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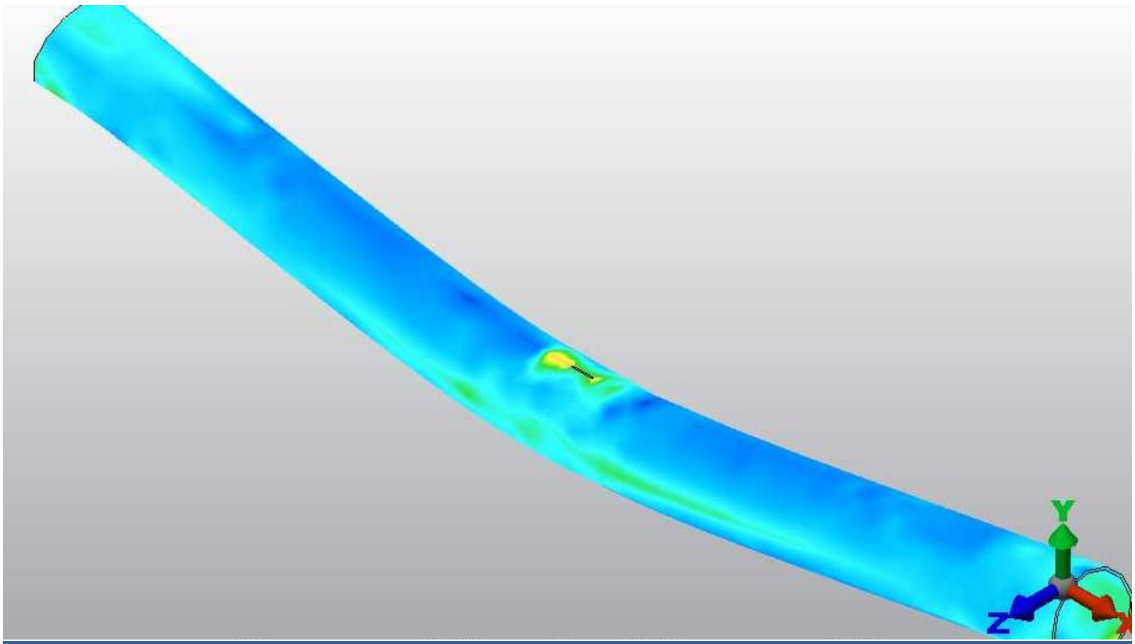
Pipeline Repair Technology
Damage and repair assessment of pipelines with high residual stresses

Master Thesis – Marine and Subsea Technology

Øyvind Høie
Spring 2015



ABSTRACT

Today in the offshore industry, there are an increasing number of pipelines that require both maintenance and repair. A wide specter of research in pipeline repair technology is available. Damage to a pipeline could be a quite complex event to analyze, due to the many different combinations of internal pipe stresses and damage types. Standards, such as DNV and ASTM have experimental based assessment methods for evaluating many of these damage combinations, however, there are some of these methods that do not have a straight forward assessment method.

In this thesis a discussion on how to assess and repair damages to pipelines with significant longitudinal stresses, in combination with an internal pressure and an external surface damage is conducted.

The study proves that damages with these types of combined loadings are very depended on the depth of the damage itself as well as the significance of the axial stresses. With the help of simple FEA simulations combined with previous experimental studies, it was possible to make a proposal for a pre-accidental repair chart. The purpose for this type of chart is to be able to rapidly decide which repair method that should be used to repair a damaged pipeline, by only taking some simple assay measurements of the damaged area. With the help of a rapid decision making, the downtime cost due to a damaged pipeline could be significant reduced, as well as repair costs.

Various types of clamps are a very common method to repair these types of damages. Clamps provide the ability to surround the damaged section of the pipe with an enclosed and pressure tight environment. Other repair methods such as composite systems or simple grinding of the damage could also be a solution where the stresses in the damaged section of the pipe are not too extensive.

As an alternative to grinding of an external damage, an idea of a milling machine using a ball mill to remove damaged material in a gouge is proposed. The machine is based on a technology using a coating removal tool, and the method of grinding an external damage. A ball mill will be used to remove the damaged material in a gouge, corrosion or a scratch in order to either reduce the stress concentrations in the area, or to prepare the damage for further repair. This further repair could be to fill the milled slot with a new molten pipe material using underwater welding, or to prepare for clamp and composite repair.

PREFACE

After three years of working with various types of pipeline repair and maintenance tools, I got an idea to expand my own knowledge around this topic in my master thesis. The semester has been a tough ride, which involved 3 weeks hospital visit after a major leg fracture. However, after some weeks of recovery I finally could continue focusing on the thesis. The writing of the thesis was a great learning experience, with challenging obstacles which greatly improved my knowledge of pipeline repair technology and assessment.

I would like to thank my fiancée Synnøve Kvadsheim for her help regarding spelling correction and comments on the thesis. Further I would like to give my thanks to the company Vest Norge Doors for assisting me with both practical training and a wide specter of relevant knowledge throughout the whole study period.

My fellow classmates have been of great assistance throughout the whole study period. This involves relevant discussions concerning exams, projects, master thesis setup and also for a great friendship.

Thanks to the University of Stavanger for five great years filled by great knowledge and many great lectures and experiences.

Øyvind Høie **…………………………….**
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NOTATIONS AND ABBREVIATIONS

$\boldsymbol{A_r}$	Circumferential area reduction factor. (DNV, 2010)
$\boldsymbol{D_P}$	Pipe diameter
$\boldsymbol{E_s}$	Strain-hardening modulus
$\boldsymbol{H_1}$	Factor to account for compressive longitudinal stresses. (DNV, 2010)
P_I	Internal pressure
P_B	Burst pressure
$\boldsymbol{d_g}$	Gouge depth
$\boldsymbol{f_u}$	Tensile strength to be used in design (DNV, 2010)
$\boldsymbol{l_g}$	Gouge length
n_b	Safety factor for bursting of pipe
$\boldsymbol{t_p}$	Pipe wall thickness
$\boldsymbol{\gamma_d}$	Partial safety factor for corrosion depth. (DNV, 2010)
$\boldsymbol{\gamma_m}$	Partial safety factor for longitudinal corrosion model prediction (DNV, 2010)
$\boldsymbol{\delta_{PF}}$	Pipe final lateral displacement
$\boldsymbol{\delta_{PI}}$	Pipe initial lateral displacement
$\boldsymbol{\sigma_{UP}}$	Ultimate strength of pipe
$\boldsymbol{\sigma_{yP}}$	Yield strength of pipe
c	Circumferential length of corroded region (mm). (DNV, 2010)
$\boldsymbol{E}$	Modulus of elasticity
$\boldsymbol{p_{corr,comp}}$	Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure and superimposed longitudinal compressive stresses (N/mm2). (DNV, 2010)

MAOP	Maximum allowable operating pressure
ROV	Robotic operated vehicle

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1 INTRODUCTION

1.1 BACKGROUND

Pipelines on the seabed can be subjected to a lot of different load combinations, such as; operating pressure, hydrostatic pressure, waves and currents. These are all normally well known, and should not be a problem to analyze. However accidental impact loads onto the pipeline could be very difficult to properly assess due to the various load combinations (bending stress, local deformations, global deformations and external damages).

This thesis will focus on the assessment and repair of pipeline damage caused by accidental lateral displacement. This displacement could be caused by; a ship anchor, a ROV, trawling board, Iceberg keel, etc. The damage caused by this type of external damage can result in a complex damage picture, which could be very difficult to assess. The damaged section could contain dents, gouges, large residual/locked-in stresses caused by bending as well as the normal loadings caused by the internal/external pressure in the pipe.

It is of interest for the author to investigate and try to simulate some of these loading combinations in order to find a way to properly assess and repair these damages. FEA Simulations will be performed for an anchor impact event, which hopefully will give some results of how an anchor impact event could affect the burst pressure of the pipeline. This will hopefully make the assessment of these damages easier, and emergency repair be arranged faster, with the proper repair method.

There have been documented accidents with interactions between subsea pipelines and ship anchors. These accidents could be quite severe and cause a lot of damage to both the pipeline and the production itself. The enormous forces from a ship dragging an anchor along the sea bottom could easily bend, or in worst case buckle or rip off a pipeline. These events are obviously more likely to occur near a harbor, where there are a lot of ship activity, and anchoring of ships.

1.2 OBJECTIVES

The main objectives of this thesis are stated below:

- How to assess pipelines with complex damage combinations?
- How will the pipeline burst pressure be affected by various load combinations of: residual stress due to bended pipe, gouges and internal/external pressure?
- Are the results trustable when compared to similar studies?
- How to repair damages with residual stress gouges and internal pressure?
- Any alternative solutions for repair?

1.3 LIMITATIONS

The limitations for the thesis are listed below.

- Standardized methods available to assess the damages for a pipeline damage with combined loadings.
- Available work to compare the work performed in this thesis with.
- Thesis is limited to simulation work only. The theories and results should be tested in real scenarios.
- Existing repair methods and their limitation with respect to pressure containment.
- Installation requirements for pipeline repair.

1.4 OBJECTIVE DESCRIPTION

How to assess pipelines with complex damage combinations?

In an optimized world where pipelines has no external damages or residual locked in stresses, most of the calculations and analysis concerning the strength capacities of a pipeline containing a high internal pressure could be performed using basic mechanic equations. However, when a damaged pipe has combined loadings, it is not easy to analyzing the strength capacities using these basic methods. Careful background studies are performed in order to gather relevant information about how to assess and repair these damages. These involves both standardized content from DNV, ASTM etc. and information gathered from previous studies such as experimental testing and case studies based on different types of damages. Comparison between the results from this thesis and existing studies will be of great importance when evaluating the reliability of the analysis.

FEA analysis software's is a good tool to have in mind. A Pipeline containing locked-in stresses, gouge and internal pressure will be simulated using Autodesk Simulation Mechanical 2015 in order to see if it is possible to find a good way to assess these problems, which will hopefully show some type of relation between the maximum stress in the damaged section itself and lateral displacement of the pipe.

How will pipeline burst pressure be affected by various load combinations of residual stress due to bended pipe, gouges and internal/external pressure?

Pipeline operators and engineers often talks about the burst pressure of a pipeline. This is basically the highest internal pressure that can be applied to an installed pipeline before it bursts.

The maximum allowable internal pressure is therefore usually calculated by dividing the burst pressure by a safety factor. If these pipelines are affected by combined loadings, such as locked-in bending stresses, advanced calculation methods are needed in order to solve these problems. FEA simulations will therefore be used to analyze how gouge depths and locked in stresses will influence on the burst pressure of the pipe.

Is this work trustable when compared to similar studies?

The whole simulation of stresses will in this thesis be mostly performed using FEA analysis. It is important to be critical to the results performed using FEA analysis. There are many small factors that could influence on the results e.g. mesh size, element definition, element type and material properties.

How to repair damages with residual stress gouges and internal pressure?

With all the different types of repair methods available, what would be the best way to repair gouge damages subjected to internal pressure and axial residual stress. What are used in previous repair cases, and what could be used as an eventual alternative?

2 BACKGROUND THEORY

This chapter will cover the background theory needed for this thesis. This involves some general knowledge around pipelines in generals, different types of damages that could occur on a pipeline, existing repair methods for repairing a gouge with longitudinal stress and two relevant case studies.

2.1 PIPELINES IN GENERAL

The gas and oil industry is completely dependent on pipelines and flow lines to transport the hydrocarbons from one location to another. There will always be different set of requirements for these pipelines concerning, pressure, corrosion, erosion, etc. All these different types of pipe properties could make the general assessment of damage to pipelines difficult to predict, and hence assessed with great caution.

There are onshore pipelines, which could be infrastructure pipelines transporting natural gas around the world to houses used for heating and stoves. In countries with large land distances, it is also common with onshore transport pipelines transporting rich or dry gas around. However, in this thesis the focus will be on offshore subsea pipelines.

Generally, the existing subsea pipelines used in the oil and gas industry is mostly made of some kind of steel alloy coated with different types of chemical coating. Usually there will also be some weight coating around the pipelines to make them stay at the sea bottom easier; this is typically achieved by using some type of concrete around the pipe. The concrete also help with the pressure containment of the pipeline.

According to (DNV, 2008) the design of subsea pipeline systems are regulated using the following ASME design codes; ASME B31.1, ASME B31.4 and ASME B31.8. ASME B31.1 Process Piping Code is the most common pipe design code for process piping on oil and gas platforms, and is widely used for subsea installations. The subsea pipes designed after this code will typically have a higher wall thickness that the other two codes. ASME B31.4 is the design code intended for distribution of liquids, and should not, in any case be used for transport of gas. The last code, ASME B31.8 is the code intended for distribution of gas in pipelines. (DNV, 2008). These codes will generally be very important when identifying pipelines with regards to the type of material used and the size of the pipeline.

2.2 PIPELINES AT THE NORWEGIAN SHELF

Today all the gas export pipelines at the Norwegian shelf are operated by the company Gassco that was founded by the Norwegian oil and energy department in 2001. The company controls roughly 5200 km of gas export pipelines around the Norwegian shelf. The first pipeline designed for long transport of oil on the Norwegian shelf was “Norpipe” installed in late 1975. This pipeline is 354 km long and transports oil from Ekofisk, Vallhall, Hod, Ula, Embla, Eldfisk and Tor to the east coast of Great Britain. Other oil transport pipelines are “Grane oljerør” which connects the “Grane” field to “Stureterminalen” (220 km long), “Oseberg Transportsystem” which was the first pipeline connecting to the Norwegian coast, “Troll oljerør I and 2“ built to transport oil from the “Troll” platform to The terminal on Mongstad, “Sleipner Øst kondensatrørledning” (245 km long) transporting oil and condensate from Sleipner, Loke and

Gungne, and “Kvitebjørn Oljerør” transporting Oil from the “Kvitebjørn” field to Mongstad. (Oljedirektoratet, 2010).

In addition to transport pipelines there are thousands of kilometers of subsea pipelines laying on the bottom of the Norwegian shelf connecting subsea infrastructure to manifolds and surface. Statoil alone has the technical responsibility for about 10000 km of subsea pipelines on the Norwegian Continental shelf, with diameters in range of 4 inches up to 44 inches. The length of the individual pipelines might be up to 1200 km and lying on water depths up to 700 meters below sea level. (Offshore-Technology, 2012).

The repair of these pipelines is crucial. At the end of year 2000, 542 pipeline incidents were reported in the North Sea alone (DNV, 2007). These incidents are summarized in Figure 2-2 which are found in DNV-RP-F113 Pipeline Subsea repair. The figure shows that 396 of the incidents that were reported were on operating lines, where 248 of these where related to the pipe itself. The damage that caused 96 of these damages to leak was caused by: 22 anchor impact events, 49 material corrosion defects and 25 other causes.

Figure 2-1- Transport pipelines at the Norwegian shelf (Bennet, 2013)

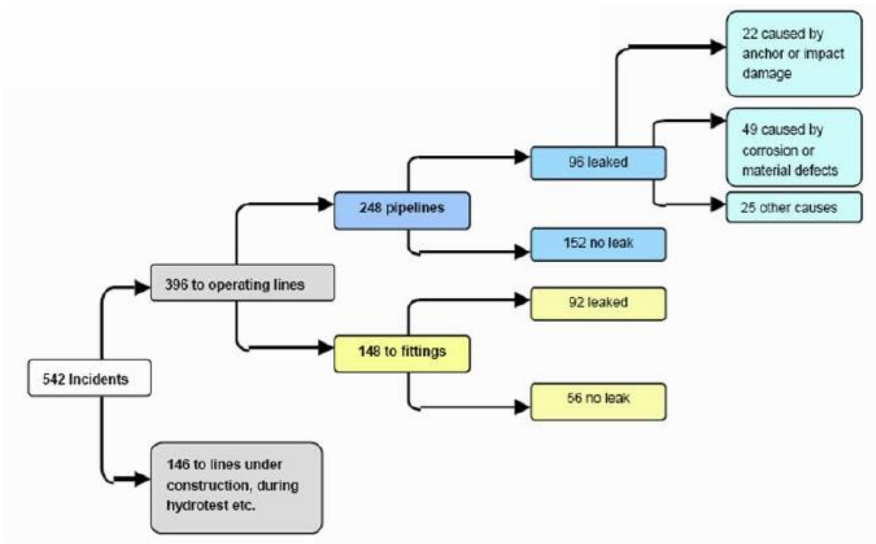


Figure 2-2 - Reported pipeline incidents in the North Sea at the end of year 2000 (DNV, 2007)

2.3 PIPELINE DAMAGE TYPES

The damage to a pipeline can be divided into two different groups of damage; internal damage and external damage.

The internal damage is mostly covered by erosion and corrosion of the internal barrier of the pipe, which could be an influence on the flow assurance capacity of the pipeline, and in worst-case lead to leakage of the pipeline. Other scenarios which may lead to internal damage or the need for pipeline repair could be wax build up and hydrate formation inside the pipeline.

The other type of pipeline damage, external damage of the pipeline generally means some kind of damage on the external part of the pipeline. The types of damages can vary a lot, but it usually starts with some kind of defect on the outer barrier of the pipeline. This could be some erosion of the coating leading to corrosion damage, or impacts of different equipment and items at the sea bottom that could lead to some severe damages to the pipe.

Dents

A dent (Figure 2-3) in a pipeline is defined as a permanent plastic deformation at the outer face of a pipe, caused by a dropped object or interference with other objects at the sea bottom. The dents cause local stress concentrations at the damaged point resulting in a local reduction of the pipeline material properties (Allouti, et al., 2014). Dents are normally treated as non-severe defects as they does not reduce the burst strength of the pipe by a noticeable amount, however dents in weld seams are treated as dangerous due to high stress and strain concentration factors. (Allouti, et al., 2014).

Gouges

"A gouge in a pipe is characterized by material removing on pipe surface." (Allouti, et al., 2014). The effect is similar to the scratching or scraping of the pipe surface. Some scenarios such as over trawling, anchor dragging, ROV impact and iceberg keel gouging could result in these types of damages. However, most of the pipelines have heavy weight coating, which also could protect the steel surface for gouging. A gouge will introduce a local reduction of the cross section thickness, and thus lower capabilities of pressure containment of the pipe. This will also be a point of high stress concentrations. When metal is removed from the pipe surface, there would also be some penetrations to the protection coatings of the surface. This could together with stress concentrations introduce local corrosion to the pipe.

External cracks

External cracks as a type of pipeline damage can be found in many different variations. It could be caused by stress concentrations in an area, i.e. inside a gouge. Due to the high stress concentrations in a crack, it has the possibility of expanding leaving it a very serious type of damage.

Figure 2-3 - Dent on pipeline (Allouti, et al., 2014)

Figure 2-4 – Gouges in a pipeline (wolverinepipeline, 2010)

Figure 2-5 - Pipeline crack (Goedecke, et al., 2014)

2.4 LOAD DEFINITIONS

DNV Submarine pipeline systems (DNV, 2012) define the following load definitions that is used in this thesis;

Interference loads

An interference load occurring on a pipeline is defined as a load, which is imposed on the pipeline system from third party activities, and has an annual probability of occurrence of more than 10^{-2} (DNV, 2012). External damage to a pipeline can occur in several different scenarios at the sea bottom. A typical event classified as interference loads are trawling loads that involves trawl impact and over-trawling. Hooking from trawling activities on the other hand has a probability of occurrence of more than 10^{-2}, and therefore this type of event is classified as an accidental load. Other interference loads described in (DNV, 2012) are interference from anchoring, impact from vessels and dropped objects.

Accidental loads

Accidental loads are unplanned and unforeseen loads occurring on a pipeline system where the probability of occurrence is less than 10^{-2} (DNV, 2012). These could be loads from extreme wave and currents, impact from grounded icebergs, movement of the seabed due to mudslides, dropped objects, dragged anchors and more. (DNV, 2012).

2.5 LOAD EVENTS

In this chapter different accidental and interference loads that results in external damage to the pipelines will be presented along with the type of damage that can occur in such events. The most studies and papers found by the author on these types of events is concerning trawling and anchor dragging activates. However, according to the possible hazards presented in DNV risk assessment of pipeline protection (DNV-2, 2010) shown in Table 2-1 below, there are many different types of external hazards that could happen to a pipeline. This thesis will focus on external damages that involves locked in bending stresses which is mainly caused by “pull over” or “hooking”, and according to the table below these damages can be summarized into 3 main types of events; Trawling activities, Anchor dragging and remote operated vehicle (ROV) activities.

The author would also like to present the possible event of ice feature seabed gouging, as this could possibly also cause severe bending damages to a pipeline.

Table 2-1 Possible external hazards presented by DNV-RP-F107 (DNV-2, 2010)

Operation/activity	*Hazard*	*Possible consequence to pipeline*
Installation of pipeline	Dropped and dragged anchor/anchor chain from pipe lay vessel Vessel collision during laying leading to dropped object, etc.	Impact damage
	Loss of tension, drop of pipe end, etc.	Damage to pipe/umbilical being laid or other pipes/umbilicals already installed
	Damage during trenching, gravel dumping, installation of protection cover, etc.	Impact damage
	Damage during crossing construction.	Impact damage
Installation of risers, modules, etc. (i.e. heavy lifts)	Dropped objects	Impact damage
	Dragged anchor chain	Pull-over and abrasion damage
Anchor handling (Rig and lay vessel operations)	Dropped anchor, breakage of anchor chain, etc.	Impact damage
	Dragged anchor	Hooking (and impact) damage
	Dragged anchor chain	Pull-over and abrasion damage
Lifting activities (Rig or Platform operations)	Drop of objects into the sea	Impact damage
Subsea operations (simultaneous operations)	ROV impact	Impact damage
	Manoeuvring failure during equipment installation/removal	Impact damage
		Pull-over and abrasion damage
Trawling activities	Trawl board impact, pull-over or hooking	Impact and pull-over damage
Tanker, supply vessel and commercial ship traffic	Collision (either powered or drifting)	Impact damage
	Emergency anchoring	Impact and/or hooking damage
	Sunken ship (e.g. after collision with platform or other ships)	Impact damage

2.5.1 Trawling

Fishing activity such as trawling can interfere with the subsea pipelines and induce stresses to the structure, which could in worst-case lead to rupture and leakage of the pipeline. The interference between trawling activity and pipelines is illustrated in Figure **2-6**. The loads occurring from trawling activities is according to (DNV, 2012) divided into three phases;

Trawl impact

Trawl impact is the initial event of a trawling interference between trawling gear and a pipeline. This is when one of the trawling boards shown in the top figure in Figure **2-6** hits the pipeline with kinetic energy. The impact may cause local damages to the pipeline such as; gouges, dents, damage to outer coating and also severe damages to the pipe which could lead to leaking or bursting of the pie. The physics behind the event is the same as when there are dropped objects landing on the pipeline.

Over-trawling

— *"Over-trawling, often referred to as pull-over, i.e. the second phase caused by the wire and trawl board or beam sliding over the pipe. This will usually give a more global response of the pipeline. "* (DNV, 2012)

Hooking

In some scenarios the trawl board could get stuck under the pipeline during an over-trawling event. This usually happens in locations where the pipeline is laying without any support beneath, also called a free span. This is a catastrophic event which is similar to an anchor dragging event. Extreme forces from the trawl boat will be transferred to the trawling gear wire, which is further transferred to the pipeline itself. Forces as large as the breaking strength of the trawling wire could be introduced to the pipeline which could lead to global bending, dent, buckling or in worst case rupture of the pipeline itself.

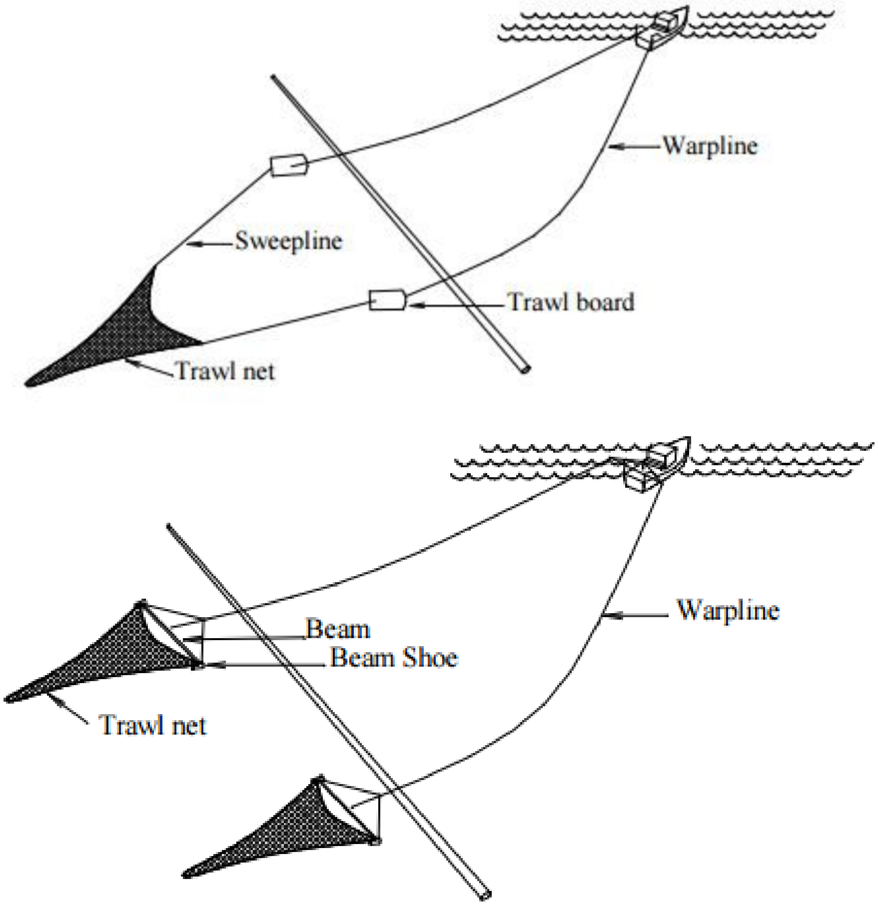


Figure 2-6 - Typical trawl gear crossing a pipeline (DNV-1, 2010)

2.5.2 Over dragging Ship anchor

When a ship is dragging an anchor over a pipeline route, there is a risk for the anchor to interfere with the pipe. In such events there are many different scenarios that can happen. If the pipeline is well protected with for instance gravel the anchor would most likely just slide over the pipeline without any significant damages (maybe just some coating damages or gouges). However, if the pipeline is not protected from underneath or if there are a lot of free spans, the anchor could drag the pipeline along the lateral direction of the pipeline route. Depending on the anchor shape, anchor wire strength and pipeline protection this event could lead to many different consequences. In best case the anchor would after some load slide over the anchor, leaving damages on the pipeline such as small bending, small dents or gouges. It could also get really stuck and transferring the whole strength of the anchor wire onto the pipeline. Depending on the strength of the anchor wire and the strength of the pipeline itself, the damage to the pipeline could be everything from small to severe. It could result in combinations of damages such as; bending, gouges, dents, local buckling or in worst case rupture of the pipeline itself, see Figure **2-7** below.

Figure 2-7 - Anchor stuck under a pipeline, leaving the pipeline damaged and lateral displaced by bending (Orsolato, et al., 2011)

2.5.3 ROV

ROV's can be used for many different operations. These operations often involve maintenance, inspection and repair of pipelines. Accidental impact between ROV and pipelines could be a possible event when maintaining, inspecting or repairing a pipe. These events could as well as over dragging anchors and trawling activities induce impact, and pull over damages on the pipe. It is assumed that the impact could lead to damages such as dents and gouges, but not any significant bending stresses. The author could not find any incidents where this event has occurred.

2.5.4 Ice gouging

One of the principal problems with arctic underwater pipelines is gouging by ice features. Ice gouging of the seafloor is a near-shore feature in cold northern areas. This gouging occurs when large masses of ice, e.g. ice ridges or icebergs, move over the sea bed, cutting deep gouges into the seabed. Up to 5 m deep and 50 m wide gouges have been reported (Singh, 2013) The force created by the continuous push from these ice features is sufficient to cut into steel pipe walls and cause significant damage; damage that can be compared to those caused by ships and anchors pulling on seabed resting pipelines. How the pipeline is affected by this gouging is dependent on the pipeline properties and the depth of the pipeline.

When designing pipelines planned for arctic regions, several important issues are considered:

- Material selection

- Line pipe qualification
- Leak detection
- Welding procedures
- Limit state criteria for strain based design
- Condition monitoring systems
- In line inspection tools

(Paulin, 2013)

The environment that would likely produce the deepest gouges would be where strong ice features are driven by high forces of drifting thick ice packs (NPC, 2015). The direction of the ice features in relation to the pipelines does matter. If the ice feature is generally orthogonal to the pipeline, there exists a higher risk of damage, but a shorter length of damage is the damage occurs. If the ice is parallel to the pipeline, the risk is statistically lower, but a longer section of pipe might be damaged in the process. Table 2-2 shows ice gouging parameters versus pipeline requirements. This load event could not be found as a previous damage event. However, with the ongoing arctic offshore development at the moment, this could be a possible damage event that should be taken account of.

Table 2-2 - Summary of ice-scour parameters versus pipeline requirements (Lewis, et al., 1986)

Summary of ice-scour parameters versus pipeline requirements

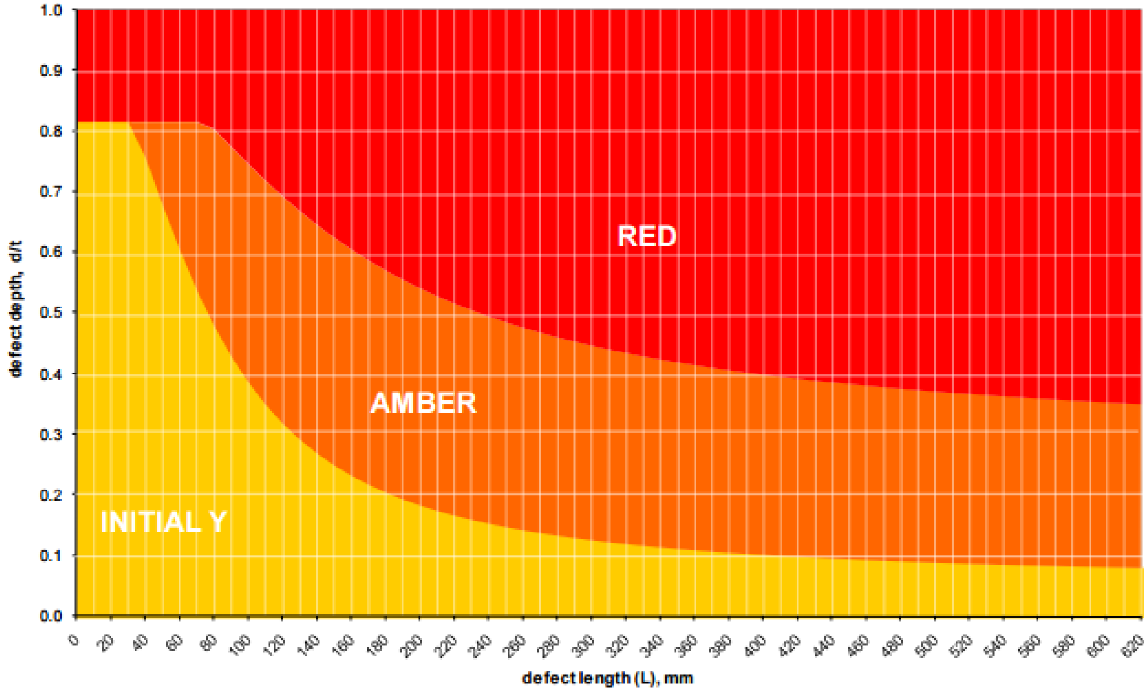
Ice-scour parameters	Effects on requirements in pipeline design
Scour depth distribution	Defines trench depth
Frequency of occurrence	Defines trench depth
Variation with water depth	Establishes practical use of dredging equipment
Critical exposure period	Influences repair response
Keel width	Defines length of damage and repair response
Directionality of scour	Influences risk and length of potential damage for specific routes
Keel residence time	Defines potential for accessibility to repair site
Mechanism of scour Keel-soil interaction Available forces Keel strength Keel shape	Defines feasible methods of protection
Correlation to surface ice conditions	Defines feasibility of operational monitoring
Influence of structures	Defines special requirements for trenching near structures

2.6 REPAIR CRITERIA

At the Rio Pipeline Conference & Exposition 2011 paper on rapid decision-making in emergency subsea pipeline repair was presented by (Palmer-Jones, et al., 2011). Two figures describing the repair criteria for two different types of damage was reviewed; Dent and gouges. These charts describes the repair requirements and the severity of the damage itself.

