**T.C.**

**ISTANBUL AYDIN UNIVERSITY**

**INSTITUTE OF GRADUATE STUDIES**

# FATIGUE ANALYSIS ON WELDMENTS – CASE STUDY ON EXCAVATOR BOOM

**MASTER'S THESIS**

**MILTON MUKALA NTUMBA**

**Department of Engineering**

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**Department of Engineering**

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**Thesis Advisor: Prof. Dr. Tuncer TOPRAK**

**JULY/2022**

# ONAY FORMU

# DECLARATION

I hereby declare with respect that the study "**Fatigue analysis on weldments – case study on excavator boom**", which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the Project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the Bibliography. ( 01/ 06/ 2022 )

Milton NTUMBA MUKALA

# FOREWORD

I wish to express my sincere and deep gratitude to Dr. Tuncer TOPRAK, for all his support along the way for my project, his advice, criticism, and insight throughout the research.

I would like to thank Dr. Atan MUGAN, for the time giving to me helping me with my work with his advice, encouragement, and insight as well throughout the research.

I would also like to express my gratitude to the company " Hidromek" for all backing received to help me improve my knowledge from my research and all the support the provided.

And I deeply would like to thank my family, my parent for all the loving support even from distance, their encouragement that help me to complete all I set in front of me.

June 2022 Milton NTUMBA MUKALA

## FATIGUE ANALYSIS ON WELDMENTS – CASE STUDY ON EXCAVATOR BOOM

## ABSTRACT

Materials and their understanding are an important aspect that will help us to achieve great things, to manufacture, to build what is necessary to experience news wonder in our universe. But one of the big threats to all that is “fatigue” failure. Fatigue, which is the formations of cracks caused by continuous damage of materials subjected to cyclic loads, causes failure in structure especially on weldment structures, that why in this paper we are going to talk about fatigue failure in details, we are going to look at the causes for fatigue failure, its effects on the life of welded structures. Different methods for fatigue evaluation will be discuss and how to prevent early fracture cause by the stresses on different structures on sites. And a general characteristics of a typical construction machine excavator boom will be considered, on how the loads are applies on the machine to better understand the effect of fatigue failure. Finally, a case study only on the boom part of a HMK 490LC vehicle model will be evaluated, FAT codes were already determined and the measurement on the boom. Then the experimental method (strain gauge) will be used to collect the data require to evaluate and to predict the fatigue life thanks to the computer software, n-code design life.

**Keywords :** Fatigue analyses, weldments structures, n-code design life

# KAYNAKLARDA YORMA ANALİZİ – İŞ MAKİNASI EKSKAVATÖR BOMU ÜZERİNDE VAKA ÇALIŞMASI


## ÖZET

Malzemeler ve endüstride kullanımı, üretimi, günlük yaşantımızın en önemli parçası haline gelmiştir. Ancak bilhassa dinamik kuvvetler etkisinde oluşan malzeme yorulması ve sonucunda ortaya çıkan hasarlar, mühendislikte büyük problemler yaratmaktadır. Bu nedenle, malzeme yorulması bugün mühendislikte en fazla araştırma yapılan konulardan biri haline gelmiştir. Bilhassa kaynaklı konstrüksiyonlarda, kaynak dikişi konumlarında gerilme yığılması ve malzeme yorulması sonucunda oluşan çatlaklar beklenmedik hasarlara neden olmaktadır. Değişik yükleme koşulları ve yapı geometrisinde, imalat şartlarından oluşan dinamik gerilme artışları, tasarım aşamasından itibaren, mühendislerin dikkatini çeken, önlemler alınmasını gerektiren durum haline gelmiştir.

Bu nedenle, tez içeriğinde malzeme yorulması detaylı olarak incelenmiş, yorulmaya neden olan faktörler değerlendirilmiş, yorulmanın konstrüksiyonların kullanım ömrüne etkileri irdelenmiştir. Değişik yorulma değerlendirme yöntemleri karşılaştırılmıştır.

Uygulama olarak, dinamik ve zor şartlarda çalışan ve bir kaynaklı konstrüksiyon örneği olan, ekskavatör iş makinasının bomuna gelen kuvvetlerin malzeme yorulmasına etkileri incelenmiştir. Ülkemizdeki en önemli iş makinası üreticisi olan Hidromek firmasının HMK 490LC tipi ekskavatörün bomu üzerindeki kaynak dikişlerinin, ilgili uluslararası literatür ve standardlarda tanımlanan FAT kodlaması yapılmıştır. Araç bomunun kritik konumlarına yerleştirilen strain gaugelerle, arazide değişik çalışma şartlarında kaydedilen strain verileri kullanılarak, sayısal yöntemlerle, gerilme ve yorulma analizi yapılmış ve ömür şartları belirlenmiştir.



**Anahtar Kelimeler:** Yorulma analizleri, kaynaklı yapılar, n-code design life

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# LIST OF SYMBOLS

| | |
|---|---|
| **A** | Amplitude ratio |
| **C** | Constant value |
| **E** | Modulus of elasticity |
| **F** | Dimensionless function of geometry |
| **IIW** | International institute of welding |
| **K** | Stress intensity factors |
| **Ke** | Effective Stress intensity factor |
| **Kf** | Fatigue Notch factor |
| **Kt** | Stress concentration factors |
| **LEMF** | Linear-elastic fracture mechanics |
| **N** | Number of cycles |
| **R** | Stress ratio |
| **S** | Strength |
| **a** | Crack length |
| **da** | Crack length |
| **dN** | Number of cycles |
| **m** | Slope |
| **r** | Radius |
| **t** | Thickness |
| **q** | Notch sensitivity |

| | |
|---|---|
| $\boldsymbol{\sigma}_{\mathbf{hs}}$ | Hot spot stress |
| $\boldsymbol{\varepsilon}_{\mathbf{hs}}$ | Hot spot strain |
| $\boldsymbol{\sigma}$ | Normal stress |
| $\Delta \mathbf{a}$ | Crack length range |
| $\Delta \mathbf{N}$ | Number of cycles range |
| $\Delta \mathbf{S}$ | Strength range |
| $\Delta \mathbf{K}$ | Intensity factor range |

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# I. INTRODUCTION TO FATIGUE

As we are moving forwards and evolving as a society and civilization, materials and theirs understanding are an important aspect that will help us to achieve great things, to manufacture, to build structures and machines to carry most difficult task and with great precision but a challenge is faced, they do not last longer in the field and sometimes accident happened on site that may cause great cost of life because of materials failure, those are due to one of the greater cause for failure in mechanical structure which is “**fatigue**”. Fatigue is a phenomenon not totally grasped by researchers, needless to say how vast its concept is since much research are still being carrying on it, it has been a scope of study for century until our days in engineering field.

Fatigue is a formation of cracks caused by continuous damage of materials subjected to cyclic loads, it is a frequent mode of failure with structure, particularly welded structure and it has caused many catastrophic disasters throughout history. That is why in our thesis we are going to focus on fatigue failure in a structure, investigate deeply on that, discussing on different method and approach used to avoid and prevent fatigue failure on a structure, and by determining the fatigue live (and total damage) on a different structure.

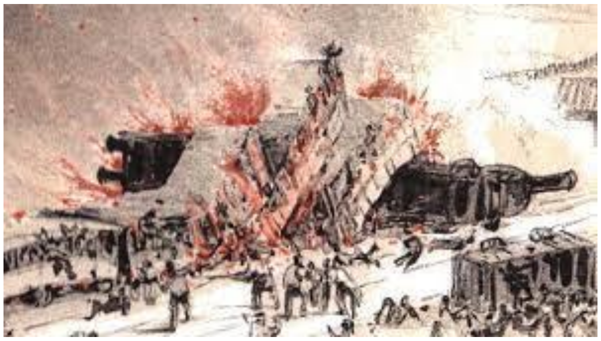

*Figure 1-1. Versailles rail accident*

There was a sad accident that happened in 1842 in Versailles frail, that calls on the need for study of fatigue phenomena. Research needed to be done on the phenomena. Around 1850s more research were conducted to understand the issue of repeated cycle loading, and during that time the word “fatigue” was used for the first time by John Braithwaite. In engineering most of the structures have dynamic loading. Especially, the welded structures have failure from the welding area affecting the lifetime of the structures. That is why, design as well as the manufacturing of these structures need special research and improvements to increase the fatigue life.

## A. Fatigue Phenomenon

The fatigue phenomena are shown with crack that developed in materials, fatigue or the damage of crack created by fatigue is represented as the materials lost its resistance with time, fatigue failure always being brittle, and fracture occurs regardless of whether the materials are ductile or brittle.

We have 4 parameters that influence the fatigue resistance:

- The applied stress
- The structural geometry
- The material of the structure
- The environment

fatigue fracture is usually normal to the direction of the applied force. It starts with a crack initiation, which usually occurs where the stress concentration is located, as we can see from this example in Fig. 1-2 as the crack propagate. And it is important to know that the crack can start on multiple location. And fatigue failure consists of 3 different stages, where the first two stages are considered to be the main ones and are more consider in examine the process of fatigue phenomena:

- Crack initiation
- Crack propagation

- Ultimate failure

Going by the experimental point of view, we can use different tests to measure both the crack nucleation and crack propagation. Generally, failure is attributed to crack propagation with structures, but where stresses are low, most of the focus are spent on cracks initiation phenomena.

