used for fatigue calculations to determine the fatigue life on the outside for comparison of previous calculations. If these results correspond, the fatigue calculations on the inside will also be reliable.

10.1 Geometry

The geometry is drawn on the basis of coordinates extracted from the global model to give a perfect fit when inserted. The coordinates given in **Table 8** are therefore global.

Table 8: Coordinates used for 3D modelling

Point	x	y	z
Center point	-8.652998	-8.668025	-26.243731
End point of chord A	-9.8455286	-7.1990647	-24.384365
End point of chord B	-7.4604683	-10.136985	-28.103096
End point of stub A	-8.0559092	-9.152914	-25.489035
End point of stub B	-9.2500877	-8.183136	-26.998428
End point of brace A	-6.9477153	-10.052865	-24.088322
End point of brace B	-10.358282	-7.2831845	-28.399139

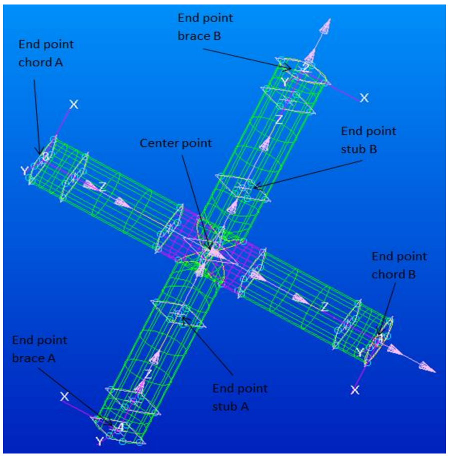


Figure 30: Contours of the x - joint

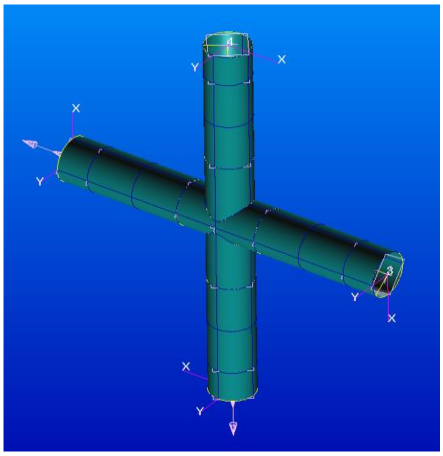


Figure 29: The complete x – joint modelled

10.2 Mesh – MPC – Supernodes

The mesh is 2D surface shell elements. To begin with the mesh is set to be less coarse closer to the area of interest which is the weld between the stub and can. After the analysis is performed, the hotspot stress will be identified and the mesh changed if any singularities found.

Table 9: Mesh specifications

	Brace	Can	Chord	Stub	MPC – connection
Element shape	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic
Mesher	Paver	Paver	Paver	Paver	Paver
Element nodes	8	8	8	8	2
Mesh size	0.060 m	0.015 m	0.060 m	0.015 m	0.10 m

For the forces in the global model to be transferred correctly to the FE – model, a super-node is created at each end point. The FE – model is connected to the global model via these supernodes which is retained in all six DOFs. The supernodes are connected to the FE – model via MPCs which have infinite stiffness.

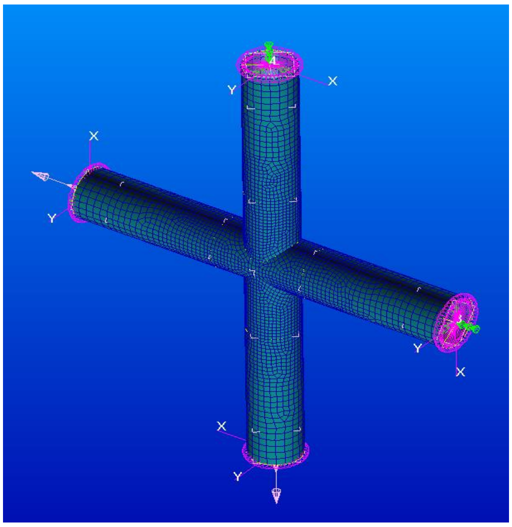


Figure 32: Mesh applied on the x – joint with supernodes at all four ends

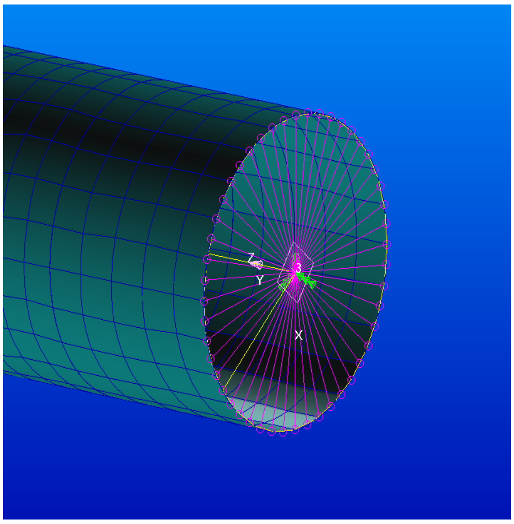


Figure 31: MPC with a supernode at centre

10.3 Integrated FE – model

The FE – model is integrated into the global beam model for a new refined fatigue analysis. To check that the integration is good, a visual animation test is performed to verify that the supernodes are 100 percent connected. The integrated FE – model is shown in green in **Figure 33**.

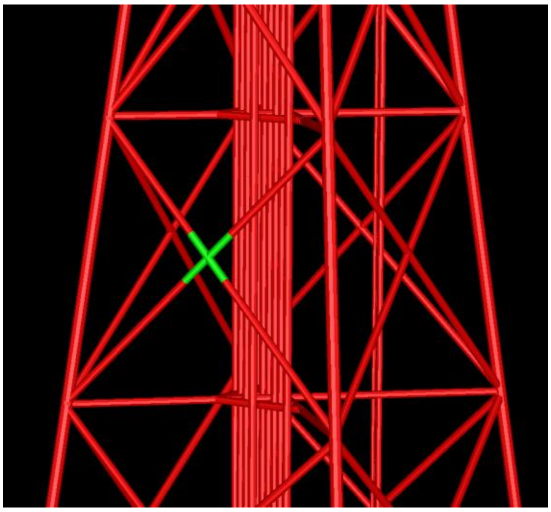


Figure 33: FE – model integrated in the global beam model

11 Fatigue analysis of integrated FE – model (outside)

The same conditions and input as the analysis performed in chapter **8 Identifying the critical x-joint using SN – fatigue** is used in this analysis. The only difference in this analysis is that the hotspot stress amplitudes are extracted from the integrated FE –model. This is done to verify that the FE – model is a good representation of the beam model.

11.1 Outside hotspot stress amplitude

Maximum principal stress 1 and minimum principal stress 2 from the outside is extracted from the FE – analysis using Sesam Xtract. These stresses are the highest maximum stresses and lowest negative stresses during the 24 step wave cycle for a given wave height and wave direction, see **Figure 11**. By scanning all 2592 load cases (9 wave heights * 12 directions * 24 steps) for the maximum principal stress 1 and minimum principal stress 2 the stress amplitudes is identified by subtracting the two peak values, see full table **Appendix 18.4**. These

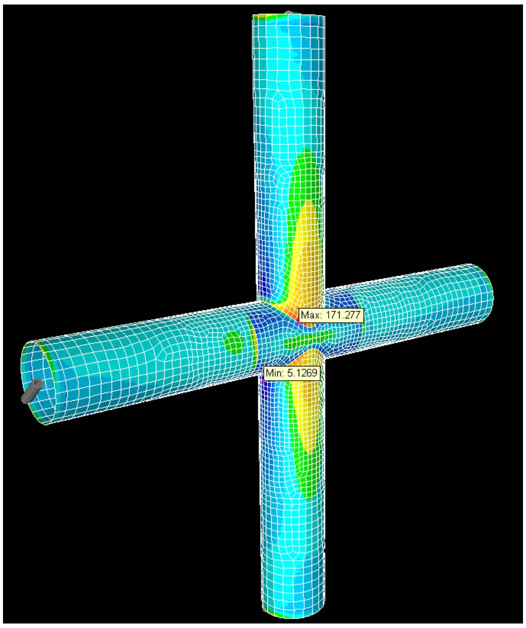


Figure 34: Maximum principal stress 1

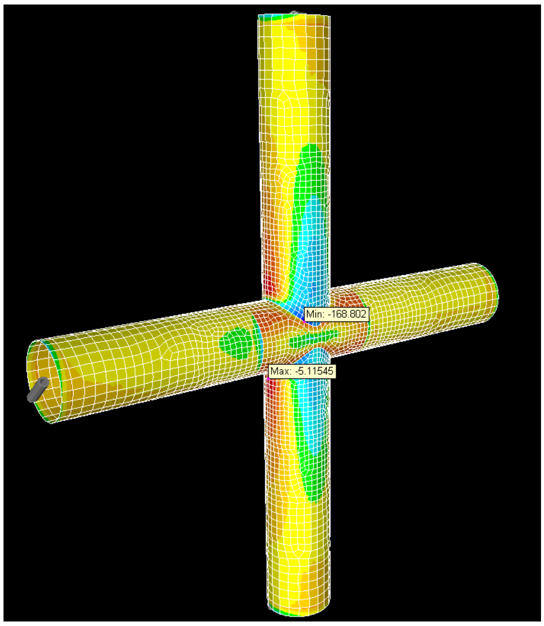


Figure 35: Minimum principal stress 2

stress amplitudes form the input used in DETFAT. **Figure 34** and **Figure 35** show the point with highest maximum stress and lowest minimum stress, this is therefore the most critical location on the x – joint, and is chosen for further analysis.

Fatigue analysis on the FE – model is performed in accordance with procedure described in standard RP – C203 [4]. The stresses which are located 0.5 and 1.5 times the plate thickness away from the maximum hotspot stress is to be used in a linear extrapolation to find the correct stress range for the fatigue analysis. This is performed in DETFAT.

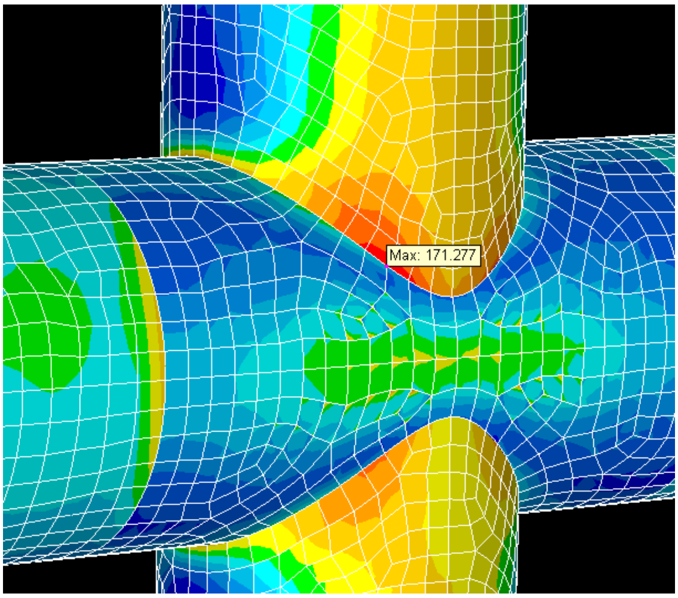


Figure 36: The most critical point identified in the FE – model

The mesh has an element size of 15 mm which means the stress on the nodes located in centrum at the two elements is used in the extrapolation, see **Figure 37**. This is done for all 2592 load cases. This gives 216 (9 wave heights * 12 directions * 2 max/min) maximum and minimum stress values, which results in 108 stress amplitudes.

