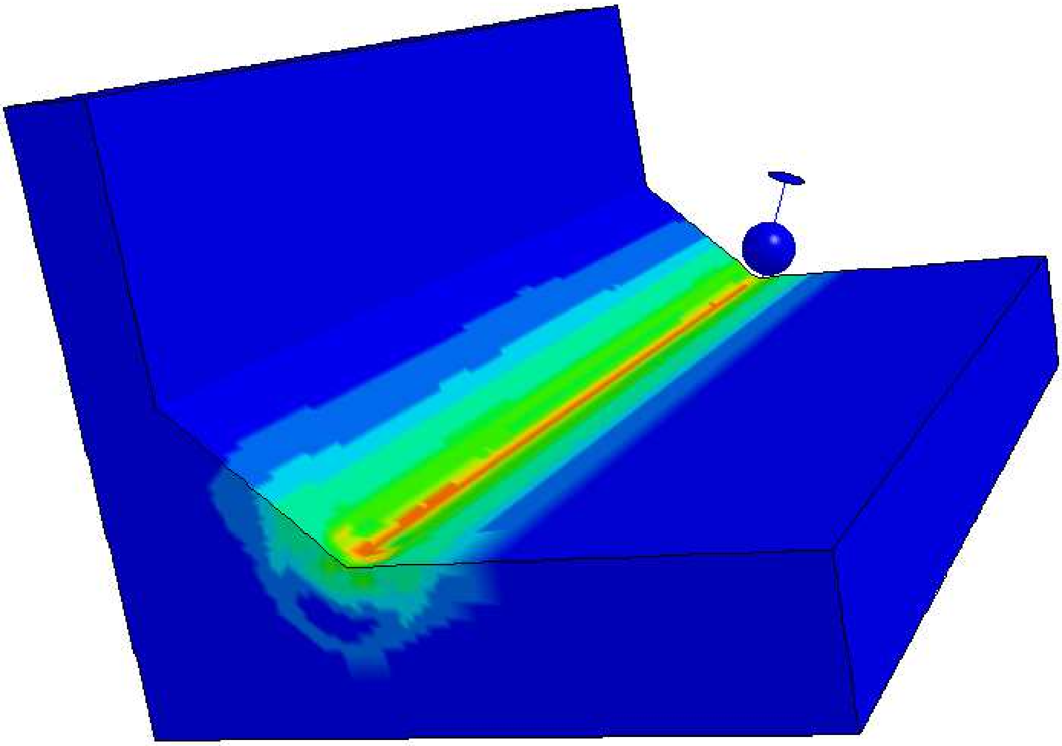
Effect of Ultrasonic Impact Treatment on Welded Details under Cyclic Loading Conditions

Master thesis DMS - Martin Riskjær Laursen



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Resumé

Dette projekt omhandler udmattelse beregninger af svejste detaljer, hvorpå der er udført levetids forbedrende processer. I dette tilfælde er der tale om den relativt nye metode; Ultrasonic Impact Treatment(UIT) Metoden er effektiv ift. forlængelse af levetid samt, at denne ikke kræver samme kræfter fra brugeren som eksempelvis hammerpeening. Dette betyder ligeledes at processen i de senere år være et interessant objekt for numeriske modeller.

En kort gennemgang af tidligere studier er givet, hvor løsnings strategierne har været henholdsvis, hastigheds-, deformations- eller kræftbestemt. Alle metoder viste gode resultater og det blev besluttet at der i denne rapport bliver arbejdet med en kræftbestemmende metode. Forskellen på de tidligere numeriske modeller og den der findes heri, er at de tidligere var lavet vha. en genstart funktion. Dette betyder at der gives et slag, hvorefter programmet lukkes ned og åbnes for at give det næste. Modellen fra denne rapport køres kontinuerligt, hvilket resulterer i en væsentlig tidsbesparelse.

Modellen er bygget op af en kugle der er hængt op i to muskel elementer, som skiftevis trækker sig sammen. Dette giver den oscillerende effekt. Yderligere er der i modellen lavet et parameter studie for materiale og proces. Materialet er parametriseret ved tangent modulet, dette påvirker hærdningsgraden og skulle simulere hårdheds ændringen ved en svejsning. Denne blev vurderet til at have en meget lille effekt. Dernæst var selve vinklen på arbejdsgangen parametriseret, hvilket viste gode resultater.

Slutteligt skulle levetids forbedringerne bestemmes, dette er gjort ud fra ”Notch Stress Approach”, hvilken bestemmer den effektive spænding, ved en spændingskoncentration. Dette blev gjort ud fra FAT200, der er anvendt til at bestemme levetiden ved ikke efterbehandlede svejsninger. Spændingsvidden blev udregnet fra den numeriske model, der var behandlet ved UIT og gav en levetids forbedring på 4.4, hvilket ikke er tilnærmelsesvis hvad standarderne foreskriver.

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Title: Effect of Ultrasonic Impact Treatment on Welded Details under Cyclic Loading Conditions
Theme: Master's Thesis
Project period: 1st of April - 1st of August, 2018

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Number of pages: 35 (48)
Completed: 01-08-2018

Synopsis

This project concerns fatigue assessment of post weld treated T-joints, applying ultrasonic impact treatment(UIT).
A numerical model is established in order to verify the process, and determine the stress ratio after UIT. This model runs continually, versus earlier studies considering the subject, where build with a restart. From this a faster model is obtained, and is validated with earlier residual stress distributions and geometrically.
The fatigue estimation is based on the notch stress approach, comparing as-welded and lifetime improved in the same detail category. This yields a improved factor of 4.4.

Preface

This thesis is written by a Master's Degree student in "Design of Mechanical System" (DMS) from the Department of Materials and Production at Aalborg University

Reading Instructions

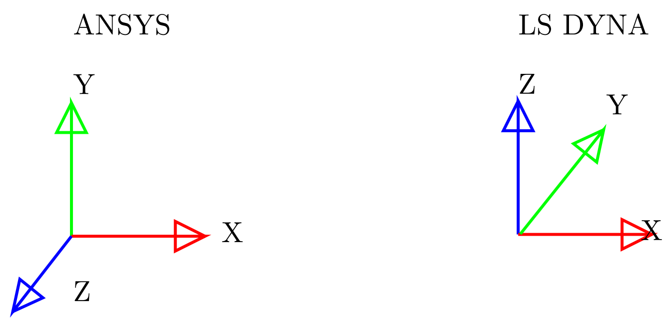
References and sources will appear in the report and displayed in alphabetical order as a list of references i.e. bibliography, which is located at the end of the report. The method of citation is Harvard and displayed in the following manner: [Lastname/webpage, Year], page numbers may be applied if statements are used.

Books as sources are written in the bibliography as [Author, title, edition and publisher], internet sources [author, title and date], and articles [author, and title].

Each Figure, table and equation is numbered such that it corresponds to the chapter, e.g. the first table in chapter 5 is numbered 5.1, the second 5.2. Captions containing the description of figures and tables are located below the figure. Symbols denote constants and functions.

The notation of numbers are done according to that of English meaning that dot(.) denotes the decimal separator and comma(,) is the delimiter of thousands e.g. $3,124.56$.

Different coordinate systems have been used for ANSYS Workbench and LS DYNA, respectively;



The following software has been used in the making of this report.

- ANSYS Workbench
- LS Dyna
- MobaXterm
- Maple
- MATLAB
- Mathcad
- Inkscape
- LaTeX

The authors would like acknowledge the supervisors Jan Schjødt Thomsen for guidance and Benny Endelt for guidance and suggestions on LS Dyna model.

Contents

Introduction 1

The focus of this project, is an investigation of the effects imposed by a post weld treatment, fatigue lifetime and numerical modelling. The following will give a short introduction to different post weld treatments, and their differences and at the same time, work as a problem analysis.

A post published in "Svejsning 2"-Landsforening [2018], by Henrik Kongsensbjerg, who is a welding specialist in HMF Group A/S, he comments on the importance of high quality welds with a focus on the toe radius. This relates directly to fatigue strength, meaning that from a quality standard A to A+ is a doubling of the lifetime. These quality standards relate to a radius of A 1mm and A+ 3mm.

1.1 Fatigue Life Improvement

In the post by Henrik the solution for a better weld toe geometry is to use a metal powder filled welding wire. A different method could be a post weld treatment, and a comparison of these was carried out on an experimental scale at the University of Aalborg, it was found in a PhD thesis from 2011 by Mikkel Melters Pedersen, Pedersen [2011]. The effect of different post weld treatment methods is split up into three different categories; geometric, residual stresses and a mixed category as illustrated in table 1.1.

Geometric	Residual+Geometric	Residual
Burr Grinding	Ultrasonic Impact Treatment	Shot-peening
TIG Dressing	Hammer-peening	Explosive Hardening

Table 1.1: *Post weld treatment processes.Serope Kalpakjian [2014]*

The benefits of a geometric process is a reduction of the stress concentration factor(SCF), since this is calculated on the geometries. Smooth rounding is well known to have a smaller stress raising than a sharp notch. The introduction of residual compression stresses are beneficial due to the fact that these needs to be surpassed before critical tension stresses are reached, i.e lowering the stress range in fatigue assessment. From Pedersen [2011], it was found that ultrasonic impact treatment is very effective in high-cycle fatigue life improvement, see figure 1.1.

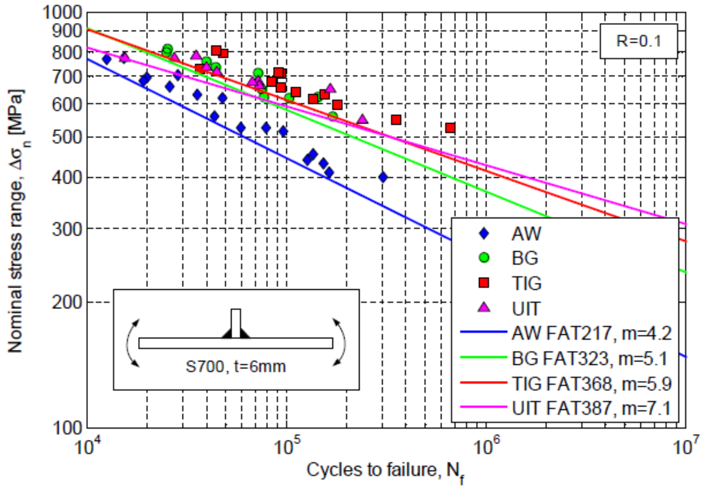


Figure 1.1: *Fatigue results from previous studies, comparing different post weld methods, Pedersen [2011].*

As a final remark, Pedersen [2011] suggested that fatigue life could be estimated using the stress notch approach with FAT360 and a flatter slope of m=5 for UIT, and for as-welded(AW) he suggests a FAT200. Similar results are presented in guideline for fatigue assessment of post weld improved welds Gary B. Marquis [2013].

1.2 Ultrasonic Impact Treatment

Ultrasonic Impact Treatment(UIT) is one of the younger post weld improvement methods, developed in Russia in the 1970s(Statnikov [2004]). This impact treatment is based on a conversion of harmonic oscillations of a ultrasonic transducer into impact pulses on the treated specimen. These oscillations are transferred through a waveguide into the work tool, either a ball or pin, and then further into to the treated specimen. When the waveguide is not active the tool allowed to move freely between waveguide and specimen surface Statnikov [1999], meaning the waveguide controlling the impact.

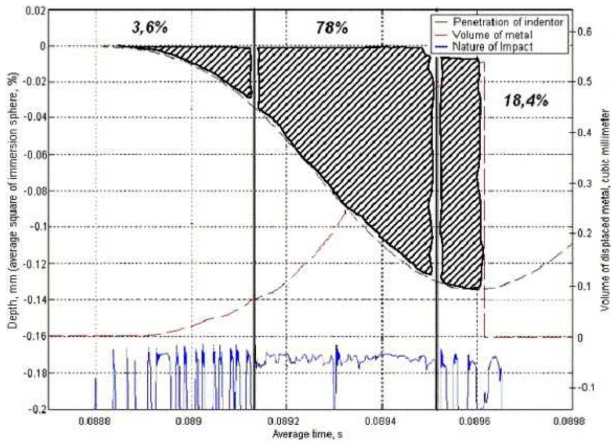


Figure 1.2: *Distribution of plastic deformation during ultrasonic impact, Efim Sh. Statnikov [2006].*

Figure 1.2 illustrates the plastic deformation for the onset of impact 3.6% and active 78% yielding reboundless oscillations Efim Sh. Statnikov [2006]. This gives an indication of the influence of the ultrasonic stress waves of 27-44kHz, which are impacted in the range of 100-120Hz.
Weich [2013] presented experimental data that showed beneficial compressive stresses are generated down to the depth of 1.5-2mm, with the maximum values at 0.4-0.5mm below surface and a permanent deformation of 0.1-0.2mm groove depth.

1.2.1 Numerical Model

The plastic deformation yields in beneficial residual stresses, as mentioned earlier, further investigation will be performed using a numerical model. Multiple studies have already been carried out with different approaches, the most significant being loading/impact modelling. Three approaches; Deformation-, Velocity- and Force controlled simulation(DCS,VCS,FCS).