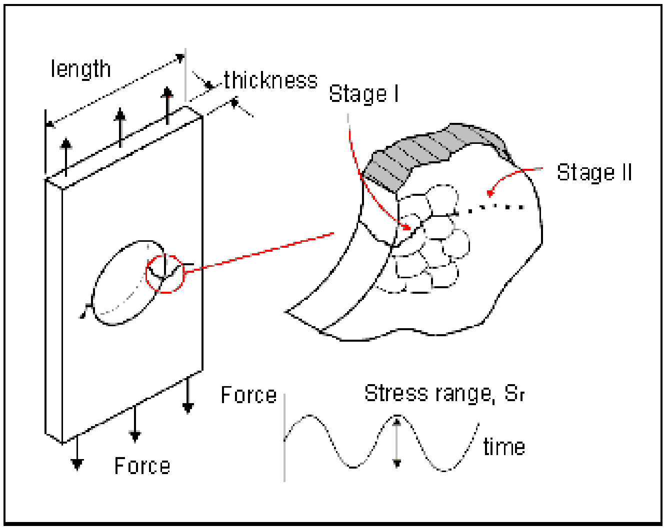


*Figure 1-2. Crack initiation and propagation*

## 1. Crack Initiation

When crack reaches the grain boundary, crack when initiate will then start to propagate (Fig.1-2). The rate of crack propagation is greatly influence on a microstructure stage. We need to decrease the roughness of surfaces, in order to accomplish that, some mechanical or thermal treatment process are used, we have shot peening or surface heat treatments, those process affect the tensile stresses and reduce the effect of cyclic loading.

## 2. Crack Propagation

After when the crack has reached approximately three grains boundaries, the physical mechanism of the element totally changes. With the growing crack $\Delta a$ that increase as the number of cycles $\Delta N$, we can form the rate of growth formula with the ratio of $\Delta a/\Delta N$ (da/dN), and we have the constant nominal stress formula ($S_{max}$ and $S_{min}$) can be introduced as well.

$$\Delta S = S_{max} - S_{min} \qquad\qquad R = \frac{\text{Smin}}{\text{Smax}} \qquad (1)$$

One of the most important parameters for fatigue evaluation is the stress intensity factor, K, and it is calculated with:

$$\Delta K = F\,\Delta S\,\sqrt{\pi a} \qquad (2)$$

The behavior of a test subject is represented by the diagram with crack growth rate da/dN and $\Delta K$, and Paul Paris first used it, the relationship can be represented in log-log plot (Fig. 1-3). We have a straight line in the plot which has the relation:

$$C(\Delta K)^m = \frac{\text{da}}{\text{dN}} \qquad (3)$$

From the formula "C" as a constant value and "m" slope in the plot, the value "m" is important since it indicates how fast the crack can grow. At low growth rate in the plot, called "*threshold* "crack growth does not happen. At the upper end of the plot, we have the same shape as the lowest one, because of the rapid unstable crack growth. And through experiment we know that increasing the stress ratio R ,we do the same with the carck growth rate.

## B. Cyclic Loading Deformation

The cyclic loads are represented differently with different diagram depending on the types of cyclic load. The damages done during fatigue process are continued and it is not always recoverable. Through the researched conducted, we learn that repeated stresses can cause fracture despite the fact that the amplitude of the stress is well between the elastic region of the material.

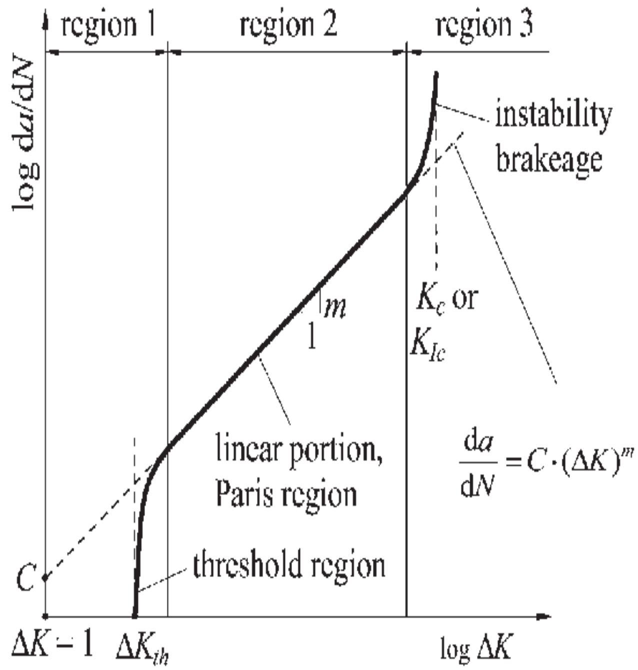


*Figure 1-3. Crack-growth curve showing characteristic regions*

More effort was put forth to understand the fatigue phenomenon rather than just observing the impact, which led to different approach we are going to discuss later.

Types of fatigue loading are:

- Fully Reversed:

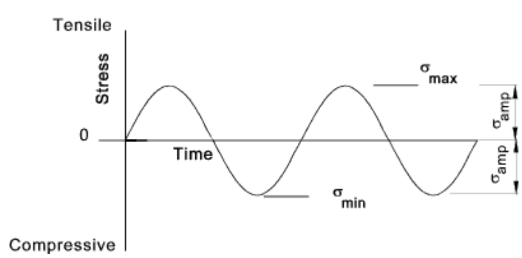


*Figure 1-4. Fully reversed cyclic loads*

- Repeated:

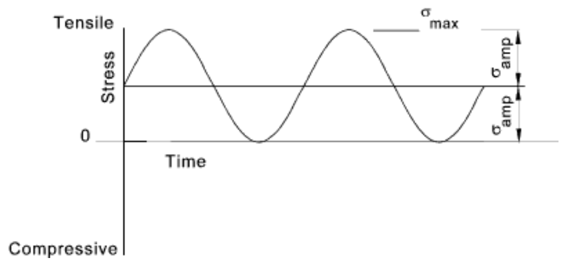


*Figure 1-5. Repeated cyclic loads*

- Fluctuating:

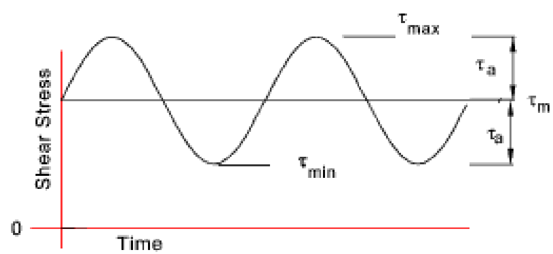


*Figure 1-6. Fluctuating cycle*

And we have some fatigue loading equations related the cyclic graph:

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$ Stress range (4)

$$\sigma_a = \frac{\Delta\sigma}{2}$$ Alternating stress (5)

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$ Mean stress (6)

$$A = \frac{\sigma_a}{\sigma_m}$$ Amplitude ratio (7)

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$ Stress ratio (8)

## C. Fatigue Life Evaluation

The mechanical fatigue is really influence by the type and amplitude of the loading because it substantially affects the stress-strain response of the structures. Different types of approaches are used, the Stress-Life (S-N) method is used when the stresses are below the yield strength of the material of the structures. The Strain-Life (E-N) method is used when the stresses are above the yield strength. The S-N method should be used until the crack initiation, because in the crack propagation region, this method is not sufficient. The E-N method should be used when there is plastic deformation. The Crack propagation approach (LEFM) is used when the components or structures are exposed to crack propagation. We are going to discuss a bit about those approaches in fatigue analysis in this study. The most used methods are based on stresses.

The S-N method was developed by August Wöhler, but the method was combining the two stages by looking at the complete process of failure of a structure, but the S-N analysis is still widely used for fatigue analysis.

### 1. Stress-Life Method

The S-N method is the oldest and the most widely used fatigue damage approach because it is more practical than other methods and there are many stresses versus life information for different materials in the literature. This method is valid in the elastic region of the material's strength. In terms of amplitude when the loading amplitude decreased which in turn increases the number of cycles for fatigue.

We should note that each curve in S-N method is determined for a specified value of the different equations discuss above in "*cycle loading deformation*" part and those parameters are represented in the Figure 1-4 (fully reverse). In Fig. 1-7 we have two different curves, the ferrous materials (A) with an endurance limit, and the one that represent the Most non-ferrous materials(B) have not endurance limit, like aluminium.

