IMPLEMENTATION OF REAL TIME FATIGUE ANALYSIS IN SHIP STRUCTURES

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Mechanical Engineering, Master's thesis

2024

Nikolas Strohecker

Examiners: Professor Timo Björk

Antti Ahola, D.Sc. (Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Mechanical Engineering

Nikolas Strohecker

Implementation of real time fatigue analysis in ship structures

Master's thesis

2024

40 pages, 16 figures and 3 tables

Examiners: Professor Timo Björk and Antti Ahola, D.Sc. (Tech.)

Keywords: fatigue, ship structures, real-time monitoring

A fatigue life monitoring system is defined and presented for two ship structures. The proposed system consists of measuring strain in the material with strain gauges, after which the data is processed and a fatigue life estimation is performed. The ship structures consist different types of welds on S690QT plates with the loading cases being defined as hogging wave, sagging wave and stillwater with unknown amplitudes. The used fatigue life estimation method is an implementation of the 4R method based on EP 4 018 171 B1. The VA nature of the loading and the possible overloading's effect on the residual stress in the welds are considered as parts of the method.

The results show that the all the described parts of the fatigue monitoring system work together. *H*- and *n*- parameters for R-O material model are defined and the SCFs are obtained using FEA on the ship structures. The memory effect in the cycle counting and a mean stress correction based on the SWT approach are used to consider the possible effects that VA loading cases produce. The accuracy of the system is not verified although the system is implemented in the ship structures. The use of the system and considerations related to implementing the system in other applications is reviewed.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Konetekniikka

Nikolas Strohecker

Reaaliaikaisen väsymisanalyysin implementoiminen laivarakenteisiin

Konetekniikan diplomityö

2024

40 sivua, 16 kuvaa ja 3 taulukkoa

Tarkastajat: Professori Timo Björk ja Antti Ahola, D.Sc. (Tech.)

Avainsanat: väsyminen, laivarakenteet, reaaliaikainen monitorointi

Tässä diplomityössä määritetään ja esitetään väsymisen seurantajärjestelmä kahdelle laivarakenteelle. Ehdotettu järjestelmä koostuu materiaalin venymän mittaamisesta venymäliuskoilla, minkä jälkeen kerätty data käsitellään ja jäljellä olevan kestoiän arviointi suoritetaan. Laivarakenteet koostuvat erilaisista S690QT-levyihin tehdyitä hitseistä, joissa kuormitustapaukset on määritelty hogging-aallon, sagging-aallon ja tyynen veden kuormituksiksi tuntemattomilla amplitudeilla. Diplomityössä käytetty kestoiän arviointimenetelmä perustuu EP 4 018 171 B1 -patenttiin. Kuormituksen VA-luonne ja mahdollisen ylikuormituksen vaikutus jäännösjännityksiin hitsisaumoissa otetaan huomioon yhtenä osana menetelmää.

Tuloksista on havaittavissa, että kaikki esitetyt väsymisen seurantajärjestelmän osat toimivat yhdessä. R-O-materiaalimallin *H*- ja *n*-parametrit määritetään ja laivarakenteiden jännityksen konsentraatiokertoimet saadaan hyödyntämällä FEA:aa. Syklien laskennassa hyödynnetään muisti-ilmiötä ja keskijännityskorjausta perustuen SWT-menetelmään, jotta voidaan ottaa huomioon VA-kuormituksen mahdolliset vaikutukset. Järjestelmän tarkkuutta ei ole varmistettu, mutta se on otettu käyttöön laivarakenteissa. Lopuksi tarkastellaan järjestelmän käyttöä ja sen käyttöönottoon muissa sovelluksissa liittyviä huomioitavia asioita.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my gratitude towards the crew at ReFaMo Oy, especially CEO Vesa Aaltonen for creating this opportunity as well as providing me support in a variety of different ways throughout the entire process of this thesis. I would also like to thank my supervisors and examiners, Timo Björk and Antti Ahola, for guiding me and giving me lots of useful advice for this thesis. I would also like to thank my family as well as my friends, namely Eetu Sukanen, Kiia Grönlund and Ida Rasilainen for giving me support during free time and for providing me with countless fond memories throughout my entire studies at LUT University. Lastly, I want to thank the crew at Meyer Turku Oy, especially Matias Tourula and Matti Rautiainen for their collaboration in this thesis.

Nikolas Strohecker

18.3.2024

SYMBOLS AND ABBREVIATIONS

Roman characters

a	throat thickness	[mm]
C_{ref}	reference curve fatigue capacity	
D	damage sum	
H	strength coefficient	[MPa]
K_f	fatigue notch factor	
K_t	notch stress concentration factor	
m	reference curve slope	
n	strain hardening exponent	
r	weld toe radius	[mm]
R	stress ratio	
R_e	electrical resistance	[Ω]
R_m	ultimate tensile strength	[MPa]

Greek characters

$\Delta\sigma_k$	linear elastic stress range	[MPa]
$\Delta\sigma_{k,eq}$	mean stress corrected equivalent stress range	[MPa]
σ_{res}	residual stress	[MPa]

Abbreviations

CA	Constant Amplitude
DNV	Det Norske Veritas

ENS	Effective Notch Stress
FEA	Finite Element Analysis
HSS	High Strength Steel
IIW	International Institute of Welding
LEFM	Linear-Elastic Fracture Mechanics
LSP	Laser Scan Profiling
NDT	Non-Destructive Testing
SCF	Stress Concentration Factor
SHSS	Structural Hot-Spot Stress method
SLP	Structured Light Projection
UHSS	Ultra High Strength Steel
VA	Variable Amplitude
WIA	Weld Impression Analysis

Table of contents

1 Introduction

Fatigue is a phenomenon, which has become a critical design criterion for a lot of different types of welded steel structures in the ship industry. There are a multitude of reasons for fatigue being a critical design criterion, which leads more accuracy needing to be focused on ensuring that the structure lasts as long as it is designed to, while staying within budget. Most approaches to fatigue life estimation are based on constant amplitude (CA) loading, which only rarely applies in practise due to the varying nature of loading at sea. For an example the size of waves that occur in the oceans can vary greatly. There may also be uncertainties in the sizes of the waves in certain locations, as well as variations in the speed of the ship and the angle at which it hits the waves, all of which contribute to the nature of the loading case to be unknown. As a result, there arises an interest to monitor the fatigue behaviour within a ship's structures in real-time to verify the fatigue life together with the loads assumed in the design phase of the ship. Real-time monitoring of the fatigue behaviour of a ship can also be utilized to help scheduling maintenance of the ship.

This is a master's thesis regarding fatigue assessment in ship structures in real-time. The aim of this research is to have a system that can do exactly that with as high accuracy as possible. The steps that will be taken in order to reach this goal include 3 main subjects. These are determining the necessary equations and algorithms that will be used to estimate the remaining fatigue life of the structure, defining the key parameters that need to be obtained from the structure itself or from literature and lastly introducing the software and hardware that will be used to carry out these calculations in real-time.

1.1 Background

The use of high strength steels (HSS) in the ship industry is a new concept. However, introducing them also brings a few obstacles that the designers need to overcome in order to get the ship to meet the industry standards. One of these obstacles is welding. In large cruise ships the plate thicknesses can go well beyond 100 mm in some parts of hull structures, which makes keeping the welding heat input within the acceptable range become a considerable issue (Sinha 2021). As a result, the residual stresses in the welds of these structures may come as difficult to keep low, which together with difficulties in carrying out treatments to lower these residual stresses in the large plates can cause for some concern in the impact these additional stresses have on the fatigue life of the structure.

Currently there are four main fatigue life estimation methods that are the most well-known ones as well as the most used ones in general. These are the nominal stress method, the structural hotspot stress method (SHSS), the effective notch stress method (ENS) As well as linear-elastic fracture mechanics (LEFM). However, none of these methods account for residual stresses specifically, which leads to them being rather conservative in some instances, where residual stresses play a key role in the fatigue life of the structure. The 4R method is utilized in this thesis. It is a fatigue life estimation method developed in Lappeenranta–Lahti University of Technology (LUT). It considers the residual stresses as well as the local behaviour of the critical structural detail and is explained more thoroughly later on.

1.2 Goal and research questions

The goal of this thesis is to develop the methodology behind a fatigue monitoring system that can reliably measure stresses and estimate the fatigue life of the two selected ship details in real-time while accounting for variable amplitude (VA) loading. The subgoals derived from this goal can be divided into two categories. These are subgoals related to the method used to estimate fatigue life and subgoals related to taking VA loading into account in the fatigue life estimation part of the monitoring system. The subgoals related to the method used to estimate fatigue life consist of gathering all the necessary parameters for the 4R method and defining the system that will carry out the fatigue life estimation. The subgoals related to taking VA loading into account consist of finding out how to consider the effects of overloading to the following load cycles and how to implement this together with the 4R method into the monitoring system.

The research questions for this research are:

- How can the fatigue life of a marine structure be monitored in real-time?
    - How can the 4R method be implemented into the monitoring system?
    - How can residual stresses be taken into account?
    - What additional considerations need to be made due to VA loading?

1.3 Limitations

There are a few limiting factors in this research. The most significant ones are the use cases themselves, which are parts of a ship hull. The use case is a considerable limitation since the stress concentration factors (SCFs) only apply to the structures that they are obtained from. It should still be kept in mind that other parts of the methodology described in this thesis can be applied to other structures so long as the SCFs are obtained appropriately. Another limiting factor is the material of the structure in question. Many of the methods described in the research are made specifically for steel structures so that should be kept in mind when utilizing similar methods. Furthermore, the used methods are focused to work on HSSs.