In Guo [2015] a single shot analysis was created using VCS in 2024 aluminium. The numerical model was controlled by varying the impact speeds and verified geometrically measuring the impact diameter. The distance between two impacts was parameterised, but only had little to no effects on the maximum residual stress.

A study of UIT was carried out in Jan Foehrenbach [2016], concerning both FCS and DCS and material s355J2H. The distance between impacts was 0.4mm and 0.2mm for DCS and FCS respectively. DCS were simply set to an experimental measured depth of 0.2mm. The FCS method was given an initial velocity, and the calculated contact force was compared to an experimental test, measured by strain gauges on impact tool($\approx$ 3000N). Afterwards the residual stresses was compared to experimental results from X-ray and neutron diffraction, these are illustrated in figure 1.3.

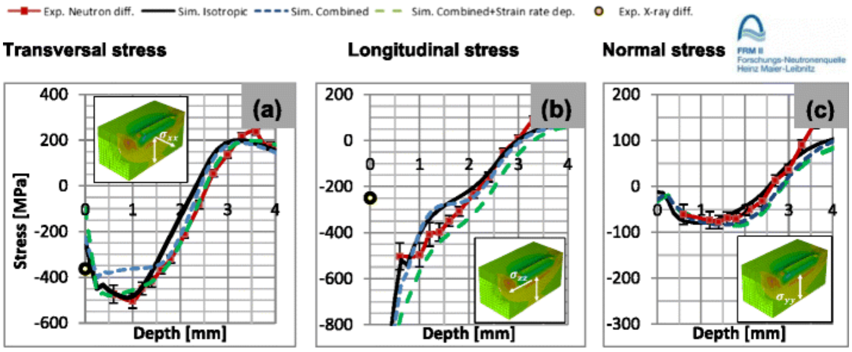


Figure 1.3: *Distribution of residual stresses after ultrasonic impact, Jan Foehrenbach [2016].*

Different material models were tested; Isotropic, Isotropic combined with Kinematic, and combined plus strain rate depending hardening. It was concluded that for DCS combined isotropic, kinematic and strain rate dependent hardening behaviour showed the best agreement. For the FCS, isotropic hardening is dominating in the top 1 mm, and for >1mm kinematic hardening is dominant. The explicit analysis was solved using ABAQUS, and took 110 hours for the 300 hits treated 60 mm (Clément Ernould [2017]).

Kuilin Yuan [2016] included the welding related residual stresses and the controlling parameter was velocity(VCS) the impact velocity was calculated at the tip of the waveguide:

$$x(t) = Asin(2\pi f_{ul}t) \quad yields: \; V_{imp} = V_{max} = 2\pi f_{ul}A \tag{1.1}$$

f_{ul} being the impact frequency and A the amplitude. Number of impacts is taken from the reboundless contact time in figure 1.2 and ultrasonic oscillations 27kHz equals around 30 cycles/impacts and a process sped of 0.4mm/hit from Jan Foehrenbach [2016]. In this model an extra material parameter is included by introducing ultrasonic softening (Statnikov [2004]):

$$\sigma_{ultrasonic} = \sigma_0(1 - \eta) \tag{1.2}$$

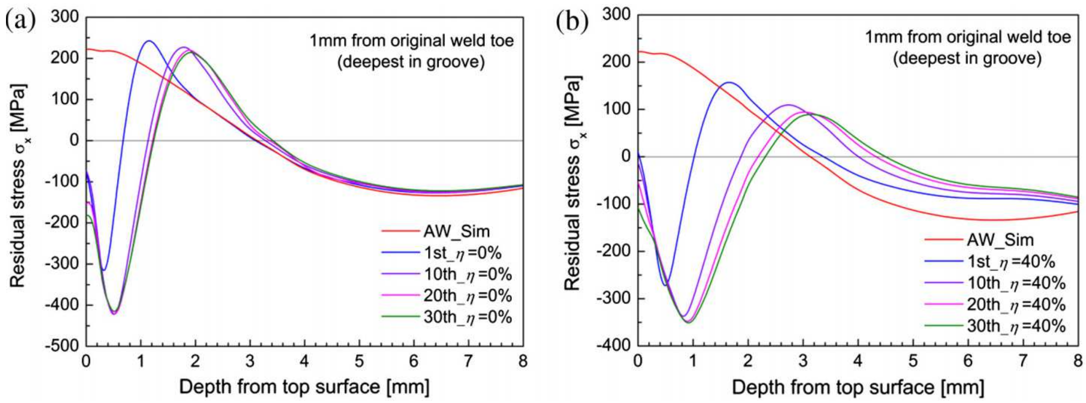


Figure 1.4: *Number of impacts vs residual stress distribution and effect of ultrasonic softening, Kuilin Yuan [2016].*

From figure 1.4 it was concluded that the residual stress increased with number of impacts and converged approaching 30th. While softening the material was verified by X-ray and neutron diffraction and showed a fairly good agreement for this cruciform joint.

1.2.2 Hardness

A master thesis; *Determination of the governing failure mechanisms for welded T-joints under cyclic loading conditions* written by Daniel Rauff Andreasen [2016] done at Aalborg University shows how the hardness in the material is affected by the welding process, due to heating the material.

$$\sigma_{ultimate} = 3.5 \cdot (HB) \tag{1.3}$$

$$HB = \frac{2P}{(\pi D)\left(D - \sqrt{D^2 - d^2}\right)} \tag{1.4}$$

Hardness is stated as the materials resistance to permanent indentation(Serope Kalpakjian [2014]), which is very much related to the ultrasonic treatment process. A relation is established between Brinell Hardness(HB) and the ultimate strength for steels loaded with 3000kg.

Project Objective and Methodology 2

2.1 Project Objective

The UIT process results in strain hardening of the material, which introduces residual stresses and should have an effect on the fatigue life. In order to validate the as-welded life time, two methods will be used; the nominal stress approach and the notch stress approach(NSA), which is done for a specific weld type. A numerical model that includes the residual stresses imposed by the ultrasonic impact treatment will be established, this will be compared to the findings in the introduction. Finally, a test specimen is cut out and loaded in the same manner as the as-welded test and compared by NSA.
Literature showing that residual stresses from welding process is overruled by UIT, thus this process is not considered in this study(Kuilin Yuan [2016], Statnikov [2004]). "The presence of welding residual stresses had a mostly negligible effect of the residual stress after treatment"(Clément Ernould [2017])

2.2 Methodology

Numerical Process
The numerical model will be the basis of an investigation of the mechanics in the process. This will give an understanding of the deformations which relates to the residual stresses, and will be used for parameter studies for more insight of the process.

Notch Stress Approach
In order to estimate fatigue life of the ultrasonic impact treated welds, the newly created numerical model of the UIT specimen will be compared against as-welded results using the notch stress approach.

Material Parameter Study
From the problem analysis, the welding process was found to have an influence on the hardness, and will be studied as the tangents modulus for a bilinear stress-strain curve, simulating the non-linear material properties of material hardening.

Process Parameter Study
Throughout this study, process parameter as the angle of the impact tool will be controlled, to determine a favorable angle.

High Cycle Fatigue 3

The basis of this chapter is to establish a background for comparison of effects from a post welding process. In this case ultrasonic impact treatment is considered which should have a positive effect on the lifetime considering cyclic loads. First of lifetime estimations are done by design codes and Notch Stress Approach for a specimen as welded.

3.1 High Cycle Fatigue

Fatigue - the process of initiation and propagation of cracks through a structural part due to action of fluctuating stresses Eurocode [1993].

High cycle fatigue(HCF) is a type of fatigue caused by small elastic strains under a high number of load cycles before failure occurs. The fluctuating stresses comes from a combination of mean and alternating stresses. The mean stresses might be caused by the residual stress e.g UIT. The alternating stress can be a mechanical stress, e.g payload on a crane. Their relationship is given by:
Stress amplitude - σ_a, Stress range - $\Delta\sigma$, Mean stress - σ_m and Stress ratio - R

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (3.1)$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad (3.2)$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (3.3)$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (3.4)$$

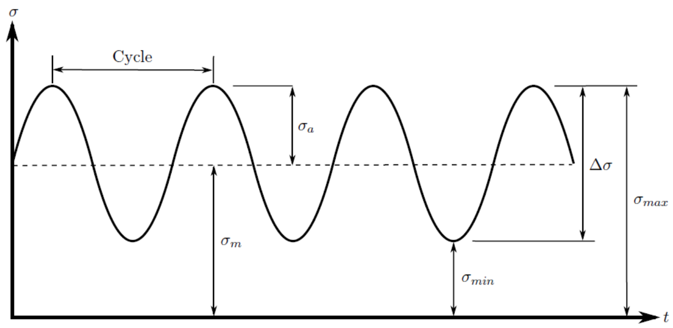


Figure 3.1: *Constant fluctuating stress.*

The stress range is the main parameter to be determined for fatigue analysis, throughout this report a constant stress range is used for simplicity. The stress range can be applied for both nominal stress and notch stress Niemi [1995]. As stress range is the main parameter, this is used for categorising the SN-curves also known as the FAT category. FAT category corresponds to the stress range with a 95% survival probability at 2e6 cycles to failure, see figure 3.2.

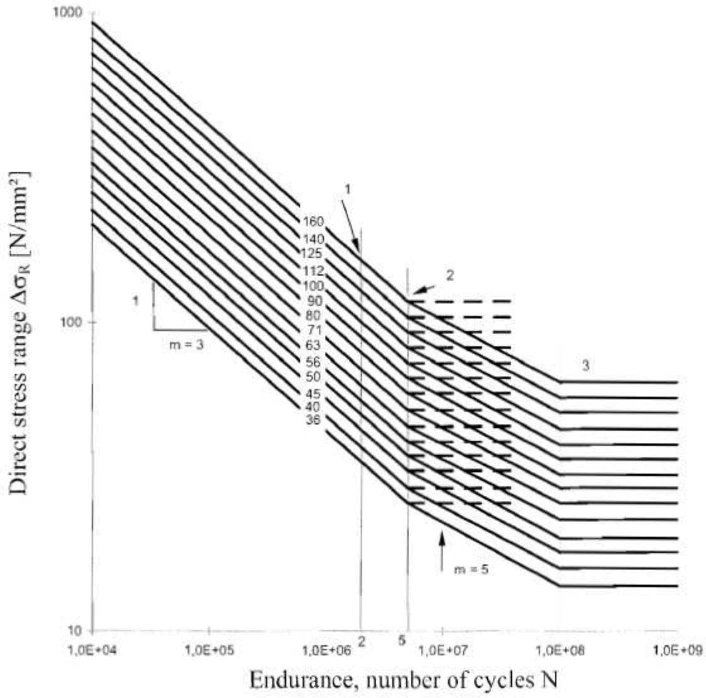


Figure 3.2: *SN curves for welded details in Eurocode 3 Eurocode [1993].*

Following the standard Eurocode [1993], only stress range, weld geometry and quality has an effect on the fatigue lifetime. Residual stresses and stress ratio are taken directly into account in this method, these two might relate to each other, and are one of the reasons for post weld treatments.

3.2 Geometry and Loading Situation

First a geometry is arbitrary chosen for the entire report, since the purpose of this is to evaluate effects of a post weld treatment, this could be any and changed for specific problems. The geometry is obtained from previous projects in Aalborg University, and chosen to be a bending T-joint. This means a bending plate, with a non-load carrying attachment.

	Plate	Attachment
Width	40mm	40mm
Height	6mm	6mm
Length	250mm	30mm
Weld	A4	-

Load scenario is a four point bending, the plate is places between four rollers, see figure 3.3.

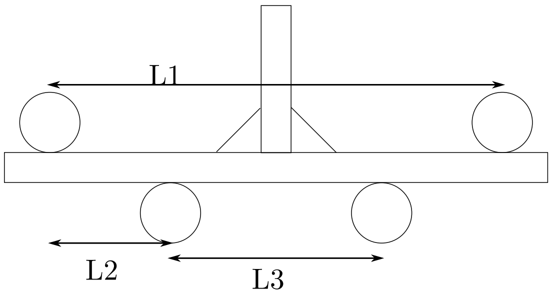


Figure 3.3: *Roller placement four point bending.*

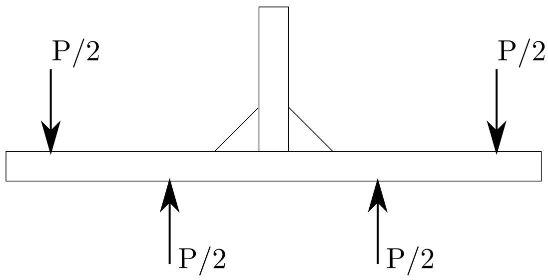


Figure 3.4: *Force four point bending, FLD.*

The reaction force from the test setup, are displayed in the FLD in figure 3.4. From the moment- and forcecurve are derived, see figure 3.5, here it becomes evident that the detail is loaded by pure moment, and second that symmetry conditions can be applied in L1/2.