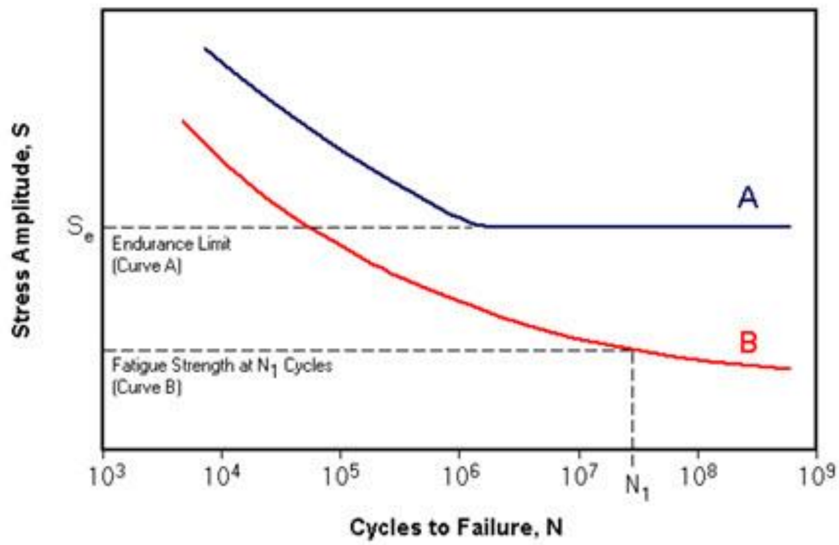


*Figure 1.7 - S-N curve.*

The S-N curve in a way provide a complete fatigue evaluation of steel structure, through testing of samples, while using the S-N curve of the materials, the mean stress effect should be investigated. If the mean stress is zero, as shown in Figure 1-4, then one can use the S-N curve directly because the S-N curves are mostly used to determine the rotating specimens which are exposed to bending stresses with zero mean. However, most loadings create non-zero mean stress profiles in the structures, as shown in Figure 1-6, then the modification should be carried out, with correcting factor.

### 2. Strain-Life (E-N) Method

This method is similar to the S-N method, but it uses strain cycles instead of stress cycles. Moreover, the S-N method can be used in elastic region only, but the E-N method can be used in both the elastic and the plastic region. The E-N method is more valid and favorable in these days because plastic strain changes the properties of a material, especially when the material experience plastic deformation. The E-N curves of the material fatigue strength include the plastic region fatigue information too. However, for different materials E-N curves are not available like the S-N curves. Due to the lack of E-N curve information and necessity of specific material E-N curve tests, still the most used method is the S-N method in fatigue analysis.

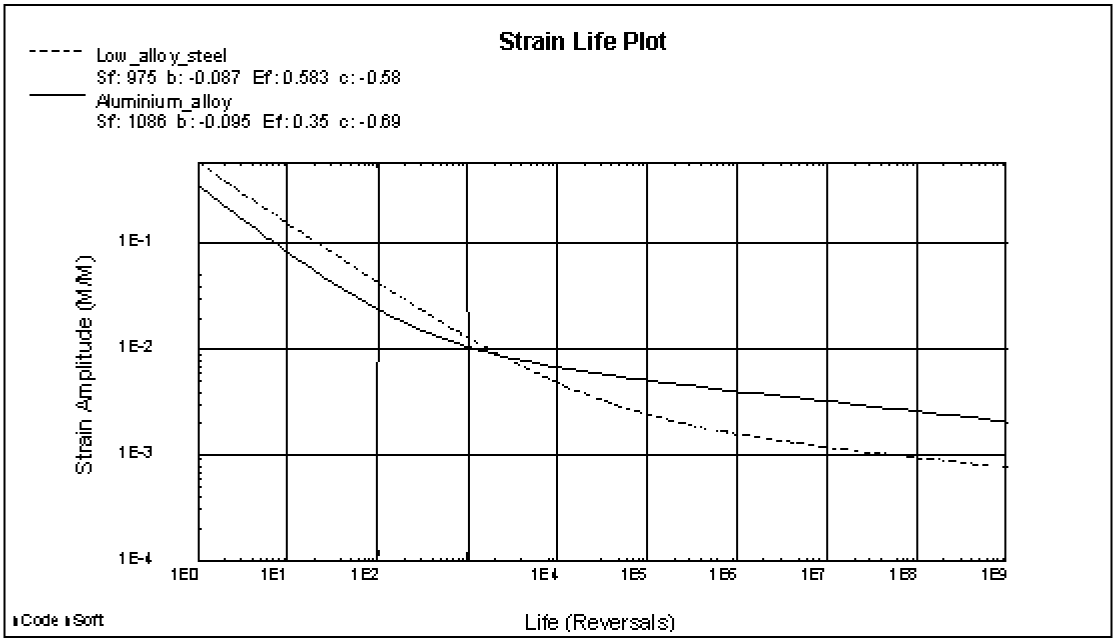


*Figure 1.8 - E-N diagram for aluminium and steel.*

### 3. Crack Propagation (LEFM)

Linear elastic fracture mechanic is used for the assessment of cracks found in service and for investigation of the fatigue of weld joints and structure containing inherent crack-like flaws at the weld toes or roots. In fracture mechanic, the crack growth fatigue is classified in three different physical modes of loading (Fig. 1.9). Mode 1 is the opening mode in which crack failure is caused by pure tensile loading stress, perpendicular to the applied loads. Mode 2 is the shearing or slide mode in which the crack advances parallel to the shear stress. Mode 3 is a tearing anti plane mode. The mode 1 is the dominate failure in most service conditions. This method deals with the processes after the crack initiation stage. Generally, in the aerospace munitions, the crack propagation stage is not allowed. The fatigue lives of the munitions are accepted from beginning of the service life to crack initiation time or critical crack size occurring time. It depends on the judgement of design engineers.

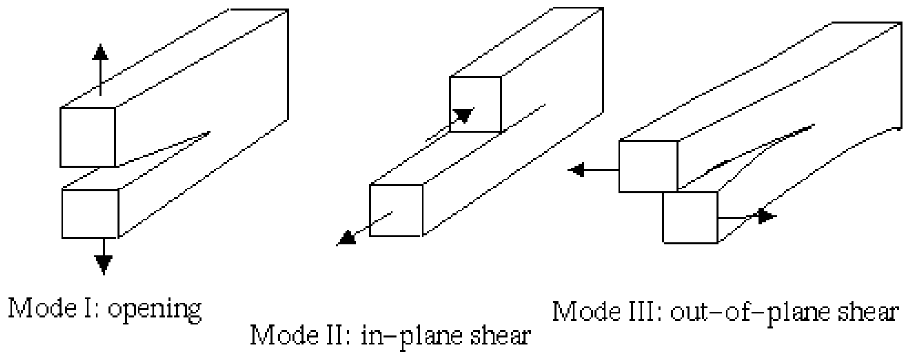


*Figure 1.9 - Basic mode of crack definitions in fracture mechanics*

# II. STRESS CRITERIA

For a better fatigue life assessment, the complete cyclic need to be considered. So, we need to be determined the stress according to the fatigue evaluation method use. Many factors need as well to be considered such as snow, wind, etc.

## A. Stress Range

The stress range and stress intensity factor are very important parameter for fatigue evaluation. And can be express as follow:

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \qquad (10)$$

$$\Delta K = K_{max} - K_{min} \qquad (11)$$

## B. Stress Components

For the stress acting on the critical locations, for example at the weld toe, it has a whole non-linear profile, but can be separate and analyzed separately. And they can be separated by the given formula:

$$\sigma_m = \frac{1}{t} \cdot \int_{x=0}^{x=t} \sigma(x).dt \quad \text{( Normal stress )} \qquad (12)$$

$$\sigma_b = \frac{6}{t^2} \cdot \int_{x=0}^{x=t} (\sigma(x) - \sigma_m) . (\frac{t}{2} - x).dx \quad \text{( Bending stress )} \quad (13)$$

$$\sigma_{nl}(x) = \sigma(x) - \sigma_m - (1 - \frac{2x}{t}) . \sigma_b \quad \text{( Non-linear peak stress )} \quad (14)$$

1. **Nominal Stress**

Nominal stress is calculated in area under critical location. Over the section under consideration the nominal stress may be different throughout the element. The nominal stress can be calculated using common beam theory at a beam like component. In case of axial misalignment, it will need to be taken into consideration during calculation (Fig. 2-2).