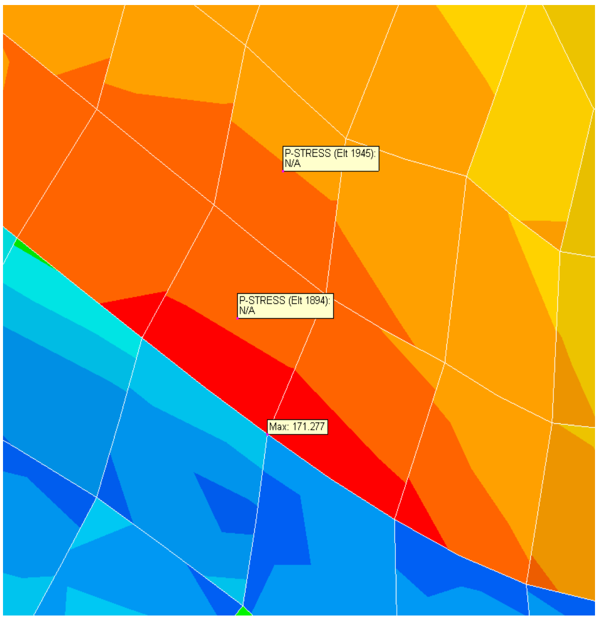


Figure 38: Element number 1984 and 1945

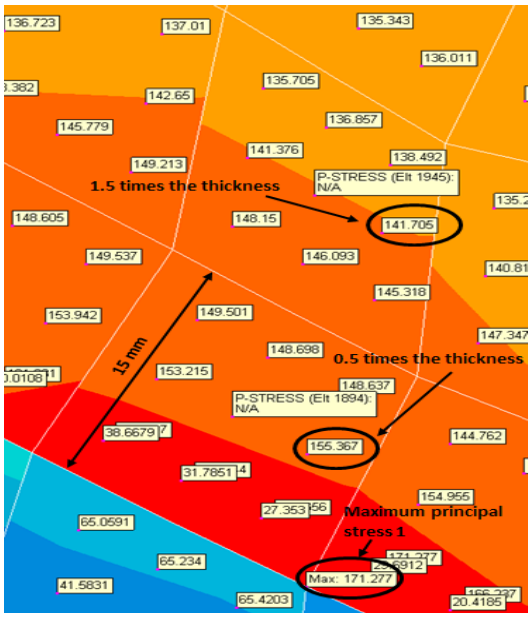


Figure 37: The two nodes used in the linear extrapolation

11.2 SN – fatigue

This analysis is based on the extrapolated hotspot stress amplitudes found in chapter **11.1 Outside hotspot stress amplitude** and the same SN – curve (T – curve in sea water with cathodic protection) as in chapter **8 Identifying the critical x-joint using SN – fatigue**.

In the critical point the calculated fatigue life is 612 years.

11.3 Fracture mechanics

This analysis is based on the extrapolated hotspot stress amplitudes found in chapter **11.1 Outside hotspot stress amplitude**.

In the critical point the calculated fatigue life is 447 years, see **Appendix 18.12** for detailed results.

11.4 Short summary

Both the beam model and FE – model produce approximately the same fatigue life, 546 years vs. 612 years and 410 years vs. 447 years. Also for both models, the brace side of the weld is governing with respect to fatigue. The FE – approach is the most conservative since it produces the lowest fatigue life in both models. This deviancy is drawn to the fact that fracture mechanics is a more accurate analysis, e.g. degree of bending is accounted for.

12 Fatigue analysis of integrated FE – model (inside)

The same conditions and input as the analysis performed in chapter **11 Fatigue analysis of integrated FE – model (outside)** is used in this analysis. The only difference in this analysis is the hotspot stress amplitudes are found from the inside of the integrated FE –model.

12.1 Inside hotspot stress amplitude

Maximum principal stress 1 and minimum principal stress 2 from the inside is extracted from the FE – analysis using Sesam Xtract. These stresses are the highest maximum stresses and lowest negative stresses during the 24 step wave cycle for a given wave height and wave direction, see **Figure 11**. By scanning all 2592 load cases (9 wave heights * 12 directions * 24 steps) for the maximum principal stress 1 and minimum principal stress 2 the stress amplitudes is identified by subtracting the two peak values, see full table **Appendix 18.5**

The highest hotspot stress is located on the chord far from the weld and is therefore not critical regarding fatigue, see **Figure 39**. Therefore the chord is removed to locate the highest hotspot stress on the brace side along the weld.

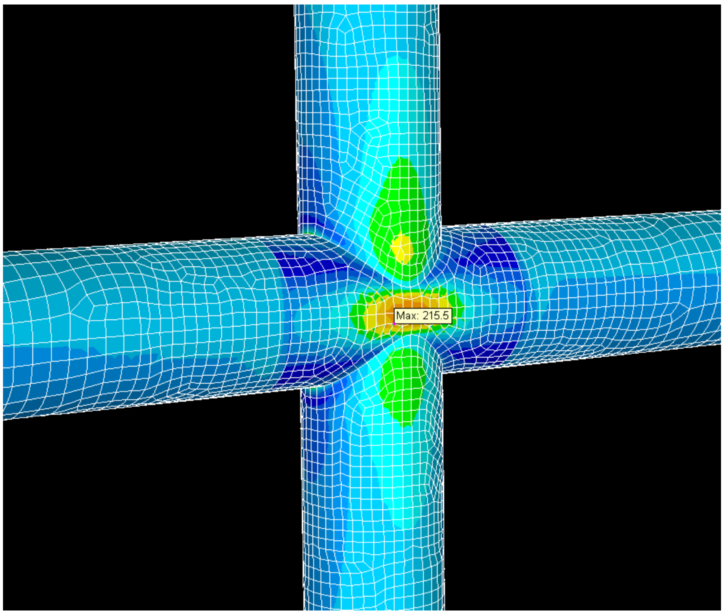


Figure 39: Maximum principal stress 1

As seen from **Figure 40** the highest hotspot stress (principal stress 1) on the brace is 129,8 MPa, several millimeters from the weld. Therefore the highest node stress closest to the weld is extracted for use in the fatigue analysis. No extrapolation is performed since the stress decreases closer to the weld.

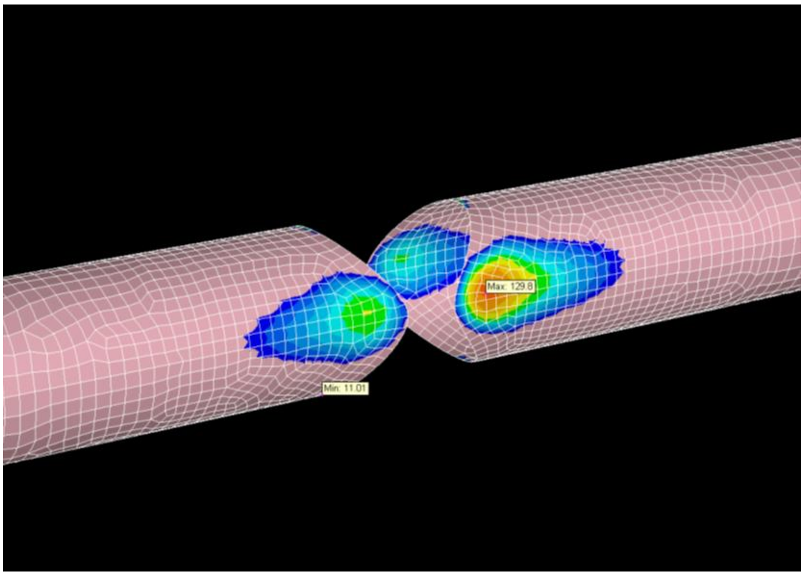


Figure 40: Maximum principal stress 1 on brace side

Along the weld element 1892 has the highest stress in node 2 with a value of 94,6 MPa, as seen in **Figure 41**. Table with hotspot stress amplitudes from node 2, see **Appendix 18.5**.

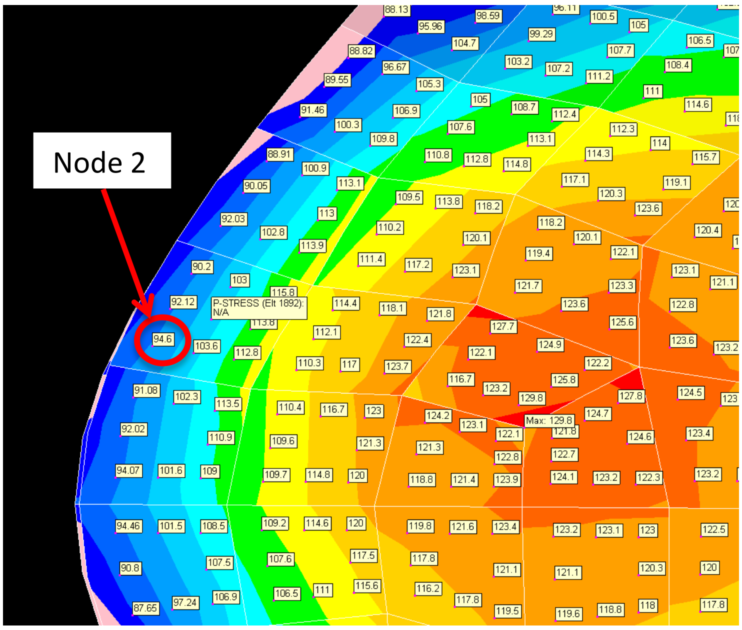


Figure 41: Maximum principal stress 1 along the weld

12.2 Fatigue analysis approaches

a) The regular approach for fatigue life assessment described in DNVGL – RP – C203 [4] is used to identify a new SN – curve for fatigue calculations on the inside. There is no sea water inside the brace so a SN – curve for air can be used, see **Appendix 18.8**.

The approach is to first calculate the fatigue life reduction factor, R, which is the ratio between a calculated fatigue life with a_i = 5mm and a_i = 1mm with an F3 curve as reference. Then establish a new SN – curve for fatigue calculations, see **Equation 23 and Equation 24**.

$$R = \frac{F(Life\ a_i{=}5mm)}{F(Life\ a_i{=}1mm)}$$ **Equation 23**

$$\log a = 11{,}546 + \log(R)$$ **Equation 24**

This procedure must then be performed for each point fatigue life is to be checked.

b) A simplified approach for fatigue life assessment is also described in DNVGL – RP – C203 [4]. This approach directly proposes to use the W3 SN – curve. The W3 curve is the worst curve in the table, and makes this a highly conservative approach.

c) Stresses used will be found from the finite element analysis, which is according to the standard, but a fracture mechanics analysis will be performed to calculate the final fatigue life and identify the critical initial crack size.

Approach a) and b) will be performed to provide a reference for approach c).

12.3 a) Regular approach

Fatigue life with a_i = 1,0 mm and c_i = 50,0 mm is calculated using fracture mechanics. The calculated fatigue life is 9517,8 years on the inside.

Fatigue life with a_i = 5,0 mm and c_i = 50,0 mm is calculated using fracture mechanics. The calculated fatigue life is 2220 years on the inside.

$$R = \frac{2220}{9517{,}8} = 0{,}2333$$

$$\log a = 11{,}546 + \log(0{,}2333) = 10{,}91$$

A $\log a$ value equal to 10,91 will result in a lower curve than W3 which has a $\log a$ value of 10,97, see **Appendix 18.8**.

12.4 b) Simplified approach

By directly using a W3 – curve the fatigue life is calculated to be 263 years on the inside.

12.5 c) Fracture mechanics approach

According to the standard [4] the lowest crack sizes detectable is 5 mm, therefore the initial crack size a_i is set to 5,0 mm. Also the standard says a long defect should be considered, therefore the initial half crack length, c_i, is set to be 50,0 mm, i.e. the total width of the crack is 100,0 mm.

There is a belief that a negative DOB is to be used because the stress intensity is increasing with crack propagation from the inside. But zero is the lowest established value and is therefore used.

Table 10: input parameters used in the fracture mechanics analysis of the inside

Input parameters	Value
Initial crack depth, a_i	5,0 mm
Initial half crack width, c_i	50,0 mm
Weld angle	15 degrees
Crack growth constant, C (stage A)	1,44*10^-17
Crack growth exponent, m (stage A)	5,0
Crack growth constant, C (stage B)	1,53*10^-12
Crack growth exponent, m (stage B)	3,0
Yield Stress	355 MPa
Ultimate stress	470 MPa
Material CTOD value	0,25 mm
DOB	0,00

This analysis gives a fatigue life of 2220 years on the inside. For detailed results, see **Appendix 18.10**

13 Critical initial crack size

To correctly identify the critical initial crack size the DFF must be taken into account. From chapter **11 Fatigue analysis of integrated FE – model (outside)** the fatigue life was calculated to be 447 years. A DFF equal to 3 for the outside of the x – joint is chosen which gives a design life of 149 years (447/3).

"Due to limited accessibility for in service inspection a higher design fatigue factor should be used for the weld root than for the outside weld toe hotspot" [4]. For the inside of the x – joint a DFF equal to 10 is therefore chosen for conservative calculations.