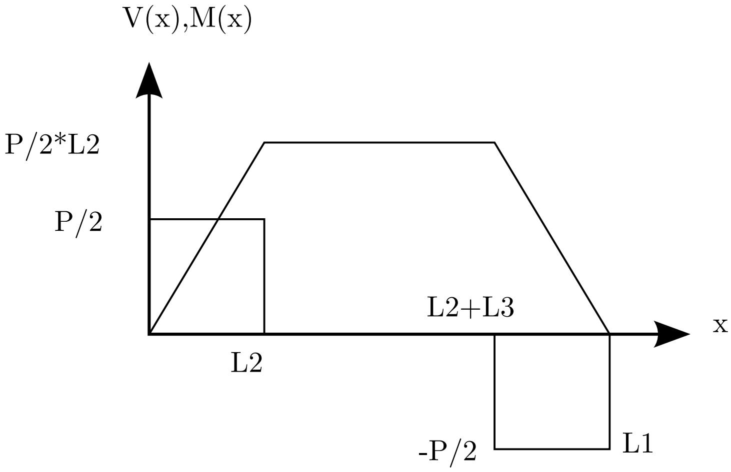
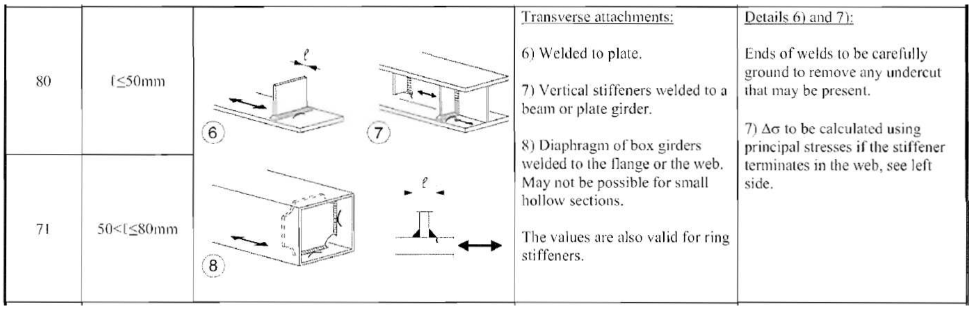


Figure 3.5: *Shear and moment force in four point bending.*

Two methods of fatigue assessment are considered in this study; The nominal stress approach and the notch stress approach.

3.3 Nominal Stress Approach

In Landsforening [2018], Mikkel Melters also has a post regarding using fatigue estimations. That the nominal stress approach with standards is still the most common, and that the numerical based are considered an academic exercise. Thus the nominal stress approach will be used as a starting point, from which the load is determined.
The detail is found to be 80 in figure 3.6, and this is chosen as the comparison point, at 2e6 N cycles, this equals a stress ratio R = 0 for simplicity.



80	l≤50mm		Transverse attachments: 6) Welded to plate. 7) Vertical stiffeners welded to a beam or plate girder. 8) Diaphragm of box girders welded to the flange or the web. May not be possible for small hollow sections. The values are also valid for ring stiffeners.	Details 6) and 7): Ends of welds to be carefully ground to remove any undercut that may be present. 7) Δσ to be calculated using principal stresses if the stiffener terminates in the web, see left side.
71	50<l≤80mm			

Figure 3.6: *Detail category of T-joint Eurocode 3 [Eurocode, 1993].*

As the nominal stress is determined for 80 MPa, the moment is solved, since the force is zero for this load case.

$$\sigma_n = \frac{F}{A} + \frac{-M \cdot y}{I} = \frac{-M \cdot y}{I} \tag{3.5}$$

$$I = \frac{bh^3}{12} = \frac{1mm \cdot (3mm)^3}{12} \tag{3.6}$$

$$M = \frac{\sigma_n \cdot I}{y} = 480N \cdot mm \tag{3.7}$$

Solved for unit thickness, and ready for a 2D analysis.

3.4 Notch Stress Approach

The notch stress approach for fatigue assessment of welded joints correlates the stress range in a optimised rounding in the weld toe to the fatigue life using a single SN curve. Following the guideline given by Fricke [2012] in the IIW. If the effective notch stress is based on FEM, a minimum of Kw = 1.6 is set for a optimised weld toe radius of 1mm Fricke [2012]. Kw being the relation between the nominal stress and the effect notch stress at the weld toe.

$$\sigma_{es} = K_w \cdot \sigma_n \tag{3.8}$$

Experiments from M.M. Pedersen [2010] mentioned in the introduction, showed that for T-joints FAT225 gave reasonably results, but if lowered to FAT200 it seems to have the same safety as in the nominal stress system, since less experimental datapoints falls below. On this background the FAT200(figure 4.18) detail category is used.

Previous mentioned symmetry conditions is applied to the center of the T-joint:

$$UX = RY = RZ = 0 \tag{3.9}$$

A maximum mesh size of 0.25mm is created in the area of interest, see figure 3.7, and are applied with quadratic shape functions. The moment of 480Nmm is applied to the end of the bottom plate, and the normal x stress is read to 79MPa, in close range to the nominal stress range.

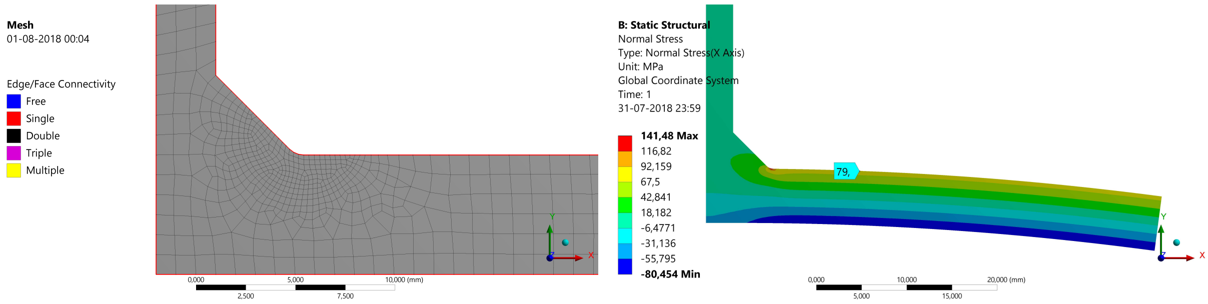


Figure 3.7: *Mesh and Normal stresses in x.*

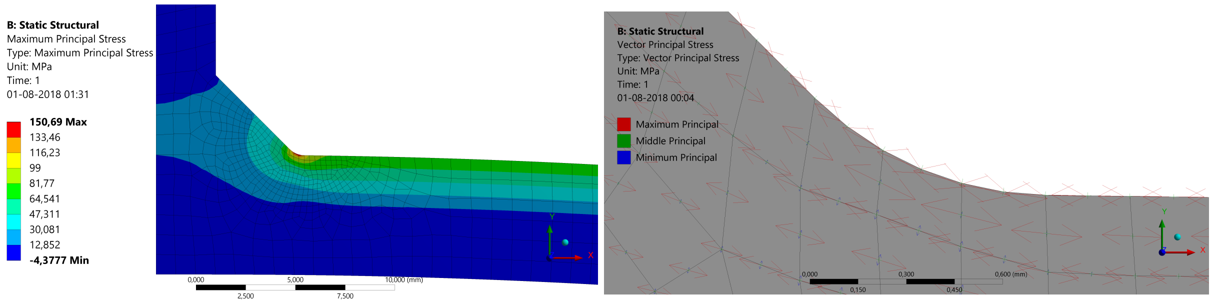


Figure 3.8: *Principal stresses and related directions.*

The principal stress is read to 150MPa and verified to be tangential to the surface(Fricke [2012]), figure 3.8. The stress range equals the maximum principal stress, and the lifetime can be derived by the equation 4.8. N = 4.7407e6, which is a factor 2,35 using the effective notch stress, thus the nominal stress approach is very conservative.

Model - LS-DYNA 4

This chapter concerns the numerical modelling of the impact treatment and a four point bending model for stress range determination. Keyword files for the numerical model are found in Appendix A and B.
The numerical models are build inside LS-DYNA LS PrePost concerning:

- Step 1 - Impact peening - Explicit
- Step 2 - Four point bending - Implicit

LS-DYNA History

LS-DYNA is chosen for this simulation, and has its origin from 1976, developed by John Hallquist at the Lawrence National Laboratory, where the purpose was to simulate the release of a FUFO bomb at low altitude. At the time, 3D simulation software was not able to simulate this kind of impact. This project was later cancelled but the development of DYNA3D continued until 1988 by Hallquist and Benson. In 1989 Hallquist started the LSTC (Livermore Software Technology Corporation), who distributes LS-DYNA, that is one of the best softwares for explicit and contact based simulation (Benson [2007]).

4.1 Explicit vs Implicit

Explicit analysis are solved directly, as the inverse of the diagonal mass matrix times the nodal force, which yields the acceleration at time n, from which the acceleration is found at time $n^{+1/2}$ and displacements at time n^{+1}. From displacements it is purely theory of elasticity(Cook [2002]), relating displacement - strains - stress and at last force for the next step (CORPORATION [2016]).
Considering non-linear implicit analysis, this needs to do a series of iterations in order to reach equilibrium. Also, this needs a numerical solver to invert the stiffness matrix, which is an expensive task, illustrated in table 4.1.

	Storage	Requirements	CPU	Requirements
Element type	2D elem.	3D elem.	2D elem.	3D elem.
Implicit	n^5	n^7	n^5	n^7
Explicit	n^2	n^3	n^3	n^4

Figure 4.1: *Requirements depending on number number of elements, type of elements and the formulation used(Nielsen [1997]).*

The explicit analysis is solved in smaller time steps, the size of these are discussed in the next section, every step is solved directly, being the faster method. A non-linear implicit a number of load step, with an numerical iterative solver for each step.

Ultrasonic Impact Treatment is solved explicit including the dynamics and contact of the impact tool, together with the plastic deformation i.e highly non-linear analysis.
The four point bending analysis is solved, using the implicit solver in LS-DYNA, the load rate is slow enough to be quasi-static, and the inertial effects has no effect on the result(Nielsen [1997]). Material behaving non-linear and contact between the T-joint and the rollers, makes the analysis non-linear. Although it is non-linear and would be a quick solve using explicit, this method can lead to large errors, e.g when updating constitutive relations will nearly always lead to lack of accuracy due to drifting(Nielsen [1997]), thus kept implicit.

4.2 Mass Scaling

Using a explicit solver for numerical models that are time dependent, yields effective results for very rapid simulations as explosions etc.. Since the time step must be less than the time it takes the sound wave to travel through the element, in order to be stable(Weimar [2001]), following equation is given:

$$\Delta t = \frac{l}{c} = \frac{l}{\sqrt{E/\rho}} \tag{4.1}$$

From this it is seen that time step is increased by; larger elements, decrease of Youngs modulus or increasing the density. However, if the mass density or Young's Modulus is tuned to increase the time step, some non-physical problem can occur, where the inertial response for the model will react an inconvenient manner.
The step size were set for 1e-7.

4.3 Model Impact Peening

The model is based on the lecture notes by Benny Endelt given at the University of Aalborg (Endelt [2018]), and will be force controlled. The number of impacts and distance in-between is function controlled found Appendix B. Basic parameters are set as follows;

Parameter	Value
Time	0.15
Amplitude	0.1
Impacts	60hit/mm
UIT Length	42 mm
Force	400N

Table 4.1: *Basic parameters.*

The force is based on suggestions from Endelt [2018] and experience with the model. Impacts relates to 30 impact/0.4mm Kuilin Yuan [2016] which is estimated as 60 impacts/mm.

4.3.1 Mesh and Boundary Conditions

The discretisation of the T-joint specimen is similar to the one from notch stress approach including; symmetry conditions and element size. Applying the notch stress approach, the geometric requirements for weld toe radius are met by impact tool geometry.

T-joint

The mesh size requirements of <0.25mm(NSA) is done in a relatively close range of the weld toe, in order to provide accurate results. This is done by the creation of squared elements in 2D and later extrusion to the width of 40mm, since this matches the size of a four point bending specimen. Mesh size outside the area of interest varies up to 4mm in length, in order to shorten the calculation time. Since the only purpose of the surrounding area, is to create a truthful boundary condition, no results will be extracted from these areas, see figure 4.2.