Dent Depth (% diameter)	Gouge in Dent?	Dent on Weld?	Repair Requirement	Schedule
<5%	Yes	Not applicable	Depressurisation, dressing and grouted sleeve	As soon as possible
<1.2%	No	No	No repair	Not applicable
≥1.2% and <3%	No	No	Grouted sleeve (note that case-specific analysis may shown that repair is not required)	6 months
	No	Yes	Grouted Sleeve	6 months
≥3% and <5%	No	No	Grouted sleeve	6 months
	No	Yes	Depressurisation and grouted sleeve	As soon as possible
≥5%	No	No	Grouted Sleeve is a temporary option to strengthen the pipeline until a cut out can be completed. Pigging may be prevented during this period	6 months
≥5%	Yes	Not applicable	Grouted Sleeve is a temporary option to strengthen the pipeline until a cut out can be completed. Pigging may be prevented during this period	As soon as possible
≥5%	No	Yes	Grouted Sleeve is a temporary option to strengthen the pipeline until a cut out can be completed. Pigging may be prevented during this period	As soon as possible

Figure 2-8 - Qatargas Dent Repair Criteria, shows how a various dents should be repaired, and the schedule for doing so (Palmer-Jones, et al., 2011)



Result from Figures	Classification and Recommended Action
Red	Red – repair required (grouted sleeve)
Amber	Amber – repair required (grouted sleeve)
Yellow	Yellow – reinstate the pipeline

Figure 2-9 - Gouge repair chart, shows the significance of a gouge damage related to a defect length with description of how these damages shoud be repaired. (Palmer-Jones, et al., 2011)

2.7 Methods for assessments of pipeline defects

Residual stress

Subsea pipelines are mostly made out of some kind of steel alloys. Steel have elastic properties, which means that if it is loaded below the yield strength (σ_y) of the material the material would go back to its original position. This means that if a pipe is loaded in such a way that it is bent, but the bending stress in the pipe does not go beyond the yield limit it should go back to its original position when unloaded. However, when a pipe is loaded further, and the stresses in the pipe go beyond the yield limit, plastic deformation occurs. This means that the pipe will not go back to its original position, which leaves residual stress within the material when unloaded. This is show with $\sigma_{e,res}$ in Figure 2-10.

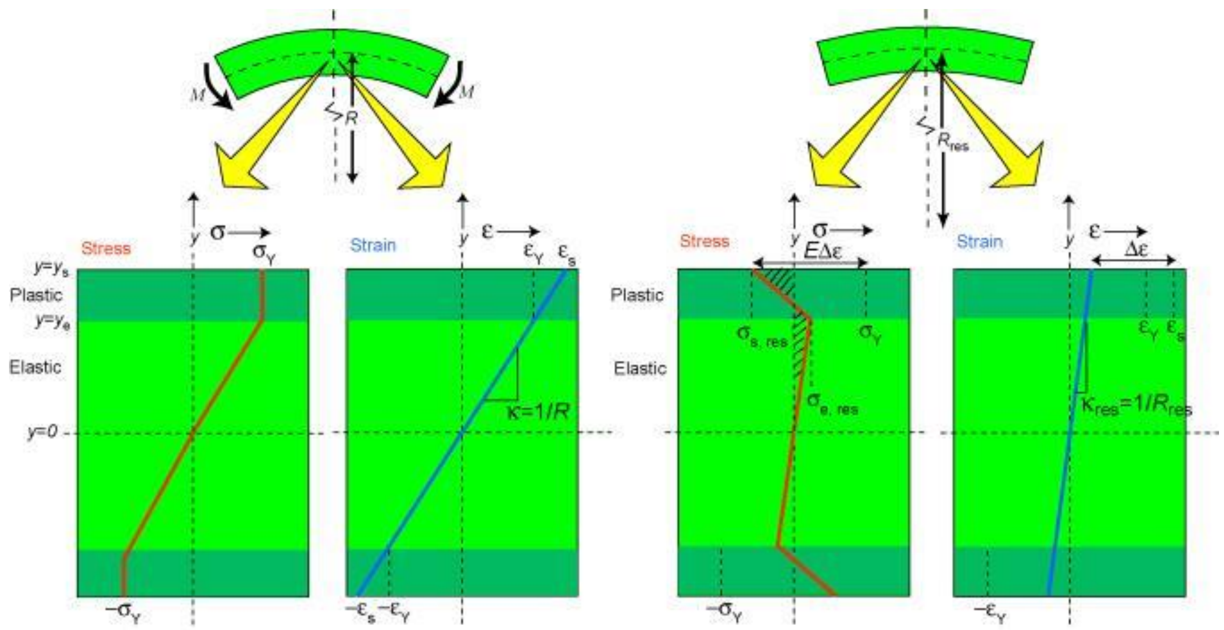


Figure 2-10 - Distributions of stress and strain within a beam before and after application of a moment sufficiently large to cause plastic deformation (University of Cambridge, 2015)

PDAM

The pipeline defect assessment manual (PDAM), was developed by a joint industry project involving different oil and gas companies around the world. The idea behind this project was to gather assessment methods for different pipeline defects into one complete manual. The types of defects that are considered in PDAM are listed below (Macdonal & Cosham, 2005):

- Defect-free pipe
- Corrosion
- Gouges
- Plain dents
- Kinked dents
- Smooth dents on welds
- Smooth dents containing gouges
- Smooth dents containing other types of defects
- Manufacturing defects in the pipe body
- Girth weld defects
- Seam weld defects
- Cracking
- Environmental cracking

The manual does not have a guide of how to assess damages containing a combined damage of gouges, compressive stresses and internal pressure. However, as presented in a case study on the BP CATS incident discussed in chapter 3.2, it was recommended to use the guidelines for a part walled corrosion defect with the combined loadings as a solution.

The recommendations in PDAM states that DNV-RP-F101 (DNV, 2010) could be used to calculate the burst strength of a corrosion effect for a moderate to high toughness pipe, which will be the assumed pipe type in the thesis. (Cosham, et al., 2006)

The following formulas; 2.7-*1* to 2.7-*1* are gathered from DNV-RP-F101 (DNV, 2010). The capacity for a pipe containing a single rectangular shaped defect is defined as:

$$P_{cap} = 1.05\frac{2t\cdot\sigma_u}{(D-t)}\left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}\left(\frac{1}{Q}\right)}\right] \qquad 2.7\text{-}1$$

Where P_{cap} is the capacity for a pipe containing a single rectangular shaped defect, $d$the depth of the gouge, t is the pipe wall thickness and σ_u, is the ultimate strength of the material. The factor Q is defined as the length correction factor, which represents the stress concentrations that occur in the defect under the influence of internal pressure. The following equation below will be used for the calculations for the length correction factor:

$$Q = \sqrt{1+0{,}31\left(\frac{l}{\sqrt{Dt}}\right)^2} \qquad 2.7\text{-}2$$

where l is the gouge length, D the pipe diameter and t the thickness of the pipe.

When assessing damages in a pipe both containing a gouge, locked in bending stresses and internal pressure the PDAM does not cover how to properly assess these. However, in the case study in chapter 3.2, it is stated that in order to estimate the burst pressure for a pipeline containing these loadings, a gouge can be estimated as a corrosion defect.

The following steps and equations (2.6-*3*, 2.6-*4*, 2.6-*5* and 2.6-*2*) given by DNV RP-F101 shows how to calculate the burst strength of a corroded pipeline subjected to longitudinal compressive stresses:

Step 1: Calculate the combined nominal longitudinal stress.

$$\sigma_L = \sigma_A + \sigma_B \qquad 2.7\text{-}3$$

where σ_L is the combined nominal stress, σ_A the axial stress and σ_B the bending stress.

Step 2: Calculate the allowable corroded pipe pressure using the following formulas (in this case this will be for allowable gouge pressure).

$$p_{corr,comp} = \gamma_m \frac{2tf_u}{(D-t)}\frac{(1-\gamma_d(d/t)^*}{\left(1-\frac{\gamma_d(d/t)^*}{Q}\right)}H_1 \qquad 2.7\text{-}4$$

$$H_1 = \frac{1+\frac{\sigma_L}{\xi f_u}\frac{1}{A_r}}{1-\frac{\gamma_m}{2\xi A_r}\frac{(1-\gamma_d(d/t)^*}{\left(1-\frac{\gamma_d(d/t)^*}{Q}\right)}} \qquad 2.7\text{-}5$$

$$A_r = \left(1-\frac{d}{t}\theta\right) \qquad 2.7\text{-}6$$

The symbols from these last 3 equations are given below as defined by DNV RP-F101 (DNV, 2010):

- A_r = Circumferential area reduction factor.
- H_l = Factor to account for compressive longitudinal stresses.
- c = Circumferential length of corroded region (mm).
- f_u = Tensile strength to be used in design
- $p_{corr,comp}$ = Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure and superimposed longitudinal compressive stresses (N/mm^2).
- γ_d = Partial safety factor for corrosion depth.
- γ_m= Partial safety factor for longitudinal corrosion model prediction. (normally set to 0,74)
- ξ = Usage factor for longitudinal stress. (normally set to 0,85)
- θ = Ratio of circumferential length of corroded region to the nominal outside circumference of the pipe, $(c/\pi D)$.

2.8 PIPELINE REPAIR METHODS

Most of the existing repair studies for repairing damages such as gouges and small bends are usually some form of clamp or sleeve. The idea behind a clamp is to enclose the damaged pipe into a robust and pressure tight vessel. The procedure of the repair is usually divided into 3 different steps.

- Lift the pipe up from the sea bottom, to allow the clamp to get around the pipe.
- Remove surface coating from the pipe.
- Insert clamp around the damage

Below are some of the types of clamps, composite and sleeve repair systems.

2.8.1 Composite repair

Corrosion of pipelines is a major issue when speaking of costs and downtime of oil and gas production. In the United States more than 2 billion dollars (Duell, et al., 2008) was lost due to corrosion issues on the subsea pipelines. To manage these issues some of the most common repair methods are either to replace the damaged pipe, or to insert a clamp around the damage. The composite repair technology provide the ability to fill the damaged part with an epoxy putty to eliminate the corrosion process, continued by a composite wrapping around the damaged pipeline (Duell, et al., 2008) without interfering with the operation of the pipe (see Figure 2-11). The composite wrapping is a Fiber-reinforced polymer (FRP), which is well suited for pipeline repair material due to a very high specific strength and stiffness, as well as a high formability and an inherent immunity to corrosion (Köpple, et al., 2012). It has been showed by industry analysis that a composite repair method is on average 24% (Duell, et al., 2008) cheaper than a welded steel clamp repair, and 73% (Duell, et al., 2008) cheaper than replacing the damaged pipe section.

One major disadvantage with using this method of repair is uncertainties in the many possible failure mechanisms that can occur; these could be fracture in the individual fibers, separation of the internal fibers or delamination between the epoxy and the fiber wrapping (Köpple, et al., 2012). A delamination between the epoxy and could occur if the pressure of inside the pipeline acts at the damaged point and provide a fluid leakage. This fluid could be trapped between the steel and the pipe in a pressurized blister, which could lead to an external leakage of the pipe.

A study concerning a ROV operable composite wrapping machine (Figure 2-12) is under development (Popineau, et al., 2012). This machine is designed to use pre impregnated composite wrapping to cover damaged parts of a pipeline beyond sea level, and have already proven good results using divers.

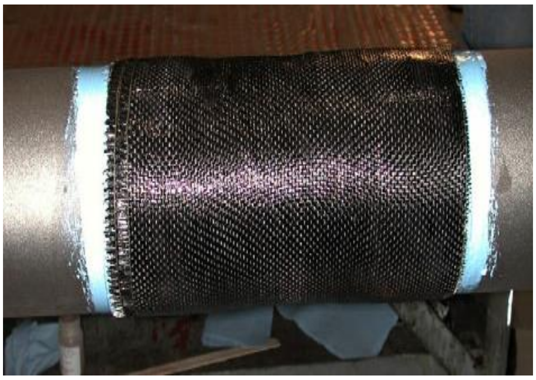


Figure 2-11 - Repaired test pipe with epoxy putty and carbon fiber wrapping (Duell, et al., 2008)

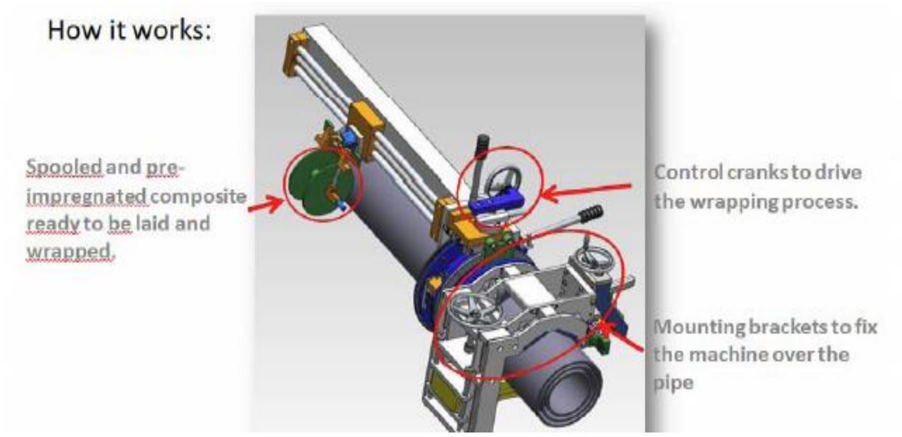


Figure 2-12 - Composite wrapping machine (Popineau, et al., 2012)

2.8.2 Welded sleeve repair

In addition to composite repair, the repair of corrosion, dents and small cracks damage on pipelines can be done with installing a welded sleeve around the pipe. The repair system consists of seam welding two half-section pipes with an inner diameter equal to the outer diameter of the pipe around the damaged section as shown in Figure 2-13. There are two types of sleeves used for this operation; Type A sleeves which are only seam welded without welding the ends to the original pipe, and type B which are welded at the ends contributing to a fully pressure containment around the damage (Alexander, et al., 2014).

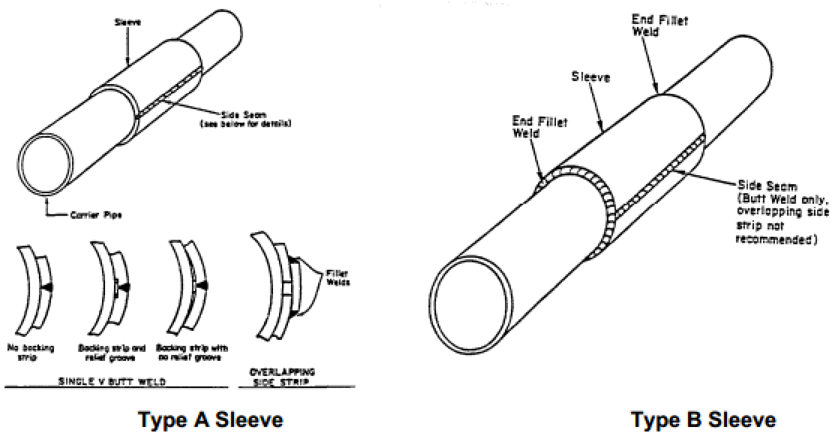


Figure 2-13 - Welded sleeve type A and B (Bruce & Amend, 2010)

2.8.3 Split and seal steel sleeve clamp

The clamp repair technology provides a repair of minor damages such as corrosion pits, dents and small cracks in the pipeline. Grip and seal split sleeve type clamps are one of the most common type sleeves used for these types of damages. This clamp acts as a high integrity pressure vessel around the pipe at the damage location (Kejser, et al., 2011) by using two clamp halves joined together by bolts (Figure 2-14). Sealing of the clamp around the pipe requires a perfect smooth surface in order to seal properly. This requires a separate coating removal tool to remove the rubber or concrete coating on the pipe. In some cases, where a weld seam exists on the pipe it may be necessary to also run a weld seam removal tool to finish the surface. When the pipe surface is completely smooth, the clamp is finally ready to be installed.

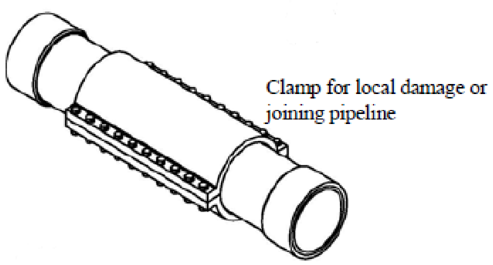


Figure 2-14 – Grip and seal split sleeve clamp (DNV, 2007)

2.8.4 Grouted clamp

Clamps used for reparation of pipelines can also be grouted as seen in Figure **2-15**. These clamps will in addition to the normal split steel sleeve clamp described in chapter 2.8.3 have an epoxy filling between the pipe and the sleeve, which will float into imperfections in the pipe. Gouges, cracks and dents will then be filled with the epoxy filling. As there is need for additional space for the epoxy filling to harden the shell it will have a much greater inner diameter than for a normal sleeve clamp, which makes the clamp much more flexible when it comes to small pipe dimensions. The properties of the grouted clamp will according to (Palmer-Jones, et al., 2011) give the following features to the pipe when installed onto a damaged pipeline:

- Preventing fatigue cracks
- Reduce axial stress at the damage location
- Reduce hoop stress induced by pressure and temperature in a deformed cross section pipeline.
- Prevent local buckling and collapse
- Reducing overall stress levels in the damaged area

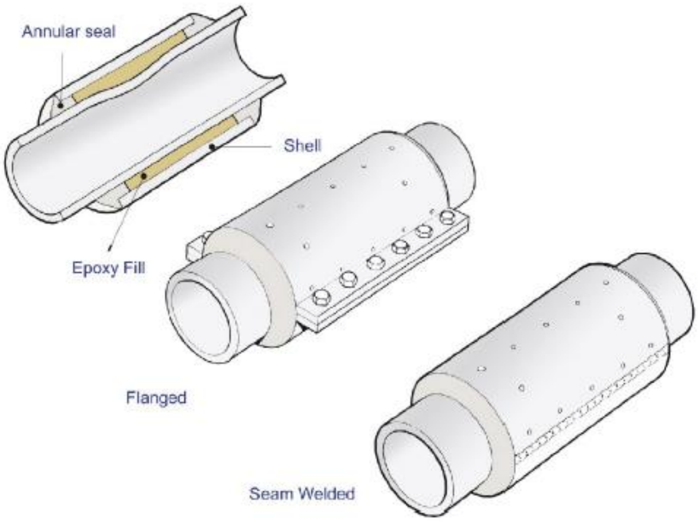


Figure 2-15 - Grouted clamp types (Palmer-Jones, et al., 2011)

2.8.5 Flexible grouted clamp/sleeve

More advanced repair which involves damages on a pipe on a section with large bend radiuses might need a more complex repair system. A flexible grouted clamp could be a good solution. This type of clamp covers the same features as the grouted clamp described in chapter 2.8.4, but it also introduce the possibility of repairing larger damages in pipes with large bending radius.

Some various types of flexible grouted clamps presented in the flexible grouted clamp at the Rio Pipeline Conference & Exposition 2011, (Palmer-Jones, et al., 2011) are shown in Figure 2-16, Figure 2-17, Figure 2-18 and Figure 2-19.

Figure 2-16, Figure 2-18 and Figure 2-19 shows almost the same concept, but more advanced. The concept is very similar to connecting many normal grouted clamps to each other with a small angle difference between them. To prevent leakage between the gaps, some special wedges with the desired angle are placed between the gaps, see Figure 2-19.

This same technology was used on the BP CATS anchor dragging incident studied later in chapter 3.2.

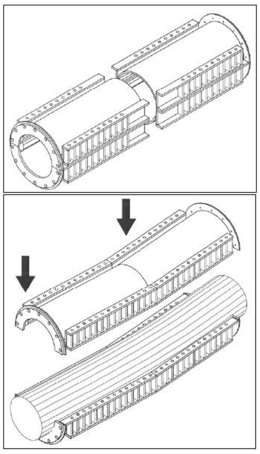


Figure 2-16 - Welded Mitered Clamp (Palmer-Jones, et al., 2011)

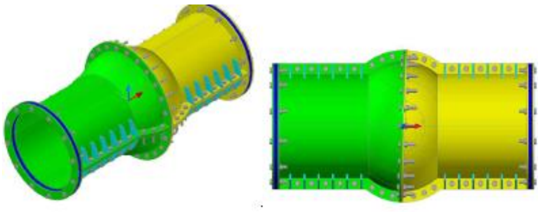


Figure 2-17 - Spherical center clamp (Palmer-Jones, et al., 2011)

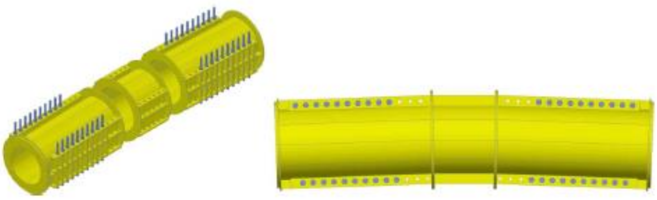


Figure 2-18 - Wedged clamp (Palmer-Jones, et al., 2011)

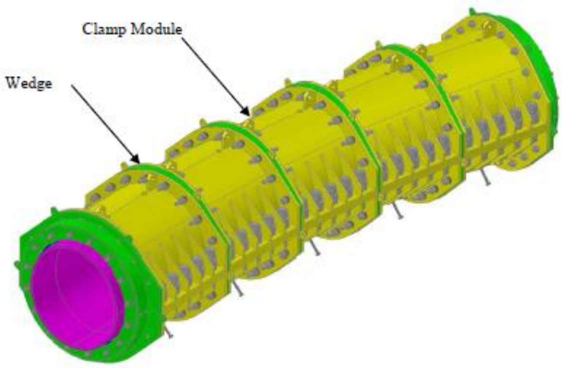


Figure 2-19 - Advanced Wedged Clamp (Palmer-Jones, et al., 2011)

2.9 PIPE SECTION REPLACEMENT METHODS

Some standardized methods of pipe section replacement and cutting will be presented. This method is more classified as a method of pipe section replacement, than pipe repair and will therefore not be very relevant to the objectives given in the thesis introduction. However, when the stresses in a damaged are is too high to repair using clamps or less heavy repair technology, these types of methods might be the only solutions in order to maintain good and stable pipeline integrity.

2.9.1 Above water tie in

For some pipeline damages it is not possible to repair the pipeline as it is. A section from the pipe needs to be changed out. There are basically two ways of doing this type of operation existing today. The first one is called above water tie in. In this method the damaged pipe section are cut out from the original pipe lying on the sea bottom using a remote operated cutting tool. It is here plugged with special designed plugs to withstand fluid from leaking out of the pipe while the rest of the repair is carried out. After this, the two ends of the pipe are lifted up to the surface, where they are joined together using a completely new pipe section. This procedure is explained further in chapter 3.1.

2.9.2 Subsea welding

In addition to above water tie in repair operations, there is also possibilities of replacing pipe segments at the bottom of the sea. Statoil have developed a technology which provides this type of technology. It is designed to do welding repair as deep as 1300 meters, and for pipelines from 30-inches up to 42-inches in diameter. The way it works is that the damaged section of the pipe is first cut out using a remote operated cutting tool and plugged, similar to the one used for above water tie in repair described above. After this operation a new pipe segment is lowered down between the two pipe ends, as shown in Figure **2-20**. After this the pipes are lifted up from the sea bottom in order to allow welding on the whole circumference. Eventually a remote welding system (Figure **2-21**) containing; a welding habitat for dry and clean welding conditions, welding power and control module and a welding tool are lowered onto the pipe joint which is to be welded. (Berge, et al., 2015)

Figure 2-20 - Lowering pipe segment between two plugged pipe ends (Berge, et al., 2015)

Figure 2-21 - Remote welding system mounted on a pipeline joint

3 CASE STUDIES

3.1 TRANS MEDITERRANEAN PIPELINES REPAIR (ANCHOR DRAGGING)

The Trans-Mediterranean pipeline system is a gas pipeline system going from northern Italy to Hassi R'Mel in Algeria. The pipeline system is land based throughout most of Italy and then crossing the Mediterranean Sea from Mazara del Vallo in Italy to Cap Bon in Tunisia See the purple line in Figure 3-1. The pipeline which consists of five (Orsolato, et al., 2011) pipelines was in December 19th 2008 (Orsolato, et al., 2011) hit by an anchor dragged by a 110000 tones tanker through the pipeline route resulting in damage in three of the pipelines at a 70 meter (Orsolato, et al., 2011) depth. The first pipeline (20 inches) was barely touched by the anchor and only got minor damages, however the two following pipelines was damaged where one of them was leaking and the other one was laterally displaced by several meters. The anchor chain eventually snapped at the end leaving the anchor lying under the third pipeline. Due to huge pressure drop readings at both the Cap Bon compressor station and at Mazara del Vallo terminal the event was discovered in short time after the incident occurred resulting in the decision to immediately shut down the pipeline system (Orsolato, et al., 2011).

Figure 3-1 - Transmediterranean Pipeline System (purple line) (Wikipedia, 2015)

Short time after the incident an inspection vessel from Saipem was appointed to investigate the damage on the pipelines. The survey showed that the third pipeline was not leaking although it was severely damaged (Figure 3-2), and that the second pipeline was completely damaged (Figure 3-3). An inspection done by one of Saipem's ROV vessels showed that the 26-inch pipeline was moved laterally 30 meters (Orsolato, et al., 2011) at the point of damage, and the 20 inch pipeline was moved laterally 43 meters (Orsolato, et al., 2011). Additionally a morphological survey was done to identify possible obstacles in the area around the damaged pipe concerning further repair activities. From this survey, the impact angle of the damage point was predicted by identifying the anchor scour on the seabed. From these observations, it was possible to run a structural analysis of the two pipelines based on the anchor pulling force and the steel properties of the pipelines. The results from this analysis are shown in Table 3-1 below:

Figure 3-2 - Third pipeline (20 inches) laterally displaced 43 meter with anchor under (Orsolato, et al., 2011)

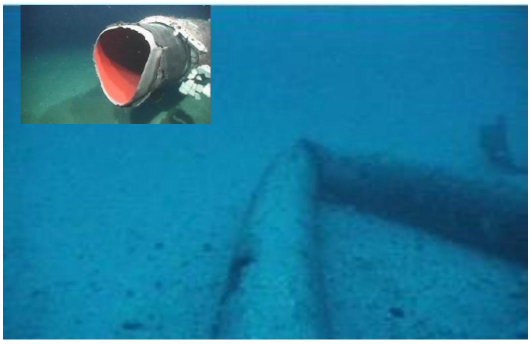


Figure 3-3 - Second pipeline (26 inches) completely damaged with the ruptured end top left (Orsolato, et al., 2011)

Table 3-1 - Results from structural analysis of anchor dragging incident (Orsolato, et al., 2011)

All results from (Orsolato, et al., 2011)	Pipeline 2 (20 inches)	Pipeline 3 (26 inches)
Anchor Force applied to pipelines	1500 to 1700 kN	
Dent depth	13 to 23 mm	
Max bending moment	2100 kNm	4300 kN
Axial force in steel	6000 to 6500 kN	7500 to 7900 kN
Maximum lateral displacement at incident	47m	40m

From these results based on the stress applied to the pipeline material in the longitude direction of the damage point, the decision was to replace 200 m of the 26-inch pipeline, and 80m of the 20-inch pipeline (Orsolato, et al., 2011).

The repair method that used in this project was an Above Water Tie-in (AWT) operation. AWT is a pipeline repair method where you cut out the section of the pipeline that normally is removed by a ROV vessel. The damaged section is retrieved to the surface for scrapping, while a pipe recovery tool (PRT) plugs the remaining ends at the subsea location. The ends were eventually mounted to an Abandonment and Recovery wire (A&R) used to lift the two pipeline ends up to the surface. On the surface, some additional pipe joints where welded to the pipe to compensate for the damaged pipe sections and to get the two pipe sections welded together. The pipelines where welded together with a double joint (inside and outside welding). Due to the increase of the length of the pipe the two pipelines was displaced laterally some distance from the original position, leaving the 26-inch pipeline crossing one of the non-damaged pipe. This was managed by trenching and gravels dumping on the non-damaged line so that the repaired line could be placed safely over the existing one.

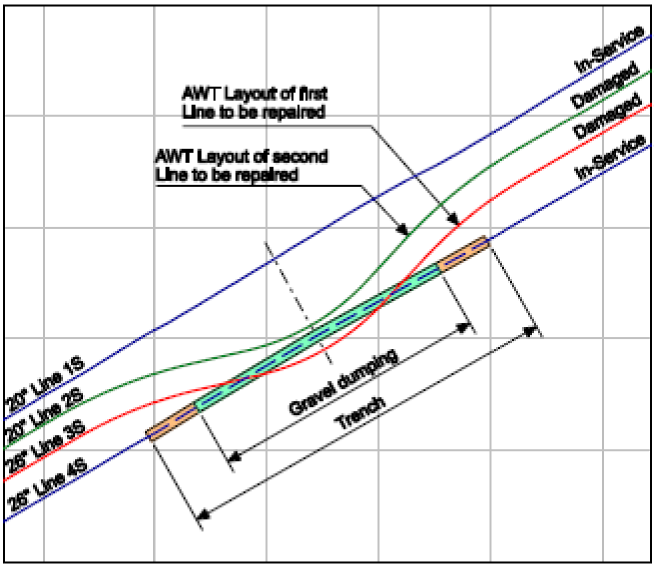


Figure 3-4 - Layout of the repaired pipelines (Orsolato, et al., 2011)

3.2 BP CATS ANCHOR DAMAGE AND REPAIR

The Central Area Transmission System (CATS) is BP operated pipeline network in the UK part of the North Sea delivering natural gas from the CATS platform to the North East coast of England. The X65 steel pipeline is 36 inches in diameter, 28.4mm , length of 404 km and a maximum allowable operation pressure (MAOP) of 180bar (Espiner, et al., 2008). At the end of June 2007, BP was notified that a tanker had dragged an anchor across the CATS pipeline at a location 6 km from shore at a depth of 32 (Espiner, et al., 2008) meters. The initial response from BP was to confirm that there was no external leakage from the pipe by monitoring the flow and pressure of the pipeline, which showed that there were no significant changes to the readings.