2 Methods

In this chapter the methods for this research will be discussed. The methods consist of the following:

- Firstly, a literature review will be conducted focusing on the core subjects of the research.
- Numerical methods will be used to determine the essential variables to the research.
- Lastly, a brief examination is conducted on some recently performed experiments to gather useful insights into the subject.

2.1 Numerical finite element methods

The method used to conduct the fatigue life estimation in this research is the 4R method. It is a notch stress method, which means that in the case of this thesis it requires SCFs.

Finite element analysis (FEA) will be used primarily to obtain the SCFs for the structures analyzed in this thesis. The reasons for choosing FEA to get the SCFs are that it is significantly faster and easier than obtaining them from literature, such as (Radaj, Sonsino & Fricke 2006, pp. 92-527) or experimental data in the cases of this thesis. The unusual geometries would also make obtaining them from other methods somewhat more difficult and possibly even more prone to errors when comparing to FEA. The finite element models are made based on effective notch stress, which is the theory followed in this thesis to obtain the SCFs.

There are a few key elements that need to be done right in order to get reliable results from FEA. The first ones are choosing the correct element type for each occasion since different types of elements have different limitations and properties. The loading and boundary conditions also need to be chosen carefully so that they resemble the real-life situation as closely as possible. The final thing that needs to be completed carefully is the meshing of the model. This helps the model give more accurate results especially at the most critical areas.

2.2 Field measurement system in the ship structure

The selected method of measuring stresses from the structures is by utilizing strain gauges. There are a few other options to measure them, but this was the chosen method due to it being the best suited one for this case. There are three main types of strain gauges, which are mechanical, optical and electrical resistance-based ones. The chosen type of strain gauge for this study is the resistance based one since they are accurate, easily available and overall the best suited for this application.

The strain gauges are placed close to the observed details of the structures that are examined. This way the stresses can be obtained from a part of the structure and together with SCFs obtained from FEA, the obtained strain values can then be converted into the stresses that reside in the most critical parts of the structures.

The signal received from the strain gauges then goes through a computing system, which filters out the noise and turns the data into a form, which can be analyzed further to estimate the remaining fatigue life of the structures.

3 4R method

The fatigue monitoring system described in this thesis requires a fatigue life estimation method as one of its primary components. In this chapter the fatigue estimation method, which is the 4R method, is discussed. Its basic principles are explained first after which all the variables that are required for it get looked at as well as how they can be obtained.

The reason for selecting the 4R method as the fatigue life estimation method is that the structures in question have welds in them, which means that the notch stresses in the weld toes need to be accounted for in some manner and thus a notch-based approach to estimating the stresses in the structures must be selected. Additionally, other popular methods such as guidelines by Det Norske Veritas (DNV), Eurocode 3 and International Institute of Welding (IIW) do not take into account some of the parameters that are included in 4R, which might make it better suited for the cases in this thesis when comparing to other methods (Björk, Mettänen, Ahola, Lindgren, & Terva 2018, p. 2).

3.1 Theoretical background

The 4R method is a fatigue life estimation method that is based on a combination of the ENS method and a number of variables that are acquired to make the calculations more accurate. The method gets its name from 4 of its main variables. These are:

- R, stress ratio
- R_m, ultimate tensile strength
- σ_{res}, residual stress
- r, weld toe radius

The weld toe radius is used in FEA to determine the notch stress concentration factor K_t, which can then be approximated to be the same as the fatigue notch factor as follows $K_f \approx K_t$ (ρ=1 mm). After obtaining the fatigue notch stress concentration factor, the maximum notch stress in the weld can be determined and the next step in the procedure can be commenced. The ultimate tensile strength of the material is used to define material behaviour and together with some curve fitting into a material model is used to determine *H* and *n* parameters for the equation of the Ramberg-Osgood material model, which will then be used to determine the stress-strain behaviour of the structure. The residual stress is used to determine the elastic-plastic stress in the structure through Neuber's rule, which is then used together with previously mentioned Ramberg-Osgood material model to estimate the material behaviour under loading. Lastly, the stress ratio is involved in the calculation of the life cycle.

After getting all the variables, the fatigue life of the structure in question can be calculated in the following manner:

$$N_f = \frac{C_{ref}}{\left(\frac{\Delta\sigma_k}{\sqrt{1\text{-}R_{local}}}\right)^{m_{ref}}} \tag{1}$$

Where C_{ref} is the fatigue capacity of the reference curve and m is the slope of the reference curve respectively. $\Delta\sigma_k$ is the linear-elastic effective notch stress. The stress ratio R_{local} is obtained after the calculations are made from the equations associated with 4R method.

$$R_{local} = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{2}$$

Where $\sigma_{\min}$ is the minimum local stress of the stress cycle being examined and $\sigma_{\max}$ is the maximum local stress respectively.

3.2 Acquiring 4R variables

Weld toe radius *r* is determined by examining the actual weld in question. It is important to note that in this case the observed structures are a part of a functional real-world structure rather than a test specimen. As a result, the methods used to find the weld toe radius must be non-destructive methods (NDT). This can be done for an example by making a silicon mould of the weld and inspecting the resulting inverted model of the weld. Another method is completing a laser scan profiling (LSP), where a laser scanner is used to determine the shape of the surface. Alternatively, the weld toe radius can also be estimated by using other means such as a structured light projection (SLP), where a known structured light is projected onto the object and then a picture is taken with a camera after which the picture is analyzed and the 3D shape of the structure is determined using triangulation. The last method is the weld impression analysis (WIA) where the impression technique is combined with image analysis. (Harati, Svensson & Karlsson 2014, pp. 2-4.) Out of these methods creating a silicon mould the most suitable method for this case since the structures in question are fairly large in size. Weld toe radius is often considered to be $r = r_{true} + 1$ mm, where r_{true} is the weld toe radius obtained from the structure. However, in this case the structure will not be able to be examined so the weld toe radius shall be defined as $r = 1$ mm instead, where r_{true} is assumed to be 0 to assume the worst-case scenario. The ultimate tensile strength R_m can be obtained from the manufacturer of the material for an example from the material certificate.

3.3 Residual stress and residual stress relaxation

Residual stress σ_{res} can also be determined by examining the structure in question, in this case the ship structures. There are also several ways of doing this. However, as with the weld toe radius, this also has to be done with an NDT method since it has to be taken from the live structure. This creates some limits on the possible methods that can be used. Some examples of NDT methods are different types of diffraction methods and methods based on the magnetic properties of steel or the acoustic-elasticity effect that appears in steel. (Rossini, Dassisti, Benyounis & Olabi 2012, pp. 4-26.) As with the weld toe radius, this also cannot be determined from the geometry, so a worst-case scenario has to be assumed here as well. For this reason, the residual stress shall be defined as being as high as the yield strength of the material $\sigma_{res} = f_y$.

Recent studies regarding the effects of overloading on residual stresses suggest that loads, that are near the yield strength to the material ($0.6fy$-$0.8fy$) have an effect on the weld toe, which causes some of the residual stresses to relax or in case of HSS and UHSS the resulting residual stress condition of the weld toe may end up under compression rather than tension, which affects the R ratio of the stress cycle and can prolong the fatigue life of the structure significantly. Figure 1 shows an example of an overloading case where a comparison is made between CA loading and CA loading after initially overloading the structure. (Grönlund, Ahola, Riski, Pesonen, Lipiäinen & Björk 2023, pp. 2-18.)

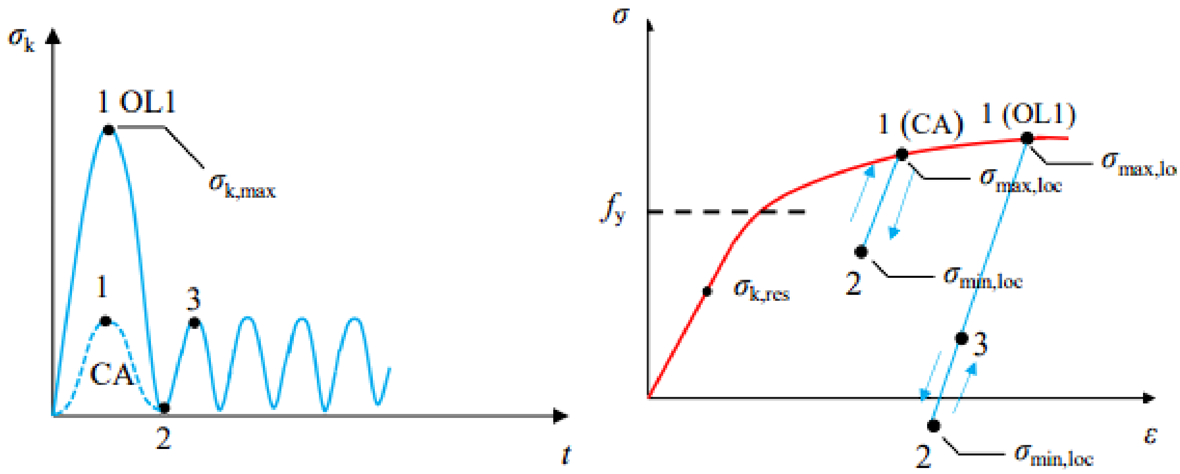

Figure 1. Example of overload's effect on the residual stresses in a structure (Grönlund et al. 2023, p. 12.)