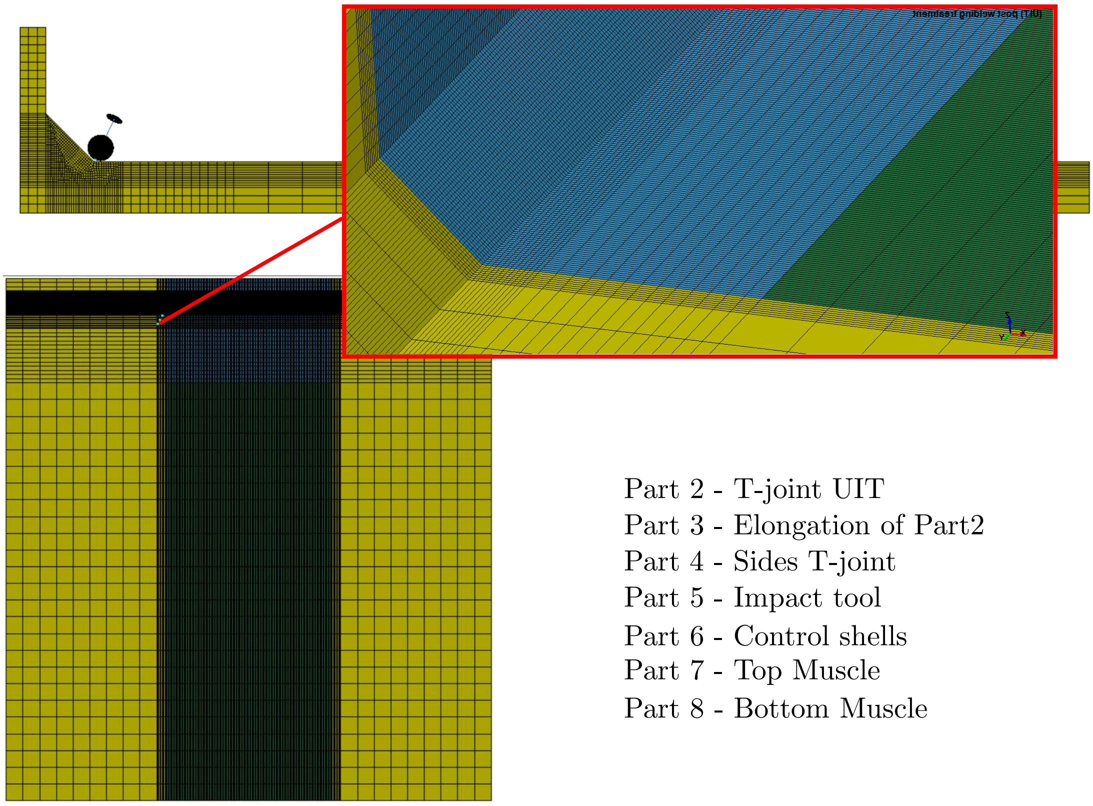


Figure 4.2: *Discretisation of the T-joint; Part 2 - T-joint (Blue), Part 3 - Elongation of T-joint(Green) and Part 4 - Sides T-joint(Yellow).*

Impact tool

The Impact tool is discretised into five pieces; Two shells, two beams elements and a ball. The tool is simplified as a ball assigned with material MAT_RIGID, since this is a very robust material model and is recommended in the LS-DYNA User Guide CORPORATION [2016] for all metal forming tools. Controlling the cycle motion the beam elements are applied with MAT_MUSCLE, between two shells which controls the process angles.

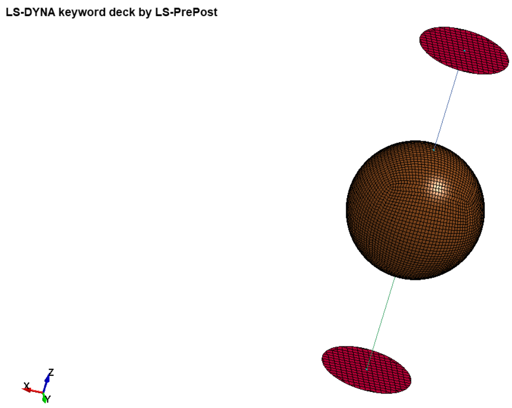


Figure 4.3: *Discretisation of the ultrasonic impact tool.*

The discretisation of the tool is strongly related to the process parameters, ball diameter and process angle. Ball diameter is locked in this study and determined to 3 mm based previous studies, but could easily be changed. The center of the ball is set to hit the weld toe, where weld and base material meet at an angle of 67.5degrees, measured from the base material, since this is half the angle from base to weld, and this is also used in Kuilin Yuan [2016] and Jing Zheng [2017].

Boundary Conditions

Four types of boundary condition, **constraints** applied by GLOBAL.k(4.3) and GLOBAL_xy.k(4.2) included in the main, in this manner these are only applied for this simulation, since bottom must be free for the moment test.

$$UZ = UY = RX = RY = 0 \quad for;\ xy - planez = 0 \tag{4.2}$$
$$UX = RY = RZ = 0 \quad for;\ yz - planex = 0 \tag{4.3}$$

Prescribed motion are applied to the shells and ball in the y-direction parallel to the welding, this is given by line 128 Appendix A. This is followed by the force curve applied on the top shell, to ensure the tool stays in place. Oscillation of the ball is determined by the activation of the muscle beam element, discussed later.
Last boundary condition is created by **extra parts**, the extra side in figure 4.2, this should ensure good results for the test specimen and eliminate problems treating the edge of the specimen.
CONTACT_SURFACE_TO_SURFACE, slave and master parts are given respectively impact tool and T-joint. Where every slave node is checked for penetration through the master surfaceCook [2002].

4.3.2 Material

As presented in the introduction the material model played a great role in results of the residual distribution. From Jan Foehrenbach [2016] it was concluded that isotropic hardening gave the best results for the top layer of 1 mm, from which the stresses for fatigue life assessment are obtained.

Steel

The material model MAT_24 is chosen, as this has a isotropic hardening profile. A secondary benefit of this material type, is the ability to show actual yield stress. It is possible to give piecewise linear material curve, but since there are no actual experimental work and purely a parametrical study the non-linear material profile is kept bilinear. The tangent modulus is obtained from ANSYS User Guide ANSYS [2017] to be 1.45GPa, and compared to the true stress-strain curve in DNV208 Veritas [2013], determined by interpolation between yielding stress and ultimate stress.

$$E_t = \frac{\sigma_{ul} - \sigma_y}{\varepsilon_{ul} - \varepsilon_y} = 1.368GPa \tag{4.4}$$

From these two values E_t is chosen as 1.4GPa for starting.

Muscle

MAT156 or MAT_MUSCLE is a material type designed for beam elements and is commonly used in simulation of car crashes, for imitation of the human body and the muscle reaction CORPORATION [2016]. This element is able to be elongated freely and is stress free when not activated, and is adapted from the MAT_S15 spring muscle model, illustrated in figure 4.4.

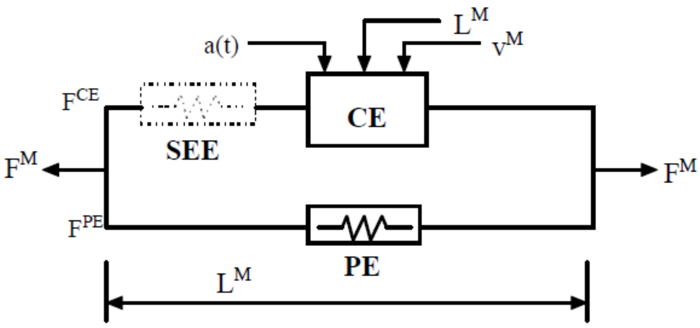


Figure 4.4: *Discrete model of the S_15 material muscle contraction(CORPORATION [2016]).*

F_M is the total force, expressed by the sum F_{PE} and F_{CE}, respectively the passive and active force. The passive element PE represent the elastic energy storage from muscle elasticity. The active element represents the force generation by the muscle when activated by the activation level $a(t)$. L_M is the length of the muscle and V_M is the contraction velocity(CORPORATION [2016]). The basic parameters are replaced by stress(force), strain(relative length) and strain rate(velocity).

Inputs for material was obtained from Endelt [2018], and set in Appendix B line 91. The contraction stress is set to *sigmax*, the force from table 4.1. The activation function is given by a sinus curve, and shifted by *pi*, for top and bottom muscle in order to obtain oscillations of the impact tool. This function also includes the termination time and total number of impacts, Impacts x UIT Length from table 4.1.

4.3.3 Results - UIT

The explicit simulation of UIT was given 28 cpu's and 4G of memory, and had a realtime running of 19 hours.
The numerical model is verified by an energy control in figure 4.5.

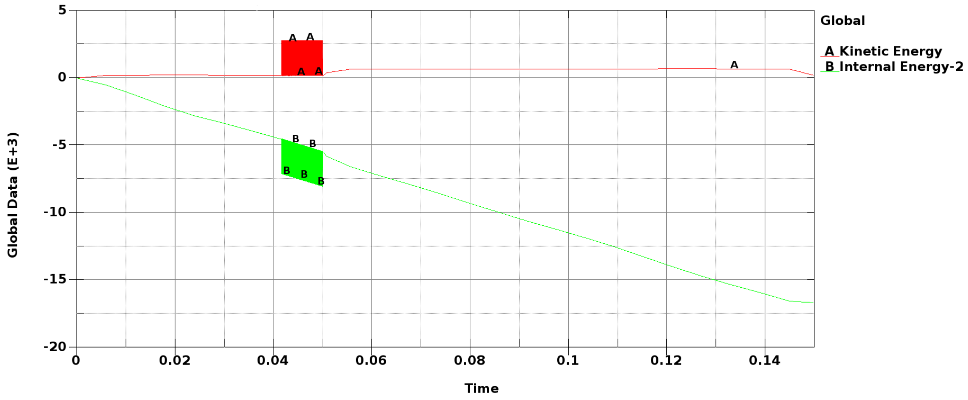


Figure 4.5: *Resultant force distribution over time of the process.*

Kinetic energy is low, this means that the parts stays in place and no movements unless the process related. Due to sampling rates set in line 115 in Appendix A, are raised for a short time, the kinetic energy of the impact tool is obtained illustrated by the peak. The internal energy increases constant throughout the whole process due to the permanent deformation creating residual stresses. It is assumed, that the negative sign is due to, that these are compressive stresses.
The tool load applied on the shell, is ramped in order to make the model more stable, but as showed in figure 4.6 the ramp is still to steep and the contact force overshoots the stable force level at 3000N, that compares well with the measurements in Jan Foehrenbach [2016].

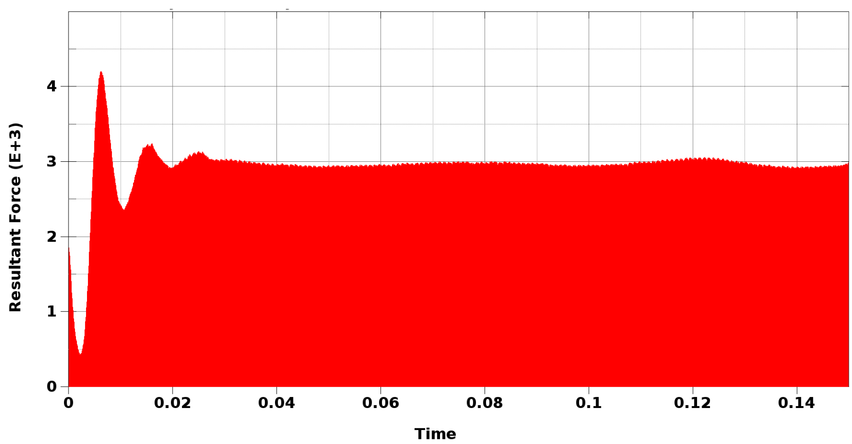
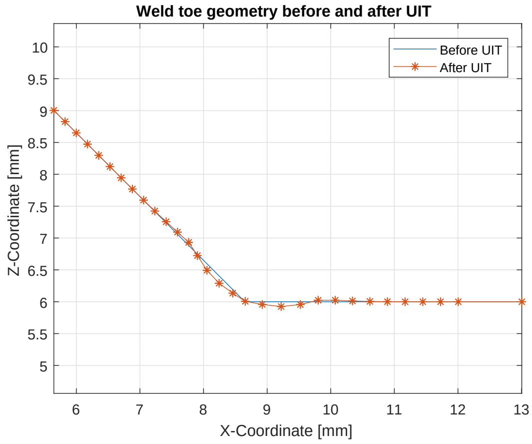


Figure 4.6: *Resultant force and energy distribution over time of the process.*

Overshoot in the beginning combined with ramped velocity of the impact tool in the y-direction, results in deeper indent 4.7, but no further tuning on the simulation is done and the area is not

included in the stress evaluation.
Geometric result of the cross section is shown in figure 4.7.



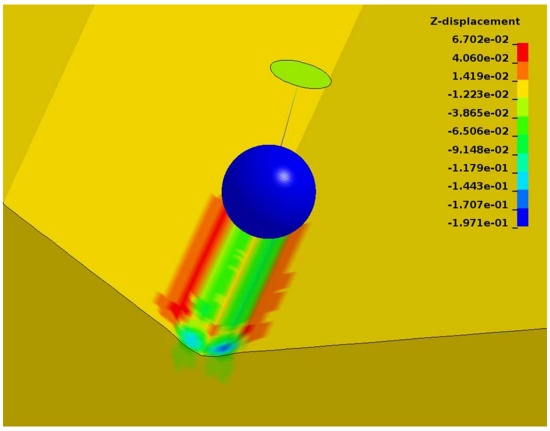


Figure 4.7: *Maximum of indention is measured for 0.06mm. and the displacement in z-direction.*

The indent is measured as 0.06mm is to the small side compared to findings in the introduction, but for the assumed geometry for the weld, it did eliminate the sharp notch at the weld toe. The distribution of stresses in the x-direction is illustrated in figure 4.8, showing a maximum of compressive stresses are reached at -500 MPa. This relates well to the experimental data from Jan Foehrenbach [2016] measured by X-ray and neutron diffusion. The depth of the maximum stress is quite low compared, this was changed using softening of the material in Kuilin Yuan [2016], and relates to a later studied parameter in section 5.1.