The inspection of the damage done by divers initially showed that there was no dents in the pipe, but as more of the concrete weight coating was removed a complex dent shaped feature appeared. Detailed geometric mapping showed that this feature stretched 4m (Espiner, et al., 2008) along the pipe longitudinal axis. Figure 3-5 shows the geometric mapping of the damaged pipe section (each section has a length of 12.5 m) (Espiner, et al., 2008) . As a consequence of this incident, an external damage on the surface of the pipe was located in the compressed section due to the pipeline displacement. The bending of a pipeline will induce locked-in compressive stresses at the compressed part of the section, which combined with dents and gouges does not have a standardized method of assessing these damages in the pipeline defect assessment manual (PDAM) (Espiner, et al., 2008). The repair method chosen for this particular damage repair was a welded mitred grouted clamp similar to the one showed in chapter Figure 2-16. As a conclusion in the inspection and assessment paper release by BP and Penspen it was stated the following: "*Methods are required to assess gouges in pipelines with significant locked-in stresses. Existing methods can lead to very onerous defect assessments*" (Espiner, et al., 2008)

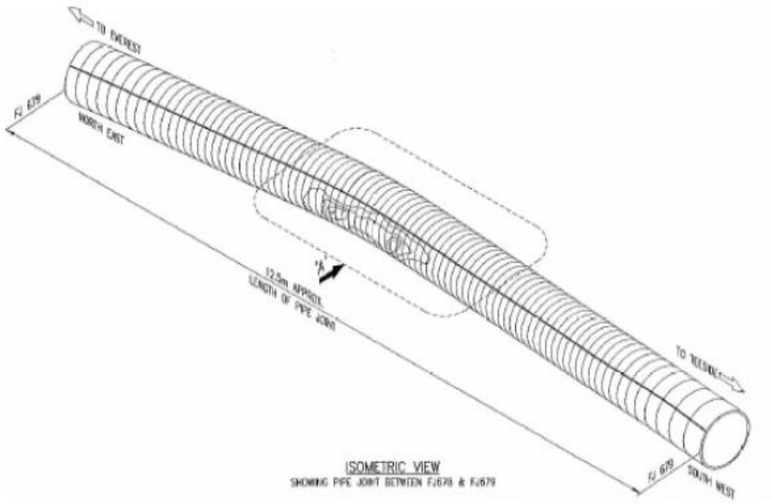


Figure 3-5 - Pipeline damage between two pipe joints (Espiner, et al., 2008)

4 ANALYSIS OF LOCKED IN STRESSES WITH PRESENT GOUGE AND INTERNAL PRESSURE

As stated previously in chapter 2.7 the pipeline defect assessment manual does not cover how to assess damages to pipeline where gouges and dents are combined with compressive stresses and bending moments. In anchor impact to pipeline events, this type of damage combination could be a likely scenario. As a pipeline defect will most likely affect the production capability of the field, a method of how to assess these types of damages can be very crucial.

After BP's CATS anchor damage described in chapter 3.2, BP stated the following:

"For subsea pipelines there is the potential for high locked-in compressive stresses to be generated as a result of pipeline displacement. The experience of the CATS incident shows that there is a need for further research to develop defect assessment methods that take account of these loads" (Espiner, et al., 2008).

This gave the author an idea to investigate how to assess these damages in a simple way, so that the damage burst pressure could easily be adjusted according to the bending radius and the depth of the gouge on the pipe. For this assessment FEA analyses will be performed. These will be compared with results from existing standardized methods described in chapter 2.7

4.1 ANALYSIS SETUP

To start with, some finite element analysis (FEA) will be prepared with various gouge depths and bend radius. To simplify a standardized pipe dimension will be used for this analysis, but this technic should also be adaptable for other dimensions. There will be carried out two different types of simulations:

1. Analysis of max stress in a gouge using standardized methods
2. Simulation of how the maximum stress in the gouge will change according to different locked in stresses caused by various forced displacement. This simulation will be done with a constant internal pressure.
3. Simulation of how the burst pressure will change with regards to different gouge depths, having forced and released a constant displacement onto the pipe.

Autodesk Simulation Mechanical 2015 software will be used in this simulation, with a simulation type called "MES with Nonlinear Material Models". The reason for using non-linear material models is to allow the pipe to plastically deform, thus give some locked-in stresses to analyze. A 3D Brick element defined as a plastic element with Von Mises hardening are used (Figure 4-2) to set up the analysis.

The gouge tested will be a V shaped gouge with a 45-degree angle between the sides (Figure 4-4), and will have a 250 mm length.

Dimensions and constants for the pipe used in this simulation are shown in Table 4-1. The material used in this simulation will be X65 pipe steel. This is the same steel type that is used in the BP CATS pipeline described in chapter 3.2.

For this simulation to work it was necessary to know the Strain hardening modulus E_s, which describes the relation between stress and strain in the plastic zone of the material. This modulus could not be found in any databases, but it can be estimated using a linear interpolation as shown with a green line in Figure **4-1**. The strain hardening modulus was calculated as:

$$E_s = \frac{575 - 450}{0{,}08 - 0{,}003} = 1623$$

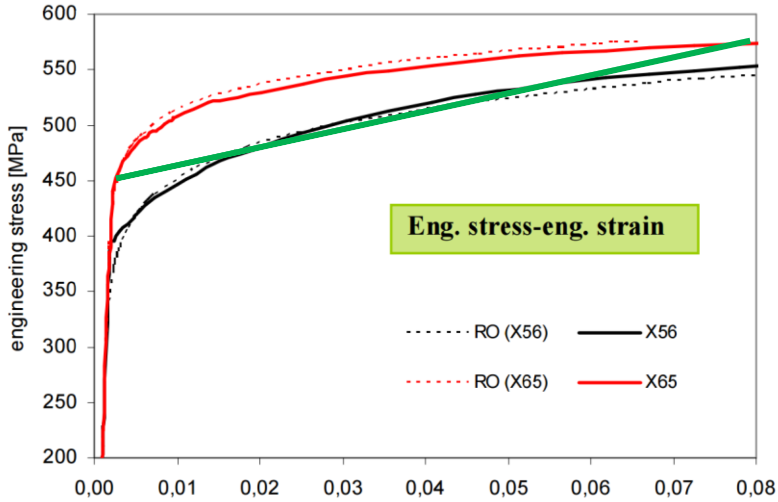


Figure 4-1 - Stress train curve for X65 and X56 steel (Liessem, et al., 2007). Green line is illustrated by the author as the strain hardening modulus relation.

Table 4-1 – Constants used in the simulation

Definition	Symbol	Value
Pipe diameter	D_P	$914{,}4\ mm\ (36\ inches)$
Pipe Wall Thickness	t_P	$28{,}4\ mm$
Gouge Length	l_g	$250\ mm$
Pipe span length	L_P	$12{,}5\ m$
Water depth	d	$32\ m$
External pressure	P_I	$3{,}2\ bar$
Internal pressure (MAOP)	P_I	$180\ bar$

Table 4-2 - Material properties for X65 steel

Definition	Symbol	Value
Yield strength	σ_{yP}	$450\ MPa$
Modulus of elasticity	E_P	$210\ GPa$
Poisson ratio	ν_P	$0{,}3$
Strain hardening modulus	$S_{\epsilon P}$	$1623\ N/mm^2$
Mass density	ρ_P	$7800\ kg/m^3$
Ultimate strength	σ_{UP}	$575\ MPa$

4.1.1 Analysis of stresses in a gouge using standardized methods

Chapter 2.7 presents some formulas from DNV-RP-F101 that can be used to calculate the burst pressure criterion for a pipe containing a part walled defect such as a V-shaped gouge. The standard itself is for calculating the pressure criterion for a corrosion part walled defect. As explained in chapter 2.6 from the PDAM part, this standard could be used in the BP CATS incident for a pipe containing a gouge with significant locked in stresses. It is therefore assumed that this could also be implemented into this analysis in order to compare the results gathered from the FEA simulations. These calculations will be done based on the data described in Table 4-1 Table 4-2 with gouge depths defined in Table 4-1.

Equations; 2.7-1 and 2.7-2 will first be used in this analysis. These equations are for calculating the internal pressure capacity of a pipe with a part walled corrosion defect (p_{corr}). The purpose of the analysis is to compare the results from this analysis with the result in the FEA analysis where there is no forced displacement.

Further the equations; 2.7-4, 2.7-5 and 2.7-6 will be used to calculate the internal pressure capacity for a pipe containing longitudinal locked-in stresses. These locked in stresses will be obtained by using a simple simulation as described in chapter 4.1.2 with no internal pressure or outer damages (gouge).

4.1.2 Simulation of stress in a gouge with various forced displacements

The pipe will be set up as a free span beam with pinned support in both ends as shown in Figure 4-3. Deformations shown are the initial deformation (δ_I) and the final deformation (δ_F), where δ_I illustrate the deformation when the load from for instance an over dragging anchor is present, and δ_F illustrates when the load is released and the deformation in the pipe reduces due to the elastic properties in the steel as shown in Figure 4-2. Loading curves that are used in this simulation is shown in Figure 4-5, which shows how the two different loadings (displacement and internal pressure) are acting on the pipe concerning the time. It is assumed for simulation simplicity that the forced displacement will take 1 second from no displacement at all, to the full displacement shown in Figure 4-5. It is assumed that after this the forced displacement is released, and the pipe is free from external loadings ruling out the pressure which is constant all the time.

The internal pressure (P_I) will be set to a constant 180 bar with no external pressure, assuming a shallow water pipeline. This analysis will be performed with seven different depths of gauges (G_{PD}) and forced displacements (δ_F) from 0- to 1000 mm with a 100 mm interval. To force locked-in stresses into the V-shaped gouge there will be forced a displacement onto the pipe, forcing the pipe to bend (Figure 4-3). This forced displacement will eventually be released, and the pipe will move back a bit according to the elasticity of the material. The data used are defined in Table 4-1 and Table 4-2 above.

Table 4-3 - Simulation combinations

Forced displacement [mm] (δ_I) (Figure 4-3)	Gouge depths [mm] (G_{PD}) (Figure 4-4)
0	4
100	8
200	12
300	16
400	20
500	24
600	28
700	
800	
900	
1000	

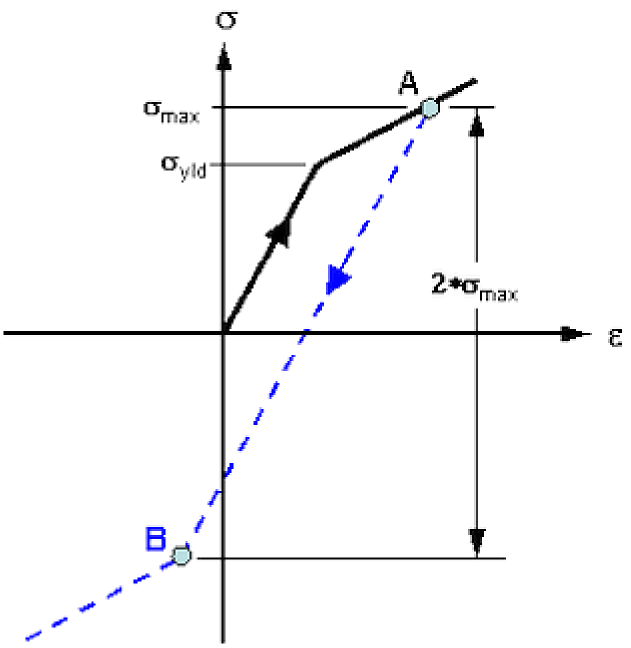


Figure 4-2 - Plastic behavior, von Mises with Isotropic Hardening (Autodesk, 2015)

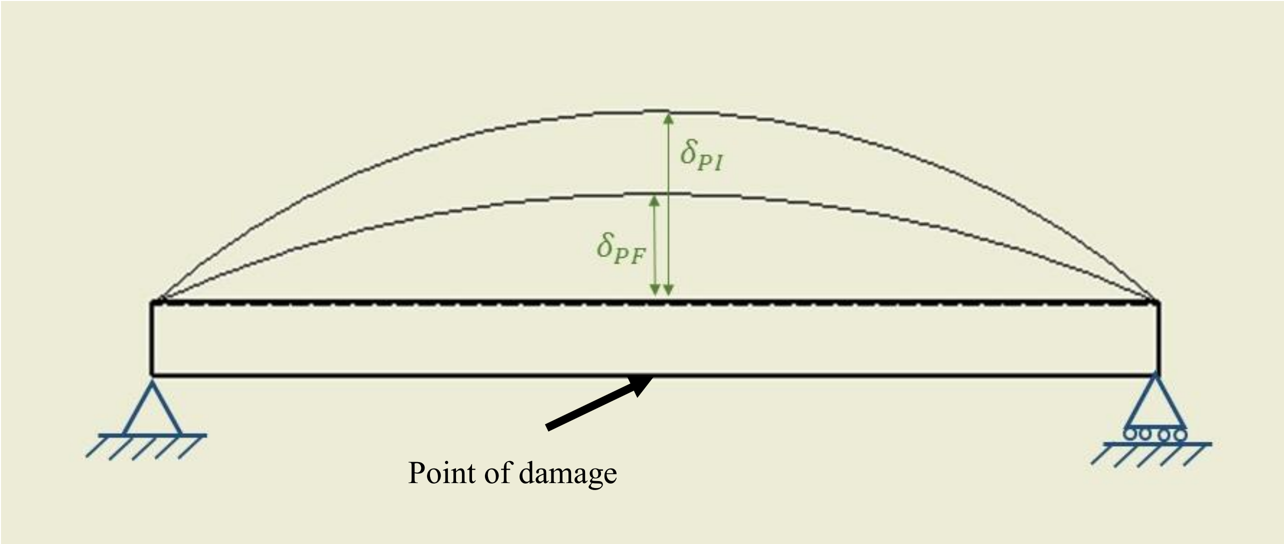


Figure 4-3 - Pipe simulation setup with constraints and Initial and final deformation

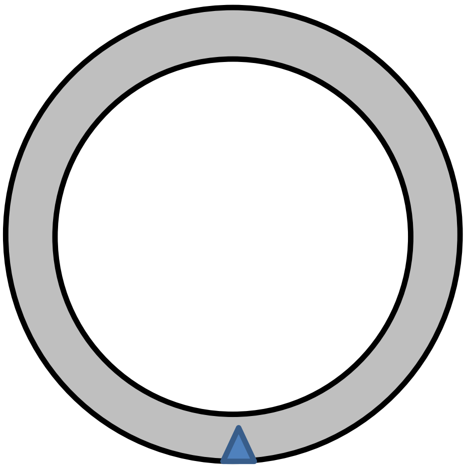


Figure 4-4 - Illustration of Gouge in the pipe cross section

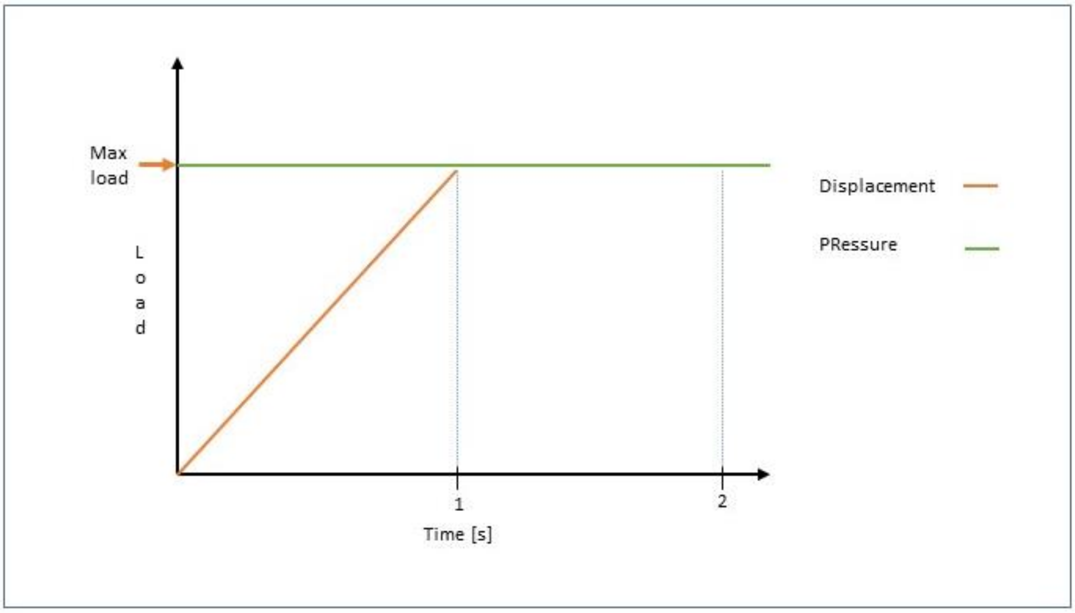


Figure 4-5 - Load curves for simulation showing how the displacement and the pressure are loaded in the simulation.

Carrying out the simulation

Carrying out the simulation was a time demanding process. After the pipe element was drawn properly according to the parameters set in Table 4-1, each of the V-shaped gouge depth in Table 4-3 are embossed into the center of the pipe surface in separate part files, all using Autodesk inventor 2015.

Afterwards each of the part files were loaded into Autodesk Simulation Mechanical 2015 one file at the time. All of the settings was set equal, to get equal conditions for all the different gouge samples. These settings can be found in appendix chapter 8.3.For each of the seven gouge samples there where performed 7 separate simulations where a forced displacement was set according to Table 4-3. The displacement followed the curve shown in Figure 4-5, which shows that it was linearly increased from zero to the desired displacement over a 1 second period, and then released. Eventually all of 49 completed simulations were carefully studied in order to find the highest stress in the pipe. This was revealed to be a difficult task, as the highest stress was at the end supports, and not in the center of the pipe. It was therefore required to manually study each of the simulation samples in order to find the node with the highest stress.

Figure 4-6 shows one of the simulations performed, which together with the load curve presented in Figure 4-5 above can be used to see how the locked in stresses are being distributed at the center of the pipe as a result of the loading changing over time.

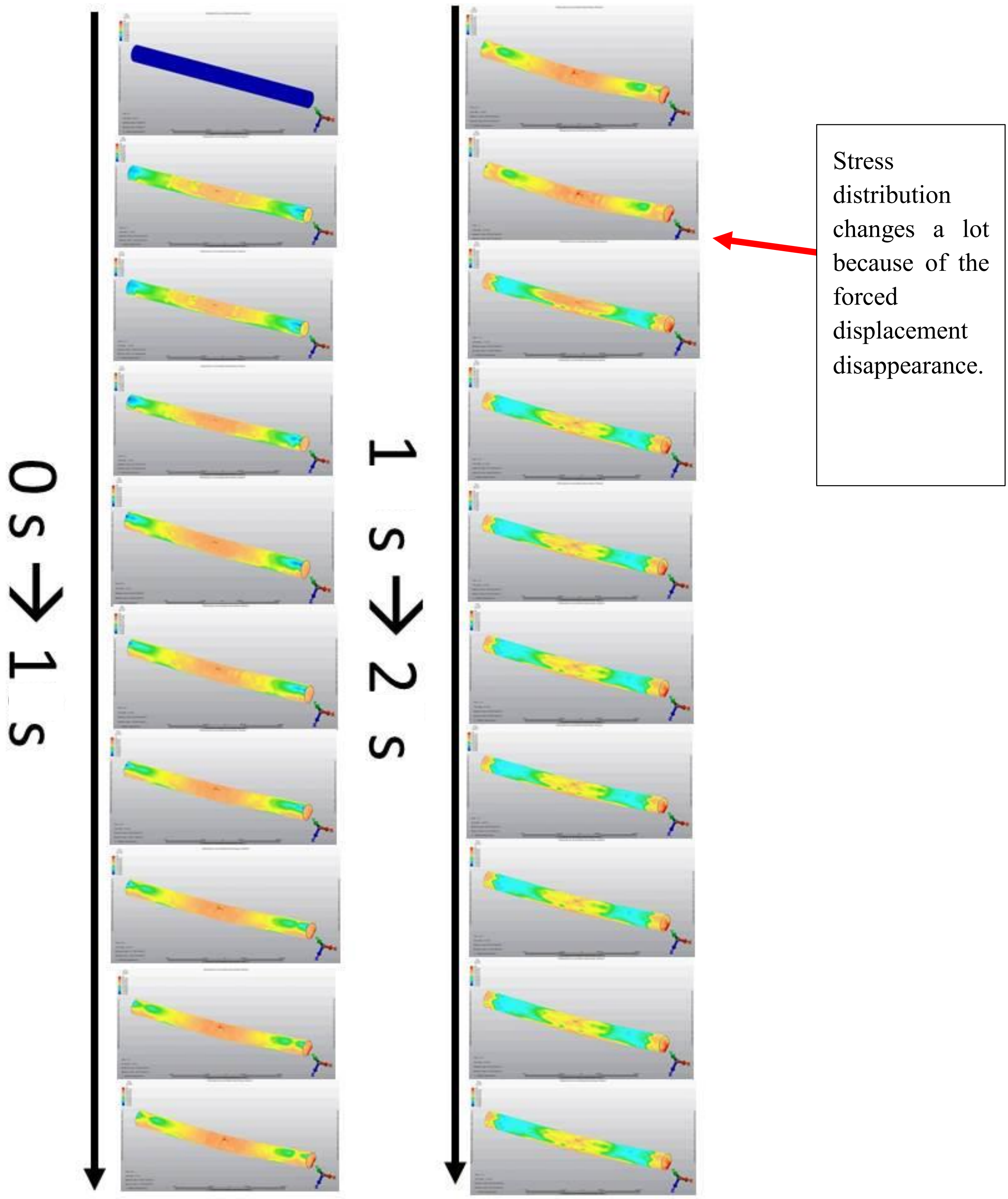


Figure 4-6 - Simulation steps from 0-2 seconds showing stress distribution along the pipe. This is seen from the top where the gauge is located.

4.1.3 Simulation of burst pressure with regards to locked in stresses and gouge

In this simulation, the pressure was variable with the intention of finding out how the burst pressure would change with various gouge depths. The first steps of the simulation were done similar to chapter 4.1.2, with a given forced displacement δ_{PI} of 500mm and 0mm resulting in locked in compressive stresses in the gouge. After this phase, the initial pressure P_I was increased to from 18bar to 36bar in a 28 seconds period as shown in Figure 4-7. The results after the simulation was expectantly going to show some change in the burst pressure of the pipe with respects to the gouge size and the locked in stresses.

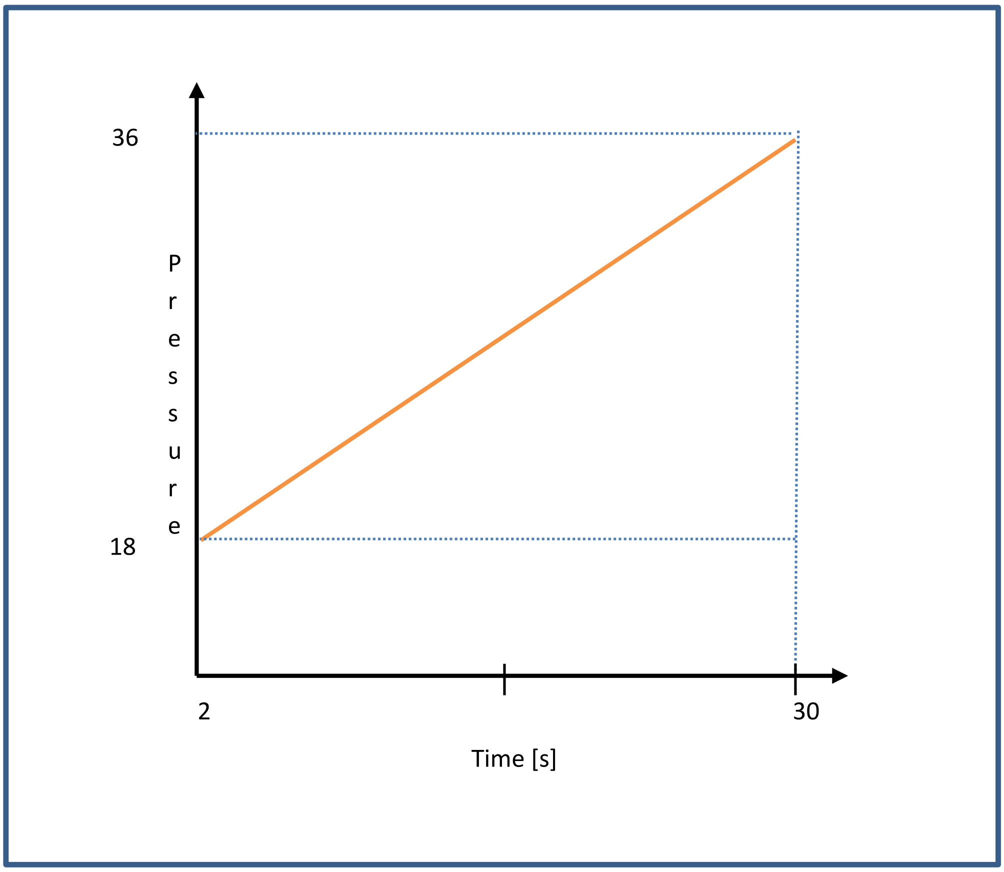


Figure 4-7 - Load curve for simulation 2

Carrying out the simulation

The simulation itself was set up as in 4.1.2 with some modifications. It was very difficult to get the simulation running with the same element definitions as in the previous simulation. For some unknown reason the simulation crashed over and over again after running for several hours. Some minor changes were made to the element type in the simulation, which resolved the issue. This change should be noted when it comes to comparing the results, as the input data are not completely equal. 14 simulations was performed, 1 for each of the 7 V-shaped gouges from Table 4-3 with δ_{PI}; 0mm, 600mm and 1200mm.

5 RESULTS AND DISCUSSION

5.1 RESULTS OF BURST PRESSURE IN A PIPE CONTAINING A GOUGE DEFECT USING STANDARDIZED METHODS

5.1.1 Calculation and results

The length correction factor is calculated using equation 2.7-2.

$$Q = \sqrt{1 + 0{,}31\left(\frac{\mathrm{l_g}}{\sqrt{\mathrm{D_p t_p}}}\right)^2} = \sqrt{1 + 0{,}31\left(\frac{250}{\sqrt{914.4 \cdot 28.4}}\right)^2} \approx 1.32$$

Further the internal pressure capacity for the pipe containing only the rectangular shaped gouge effect is calculated for a 4mm deep gouge using equation 2.7-1. The data used are gathered from Table 4-1 and Table 4-2. This method will be used to estimate the burst pressure capacity (P_{cap}) of a pipe only subjected to an outer part-walled defect (in this case a 250 mm gouge), which will be needed when estimating the compensated burst pressure capacity ($P_{cap,comp}$) later for a combined loading effect:

$$P_{cap} = 1.05\frac{2t_p \cdot \sigma_{up}}{(D_p - t_p)}\left[\frac{1-\frac{d_g}{t_p}}{1-\frac{d_g}{t_p}\left(\frac{1}{Q}\right)}\right] = P_{cap} = 1.05\frac{2 \cdot 28.4 \cdot 575}{(914.4 - 28.4)}\left[\frac{1-\frac{0}{28.4}}{1-\frac{0}{28{,}4}\left(\frac{1}{1.32}\right)}\right] = 38{,}7 N/mm^2 = 387 bar$$

The rest of the burst pressure capacities (P_{cap}) for the various gouge depths (d_g) are plotted in Figure 5-1. These results can be used to make a curve in order to gather results from other gouge depths.

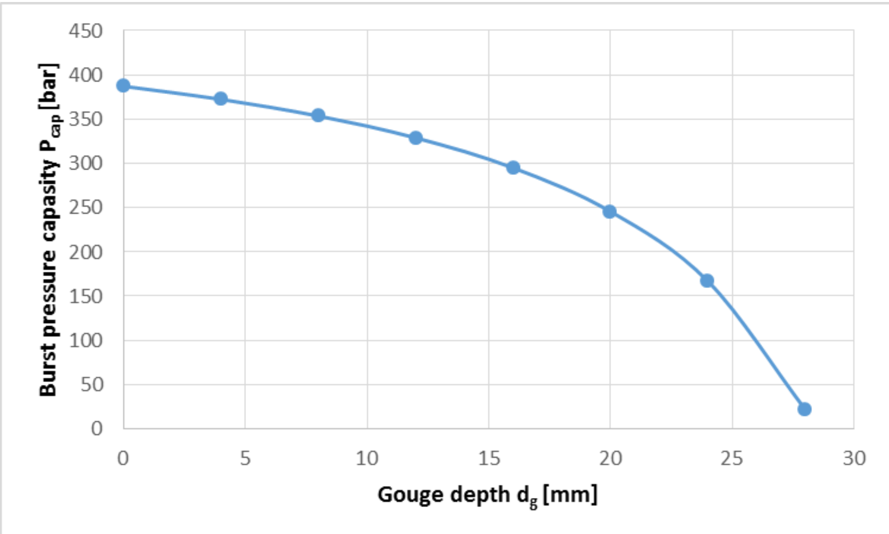


Figure 5-1 – Burst pressure capacity for pipe containing gouge of 250 length in a 36 inch pipe.

When calculating the burst pressure capacity for a pipe containing a gouge and residual bending stresses the procedure is not straight forward. The formulas given in chapter 2.7 for calculating the burst pressure for a combined loading requires the longitudinal stress in the area which are to be calculated. This is the residual stress, which is not easy to calculate as there are many material factors involved, such as strain hardening modulus which is the relation between the stress and strain in the plastic region of the material. These values were therefore gathered from a simple simulation which was done with the same parameters as the previous simulations in chapter 3, but without the internal pressure present. The gouge depth of this simple simulation was set to zero, as the gouge itself was implemented later in the equation (2.7-4).

The results from the simple simulation of the residual stress from a pipe, only subjected to bending are shown in Table 5-1 below:

Table 5-1 - Residual longitudinal stresses in a pipe with no external damage.

Initial displacement $\boldsymbol{\delta_{PI}}$	Final displacement $\boldsymbol{\delta_{PF}}$	Longitudinal residual stress $\boldsymbol{\sigma_{PL}}$
200	103	133
400	285	119
600	481	120
800	670	118
1000	869	140
1200	1071	126

It should be noted that when using FEA simulations to calculate longitudinal stresses in a bent pipe, it is important to have an understanding of weather the section you look at is under the influence of compressive or tensile stresses, as this will influence on the sign of the stress used for σ_{PL}.

After this simulation the calculation was performed using excel based on the results in Table 5-1 and equations 2.7-3 to 2.7-6.

There was one constant that was not easy to obtain, which was the partial safety factor for corrosion depth (γ_d) and the Partial safety factor for longitudinal corrosion model prediction This was for simplicity set to 1.2 which is the average for normal safety class. The reason for this choice was that this safety factor is depended on the depth of the gouge itself and would be very difficult to decide. $\gamma_m$was found to be 0,65 by iterating equation 2.7-6 in order to get the same results for $P_{corr,comp}$ and P_{cap} for a pipeline not subjected to any external loadings. The term $(d/t)^*$ is related to the confidence level of the gouge depth to thickness relation. It is assumed that for these calculations the gouge depth confidence is 100% certain, as it will be compared with the simulations later containing gouges with exact depths. This means that the term $(d/t)^* = (d/t)$. The results from the calculations are presented in Figure 5-2.