The effect on residual stresses can be represented numerically by recalculating the new equivalent stress range value $\Delta\sigma_{k,eq}$ utilizing the Smith-Watson-Topper (SWT) rule in the following manner:

$$\Delta\sigma_{k,eq} = \sqrt[m]{\frac{1}{D}\frac{\sum n_i \left(\frac{\Delta\sigma_{k,i}}{\sqrt{1\text{-}R_{local,i}}}\right)^m}{\sum n_i}} \tag{3}$$

Where $\Delta\sigma_{k,eq}$ represents the mean stress corrected equivalent stress, m represents the slope of the reference curve, D is the damage sum and n_i the number of cycles in a sample. This way the VA loading cycles can be handled while taking into account the effect, that an overloading event has on the residual stresses of a structure.

4 Real-time monitoring of ship details

This section provides definitions of the structural details that will be taken a look at, examinations of their geometrical features together with any considerations that will have to made due to them. The materials used, residual stresses in the welds as well as the loading cases and FEA are also introduced in this chapter.

4.1 Structural details

There are two different structural details that are studied in this thesis. These are the following:

- A fillet welded stiffener to plate joint.
- A butt-welded plate joint.

Below are figures 2 and 3, where these joints are demonstrated. The critical welds are circled in red in both figures.

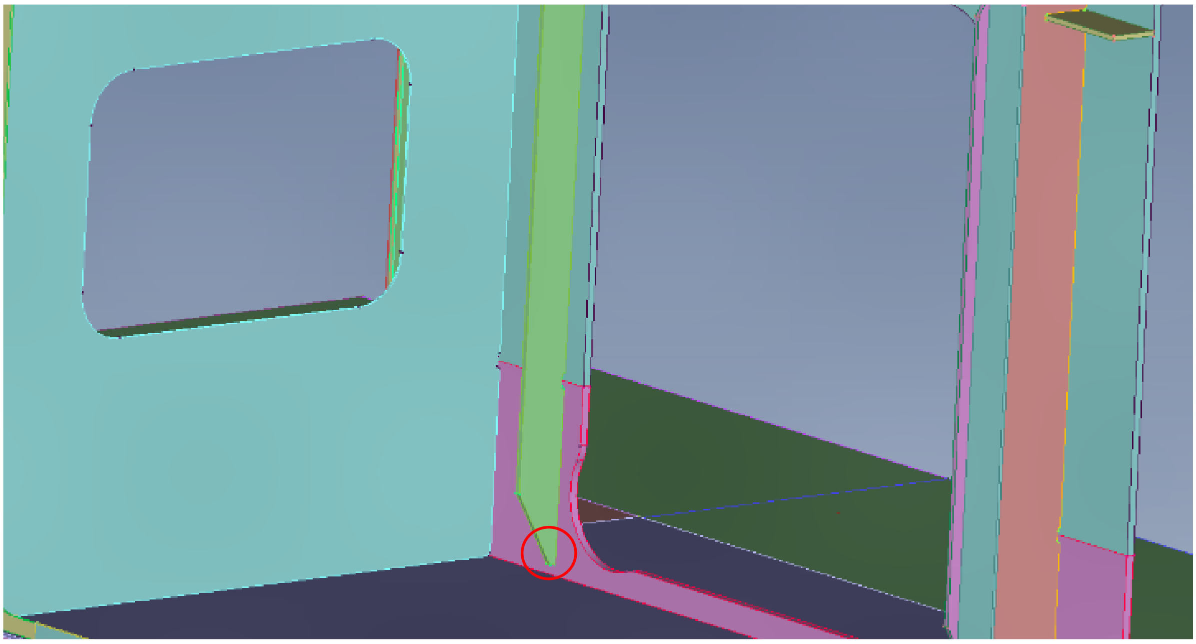

Figure 2. The fillet welded stiffener to plate joint.

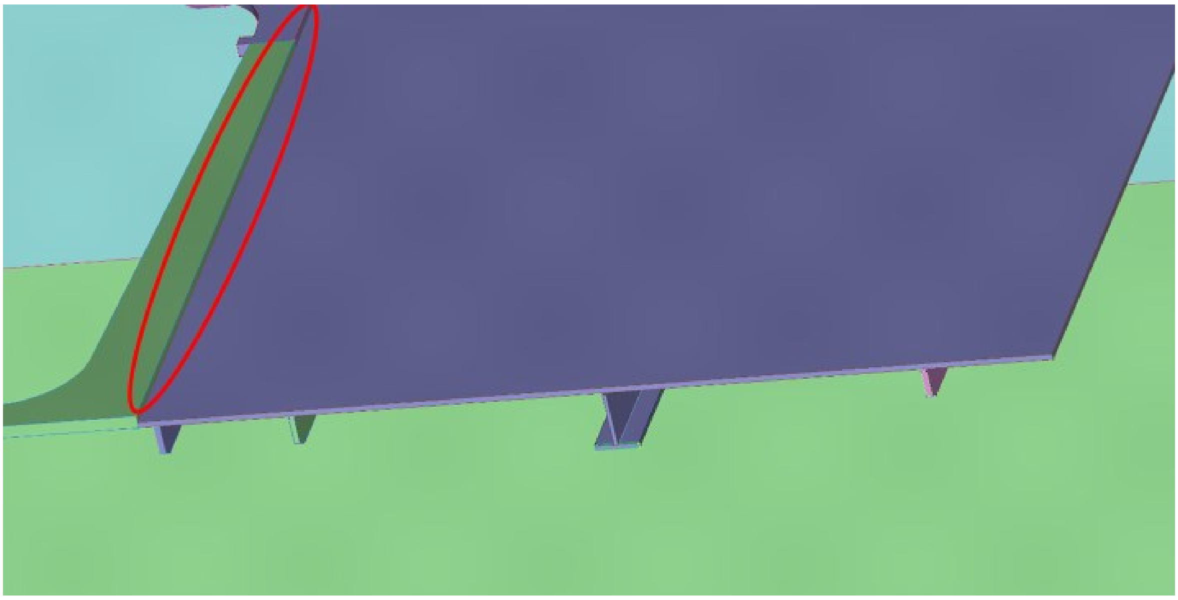

Figure 3. The butt-welded plate joint.

The main geometrical features that need to be considered come from there being varying plate thicknesses and the joints between these varying thickness plates being unaligned. There is also a lack of symmetry in any direction in both structures, which means that symmetry cannot be taken an advantage of either. There are also a multitude of plates intersecting across different axis as well as multiple stiffeners, which complicate the load distribution in the structure. These facts coupled with the large number of components compose the majority of geometrical issues that come with analyzing the structures in question.

4.2 Measuring and handling of data

It is important to note that as the subject of this thesis is to present a system which works in real-time, no strain data will be collected or presented in this thesis apart from an example presented later. Rather, the methods of handling the data obtained from strain gauges will be described.

The method used for obtaining the stresses from inside the structures is by placing strain gauges on them at predetermined locations near the critical welds. There are strain gauges placed in one place in each structural detail near the critical area. There are two strain gauges in total per structural detail. The reason for using two specifically is to ensure that if an event occurs, where one of the strain gauges becomes faulty for any reason, that data can still be collected for analysis through the second strain gauge.

On the stiffener to plate joint the strain gauges are placed by the joint, but on the opposite side of the plate due to the welds near the joint presenting some problems with the installation process. The gauges are placed 10 mm (0.4*t*) away from the weld toe and 10 mm lower than the critical joint. The strain gauges on the stiffener to plate joint are presented in figure 4.