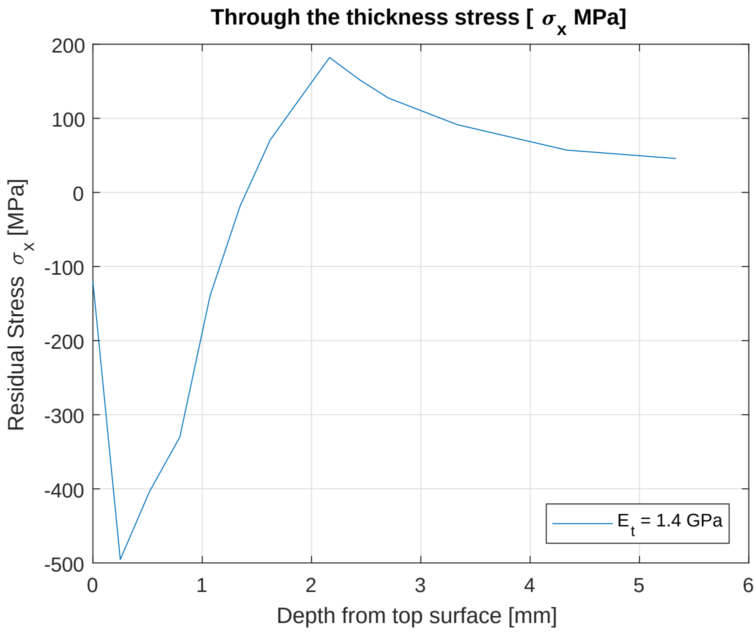


Figure 4.8: *Stress distribution through depth, measured from lowest point in the UIT groove.*

4.4 Model Four Point Bending

The implicit simulation of four point bending was given 4 cpu's and 8G of memory, and had a solution time of 6 hours.
The author did not have any luck applying a moment directly as in ANSYS Workbench, instead a four point bending analysis is made. This is solved with symmetry conditions as those from equation 4.3 applied as previous, model is designed as in figure 4.9 with rollers 55 mm apart and applied with MAT_RIGID. Within the material model the boundary conditions are given for the rollers:

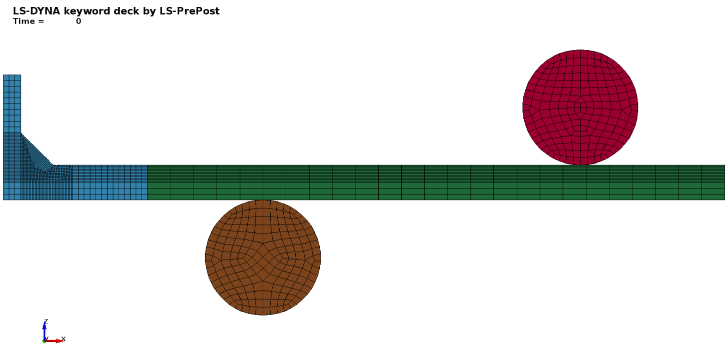


Figure 4.9: *Four point bending with symmetry conditions, rollers 55 mm apart.*

Within the material model the boundary conditions are given for the rollers:

$$UZ = UY = UX = RX = RZ = 0 \quad for;\ Bottomroller \tag{4.5}$$

$$UY = UX = RX = RZ = 0 \quad for;\ Toproller \tag{4.6}$$

They free to rotate around y-axis, and the top roller is used for the load appliance. As the model is created by a copy of previous simulation the discretisation is the same, meaning mesh size is 0.25mm, but element formulation is improved to full integration for more accurate results.
A load of 2000N is applied at the top roller, and LS-DYNA automatically controls the load step size, the load step for comparison to as-welded is then within this range.

$$\Delta F_{roller} = \frac{\frac{480N \cdot mm}{1mm} \cdot 40mm}{55mm} = 349N \tag{4.7}$$

4.4.1 Relaxation

The T-joint test specimen is created by INTERFACE_SPRINGBACK line 148 in Appendix A, and a part set of the center pieces. This creates a dynain file with the deformed mesh, and when material is applied stresses and strains are calculated. Before the specimen is loaded it is relaxed by removing constraints on the bottom and the extra sides leaving the edges stress free. After the UIT, cast of the specimen is observed when it is cut free, see figure 4.10.

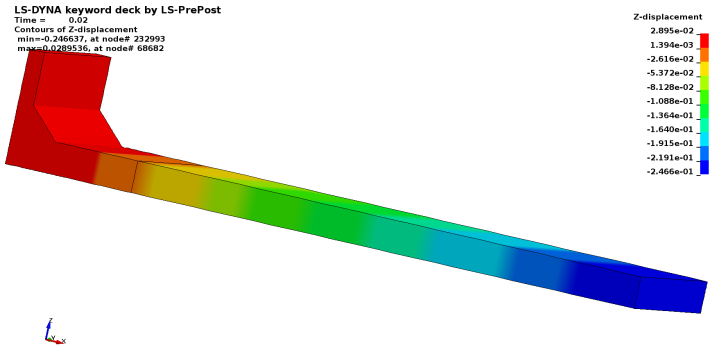


Figure 4.10: *Cast after UIT, measured in the Z-direction.*

The cast is captured by the deflection in the z-direction and caused by relaxation of the large compressive residual stresses in top of the beam, when searching for equilibrium after constraint removal. This has a negative effect on the top layer, since this shifts from compressive stresses, beneficial in improving fatigue live, to tension stresses. This is illustrated in figure 4.11.

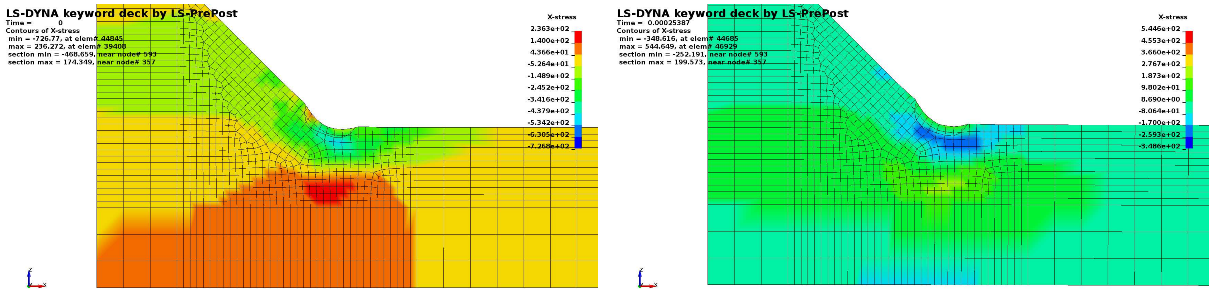


Figure 4.11: *X stresses in the center before and after relaxation,* ***attention*** *fringe scales are different.*

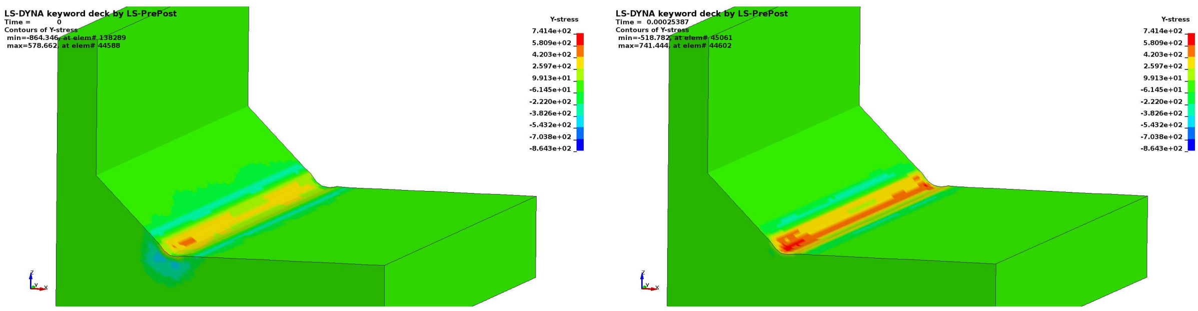


Figure 4.12: *Y stresses on the edge before and after relaxation.*

The y-stresses plotted in figure 4.12, shows that the edge is stress free, when sides are cut of, these are distributed in the groove instead.

4.4.2 Results - Fatigue

Fatigue strength can be estimated by following the guideline in IIW, at it was done in section 3.4, IIW states that for mild steel notch stresses, radius of the weld toe may vary from 1-3 mm, thus this allows the method to be used in cases with post weld treatments Fricke [2012]. Comparison

is done on stress ranges and FAT200 lifetime estimations, in order to check maximum number of cycles. The number of cycles for the new stress range is the compared to the number cycles found in Gary B. Marquis [2013]. This is a guide on assessment of fatigue life of post weld treated specimens, evaluated on the effective notch stress found for category FAT360, based on experimental data from IIW, and the ones from Pedersen [2011]. The results were similar to those presented in the introduction, using FAT360 with effective notch stress. The guideline and Pedersen [2011] purpose a slope of m=5 in the region of 1e4<N<1e7 and m9 for 1e7<N.
Comparing method:

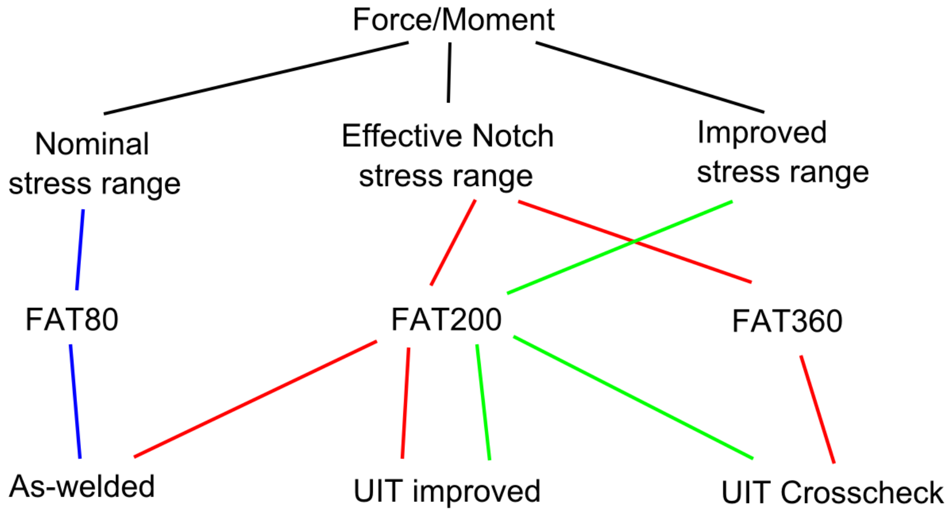


Figure 4.13: *Data in for comparing as-welded and UIT improved and cross checking fatigue life.*

The load step of which the force equals equation 4.7 is found, and the nominal stresses observed to be in the range of 80 MPa, see figure 4.14.

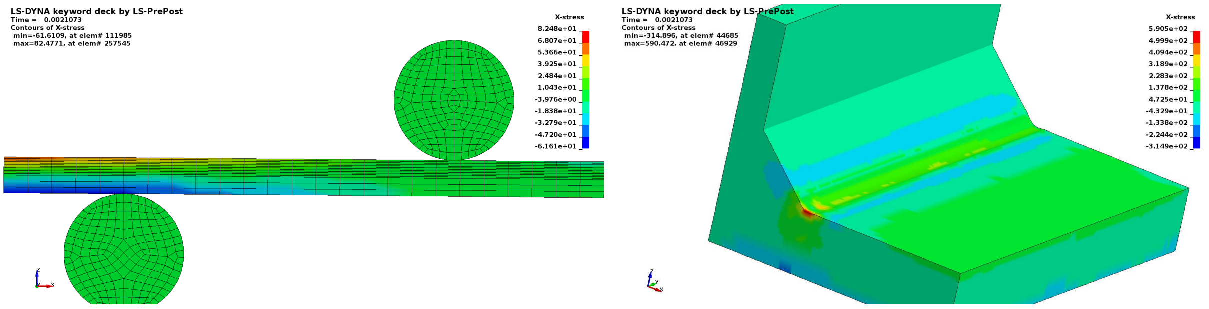


Figure 4.14: *X stresses for a nominal stresses 80 MPa by for point bending.*

Next step is to establish the stress range by the principal stresses, but as it is illustrated in figure 4.15 these are complex after relaxation. The figure in the left side shows principal stresses before relaxation, and the 3rd and smallest is found to be compressive. After relaxation the path is plotted and the stress orientation is complex.