Table 11: Critical initial crack size identified by performing several analyzes

Run	Initial crack depth, a_i [mm]	Initial crack half width, c_i [mm]	Fatigue life [years]	Design life [years] DFF=10
1	5,00	50	2220,4	220
2	6,00	60	1653,0	165,3
3	6,10	61	1605,2	160,5
4	6,20	62	1558,9	155,9
5	6,30	63	1513,5	151,3
6	**6,35**	**63,5**	**1490,6**	**149**
7	7,00	70	1223,0	122,3
8	8,00	80	881,3	88,1
9	9,00	90	619,5	61,9
10	10,00	100	425,7	42,6
11	11,00	110	286,5	28,6
12	12,00	120	189,4	18,9
13	13,00	130	121,5	12,1
14	14,00	140	70,0	7,0

The critical initial crack depth and crack half width is identified by performing several fracture mechanics analyses increasing the initial values until design life is reached. For the inside to have the same safety level as the outside (same design life), critical initial crack depth, a_i, is equal to 6,35 mm and critical initial crack half width, c_i, is equal to 63,5 mm.

13.1 Short summary

With a DFF equal to 10 the design life on the inside is 149 years and the critical initial crack size is:

a_i = 6,35 mm

c_i = 63,5 mm

14 Summary of all fatigue results

The calculated fatigue life listed in **Table 12** is has not been multiplied with a DFF.

Table 12: Overview of the fatigue assessment approaches and their corresponding fatigue life results (without DFF)

Approach	Beam model (outside)	FE –model (outside)	FE – model (inside)	Error rate (Beam model/ FE – model (outside))
SN – fatigue life Curve	546 years T - curve	612 years T - curve	263 years W3 - curve	0,89
FM – fatigue life a_i x c_i	410 years 3 x 7,5	447 years 3 x 7,5	2220 years 5 x 50	0,92
Error rate (FM – fatigue/ SN – fatigue)	0,75	0,73	8,44	

15 Discussion

To identify the critical initial crack size on the inside of one of the x – joints in the Oseberg UWP, it was necessary to establish a foundation/basis for the calculations. This foundation consisted of two different fatigue assessment approaches which were performed on two models; one beam model and one with an integrated FE – model. The results from these analyses are presented in **Table 12**. Both approaches agree on the brace side being the most critical in regards of fatigue life. The fatigue life when comparing SN – fatigue with FM – fatigue on the same model has some deviations as expected (0,75 and 0,73), but when it comes to fatigue life calculations this is a small deviation. The fatigue life when comparing the two FM – fatigue analysis and the two SN – fatigue analysis on the different models, the deviation is smaller (0,89 and 0,92). This is a positive indication that the FE – model appears to be a good representation for the beam joint which makes the fatigue life results reliable, and therefore can be established as a good foundation for fatigue calculations on the inside.

The calculated fatigue life from fracture mechanics (2220 years) differ significantly from the fatigue life calculated on the basis of DNVGL – RP – C203 [4] (263 years). The reason for this might be that the procedure described in the standard is to cover the worst case scenario with a highly complex joint (more than 4 braces making up the joint) and β – value approximately equal to 1,0. Therefore it seems that this procedure is too conservative in this case, and the calculated fatigue life results using FM – fatigue on the simple x – joint with a β – value of 0,91 is quite reliable. If the standard were to be followed to the letter it would result in unnecessary high production costs and maybe even make the design impossible. Also the FM – fatigue calculations consistently gave the lowest fatigue life in the two analyses performed to establish the foundation/basis. This makes it a conservative approach, which is preferable.

It is important to keep in mind that this analysis is only performed on one type of joint with one β – value. Therefore several analyses with the same approach as performed in this report should be executed on different situations to provide more results for comparison. Thereafter a conclusion regarding the safety level and conservativism of DNVGL – RP – C203 [4] can be drawn.

In the fracture mechanics approach the DOB factor, which has a significant impact on the fatigue life, is set to be equal to zero when evaluating fracture from the inside even though a negative value is believed to be used. The reason for this is that the stress amplitude increases as the crack grows through the cross section from the inside towards the outside. Unfortunately no studies or papers on a negative DOB were found in the literature search, meaning this might be a source of error. Also the interpretation of “a long defect should be considered here with the defect size measured in the thickness direction of the tubular” [4] may be a source of error, but a factor of 10 between the initial crack depth and initial crack half width were used. In comparison a factor of 2,5 were used for the outside FM – fatigue analysis.

16 **Conclusion**

A SN – fatigue and FM – fatigue analysis on a beam model of the Oseberg UWP was performed and the most critical joint on the jacket was identified. Further a FE – model of the joint was created and the same analysis performed. The comparison of the fatigue assessment approaches on the two different models showed to provide a good foundation/basis for analyzing the inside of the joint. With the FE – model as a good representation for the beam joint the stress amplitudes on the inside could be directly extracted for fatigue calculations.

The result produced by the FM – fatigue approach was based on the extracted stress amplitudes on the inside and is therefore reliable. The calculated fatigue life on the inside without a DFF is 2220 years. With a DFF equal to 10 and the same safety level as the outside of the weld, the design life is 149 years and the corresponding critical initial crack size was identified to be:

a_i = 6,35 mm
c_i = 63,5 mm

The critical initial crack size is larger than the smallest detectable crack size (5 mm) using ultrasonic inspection (NDT), which results in the calculated design life (149 years) being higher than the required design life (25 years).

The procedure described in DNVGL – RP – C203 gives a fatigue life of 263 years without a DFF and is believed to be too conservative for a x – joint with a β – value of 0,91.

Based on the inside stress increasing and becoming more equal to the outside stress with an increasing β – value, a parameter study with higher β – values is recommended to be performed to investigate how this will influence the fatigue life. The fatigue life analysis should be performed as described in this report to evaluate whether the procedure described in DNVGL – RP – C203 is too conservative or not.

Further I would recommend a study investigating how a negative DOB would influence the fatigue life when crack propagation is from the inside out.

17 Reference list

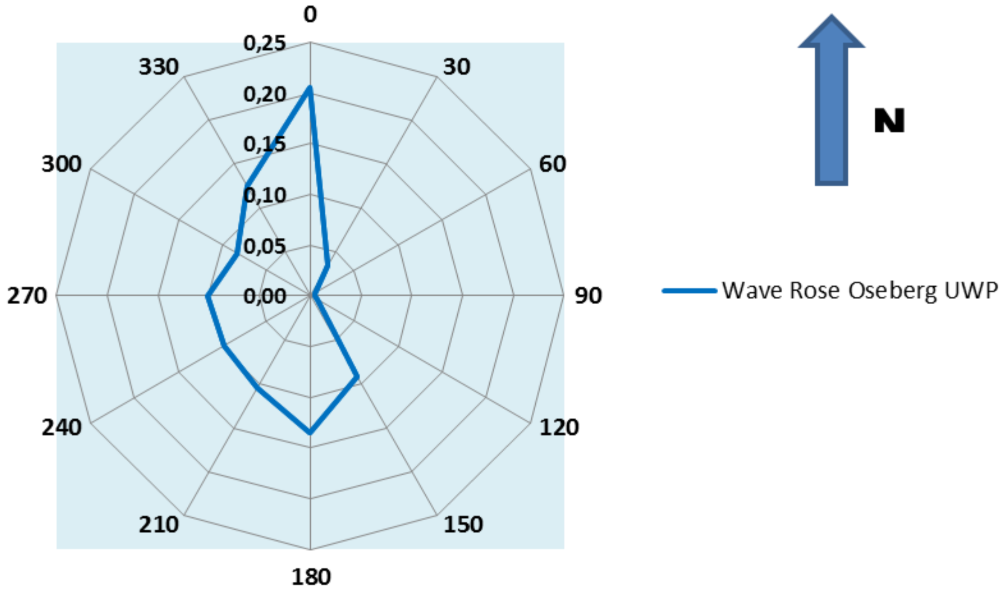
[1]	Almar-Næss, A., 1985. *Fatigue Handbook - Offshore Steel Structures.* 1st ed. Trondheim: Tapir Publishers.
[2]	Bowness, D. & Lee, M. M. K., 2002. *Fracture mechanics assessment of fatigue cracks in offshore tubular structures ,* Swansea: University of Wales, Department of Civil Engineering .
[3]	Broek, D., 1998. *The Practical Use of Fracture Mechanics.* 3rd ed. Galena, OH, USA: Kluwer Academic Publishers.
[4]	DNVGL, 2014. *RP-C203: Fatigue design of offshore steel structures,* DNVGL.
[5]	DNVGL, 2015. *RP-C210: Probabilistic methods for planning of inspection for fatigue cracks in offshore structures*, DNVGL.
[6]	Haagensen, P. P. J., 2012. *Fatigue Design - Introduction to fatigue ,* Trondheim: Norwegian University of Science and Technology, Department of Engineering Design and Materials.
[7]	Kværner Jacket Technology, 1998. *DETFAT user's manual,* Oslo
[8]	Kværner Jacket Technology, 2016. *Fracture Mechanics Evaluation Report,* Oslo
[9]	Statoil, 2015. *Statoil News and Media.* [Online] Available at: http://www.statoil.com/no/NewsAndMedia/News/2015/Pages/09Feb_Oseberg_wellhead.aspx [Accessed 3 January 2016].
[10]	Suresh, S., 1991. *Fatigue of materials.* 1st ed. Cambridge: Cambridge University Press.
[11]	The British Standards Institution, 2015. *BS 7910: Guide to methods for assessing the acceptability of flaws in metallic structures ,* BSI Standards Limited .
[12]	Statoil, 2014. *Inplace presentation, Oseberg UWP C-study,* Oslo

Sotwares used:
- DETFAT
- Patran Sesam 2010
- Wajac
- Presel
- Sestra
- Sesam Xtract

18 Appendix

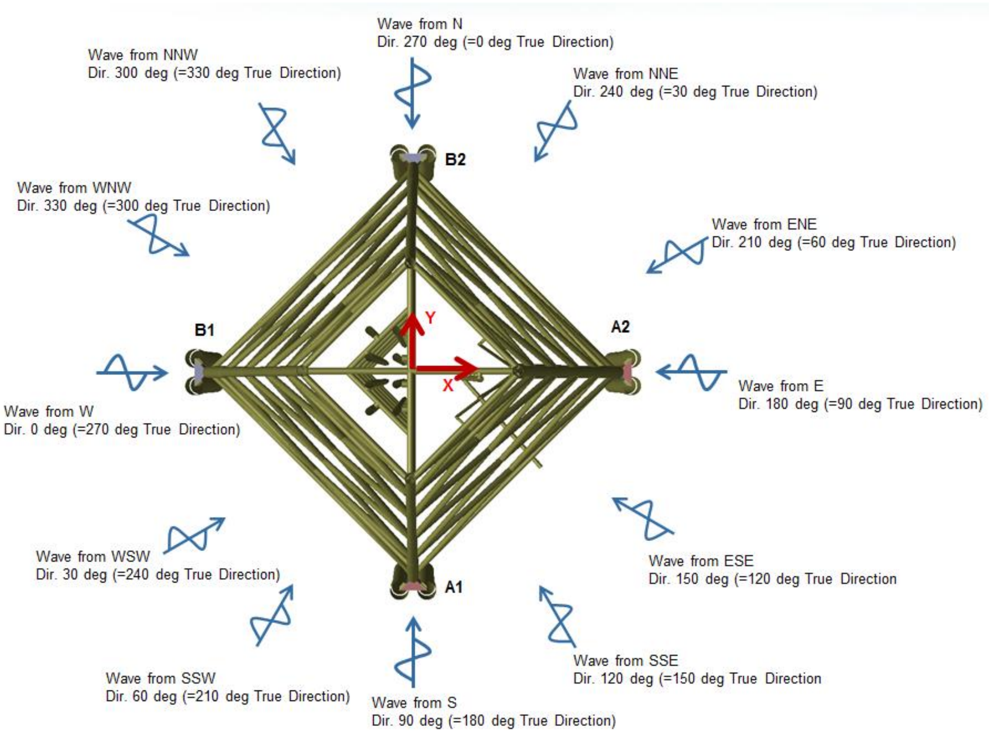
18.1 Wave rose

Wave rose form the installation area of the Oseberg UWP showing long term distribution of wave heights in percentage and their corresponding directions.