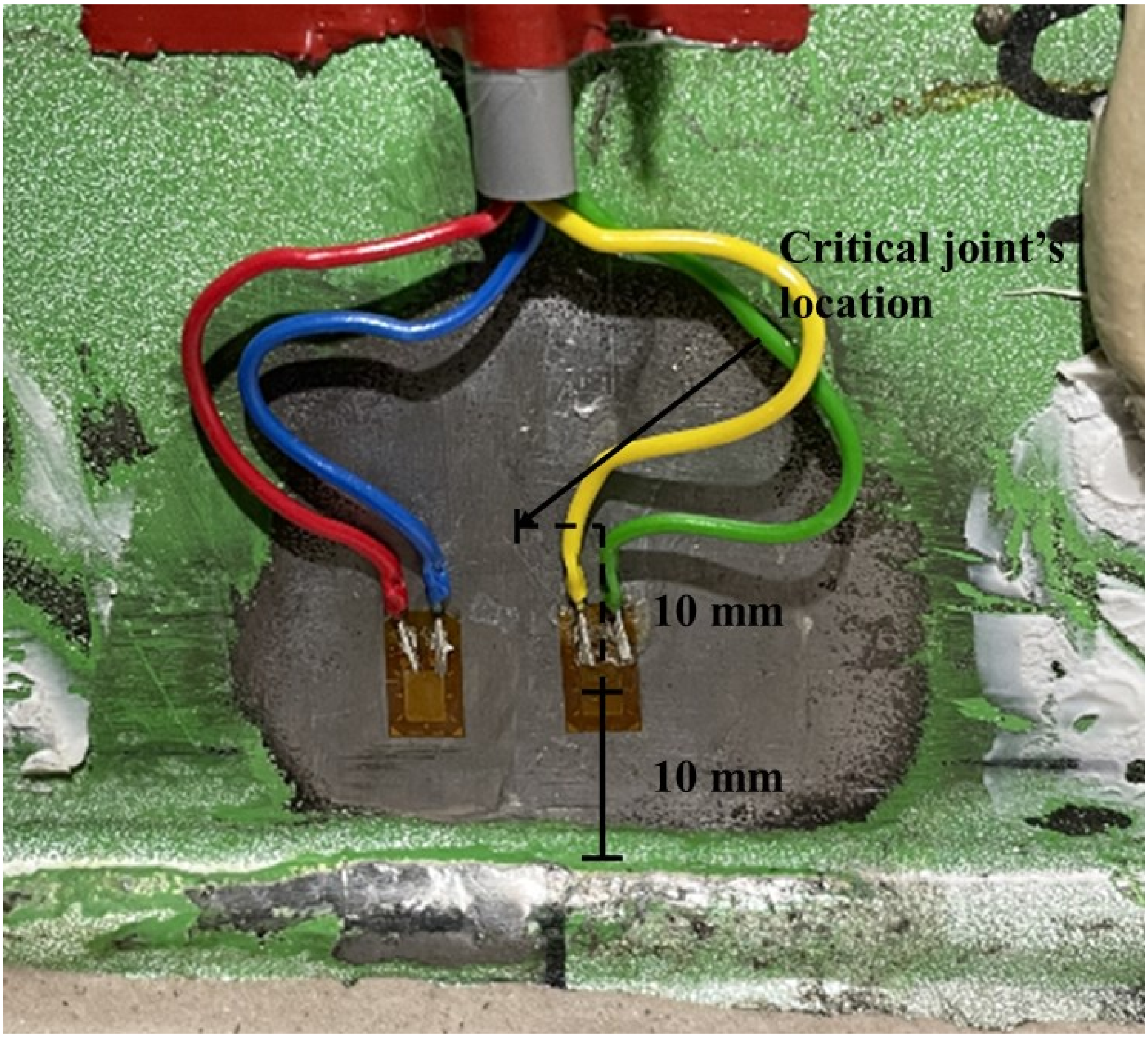

Figure 4. Strain gauges on the stiffener to plate joint.

For the butt-welded plate joint the strain gauges are placed near the weld on the thinner plate, 680 mm from the joint with the plate above and 10 mm from the weld toe. The strain gauges on the butt-welded plate joint are presented in figure 5.

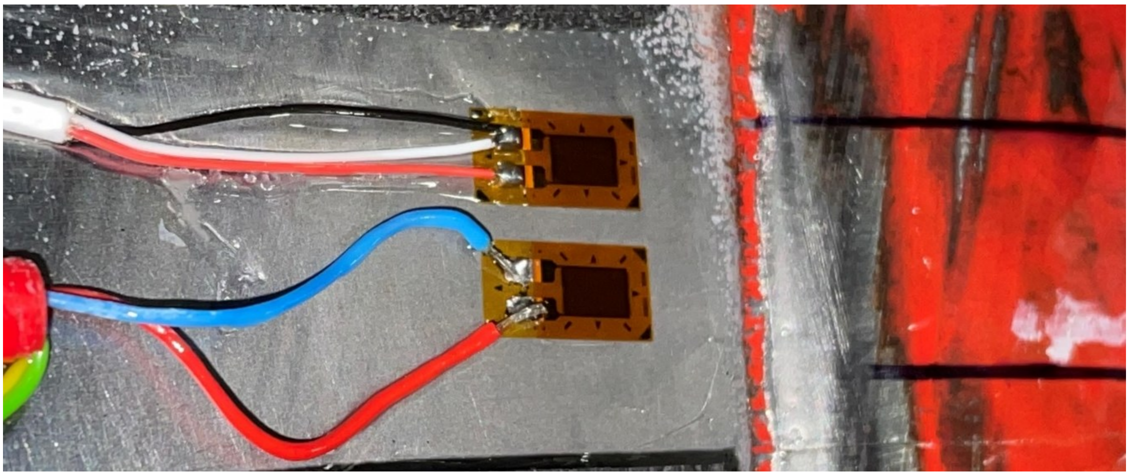

Figure 5. strain gauges near the butt-welded plate joint.

Figure 6 shows a description of the data processing of a fatigue life estimation system that works in real-time. This is just one example of how the incoming data from the strain gauge can be handled to produce an index to describe the estimated fatigue life in the structure.

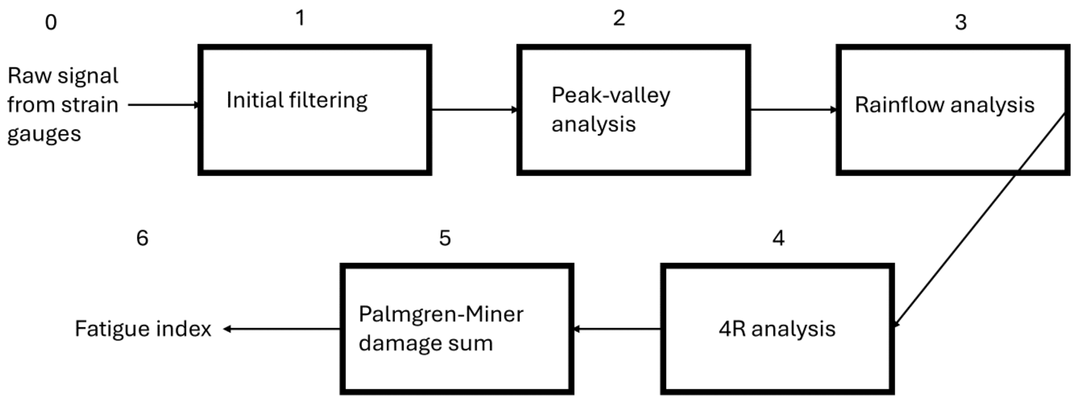

Figure 6. Description of the fatigue analysis system.

Step 0 represents the data that is sent from the strain gauges. This raw data takes up a lot of memory and can be difficult to process due to it containing multiple types of interferences such as noise and errors so the data must be handled in some way to make it more compact and easier to handle. This initial filtering is done in step 1 of the process.

After the initial filtering the data is in a form that is easier to process so the next step is to perform a peak-valley analysis on it on step 2. This way the only data that remains consists of the highest and lowest points of every cycle that can be found from the data. At this point of the analysis, it is crucial to ensure that only the intended cycles and all of the intended cycles remain at this point.

In step 3, the now remaining cycle data can be handled utilizing a form of cycle counting algorithm e.g. rainflow counting to further calculate the amount of different size full cycles from the peak-valley data. Depending on the selected approach to cycle counting, also half cycles may be counted in. However, in this thesis the assumed approach is a cycle counting method that only counts full cycles, which is carried out to the next step of the process.

Once the amount of full load cycles are calculated the next step is to perform a fatigue analysis on them. As the 4R method is the chosen method for this thesis, it is the method used to complete the fatigue life estimation on the load cycles. The rainflow counting as well as the 4R method are used in the same manner as described in European patent EP 4 018 171 B1. The way it is done in the patent is by creating a matrix, which shall be referred to as the rainflow matrix. In the rainflow matrix each element represents a full load cycle, and the value of the element represents the amount of load cycles that have happened in the elements' respective range. It should be noted that exact values cannot be used, or else no full load cycles are able to form due to the infinitesimally small differences between all the peak and valley values. As a result, the values must be rounded to a specified range e.g. to the closet 10 MPa so full cycles can be formed, and the data can be processed further. (Björk & Ahola 2023, pp. 2-10.)

The fatigue analysis is depicted in a manner, where another matrix is formed, which shall be referred to as the 4R matrix. In the 4R matrix each element has a corresponding load cycle value as described in the rainflow matrix. However, the values in the 4R matrix represent the inverse of fatigue life estimates for each of the load cycles found in the rainflow matrix.

These values are computed using equation 1 described in 3.1. (Björk & Ahola 2023, pp. 2-5.)

Step 5 consists of adding up the results of the 4R method to form the damage sum describing the total built up fatigue by using Palmgren-Miner rule as shown in the equation below. While using Palmgren-Miner rule, the theoretical fatigue life should be used up when the damage sum equals 1. This resulting damage sum is described as step 6 in figure 6. (Björk & Ahola 2023, p. 5.)

$$D=\sum\frac{n}{N} \tag{4}$$

Where N represents the response values of each different load cycle and n represents the number of the corresponding load cycles that have occurred and can be found in the rainflow matrix.

There are a few different equations that can be used to derive the strain of the material from the signal that the strain gauges emit. The correct equation depends on the way that the gauges are set up. For both cases in this thesis the direction of the most critical stresses is known, which results in being able to place all the strain gauges parallel to the principal stress direction. As a result, the one-dimensional version of the equation applies to both considered cases. The equation in question is the following:

$$\varepsilon=\frac{\frac{\Delta R_e}{R_e}}{K} \tag{5}$$

Where ε is strain, R_e is the initial electrical resistance of the strain gauge, ΔR_e is the change in the initial electrical resistance and K is the gauge factor. (DAV University 2013, pp. 2-31.)

After obtaining the strain in the material, it needs to be converted into stress. Since this study focuses on VA loading, where the maximum loads can exceed the yield strength of the material, both elastic and plastic areas of the material model need to be considered when converting the measured strains into stresses. For this reason, the material model that will be used for this conversion needs to be a linear-elastic, nonlinear-plastic material model so that the cyclic behaviour and more importantly the plastic behaviour of the material can be accurately represented in the calculations. Ramberg-Osgood types of material models fit these criteria and the Ramberg-Osgood material model is therefore the selected material model in this thesis.

Although the material behaviour in the critical locations can be elastic-plastic, the strain gauges are placed in an area, that is a small distance away and where the material behaviour is assumed to be linear-elastic. The reason for this placement is that the stress gradient is not as steep at a distance from the weld toe. Another reason for the placement of the strain gauges is to avoid any inaccuracies caused by the possible plastic behaviour around the measured area. The linear-elastic stress in the measurement area is converted to elastic-plastic stress through multiplication with the respective SCFs to estimate the local material behaviour.

4.3 Material model and material information

The base material for all the cases consists of the critical plates being S690QT as well as some other plates being lower strength alloys. However, as these lower strength alloyed plates are not located in the areas, that are taken a closer look at, they will not be considered any further.