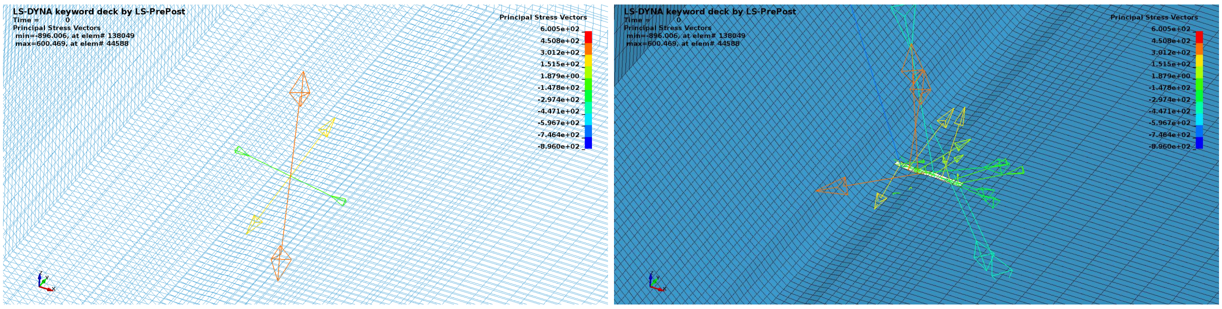


Figure 4.15: *Y stresses on the edge before and after relaxation.*

Instead the stress range for fatigue life estimation is determined on stresses in the x-direction at the weld toe, as these were found to be similar to the principal stresses in section 3.4. In figure 4.16 the x stress are plotted for the center of the specimen. These are also find in figure 4.17, plotted in graph for through thickness and on surface from weld toe.

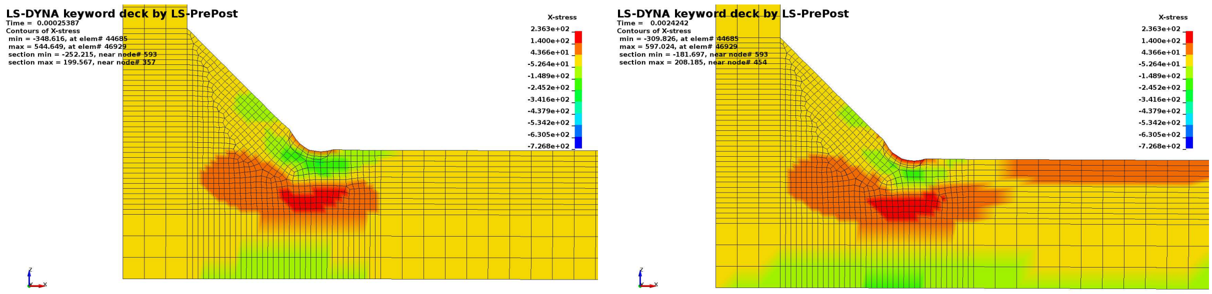


Figure 4.16: *X stresses in the center of the test specimen relaxed vs. nominal stress of 80 MPa.*

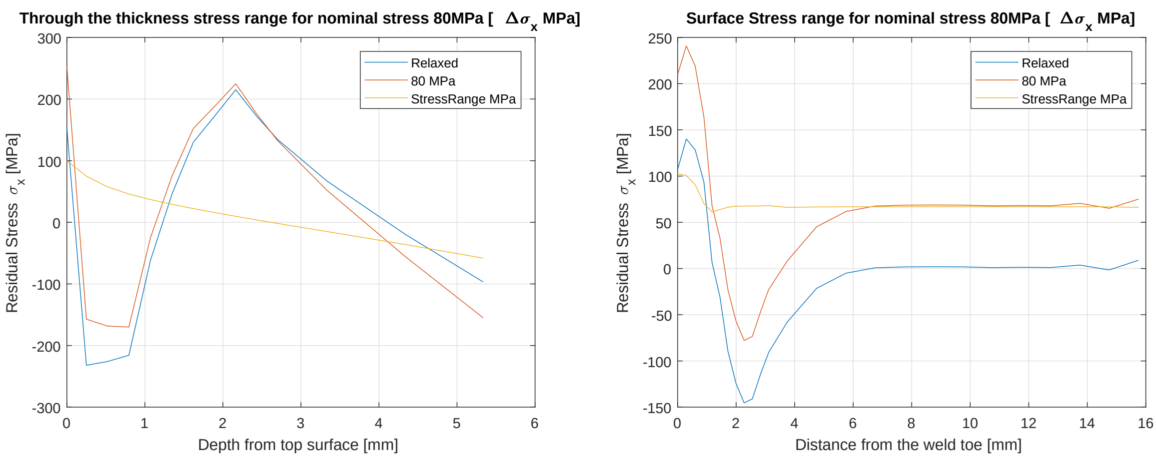


Figure 4.17: *Stress range σ_x through thickness and the top surface.*

The maximal stress range measured in UIT zone is 100 MPa at the weld toe, and then it decreases linearly through thickness and shifts at the center due to the loading scenario. As for the surface stress range this stays constant. The lifetime can be calculated by following and the results are collected in table 4.19.

$$\Delta\sigma_R^m \cdot N_R = \Delta\sigma_C^m \cdot N_C \tag{4.8}$$

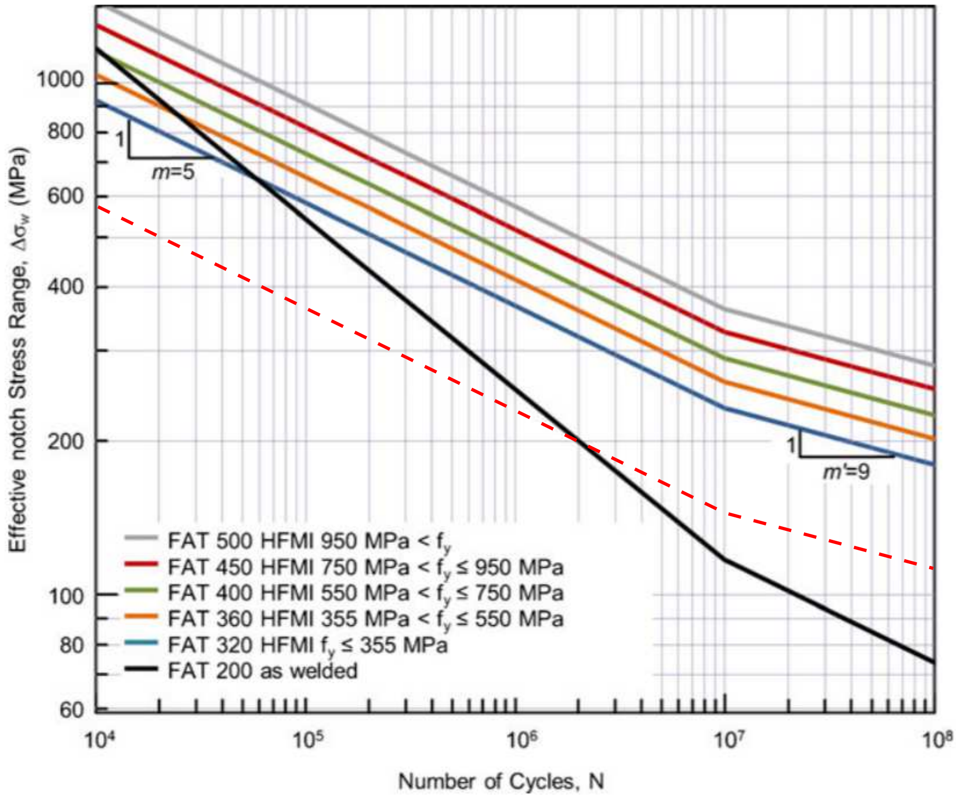


Figure 4.18: *SN curves for FAT360 and FAT200, FAT200 with High-Frequency-Mechanical-Impact slope correction was added.(Gary B. Marquis [2013])*

The table includes the nominal stress range from the load was determined. A comparison of the lifetime estimated by FAT200, effective notch stress and the UIT normal stress x. Then a FAT200 HFMI was created, in order to get closer the result from FAT360, which is experimental determined.

	Nominal	NSA	UIT
StressRange	80MPa	150MPa	100MPa
FAT80	N = 2e6	-	-
FAT200	-	N = 4.7407e6	N = 2.1003e7
FAT200HFMI	-	-	N = 2.6623e8
FAT360HFMI	-	N = 1.4123e9	-

Figure 4.19: *Estimated lifetime based on different methods.*

By following the approach of NSA using FAT200, lifetime is estimated to be improved by a factor of 4.4. This is not in range of what is found by FAT360, given by the standards, as this is improved by a factor 298. Hence the FAT200HFMI was created and yielded a factor of 56.

The following parameter study of material behaviour and process, will search to find better results closer to the factor of FAT360.

Parameter Study 5

5.1 Material

Hardness is the resistance of permanent deformation, and this relates to the residual stresses from the UIT. Thus the ultimate strength is related to the hardness(Serope Kalpakjian [2014]), this will affect the slope of the tangents modulus. This is parameterised as follows:

	E_t	Parameter	E_t*
mat2		0.8	1.12GPa
mat1	1.40GPa	1.0	1.40GPa
mat3		1.2	1.68GPa

Table 5.1: *Cohesive material parameters.*

The stress distribution through thickness and on the surface is displayed in figure 5.1, this shows almost no change. The only difference is found figure 5.2, that the current yield stress is raised by a 100MPa. This is beneficial when considering one time big load, if the weld toe is not plastic deformed, the compressive residual stresses does not relax.

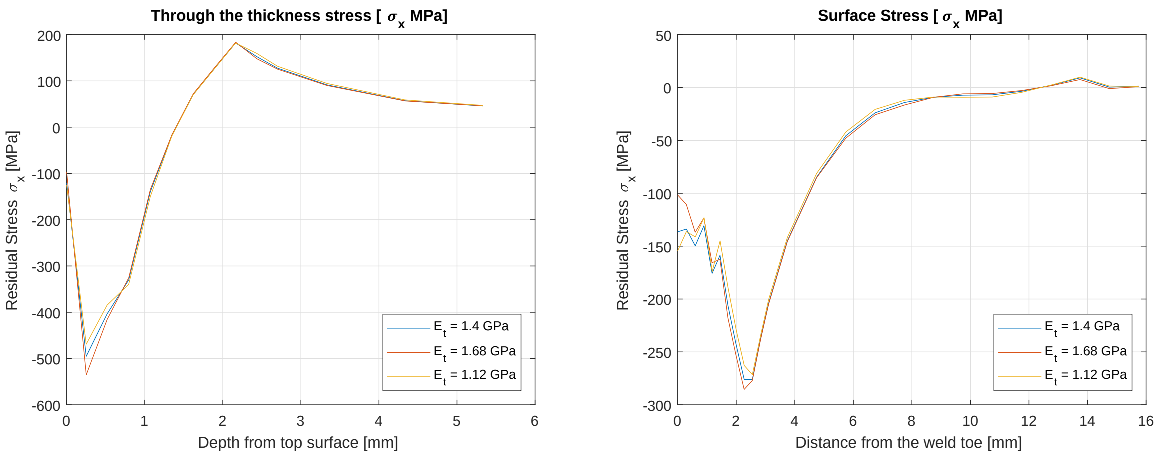


Figure 5.1: *Residual stresses through thickness and on surface, measured from the lowest point in the UIT zone.*

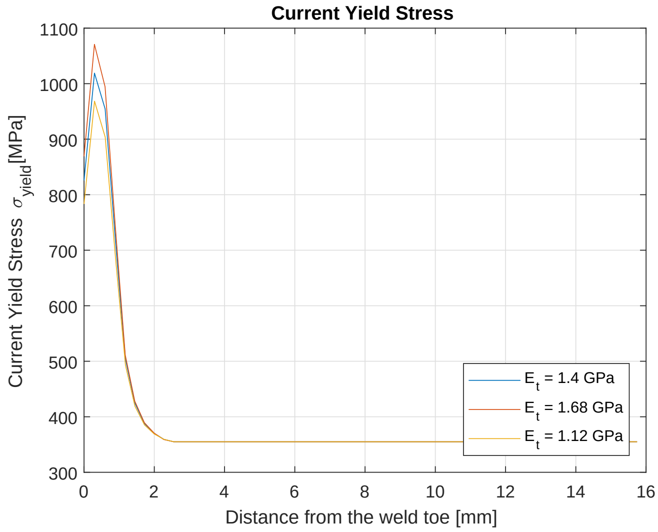


Figure 5.2: *Surface stresses from the weld toe, measured from the lowest point in the UIT zone.*

As no great results were found changing the tangents modulus, the material is changed to a weldable high-strength steel Strenx1100 Steel [2017], in order to check the effect on a model with higher yield strength. Secondly that Gary B. Marquis [2013] gave different detail categories depending on the ultimate strength of the material, this was not included for the as-welded design codes.