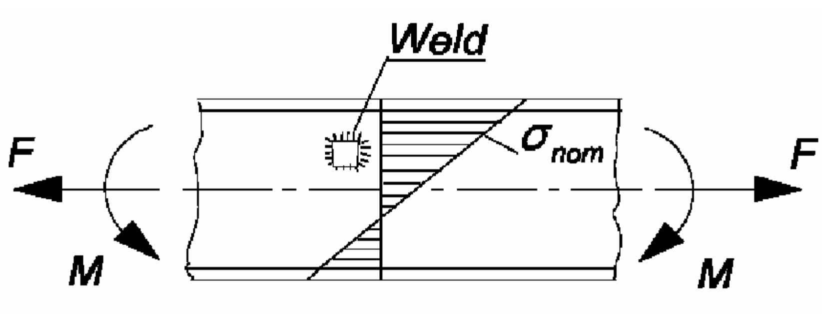


*Figure 2-1. Nominal stress on a beam.*

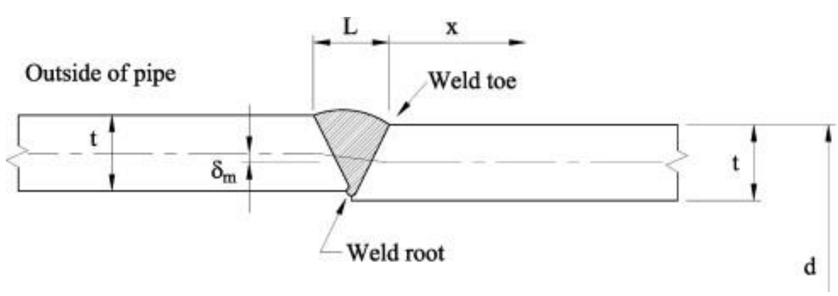


*Figure 2-2. Axial and angular misalignment*

### a. Nominal stress calculation

nominal stress is calculated by assuming linear-elastic behavior of the material. And finite element method (FEM) can be model as well and use for finding nominal stress for complicated structure where it is difficult finding the stress analytically. When using the finite element method, simple and coarse mesh are used. To measure nominal stress from the structure, we can use strain gauges to collect the strain data and compute for the stress values.

## 2. Structural Hot Spot Stress

The structural hot spot stress can be determined on the surface of the components. And it can be found and use in situation where it is not easy or possible to find the nominal stress discussed previously due for example of the complicity of the geometry or when we don't have classified structural detail comparable to the structural discontinuity. The method is not only limited for assessment at the weld toe but can be extended as well to different location at the weld root.

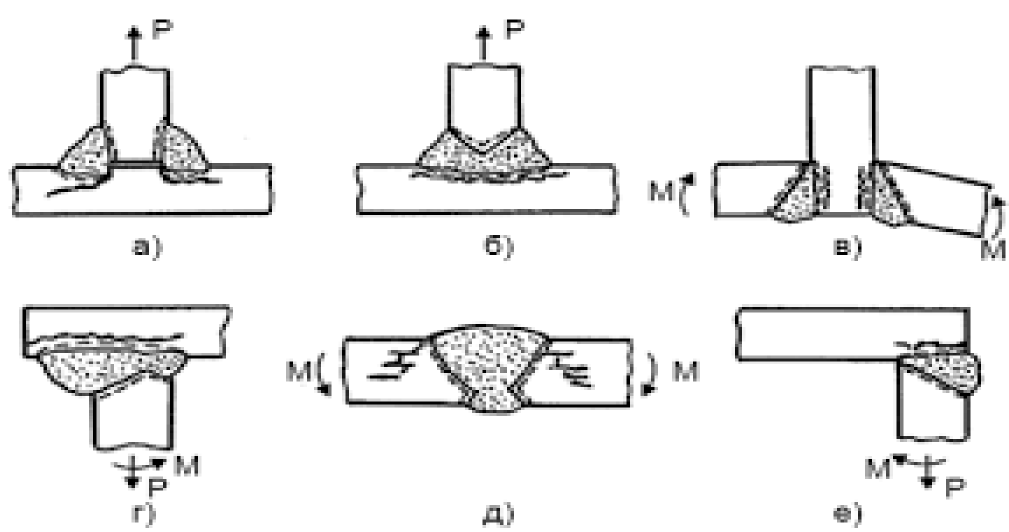


*Figure 2-3. Examples of different crack propagation in welded joints*

We know two types of hot spot, as we can see in figure 2-4, we have the “weld toe on plane surface (a)” and “weld toe at plate edge (b)”, and we can evaluate both types by FEM or measurement and extrapolation.

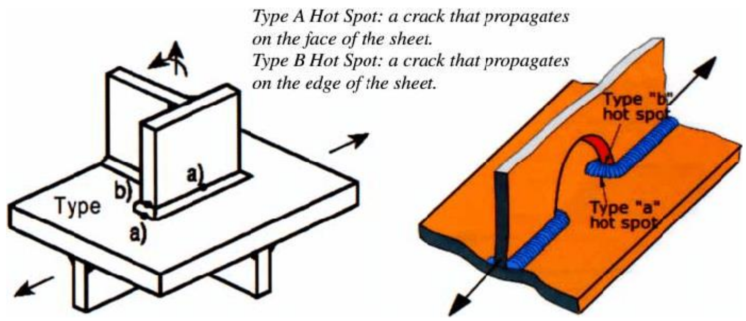


*Figure 2-4. Types of hot spots*

### a. Determination of structural hot spot stress

We can determine the structural hot spot stress by calculation, using reference points by extrapolation to the weld toe we are considering. And to identify the critical point (hot spots) we can use methods such as by analyzing the FEM model or using existing component that had already failed.

It is not always applicable to used analytical method to find the hot spot, that is why because of not availability of parametric formula the finite element method is generally used. We calculate the structural hot spot by assuming perfect idealized aligned welded joint. The guidance for using FEM in this case is provide in (C. M. Sonsino, vol. 53, no. 3-4, pp. 64–75, 2009). By recommendation 8-noded elements need to be placed, when dealing with simple models the welds part don’t need to be modelled. For the modelling of welds part as we can see in figure 2-5 as recommended, we have a multi-layer arrangement of solid elements. For the modelling, the finer mesh and Coarser meshes can be use as well, we have examples of extrapolation paths shown in figure 2-6 to determine the stress when the welds are not model.

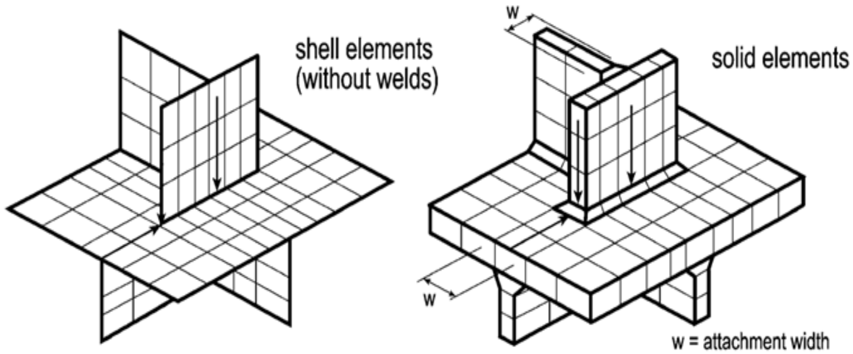


*Figure 2-5. Model element for welded joint.*

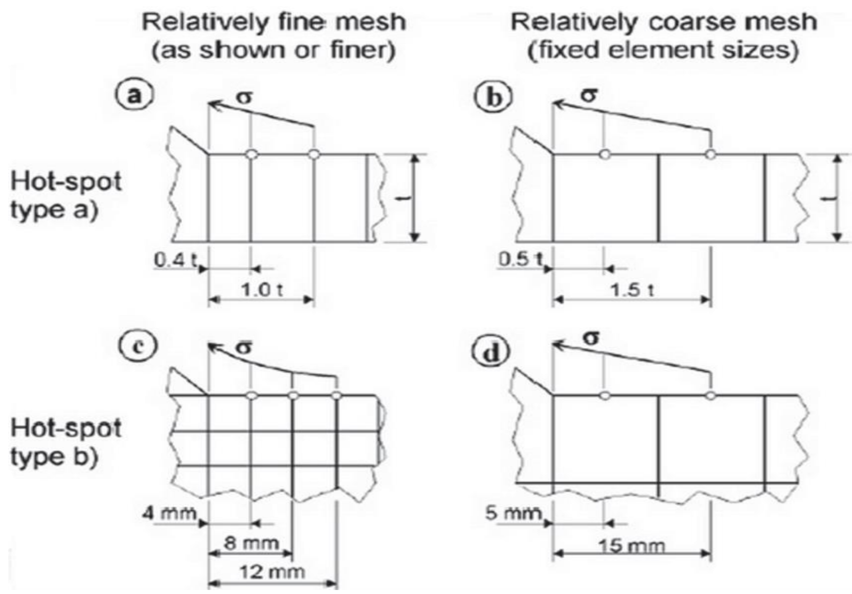


*Figure 2-6. Examples of references points.* .

With the experimental measurement using strain gauges, the gauges should not exceed **0.2 t** of length, and the location of the first gauge should be at **0.4 t**, with “t” as the thickness. When we use the multi-grid strip strain gauges, we don’t need to worry about the precise position of the gauges, since the result obtain can be plot with different variation and the stress can be read from the corresponding curse. To **determine the stress**, after obtaining the total strain value of different element through appropriate formulas, thanks to the strain gauges, we can use the Eq. 15 to find the stress if it has a uniaxial state.

$$\boldsymbol{\sigma_{hs}} = \boldsymbol{E} \,.\, \boldsymbol{\varepsilon_{hs}} \qquad (15)$$

## 3. Effective Notch Stress

In short, the effective notch stress is the total stress at the root of a notch, we need to assume the linear elastic behavior of the element when evaluating. During the assessment, other modes of fatigue failure affecting the welded structure such as crack growth from surface roughness are not talking into consideration. Generally, when modelling the welds, the flank angles should be of $30^\circ$ for butt welds and $45^\circ$ for fillet welds. and more details regarding the application for effective notch stress can be found in reference (D. Radaj, C. M. Sonsino, UK, 2nd edition, 2004).