S690QT is a structural steel, where QT means that it has been quenched and tempered (SFS-EN 10027-1 2016).

Material information regarding S690QT is presented in table 1:

Table 1. Material Information regarding S690QT.

Name	Yield strength f_y	Ultimate tensile strength R_m	Elongation ε
S690QT	690 MPa	770–940 MPa	14 %

The material model used is a Ramberg-Osgood type material model, which is mainly used to approximate the nonlinear relationship between stress and strain in steels when exceeding the yield strength of the material and when studying cyclic behaviour in material.

It consists of having two parts. First one is Hooke's law, which represents the elastic strain caused by the stress in the material and the second one represents the plastic strain caused by the stress. The equations go as follows:

$$\varepsilon_y = \frac{\sigma}{E} \tag{6}$$

$$\varepsilon_p = \left(\frac{\sigma}{H}\right)^{\frac{1}{n}} \tag{7}$$

Where H and n are parameters that depend on the material chosen. Parameter H is the strength coefficient and is tied to the ultimate tensile strength of the material, usually being $1.65{*}R_m$ for steels with a mild yield strength, such as S355. Parameter n is the strain hardening exponent and is usually around 0.15 for mild yield strength steels (Radaj et al. 2006, p. 206). However, as the material in this thesis is a HSS, the values for H and n will be calculated separately. Equations 6 and 7 can be then combined to count for both elastic and plastic strain inside the material. This will the form of the equations that is used in this thesis, which is the following (Ramberg and Osgood 1943, pp. 2-12.):

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{H}\right)^{\frac{1}{n}} \tag{8}$$

In cyclic loading the above-mentioned equation is used as the monotonic curve, which is used when first applying a load to a structure, either monotonic or cyclic. There is also a cyclic curve, which follows the kinematic hardening rule and is applicable for unloading and is also used for reloading. It is the following:

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2H}\right)^{\frac{1}{n}} \tag{9}$$

In fatigue life estimations, the monotonic curve is used to estimate the effect of the loading phase of the stress cycle. Respectively, the cyclic curve is used to describe the material behaviour when unloading and reloading. (Dowling, Prasad and Narayanasamy 2013, pp. 668-680.)

In VA loading the effect of the stress peaks as well as the possible small load cycles that follow high load cycles needs to be taken into account in the fatigue life estimation of the material since the monotonic curve does not describe them accurately. However, the cyclic curve represents this type of behaviour more accurately and is used to describe the material behaviour in peak loading cases in the following way. (Dowling et al. 2013, pp. 668-680.)

A monotonic loading case is presented in figure 7. This is presented in the form of strain since that is the form that the input will be coming in from the strain gauges. The data is in the pre-processed peak-valley form since this is the form that it is in when it is run through equations 8 and 9. The graph consists of three points, which are the beginning point 0, maximum point A and minimum point B. And as shown in figure 7, the data first goes from 0-A and subsequently oscillates between A and B. In figure 8 the stress-strain response of the loading is presented. The first loading phase from 0-A is mapped out with the monotonic curve shown in red while the following unloading and reloading cycles between A and B are mapped out with the cyclic curve shown as blue.

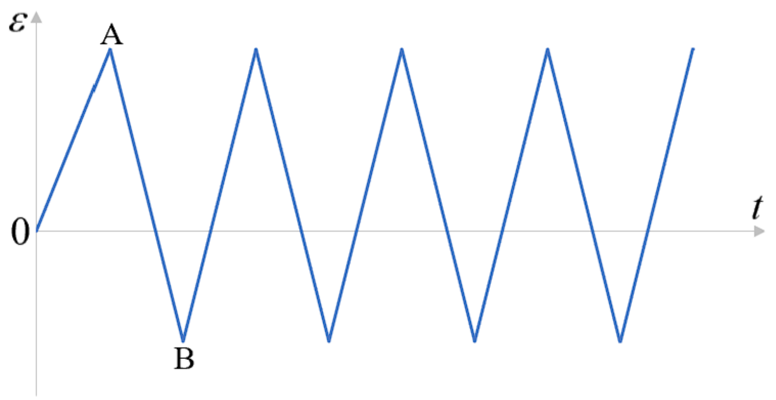

Figure 7. Example of monotonic loading case.

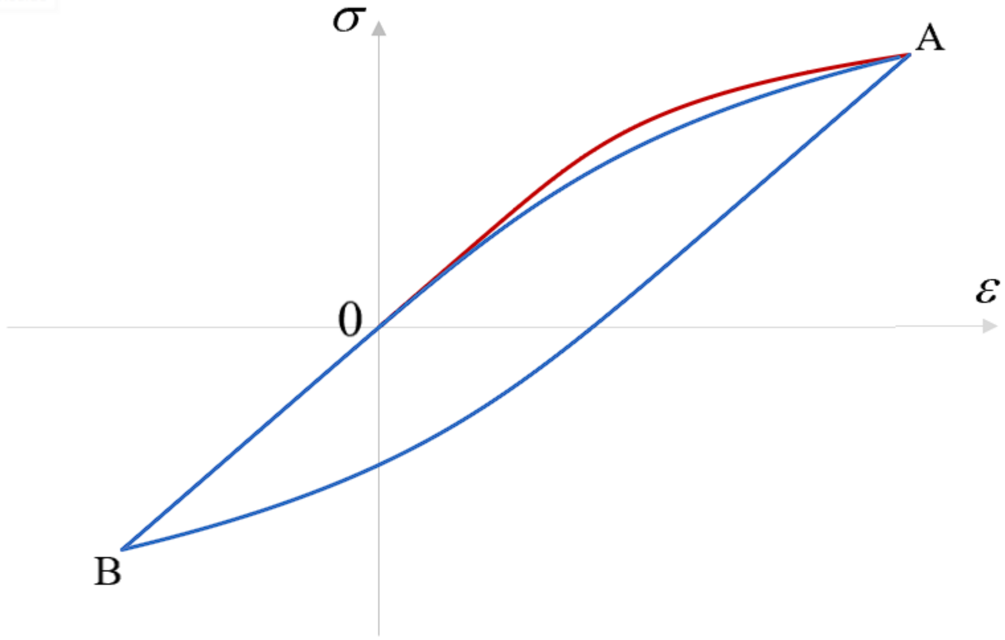

Figure 8. Stress-strain response of the monotonic loading.

A VA load case is presented in figure 9. It is also presented as input strain data. There are three closed loops that can be observed here. These loops are A-D-A’, B-C-B’ and F-G-F’.

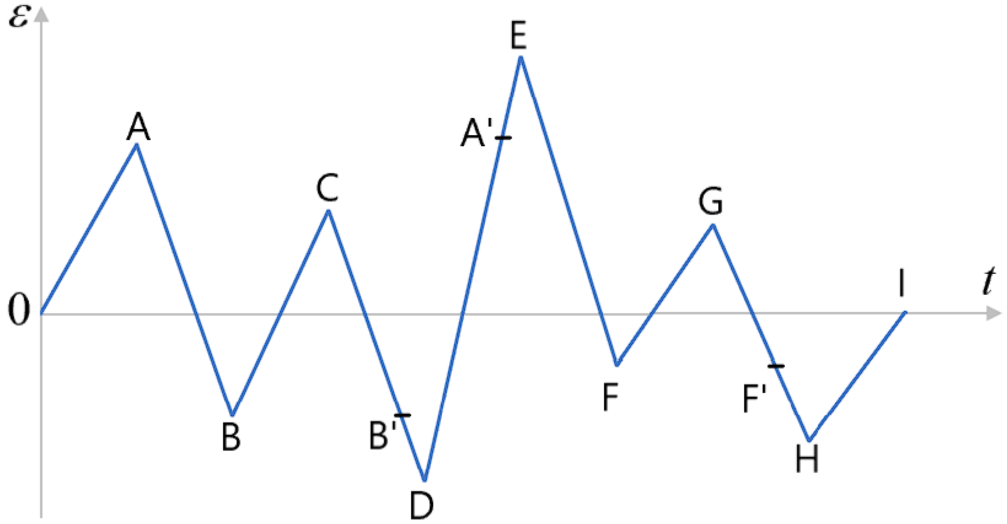

Figure 9. Example VA loading data.

In figure 10 the stress-strain response for this input data is plotted. It should be noted that after the previously mentioned loops are closed, the plotting continues from where it left off in the previous cycle. After closing the A-D-A' cycle, the A'-E continues from point A along the 0-E half-cycle. Similarly, B'-D continues from point B along the A-D half-cycle and F'-H continues as F-H along the E-H half-cycle.