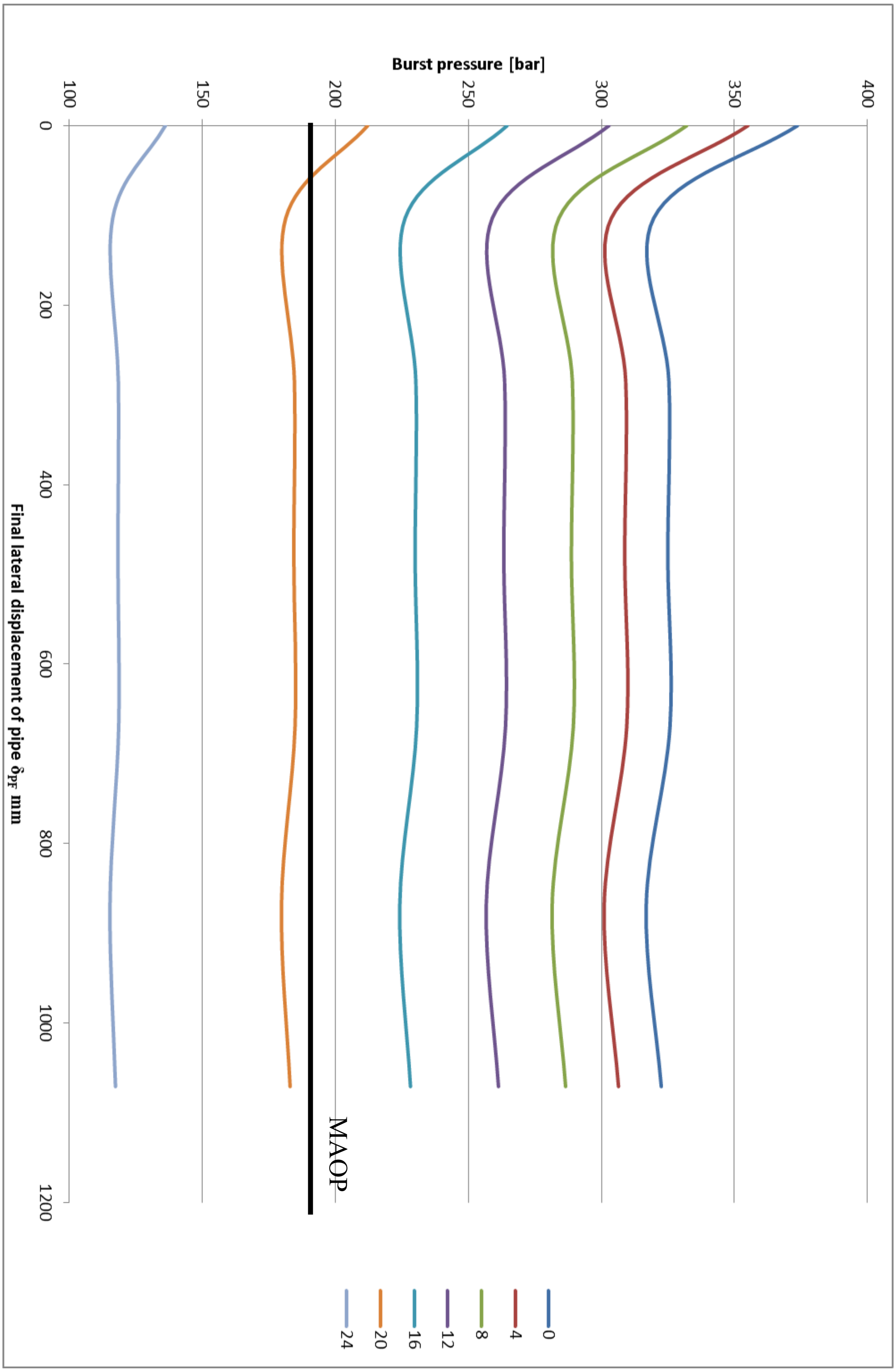


Figure 5-2 - Burst pressure versus lateral displacement of a pipe containing an external gouge damage in, using DNV-RP-F101

Discussion of existing methods for evaluating burst pressure

By comparing the burst pressures from Figure 5-2 where no longitudinal deformation is present, with Figure 5-1 it can be observed that the stresses here are more or less the same. It is therefore assumed that the calculations presented in Figure 5-2 can be trusted

Figure 5-1 and Figure 5-2 showing the burst pressure versus the gouge depth and the lateral displacement can be a good tool when making an emergency repair plan for a damaged pipeline. Figure 5-2 shows that gouges with depths from 0 to 12 mm do have a bursting pressure above the MAOP of this particular pipe. This means that these pipes can be operated as usual, but should still be evaluated for repair. Damages such as these can be very complex, and could evolve to larger damages due to crack growth around the damage.

The simulations with gouge depths of 20-24 mm are mostly below MAOP at displacement shown in the figure. Theoretically, if the pipes here were operating with a MAOP of 180bar when the accident occurred, the pipe should most likely have some leakage prior the damage inspection.

5.2 RESULTS FROM SIMULATION WITH VARIOUS FORCED DISPLACEMENTS

The results from the simulations are presented in Figure 5-3 to Figure 5-9, which are based on the result tables in appendix 8.1. From these plots it is possible to estimate the actual maximum von-mieses stress in a gouge with respect to the bend lateral displacement of the pipe.

The blue dots indicate the maximum final stress σ_{PF} in the gouge where the pipe is at rest at δ_{PF}. The red dots represent the maximum initial stress σ_{PI} that occur under an operation, such as an anchor dragging incident, which introduce a forced displacement into the pipe. The black line indicates the ultimate stress of the material σ_{PU}. The orange vertical line indicates where the initial maximum stress σ_{PI} goes beyond the ultimate strength of the material σ_{PU}, where there is expected to be a burst of the pipeline. The results on the right side of this line are assumed to be results after a burst of the pipeline, and could not be possible in a real event. Ignoring these results on the right side of the orange line therefore seems like a viable assumption.

Figure 5-10 and Figure 5-11 shows the maximum final stress σ_{PF} for all gouge depths combined in one diagram. Figure 5-10 shows all the results that was simulated, while Figure 5-11 shows a modified plot were the disregarded results are removed and polynomial regression has been used in order to present the values as curves. The red circles in figure 5-11 indicate the point where the maximum initial stress σ_{PI} went beyond the ultimate stress limit, and thus evaluated as a burst pipe.

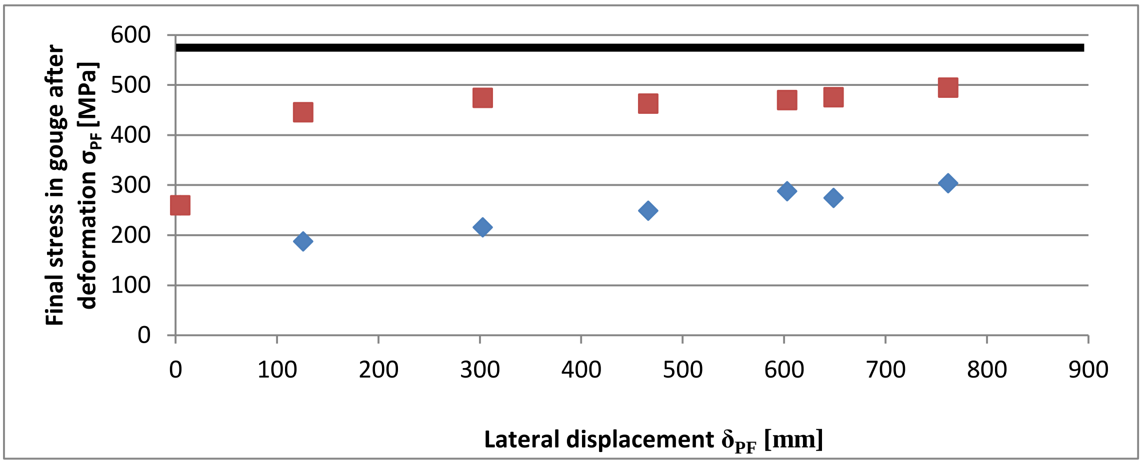


Figure 5-3 - Simulation results for maximum stress in 0mm gouge.

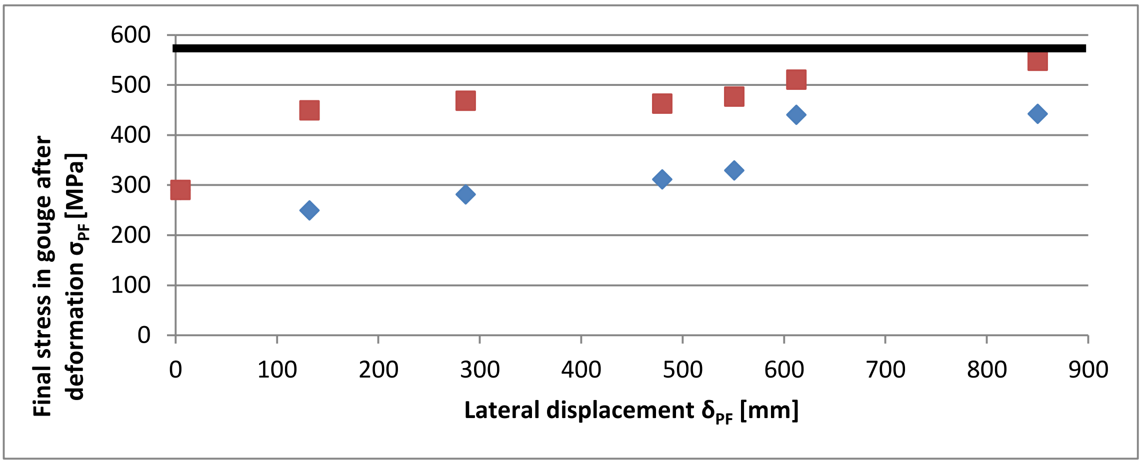


Figure 5-4 - Simulation results for maximum stress in 4mm gouge.

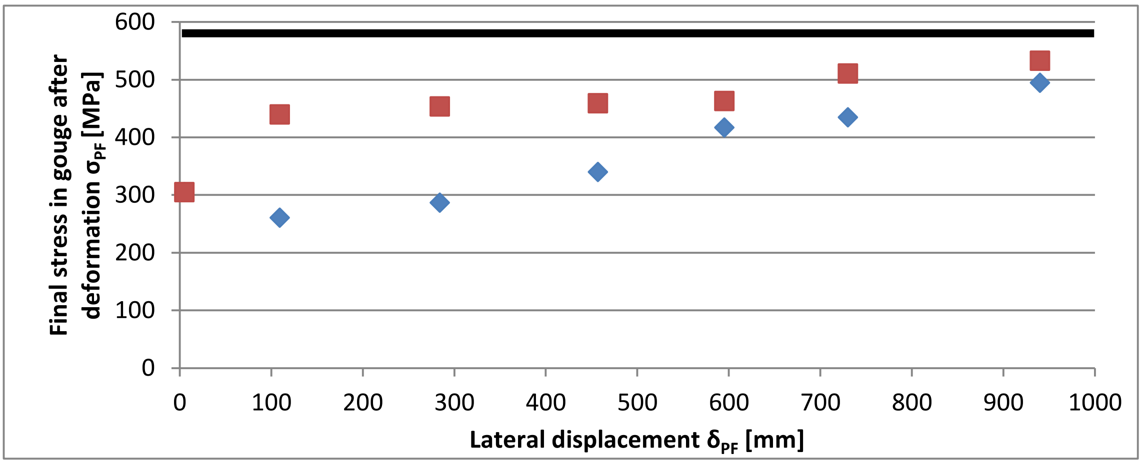


Figure 5-5 - Simulation results for maximum stress in 8mm gouge.

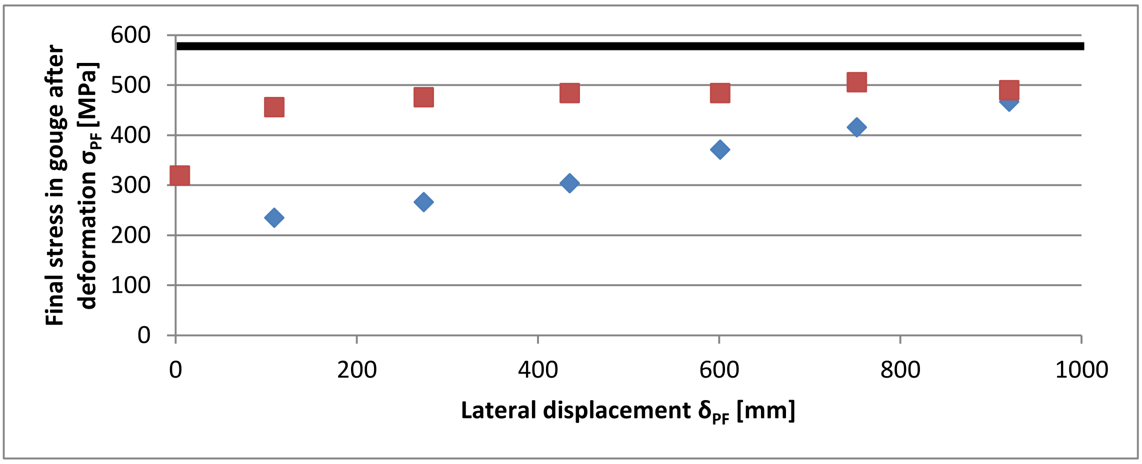


Figure 5-6 - Simulation results for maximum stress in 12mm gouge.

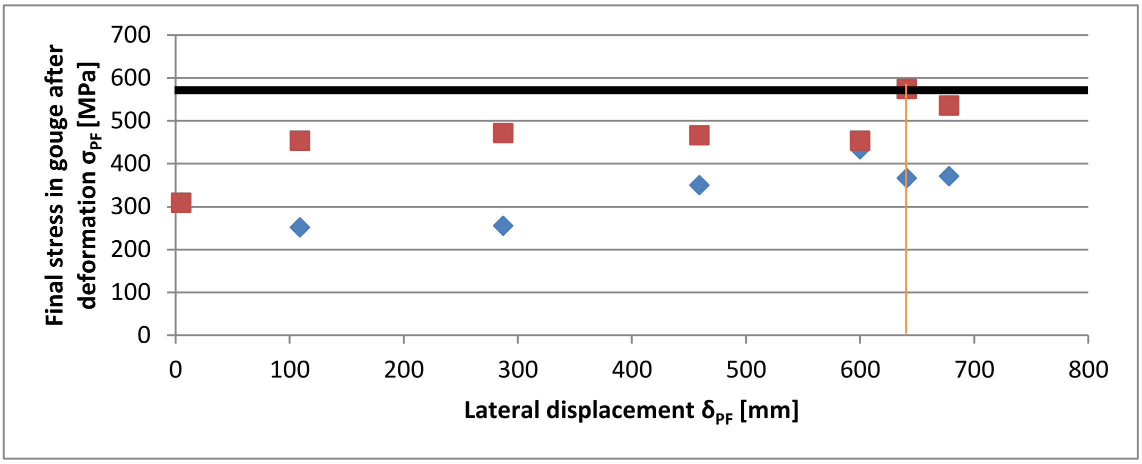


Figure 5-7 - Simulation results for maximum stress in 16mm gouge.

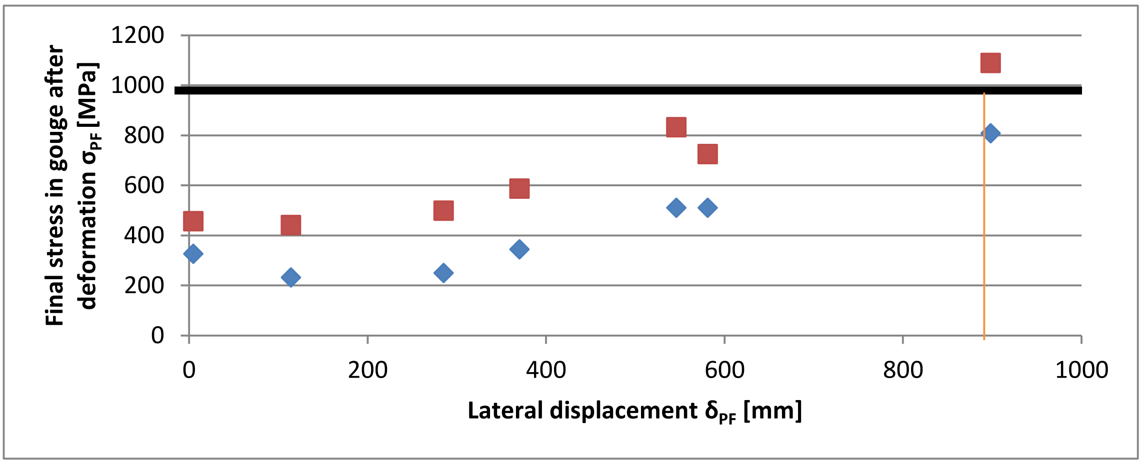


Figure 5-8 - Simulation results for maximum stress in 20mm gouge.

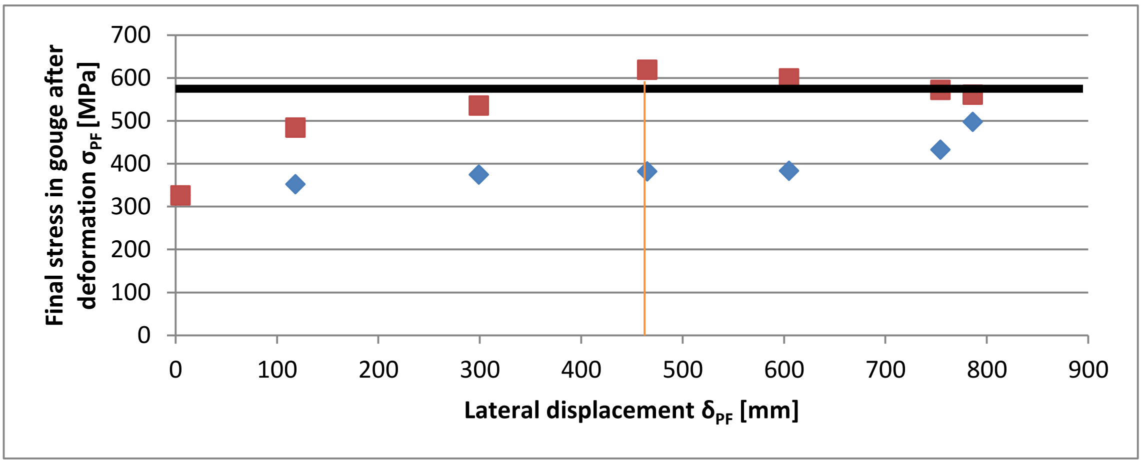


Figure 5-9 - Simulation results for maximum stress in 24mm gouge.

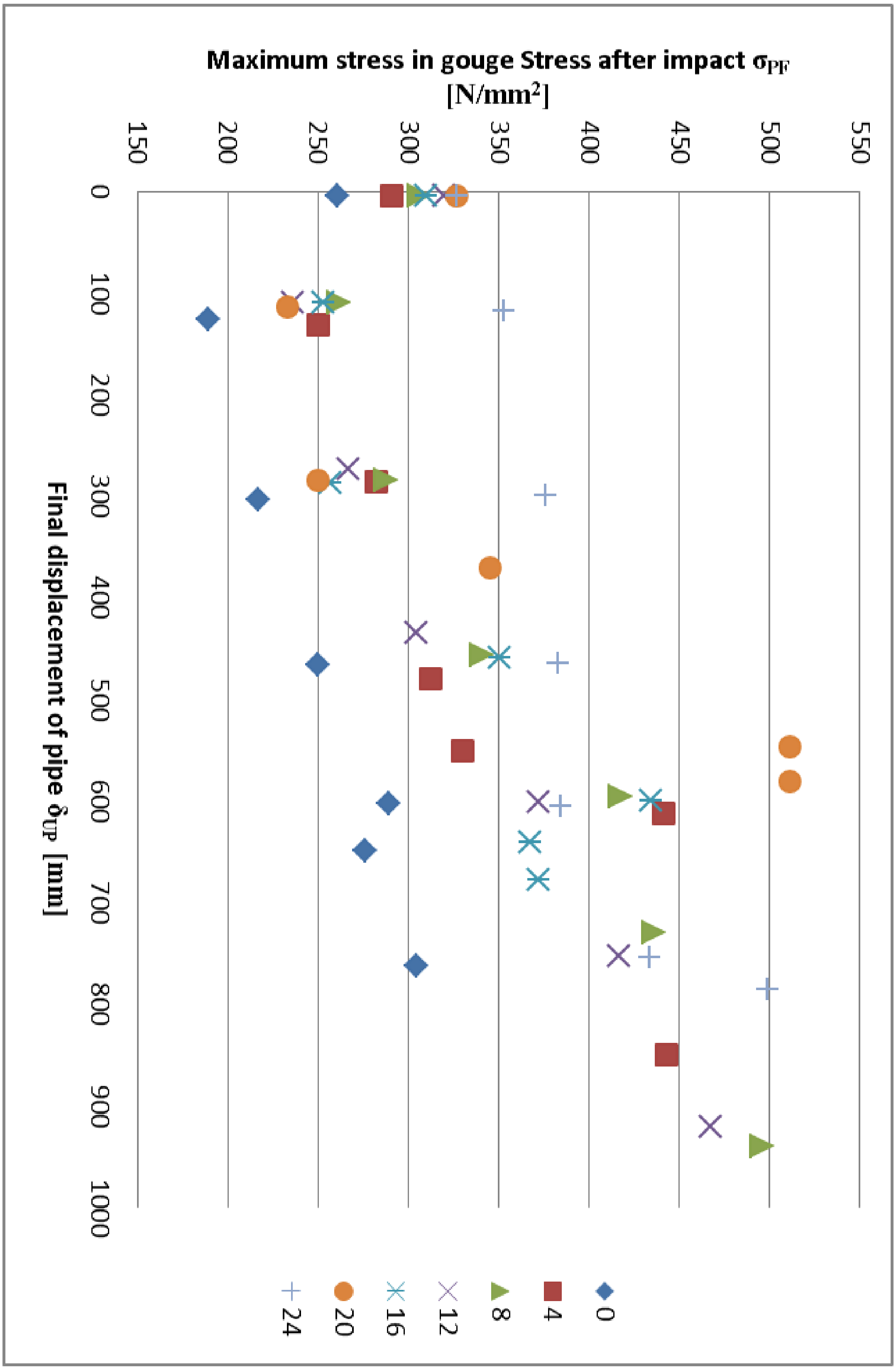


Figure 5-10 - Maximum Stress in V-shaped gouge due to a combination internal pressure and residual locked in bending stresses.

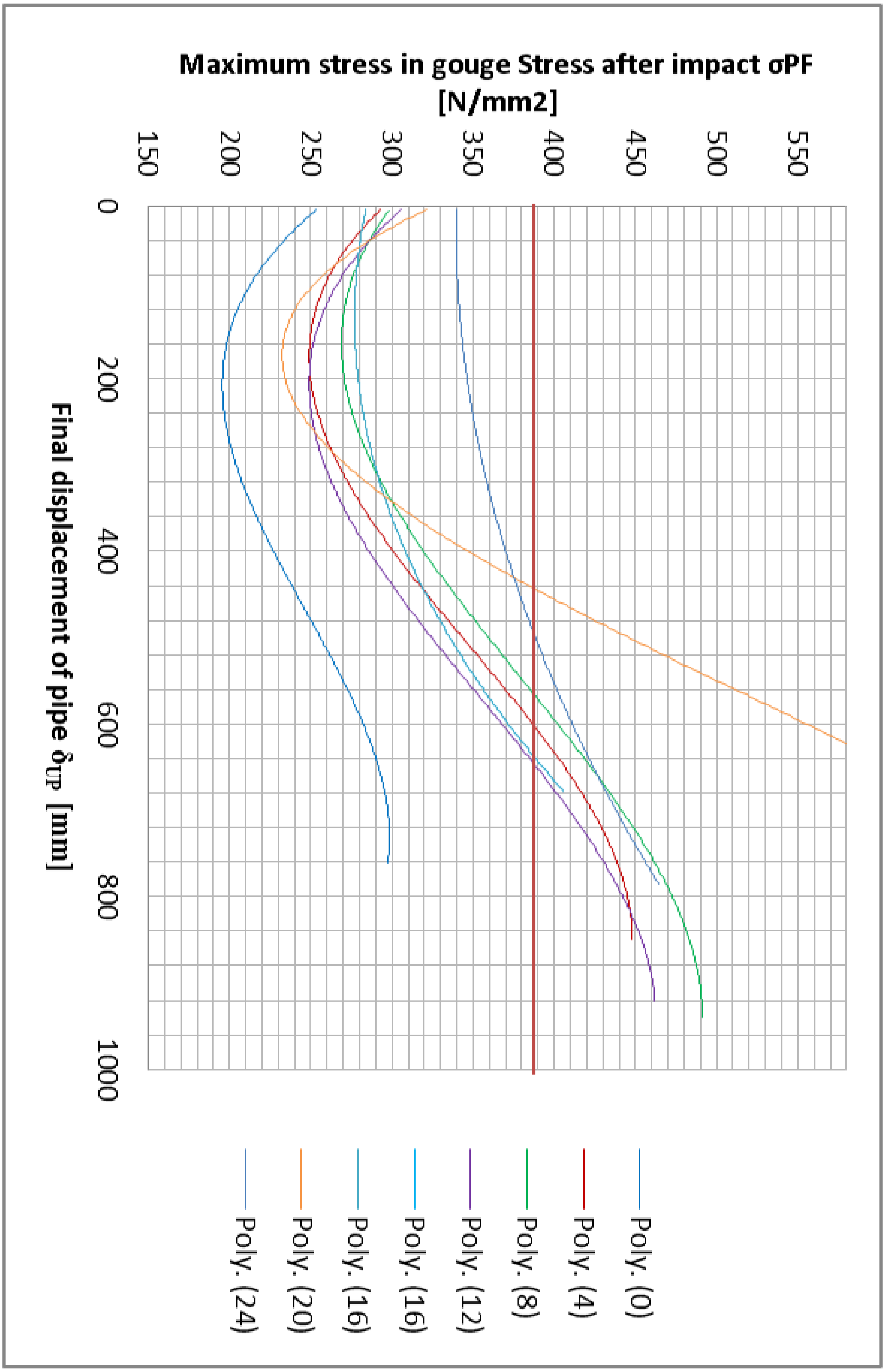


Figure 5-11 - Maximum Stress curves in V-shaped gouge due to a combination internal pressure and residual locked in bending stresses. The presentation shows a polynomial regression of the results. The red line indicates the yield strength σ_{PY} divided by a safety factor $n_B = 1.2$

Discussion

The results given in Figure 5-3 to Figure 5-9 shows how the maximum stress in a gouge varies with the forced lateral displacement of the pipe (δ_{PI}). It can be observed that the maximum stress (σ_{PF}) does not change much with the forced displacement (δ_{PF}). The reason for this can be explained by looking at Table 5-1 from the previous results. It can here be observed that the longitudinal stresses do not vary much with the final displacement of the pipe (δ_{PF}).

These results seemed confusing at first, but after some further research regarding material elasticity, this could be explained as: When a pipe is bended in such way that it exceed the yield limit of the material, it will start to plastically deform, and when the forced displacement is released, the pipe will follow the E-modulus back, leaving some residual strain (ε_r). This strain is what effects on the residual stress, see Figure 5-12. It can be observed that the residual strain does not change a lot with the displacement, and thus the residual stress should not be affected in a very significant matter by the increase of the plastic strain.

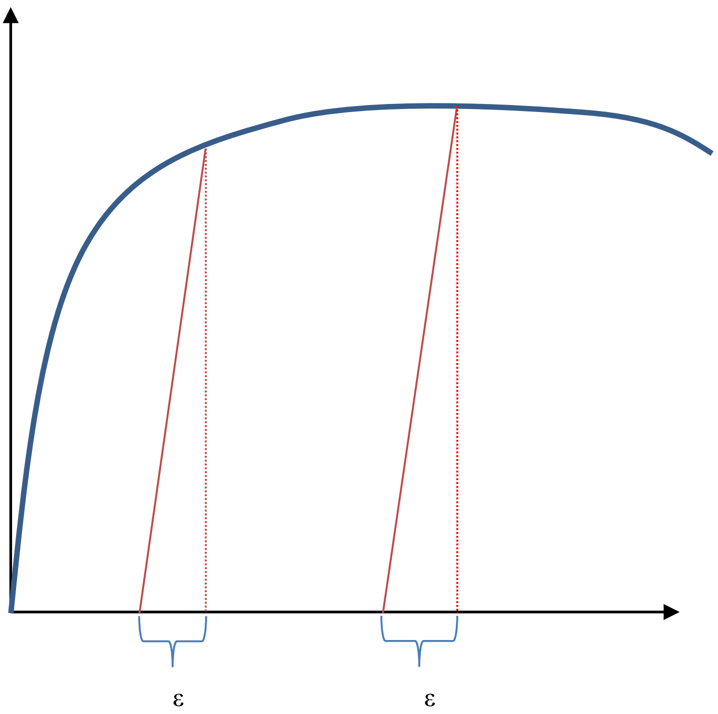


Figure 5-12 - Residual strain

Figure 5-11 shows all values from Figure 5-3 to Figure 5-9 in one single plot. These results are of great interest to the author of this thesis. With the help of some simple simulations, it is possible to give the pipeline operator an idea of which stresses he could expect with respect to different bending radiuses on the damaged pipeline containing both internal pressure and a gouge damage. It could for instance be carried out various simulations such as these with different types of external damages; gouges, dents and gouge plus dents for standardized pipe dimensions and pressures.

By comparing these results with the results from chapter 5.1.1 it is not that clear as anticipated beforehand how the maximum stress in a gouge effects on the burst pressure of the pipe. To verify this there should be carried out some experimental work. However, the results are of great interest when making an assessment plan for pipeline repair. High stresses in a gouge which goes beyond the yield limit indicates that there could be cracks growing in the area of the damage. A method of repair should rapidly be decided in order to stop this crack growth as soon as possible.

This is where the simulation results come in good use. Using a combination of the results presented above, and the results presented in chapter 5.1.1 a pipeline quick repair chart could be carried out. One proposed repair chart for this particular pipe is carried out in Figure 5-13. The idea behind this type of repair chart came from the rapid decision making charts discussed in chapter 2.6. The various areas enclosed by the black dashed lines represent different repair methods that could be used for the various types of gouge depths and lateral displacement. From the top, the first line is set to the yield limit of the material. This means that the maximum stresses in a gouge is under plastic deformation and could if loaded further result in a leakage or burst of the pipeline. The area below this line represent stresses larger than the allowable stress ($\sigma_{allow} = 375\ N/mm^2$) which is the yield stress σ_y divided by a safety factor n_b of 1.2. Further down represent areas that should be repaired with help of various types of claps, depending on the lateral displacement on the pipe. Composite repair are proposed as the lowest option of repair methods in this case.

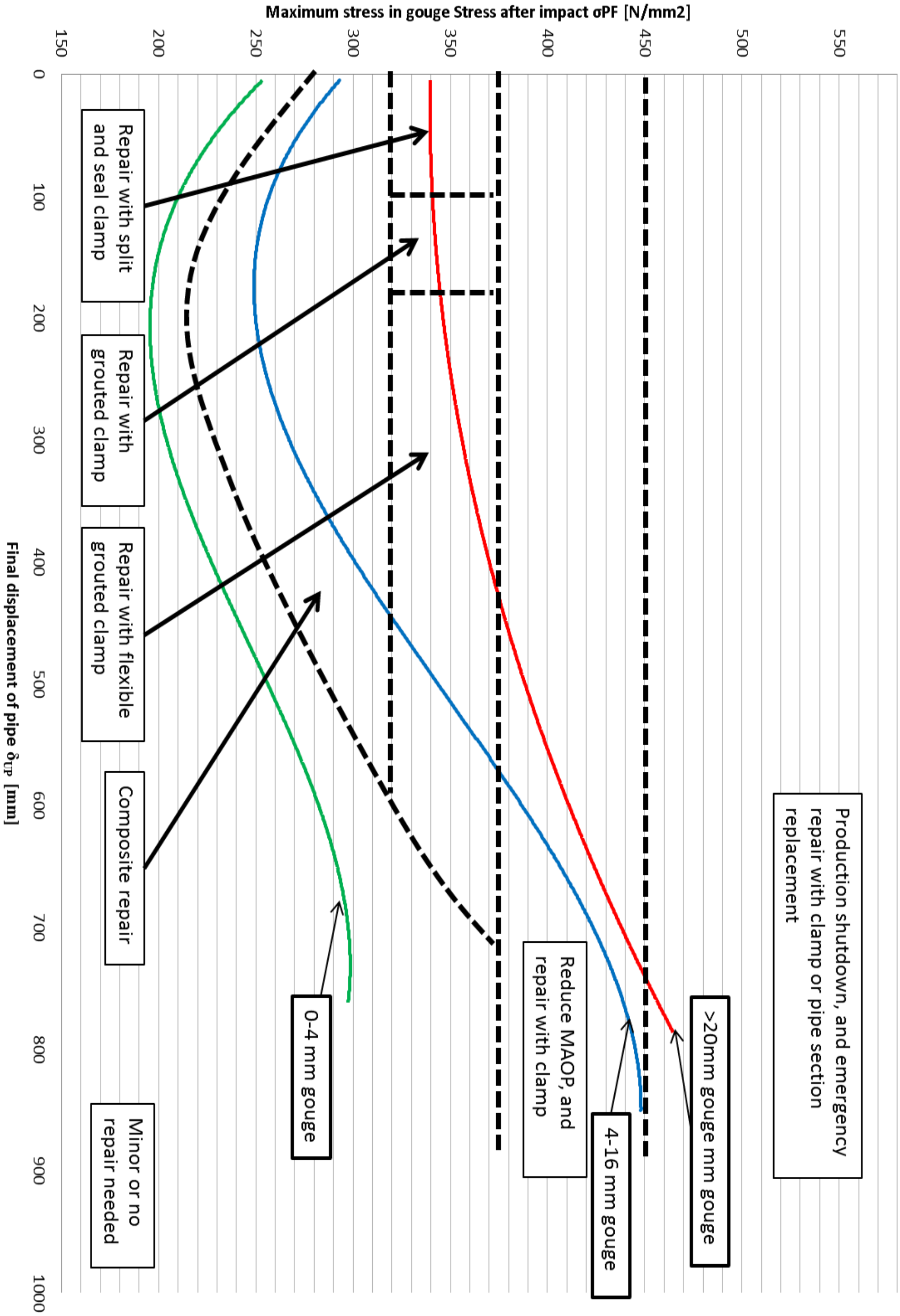


Figure 5-13 - Repair chart for Gouge damage combined with lateral displacement.