σ_{yield}	σ_{ul}	E_t
1100MPa	1250MPa	1.85MPa

Table 5.2: *Material parameters Strenx 1100.*

Force in the muscle and on the top shell was changed to 800N, in order achieve the same geometry as before. This resulted in a contact force of 4500N, and literature were found to verify this. Mat4(400N) and Mat5(800N) are both compared against previous Mat1 in figure 5.3 Stress distribution outside of UIT improved notch is the same for S355 and Strenx1100(800N-loaded) since this related to deformation and Young's Modulus, deformation being the same measured in the maximum indent of the treatment.

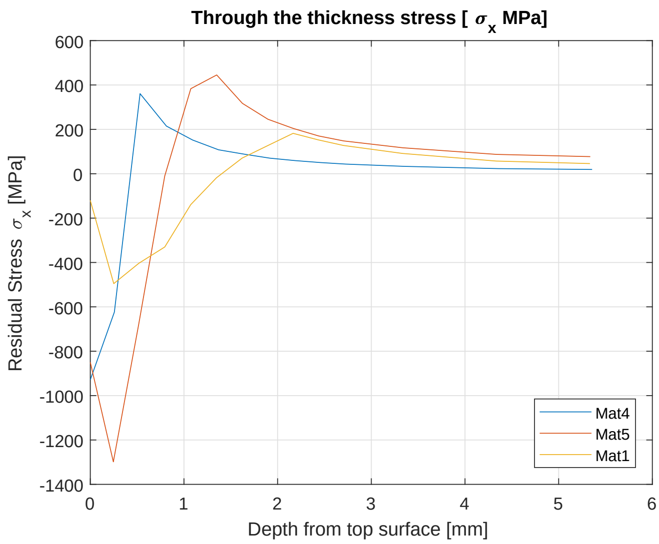


Figure 5.3: *Residual stresses through thickness in material Strenx1100, measured from the lowest point in the UIT zone. Mat4 = 400N and Mat5 = 800N, both Strenx1100.*

5.2 Process

The process parameter was rotated respectively 0 deg, 10 deg and20 deg around the x-axis, in mat1 5.1. This gives a small forward motion of the impact tool. Once again this affect mostly the current yield stress, since larger y-stresses created.

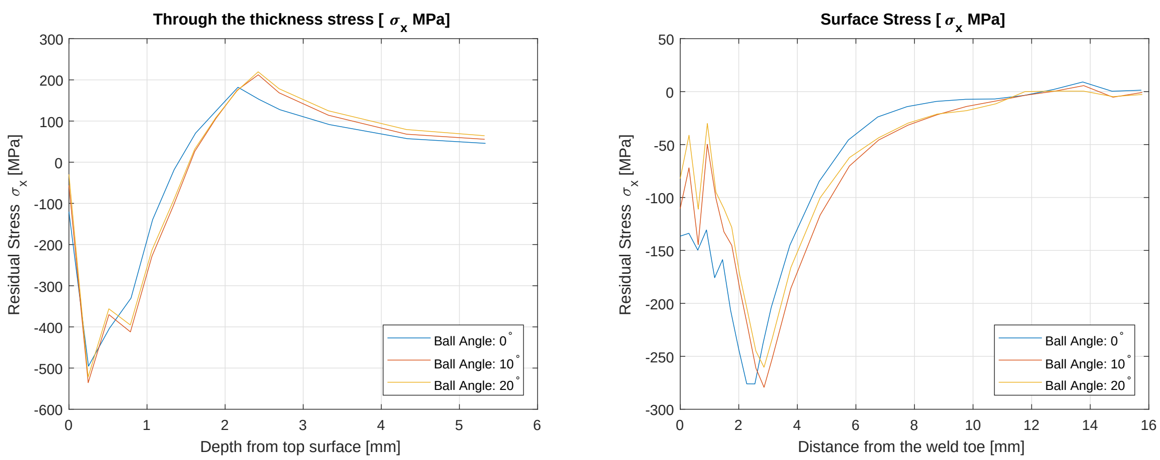


Figure 5.4: *Residual stresses through thickness and on surface, measured from the lowest point in the UIT zone.*

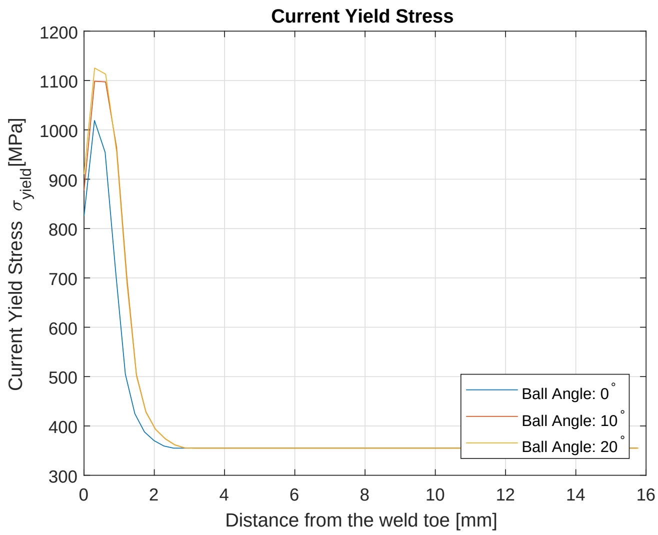


Figure 5.5: *Surface stresses from the weld toe, measured from the lowest point in the UIT zone.*

The weld toe geometry is controlled for the different parameters, and is kept close to each other. All of them eliminated the previous sharp notch at the weld toe.

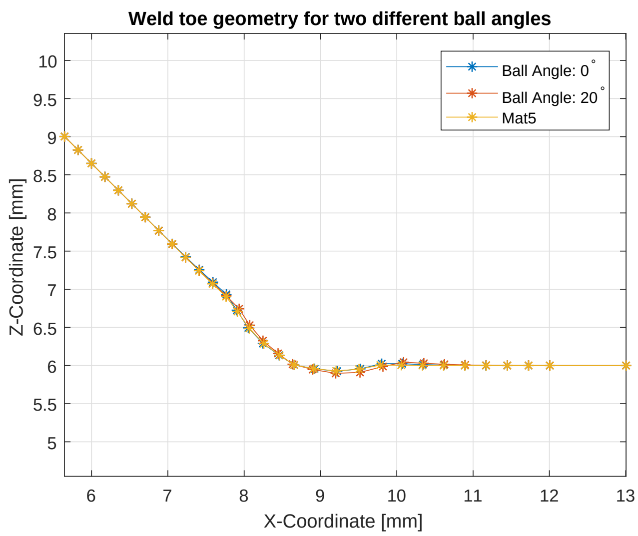


Figure 5.6: *Control of enhanced geometries.*

5.3 Relaxation

A collection of the different parameters effect on relaxation or cut out are illustrated in figure 5.7. No further difference between ball angle 0 deg and 20 deg, but beneficial compressive residual stresses are kept in high strength steel. This is well compared with figure 4.18.

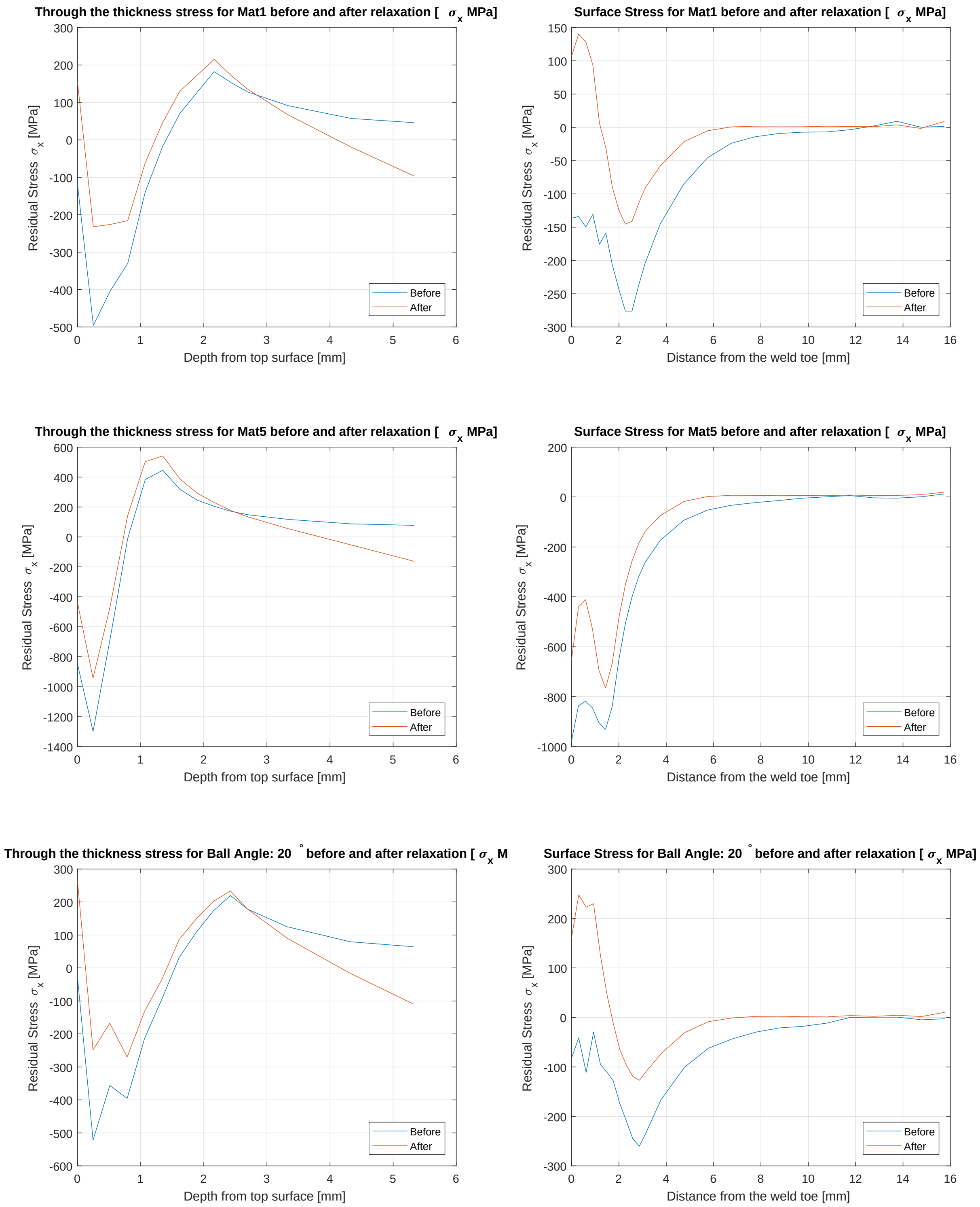


Figure 5.7: *Residual stresses through thickness and on surface, changed when relaxed.*

5.4 Discussion

The numerical model in general showed good results compared to previous studies, both numerical and experimental. The number of hits per mm was not changed at any time, and a high number should be kept in order to create a smooth surface.

Minimum thickness for UIT, from IIW specimens of 5-50mm were included. This type of cast was not found in any of the earlier studies, but model were similar with a full length of treatment in fairly thin plates.

The different tangent modulus did not show significantly differences in the stress distribution, in order for better softening effects, both yield- and ultimate strength must be adjusted. Preferably the yield strength, for soft material, and ultimate for post treatment current yield strength.
The high strength steel, yields better results when impact treated, although a higher force was needed to obtain same geometry. This may be reflected by in SN curves given by Gary B. Marquis [2013], as for higher strength steels, a larger detail category. This is not don for as-welded, thus impact treating are more effective in high strength steel.

Mesh size should affect the stress distribution, since the cheapest elements were chosen, type1 = constant stress. This yields only 24 sampling point through the thickness.

Stress evaluation done by x stresses instead of principle, due to that these changed direction. Cracks are known to start at the surface, thus the stress component in the surface should give crack initiation. This combined with chosen load scenario gave the chosen stress component.

Conclusion 6

The project has concerned fatigue assessment for lifetime improved welding, including the hardening of the post weld process.

The numerical model were able to produce truthful residual stresses after a ultrasonic impact treatment, these were in a range up to -500MPa, which was compared against experimental data from Jan Foehrenbach [2016] measured by X-ray and neutron diffusion.
The depth of the maximum residual stress varied from different studies, but seemed to be for the shallow side in this model. This was tried to be lowered in the parameter study, but had no effect.
The indent were measured to 0.06mm, another result parameter to the low side, but acceptable compared to other studies.

The numerical simulation of the UIT was done continually, versus earlier studies that were restarted after impact. This resulted in a fair running time compared to the number of impact versus a restart simulation CORPORATION [2016]. Running time 19 hours, for 42mm treated and 60impacts/mm.

The material were parameterised by the tangents modulus, this showed very little effect in the distribution of residual stresses. The softening effect of welding were assumed to only affect the ultimate strength, which then changed the tangents modulus. But if this were set to affect both the yield and ultimate strength, it would have had the wished effect as in Kuilin Yuan [2016].