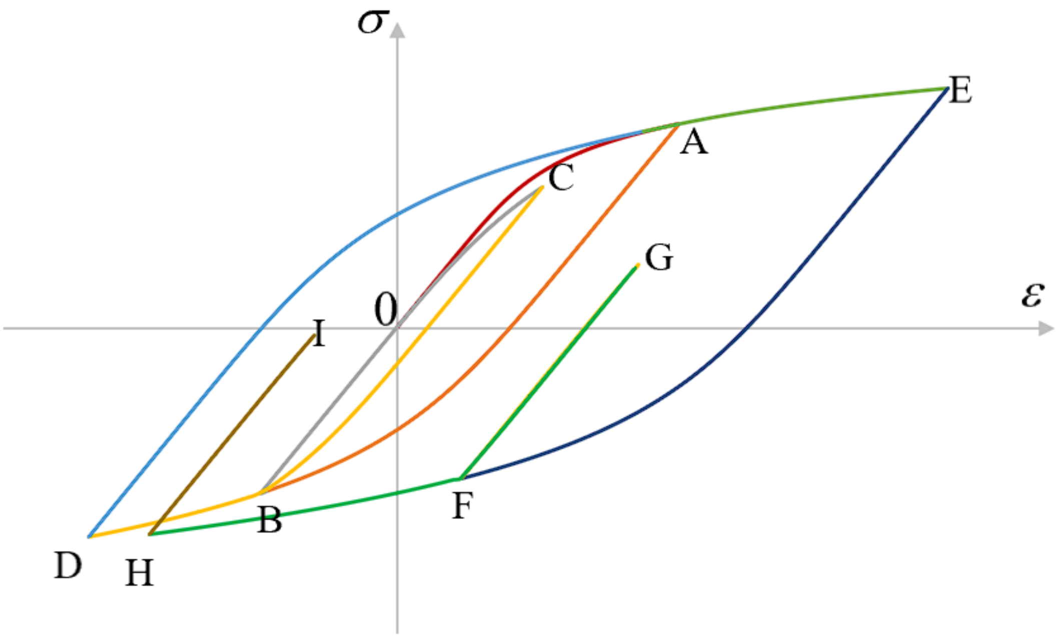

Figure 10. Stress-strain response for the VA loading case.

This phenomenon is also known as the memory effect. The memory effect consists of using the monotonic and cyclic curves normally until a cycle closes. And after the closing of a cycle, the data continues along the previous half-cycle. (Dowling et al. 2013, p. 196.) This is done similarly as in cycle counting methods, such as the rainflow-counting method. It should be noted that the memory effect can be used for data sets of any length and as a result can be beneficial for the unknown loading case in this thesis.

The derivation for the *H* and *n* parameters for S690QT is done by utilizing curve fitting on equation 6. Curve fitting is done since the examples listed in 4.3 only apply well to mild steels of similar grades to S355. The method carried out here involved finding two known points for S690QT, which were the yield point f_y and ultimate point R_m. After this the resulting equations derived from 9 are solved for *H* and *n* parameters through equation pair solving and the results can be found in table 2.

Table 2. Material parameters for S690QT.

Parameter	*H*	*n*
Value	1045	0.04

These values are used in equations (8) and (9) to determine the remaining fatigue life of the structure.

4.4 Loading

Due to the structures in question being parts of a ship, the main loads they will be subjected to consist of both structural loads caused by the mass of the ship as well as external loads caused by waves at the sea. As a result, there is a combination of both a consistent loading as well as VA fatigue loading. The size of the load correlates with the size of the wave, that the ship encounters. The distribution method used in this thesis for estimating probabilities of encountering different heights of waves is Weibull distribution.

The combined load results in a VA load with a non-zero initial value. Due to the size of the load depending on the Weibull distribution, there is a chance that some waves occur that cause stress peaks which may be higher than the yield strength of the material. These stress peaks, although unlikely can still cause yielding to occur in the structure, in which case additional considerations have to be made. The way that this will be accounted for in the calculations is by utilizing the memory effect described earlier.

There are three types of wave loads that will be considered in thesis. These are the still water, sagging wave, and hogging wave. Stillwater is when the water is still and thus the only loading component is caused by the mass of the ship floating on the surface of the water. Hogging wave is when the wave pushes the middle of the ship upwards and causes the front and back to be pulled downwards. Sagging works similarly, but in the opposite way, where it lifts both ends of the ship and pulls the middle downwards. Both of these are of different timings of the same wave passing through the ship. Sagging and hogging are demonstrated in figure 11.

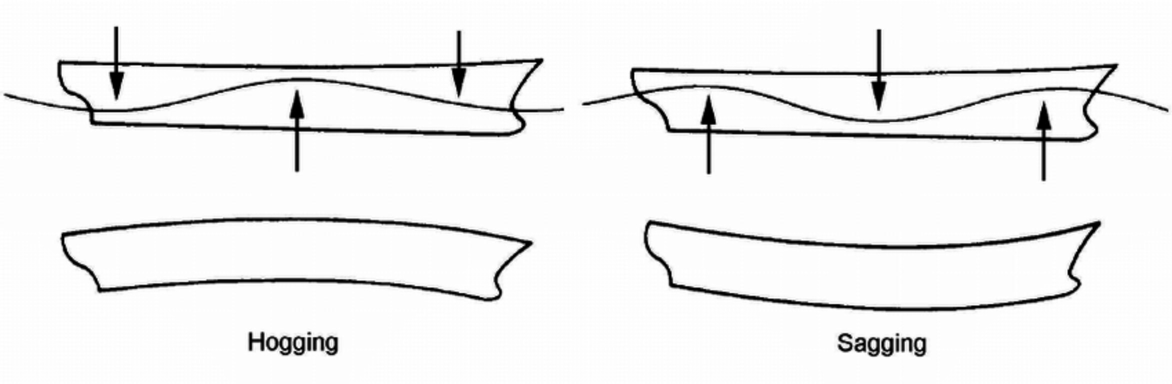

Figure 11. Hogging and sagging waves (Fagerberg 2003).

4.5 Finite element analysis

The FEA of the structure was completed by using Femap software together with NX Nastran solver. The models themselves are large, which is why the element sizes played a key role in the modelling. However, if the element size is too large, the results become too inaccurate. As a result, the models consist of having element sizes smaller than 1 mm in the radial and tangential directions of the weld toe while having element sizes of larger than 100 mm x 100 mm near the edges of the model while having gradually varying sizes of elements in the area between the edges and the welds.

The loads are transferred from global models as displacements to the edge nodes of the models used in this thesis. The boundary conditions were defined so that translations were prevented at the same edge nodes that the loads were applied in.

All of the critical areas near the welds were modelled using hexagonal solid elements and since all the rest of the structures are different types of plates with varying thicknesses, plate elements were used to model them. There arises a problem with connecting the plate elements to the solid elements, which is that solid elements cannot take in rotations in their nodes. This property regarding the connections between the plate elements and the solid elements was dealt with by using plate elements surrounded by solid elements, that share nodes with the plate elements, which in turn helps transfer all the loads from the plate elements to the solid elements. This does however increase the stiffness around the area to a high level, which is why these transitional areas were placed a long distance away from the critical areas so the effect of the additional stiffness can be minimized.

As stated earlier, the welds were modelled with a weld toe radius of $r = 1$ mm and 4 elements along the curve to get an ENS level of accuracy in the results. The stiffener to plate joint's throat thickness is $a = 4$ mm and the butt-welded plate to plate joint's throat thickness is 4.3 mm and width is 27.9 mm.

In figure 12 the results of the analysis for the butt-welded plate joint can be seen together with the location of the strain gauges. The stress flow goes as expected in a way so that the two peaks occur in the arch at the edge of the plate as well as in both weld toes. It can also be seen that the main stress flow occurring near and in the weld comes from the thinner plate's side on the left hand side in figure 12.

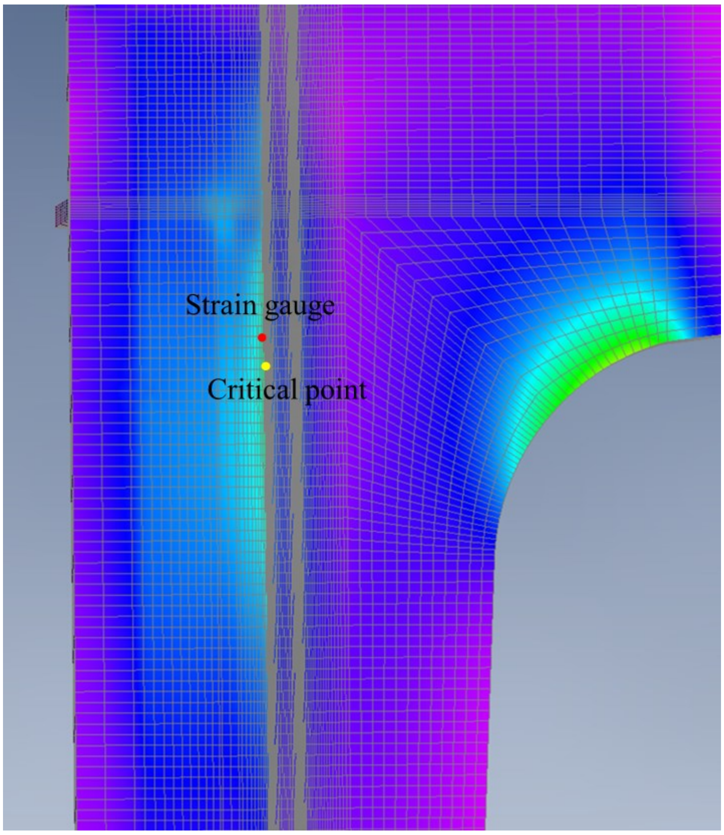

Figure 12. Wide perspective of the analysis results for butt-welded plate joint.

In figure 13 a closeup of the results at the weld are presented. Here it can be seen that the weld toe on the thinner plate's side has higher stress than the one at the thicker plate's side and thus is the more critical weld toe.