5.3 RESULTS FROM SIMULATION OF BURST PRESSURE DUE TO LOCKED IN STRESSES AND GOUGES

The results from this test can be found in the plots in Appendix chapter 8.2. The pressures that introduced stresses beyond the ultimate strength of the material are plotted in Figure 5-2. The figure shows very uneven results, which does not seem to fit with the previous analysis. By comparing these plots in Appendix chapter 8.2 with Figure 5-2 and Figure 5-1, which was calculated using an equation from DNV-RP-F101 it is clear that these simulated results are far from the results from DNV. The burst pressure in the analysis does not seem to reduce due to the depth of the gouge in a significant matter. Burst pressure of a pipe should of course be reduced when there are significant damages at the surface of the pipe.

This error could be caused by a change in the parameters in the simulation, which was chosen by the author in order to get the simulation to run. The change was the stress update method of the analysis to explicit instead of implicit. However, these details are not relevant to this thesis, and will not be discussed further. There were several attempts to fix these simulations in order to get some trustable results, but it all resulted in failure. From the author's perspective this seems to be related to the memory limitations in the computer used.

Lesson learned from this task is that results from FEA analysis should be carefully evaluated before it is used. Another software for simulation would probably be a better idea to use, if further work concerning this should be performed.

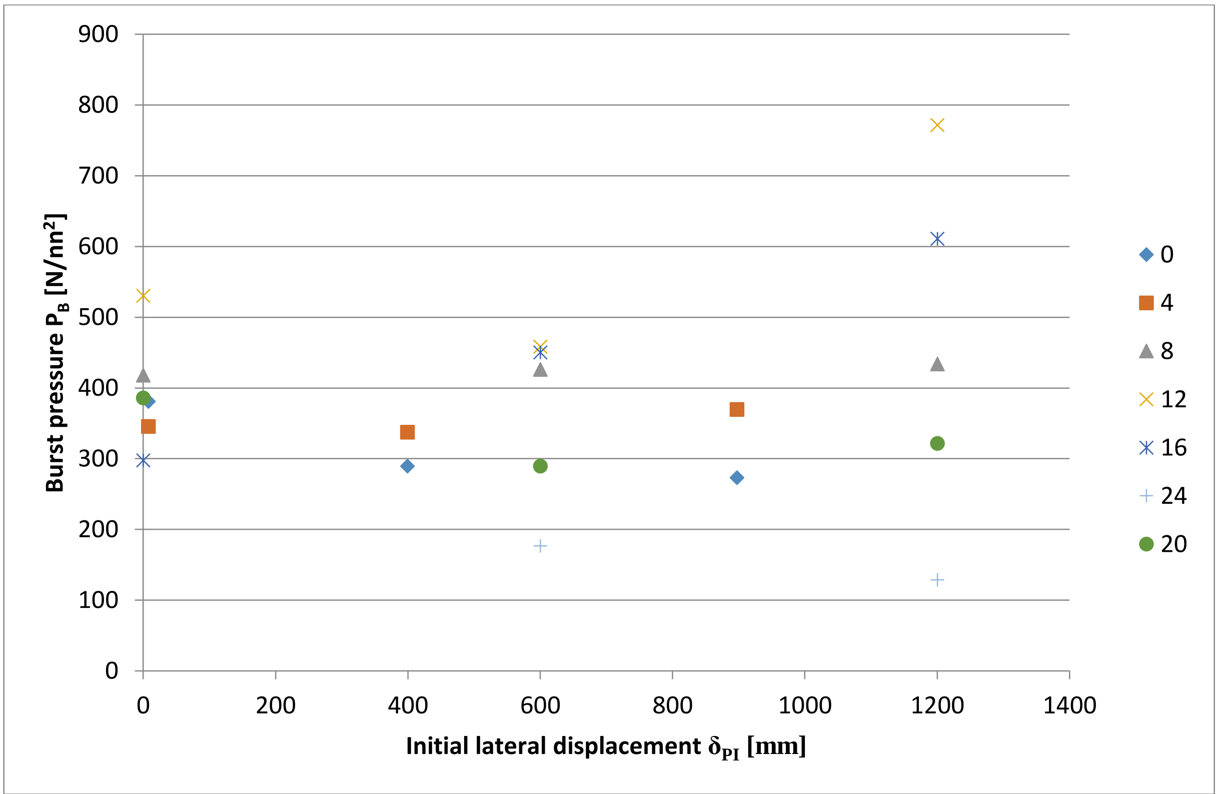


Figure 5-14 - Results from burst pressure simulation

5.4 RECOMMENDED REPAIR METHODS

Bases on the results described above, regarding the burst pressure of a damaged pipeline with different types of forced displacement, various methods of repair could be used. From Figure 5-11 the red horizontal line represent yield strength of the material divided by a safety factor of 1,2. According to these data, damaged pipes beyond this limit should have a repair method that safely enclosure the damaged point and acts as a pressure vessel around the damage.

The recommended repair methods for the various damage severities can be categorized into four different categories of damage complexity; severe, high, medium and minor damages, where;

- **Very high severity** – Damage on a pipe which results in a burst of the pipeline, with possible leakage of hydrocarbons into the sea. Emergency shutdown of the pipeline is necessary before replacing the damaged section. The ruptured pipe from the trans Mediterranean pipeline repair event described in chapter 3.1 is an example of a severe damage.
- **High severity –** Damages on a pipe which there is a leakage or the possibility of a leakage in the near future. It could also be damages caused by complex loadings, where there are either large longitudinal stresses involved. MAOP should be reduced in order to imminently repair the damaged section. The damaged pipe from BP CATS incident described in chapter 3.2 could be categorized as this type of damage, as there was no leakage from the pipe.
- **Medium severity –** Damages with bending stresses or stress concentrations. Strengthening of the damaged section is required in order to safely maintain the MAOP.
- **Low damages –** These damages involves small scratches and small dents on the pipe surface that alone does not affect any of the strength capacities of the material properties. However these are imperfections in the pipe surface, and could be exposed to corrosion and erosion.

5.4.1 Repair of Very high severity damages

Above water tie in

Repair method by lifting the pipe up to the surface for the intension of cutting out the damaged part of the pipe and replacing it. This method was used in the case studied in 3.1. It is a very advanced method which requires a lot of work to be done. This method is also very limited to shallow water depths.

Habitat welding

A more effective way to replace a pipeline is to weld the pipe section subsea. With a habitat system as described in chapter 2.9.2 this will ensure a perfect welding environment for the pipe connections. However, this method requires a lot of various tools and time in order to be performed, and should therefore be chosen carefully in order to keep the downtime of the pipeline as short as possible.

5.4.2 Repair of high severity damages

Grouted clamp

The Grouted clamp explained in chapter 2.8.4 looks to be the best way to repair a pipeline subjected to both external damage and bending stresses. The grout itself can be "tailor" made in order to withstand the required stress to prevent bursting of the pipe. This technique also allow for some angular change of the pipelines longitudinal axis, as the diameter of the clamp can be made much larger than the pipe diameter itself, see Figure 5-15. The clamp will also provide some extra external weight and protection of the pipeline, as eventual concrete coating will have to be removed before installation of the clamp.

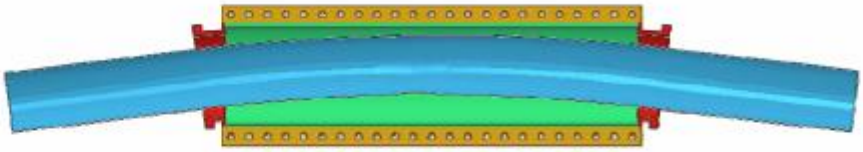


Figure 5-15 – Grouted clamp showing how a large inner diameter clamp can be used to repair a bent pipe. (Alexander, et al., 2012)

Split and seal clamp.

Where there is not any significant longitudinal bending on the damaged pipe section, the split and seal clamp described in chapter 2.8.3 could be a good solution. This method provides great pressure containment around the pipe due to the massive steel sleeve, as well as protects the damaged point from the surrounding environment with respect to corrosion and erosion.

5.4.3 Repair of Medium severity damages

Composite repair

For small depth gouges without any significant locked in stresses, a composite repair solution could be evaluated. However, it is important to notice that there might be unknown damages in the individual fibers of the wrapping, which could result in weak points in the repaired section. These weak spots might over time be increased to larger significant damages, which could lead to another repair operation. The author's recommendation is that this repair method could be a very good solution in pipeline sections which are well monitored and on pipelines with minor and not severe damages.

5.4.4 Repair of Low severity damages

Grinding of damage

Grinding the damaged area of the pipe surface might reduce the change of cracks developing due to high stress concentrations. This method does not require much tooling to be carried out properly. However, it is not so easy to assure that the grinded slot is perfectly smooth.

5.5 OTHER REPAIR TOOLS

From the introduction, it was stated that it was of interest to investigate if there could be any other solutions for repairing a pipeline subjected to combined loadings. The repair methods available all have one thing in common, which is that they all require that the pipeline damage is either located on a free span or that the pipeline is lifted up for the installation of the clamp.

5.5.1 Subsea pipe-surface welding

As seen from Figure 5-1 and Figure 5-2, the depth of a gouge (d_g) will have a significant influence on the burst pressure (P_B) of a damaged pipeline containing locked in stresses.

Pipeline repair by filling the damage point with melted metal using welding is not a very common way of repairing a pipeline. However, it could be a solution for repairing of gouges that significantly influence on the pipe burst pressure capacity. This could especially be a good approach when repairing pipelines in areas where there is not much room for repairs, or where there are issues with lifting up the pipeline for installation of clamp or composite repair.

5.5.2 Coating removal

Prior to most proposed repair solutions discussed in this paper, a removal of the concrete or rubber coating is needed. The author of this thesis have been working with both manufacturing and development of these types of ROV operated tools over the last 3 years, alongside with the studies in a company called Vest Norge Doors AS, and would like to present one of these products in order to discuss a future pipeline repair method, based on this design. The tool presented is shown in Figure 5-16 is photos taken by the author. The tool is powered only by hydraulic power and high pressurized water, which is provided from the surface via a ROV. It is designed to remove rubber coating from a pipe section prior to repair or inspection of the pipe. The whole installation is supported by buoyancy elements, so that it has a neutral weight in water.

When used this tool is lowered onto the top of a pipeline using a ROV, where it is clamped in place using hydraulic power provided by the ROV itself. A high pressure water nozzle then starts to remove the coating, while hydraulic power supplied by the ROV is used to rotate the nozzle around the pipes longitudinal axis. After the rubber on the whole 360 degree surface of the pipeline has been removed, the tool head configuration (bottom picture) is moved along the x-axis with the help of hydraulic cylinders. When the tool head reaches the x-axis limit, the clamp is released, and moved to an eventual new position using the ROV.

The high pressure nozzle can be adjusted along the radial axis of the pipeline, in order to adjust the distance between the nozzle and the pipeline face.

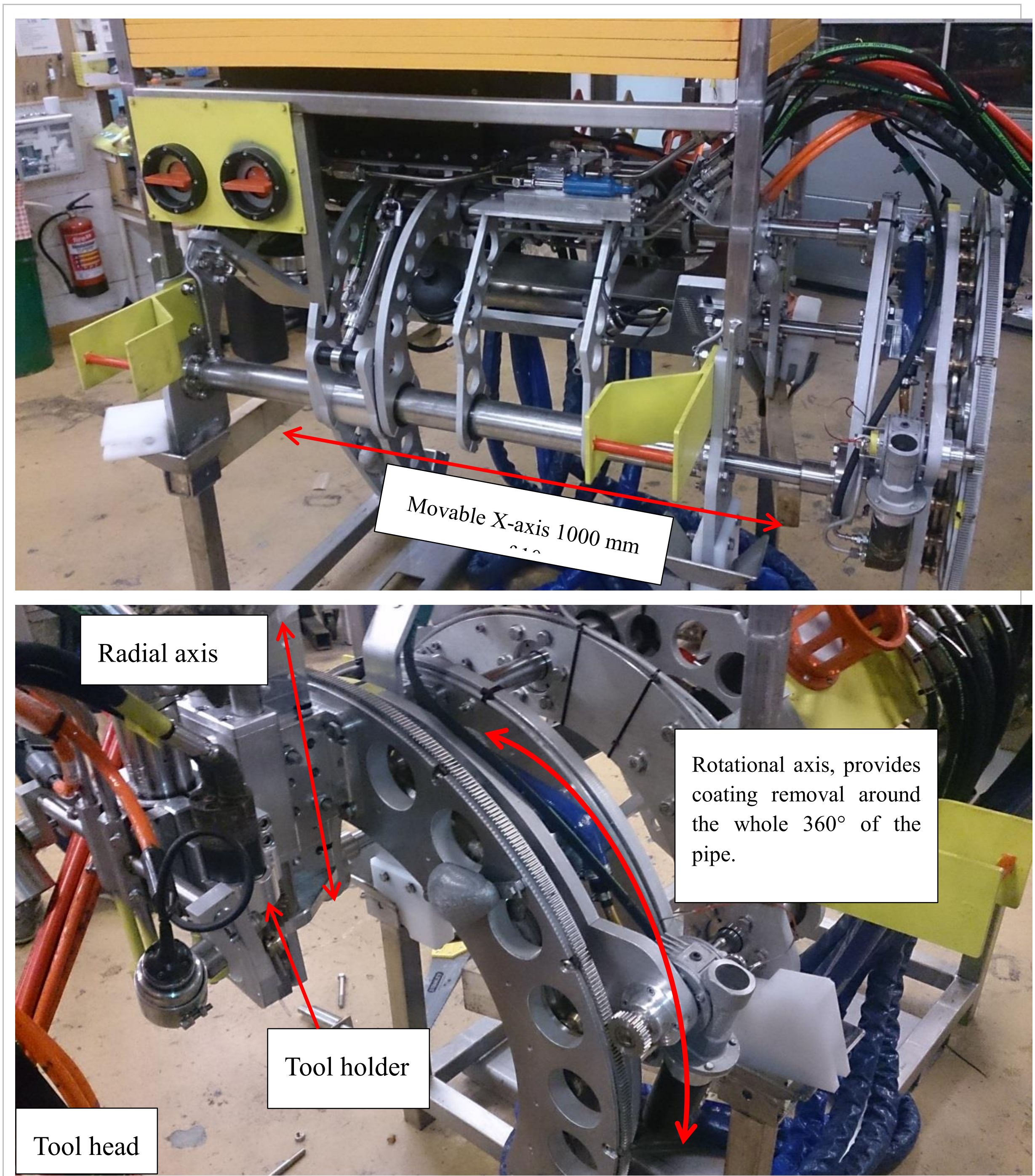


Figure 5-16 - Rubber removal tool for a straight pipeline. Photos taken by the author, with permission to present in this thesis by Vest Norge Doors AS.

5.6 FUTURE PIPELINE REPAIR METHODS

5.6.1 Repair using ball milling operations

Pipelines subjected to a part walled corrosion defect (gouge or corrosion) have to be maintained or repaired in order to secure a safe and steady operation of the pipeline route. The grouted clamp, split and seal sleeve and flexible grouted clamp all looks to be very trustable repair methods for subsea repairing. However, the methods can in some load combinations be over dimensioned.

This gave the author an idea of combining the rubber removal tool design showed in Figure 5-16 with a conventional ball mill showed in Figure 5-17. The high pressure water nozzle will in this case be changed out with a simple hydraulic motor, running a ball mill spindle. The design of the coating- removal tool in Figure 5-16 will also provide radial adjustment of the tool holder, which can be used in this design to adjust the depth of the milling tool.

There was performed a simple static simulation of how the stress concentrations in the gouge are influencing the stresses prior, and after a repair, which can be seen in Figure 5-18. The figure shows a 12mm deep and 250mm long V-shaped gouge to the left, while the right side shows a 250mm long slot milled with a 60mm in diameter ball mill with a depth of 12mm. The color ranges in the plots were set equal, with a maximum stress of $370N/mm^2$ and minimum stress of $200N/mm^2$. It is confirmed by the simulation that this method could be a good way of repairing minor gouges.

With this in mind it should be noted that this method only provides the reduction of stress concentrations in a gouge or a corrosion defect. When the cross sectional (t_p) wall thickness in a pipe gets too small as a result of deep defects, other methods of repair should be considered.

This technology provides the following advantages and limitations for repair of minor gouges:

Advantages

- Can be used on gouges oriented in all directions on the pipe surface.
- Remotely controlled operation by ROV
- Visual inspection by camera on tool holder
- Significantly reduce stress concentrations
- Reduce growth of crack, gouge or corrosion by removing the damaged material.
- Water depth of repair is only limited to the limitation of the ROV operational depth.
- Could also be used to prepare a crack, gouge or corrosion defect for further repair. i.e.

Limitations

- Limited to minor damages that does not reduce the cross sectional wall thickness of the pipe by a significant amount.
- Requires coating removal prior repair.
- Requires additional protection after repair in order to protect the surface from corrosion and erosion.
- Requires the pipeline to be lifted from the ground before repair if it is lying on the ground or buried.

Figure 5-17 – Typical ball mill used for milling operations in the metal working industry (Kennametal.com, 2015)

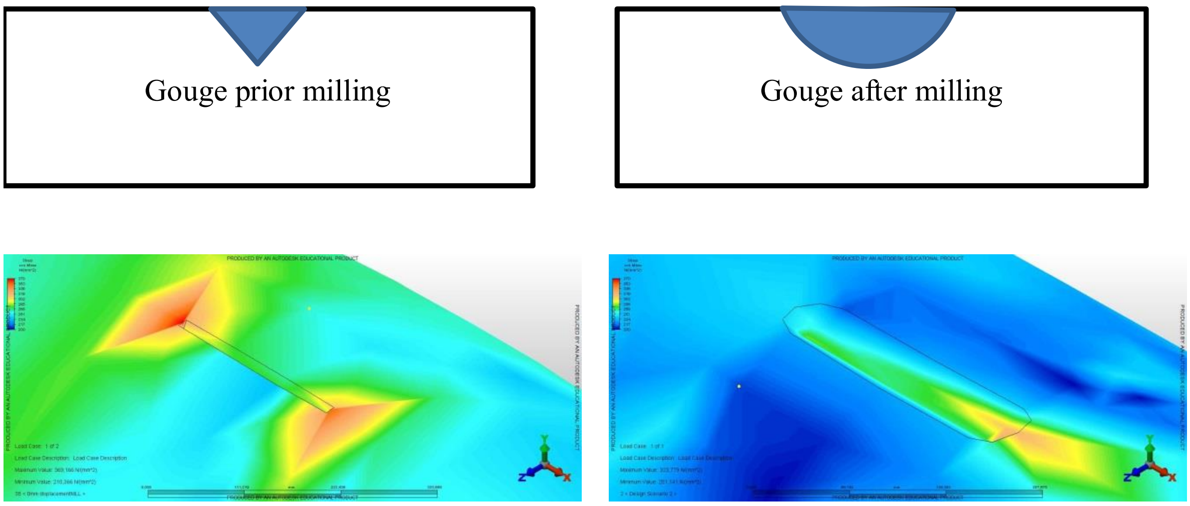


Figure 5-18 - Gouge shape and stress distribution prior, and after repair with a 20mm ball mill in a 12mm deep V-shaped gouge.

CONCLUSION

As a result of my thesis investigation, I have concluded there is no straight forward method to assess pipe damage with a gouge defect in combination with internal pressure and axial stresses. DNV-RP-F101 however, describes an approach of how a corrosion defect with these loading combinations can be assessed. Previous studies around gouge damages have been directed to this standard for assessment by the pipeline defect and assessment manual.

For gouge damages, the significance of the depth seemed to have a great influence on both the bursting pressure of the pipe and on the maximum stresses in the gouge. In order to safely maintain the required maximum allowable operating stress of a pipeline route, a pre- accidental damage assessment should be carried out for all types of damage events. This will be of assistance when deciding the required repair method.

The method shown by carrying out a pre-accidental pipeline repair should be in good use when deciding the required repair method and the criticality of the damage. However, the data calculated in this thesis should all be proven by experimental methods before trusted completely. The reasoning for this is that the FEA analysis performed was completed using various methods of solving engines in order to get the simulations running. It should also be mentioned that it is very important to use great caution when dealing with FEA simulated data, especially when there are many combined loads present in the damaged pipe section.

Previous studies show that pipeline repair using various types of clamps around the damage is a common repair method, which in most cases is a good choice for that particular damage. For minor gouges and corrosion pits, however, this method can be quite over-dimensioned for its purpose.

Techniques using composite wrapping together with an epoxy putty will repair the minor part walled defects in two significant matters. One is for stopping the corrosion or crack growth in the gouge, and the other one for pipe surface reinforcement. For minor damages such as scratches and shallow gouges, where damage itself does not change the pipe burst pressure capacities, a minor repair method should be decided. These methods could either be grinding or milling of the damage itself.

As an alternative solution of pipeline repair, a ball mill repair tool is proposed. This method could be used to reduce the stress concentrations in a damaged section, or to prepare the damage for further repair such as clamp or composite repair.

6 FUTURE WORK

- Experimental testing with pipes subjected to axial locked in stresses, internal pressure and external part-walled defects.
- Fatigue analysis of how these types of damages and loading combinations are affected by cyclic stresses induced by uneven flow.
- Planning and development of a subsea pipeline milling repair machine for repair of minor gouges, cracks or corrosion defects.
- Further investigation concerning ice scouring interference with pipeline routes is of interest. How to protect pipelines from such events, and how to assess the possible damages.

7 REFERENCES

Alexander, C. et al., 2012. Evaluating Anchor Impact Damage to the Subsea Canyon Chief Pipeline Using Analysis And Full-Scale Testing Methods. *IPC,* Issue 9.

Alexander, C., Vyvial, B. & Wilson, F., 2014. Pipeline repair of corrosion and dents: a comparison of composite repairs and steel sleeves. *International Pipeline Conference,* Issue 10.

Allouti, M., Schmitt, C. & Pluvinage, G., 2014. Assessment of a gouge and dent defect in a pipeline by a combined criterion. *Engineering Failure Analysis,* Issue 36, pp. 1-13.

Autodesk, 2015. *HELP.AUTODESK.COM.* [Online]
Available at: http://help.autodesk.com/view/ASMECH/2015/ENU/?guid=GUID-3BDBFBCD-6870-4428-BBB1-461FDAAF7969
[Accessed 14 June 2015].

Bennet, M., 2013. *Cryopolitics.* [Internett]
Available at: http://cryopolitics.com/2013/02/
[Funnet 06 June 2015].

Berge, J. O., Armstrong, M. & Woodward, N., 2015. Welding Robot Repairing Subsea Pipelines. *OTC,* Issue 25969.

Bruce, W. & Amend, W., 2010. Advantages of Steel Sleeves over Composite Materials for Pipeline Repair. *Evaluation, Rehabilitation & Repair of Pipelines.*

Cosham, A., Hopkins, P. & Macdonald, K., 2006. Best practice for the assessment of defects in pipelines - Corrosion. *Engineering Failure Analysis,* Issue 14, pp. 1245-1265.

DNV-1, 2010. Interference Between Trawl Gear And Pipelines. *Recommended Practice,* Issue DNV-RP-F111.

DNV, 2007. *PIPELINE SUBSEA REPAIR.* Høvik: Det Norske Veritas.

DNV, 2008. *STRUCTURAL ANALYSIS OF PIPING SYSTEMS.* s.l.:Det Norske Veritas.

DNV, 2010. Corroded Pipelines. *Recommended Practice,* Issue DNV-RP-F101.

DNV, 2012. *Submarine Pipeline Systems.* s.l.:DNV.

DNV-2, 2010. Risk Assessment Of Pipeline Protection. *Recommended Practice,* Issue DNV-RP-F107.

Duell, J., Wilson, J. & Kessler, M., 2008. Analysis of a carbon composite overwrap pipeline repair system. *International Journal of Pressure Vessels and Piping,* Issue 85, pp. 782-788.

Ellinas, C., King, B. & Davies, R., 1995. Evaluation of Fishing Gear Induced Pipeline Damage. *International Offshore and Polar Engineering Conference,* Volume II, pp. 134-141.

Espiner, R., Goodfellow, G., Kaye, D. & Hopkins, P., 2008. Inspection & assessment of damaged subsea pipelines: a case study. *ASME International Pipeline Conference,* IV(7), pp. 291-298.

Goedecke, H. et al., 2014. *Subsea Pipeline.* [Internett]
Available at: https://farizqa037.wordpress.com/2014/01/29/crack-detection-in-gas-pipelines/
[Funnet 13 June 2015].

Kejser, E., Povloski, B., Robles, M. & Mota, H., 2011. Innovative Method for Creating New Deepwater Tie-in Points on Existing Pipeline System, Using Proven Pipeline Repair Equipment. *Offshore Technology Conference,* Issue 22181.

Kennametal.com, 2015. *Ball Nose End Mills.* [Online]
Available at: http://www.kennametal.com/en/featured/harvi-3-ujbe-ball-nose-end-mills.html
[Accessed 13 June 2015].

Köpple, M., Lauterbach, S. & Wagner, W., 2012. Composite repair of through-wall defects in pipework - Analytical and numerical models with respect to ISO/TS 24817. *Composite Structures,* Issue 95, pp. 173-178.

Lewis, C., Parrot, D., Simpkin, P. & Buckley, J., 1986. *Ice Scour and Seabed Engineering. Enviromental studies revolving funds Report No 049.* 49 ed. Ottawa: s.n.

Liessem, A., Knauf, G. & Zimmermann, S., 2007. Strain Based Design - What the Contribution of a Pipe Manufacturer Can Be. *ISOPE,* Issue SBD14.

Macdonal, K. & Cosham, A., 2005. Best practise for the assessment of defects in pipelines - gouges and dents. *Engineering Failure Analysis,* Issue 12, pp. 720-745.

NPC, 2015. Arctic Subsea Pipelines and Subsea Production Facilities. *Arctic Potential,* Issue 6-6.

Offshore-Technology, 2012. *Maintenance challenges of the Norwegian Continental Shelf.* [Online]
Available at: http://www.offshore-technology.com/features/featuremaintenance-challenges-of-the-norwegian-continental-shelf/
[Accessed 10 February 2015].

Oljedirektoratet, 2010. *Rørledninger.* [Online]
Available at: http://www.npd.no/Publikasjoner/Rapporter/Helhetlig-forvaltningsplan-for-Nordsjoen-og-Skagerrak/11-Rorledninger-/
[Accessed 09 02 2015].

Orsolato, R., Fabri, S. & Cherubini, P., 2011. Transmediterranean Pipeline Repair. *Offshore Mediterranean Conference,* March.

Palmer-Jones, R., Paterson, G. & Aldo Nespeca, G., 2011. THE FLEXIBLE GROUTED CLAMP - A NOVEL APPROACH TO EMERGENCY PIPELINE REPAIR. *IBP,* Issue 1033.

Palmer-Jones, R., Turner, T., John, R. & Nespeca, A., 2011. Rapid Decision-Making in Emergency Subsea Pipeline Repair. *IBP,* Issue 1032.

Paulin, M., 2013. Arctic Offshore Pipeline Design and Installation Challanges. *Society of Petroleum Engineers,* Issue 166881.

Popineau, D., Wiet, P. & d'Auria, S. B., 2012. Subsea Pipeline,. *Society of Petroleum engineers,* Issue 162509.

Singh, R., 2013. *Arctic Pipeline Planning: Design, Construction, and Equipment.* s.l.:Gulf Professional Publishing.

University of Cambridge, 2015. [Online]
Available at: http://www.doitpoms.ac.uk/tlplib/beam_bending/plastic.php
[Accessed 03 Juni 2015].

Wikipedia, 2015. *Trans-Mediterranean Pipeline.* [Online]
Available at: http://en.wikipedia.org/wiki/Trans-Mediterranean_Pipeline#mediaviewer/File:Gas_pipelines_across_Mediterranee_and_Sahara_map-en.svg
[Accessed 14 June 2015].

wolverinepipeline, 2010. [Online]
Available at: http://wolverinepipeline.com/community/integrity-assurance/
[Accessed 11 June 2015].