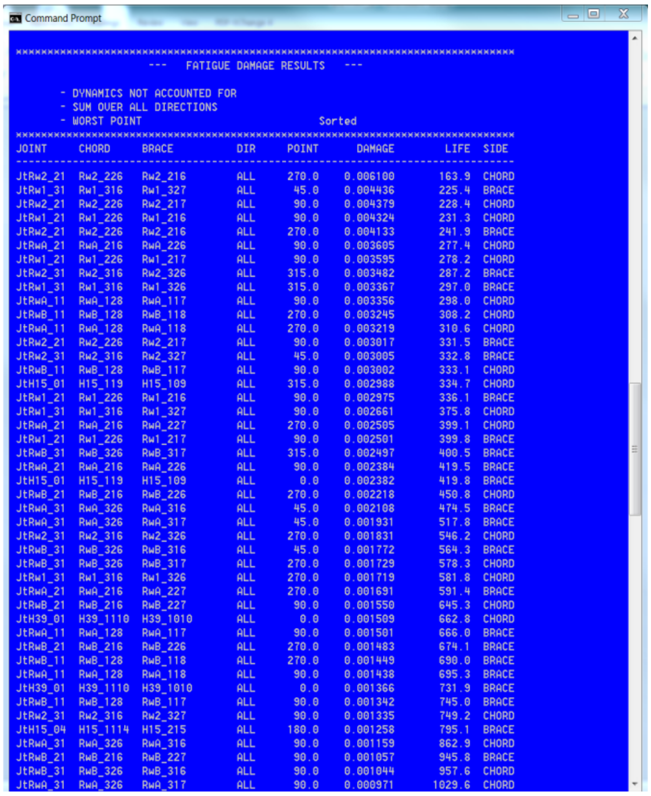
18.2 Wave directions

Sketch showing the 12 different angels of attack form waves on the Oseberg UWP used in the fatigue analysis.



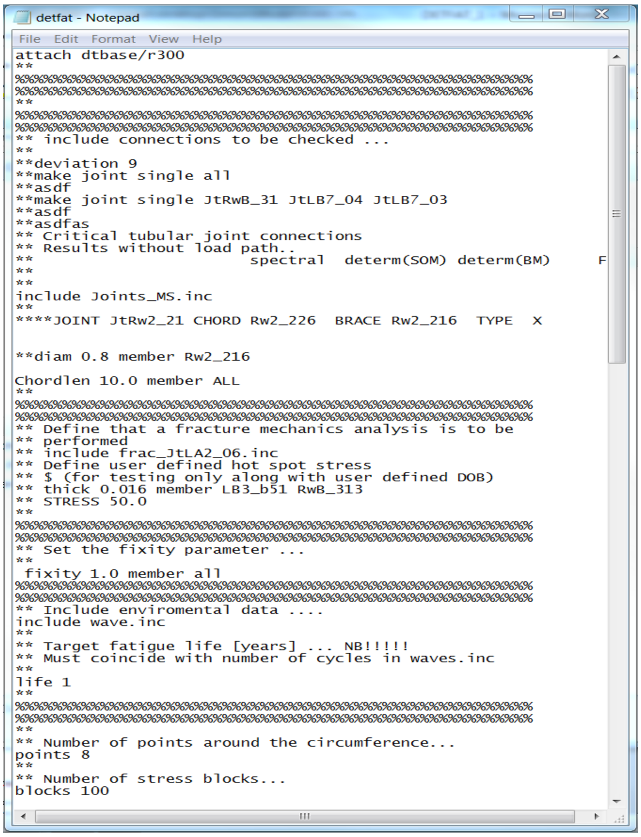
18.3 DETFAT

Shown below is a typical output file with fatigue lives and a transcript of its corresponding input file.



```
Command Prompt
*****************************************************************************
                    ---   FATIGUE DAMAGE RESULTS   ---

       - DYNAMICS NOT ACCOUNTED FOR
       - SUM OVER ALL DIRECTIONS
       - WORST POINT                           Sorted
*****************************************************************************
JOINT     CHORD     BRACE          DIR     POINT      DAMAGE       LIFE  SIDE
-----------------------------------------------------------------------------
JtRw2_21  Rw2_226   Rw2_216        ALL     270.0    0.006100      163.9  CHORD
JtRw1_31  Rw1_316   Rw1_327        ALL      45.0    0.004436      225.4  BRACE
JtRw2_21  Rw2_226   Rw2_217        ALL      90.0    0.004379      228.4  CHORD
JtRw1_21  Rw1_226   Rw1_216        ALL      90.0    0.004324      231.3  CHORD
JtRw2_21  Rw2_226   Rw2_216        ALL     270.0    0.004133      241.9  BRACE
JtRwA_21  RwA_216   RwA_226        ALL      90.0    0.003605      277.4  CHORD
JtRw1_21  Rw1_226   Rw1_217        ALL      90.0    0.003595      278.2  CHORD
JtRw2_31  Rw2_316   Rw2_326        ALL     315.0    0.003482      287.2  BRACE
JtRw1_31  Rw1_316   Rw1_326        ALL     315.0    0.003367      297.0  BRACE
JtRwA_11  RwA_128   RwA_117        ALL      90.0    0.003356      298.0  CHORD
JtRwB_11  RwB_128   RwB_118        ALL     270.0    0.003245      308.2  CHORD
JtRwA_11  RwA_128   RwA_118        ALL     270.0    0.003219      310.6  CHORD
JtRw2_21  Rw2_226   Rw2_217        ALL      90.0    0.003017      331.5  BRACE
JtRw2_31  Rw2_316   Rw2_327        ALL      45.0    0.003005      332.8  BRACE
JtRwB_11  RwB_128   RwB_117        ALL      90.0    0.003002      333.1  CHORD
JtH15_01  H15_119   H15_109        ALL     315.0    0.002988      334.7  CHORD
JtRw1_21  Rw1_226   Rw1_216        ALL      90.0    0.002975      336.1  BRACE
JtRw1_31  Rw1_316   Rw1_327        ALL      90.0    0.002661      375.8  CHORD
JtRwA_21  RwA_216   RwA_227        ALL     270.0    0.002505      399.1  CHORD
JtRw1_21  Rw1_226   Rw1_217        ALL      90.0    0.002501      399.8  BRACE
JtRwB_31  RwB_326   RwB_317        ALL     315.0    0.002497      400.5  BRACE
JtRwA_21  RwA_216   RwA_226        ALL      90.0    0.002384      419.5  BRACE
JtH15_01  H15_119   H15_109        ALL       0.0    0.002382      419.8  BRACE
JtRwB_21  RwB_216   RwB_226        ALL     270.0    0.002218      450.8  CHORD
JtRwA_31  RwA_326   RwA_316        ALL      45.0    0.002108      474.5  BRACE
JtRwA_31  RwA_326   RwA_317        ALL      45.0    0.001931      517.8  BRACE
JtRw2_31  Rw2_316   Rw2_326        ALL     270.0    0.001831      546.2  CHORD
JtRwB_31  RwB_326   RwB_316        ALL      45.0    0.001772      564.3  BRACE
JtRwB_31  RwB_326   RwB_317        ALL     270.0    0.001729      578.3  CHORD
JtRw1_31  Rw1_316   Rw1_326        ALL     270.0    0.001719      581.8  CHORD
JtRwA_21  RwA_216   RwA_227        ALL     270.0    0.001691      591.4  BRACE
JtRwB_21  RwB_216   RwB_227        ALL      90.0    0.001550      645.3  CHORD
JtH39_01  H39_1110  H39_1010       ALL       0.0    0.001509      662.8  CHORD
JtRwA_11  RwA_128   RwA_117        ALL      90.0    0.001501      666.0  BRACE
JtRwB_21  RwB_216   RwB_226        ALL     270.0    0.001483      674.1  BRACE
JtRwB_11  RwB_128   RwB_118        ALL     270.0    0.001449      690.0  BRACE
JtRwA_11  RwA_128   RwA_118        ALL      90.0    0.001438      695.3  BRACE
JtH39_01  H39_1110  H39_1010       ALL       0.0    0.001366      731.9  BRACE
JtRwB_11  RwB_128   RwB_117        ALL      90.0    0.001342      745.0  BRACE
JtRw2_31  Rw2_316   Rw2_327        ALL      90.0    0.001335      749.2  CHORD
JtH15_04  H15_1114  H15_215        ALL     180.0    0.001258      795.1  BRACE
JtRwA_31  RwA_326   RwA_316        ALL      90.0    0.001159      862.9  CHORD
JtRwB_21  RwB_216   RwB_227        ALL      90.0    0.001057      945.8  BRACE
JtRwB_31  RwB_326   RwB_316        ALL      90.0    0.001044      957.6  CHORD
JtRwA_31  RwA_326   RwA_317        ALL      90.0    0.000971     1029.6  CHORD
```



```
detfat - Notepad
File  Edit  Format  View  Help
attach dtbase/r300
**
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
**
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
** include connections to be checked ...
**
**deviation 9
**make joint single all
**asdf
**make joint single JtRwB_31 JtLB7_04 JtLB7_03
**asdf
**asdfas
** Critical tubular joint connections
** Results without load path..
**                        spectral   determ(SOM) determ(BM)      F
**
**
include Joints_MS.inc
**
****JOINT JtRw2_21 CHORD Rw2_226   BRACE Rw2_216   TYPE   X


**diam 0.8 member Rw2_216

Chordlen 10.0 member ALL
**
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
** Define that a fracture mechanics analysis is to be
** performed
** include frac_JtLA2_06.inc
** Define user defined hot spot stress
** $ (for testing only along with user defined DOB)
** thick 0.016 member LB3_b51 RwB_313
** STRESS 50.0
**
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
** Set the fixity parameter ...
**
 fixity 1.0 member all
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
** Include enviromental data ....
include wave.inc
**
** Target fatigue life [years] ... NB!!!!!
** Must coincide with number of cycles in waves.inc
**
life 1
**
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
**
** Number of points around the circumference...
points 8
**
** Number of stress blocks...
blocks 100
```

Formulas DETFAT uses to calculate SCF's for an x – joint:

Axial load / chord saddle	$SCS\_AX = [X7]_A + \frac{F_B \sin(\theta_B)}{F_A \sin(\theta_A)}\left[[X1]_A - [X7]_A\right]$
Axial load / chord crown	$SCC\_AX = [T6]_A + \frac{F_B \sin(\theta_B)}{F_A \sin(\theta_A)}\left[[X2]_A - [T6]_A\right]$
Axial load / brace saddle	$SBS\_AX = [X8]_A + \frac{F_B \sin(\theta_B)}{F_A \sin(\theta_A)}\left[[X3]_A - [X8]_A\right]$
Axial load / brace crown	$SBC\_AX = [T7]_A + \frac{F_B \sin(\theta_B)}{F_A \sin(\theta_A)}\left[[X4]_A - [T7]_A\right]$
IPB / chord crown	$SC\_IPB = [T8]$
OPB / chord saddle	$SC\_OPB = [T10]_A + \frac{M_{ZB} \sin(\theta_B)}{M_{ZA} \sin(\theta_A)}\left[[X5]_A - [T10]_A\right]$
IPB / brace crown	$SB\_IPB = [T9]$
OPB / brace saddle	$SB\_OPB = [T11]_A + \frac{M_{ZB} \sin(\theta_B)}{M_{ZA} \sin(\theta_A)}\left[[X6]_A - [T11]_A\right]$

18.4 Outside hotspot stress ranges from FE – analysis

The table shows the outside stress amplitudes from the different directions extracted from the FE – analysis. The stress ranges corresponds with the wave heights (2m, 4m, 6m, 7m, 8m, 10m, 12m, 14m, 24m).