### a. Determination of the effective notch stress

As we discussed, the same as with different types of hot spot, different equation are formulated to calculate its stress, the same goes with the effective notch stress, depending as well on the modelling approach used for the structure evaluated. Or the finite element method (FEM) can be used to model and calculate the effective notch stress.

# III. METHODS FOR FATIGUE EVALUATION

Different methods are used for fatigue evaluation, those methods are categorized in: the global and local methods. The crack initiation can be easily analyzed with the “notch root approach”, where for the other process they start from an existing crack. The simplest and most common method used is the nominal stress that belong to the global method. For the first step for fatigue analysis, we need to formulate the mathematical model which include of course the variables affecting the fatigue behavior. And then estimation based on different analysis are conducted.

## A. Nominal Stress Approach

As we have seen form figure 2-2, the stress is being calculated close to the weld location, after collection of data, as it will be done in our case, the evaluation can be conducted accordingly. The S-N curve available take into account the local effects, more details can be found for example in IIW recommendations. Nominal stress-based approach cannot be use when we cannot calculate the nominal stress, so, we can turn to different local approach based.

There have been furthermore investigations which greatly advance the understanding for fatigue, and standard updated dealing with the weld imperfection with the fatigue resistance classes helping many constructors and design engineer.

**B. Hot Spot Approach**

It is one of the most  fatigue life assessments used. The hot spot is the critical location on a weld toe, as seen from figure 2-5, and it where a crack is being expected. This approach is use where we cannot determine the nominal stress or when we cannot match the categorize detail of the element with the standard of nominal stress available. A model is used in FEA to have the stress and evaluate the structure. The S-N curves for hot spot stresses can be found in (D. Radaj, International Journal of Fatigue, vol. 51, pp. 105–115, 2013.).

**C. Notch Stress Approach**

This approach consists of modeling as well, a weld root or toe with a notch of certain referent radius (Fig. 3-1). The geometry of the weld and the stresses of the weld itself are the sum of local stresses. And this stress depends greatly on notch sharpness or radius.

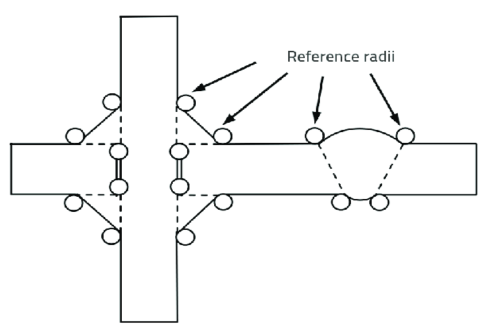


*Figure 3.1 - notch of certain referent radius.*

For the reference radius mention earlier for the notch stress approach, we have two imaginative radii most used in modelling, of 1 mm and 0.05 mm.

### D. Mesh-Insensitive Structural Stress Method

A little bit about this news approach, it was developed in mainly to remove or minimize the finite element size effect during stress calculation. As all beginning, it was first use for simple calculation and later for more advance and complex applications for welded structure, for example in offshore/marine structure. By using this approach, we can easily have stress parameter from the element evaluated, and we can easily use coarse mesh for modeling. And from the figure 3.2. we can see the stress distribution obtained in figure 3-2(a). and the simplifier version from Figure 3-2(b) that we can obtained from this method.

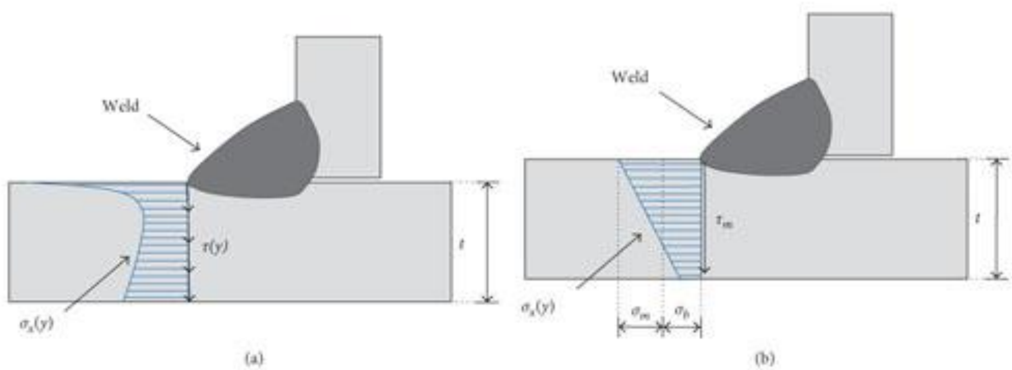


*Figure 3.2 - (a) Local through thickness stress (b)corresponding simple structural*

# IV. FATIGUE OF WELDED STRUCTURES

## A. Stress Concentration

Thanks to the stress raisers theory we can relate the peak stress, $\sigma_{p,}$ which is close to a discontinuity for tension or bending to $\sigma_{net}$ (net stress). So, we derived the following equations:

$$\sigma_p = k_t * \sigma_{net} \quad (16)$$

$$\tau_p = k_{ts} * \tau_{net} \quad (17)$$

Fatigue crack are not easy to detect  because of the lack of clear deformation in the location, that why in design prediction we have to consider possible types of failure in the structure.

$$q = \frac{Ke - 1}{Kt - 1} \quad (18)$$

For fatigue design, both $q$ and $Ke$ (effective stress concentration factor) concepts are used, and as well this two more factor $K_{f,}$ or $K_{fs}$ defined as:

$$K_f = \frac{Fatigue\ limite\ of\ unnocthed\ specimen\ (\ axial\ or\ bending\ )}{Fatigue\ limite\ of\ nocthed\ specimen\ (\ axial\ or\ bending\ )} = \frac{\sigma_f}{\sigma_{nf}} \quad (19)$$

$$K_{fs} = \frac{Fatigue\ limite\ of\ unnocthed\ specimen\ (\ shear\ stress\ )}{Fatigue\ limite\ of\ nocthed\ specimen\ (\ shear\ stress\ )} = \frac{\tau_f}{\tau_{nf}} \quad (20)$$

$K_f$ and $K_{fs}$ are the fatigue notch factor, and more information on them can be found in (Radaj, D.,1st ed. Cambridge, Abington Publ, 1990.) Further way to get "*q*" is with the following formula:

$$q = \frac{1}{1 + \alpha/r} \tag{31}$$

$$q = \frac{1}{1 + \sqrt{\rho'/\alpha}} \tag{32}$$

Where $\alpha$ and $\rho'$ are material constants determine by test data. The residual stresses from the weld are release during cyclic loading, the strain approach consider the same effect as well. And there are more equations related both parameters $K_f$ and $K_t$. *Ke* and $K_f$ are commonly found lower respectively in bending but are not generally the case for all types of joints.

Experimental technics such as strain gauges or photo elastic are used to collect data(stresses) from the structure when mathematical solution is not available. It is recommended to use a short strain gauge as possible to have a better accuracy measurement, since it is close to the stress concentration area. There are more researches conducted on stress field, that can be used for guidelines as well.

## B. Fatigue Design Rules for Welded Structures

Statistical analysis is used on welded specimen with constant amplitude to obtain the S-N graph. For the process, the fatigue limit can be based on life or particular stress. We have classification system that describing the weld details with the corresponding S-N curves (Fig. 4-1), the proprieties provide from S-N curves are very important since it will help us to classify materials or structures details that are not specifically described.

## 1. Influence of Residual Stress

During welding operation, the localize heat produce extend on the materials which create section over the surface of the structure having compressive stresses and other tensile stresses. The most undesirable one is tensile stress, that need to be reduced or completely eliminated, because of this stress, the pattern of applied stress during the loading cycles are significantly influences leading to rapid failure. Needless to say, during the dynamic loading those circumstances causes a high risk of damage of welded structure, but to improve the fatigue life of the welded structures by reducing those stresses various thermal/mechanical treatment are widely used to cancel the residual stress field on the element.