8 APPENDIX

8.1 TABLES

Table 8-1 - Results for stress in V-shaped gouge depth of 0mm

Forced displacement δ_{PI} [mm]	**Final displacement δ_{PF}**	**Max Initial stress σ_{PI} $[N/mm^2]$**	**Max Final stress σ_{PF} $[N/mm^2]$**
0	4,8	291	291
200	132	471	286
400	325	505	274
600	513	536	276
800	722	548	269
1000	917	620	417
1200	1118	660	375

Table 8-2 - Results for stress in V-shaped gouge depth of 4mm

Forced displacement δ_{PI} [mm]	Final displacement δ_{PF}	Max Initial stress σ_{PI} $[N/mm^2]$	Max Final stress σ_{PF} $[N/mm^2]$
0	4,7	300	300
200	119	450	287
400	323	457	317
600	534	494	401
800	738	528	483
1000	928	511	441
1200	1112	544	462

Table 8-3 - Results for stress in V-shaped gouge depth of 8mm

Forced displacement δ_{PI} [mm]	Final displacement δ_{PF}	Max Initial stress σ_{PI} $[N/mm^2]$	Max Final stress σ_{PF} $[N/mm^2]$
0	4,8	346	346
200	120	437	362
400	317	453	347
600	522	469	400
800	721	521	442
1000	934	489	453
1200	1116	526	405

Table 8-4 - Results for stress in V-shaped gouge depth of 12mm

Forced displacement δ_{PI} [mm]	Final displacement δ_{PF}	Max Initial stress σ_{PI} $[N/mm^2]$	Max Final stress σ_{PF} $[N/mm^2]$
0	4,8	324	319
200	109	456	235
400	319	461	392
600	521	481	402
800	728	484	447
1000	930	517	427
1200	1145	527	415

Table 8-5 - Results for stress in V-shaped gouge depth of 16mm

Forced displacement $\boldsymbol{\delta_{PI}}$ [mm]	Final displacement $\boldsymbol{\delta_{PF}}$	Max Initial stress $\boldsymbol{\sigma_{PI}}$ $[\boldsymbol{N/mm^2}]$	Max Final stress $\boldsymbol{\sigma_{PF}}$ $[\boldsymbol{N/mm^2}]$
0	4,8	315	315
200	114	443	392
400	279	449	418
600	412	583	573
800	454	746	636
1000	551	1087	983
1200	558	1449	1240

Table 8-6 - Results for stress in V-shaped gouge depth of 20mm

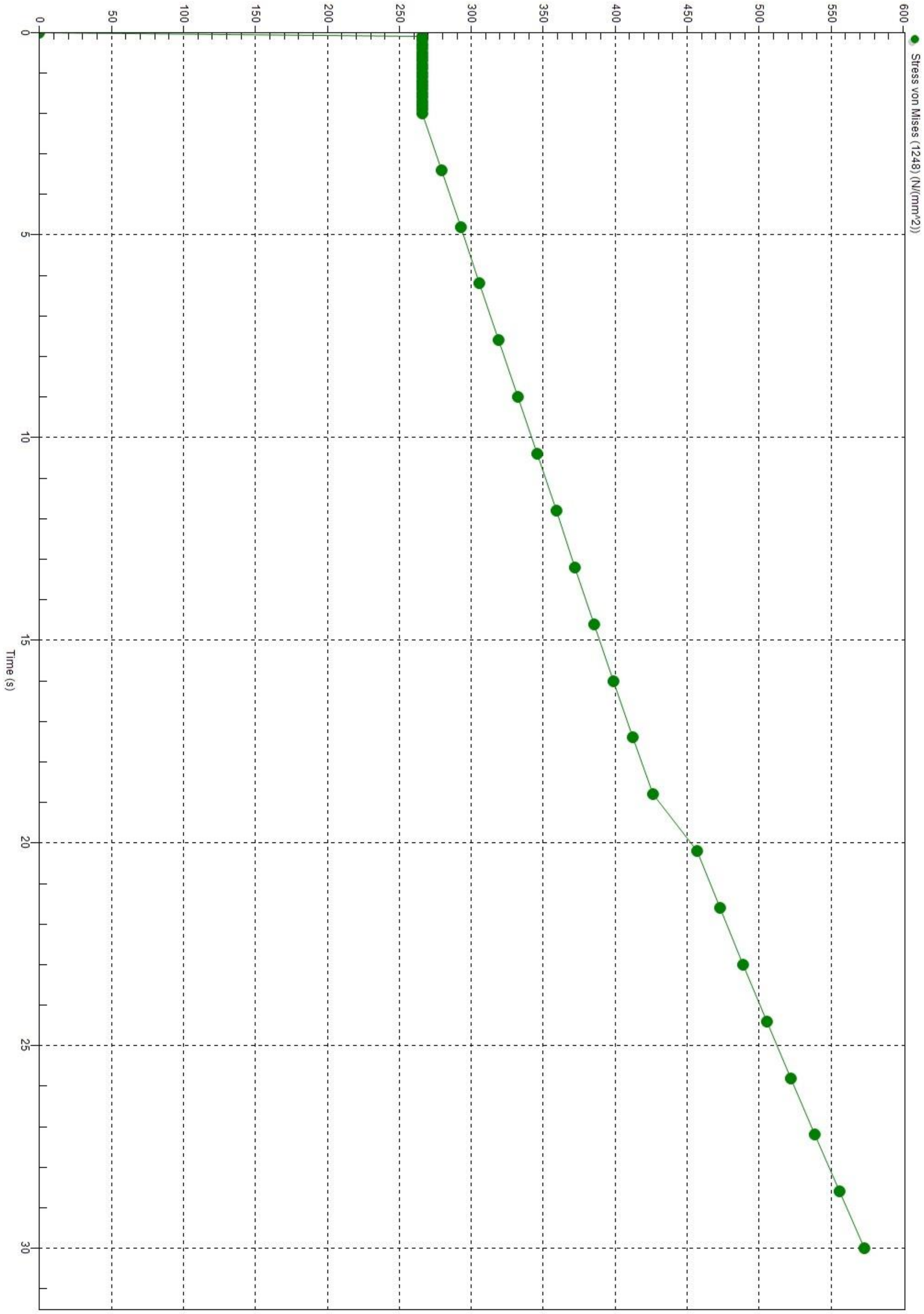
Forced displacement $\boldsymbol{\delta_{PI}}$ [mm]	Final displacement $\boldsymbol{\delta_{PF}}$	Max Initial stress $\boldsymbol{\sigma_{PI}}$ $[\boldsymbol{N/mm^2}]$	Max Final stress $\boldsymbol{\sigma_{PF}}$ $[\boldsymbol{N/mm^2}]$
0	4,8	327	336
200	124	441	407
400	330	525	513
600	542	615	601
800	747	824	814
1000	921	675	672
1200	1108	511	510

Table 8-7 - Results for stress in V-shaped gouge depth of 24mm

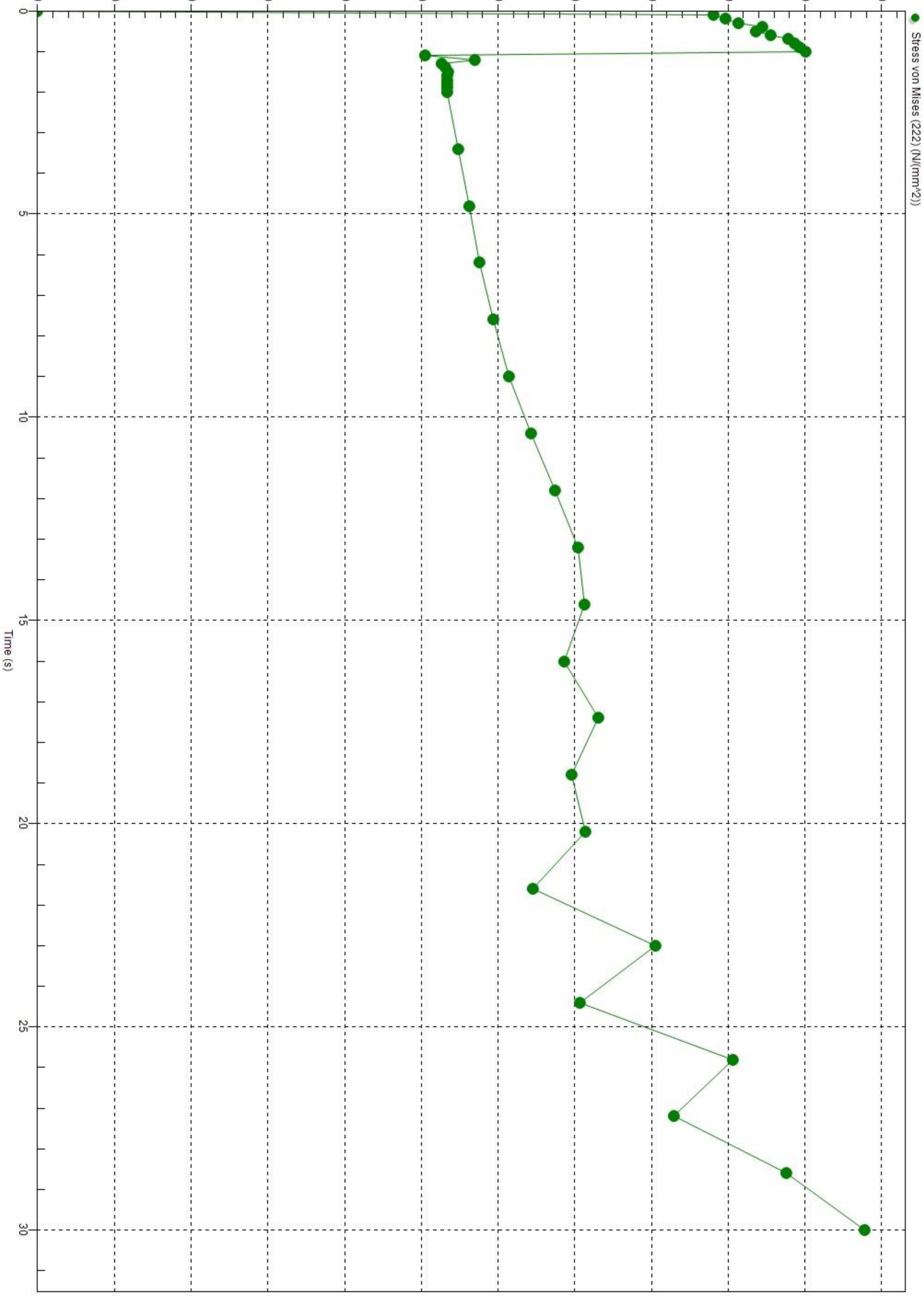
Forced displacement $\boldsymbol{\delta_{PI}}$ [mm]	Final displacement $\boldsymbol{\delta_{PF}}$	Max Initial stress stress $\boldsymbol{\sigma_{PI}}$ $[\boldsymbol{N/mm^2}]$	Max Final stress $\boldsymbol{\sigma_{PF}}$ $[\boldsymbol{N/mm^2}]$
0	5	328	326
200	43	374	374
400	135	447	445
600	212	557	481
800	325	586	563
1200	377	494	494