	Stress range	Stress amplitude [MPa]	n	p	n*p
Direction 0	1	4,79	1008500	0,1000	100850,0
	2	8,15	161230	0,1000	16123,0
	3	11,58	30345	0,1000	3034,5
	4	13,6	13651	0,1000	1365,1
	5	15,7	6239	0,1000	623,9
	6	20,28	1354	0,1000	135,4
	7	25,94	307	0,1000	30,7
	8	32,16	72	0,1000	7,2
	9	75,04	10	0,1000	1,0
Direction 30	10	2,48	1008500	0,1000	100850,0
	11	6,61	161230	0,1000	16123,0
	12	11,08	30345	0,1000	3034,5
	13	13,46	13651	0,1000	1365,1
	14	15,82	6239	0,1000	623,9
	15	21,26	1354	0,1000	135,4
	16	28,07	307	0,1000	30,7
	17	36,94	72	0,1000	7,2
	18	107,38	10	0,1000	1,0
Direction 60	19	6,26	1008500	0,1200	121020,0
	20	14,9	161230	0,1200	19347,0
	21	23,66	30345	0,1200	3641,4
	22	28,21	13651	0,1200	1638,1
	23	32,91	6239	0,1200	748,7
	24	44,31	1354	0,1200	162,5
	25	58,54	307	0,1200	36,8
	26	76,68	72	0,1200	8,6
	27	210,65	10	0,1200	1,2
Direction 90	28	9,42	1008500	0,1300	131100,0
	29	20,69	161230	0,1300	20960,0
	30	31,74	30345	0,1300	3944,8
	31	37,54	13651	0,1300	1774,6
	32	43,88	6239	0,1300	811,1
	33	58,47	1354	0,1300	176,0
	34	77,08	307	0,1300	39,9
	35	98,72	72	0,1300	9,4
	36	259,1	10	0,1300	1,3
Direction 120	37	10,23	1008500	0,0850	85722,0
	38	21,38	161230	0,0850	13704,0
	39	32,22	30345	0,0850	2579,3
	40	38,18	13651	0,0850	1160,3
	41	44,63	6239	0,0850	530,3
	42	59,6	1354	0,0850	115,1
	43	77,66	307	0,0850	26,1
	44	98,79	72	0,0850	6,1
	45	250,29	10	0,0850	0,9

Direction 150	46	8,41	1008500	0,0001	100,9
	47	16,33	161230	0,0001	16,1
	48	24,3	30345	0,0001	3,0
	49	28,87	13651	0,0001	1,4
	50	33,76	6239	0,0001	0,6
	51	45,49	1354	0,0001	0,1
	52	59,65	307	0,0001	0,0
	53	76,14	72	0,0001	0,0
	54	190,03	10	0,0001	0,0
Direction 180	55	4,56	1008500	0,0001	100,9
	56	7,26	161230	0,0001	16,1
	57	9,88	30345	0,0001	3,0
	58	11,62	13651	0,0001	1,4
	59	13,61	6239	0,0001	0,6
	60	18,03	1354	0,0001	0,1
	61	23,46	307	0,0001	0,0
	62	29,71	72	0,0001	0,0
	63	73,8	10	0,0001	0,0
Direction 210	64	2,21	1008500	0,0100	10085,0
	65	5,75	161230	0,0100	1612,3
	66	9,56	30345	0,0100	303,5
	67	11,65	13651	0,0100	136,5
	68	13,95	6239	0,0100	62,4
	69	19,53	1354	0,0100	13,5
	70	26,41	307	0,0100	3,1
	71	35,17	72	0,0100	0,7
	72	104,08	10	0,0100	0,1
Direction 240	73	6,46	1008500	0,0400	40340,0
	74	15,17	161230	0,0400	6449,2
	75	24,1	30345	0,0400	1213,8
	76	28,93	13651	0,0400	546,0
	77	34,36	6239	0,0400	249,6
	78	46,89	1354	0,0400	54,2
	79	62,25	307	0,0400	12,3
	80	80,85	72	0,0400	2,9
	81	214,59	10	0,0400	0,4
Direction 270	82	9,68	1008500	0,2100	211780,0
	83	21,19	161230	0,2100	33858,0
	84	32,88	30345	0,2100	6372,4
	85	39,16	13651	0,2100	2866,7
	86	46,1	6239	0,2100	1310,2
	87	62,1	1354	0,2100	284,3
	88	81,29	307	0,2100	64,5
	89	104,05	72	0,2100	15,1
	90	263,44	10	0,2100	2,1

Direction 300	91	10,42	1008500	0,1240	125050,0
	92	21,78	161230	0,1240	19992,0
	93	32,95	30345	0,1240	3762,8
	94	39,18	13651	0,1240	1692,7
	95	45,61	6239	0,1240	773,6
	96	61	1354	0,1240	167,9
	97	78,76	307	0,1240	38,1
	98	100,26	72	0,1240	8,9
	99	247,56	10	0,1240	1,2
Direction 330	100	8,58	1008500	0,0800	80680,0
	101	16,75	161230	0,0800	12898,0
	102	24,7	30345	0,0800	2427,6
	103	29,07	13651	0,0800	1092,1
	104	33,93	6239	0,0800	499,1
	105	44,8	1354	0,0800	108,3
	106	58,2	307	0,0800	24,6
	107	73,46	72	0,0800	5,8
	108	177,19	10	0,0800	0,8

18.5 Inside hotspot stress ranges from FE – analysis

The table shows the inside stress amplitudes from the different directions extracted from the FE – analysis. The stress ranges corresponds with the wave heights (2m, 4m, 6m, 7m, 8m, 10m, 12m, 14m, 24m).

	Stress range	Stress amplitude [MPa]	n	p	n*p
Direction 0	1	3,79	1008500	0,1000	100850,00000
	2	7,18	161230	0,1000	16123,00000
	3	10,56	30345	0,1000	3034,50000
	4	12,41	13651	0,1000	1365,10000
	5	14,45	6239	0,1000	623,90000
	6	19,08	1354	0,1000	135,40000
	7	24,82	307	0,1000	30,70000
	8	31,39	72	0,1000	7,20000
	9	75,33	10	0,1000	1,00000
Direction 30	10	0,91	1008500	0,1000	100850,00000
	11	1,62	161230	0,1000	16123,00000
	12	2,34	30345	0,1000	3034,50000
	13	2,77	13651	0,1000	1365,10000
	14	3,25	6239	0,1000	623,90000
	15	4,44	1354	0,1000	135,40000
	16	5,94	307	0,1000	30,70000
	17	7,64	72	0,1000	7,20000
	18	20,91	10	0,1000	1,00000
Direction 60	19	2,07	1008500	0,1200	121020,00000
	20	4,45	161230	0,1200	19347,00000
	21	6,78	30345	0,1200	3641,40000
	22	8,03	13651	0,1200	1638,10000
	23	9,43	6239	0,1200	748,68000
	24	12,67	1354	0,1200	162,48000
	25	16,80	307	0,1200	36,84000
	26	21,53	72	0,1200	8,64000
	27	57,16	10	0,1200	1,20000
Direction 90	28	4,51	1008500	0,1300	131100,00000
	29	9,11	161230	0,1300	20960,00000
	30	13,55	30345	0,1300	3944,80000
	31	16,07	13651	0,1300	1774,60000
	32	18,66	6239	0,1300	811,07000
	33	24,98	1354	0,1300	176,02000
	34	32,57	307	0,1300	39,91000
	35	41,66	72	0,1300	9,36000
	36	104,34	10	0,1300	1,30000
Direction 120	37	5,77	1008500	0,0850	85722,00000
	38	11,49	161230	0,0850	13704,00000
	39	17,14	30345	0,0850	2579,30000
	40	20,27	13651	0,0850	1160,30000
	41	23,53	6239	0,0850	530,32000
	42	31,37	1354	0,0850	115,09000
	43	40,83	307	0,0850	26,09500
	44	51,89	72	0,0850	6,12000
	45	127,29	10	0,0850	0,85000

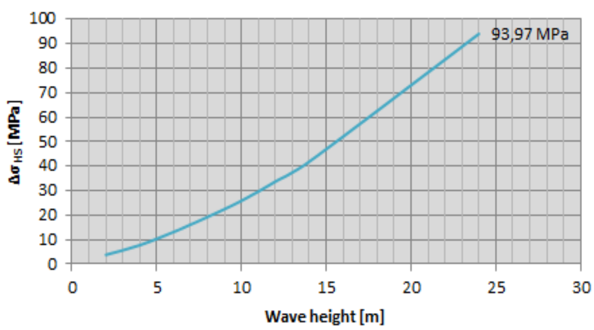
Direction 150	46	5,55	1008500	0,0001	100,85000
	47	10,89	161230	0,0001	16,12300
	48	16,22	30345	0,0001	3,03450
	49	19,13	13651	0,0001	1,36510
	50	22,42	6239	0,0001	0,62390
	51	29,94	1354	0,0001	0,13540
	52	39,01	307	0,0001	0,03070
	53	49,47	72	0,0001	0,00720
	54	120,41	10	0,0001	0,00100
Direction 180	55	3,84	1008500	0,0001	100,85000
	56	7,29	161230	0,0001	16,12300
	57	10,77	30345	0,0001	3,03450
	58	12,71	13651	0,0001	1,36510
	59	14,91	6239	0,0001	0,62390
	60	19,90	1354	0,0001	0,13540
	61	26,04	307	0,0001	0,03070
	62	33,07	72	0,0001	0,00720
	63	79,37	10	0,0001	0,00100
Direction 210	64	1,05	1008500	0,0100	10085,00000
	65	1,87	161230	0,0100	1612,30000
	66	2,71	30345	0,0100	303,45000
	67	3,20	13651	0,0100	136,51000
	68	3,73	6239	0,0100	62,39000
	69	4,99	1354	0,0100	13,54000
	70	6,61	307	0,0100	3,07000
	71	8,64	72	0,0100	0,72000
	72	23,14	10	0,0100	0,10000
Direction 240	73	2,13	1008500	0,0400	40340,00000
	74	4,53	161230	0,0400	6449,20000
	75	6,90	30345	0,0400	1213,80000
	76	8,20	13651	0,0400	546,04000
	77	9,71	6239	0,0400	249,56000
	78	13,20	1354	0,0400	54,16000
	79	17,49	307	0,0400	12,28000
	80	22,50	72	0,0400	2,88000
	81	57,86	10	0,0400	0,40000
Direction 270	82	4,55	1008500	0,2100	211780,00000
	83	9,24	161230	0,2100	33858,00000
	84	13,90	30345	0,2100	6372,40000
	85	16,50	13651	0,2100	2866,70000
	86	19,35	6239	0,2100	1310,20000
	87	26,09	1354	0,2100	284,34000
	88	34,07	307	0,2100	64,47000
	89	43,57	72	0,2100	15,12000
	90	107,48	10	0,2100	2,10000

Direction 300	91	5,78	1008500	0,1240	125050,00000
	92	11,60	161230	0,1240	19992,00000
	93	17,37	30345	0,1240	3762,80000
	94	20,55	13651	0,1240	1692,70000
	95	24,00	6239	0,1240	773,64000
	96	32,11	1354	0,1240	167,90000
	97	41,62	307	0,1240	38,06800
	98	52,90	72	0,1240	8,92800
	99	129,52	10	0,1240	1,24000
Direction 330	100	5,54	1008500	0,0800	80680,00000
	101	10,84	161230	0,0800	12898,00000
	102	16,10	30345	0,0800	2427,60000
	103	18,98	13651	0,0800	1092,10000
	104	22,04	6239	0,0800	499,12000
	105	29,28	1354	0,0800	108,32000
	106	38,03	307	0,0800	24,56000
	107	48,21	72	0,0800	5,76000
	108	117,17	10	0,0800	0,80000

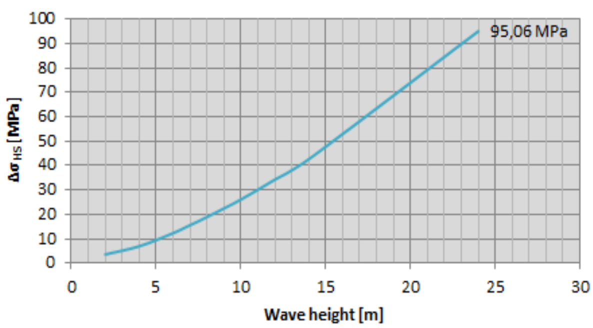
18.6 Hotspot stress amplitudes form chapter 8

The hotspot stress amplitudes for all the 12 wave directions found in chapter **8 Identifying the critical x – joint using SN – fatigue**.