Process parameter tested in the numerical model, was the secondary angle of the impact tool. This had a beneficial effect on the current yield strength, that was raised by 100MPa.

Fatigue assessment by notch stress approach using the same FAT category for both, as-welded and post weld treated. This yields a factor of 4.4, for fatigue life improvement, when only the stress range is considered. The improvement exist, although the surface stresses are in tension, due to the high compressive stresses just below the surface.

7 Reflection

Investigation of positive stresses in the surface of the impact treated zone, that displays after the test specimen of 40mm is cut/relaxed. Check if it is related to the boundary condition applied for the bottom of the model while ultrasonic impact treatment is on. What would the result be if these were to be removed.
Mesh convergence related to stress distribution after UIT, and material model influence considering harding could be investigated to obtain a deeper maximum residual stress.

Include the welding process, this will introduce the tension residual stresses. This will allow the verification of, the effect of these on the final stress state in the weld toe area after an ultrasonic impact treatment. But more over the effect on softening the material in the heat affected zone. Another softening behavior to solve the depth of maximum residual stresses, is ultrasonic softening implementation and validation of this (Kuilin Yuan [2016]).

Is the recommended minimum thickness 5mm-50mm(Statnikov [2004]) enough for ultrasonic impact treatment. Experimental test in order to validate the cast of the T-joint, together with thorough investigation of process parameters effect on fatigue life combined with numerical model, and more type of welds.

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Part I

Appendiks

A Keyword - Main

- Part 2 - T-joint Ultrasonic Impact Treated
- Part 3 - Elongation of part 2
- Part 4 - Sides of T-joint
- Part 5 - Ball
- Part 6 - Control shells
- Part 7 - Muscle top
- Part 8 - Muscle bottom ...

```
$# LS-DYNA Keyword file created by LS-PrePost(R) V4.3 - 27Sep2016(10:00)
$# Created on Jul-17-2018 (10:00:27)
*KEYWORD
*PARAMETER
$ TT termination time [sec]
$ NP number of UI oscillations
$ amp UIP amplitude [mm]
$ UIP travel distance i.e length of the treated specimen [mm]
$#   prmr1      val1     prmr2      val2     prmr3      val3     prmr4      val4
Rtt      0.15
$RNP   ,       1300
$RNP   ,        2500
$RNP   ,        2700
$ amp 100 equals and amplitude of 0.2
Rball_amp 0.10
$Ramp  ,       100.0
$RUIForce ,    2000.0
$RUIForce ,    1600.0
$RUIForce ,    1400.0
$Ruiforce 800.0
$ 400 N produce a good result
Ruiforce 400.0
Rui_disp 42.
Rn_d3plot 2700
Ra_beam  2.0
$ TT termination time [sec]
$ NP number of UI oscillations
$ amp UIP amplitude [mm]
$ UIP travel distance i.e length of the treated specimen [mm]
*PARAMETER_EXPRESSION
RNP      &UI_disp*60.0
Ramp     1.0*&UIForce*&ball_amp
RUI_mus  &UIForce/4.
RSig_max 1.*&UIForce/&A_beam
Rtau_fric,355./sqrt(3.)
Rd3_fast 0.25*&tt/&NP
Rd3_slow 100.*&tt/&NP
*TITLE
$#                                                                   title
```

```
(UIT) post welding treatment
*CONTROL_CONTACT
$#  slsfac    rwpnal    islchk    shlthk    penopt    thkchg     orien    enmass
       0.1       0.0         1         1         1         1         1         0
$#  usrstr    usrfrc     nsbcs    interm     xpene     ssthk      ecdt  tiedprj
         0         0         0         0       4.0         0         0         0
$#   sfric     dfric       edc       vfc        th     th_sf    pen_sf
       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$#  ignore    frceng   skiprwg    outseg   spotstp   spotdel   spothin
         0         0         0         0         0         0       0.0
$#    isym    nserod    rwgaps    rwgdth     rwksf      icov    swradf    ithoff
         0         0         1       0.0       1.0         0       0.0         0
$#  shledg    pstiff    ithcnt    tdcnof     ftall    unused    shltrw
         0         0         0         0         0                 0.0
*CONTROL_HOURGLASS
$#     ihq        qh
         5       0.1
*CONTROL_TERMINATION
$#  endtim    endcyc     dtmin    endeng    endmas
&tt                0       0.0       0.0       0.0
*CONTROL_TIMESTEP
$#  dtinit    tssfac      isdo    tslimt     dt2ms      lctm     erode     ms1st
       0.0       0.9         0       0.01.00000E-7         0         0         0
$#  dt2msf   dt2mslc     imscl    unused    unused     rmscl
       0.0         0         0                           0.0
*DATABASE_BINARY_D3PLOT
$      0.0         0         0&n_d3plot         0
$#      dt      lcdt      beam     npltc    psetid
       0.0      4321         0         0         0
$#   ioopt
         0
*DATABASE_EXTENT_BINARY
$#   neiph     neips    maxint    strflg    sigflg    epsflg    rltflg    engflg
        10        10         3        11         1         1         1         1
$#  cmpflg    ieverp    beamip     dcomp      shge     stssz    n3thdt   ialemat
         0         0         0         1         1         1         2         1
$# nintsld   pkp_sen      sclp     hydro     msscl     therm    intout    nodout
         0         0       1.0         0         0         0ALL       STRESS_GL
$#    dtdt    resplt     neipb
         0         0         0
*BOUNDARY_PRESCRIBED_MOTION_RIGID
$ ball forward motion along y
$#     pid       dof       vad      lcid        sf       vid     death     birth
         5         2         2      5551       1.0         01.00000E28       0.0
$ unit forward motion along y
$#     pid       dof       vad      lcid        sf       vid     death     birth
         6         2         2      5551       1.0         01.00000E28       0.0
*LOAD_RIGID_BODY
$ load ultra sonic tool z direction
$#     pid       dof      lcid        sf       cid        m1        m2        m3
         6         3      5552      -1.0         1         0         0         0
*CONTACT_SURFACE_TO_SURFACE_ID
$#     cid                                                                 title
         1
$ load ultra sonic tool z direction
$        6         1      5552      -0.0         0         0         0         0
$#    ssid      msid     sstyp     mstyp    sboxid    mboxid       spr       mpr
         1         5         2         3         0         0         0         0
$#      fs        fd        dc        vc       vdc    penchk        bt        dt
```

```
      0.1       0.0       0.0       0.0      80.0         2       0.01.00000E20
$#     sfs       sfm       sst       mst      sfst      sfmt       fsf       vsf
       1.0       1.0       0.0       0.0       1.0       1.0       1.0       1.0
*SET_PART_LIST
$#     sid       da1       da2       da3       da4    solver
         1       0.0       0.0       0.0       0.0MECH
$#    pid1      pid2      pid3      pid4      pid5      pid6      pid7      pid8
         2         4         0         0         0         0         0         0
*PART_MOVE
$ d=3mm or r=1.5mm
$#   pid            xmov            ymov            zmov     cid    iset
       5             9.3             1.0             7.6       0       0
*PART_MOVE
$#   pid            xmov            ymov            zmov     cid    iset
       6             9.3             1.0             7.6       0       0
*DEFINE_CURVE
$ Sampling curve
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
      4321         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0&d3_slow
               0.039&d3_slow
                0.04&d3_fast
                0.05&d3_fast
               0.051&d3_slow
&tt                 &d3_slow
*DEFINE_CURVE
$Move in y direction
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
      5551         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0                 0.0
&tt                 &ui_disp
   1.0000000200e+020&ui_disp
*DEFINE_CURVE
$Load on end plates
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
      5552         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0                 0.0
               0.005&uiforce
&tt                 &uiforce
*SET_PART_LIST_TITLE
Til bending
$#     sid       da1       da2       da3       da4    solver
         2       0.0       0.0       0.0       0.0MECH
$#    pid1      pid2      pid3      pid4      pid5      pid6      pid7      pid8
         2         3         0         0         0         0         0         0
*INTERFACE_SPRINGBACK_LSDYNA
$#    psid      nshv     ftype         _    ftensr    nthhsv         _   intstrn
         2         0         0         0         0         0         0         0
*NODE_MERGE_TOLERANCE
$#    tolr
  0.007454
*INCLUDE
ball_muscle_r15_225deg_20deg_v4.k
*INCLUDE
GLOBAL.k
*INCLUDE
```

```
GLOBAL_xy.k
*INCLUDE
Geometry.k
*END
```

B Keyword - Impact Tool

Element and Node lists are cut out.

```
$# LS-DYNA Keyword file created by LS-PrePost(R) V4.3 - 12Aug2016(11:30)
$# Created on Jul-3-2018 (09:48:50)
*KEYWORD
*TITLE
$#                                                                         title
LS-DYNA keyword deck by LS-PrePost
*DATABASE_ELOUT
$  DT/CYCL
$#      dt    binary      lcur     ioopt   option1   option2   option3   option4
1.00000E-6         0         0         1         0         0         0         0
*DATABASE_GLSTAT
$  DT/CYCL
$#      dt    binary      lcur     ioopt
1.00000E-6         0         0         1
*DATABASE_MATSUM
$  DT/CYCL
$#      dt    binary      lcur     ioopt
1.00000E-6         0         0         1
*DATABASE_NODFOR
$  DT/CYCL
$#      dt    binary      lcur     ioopt
1.00000E-6         0         0         1
*DATABASE_NODOUT
$  DT/CYCL
$#      dt    binary      lcur     ioopt   option1   option2
1.00000E-6         0         0         1       0.0         0
*DATABASE_RCFORC
$#      dt    binary      lcur     ioopt
1.00000E-6         0         0         1
$ 6000002 5003259  1.000000e-06      0
$ 6000003 5003323  1.000000e-06      0
*PART
$#                                                                         title
LSHELL1
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         5         5         5         0         0         0         0         0

*SECTION_SHELL
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         5         2       0.0         0       1.0         0         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgeset
       0.2       0.2       0.2       0.2       0.0       0.0       0.0         0
*MAT_RIGID
$#     mid        ro         e        pr         n    couple         m     alias
         57.00000E-9 200000.0       0.3       0.0       0.0       0.0
$       0.0         0         0
$#     cmo      con1      con2
      -1.0       1110111
```

```
$#lco or a1        a2        a3        v1        v2        v3
       0.0       0.0       0.0       0.0       0.0       0.0
*PART
$#                                                                         title
LSHELL2
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         6         6         6         0         0         0         0         0
*SECTION_SHELL
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         6         2       0.0         0       1.0         0         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
       0.2       0.2       0.2       0.2       0.0       0.0       0.0         0
*MAT_RIGID
$#     mid        ro         e        pr         n    couple         m     alias
         67.90000E-9  200000.0       0.3       0.0       0.0       0.0
$       1.0         1         7
$#     cmo      con1      con2
      -1.0      1100111
$#lco or a1        a2        a3        v1        v2        v3
       0.0       0.0       0.0       0.0       0.0       0.0
*PART
$#                                                                         title
MUSCLE 1
$      PID       SID       MID
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         7         7         7         0         0         0         0         0
*SECTION_BEAM
$#   secid    elform      shrf   qr/irid       cst     scoor       nsm
         7         3       1.0         2         0       0.0       0.0
$#       a     rampt    stress
       2.0       0.0       0.0
*MAT_MUSCLE
$#     mid        ro       sno       srm       pis       ssm       cer       dmp
         71.05000E-6       1.0       2.0&sig_max       1.0       2.0       1.0
$#     alm       sfr       svs       svr       ssp
        -5       1.0       1.0       1.0        -7
*PART
$#                                                                         title
MUSCLE 2
$      PID       SID       MID
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         8         7         8         0         0         0         0         0
*MAT_MUSCLE
$#     mid        ro       sno       srm       pis       ssm       cer       dmp
         81.05000E-6       1.0       2.0&sig_max       1.0       2.0       1.0
$#     alm       sfr       svs       svr       ssp
        -6       1.0       1.0       1.0        -7
*DEFINE_COORDINATE_NODES
$#     cid        n1        n2        n3      flag       dir
         1   5008396   5006530   5008474        0X
$         1   5008396   5006530   5008490         0         X
$         1   5008396   5006530   5008687         0         X
$ TT termination time [sec]
$ NP number of UI oscillations
$ amp UIP amplitude [mm]
$ UIP travel distance i.e length of the treated specimen [mm]
*DEFINE_CURVE_FUNCTION
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
         5         0       1.0       1.0       0.0       0.0         0
```

```
$#                                                            function
&amp*sin(&NP*TIME*2.*PI/&TT)
*DEFINE_CURVE_FUNCTION
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
         6         0       1.0       1.0       0.0       0.0         0
$#                                                            function
&amp*sin(PI+&NP*TIME*2.*PI/&TT)
*DEFINE_CURVE
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         7         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
               0.1-&ui_mus
               0.8-&ui_mus
               1.0                 0.0
               1.2&ui_mus
               2.0&ui_mus

*END
```