8.2 FIGURES

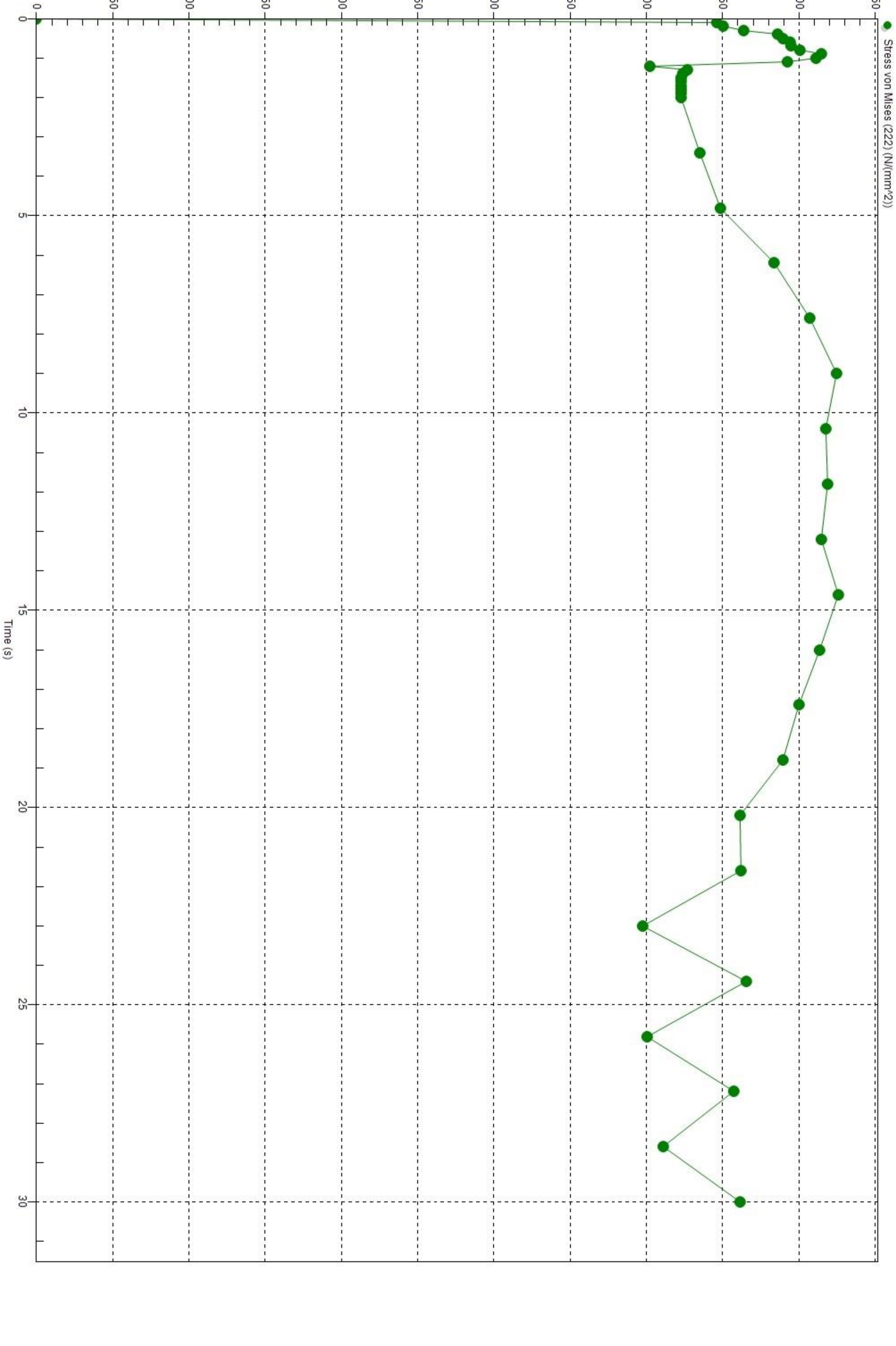
0 mm gouge, 0mm displacement



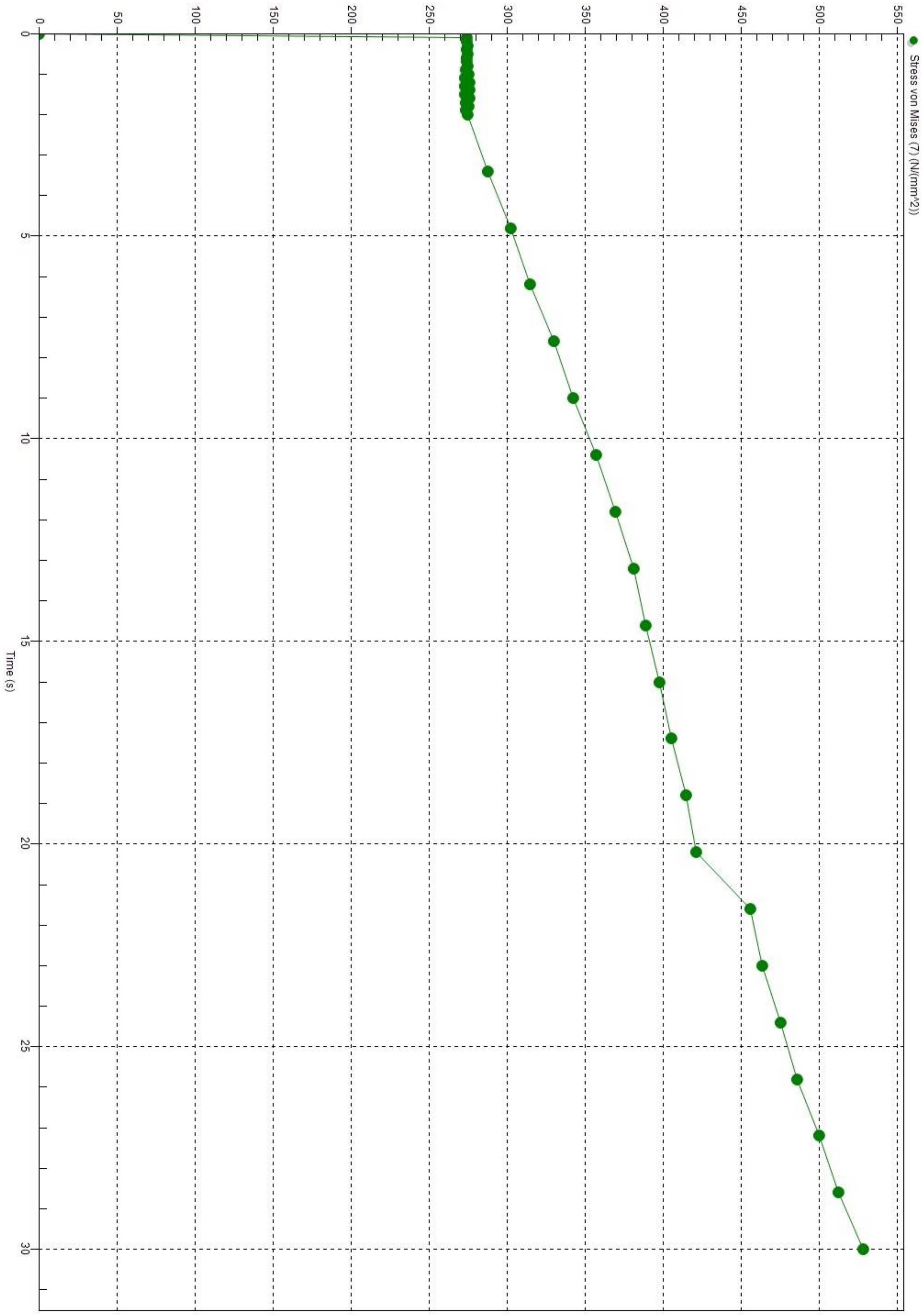
0 mm gouge, 600mm displacement



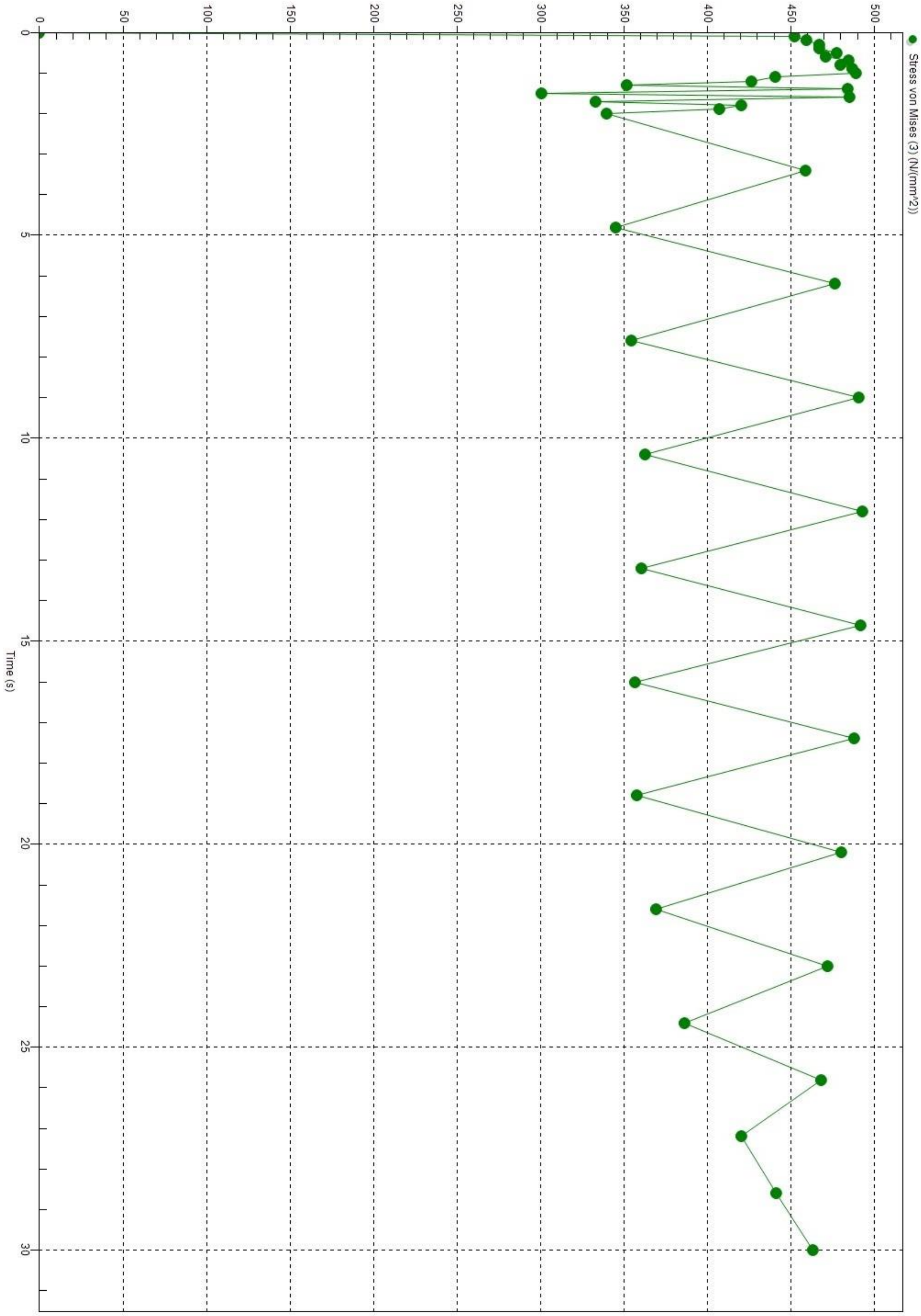
0 mm gouge, 1200mm displacement



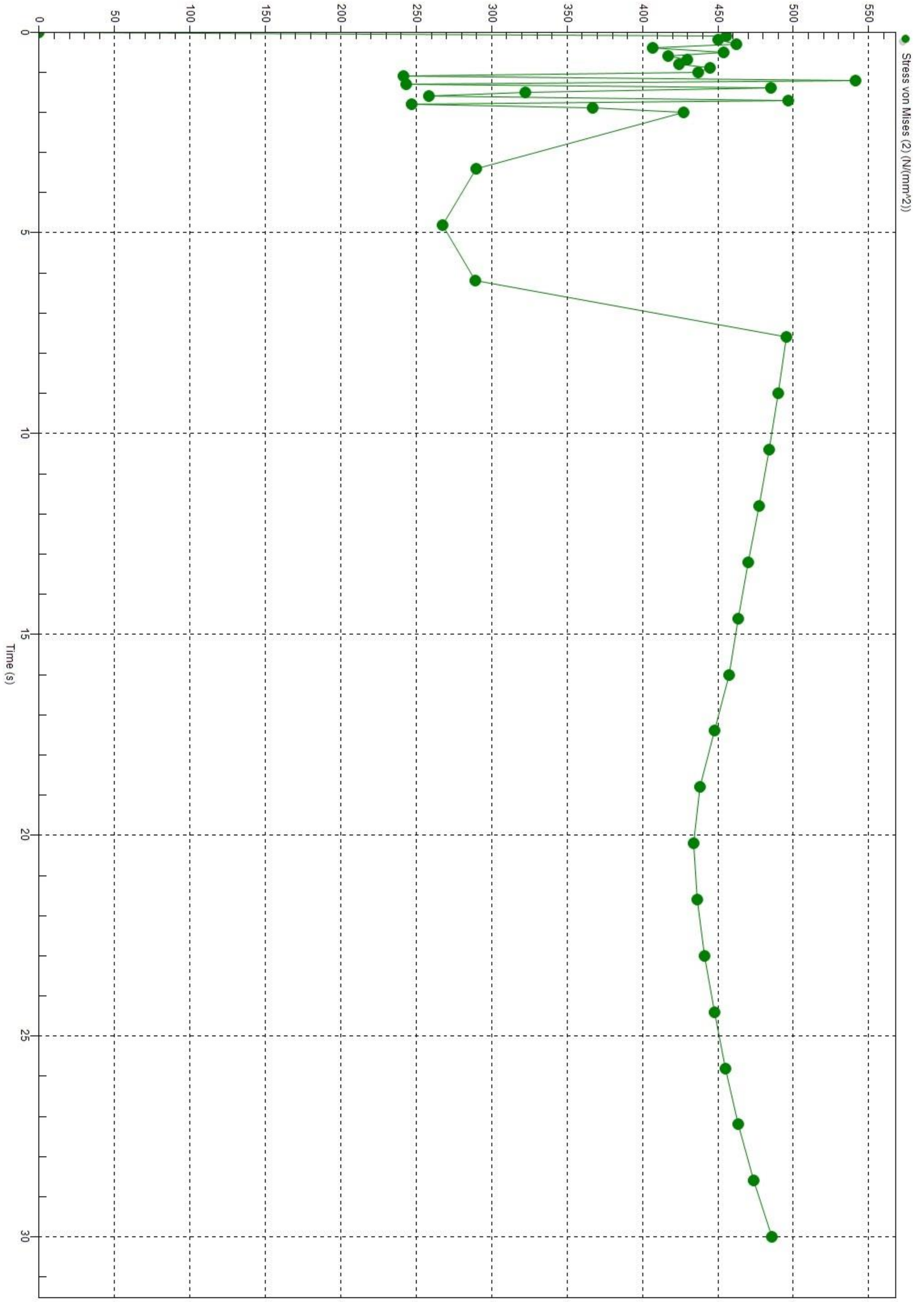
4 mm gouge, 0mm displacement



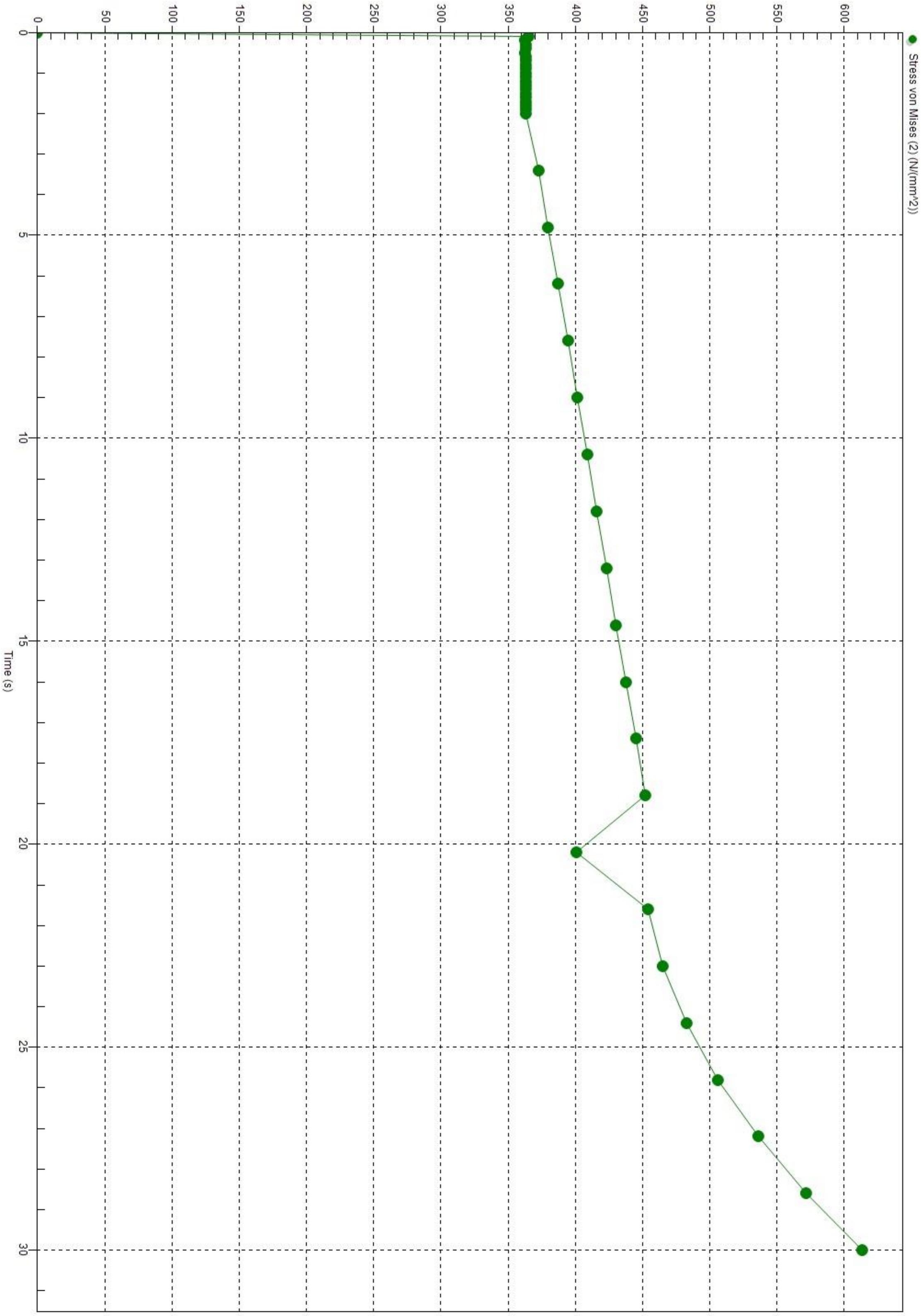
4 mm gouge, 600mm displacement



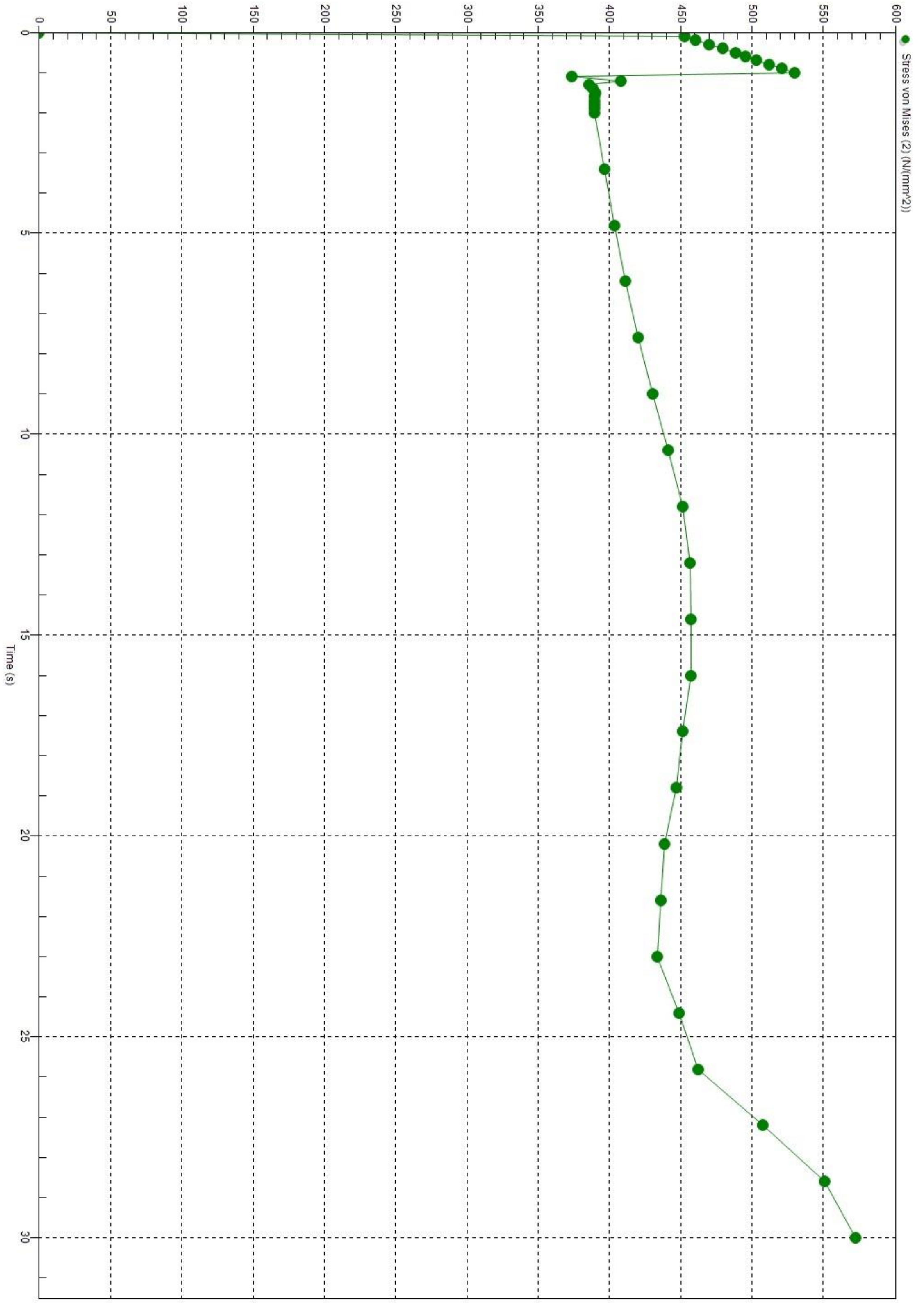
4 mm gouge, 1200mm displacement



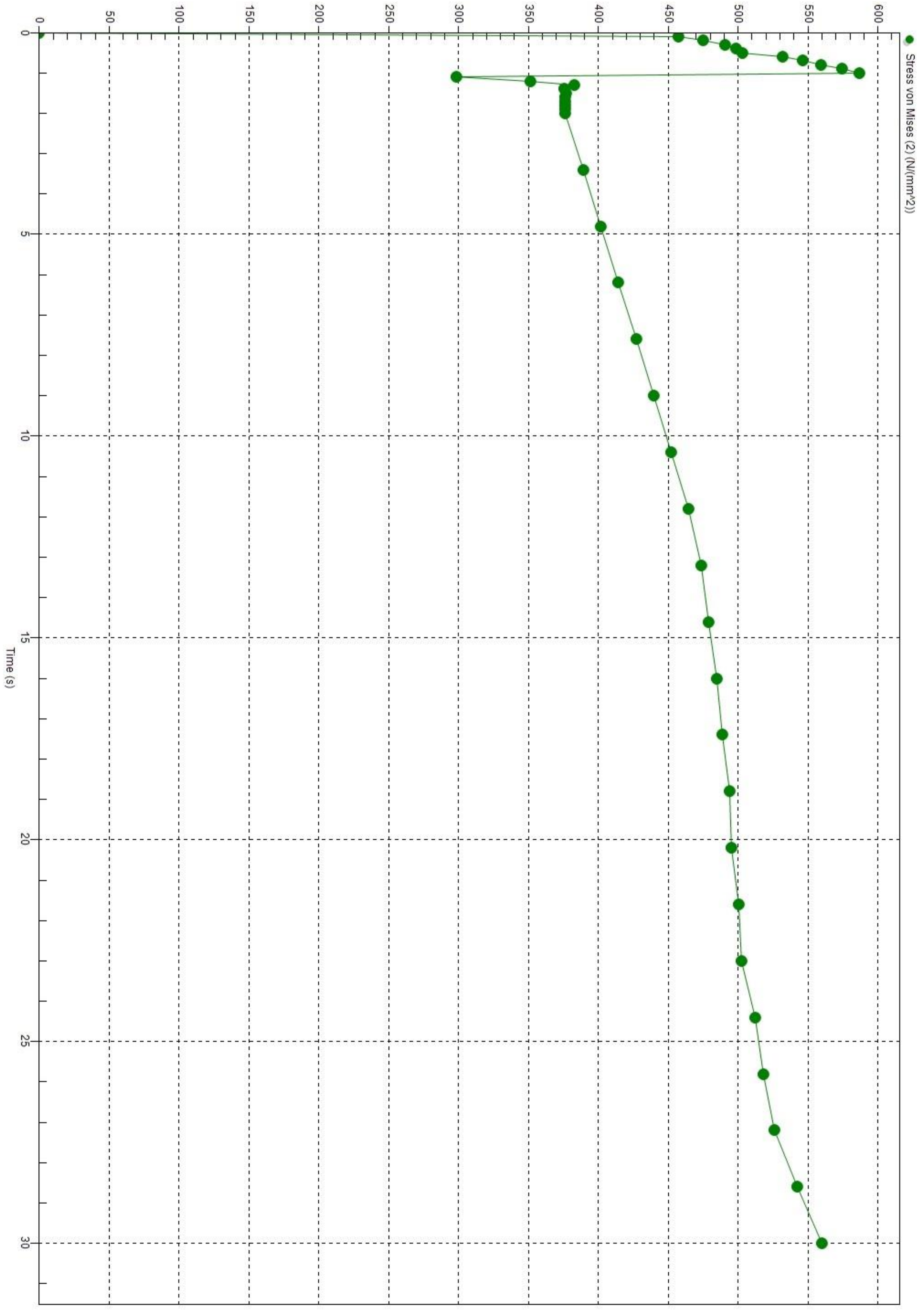
8 mm gouge, 0mm displacement



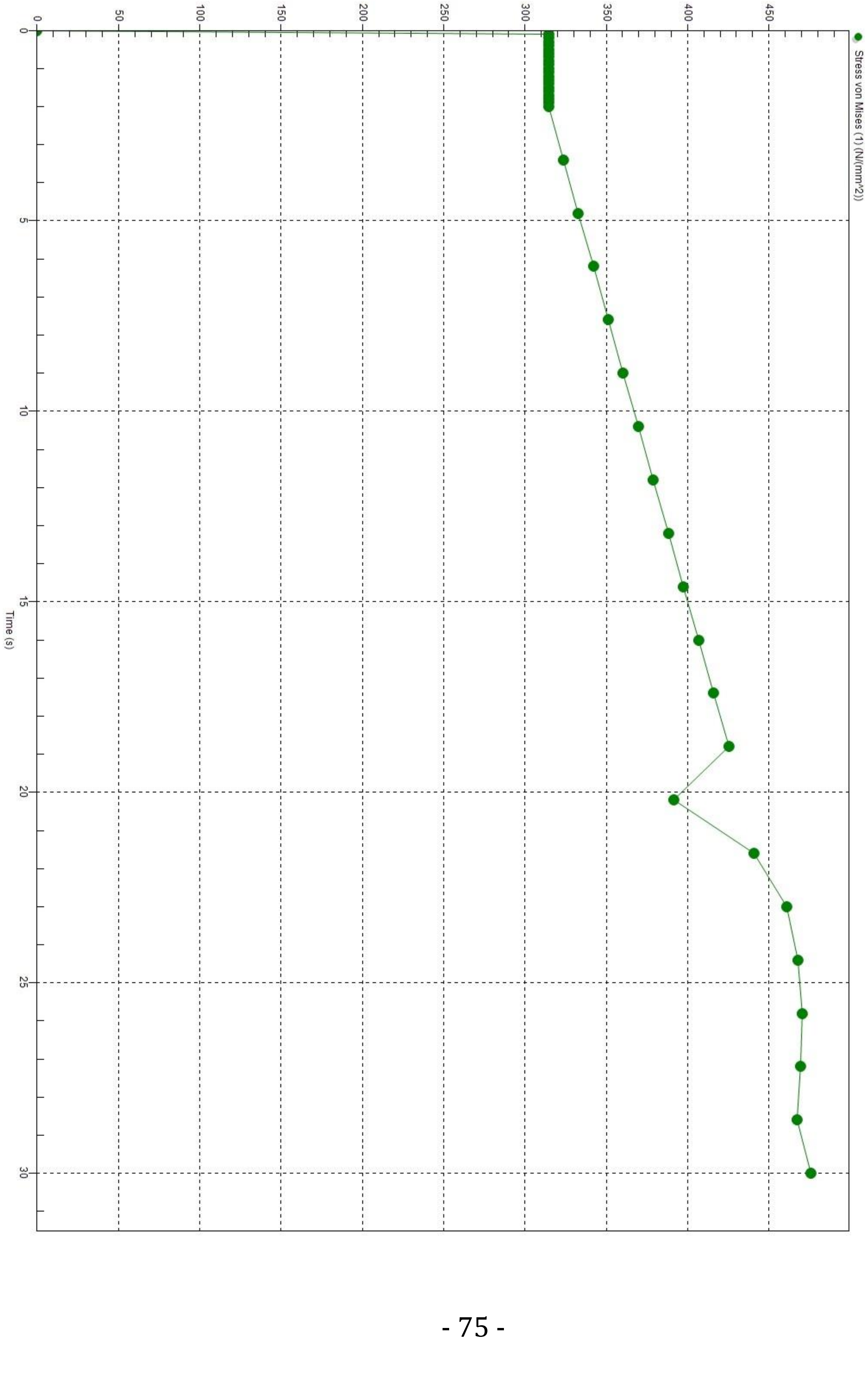
8 mm gouge,600mm displacement



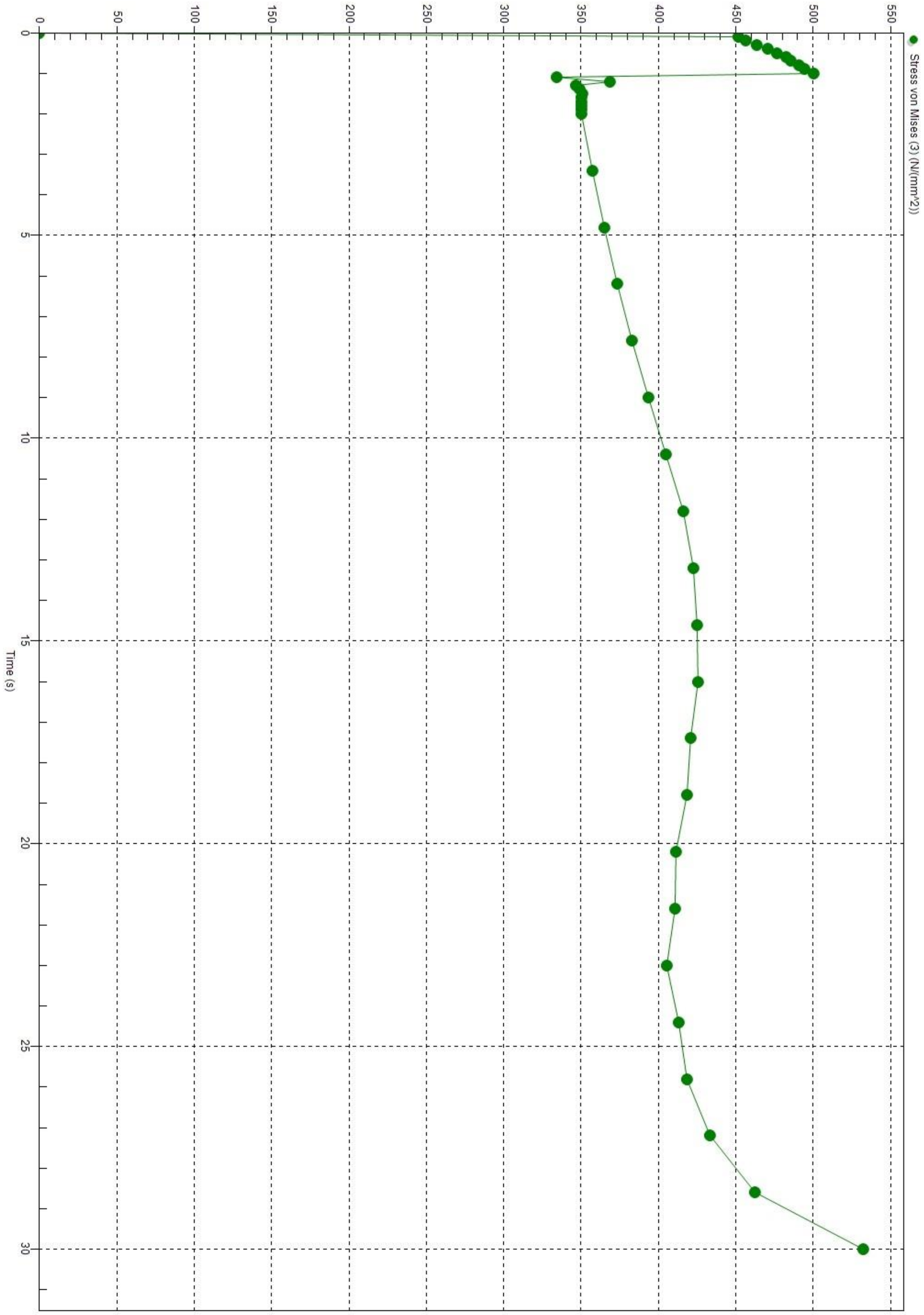
8 mm gouge,1200mm displacement



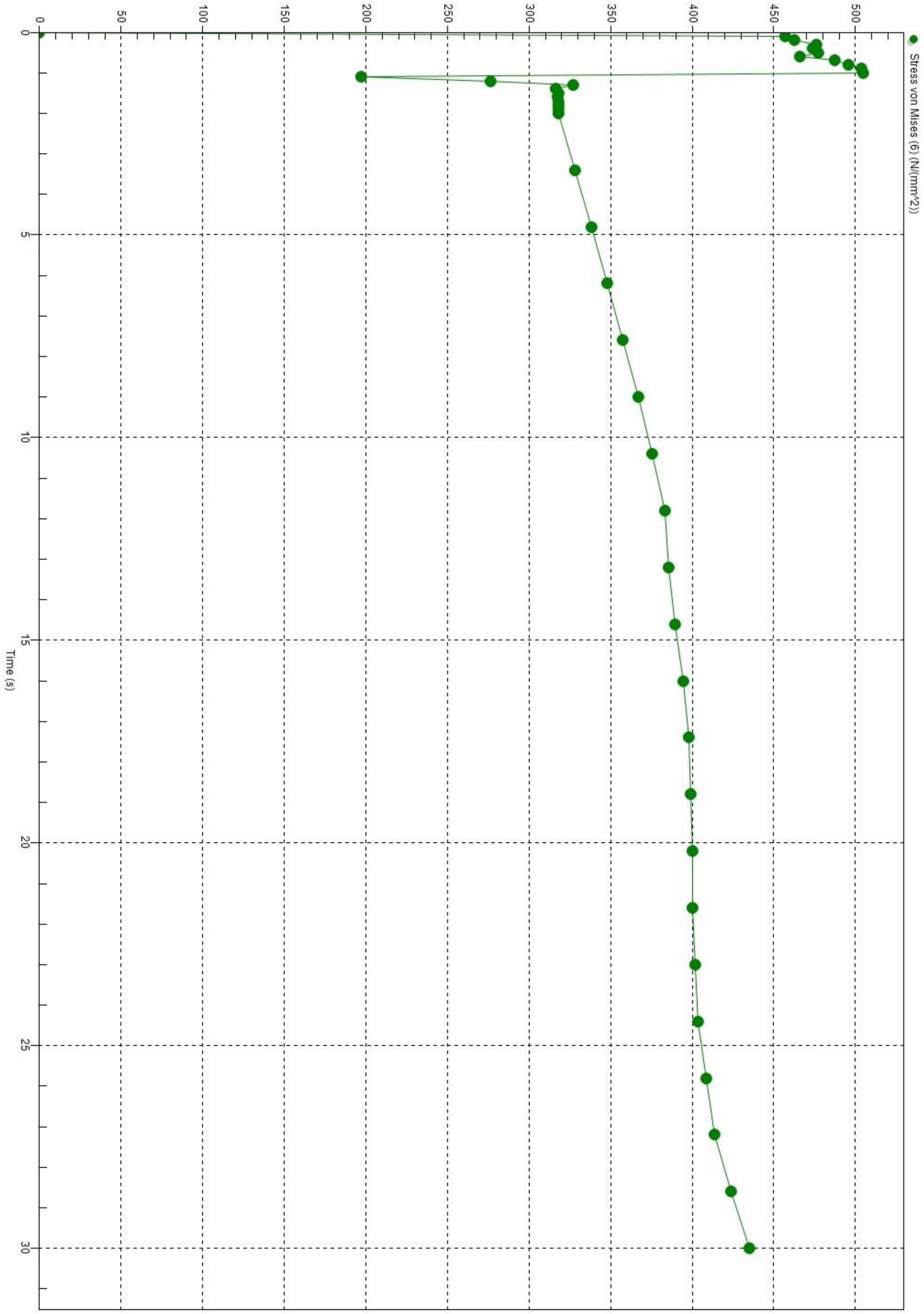
12 mm gouge, 00mm displacement.