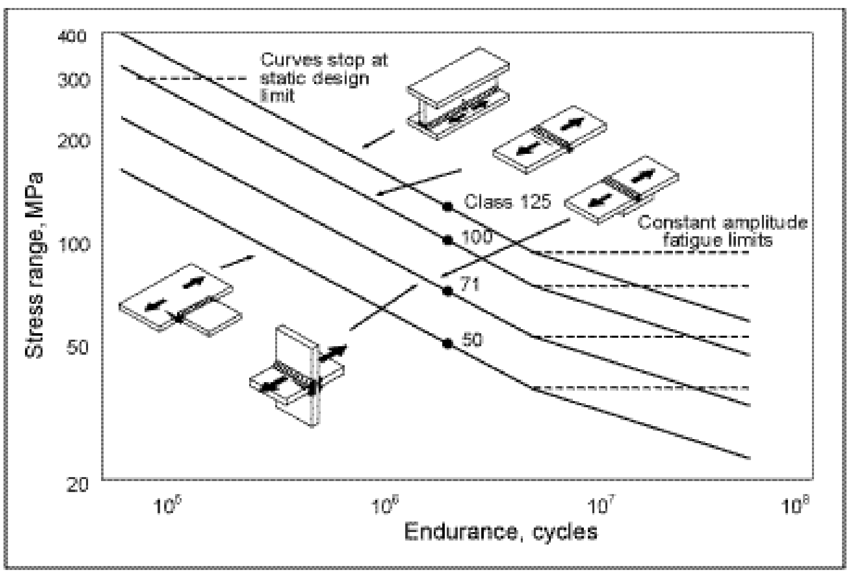


*Figure 4-1. Typical fatigue design S-N curves, and some specification*

Residual stresses in weld joint are divided into several types depending on the dimension of the joints. First order residual stresses cause macroscopic strains in the joints. Second and third order residual stresses are those that cause micro-strains in the grains and crystals respectively. Residual stress of the first order plays a major role in fatigue behavior of the welded joint while the second and third order stresses play a part in the stability of the residual stresses under cyclic loadings. Some more research conducted on this account regarding residual stresses and their effect are find at (Ninh T. Nguyen, Advanced modelling of the fatigue of Butt-Welded Structures, March 1996).

Because of the imperfection fit-up we can as well have residual stresses, long range ones, when sub-assemblies are connected together. As we are trying to reduce the effect of residual stress, that will result on having the fatigue life depending on the stress range but not necessarily on mean stress, even in the case of compressive residual stress. It can be beneficial to have stress relief conducted as shown many studies, but it is not always practical to achieve complete stress relief.

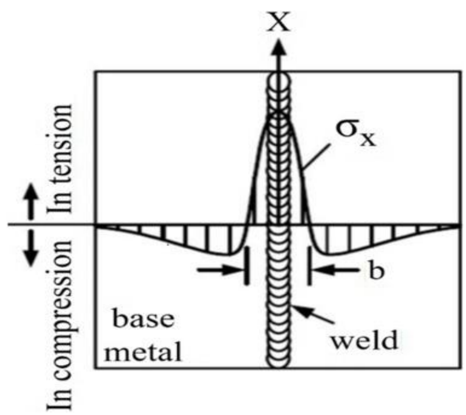


*Figure 4-2. Residual stress on welding material*

The same goes for residual strains develop on the structure that may lead to distortion after welding, for butt and fillet welds. From a fatigue point of view high tensile residual stresses are not desired, since it causes significant change in the component, that why compressive stress is much more prefer, since it contribute to the enhance of fatigue strength.

# V. FATIGUE EVALUATION OF AN EXCAVATOR BOOM

After discussing in details about fatigue failure and different methods for fatigue evaluation for welded structure, a case study was selected as example for fatigue evaluation of a welded structure for a better understanding. A construction machine was selected, a hydraulic excavator vehicle model HMK 490 LC, for evaluation only on the boom part (Fig. 5-1) which is the most critical part. With the great support of the Hidromek company, providing us the data needed to predict the fatigue life of the excavator boom using the computer software N-code Designlife.

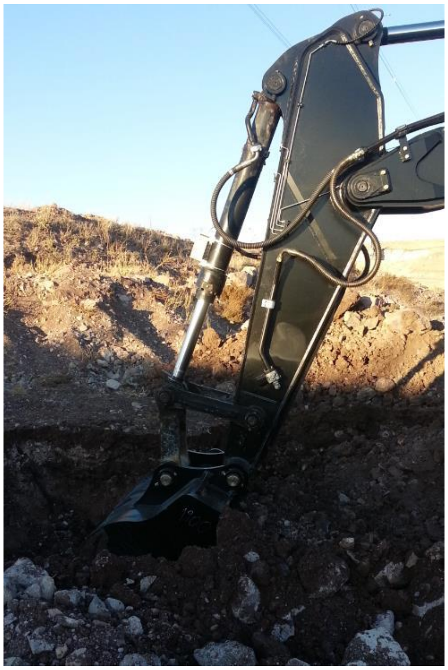

*Figure 5-1. Position of the boom for test No. 2.*

Generally, a hydraulic excavator machine is a big vehicle machine, it has as parts an upper rotatable chassis on top of a drivable body with wheel or track, and the upper chassis contain a boom, arm and bucket, the machine function hydraulically so its mechanism is actuated by the help of hydraulic cylinders. The machine can be used for different operations such as, for digging, lifting, breaking big rocks and cleanup purpose on the site. We have trench digging perform for the application of placing pipes. Different ends attachments can be used to perform different kind of operation on site mentioned earlier.

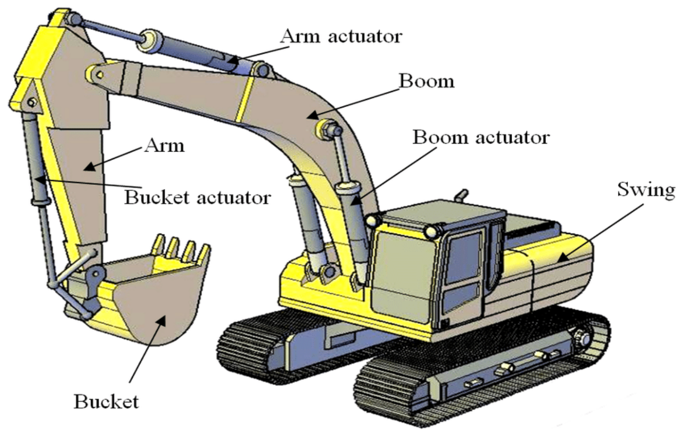


*Figure 5-2. excavator boom view.*

For the excavator boom part, it is connected at the upper chassis and an arm mounting bracket at the tip end of the body, as we can see from figure 5-2. We have an arm cylinder connection bracket that is welded on top of the boom and another boom cylinder placed in the middle of the vertical side plates connected to upper chassis. For the boom design additionally, we may have reinforcement plates connected inside the boom to form a closed box section in order to have better criteria. The boom(Fig. 5-3) is subjected to different high loading conditions throughout its life span that may speed up the fatigue failure process and shorten the life expectancy that is why ways to improve the design are always of concern. For the boom design and evaluation for fatigue life, most severe digging positions and different operation conditions need to be considered to have better performing and safe machine on site. The boom, arm and bucket are exposed to two different forces during operations, we have $F_{arm}$ ( Arm force ), breakout force at the bucket tip during excavation of the earth and also a lateral force perpendicular to the lengthwise direction of the arm and bucket at the bucket tip during the sweeping motion operation. Those two loads cause bending, axial loading, and torsion (combined loading) in the boom structure, this loading conditions can be used for the evaluation of the boom and improve the design if necessary.

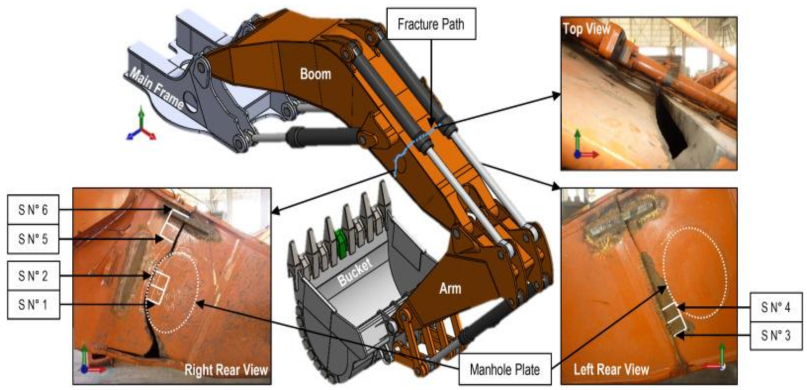


*Figure 5-3. crack on the excavator boom.*

In general, two types of welding operations are used for manufacturing of the excavator boom, the butt and fillet welds. The fillet welding constitutes the most part of operation for the construction of excavator boom with approximately 80% of the total welding. The welding type and quality influence greatly the life span of excavator boom on site, so the operations should be conducted with great precision. In our case, the boom should be designed such that the lifetime cycle is above the design cycle selected by the manufacturer.

### A. Fatigue Evaluation Using N-code Designlife

In order to have a complete fatigue analysis and the design approval of the construction machine excavator boom HMK 490LC, two model 1 and 2 were determined with different **Test** scenarios, the two models had different working conditions selected and simulated for the test scenarios by  Hidromek technical personnel. The lifetime cycle selected by the designer for the approval of the machine is of 2.00E+06. In order to have the design approval of the machine the data of the two models and all different test condition must be used. But in our paper only the data for model 1, and Test No. 2 which the machine excavates to 0 - 1 meter (Fig. 7-1)  has been used as example of Fatigue Analysis application. For the collection of data and calculation of stress in different critical location on the boom one of the experimental mechanical methods was used in our case the strain gauges; Rosette strain gauges were place in different part of the excavator boom where the stress case is 2D to collect the strain data and to determine the stresses in critical location on the boom part, and the corresponding FAT code were determined as well in the boom part, as shown in Figure 5-4.