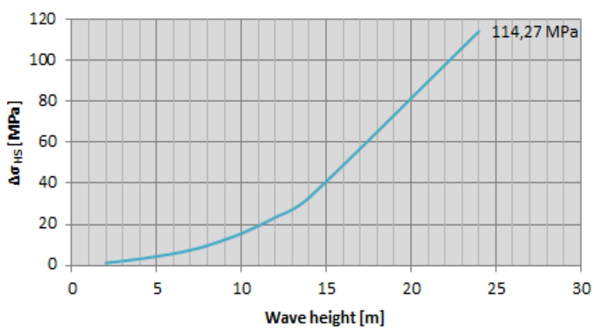
Wave direction 0



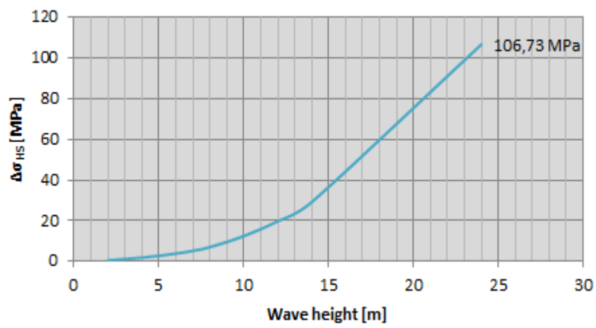
Wave direction 180



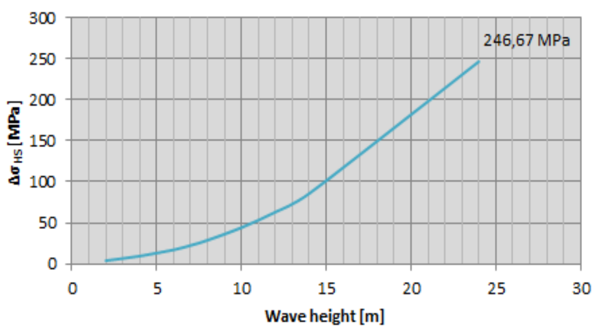
Wave direction 30



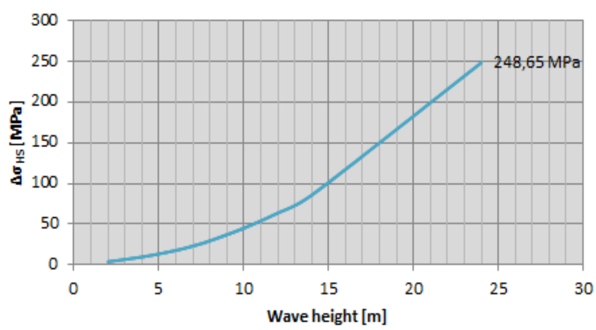
Wave direction 210



Wave direction 60

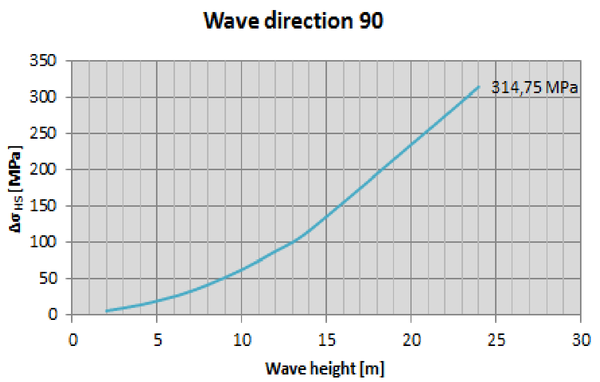


Wave direction 240

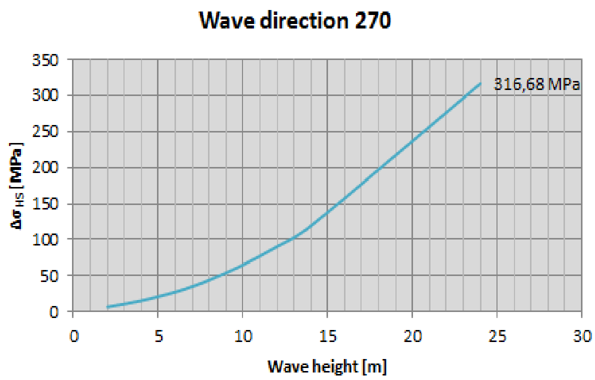


Wave direction 90

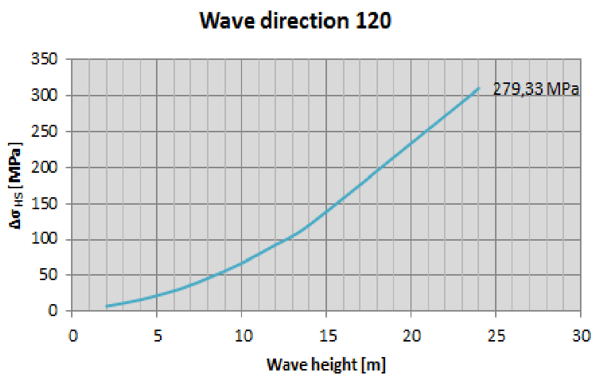
Wave direction 270



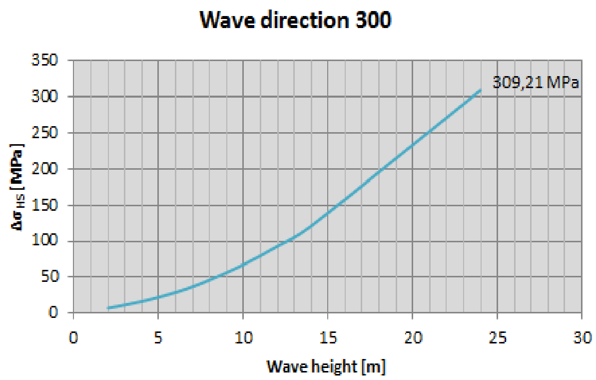
Wave direction 90
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
314,75 MPa
Δσ HS [MPa]
Wave height [m]



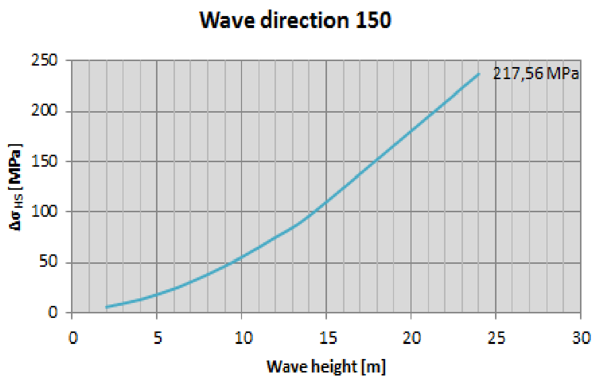
Wave direction 270
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
316,68 MPa
Δσ HS [MPa]
Wave height [m]



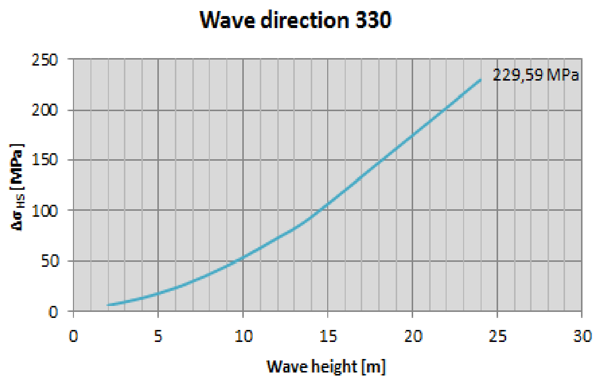
Wave direction 120
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
279,33 MPa
Δσ HS [MPa]
Wave height [m]



Wave direction 300
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
309,21 MPa
Δσ HS [MPa]
Wave height [m]



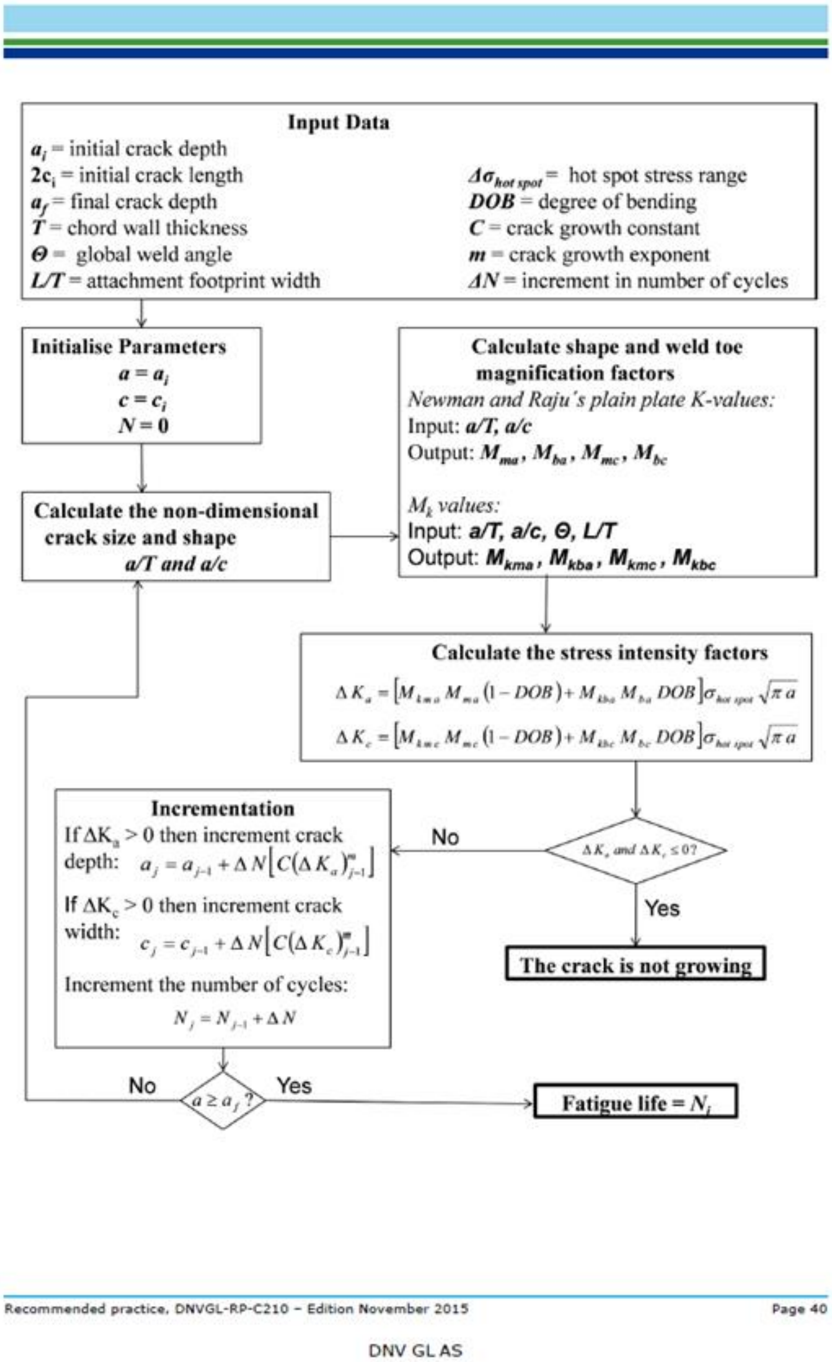
Wave direction 150
250
200
150
100
50
0
0
5
10
15
20
25
30
217,56 MPa
Δσ HS [MPa]
Wave height [m]



Wave direction 330
250
200
150
100
50
0
0
5
10
15
20
25
30
229,59 MPa
Δσ HS [MPa]
Wave height [m]

18.7 Schematic crack growth analysis procedure

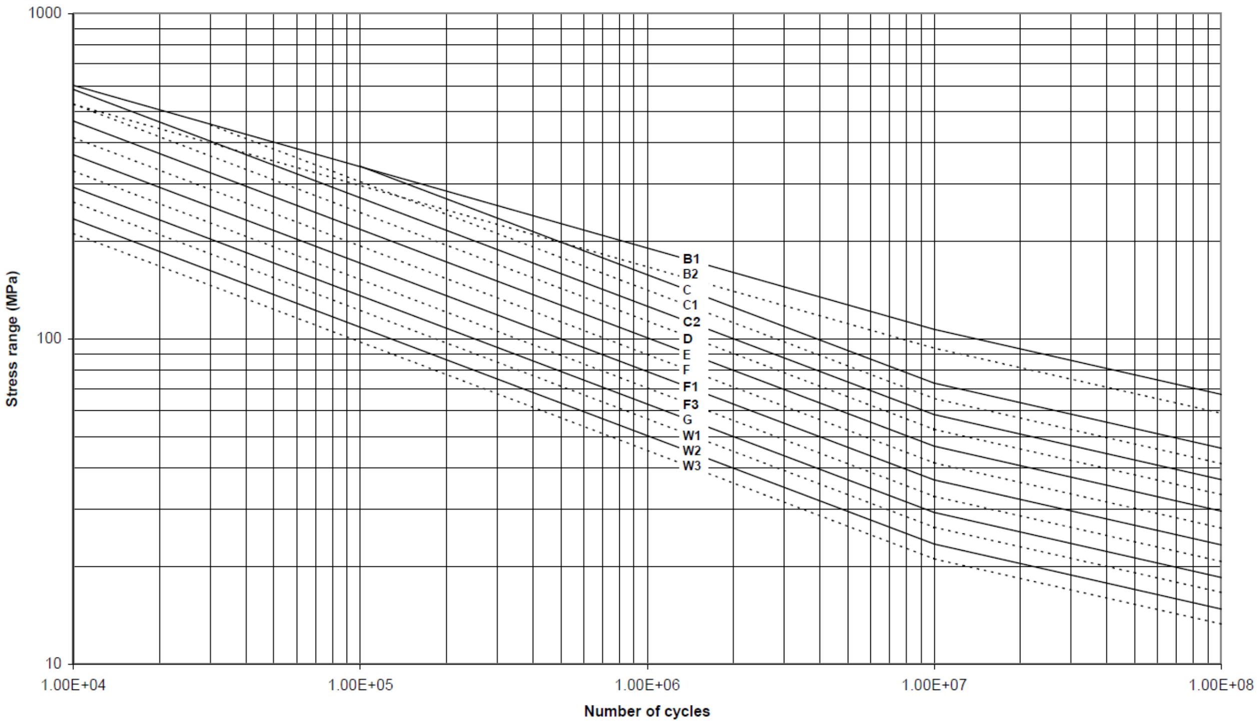
DETFAT evaluate crack growth in accordance to the following schematic procedure [5]:



18.8 SN – curves in air

Tables extracted form DNVGL – RP – C203 [4]:

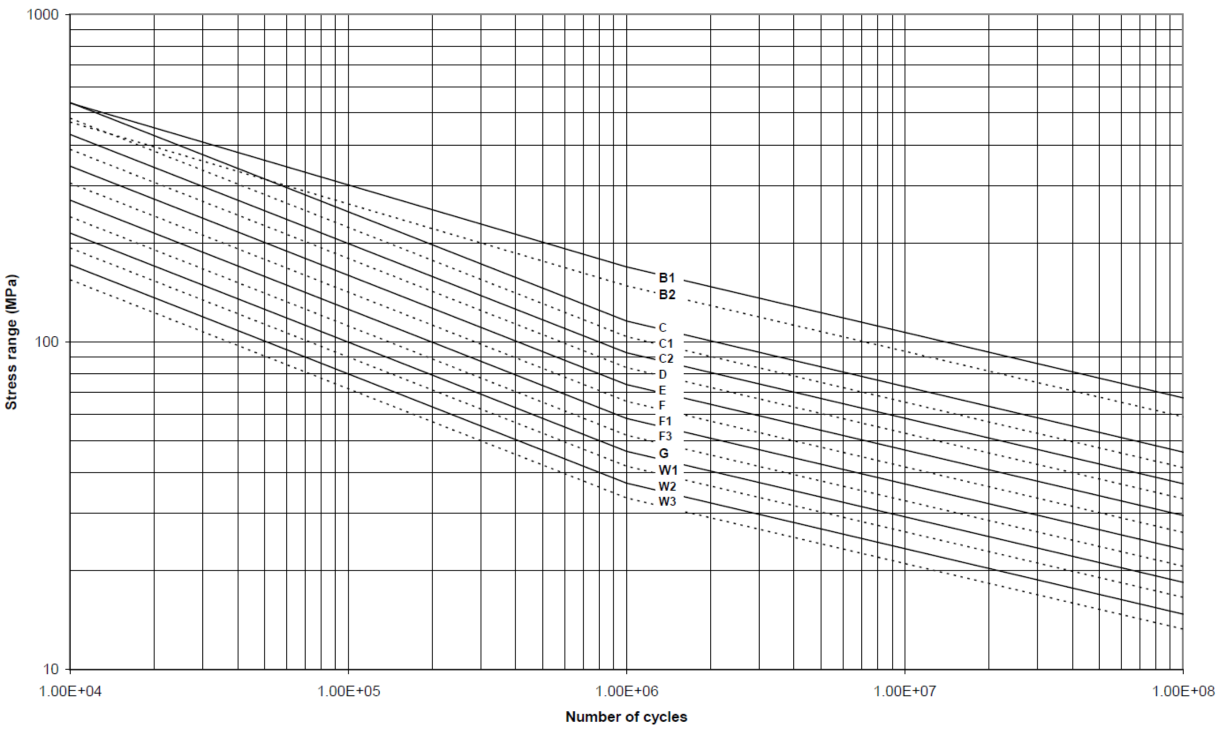
S-N curve	$N \le 10^7$ cycles		$N > 10^7$ cycles $\log \bar{a}_2$	Fatigue limit at 10^7 cycles *)	Thickness exponent k	Structural stress concentration embedded in the detail (S-N class), ref. also equation (2.3.2)
	m_1	$\log \bar{a}_1$	$m_2 = 5.0$			
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.05	
C1	3.0	12.449	16.081	65.50	0.10	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50
T	3.0	12.164	15.606	52.63	0.25 for SCF ≤ 10.0 0.30 for SCF >10.0	1.00



18.9 SN curves in seawater with cathodic protection

Tables extracted form DNVGL – RP – C203 [4]:

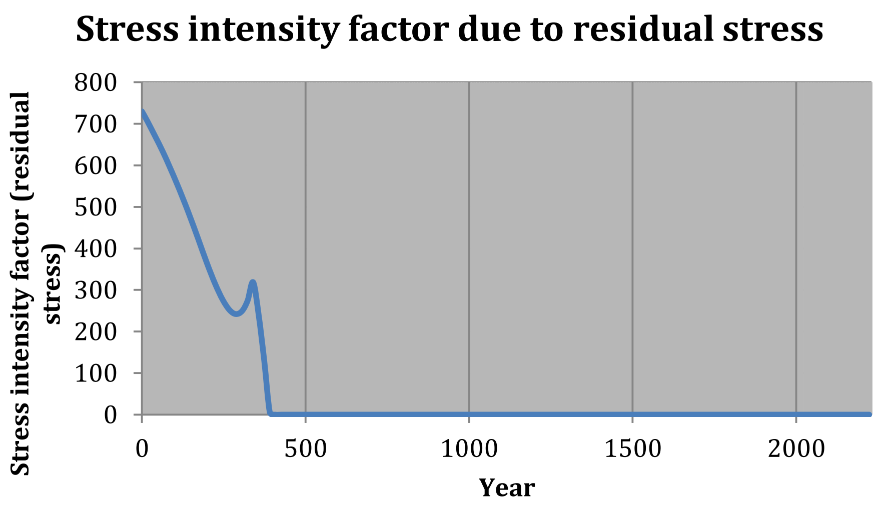
S-N curve	$N \le 10^6$ cycles		$N > 10^6$ cycles $\log \bar{a}_2$ $m_2 = 5.0$	Fatigue limit at 10^7 cycles*)	Thickness exponent k	Stress concentration in the S-N detail as derived by the hot spot method
	m_1	$\log \bar{a}_1$				
B1	4.0	14.917	17.146	106.97	0	
B2	4.0	14.685	16.856	93.59	0	
C	3.0	12.192	16.320	73.10	0.05	
C1	3.0	12.049	16.081	65.50	0.10	
C2	3.0	11.901	15.835	58.48	0.15	
D	3.0	11.764	15.606	52.63	0.20	1.00
E	3.0	11.610	15.350	46.78	0.20	1.13
F	3.0	11.455	15.091	41.52	0.25	1.27
F1	3.0	11.299	14.832	36.84	0.25	1.43
F3	3.0	11.146	14.576	32.75	0.25	1.61
G	3.0	10.998	14.330	29.24	0.25	1.80
W1	3.0	10.861	14.101	26.32	0.25	2.00
W2	3.0	10.707	13.845	23.39	0.25	2.25
W3	3.0	10.570	13.617	21.05	0.25	2.50
T	3.0	11.764	15.606	52.63	0.25 for SCF ≤ 10.0 0.30 for SCF >10.0	1.00

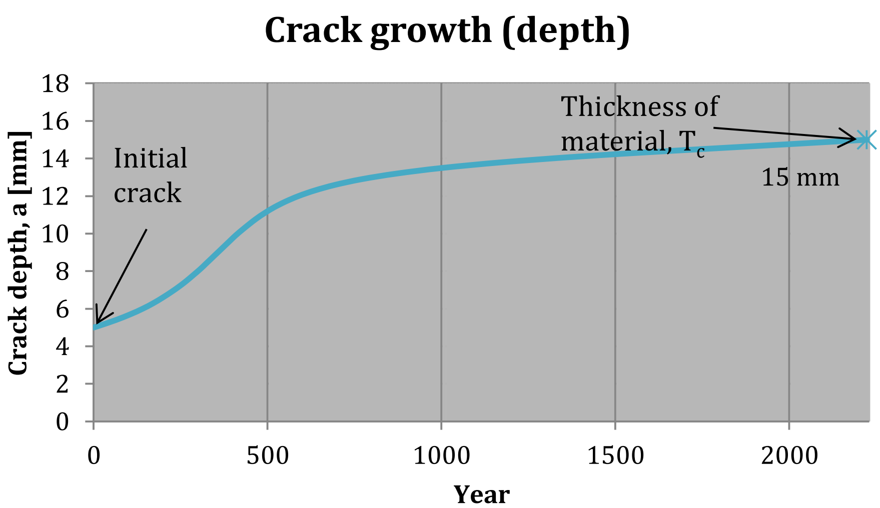


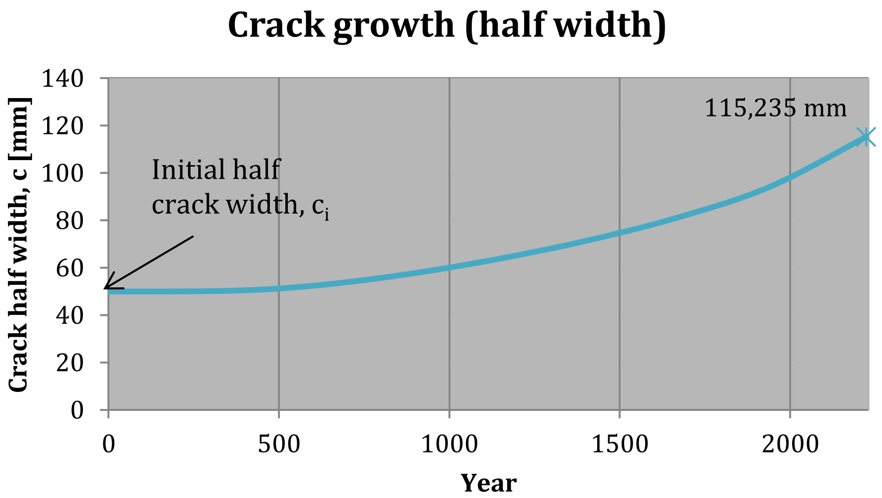
18.10 Fracture mechanics results for the inside

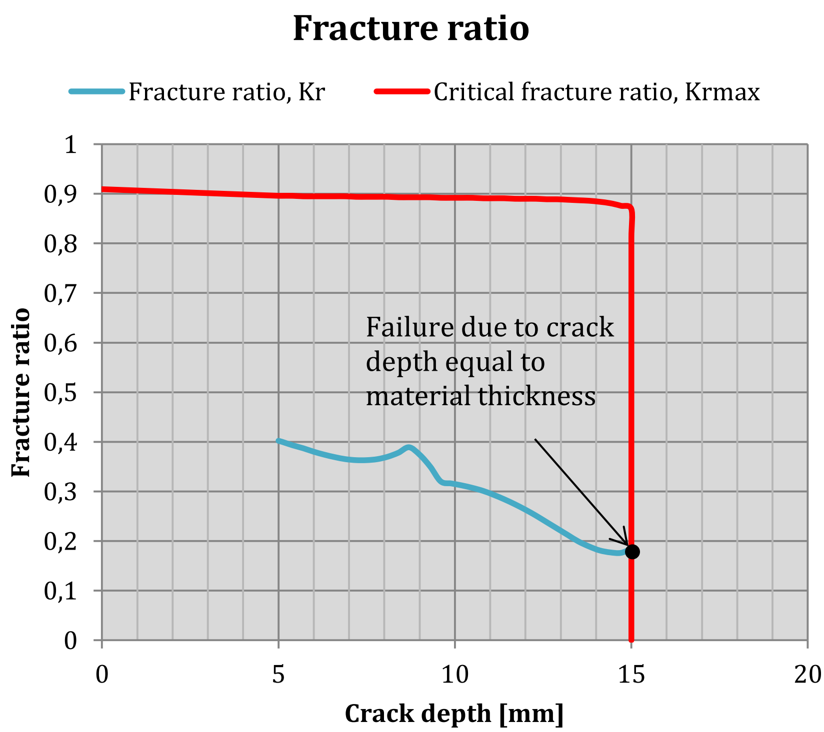
Fracture mechanics analysis results for the inside of the brace.