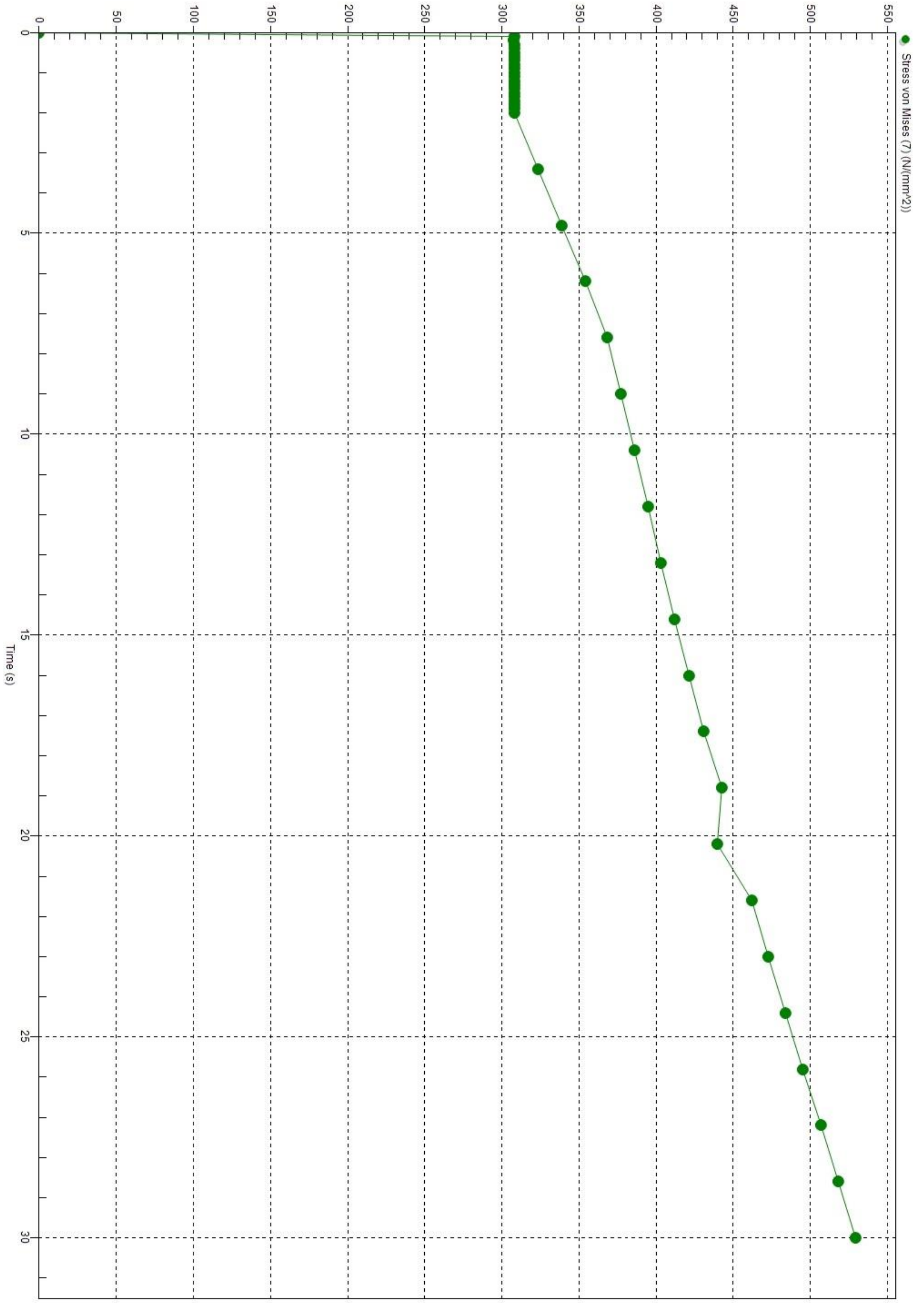
12 mm gouge, 600mm displacement



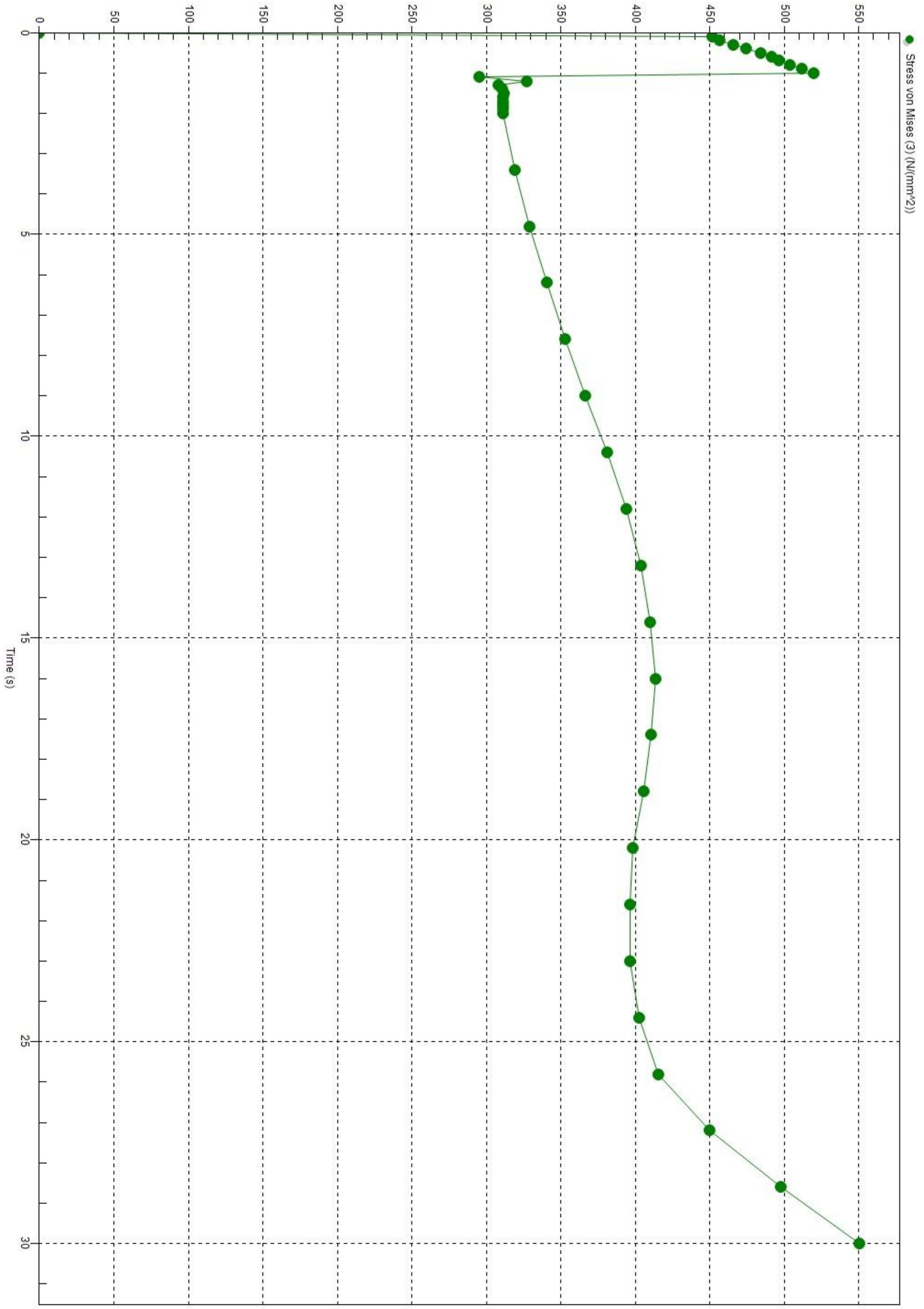
12 mm gouge, 1200mm displacement



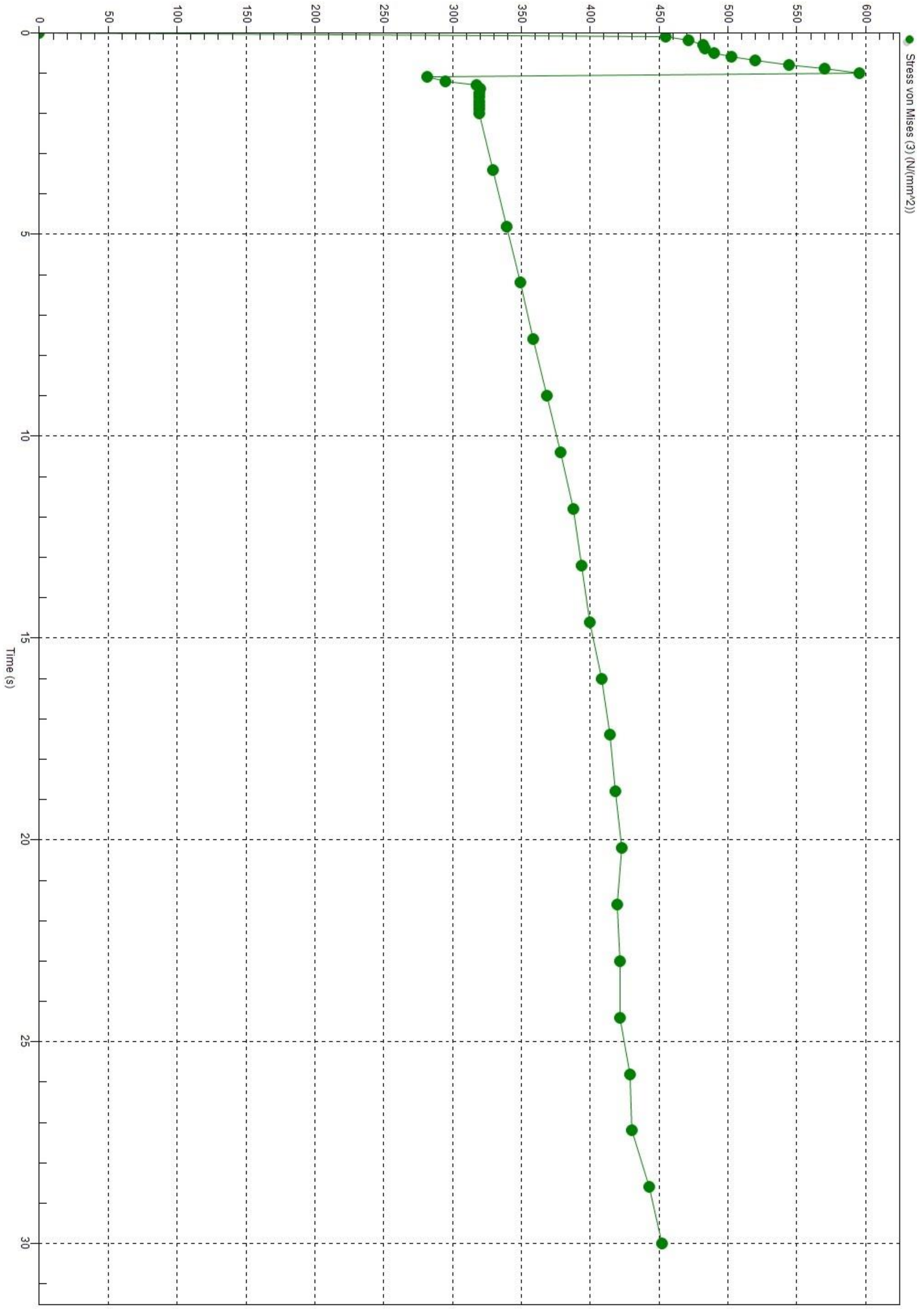
16mm gouge, 0mm displacement



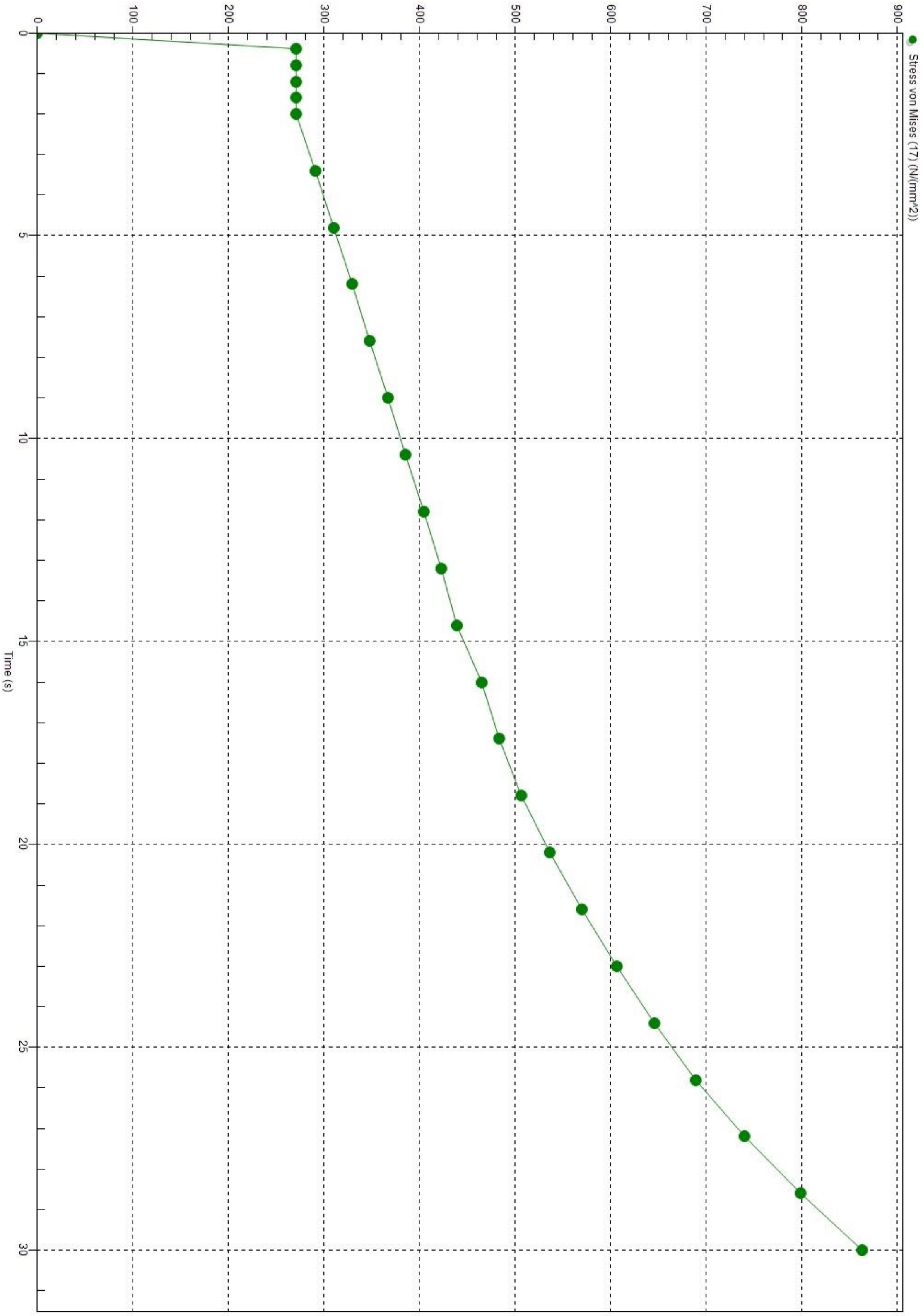
16mm gouge, 600mm displacement



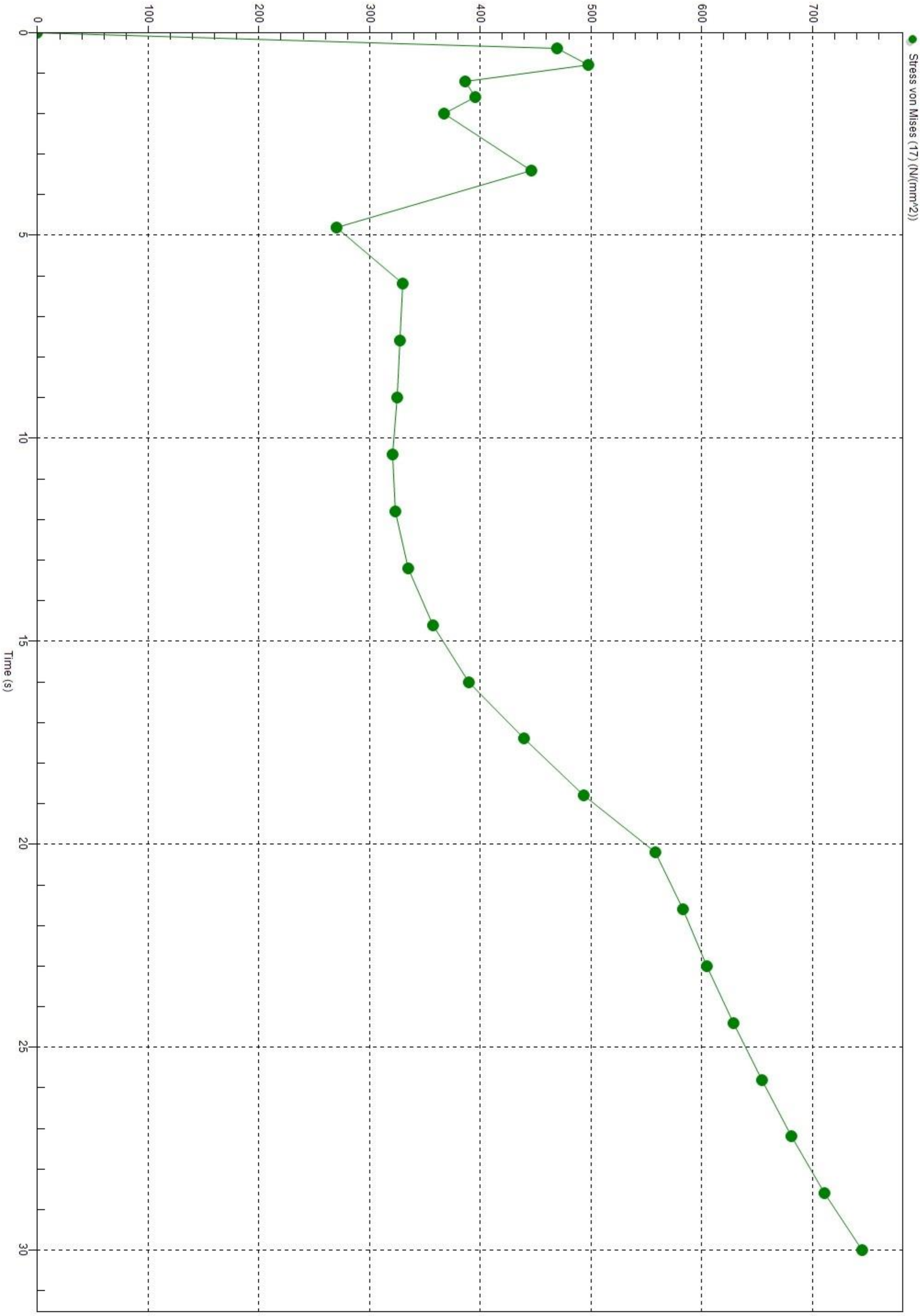
16mm gouge,1200mm displacement



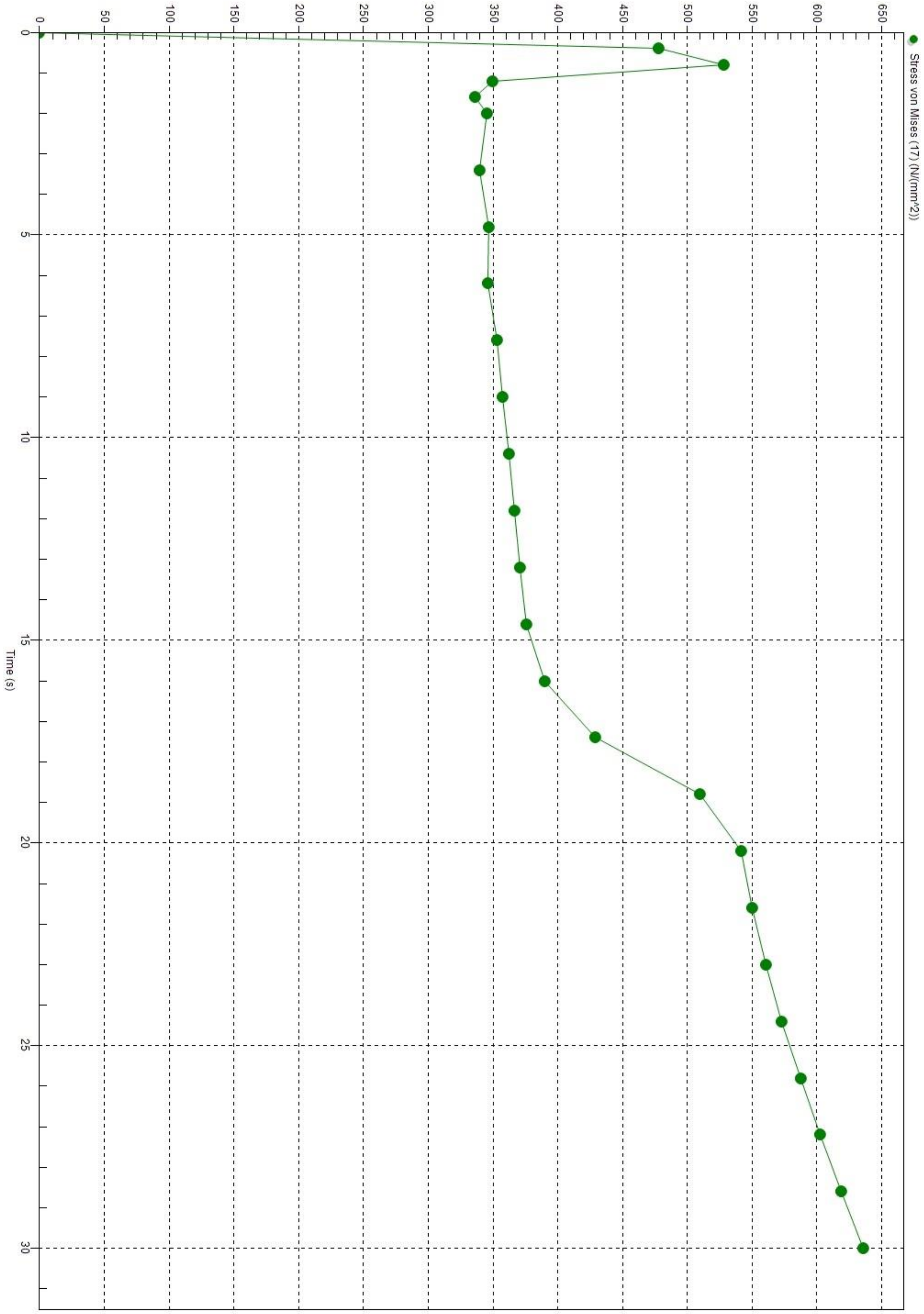
20 mm gouge,0mm displacement



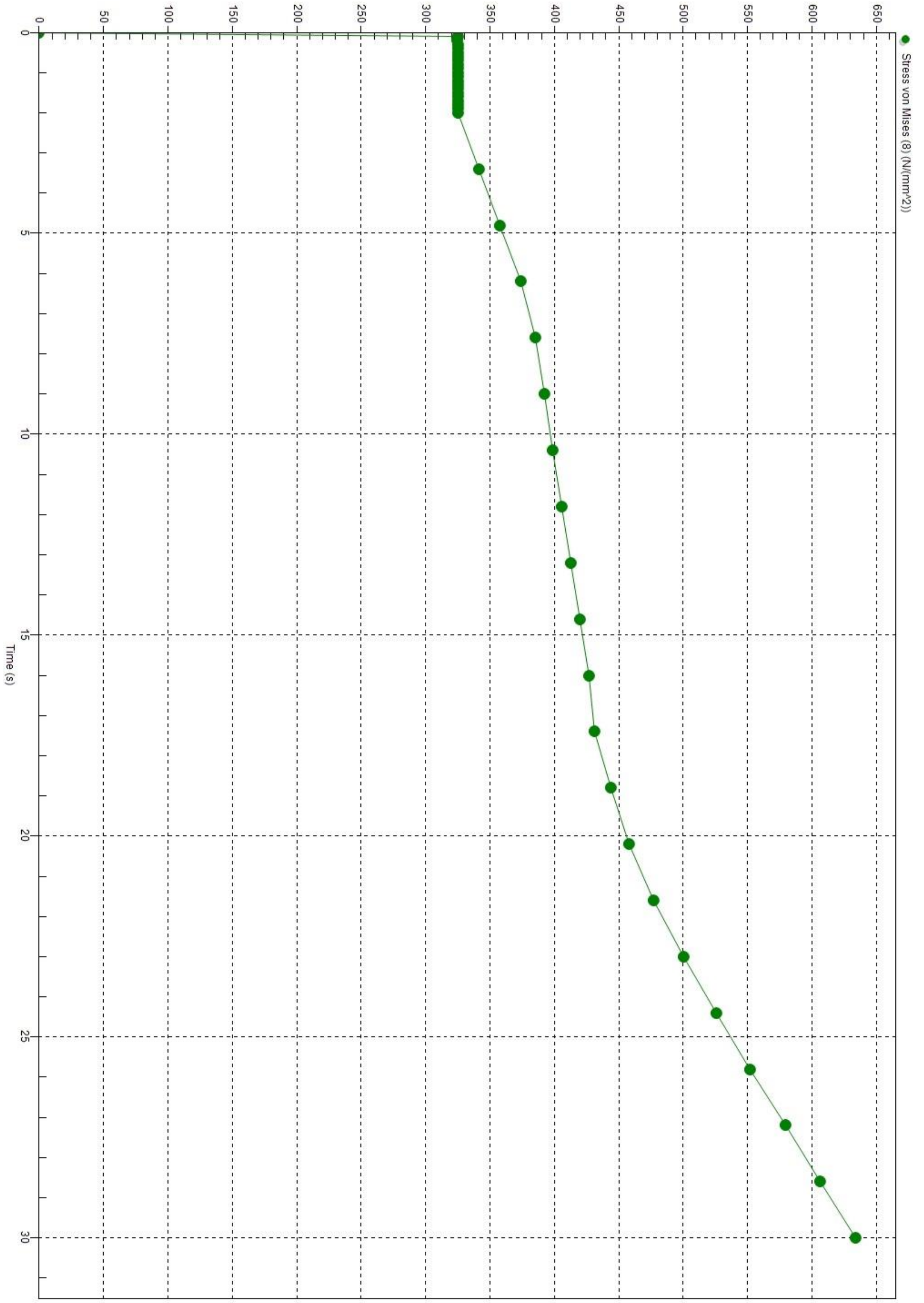
20 mm gouge,600mm displacement



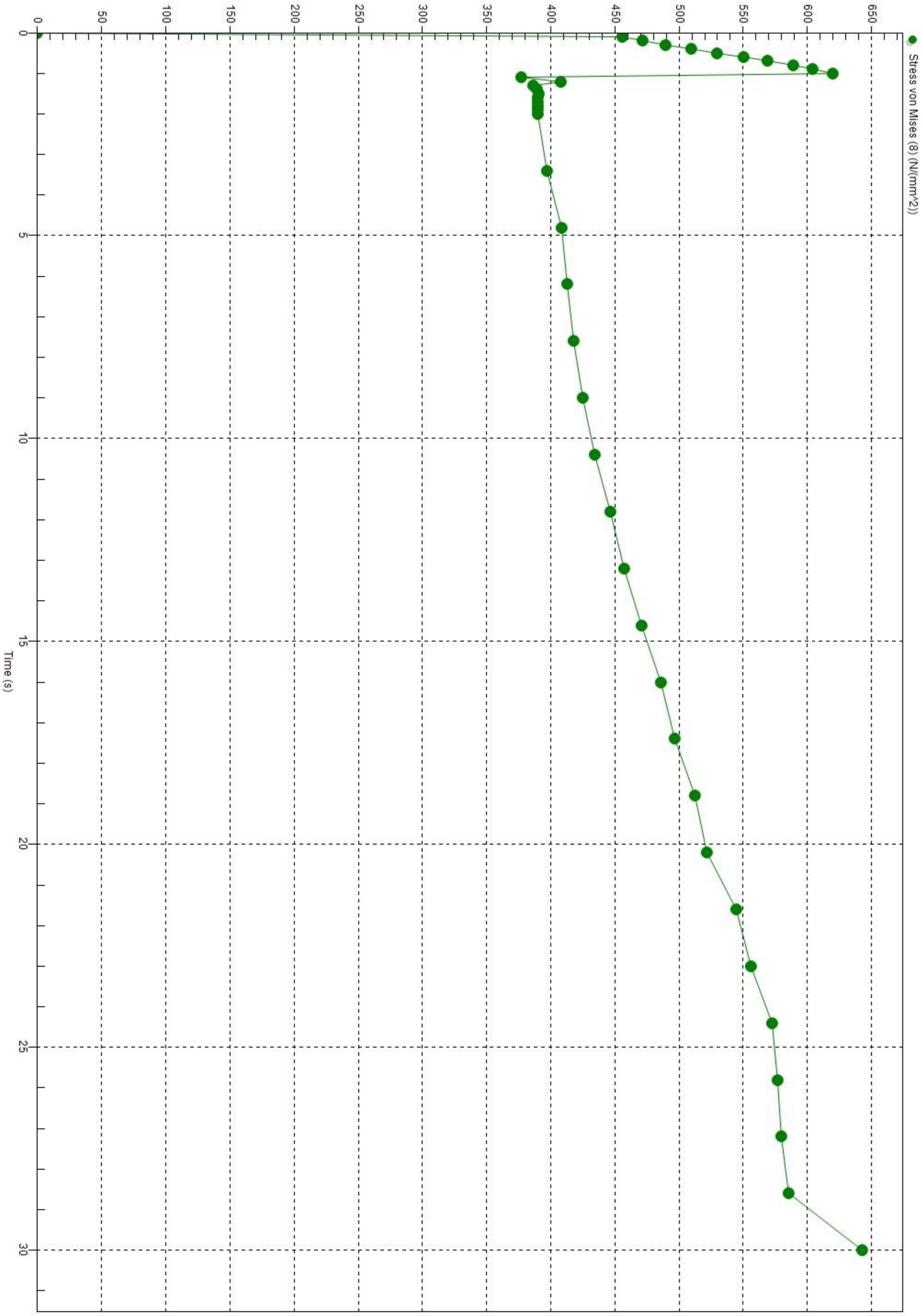
20mm gouge,1200mm displacement



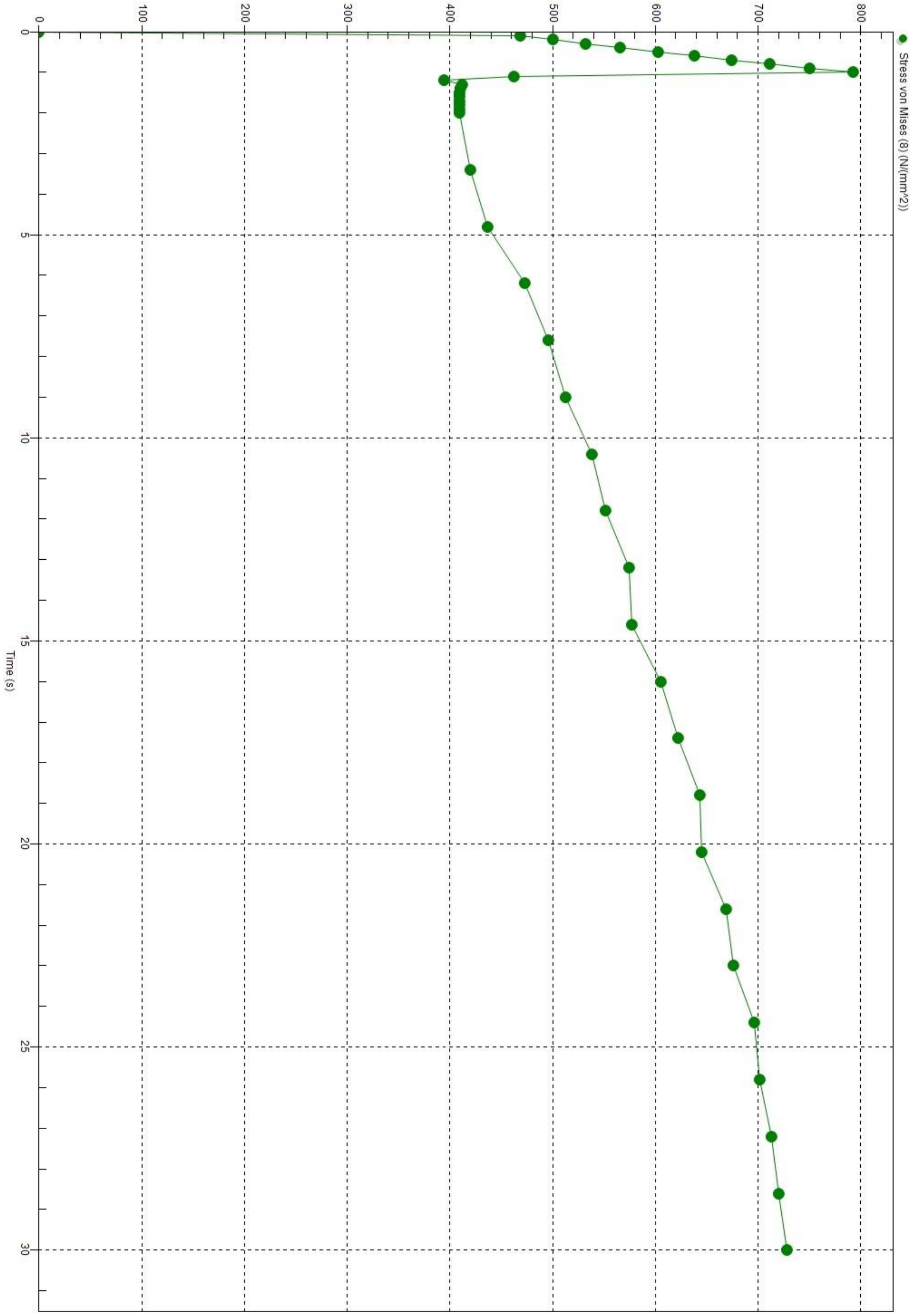
24 mm gouge, 0mm displacement



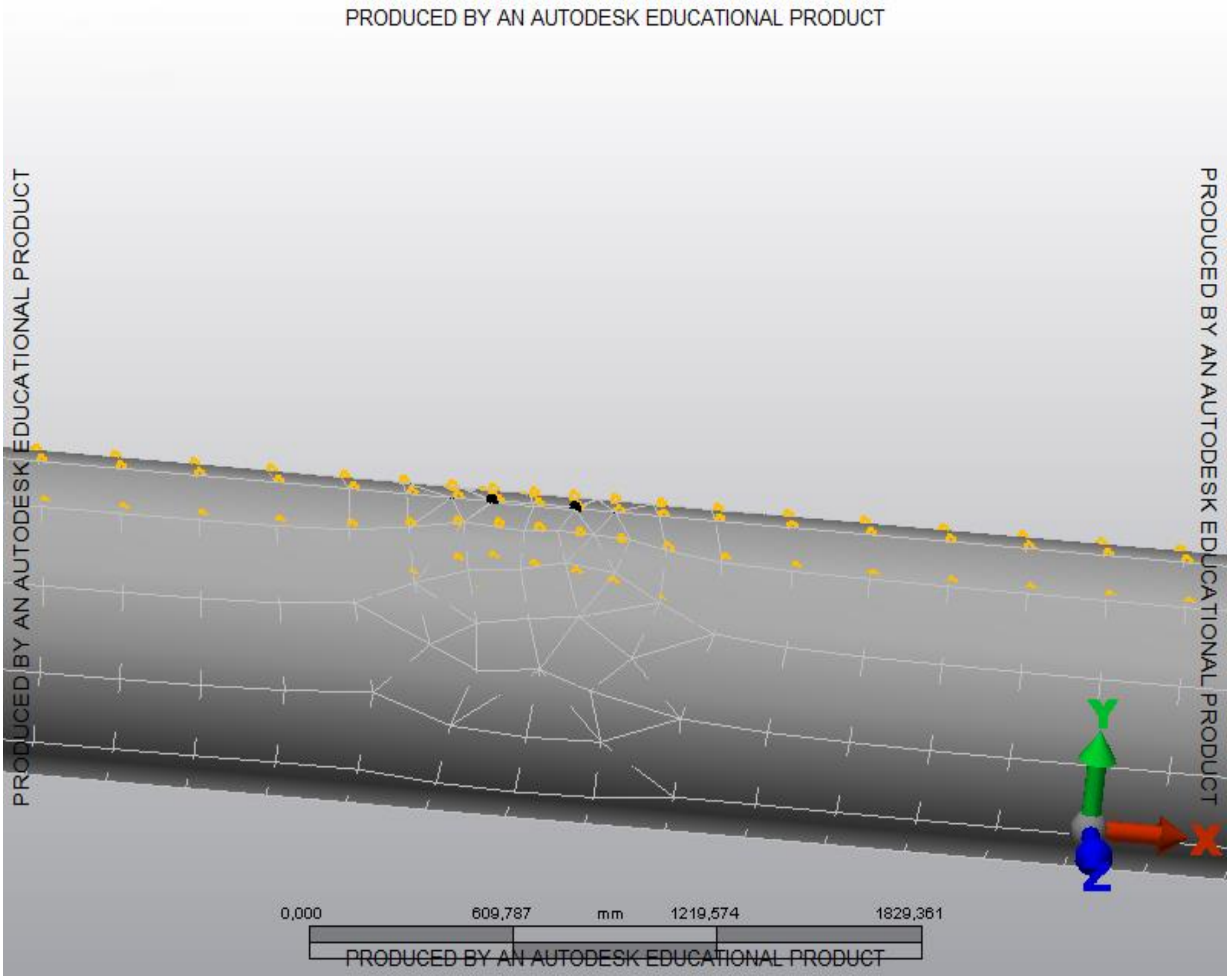
24 mm gouge, 600mm displacement



24 mm gouge,1200mm displacement



8.3 Simulation setup



Simulation of a 24mm deep gouge with constant internal pressure

Created by

Author: Øyvind Høie

Department: UiS

Created Date: 13.06.2015

Executive Summary

This setup was used for all gouge depths described, and for all lateral displacements

Summary

Model Information

Analysis Type - MES with Nonlinear Material Models

Units - Custom - (N, mm, s, °C, K, V, ohm, A, J)

Model location - C:\Users\Øyvind\Documents\Inventor\Masterpipelineoppgave\BAre gouge\V shape gouge24mm.fem

Design scenario description - 1200mm displacementNs

Analysis Parameters Information

Event Information

Number of interval zones = 1

Time Zone Index	Duration (s)	Number of time steps
1	3	30

Gravity Information

Acceleration Due To Body Force = 0 mm/s²

Load Curve Number for Gravity Load = 1

Acceleration/Gravity X Multiplier	Acceleration/Gravity Y Multiplier	Acceleration/Gravity Z Multiplier
0	0	-1

Centrifugal Information

Angular Velocity (Omega) Magnitude = 0 (RPM)

Load Curve Multiplier = 1

Load Curve Number = 1

	X	Y	Z
Rotation Center Point (mm)	0	0	0
Rotation Axis	0	0	0

Angular Acceleration (Alpha) Magnitude = 0 (RPM/s)

Load Curve Multiplier = 1

Load Curve Number = 1

	X	Y	Z
Rotation Center Point (mm)	0	0	0
Rotation Axis	0	0	0

Load Curve Information

Load Curve 1: Load Curve

Time (s)	Multiplier
0	0
1	1

Load Curve 2:

Time (s)	Multiplier
0	1
5	1

Multiphysics Information

Default Nodal Temperature	0 °C

Processor Information

Analysis Type	Fully Manual
Type of Shell Pressure Loading	None
Load Curve Number for Shell Pressure Loads	
Smooth Shell Pressure	No
Hydrostatic Pressure Control for Shell Elements	None
Z Coordinate Datum for Hydrostatic Pressure	mm
Weight Density of Fluid Causing Shell Hydrostatic Pressure	N/mm^3
Nodal Temperature Time-Variation Load Curve Index	1
Where On Disk Is Nodal Temperature Data Stored	No thermal Data
Temperature Data File	None
Output Results of All Time Steps	No
Output Results of All Time Steps With Wall Interaction	No
Calculate and Output Strains	No
Output Reaction Forces	Calculated
Number of time steps	
Initial Time Step Size	0 s
Nonlinear Iterative Solution Method	Unknown Value
Maximum Number of Iterations	15
Convergence Criteria	Displacement
Displacement Tolerance	1e-4

Force Tolerance	1e-15
Line Search Convergence Tolerance	0.5
Number of Time Steps Between Iterations	1
Number of Time Steps Between Reforming Stiffness Matrix	1
Time Integration Methods Suggested for Type of Analysis	General: MES, NLS
Parameter for MES Integration Method	1
First Parameter for LS Integration Method	0.50
Second Parameter for LS Integration Method	0.25
Output interval	1
Starting Time for Event	0 s
Interval to save restart data.	Last step only.
Resume from Step	0
Resume/Extend Run	No
Time Step Number Extension	0
Use A Constant Time Step Size	No
Decrease Trigger: Rate of convergence	Unknown Value
Decrease Trigger: Allow for Non-monotonic convergence	Yes
Decrease Trigger: High Solution Tolerance	Yes
Time Step Change Factor	2
Increase Trigger: Number of Convergent Time Steps	4
Increase Trigger: Increment to Number of Convergent Time Steps	4
Time step reduction if there are distorted elements	Yes
Apply Rayleigh Damping	No

Mass-related Rayleigh Damping Coeeficient	0.05
Stiffness-related Rayleigh Damping Coefficient	0.05
Time Step Data In Output File	No
Equation Numbers Data in Output File	No
Element Stiffness In Output File	No
Global Stiffness In Output File	No
Displacement of Nodes In Output File	No
Velocity of Nodes In Output File	No
Acceleration of Nodes In Output File	No
Element Input Data in Output File	No
Nodal Input Data in Output File	No
Initial Condition Input Data In Output File	No
Printout Blocks Output To File	No
Mass Representation	Lumped
Matrix Reform Interval Within Each Time Step	1
Maximum Stiffness Reformations Per Interval	1
Number of Time Steps Between Reforming Stiffness Matrix	1
Avoid Bandwidth Optimization	No
Bandwidth Optimization Method	Single Body
Convergence tolerance	1E-6
Maximum Number of Iterations	1000
Number of processors	-1
Run Static Analysis	No
Type of Solver	Automatic
Tolerance for stiffness matrix entries	0

Part Information

Part ID	Part Name	Element Type	Material Name
1	V shape gouge24mm	Brick	X65

Element Information

Element Properties used for:

• V shape gouge24mm

Element Type	Brick
Material Model	von Mises with Isotropic Hardening
Midside Nodes	Not Included
Orthotropic Material Principle Axis	X-direction
Material Axis Rotation Angle	0 °
Analysis Formulation	Material Nonlinear Only
Compatibility	Not Enforced
1st Integration Order	Unknown Value
2nd Integration Order	Unknown Value
Allow for overlapping elements	No
Selective Reduced Integration (mean-dilation)	No

Material Information

X65 -Brick

Material Model	Standard
Material Source	API libary
Material Source File	H:\Sim libary\API libary.mlb
Date Last Updated	2015/07/06-18:12:34
Material Description	None

Damping	0 s
Mass Density	7 N·s²/mm/mm³
Modulus of Elasticity	210000 N/mm²
Poisson's Ratio	0.3
Strain Hardening Modulus	1623 N/mm²
Yield Stress	450 N/mm²
Ultimate stress	575 N/mm²

Loads

FEA Object Group 4: Surface Pressure/Tractions

Surface Pressure/Traction

ID	Description	Part Number	Surface Number	Magnitude (N/mm²)	Load Curve	Type	Follows Displacement
1	Unnamed	1	5	18	2	Pressure	No

Constraints

FEA Object Group 1: Nodal General Constraints

Nodal General Constraint

ID	Description	Vertex Number	Node Number	Tx	Ty	Tz	Rx	Ry	Rz
1	Unnamed	13	13	Yes	Yes	Yes	No	No	No

FEA Object Group 2: Nodal General Constraints

Nodal General Constraint

ID	Description	Vertex Number	Node Number	Tx	Ty	Tz	Rx	Ry	Rz
2	Unnamed	15	15	No	Yes	Yes	No	No	No

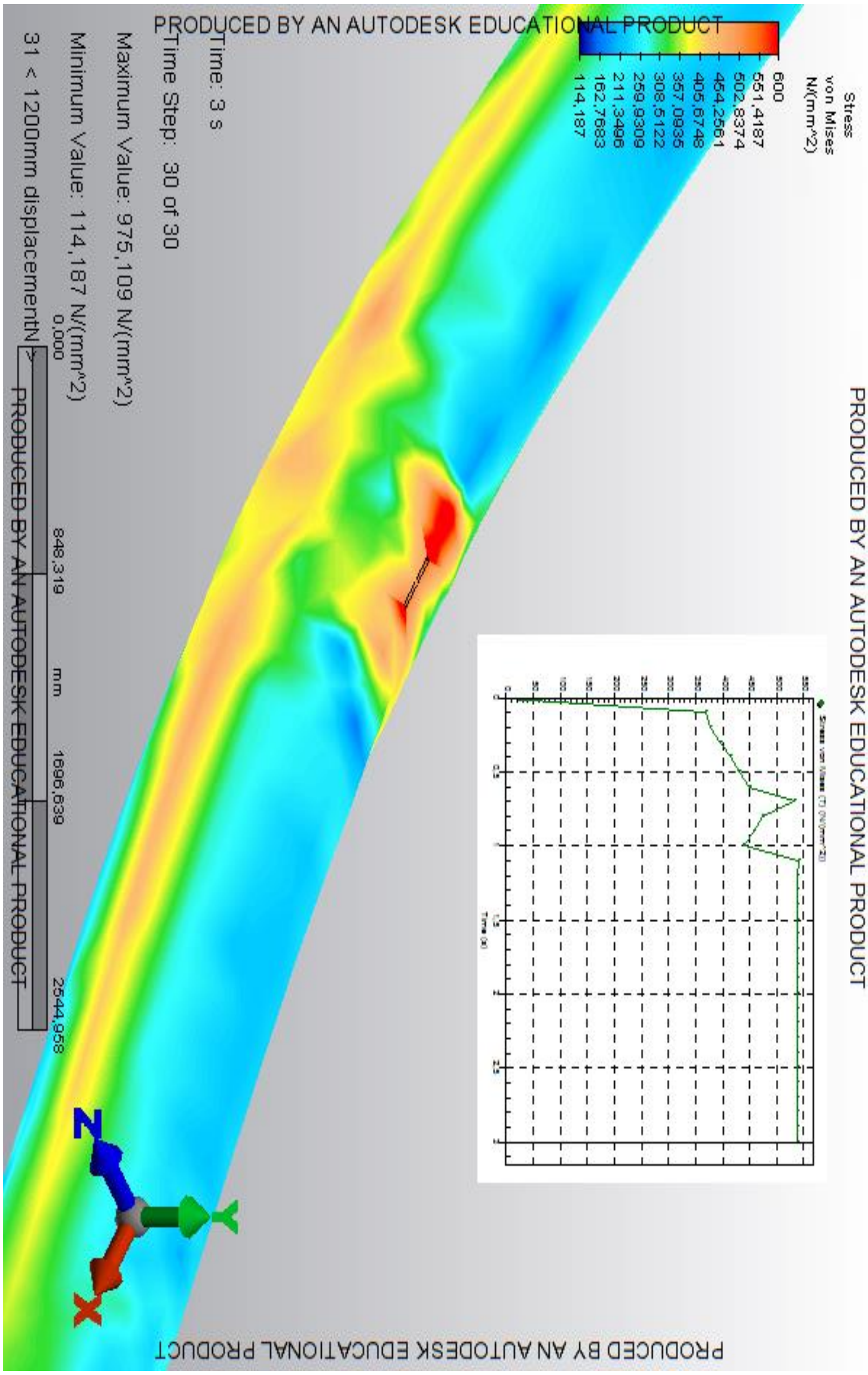
FEA Object Group 6: Nodal Prescribed Displacements

Nodal Prescribed Displacement

ID	Description	Coordinates at Time=0	Type	Magnitude	Direction	Coordinate System	Active Range Index	Load Curve Number
2	Unnamed	X=246,674 Y=457,2 Z=5,59909e-014	Translational	1200	Vector X=0 Y=-1 Z=0	Global	1	1
3	Unnamed	X=-246,407 Y=457,2 Z=5,59909e-014	Translational	1200	Vector X=0 Y=-1 Z=0	Global	1	1

Results Presentation Images

Stress



Displacement