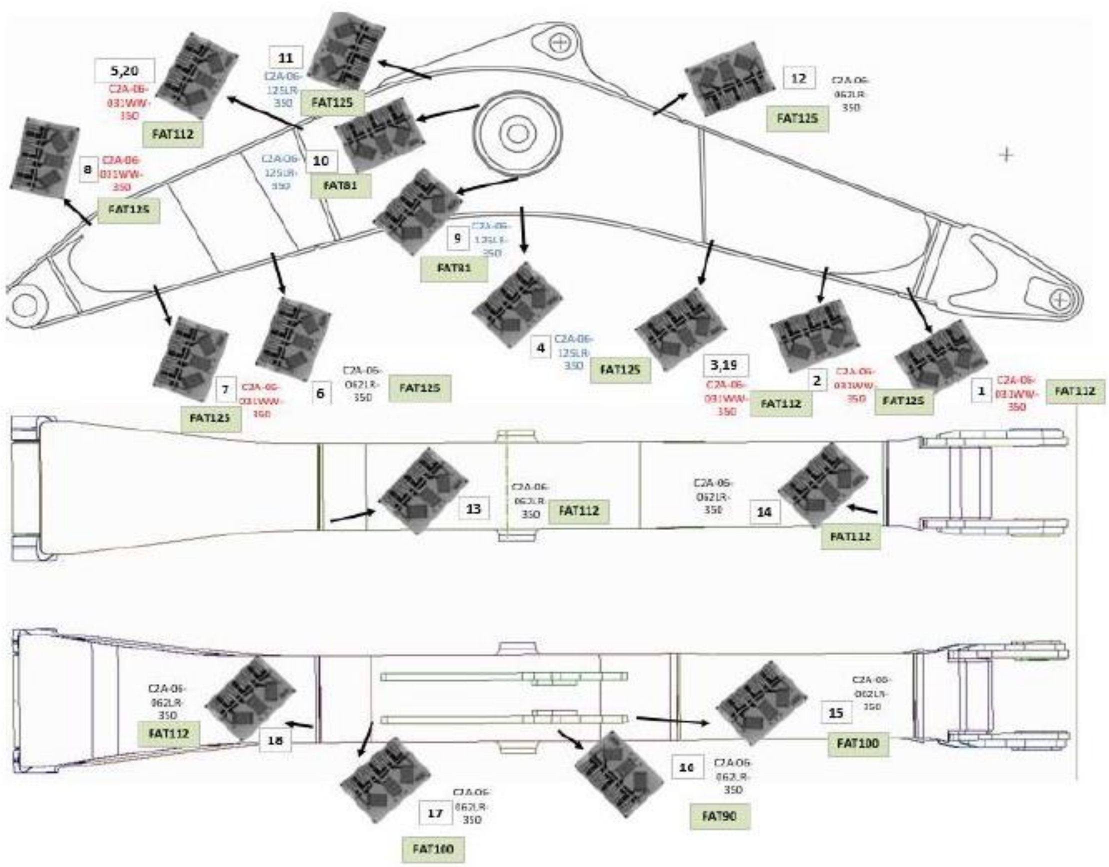


*Figure 5-4.  Measurement Points and Corresponding FAT Codes on the boom.*

After the tests were completed, the recorded data were evaluated, as we can see from Table 5-1 at each different point. Stress components, principal stresses, Von Mises stresses were calculated and their graphs of change over time were determined.

*Table 5-1. Stress Components values, Principal Stresses and Von Mises Stress at Different Points for Test No. 2*

| | $\sigma_x$(min) | $\sigma_x$(max) | $\sigma_y$(min) | $\sigma_y$(max) | $\sigma_1$(min) | $\sigma_1$(max) | $\sigma_2$(min) | $\sigma_2$(max) | $\tau_{12}$(min) | $\tau_{12}$(max) | $\sigma_v$(min) | $\sigma_v$(max) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -35.709 | 47.201 | -9.109 | 12.889 | -6.943 | 52.809 | -38.472 | 11.197 | 0.322 | 52.809 | 0.281 | 49.573 |
| 2 | -7.328 | 6.77 | -24.288 | 22.58 | -3.802 | 25.849 | -27.814 | 3.501 | 0.002 | 27.814 | 0.002 | 26.121 |
| 3 | -50.691 | 78.162 | -23.19 | 37.717 | -19.291 | 79.768 | -50.691 | 29.874 | 0.161 | 79.768 | 0.139 | 71.305 |
| 4 | -44.177 | 56.627 | -60.747 | 48.696 | -19.828 | 59.69 | -61.249 | 24.648 | 0.585 | 81.231 | 0.55 | 70.427 |
| 5 | -20.119 | 7.36 | -44.857 | 46.734 | -18.754 | 46.865 | -46.374 | 7.255 | 4.651 | 46.865 | 4.031 | 43.702 |
| 6 | -63.582 | 92.915 | -52.592 | 39.244 | -27.251 | 111.142 | -87.217 | 20.789 | 0.943 | 111.142 | 0.913 | 102.449 |
| 7 | -42.455 | 58.03 | -38.148 | 33.07 | -21.577 | 67.579 | -48.833 | 23.211 | 0.243 | 67.579 | 0.229 | 59.519 |
| 8 | -53.447 | 49.427 | -14.057 | 13.243 | -7.687 | 55.799 | -59.913 | 6.835 | 0.896 | 59.913 | 0.783 | 56.501 |
| 9 | -24.375 | 39.185 | -36.209 | 37.987 | -21.836 | 49.297 | -37.269 | 27.619 | 0.559 | 57.584 | 0.486 | 53.816 |
| 10 | -43.144 | 45.572 | -14.357 | 20.05 | -14.326 | 46.476 | -43.595 | 15.665 | 0.326 | 46.476 | 0.296 | 42.469 |
| 11 | -56.341 | 45.862 | -28.149 | 38.101 | -26.229 | 46.082 | -56.341 | 27.774 | 0.127 | 56.341 | 0.111 | 52.094 |
| 12 | -52.445 | 41.894 | -48.245 | 35.827 | -46.657 | 43.909 | -52.72 | 31.359 | 0.946 | 52.72 | 0.863 | 49.464 |
| 14 | -30.845 | 52.054 | -10.943 | 13.293 | -2.498 | 61.072 | -42.191 | 4.311 | 0.287 | 61.072 | 0.272 | 59.464 |
| 15 | -35.712 | 69.543 | -11.048 | 27.39 | -4.42 | 75.51 | -41.154 | 23.362 | 0.47 | 75.51 | 0.425 | 67.526 |
| 16 | -65.535 | 74.235 | -14.662 | 29.636 | -9.865 | 74.342 | -65.548 | 28.335 | 1.479 | 74.342 | 1.281 | 71.602 |
| 17 | -40.852 | 37.446 | -22.626 | 28.786 | -1.958 | 38.047 | -40.852 | 3.546 | 0.504 | 66.651 | 0.436 | 58.082 |
| 18 | -66.441 | 64.831 | -39.817 | 46.611 | -20.914 | 77.45 | -75.526 | 22.197 | 0.808 | 77.45 | 0.702 | 73.233 |
| 19 | -51.21 | 68.915 | -16.337 | 22.536 | -12.321 | 80.904 | -56.987 | 20.084 | 0.173 | 80.904 | 0.163 | 76.511 |
| 20 | -25.469 | 22.614 | -62.126 | 55.615 | -15.168 | 64.51 | -71.572 | 13.718 | 0.07 | 71.572 | 0.064 | 65.322 |