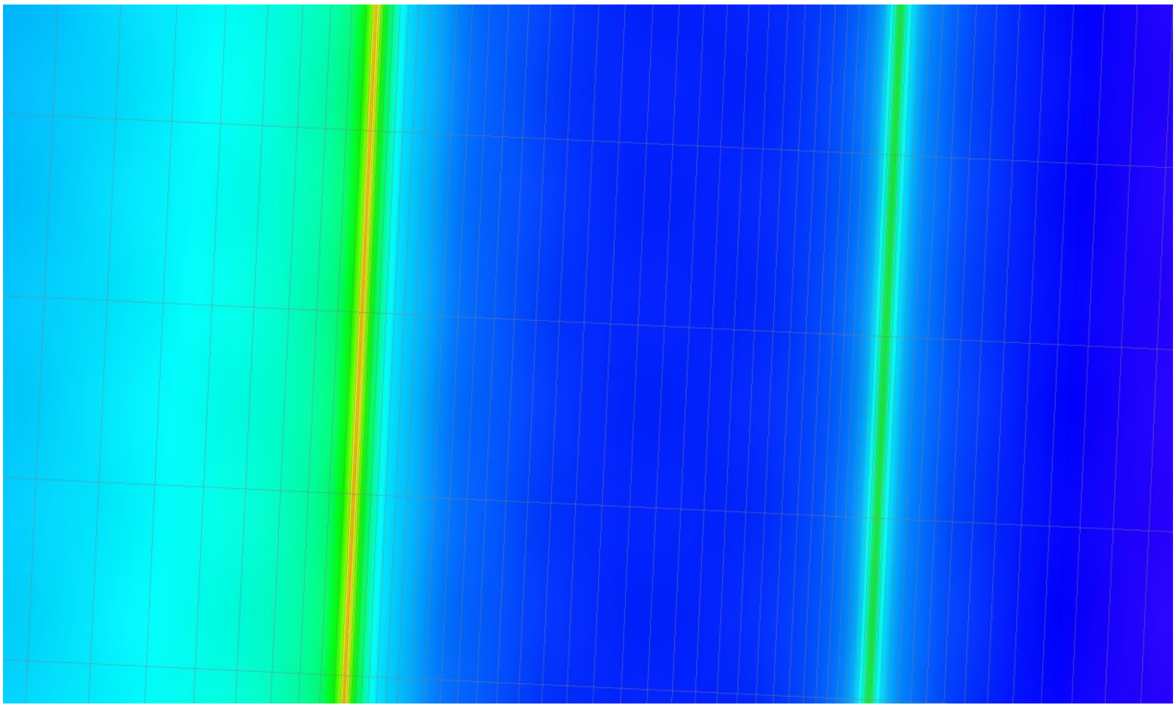

Figure 13. Stress peak at weld toe in the butt-welded plate joint.

In the stiffener to plate joint the stress also flows similarly in a way where it peaks at the arch on the edge of the plate as well as at the joint itself. These two peaks can be seen in figure 14. There is also a weld on the joint between the two plates, but this weld does not carry as much stress as the weld between the stiffener and the plate and for that reason is taken out of consideration.

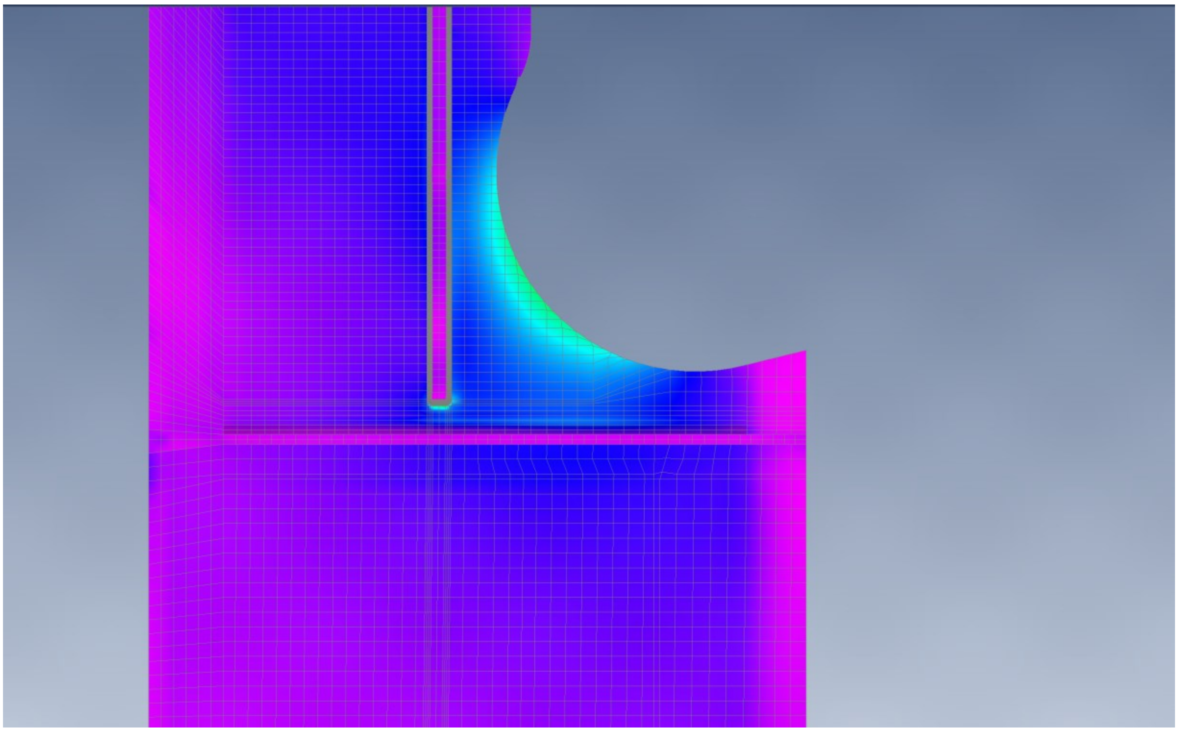

Figure 14. Wide perspective of stiffener to plate joint.

In figure 15 the results of the joint are presented. Here it can be seen that the weld toe that is connected to the plate carries the highest stress and has the most critical weld toe as it was estimated.

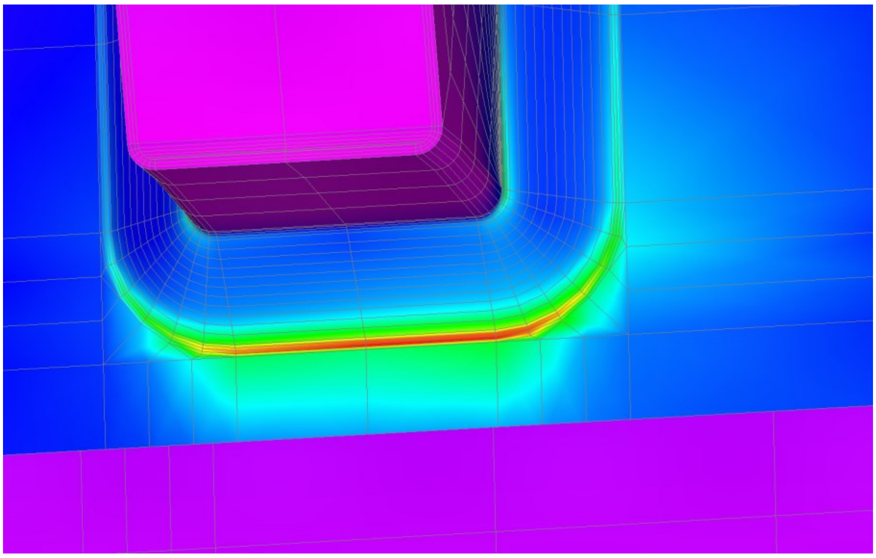

Figure 15. Stress peak in the stiffener to plate joint.

In figure 16 the location of the strain gauge is presented in relation with the location of the critical point.

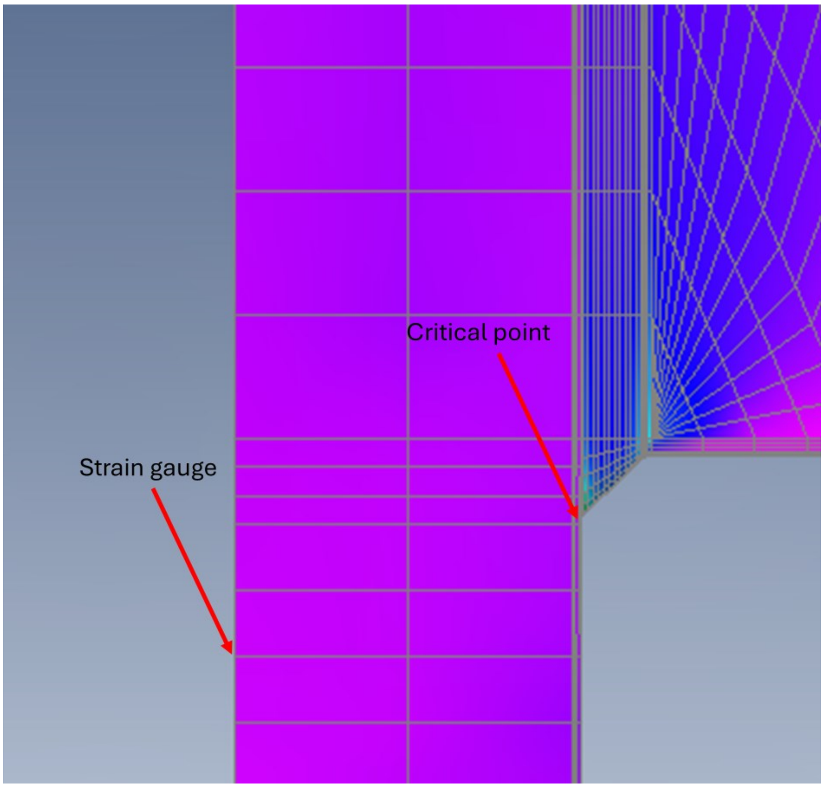

Figure 16. Locations of the strain gauge as well as the critical point in the stiffener to plate joint.