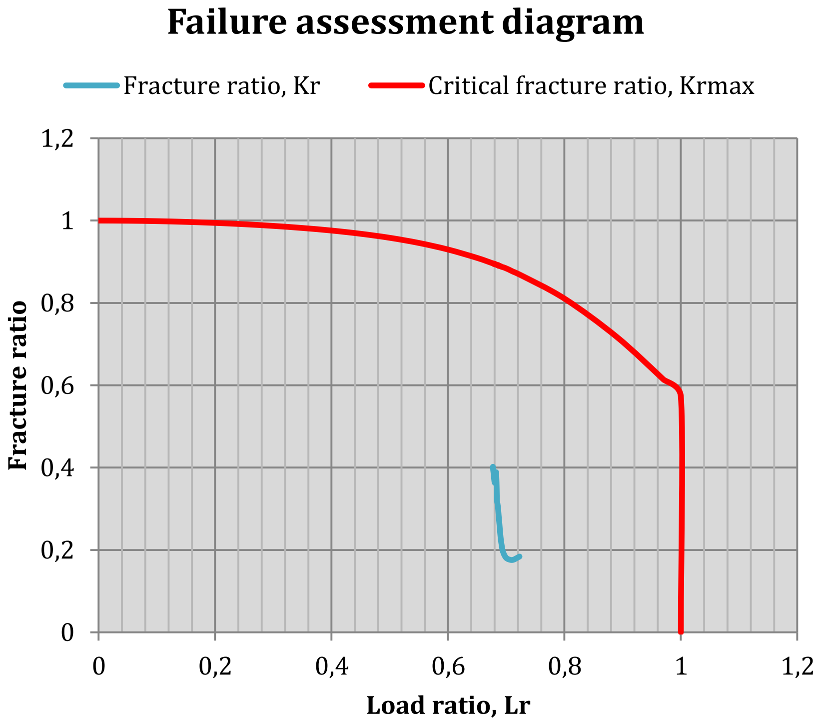
After 400 years the residual stresses in the x – joint is vanished which explains the change of crack growth rate.






Crack growth (half width)
Crack half width, c [mm]
140
120
100
80
60
40
20
0
Initial half
crack width, c_i
115,235 mm
0
500
1000
1500
2000
Year

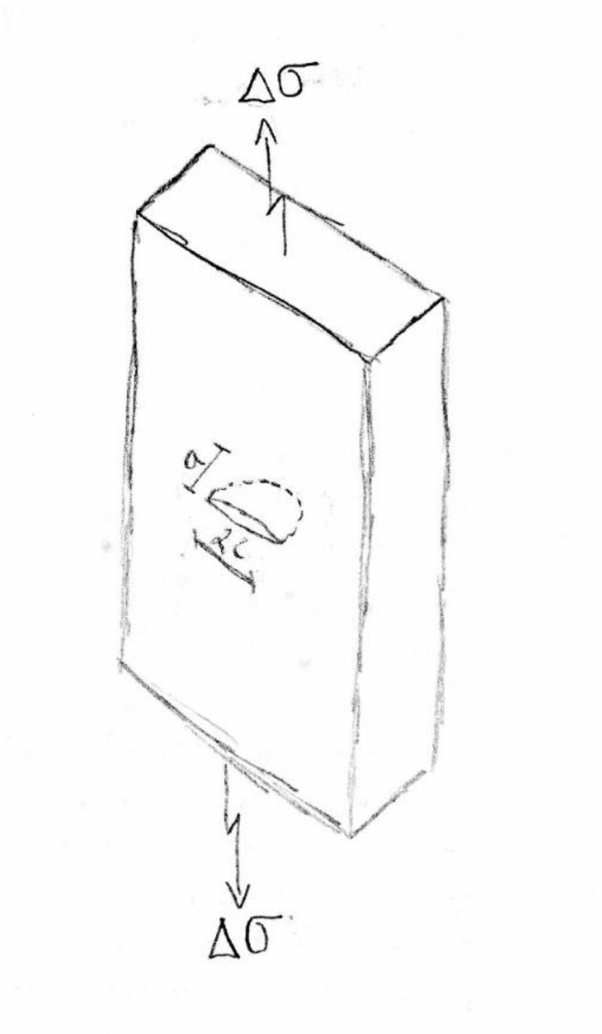

Fracture ratio
Fracture ratio, Kr
Critical fracture ratio, Krmax
Fracture ratio
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Failure due to crack
depth equal to
material thickness
0
5
10
15
20
Crack depth [mm]


Failure assessment diagram
Fracture ratio, Kr
Critical fracture ratio, Krmax
Fracture ratio
Load ratio, Lr
0
0,2
0,4
0,6
0,8
1
1,2

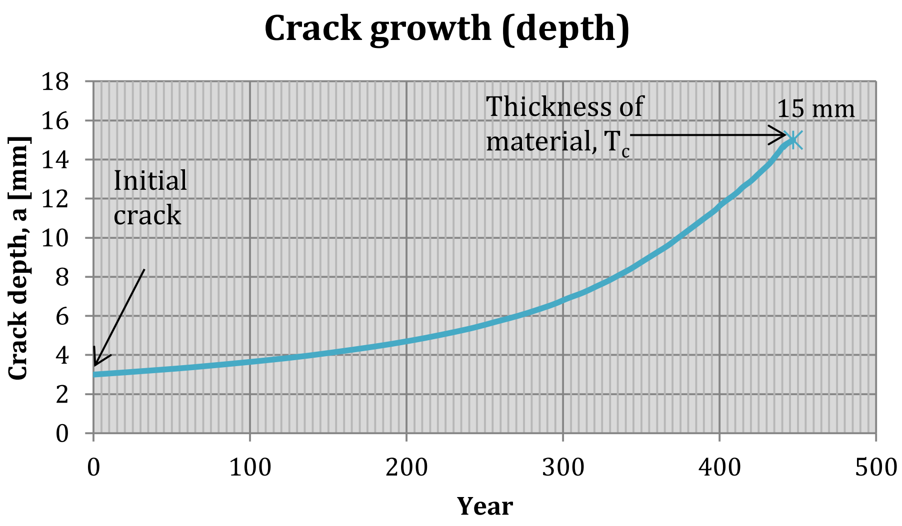
18.11 Sketch of crack dimensions

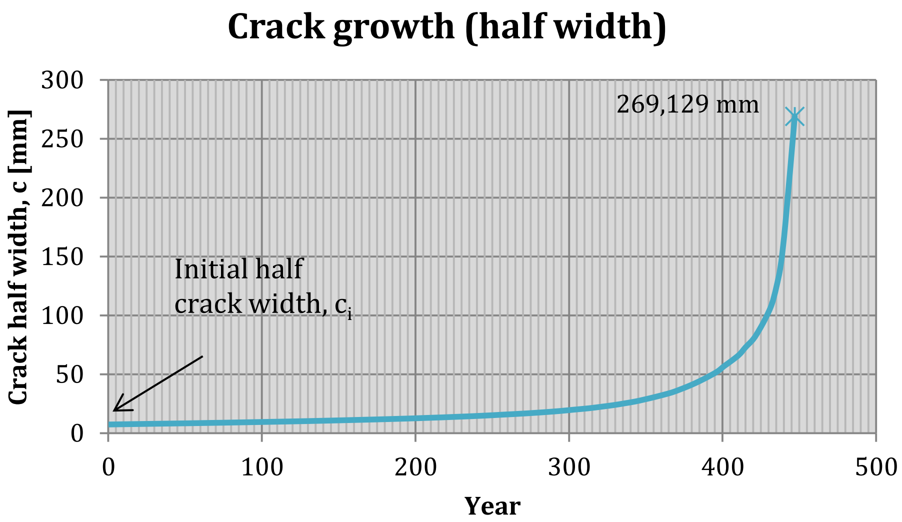
a: crack depth

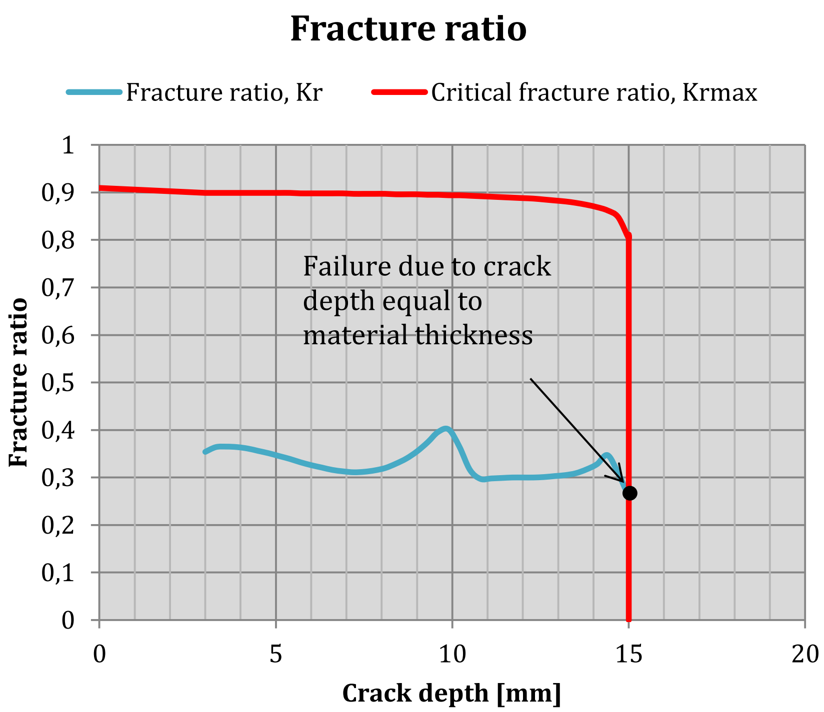
c: crack half width



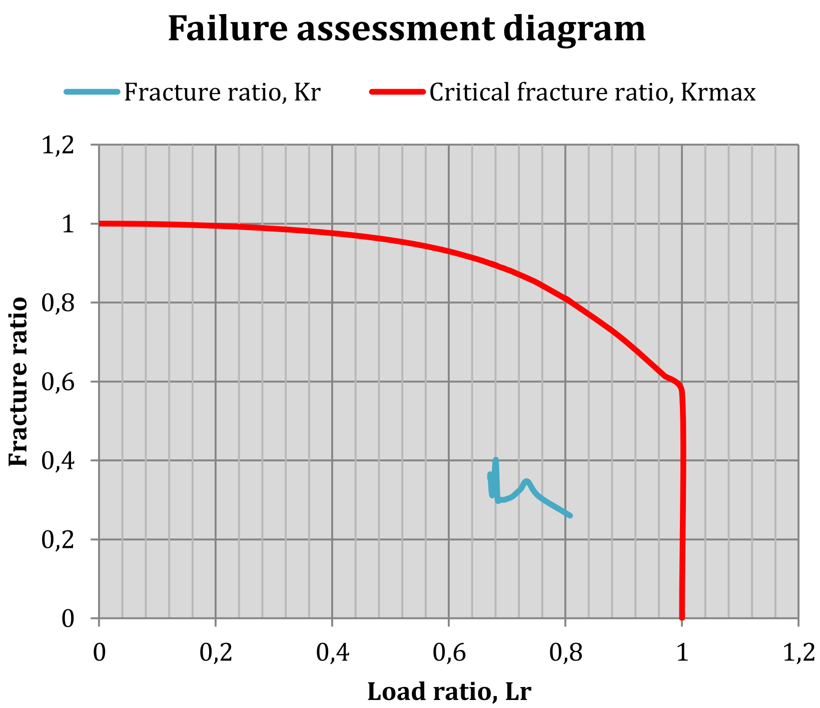
18.12 Fracture mechanics results for the outside







Fracture ratio
Fracture ratio, Kr
Critical fracture ratio, Krmax
Failure due to crack depth equal to material thickness
Fracture ratio
Crack depth [mm]
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
5
10
15
20



Failure assessment diagram
Fracture ratio, Kr
Critical fracture ratio, Krmax
Fracture ratio
Load ratio, Lr
1,2
1
0,8
0,6
0,4
0,2
0
0
0,2
0,4
0,6
0,8
1
1,2