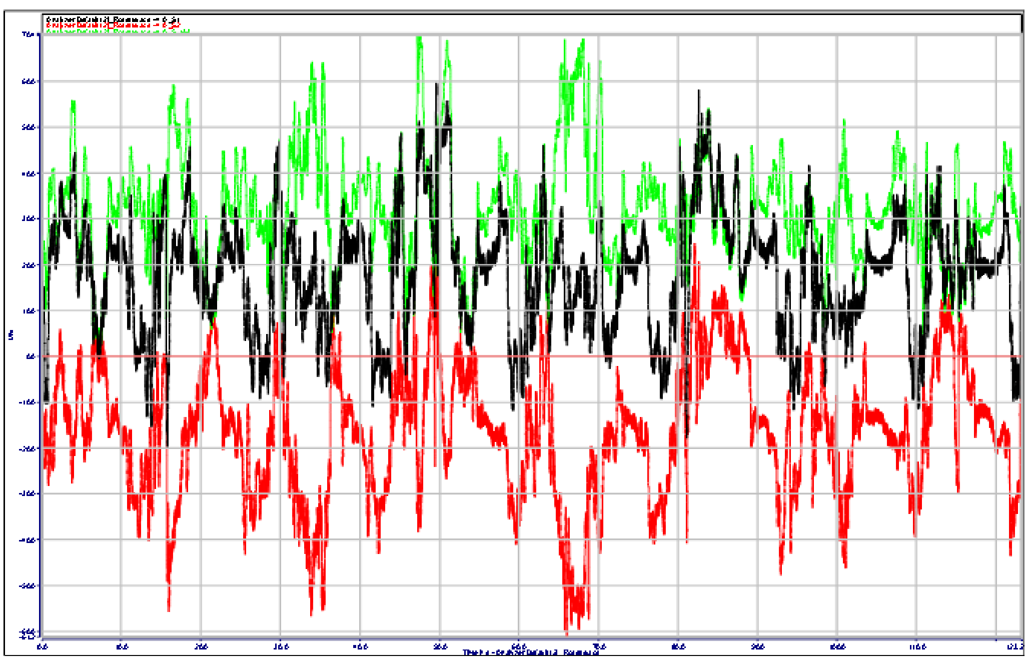

*Figure 5-5. Principal and Von Mises Stresses at Point 4.*

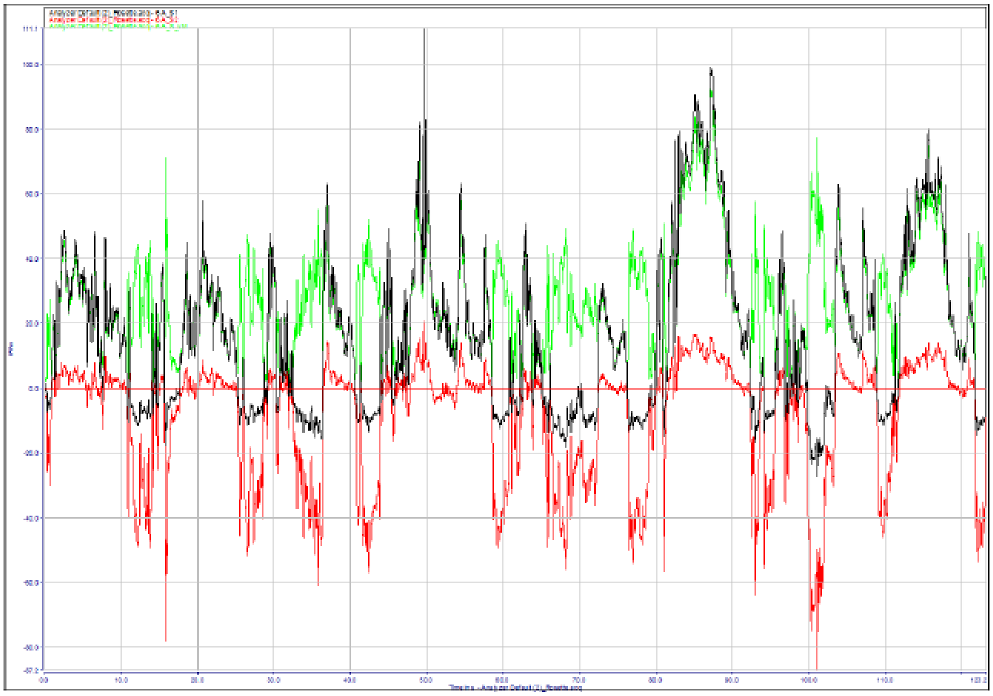

*Figure 5-6. Principal and Von Mises Stresses at Point 6.*

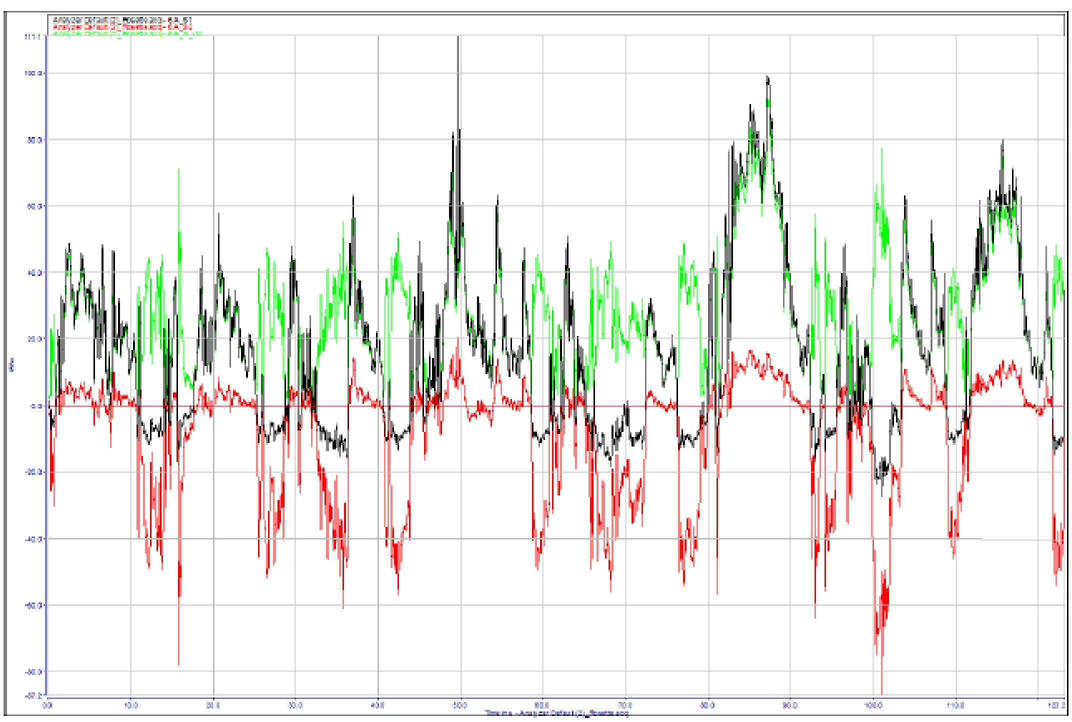

*Figure 5-7. Principal and Von Mises Stresses at Point 16.*

Then dynamic data recorded in the test results for the model 1 Test No. 2 were evaluated using n-code design life computer software to find fatigue life from the excavator boom, which was our focus in this work, appropriate Glyph on the software were used and connected between them, and then the results obtain for the lifetime cycle and total damage have been determined as shown in Table 5-2. Set on the eight-time signal repetition.

*Table 5-2. Result on Fatigue Life Cycle*

| Point | **Lifetime cycle** | **Total Damage** | **Signal repetition** |
|---|---|---|---|
| 1 | **2.98E+05** | **3.36E-06** | **8** |
| 2 | **5.56E+06** | **1.80E-07** | **8** |
| 3 | **1.12E+05** | **8.92E-06** | **8** |
| 4 | **7.19E+04** | **1.39E-05** | **8** |
| 5 | **2.99E+05** | **3.35E-06** | **8** |
| 6 | **5.36E+04** | **1.87E-05** | **8** |
| 7 | **1.88E+05** | **5.31E-06** | **8** |
| 8 | **1.93E+05** | **5.19E-06** | **8** |
| 9 | **3.11E+04** | **3.22E-05** | **8** |
| 10 | **1.02E+05** | **9.79E-06** | **8** |
| 11 | **2.80E+05** | **3.57E-06** | **8** |
| 12 | **3.00E+05** | **3.34E-06** | **8** |
| 13 | **2.30E+05** | **4.34E-06** | **8** |
| 14 | **1.56E+05** | **6.41E-06** | **8** |
| 15 | **2.91E+04** | **3.43E-05** | **8** |
| 16 | **8.71E+04** | **1.15E-05** | **8** |
| 17 | **4.67E+04** | **2.14E-05** | **8** |
| 18 | **6.82E+04** | **1.47E-05** | **8** |
| 19 | **1.00E+05** | **9.98E-06** | **8** |

As we can see from the table above since the life decided by the manufacturer according to the applied test scenario is 2.00E+06, the calculated lifetime values at many points remain below this limit value. Therefore, improvements in design will be required to reach the attended lifecycle, and more test may be conducted to see what to improve to have a better functioning machine.

# VI. CONCLUSION

As we have seen, fatigue failure is a great concern in engineering field, and when crack initiate, we cannot really control the rate of crack growth, but thanks to calculation we are able to predict the fatigue life of structure before failure occurs. We can take proper steps to prevent any accident or losses, and different methods of evaluation for fatigue can be used depending on what stage of fatigue the structure is currently in, there are the stress-Life, strain-Life and Crack Propagation method (LEFM). We investigated about different approach to evaluate the life for different welded structures, which are **the nominal stress**, **hot spot approach**, **notch stress approach** and **Mesh-Insensitive Structural Stress Method**, with the nominal stress as the most approach used with its simplicity whereas with other approach a FEM model will need to be construct and used for the fatigue analyses of the element. But when working on the real structure, collection of data is in order in critical location for the evaluation of fatigue life like it was done in our case with experimental method using strain gauges. And some heat treatment can be used after welding operation for a better fatigue strength of the structure

As it is the case with our vehicle Excavator model HMK 490 LC, generally the designer decides the fatigue life cycle or the working hour of the structures or machine to be manufactured and be used on site, after that test can be conducted to determine if improvements in the design is required in view of reaching the desire standard fixed by the manufacturer. In our case after collecting data through experiment with different test scenarios, we used the computer software n-code Designlife to determine the cycle life of the boom of the construction machine, as we have seen the life cycle on different point were lower to the limit set by the manufacturer, so improvement in design were required to increase the fatigue life.

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