In table 3 are listed the SCFs for both the joints under all the loading conditions considered in this thesis as well as the average of these loading conditions. From here it can be seen that the SCFs for the plate to stiffener joint are considerably higher than the ones for the butt-welded joint. The most likely explanation is the differing locations of the strain gauges as depicted in figures 11 & 16.

Table 3. SCFs obtained from FEA.

	Strain gauge	Stillwater	Hogging	Sagging	Average
Butt-welded plate to plate joint	1.00	1.78	1.75	1.76	1.76
Fillet welded plate to stiffener joint	1.00	5.01	5.03	5.03	5.02

5 Discussion

In this section the results from the previous sections are reviewed. The findings, implications and additional considerations that need to be made in regards of the presented solution in this thesis are also gone through in this section. Finally, proposals for possible future work relating to the subject are made.

The goal of this research was to describe a system, that can monitor the stresses occurring in two different ship structures and estimate the effect these stresses have on the structures' fatigue lives. In order to do that effectively, the VA nature of the load had to be accounted for. The VA loading was also found to be of a nature, where it has a chance to develop stress peaks that can cause overloading to occur, which can have significant effects on the residual stresses in the structures. As a result, the effect that the possible overloads have on the residual stresses in the welds of the studied structures had to be accounted for as well.

The method presented in this thesis for obtaining the stresses from the structures consists of placing strain gauges on them and afterwards converting the output strain signal into stresses. Once the stresses are obtained, the signal can be further analyzed to form a peak-valley type of signal, which can be used to count full stress cycles. The cycles are then converted into damage sums utilizing the 4R method in conjunction with the Palmgren-Miner rule, which outputs the theoretical used up fatigue life.

It was found that the memory effect allows to take into account the VA loading by performing the cycle counting more precisely over long periods of time. The precision of the cycle counting was further increased by choosing a Ramberg-Osgood type of material model to describe the material behaviour. The Ramberg-Osgood type material model allows accounting for the elastic-plastic behaviour of the material while the memory effect helps count the fatigue cycles in a correct manner. Since the loading case consists of essentially random sized loads in a randomized order, the previously mentioned effects are necessary to be able to reliably estimate the loads occurring in the structures throughout their life cycles.

It was also discovered that overloading causes relaxation to happen for the residual stresses in welds. As residual stresses are purely internal stresses, estimating their magnitude as well as their behaviour throughout time can prove to be difficult. It was discovered that the possible relaxation can be estimated numerically through utilizing SWT rule to perform a mean stress correction. Considering the relaxation of residual stresses has the possibility of further increasing the accuracy of the fatigue life estimation method by several fold if done accurately.

The combination of the system and the phenomena mentioned above form the core results of this thesis. The system with the integration of the memory effect and considering residual stress relaxation allows for monitoring to be conducted on the ship structures mentioned in this thesis. When adding in the SCFs obtained from FEA, the system introduced in this thesis combined with the previously mentioned effects introduces the possibility of estimating the fatigue lives of the structures mentioned in this thesis.

5.1 Considerations

There are a few things that need to be considered in regards of the solution presented in this thesis. They are the following:

- Possible errors and interferences in the signal produced as well as the initial handling of the signal.
- The method introduced to estimate the fatigue life of the structure is a patented method.
- The SCFs, loading, material information and residual stress states only apply to the structures studied in this thesis.

The raw signal that is produced by the strain gauges contains some amount of noise and might contain singular misreadings for various reasons. The methods for handling these phenomena as well as converting the raw data into a peak-valley format were not introduced in this thesis for they are outside the scope of this thesis. However, there are a multitude of methods that can be utilized to solve these issues, so no further research is needed to do the initial part of the data handling. However, it should be noted that it is important to select the correct methods and parameters for those methods since filtering the signal too much or too little can cause severe errors. There is also an additional consideration relating to the calibration of the system. The sizes of the individual external loads are unknown, which makes it difficult to verify, whether the system is displaying the correct values. The verification can however be completed to some degree, as the loading for the stillwater condition is known although there can be a small error caused by any small disturbances occurring during the verification process.

The solution introduced to implement the 4R method as the fatigue life estimation method is a patented method, which means that it can only be used by the owners of the patent and entities with a license or another form of permission from the owners of the patent. As a direct result, the applications of the method described in this thesis can be limited by some degree or an alternative solution to the implementation of the 4R method must be utilized to obtain similar results. Alternatively, a different approach to fatigue life estimation can also be used but might consequently lead to different results.

The SCFs, loading, residual stress states and material information only apply to the structures introduced in this thesis. However, if another structure has vast similarities in terms of loading, initial residual stress state and/or material, the values introduced in this thesis can be used as a baseline to approximate the fatigue life behaviour in another structure so long as correct methodology is used to account for any possible differences. The method introduced to the data processing can also be replicated in other structures if keeping in mind that parts of the methodology are patented.

5.2 Future work

The numerical model for representing residual stress relaxation as well as the method described in this thesis to estimate the fatigue life of a structure in real-time both require further verification within the context presented in this thesis.

The references in this thesis regarding residual stress relaxation were verified under laboratory conditions. As the loading case essentially contains loads of varying sizes in a randomly generated order and continues for an extended period of time, it may not follow any sequences and thus might not correlate with laboratory conditions. For this reason, some more research needs to be conducted to verify that the listed methods work under other conditions as well. Furthermore, as of the submission date of this thesis, the system described in this thesis has been implemented in the ship structures described in 4.1. However, no collected data could be presented as a part of the results of this thesis so analysis of the fatigue life describing data will be left to be a part of future research on the subject.

As the method described in this thesis is new, it still requires further field testing in order to verify its legitimacy and compare its accuracy to possible alternative approaches. However, as this includes monitoring the mentioned ship structures throughout the entirety of the lifespan of the ship in question, this was not performed as a part of this thesis. It should be noted that all the individual parts of the method have been verified, but their combination in conjunction with the calibration of parameters such as the definitions of overloading points for different materials need to be defined.

6 Summary

A real-time method for monitoring the stresses and estimating the fatigue life of two ship structures based on these stresses has been developed in this thesis. This method involves utilizing strain gauges as the monitoring method and completing analysis on the data gathered from them with using the 4R method as the fatigue life estimation method in the same manner as described in EP 4 018 171 B1. The parameters for the 4R method were gathered using ENS for the SCFs, analysis of the structures for their initial residual stress state and curve fitting for the H and n parameters.

The scope of the thesis included describing the system used to monitor the fatigue life of the two selected ship structures, as well as defining the load condition and 4R parameters for the structures. The description did not include the definition for filtering the raw data to a peak-valley form as well as the testing of the system was not performed either within this thesis although the described system has been installed in the ship.

The loading cases were defined as hogging, sagging and stillwater wave loads for the studied ship structures. It was determined that the loading cases consist of VA loading, which had to be taken into account, when developing the fatigue monitoring system. The overloading effects caused by the stress peaks occurring in the VA loading cases was accounted for by considering the memory effect. It was found that the VA nature of the loading cases requires additional considerations when estimating the fatigue behaviour of the structures. The first consideration was found to relate to the cycle counting and was handled by utilizing the memory effect. The second consideration relates to the effect overloading has on residual stresses in the weld, which was found to be able to be handled using a form of SWT mean stress correction.

It was discovered that there are some limitations on the applications the methodology of this thesis applies to, especially when considering the parameters gathered for the 4R method. Subjects for future research were also defined regarding testing the described system as well as verifying the considered theory under the conditions defined in the thesis.

References

Björk, T. & Ahola, A. 2023. A System and a Method for Monitoring Material Fatigue. Patent no. EP4018171B1. Appl. 20740358.5, 2020-06-24. Publ. 2022-08-21. 19 p.

Björk, T., Mettänen, H., Ahola, A., Lindgren, M. & Terva, J. 2018. Fatigue strength assessment of duplex and super-duplex stainless steels by 4R method. 21 p.

DAV University. 2013. Stress-Strain Measurement and Strain Gauge. DAV University. 31 p. Available: https://www.davuniversity.org/images/files/study-material/MEC260-Mechanical%20Measurement-Stress-Strain%20Measurement%20and%20Strain%20Gauge.pdf

Dowling, N.E., Prasad. S.K. & Narayanasamy, R. 2013. Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue. Harlow: Pearson Education. 977 p.

Grönlund, K., Ahola, A., Riski, J., Pesonen, T., Lipiäinen, K. & Björk, T. 2023. Overload and variable amplitude load effects on the fatigue strength of welded joints. Welding in the World 68. 22 p.

Harati, E., Svensson, L. & Karlsson, L. 2014. The Measurement of Weld Toe Radius using Three Non-Destructive Techniques. 6th International Swedish Production Symposium. 8 p.

Radaj, D., Sonsino, C.M. & Fricke, W. 2006. Fatigue Assessment of Welded Joints by Local Approaches. Sawston: Woodhead Publishing. 660 p.

Ramberg, W. & Osgood, W.R.1943. Description of Stress-Strain Curves by Three Parameters. NASA Scientific and Technical Information Faciolity. 32 p.

Rossini N.S., Dassisti M., Benyounis K.Y. & Olabi A.G. 2012. Methods of measuring residual stresses in components. Materials & Design 35: Pp. 572-588.

SFS-EN 10027-1. 2016. Designation Systems for Steels Part 1: Steel Names. Helsinki: Suomen standardisoimisliitto SFS. 26 p.

Sinha, S. 2021. Titanic vs modern cruise ship: How ships have evolved. Marine Insight. Available: https://www.marineinsight.com/know-more/titanic-vs-modern-cruise-ship-how-ships-have-evolved/